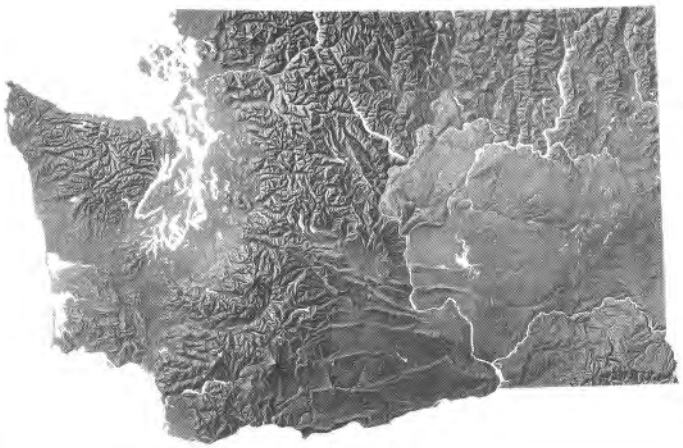

WASHINGTON GEOLOGY

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Cross-bedded sandstone of the Governors Point Member of the Chuckanut Formation at an outcrop west of Bellingham. S. Y. Johnson (USGS) interprets these as braided river deposits; their source was a rapidly eroding highland on and near Lummi Island. See related article, p.12. Photo by T. J. Walsh.

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WASHINGTON GEOLOGY

Washington Geology (formerly the Washington Geologic Newsletter) is published four times a year by the Washington Division of Geology and Earth Resources, Department of Natural Resources. This publication is free upon request. The Division also publishes bulletins, information circulars, reports of investigations, geologic maps, and open-file reports. A list of these publications will be sent upon request.

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The Value of Division Products

by Raymond Lasmanis

A question frequently addressed to geologists is: "What is the worth of a geological or geophysical report?" Pragmatic economists will ask for cost-benefit analyses, annual performance measures, and workload/output estimates. The Division's products cannot be easily analyzed in these terms.

The legislation that established the Division states that the Division has the responsibility to examine the economic mineral resources and geological features of the state with reference to their practical bearing on the occupations and well-being of the public. The results of those examinations appear in our publications.

One practical application of geologic data is their use in developing mineral targets that, after exploration, may develop into viable mining enterprises. An example of the value of the Division's work was recently related by Walt H. Hunt, Superintendent of Technical Services with Echo Bay Minerals Co. He stated that the exploration for and discovery of the gold deposits at the new Overlook, Key West, and Key East mines in Ferry County were directly related to two Division reports: Bulletin 37, Inventory of Washington minerals, Part II, Metallic minerals, published in 1956, and Report of Investigations 20, Geological interpretation of airborne magnetometer and scintillometer survey—Mt. Bonaparte, Bodie Mountain, Curlew, Aeneas, and Republic quadrangles, Okanogan and Ferry Counties, Washington, released in 1960. The resulting economic benefits to Ferry County and the state demonstrate the utility and value of these two Division products.

Much geologic literature is based on observations that remain useful long after they were made. A publication produced by the Division may sit on a library shelf for years, but applicability of its data, observations, or mapping—its value—is not diminished by time. ⚒

Oil and Gas Lease Auction

The Washington Department of Natural Resources has set February 27, 1992, as the date for a public auction of oil and gas leases for exploration and development. This sealed-bid auction will be held in Olympia, Washington. The Department is accepting bidders' nominations of specific parcels on state-owned lands for inclusion in this auction list.

For applications to nominate parcels for the lease auction, contact Nancy Joseph, Department of Natural Resources, Division of Lands and Minerals, P.O. Box 47014, Olympia, WA 98504-7014 or phone her at 206/586-6382. Each lease application, regardless of the size of the parcel, must be accompanied by a $25 application fee and a bid deposit of $150. The bid deposit of a successful bidder will be credited against the first year's annual rent; it will be refunded if the bidder is not successful. The deposit is forfeited if the successful bidder fails to execute the lease.

The announced deadline for receipt of applications was November 21, but later applications will be considered for the auction if there is sufficient time to complete the necessary field work and environmental review.

Northwest Petroleum Association Symposium

The following extended abstracts are from papers given at the 8th Annual Northwest Petroleum Association Symposium held September 8–10 in Bellingham. About 75 people attended the meeting and participated in the field trip.

The theme of the symposium was the geology and petroleum potential of the Georgia Basin and Bellingham subbasin. The first several abstracts present a regional tectonic overview. They are followed by more detailed discussions of structural, stratigraphic, and sedimentologic features of basins in the region, treated from north to south.

Hydrocarbon, coalbed methane, and geothermal energy potentials of the region were also discussed. Other speakers presented information about pipeline marketing, legal aspects of underground storage of natural gas, and the petroleum geochemistry of Washington.

The field trip, led by S. Y. Johnson of the U.S. Geological Survey, made stops at several outcrops near Bellingham of the Paleocene(?) and Eocene Chuckanut Formation, an unusually thick siliciclastic alluvial and deltaic sequence. (See cover photo.)

Late Mesozoic to Recent Evolution of the Georgia Strait–Puget Sound Region, British Columbia and Washington

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In the Georgia Strait–Puget Sound region, hydrocarbons occur locally in Upper Cretaceous to Neogene marine and nonmarine "molassic" clastic rocks of the Nanaimo Group and Chuckanut, Huntingdon and younger formations. These clastic rocks were derived from uplifted areas mainly in the Coast Mountains and north Cascade Range. Prior to Late Cretaceous time, these areas were marine basins. In early Late Cretaceous time, inter- or intra-arc collision of material now in the southwestern Coast Mountains and Vancouver Island with earlier accreted material to the east (southeastern Coast Mountains and Intermontane Belt, Fig. 1) caused rapid uplift and consequent erosion within the southeastern Coast and northern Cascade mountains. This collision was possibly associated with rapid convergence between the North American and various Pacific plates at this time. Since early Late Cretaceous time, the region has been located on the North American plate margin above an east-dipping subduction zone, where fault motion has varied from convergent to dextral transcurrent. Today, Upper Cretaceous to Neogene clastic deposits are preserved in a Neogene to Recent downwarp of regional extent (Georgia–Puget Depression; Figs. 1, 2A) and in local downdropped fault blocks.

Basements: Upper Cretaceous to Recent Clastic Sedimentation

The record of tectonic settings extant during deposition of the Upper Cretaceous to Recent clastic rocks is most completely preserved or inferred from evidence in the three basements on which these rocks were deposited: (1) the Wrangellia terrane, which forms much of Vancouver Island;

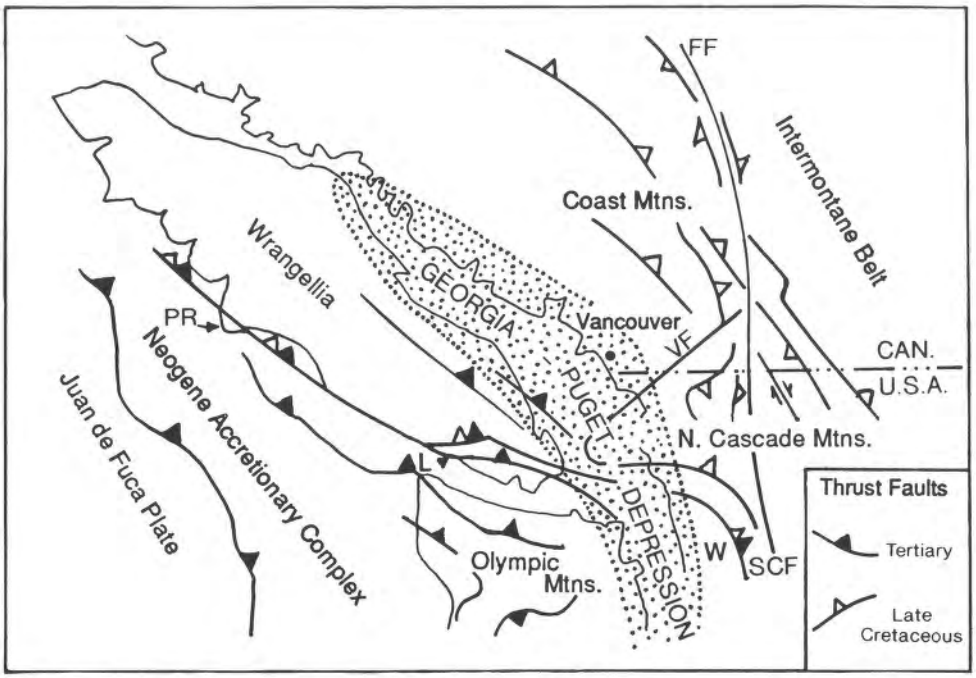

Figure 1. Major morphogeological provinces of the Georgia Strait–Puget Sound region. PR, Pacific Rim Complex; L, Leech River Schist; W, Western melange belt; FF, Fraser fault; SCF, Straight Creek fault; VF, Vedder fault.

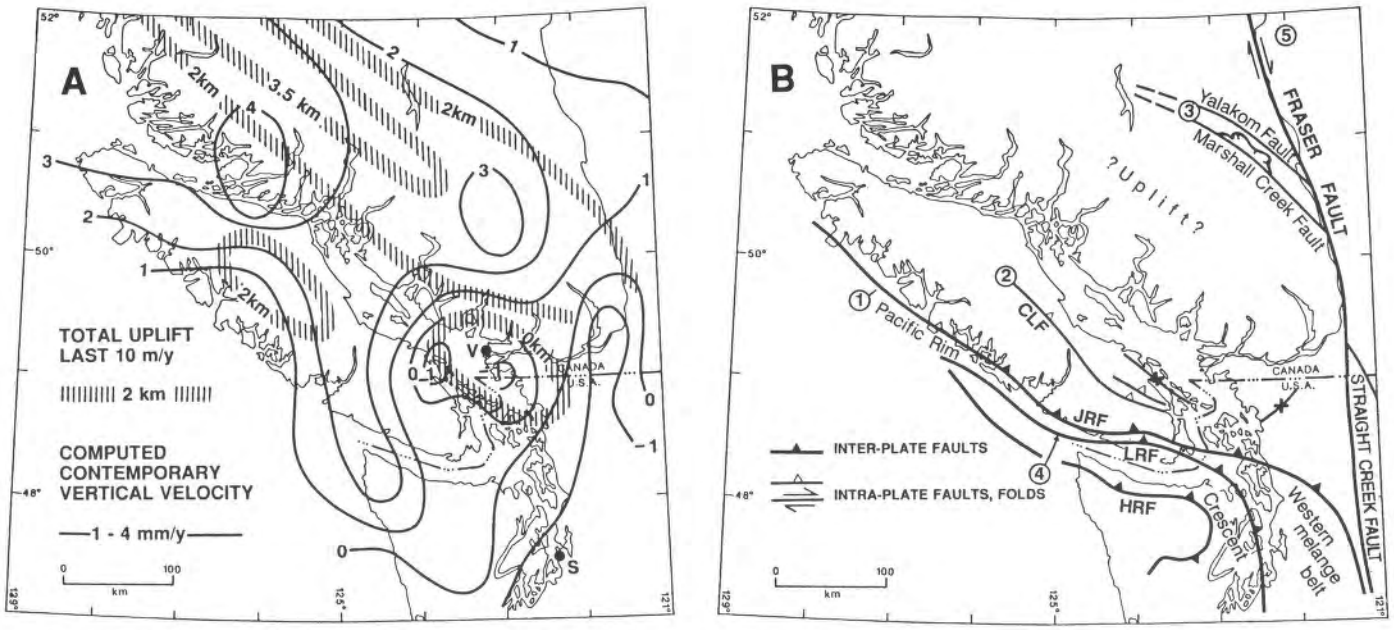

Figure 2. A. Vertical movements in the last 10 m.y. Contours showing total uplift in this period have been drawn assuming that the land surface was at sea level 10 m.y. ago and the geothermal gradient was 25°C/km (Parrish, 1983). Computed contemporary vertical velocity is taken from Holdahl and others (1989). V, Vancouver; S, Seattle.

B. Early Tertiary structural features. 1. Late Cretaceous–early Tertiary (pre-53 Ma) contraction; JRF, Jordan River fault. 2. Late Cretaceous(?)–early Tertiary(?) contraction; CLF, Cowichan Lake fault (Cowichan fold and thrust belt of England and Calon, 1991). 3. Early Tertiary (ca. 45 Ma) extension and uplift. 4. Early Tertiary (ca. 40 Ma) contraction; LRF, Leech River fault. 5. Early Tertiary (45–35 Ma) right-lateral displacement of 80–(?)180 km; HRF, Hurricane Ridge fault, is late Eocene or younger.

(2) the Coast Mountains; and (3) the north Cascade Range (Fig. 1). The Olympic Mountains contribute important information about the very late evolution of the region.

(1) *Wrangellia* consists of Devonian through Jurassic subgreenschist-facies sedimentary volcanic strata, as well as granitic intrusions comagmatic with some of the volcanic rocks. LITHOPROBE seismic reflection profiling shows that this terrane is an east-dipping, internally imbricated thrust sheet as much as 20 km thick. Upper Cretaceous Nanaimo strata were deposited on Wrangellia and are involved in the imbrication, which is probably of Eocene age (Fig. 2B) (Clowes and others, 1987; England and Calon, 1991).

Wrangellia on Vancouver Island forms the uppermost element of a thrust stack of crustal dimensions. Thrust fault-bounded elements structurally below Wrangellia, from top to base, are: (i) Triassic to Cretaceous clastic and volcanic rocks of the Pacific Rim Complex and Leech River Schist exposed on westernmost and southern Vancouver Island; (ii) Eocene basic volcanic rocks exposed on southern Vancouver Island and correlative with those in the Olympic Mountains (Mechosin = Crescent Formations); (iii) a Neogene accretionary complex that is submerged except in the Olympic Mountains; and (iv) the presently subducting oceanic Juan de Fuca Plate (Fig. 1).

East of Vancouver Island, the presence of Wrangellian strata within the mainly granitic western Coast Mountains shows these two basements were together by Late Jurassic time (170 Ma) (Monger, 1991a).

(2) *The southern Coast Mountains*, composed predominantly (80%) of granitic rocks, consists of two parts (Crickmay, 1930; Friedman and Armstrong, 1990; Monger, 1990, 1991a; J. M. Journeay and R. M. Friedman, written commun., 1991). The *southwestern part* located west of Harrison Lake (100 km east of the city of Vancouver) features granitic rocks of Late Jurassic and Early Cretaceous ages (170–100 Ma), minor septa and fault slices of Upper Triassic to Lower Cretaceous strata (in part, Wrangellia), Jurassic and Cretaceous normal faults, and on its eastern side, southwest-directed thrust faults. The *southeastern part* (east of Harrison Lake) consists of Upper Cretaceous and lower Tertiary granitic rocks (100–45 Ma), a variety of terranes ranging in age from late Paleozoic to Cretaceous, and early Late Cretaceous (96–92 Ma) southwest-vergent thrust faults interleaved with partly coeval, partly younger, orogen-parallel dextral strike-slip faults (Fig. 2C). Metamorphic grade is mainly greenschist in the southwestern part of the Coast Mountains, but drops to zeolite and lawsonite–albite facies near Harrison Lake. The grade rises rapidly east of Harrison Lake to amphibolite facies and drops to subgreenschist facies farther east.

Preliminary evidence suggests that the Coast Mountains have undergone several episodes of uplift since mid-Cretaceous time. P-T-t studies in the southeastern Coast Mountains (Journeay, 1990) suggest that the rocks there underwent about 10–15 km of uplift between 96 Ma and 85 Ma. Products of erosion of this uplift presumably are major contributors to Nanaimo sedimentation, which was initiated in the Turonian (91–88 Ma; J. Haggart, Geol. Surv. of Canada, oral commun., 1990). Subsequently, the easternmost Coast Mountains were elevated in later Cretaceous time, and in late Eocene time, mid-crustal (10+ km deep) rocks were exposed on normal faults (Fig. 2B) (Coleman and Parrish, in press), although it is not clear how much, if any, regional elevation could result from this deformation. Finally, the mountains were elevated by as much as 4 km in the last

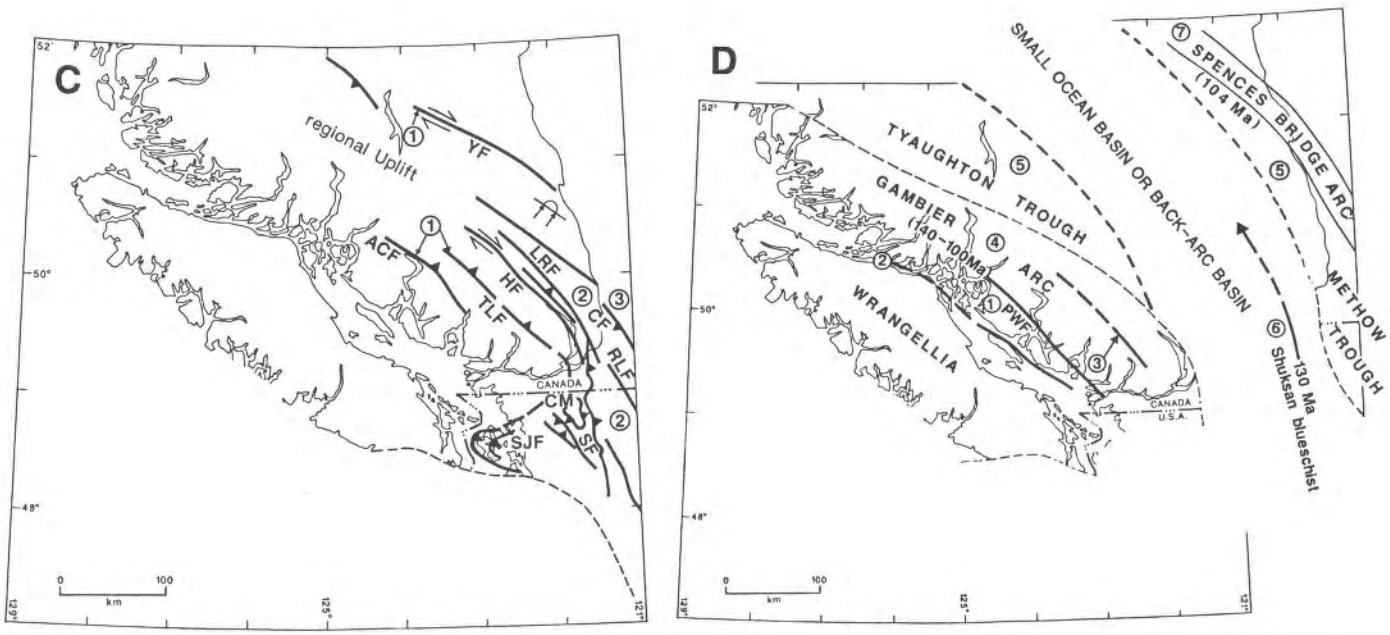

Figure 2 (continued). **C.** Late Cretaceous (earliest Tertiary?) structural features. 1. Early Late Cretaceous (92–96 Ma) major southwest-directed intra- and(?) interplate thrusts (ACF, Ashlu Creek fault; TLF, Thomas Lake fault; LRF, Lillooet River fault; SF, Shuksan fault; CM, Church Mountain fault; SJF, San Juan fault) and contemporaneous and later dextral strike-slip faults (HF, Harrison fault; YF, Yalakom fault). 2. Area of high-grade Barrovian metamorphism. 3. Post-84 but pre-48 Ma northeast-directed thrust (CF, Chuwanten fault; RLF, Ross Lake fault).

D. Late Cretaceous to Early Jurassic structures. 1. Middle to Late Jurassic (185–155 Ma) tight to isoclinal folding, southwest Coast Belt. 2. Late Jurassic(?) (ca. 155 Ma) normal faulting; coeval plutonism, southwest boundary of Coast Belt. 3. Early Cretaceous normal faulting (PWF, Prince of Wales fault); widespread in southwest Coast Belt; coeval with 4. 4. Early Cretaceous (138–102 Ma) Gambier Arc (plutonic and volcanic rocks). 5. Early Cretaceous (and older) sedimentation indicating the presence of Late Jurassic–Early Cretaceous Methow and Tyaughton troughs. 6. Early Cretaceous (ca. 130 Ma) blueschist metamorphism. 7. Early Cretaceous (104 Ma) Spences Bridge Arc.

10 million years (Parrish, 1983), and they are currently rising at rates between 1 and 4 mm/yr (Holdahl and others, 1989). More work is needed to clarify timing and amount of uplift in these episodes, but all created potential sources for the molassic clastic sedimentation.

Interpretation of LITHOPROBE seismic reflection profiling (Clowes, 1990; J. Varsek, Univ. of Calgary, written commun., 1991) shows Wrangellian and structurally lower thrust sheets dipping east beneath the westernmost Coast Mountains to depths of 45 km, but much of the remainder of the southwestern Coast Mountains, an area of high heat flow, shows poor reflectivity. The eastern Coast Mountains have a flat Moho at 32 km, above which east-dipping reflectors, correlated with the early Late Cretaceous west-vergent thrust faults at the surface, are intercepted at depths of 10–15 km by west-dipping reflectors. These reflectors are probable images at depth of east-vergent, slightly younger thrusts that surface on the east side of the Coast and north Cascade mountains (Fig. 2C) (Rusmore and Woodsworth, 1991). The east- and west-dipping thrust faults are believed by the writer to be responsible for the major, initial elevation of the eastern Coast Belt (and probably its southward continuation, the Cascade Metamorphic Core).

The Fraser River is the physiographic boundary between the Coast Mountains and the north Cascade mountains along strike. The eastern boundary of the Coast Belt is marked by the north-trending late Eocene (46–35 Ma) Fraser fault (FF, Fig. 1; Fig. 2B; called Straight Creek fault in Washington and labelled SCF in Fig. 1). This is a strike-slip fault that acutely transects and dextrally displaces older rocks and orogen-parallel structures for distances variously estimated at between 80 and 180 km. (The most recent estimation uses piercing points of Permian and Eocene ages to suggest a displacement of about 145 km.) The southern boundary of the Coast Belt is the Neogene (25–16? Ma), probably extensional Vedder fault (VF, Fig. 1).

The Tertiary faults disrupt and obscure the fundamental Upper Cretaceous–lowest Tertiary regional fabric. Rock units, structures, and the metamorphic and plutonic history of the *southeastern* Coast Mountains are reflected in along-strike elements of the North Cascades (Monger, 1991b). The *southwestern* part of the southern Coast Mountains is represented in the North Cascades by strata (Wells Creek volcanic and Nooksack clastic rocks) exposed only in the small Mount Baker window, although early Late Cretaceous thrust faults in the eastern side of the southwestern Coast Belt have the same vergence and age as those in the Northwest Cascade system (NWCS) (Brown, 1987).

(3) *The North Cascade mountains* comprise three discrete structural and metamorphic domains (Misch, 1966; Tabor and others, 1989): (i) on the west, the NWCS features subgreenschist terranes containing stratified rocks ranging in age from Devonian through Cretaceous and cut by mainly early Late Cretaceous west-vergent thrust and dextral orogen-parallel strike-slip faults; (ii) east of this, and separated from it by the Eocene Straight Creek (= Fraser) fault, the core of the North Cascades is made up of amphibolite and greenschist-facies metamorphic and granitic rocks that have

been affected by Late Cretaceous and Early Tertiary metamorphism and intrusion; and (iii) the eastern Cascades, mainly subgreenschist Carboniferous through Cretaceous strata and local Tertiary granitic rocks, are involved in east-vergent thrust faulting near latitude 49°N (Fig. 2C).

Currently, considerable but unresolved debate concerns the relative importance of Late Cretaceous–earliest Tertiary contractional and dextral transcurrent displacements in North Cascades evolution (Brown, 1987; Brandon and others, 1988). The writer favors the dominance of contraction, although there is no doubt that structures representing both structural regimes are present. Palinspastic reconstruction suggests that the Cascades underwent a *minimum* of between 400 and 500 km of east-west contraction in middle to early Late Cretaceous time (115–85 Ma; McGroder, 1991). As in the eastern Coast Mountains, the Cascades underwent very rapid uplift between 100 Ma and 84 Ma, and material derived from northwest Cascades thrust sheets contributed to Nanaimo sedimentation (Brandon and others, 1988). As in along-strike parts of the Coast Mountains, the eastern part of the metamorphic core underwent early Tertiary exposure (Tabor and others, 1989; McGroder, 1991).

Between the Cascade and Olympic mountains, in the westernmost Cascade foothills, is a tract of complexly deformed Jurassic and Cretaceous clastic and volcanic rocks called the Western Melange Belt by Frizzell and others (1987; W of Fig. 1). It is possibly correlative with rocks on southern and western Vancouver Island (Leech River; Pandora Peak; Pacific Rim; L and PR of Fig. 1) that on Vancouver Island are shown by seismic reflection profiling to be structurally sandwiched between overlying Wrangellian and underlying Olympic thrust sheets. The upper thrust is dated at pre-54 Ma and the lower one at 42 Ma. England and Calon (1991) suggest that Nanaimo Group imbrication (their Cowichan fold and thrust system) occurred during accretion of sub-Wrangellian material.

The regional significance of this tract is that in Washington it is juxtaposed against rocks belonging to the NWCS, whereas in British Columbia it is separated from rocks in the southeastern Coast Mountains probably correlative with those in the NWCS by a distance of 200 km. This gap is filled with Wrangellian rocks and those of the southwestern Coast Mountains (Fig. 1; Monger, 1991b). The bifurcation of western Cascades structures around a block in the western Coast Mountains was recognized long ago by Crickmay (1930) and Misch (1966). Wrangellian and western Coast Mountains rocks, largely absent from the NWCS, appear to form a large, relatively rigid block within the evolving Late Cretaceous and early Tertiary thrust complex (Fig. 2D). This block acts as *foreland* to early Late Cretaceous west-directed thrust faulting; Nanaimo sedimentation took place on it (Fig. 2C).

(4) *The Olympic Mountains* comprise an east-dipping arcuate rim of Eocene basalt (Crescent, Mechosin Formations) that is separated by a major fault from a subduction-underplated, thrust-imbricated core of Eocene to Miocene strata (Neogene accretionary complex, Fig. 1; Tabor and Cady, 1978; Brandon and Calderwood, 1990). Although a similar configuration occurs north and south of the Olympics, the rocks in those places are not as strongly elevated as they are in the Olympics. The origin of uplift of the Olympics is unclear; most recently, Brandon and Calderwood (1991) argue that Neogene (12–7 Ma) uparching of the core to form the present Olympic Mountains is a response to westward Basin and Range extension to the south, with a pivot in this region.

Tectonic Settings: Late Cretaceous to Recent Rocks

(1) The writer agrees with Brandon and others (1988) that *Late Cretaceous and (?) earliest Tertiary* Nanaimo deposition was most probably in a foreland basin setting and was associated with west-vergent thrust faulting, crustal thickening, and regional uplift in the eastern Coast and North Cascade mountains (Fig. 2C). The basin clastics are currently separated from their Coast Mountains sources by Neogene uplift and erosion. The basin may have extended far to the west of its present area; Vancouver Island is tilted eastward, and its western parts are the most deeply eroded. Alternatively, as suggested most recently by England and Calon (1991), Nanaimo sedimentation was in a forearc setting relative to Late Cretaceous plutonism in the eastern Coast and Cascade Mountains. It may be that neither "foreland" nor "forearc" are appropriate terms to describe the setting of this basin, but regardless, deposition appears to be related to structurally controlled elevation of rocks in the eastern Coast and central Cascade mountains.

(2) The *lower Tertiary* Chuckanut and Huntingdon Formations, derived from the Coast and North Cascade mountains, probably were deposited in a similar general setting and related to uplift of that age. Although Johnson (1985) suggested that deposition was in pull-apart basins related to dextral strike-slip faults, all early Tertiary strike-slip faults so far recognized are in the eastern Coast and Cascade mountains, well east of the main depocenters (Figs. 2B, 2C). Possibly the Wrangellian–southwestern Coast Mountains block moved northward faster than the Cascades during Paleocene to middle Eocene time on such *orogen-parallel* dextral strike-slip faults as the Ross Lake, Yalakom, and (?)Harrison faults. The acutely cross-cutting Fraser–Straight Creek fault appears to be too young (late Eocene or Oligocene) to leave pull-apart basins behind in which rocks as old as Chuckanut were deposited. In addition, preservation of these sediments is at least in part due to downdropping on Neogene northeast-trending extensional faults (for example, VF of Fig. 1) that locally show small dextral displacements.

(3) *Neogene and Recent* sedimentation, mainly in the area near the postglacial Fraser River delta, is partly controlled by northeast- and(?) north-northwest-trending faults, perhaps coupled with active downwarping at a present-day rate of 1 mm/yr near the International Boundary south of Vancouver (Fig. 2A).

References Cited

Brandon, M. T.; Calderwood, A. R., 1990, High-pressure metamorphism and uplift of the Olympic subduction complex: Geology, v. 18, no. 12, p. 1252–1255.

Brandon, M. T.; Cowan, D. S.; Vance, J. A., 1988, The Late Cretaceous San Juan thrust system, San Juan Islands, Washington: Geological Society of America Special Paper 221, 81 p., 1 plate.

Brown, E. H., 1987, Structural geology and accretionary history of the northwest Cascades system, Washington and British Columbia: Geological Society of America Bulletin, v. 99, no. 2, p. 201–214.

Clowes, R. M., 1990, LITHOPROBE—Multidisciplinary studies of continental evolution; An example from western Canada. *In* Proceedings, Pacific Rim Congress '90, Australasian Institute of Mining and Metallurgy, Gold Coast, Queensland, May 6–12, 1990: Australasian Institute of Mining and Metallurgy, III, p. 83–97.

Clowes, R. M.; Brandon, M. T.; Green, A. G.; Yorath, C. J.; Sutherland Brown, A.; Kanasewich, E. R.; Spencer, C. J., 1987, LITHOPROBE—Southern Vancouver Island—Cenozoic subduction complex imaged by deep seismic reflections: Canadian Journal of Earth Sciences, v. 24, no. 1, p. 31–51.

Coleman, M. E.; Parrish, R. R., in press, Eocene dextral strike-slip and extensional faulting in the Bridge River terrane, southwestern British Columbia: Tectonics.

Crickmay, C. H., 1930, The structural connection between the Coast Range of British Columbia and the Cascade Range of Washington: Geological Magazine, v. 67, no. 797, p. 482–491.

England, T. D. J.; Calon, T. J., 1991, The Cowichan fold and thrust system, Vancouver Island, southwestern British Columbia: Geological Society of America Bulletin, v. 103, no. 3, p. 336–362.

Friedman, R. M.; Armstrong, R. L., 1990, U-Pb dating, southern Coast Belt (49°–51°), southwestern British Columbia—Proceedings, LITHOPROBE: Southern Canadian Cordilleran Workshop, University of Calgary, Calgary, Alta, p. 146–155.

Frizzell, V. A., Jr.; Tabor, R. W.; Zartman, R. E.; Blome, C. D., 1987, Late Mesozoic or early Tertiary melanges in the western Cascades of Washington. *In* Schuster, J. E., editor, Selected papers on the geology of Washington: Washington Division of Geology and Earth Resources Bulletin 77, p. 129–148.

Holdahl, S. R.; Faucher, Francois; Dragert, Herb, 1989, Contemporary vertical crustal motion in the Pacific Northwest. *In* Cohen, S. C.; Vanicek, Petr, editors, Slow deformation and transmission of stress in the Earth: American Geophysical Union IUGG Geophysical Monograph 49, v. 4, p. 17–29.

Johnson, S. Y., 1985, Eocene strike-slip faulting and nonmarine basin formation in Washington. *In* Biddle, K. T.; Christie-Blick, Nicholas, editors, Strike-slip deformation, basin formation, and sedimentation: Society of Economic Paleontologists and Mineralogists Special Publication 37, p. 283–302.

Journeay, J. M., 1990, A progress report on the structural and tectonic framework of the southern Coast Belt, British Columbia. *In* Current Research, Part E: Geological Survey of Canada Paper 90-1E, p. 183–195.

McGroder, M. F., 1991, Reconciliation of two-sided thrusting, burial metamorphism, and diachronous uplift in the Cascades of Washington and British Columbia: Geological Society of America Bulletin, v. 103, no. 2, p. 189–209.

Misch, Peter, 1966, Tectonic evolution of the northern Cascades of Washington—A west-cordilleran case history. *In* Canadian Institute of Mining and Metallurgy; and others, A symposium on the tectonic history and mineral deposits of the western Cordillera in British Columbia and neighbouring parts of the United States, Vancouver, 1964: Canadian Institute of Mining and Metallurgy Special Volume 8, p. 101–148.

Monger, J. W. H., 1990, Georgia Basin—Regional setting and adjacent Coast Mountains geology, British Columbia. *In* Current Research, Part F: Geological Survey of Canada Paper 90-1F, p. 95–108.

Monger, J. W. H., 1991a, Georgia Basin Project—Structural evolution of parts of southern Insular and southwestern Coast belts, British Columbia. *In* Current Research, Part A: Geological Survey of Canada Paper 91-1A, p. 219–228.

Monger, J. W. H., 1991b, Correlation of Settler Schist with Darrington Phyllite and Shuksan Greenschist and its tectonic implications, Coast and Cascade mountains, British Columbia and Washington: Canadian Journal of Earth Sciences, v. 28, no. 3, p. 447–458.

Parrish, R. R., 1983, Cenozoic thermal evolution and tectonics of the Coast Mountains of British Columbia; 1. Fission track dating, apparent uplift rates, and patterns of uplift: Tectonics, v. 2, no. 6, p. 601–631.

Rusmore, M. E.; Woodsworth, G. J., 1991, Coast Plutonic Complex—A mid-Cretaceous contractional orogen: Geology, v. 19, no. 9, p. 941–994.

Tabor, R. W.; Cady, W. M., 1978, The structure of the Olympic Mountains, Washington—Analysis of a subduction zone: U.S. Geological Survey Professional Paper 1033, 38 p.

Tabor, R. W.; Haugerud, R. A.; Brown, E. H.; Babcock, R. S.; Miller, R. B., 1989, Accreted terranes of the North Cascades Range, Washington—Spokane to Seattle, Washington[,] July 21–29, 1989: International Geological Congress, 28th, Field Trip Guidebook T307, 62 p.

Geological Survey of Canada Contribution number 20491

Stratigraphy and Sedimentology of the Georgia Basin, British Columbia and Washington State

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The Georgia Basin is a northwest-trending structural and topographic depression that includes Georgia Strait, eastern Vancouver Island, the Fraser River lowlands of British Columbia, and northwest Washington State (Fig. 1A). Sedimentary rocks of the Georgia Basin comprise two main packages: the Upper Cretaceous Nanaimo Group, exposed mainly on the east side of Vancouver Island and on the Gulf Islands of Georgia Strait; and Paleocene to Miocene rocks exposed in the Vancouver area and northwest Washington and preserved in the subsurface beneath the Quaternary to Recent glacial and interglacial deposits, including those of the Fraser River delta (Fig. 1B).

The main structural control on the sub-Georgia Basin rocks and to some extent Georgia Basin itself is southwest- to west-vergent thrusting that took place from Late Jurassic to Holocene time as a response to underthrusting of the Farallon/Kula (now Juan de Fuca) oceanic plate beneath the North American plate. The present Georgia Basin is an

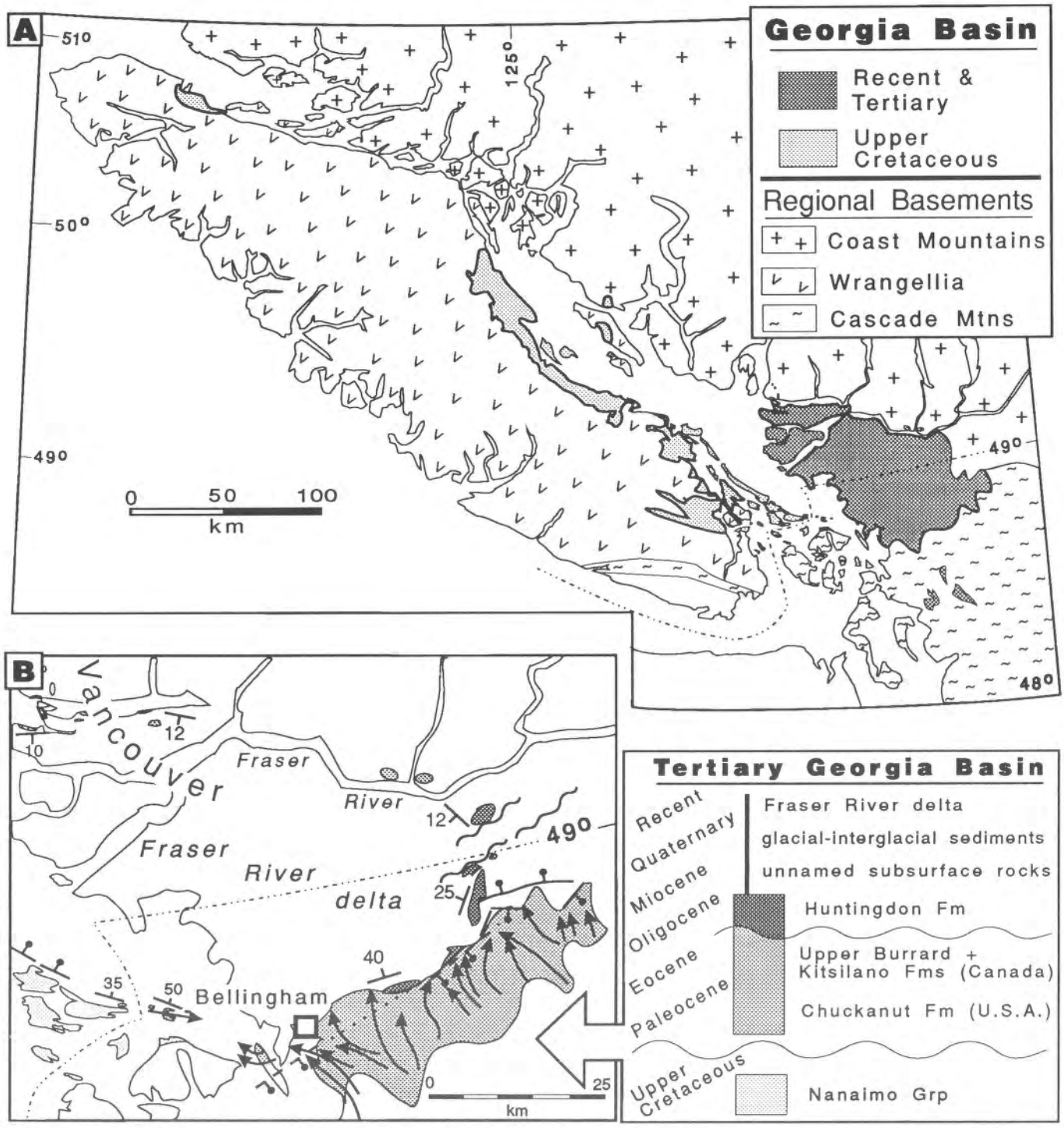

Figure 1. A. Regional setting of Georgia Basin. **B.** The Tertiary part of Georgia Basin (Bellingham or Whatcom basin of some authors) showing the major outcrop belts that define the present margins of the basin. Arrowed lines in the northwest Washington outcrop belts are surface traces of major fold axes. These folds generally trend and plunge to the northwest.

erosional remnant, and its configuration is largely the result of post-depositional deformation. The extent of the original basin is not well constrained; for much of its depositional history, the basin appears to have extended considerably farther to the west.

The Nanaimo Group comprises as much as 4 km of sedimentary rocks of Turonian to Maastrichtian age. The strata are commonly subdivided into nine formations comprising conglomerate, sandstone, and mudstone, with significant coal deposits in the lower formations. The basal, coal-bearing units formed in coastal plain to deltaic environments (Muller and Jeletzky, 1970). The upper six formations of the Nanaimo Group occur as a tripartite stack of megasequences that generally coarsen upward. These megasequences are hundreds of meters to more than a kilometer thick in some places. Each is made up of a basal mudstone-dominated unit that commonly coarsens and thickens up to sandstone- or conglomerate-dominated upper units. Internal lateral and ver-

tical thickness and facies variations are common, but the megasequences contain abundant features characteristic of submarine fan complexes (Pacht, 1984; England, 1990).

Interpretations of the tectonic controls on basin history have included forearc, strike-slip, and foreland tectonic models (Muller and Jeletzky, 1970; Pacht, 1984; Brandon and others, 1988; England, 1990). Recent evidence supports the foreland tectonic model in which most material was derived from the Coast Belt to the east and northwest Cascades to the southeast and shed onto a foreland of the Paleozoic and Mesozoic Wrangellia terrane and the western Coast Belt (Mustard and Monger, 1991). Late Cretaceous southwest-vergent thrusting has recently been documented in the Coast Belt east of the Georgia Basin (Journeay, 1990; Monger, 1990). Current radiometric constraints on the timing of the thrusting are 96–92 Ma, predating the oldest known Nanaimo Group rocks (about 91–88 Ma). However, the age of many thrusts is not precisely constrained. The small difference between the known age of thrusting and initial Nanaimo Group deposition suggests that thrusting influenced at least initial basin formation.

Most of the strata exposed on the British Columbia–Washington mainland are of Tertiary ages. The major exception is a 600-m-thick Upper Cretaceous succession of fluvial sandstone, mudstone, and minor conglomerate in the Vancouver area that forms the lower part of the Burrard Formation (Rouse and others, 1975). The upper part of the Burrard Formation and the overlying Kitsilano Formation are Eocene fluvial clastic rocks derived from the east or northeast. In Washington, Eocene (locally Paleocene) strata of the Chuckanut Formation comprise as much as 6 km of nonmarine conglomerate, sandstone, mudstone, and minor coal. Deposition occurred in meandering and braided fluvial deposystems in which alluvial fan deposits accumulated in areas proximal to preserved synsedimentary normal faults (Johnson, 1984). The Huntingdon Formation is upper Eocene to Oligocene succession of terrestrial clastic rocks as much as 500 m thick that unconformably overlies the Chuckanut Formation east of Bellingham and Cascade or Coast Belt metavolcanic rocks in the Sumas area. In the upper Fraser Valley, the Huntingdon Formation comprises repeated coarsening-upward megasequences (100-m scale) interpreted to be the result of repeated progradation of lower alluvial fan facies over braided stream and floodplain facies. Paleocurrent and clast composition data suggest derivation from the Cascades to the east and southeast.

Movement on northwest-trending dextral strike-slip faults has been inferred to have controlled formation and evolution of the Chuckanut basin (Johnson, 1984, 1985). Recent recognition of a southwest-vergent thrust belt of probable Eocene age in the Nanaimo Group (England and Calon, 1991) suggests reinterpretation of early Tertiary basin models in terms of piggyback basins within an active thrust belt (Mustard and Monger, 1991).

Younger sedimentary rocks of the greater Vancouver area and northwest Washington are known mainly from drilling; as much as 1,200 m of Miocene sandstone and mudstone have been intercepted. These are terrestrial, probably fluvial deposits. The absence of outcrop and lack of detailed subsurface data preclude more detailed interpretation of these younger rocks.

References Cited

Brandon, M. T.; Cowan, D. S.; Vance, J. A., 1988, The Late Cretaceous San Juan thrust system, San Juan Islands, Washington: Geological Society of America Special Paper 221, 81 p., 1 plate.

England, T. D. J., 1990, Late Cretaceous to Paleogene evolution of the Georgia Basin, southwestern British Columbia: Memorial University of Newfoundland Doctor of Philosophy thesis, 481 p.

England, T. D. J.; Calon, T. J., 1991, The Cowichan fold and thrust system, Vancouver Island, southwestern British Columbia: Geological Society of America Bulletin, v. 103, no. 3, p. 336–362.

Johnson, S. Y., 1984, Stratigraphy, age, and paleogeography of the Eocene Chuckanut Formation, northwest Washington: Canadian Journal of Earth Sciences, v. 21, no. 1, p. 92–106.

Johnson, S. Y., 1985, Eocene strike-slip faulting and nonmarine basin formation in Washington. *In* Biddle, K. T.; Christie-Blick, Nicholas, editors, Strike-slip deformation, basin formation, and sedimentation: Society of Economic Paleontologists and Mineralogists Special Publication 37, p. 283–302.

Journeay, J. M., 1990, A progress report on the structural and tectonic framework of the southern Coast Belt, British Columbia: Geological Survey of Canada Paper 90-1E, p. 183–195.

Monger, J. W. H., 1990, Georgia Basin—Regional setting and adjacent Coast Mountains geology, British Columbia: Geological Survey of Canada Paper 90-1F, p. 95–108.

Muller, J. E.; Jeletzky, J. A., 1970, Geology of the Upper Cretaceous Nanaimo Group, Vancouver Island and Gulf Islands, British Columbia: Geological Survey of Canada Paper 69-25, 77 p., 1 plate.

Mustard, P. S.; Monger, J. W. H., 1991, Upper Cretaceous–Tertiary Georgia Basin, British Columbia—Forearc or foreland [abstract]: Geological Association of Canada Annual Meeting Abstracts with Program, v. 16, p. A88.

Pacht, J. A., 1984, Petrologic evolution and paleogeography of the Late Cretaceous Nanaimo Basin, Washington and British Columbia—Implications for Cretaceous tectonics: Geological Society of America Bulletin, v. 95, no. 7, p. 766–778.

Rouse, G. E.; Mathews, W. H.; Blunden, R. H., 1975, The Lions Gate Member—A new Late Cretaceous sedimentary subdivision in the Vancouver area of British Columbia: Canadian Journal of Earth Sciences, v. 12, no. 3, p. 464–471.

Late Cretaceous to Paleogene Structural and Stratigraphic Evolution of Georgia Basin, Southwestern British Columbia: Implications for Hydrocarbon Potential

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Georgia Basin is a large, elongate sedimentary trough that developed on the Pacific margin of North America from Late Mesozoic through Cenozoic time (Fig. 1). At various times the basin has been subject to contractional, extensional, and minor(?) strike-slip displacements in concert with local changes in the tectonic environment. During the Late Cretaceous, the basin subsided rapidly in response to regional crustal downwarping in a large arc-trench system (Dickinson, 1976). The North American plate was rapidly convergent with the Farallon plate and obliquely convergent with the Kula plate during this time; this rapid convergence was synchronous with large-scale Laramide deformation in western North America (Engebretson and others, 1985). The trench is hypothesized to have been situated outboard of Vancouver Island and trench sediments may have been subducted. The position of the arc is evident from igneous rock suites in the Coast Crystalline Complex (Coast Ranges), which establish a

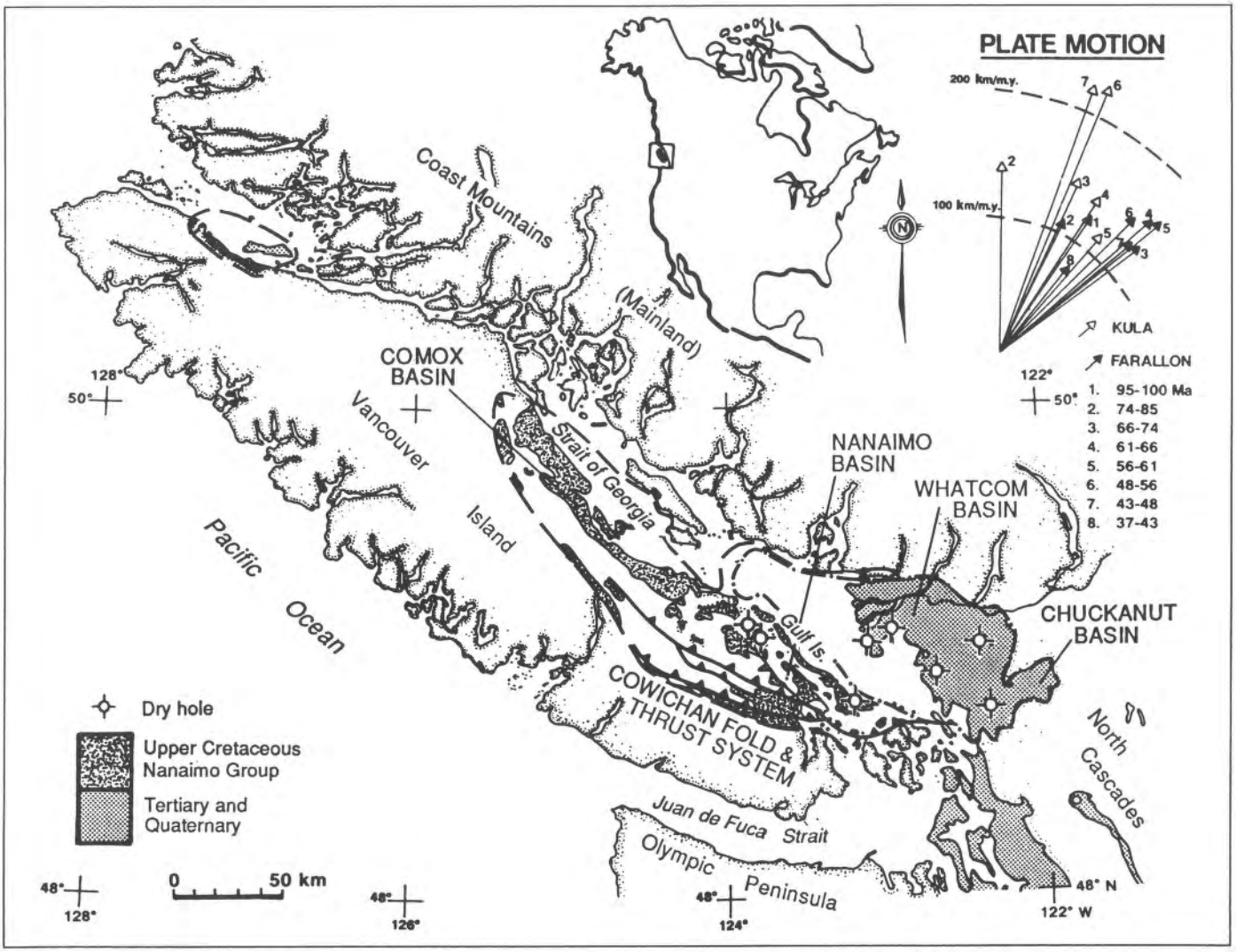

Figure 1. Index map of Georgia Basin showing locations of Cretaceous depocenters (dashed outline), Tertiary depocenters (dash-dot outline), Cowichan fold and thrust system, and key well penetrations. Georgia Basin mainly overlies variously metamorphosed sedimentary and crystalline rocks of Wrangellia. The orientation of Georgia Basin is generally perpendicular to plate-motion vectors of oceanic plates converging with North America (with North America fixed) for the Late Cretaceous to Paleogene; the exception is the Kula–North American plate convergence from 74 to 85 Ma, which is oblique to the orientation of the basin (data from Engebretson and others, 1985). Plate motion vectors show azimuths and rates (100 km/m.y. dashed arc) of convergence for the Farallon and Kula plates for episodes of the Late Cretaceous and Paleogene.

magmatic episode for the period 84 to 64 Ma on the basis of radiometric ages (Muller, 1977; Armstrong, 1988).

The Turonian to Maastrichtian Nanaimo Group (Muller and Jeletzky, 1970; Haggart, 1991) comprises as much as 5 km of siliciclastic sediments that accumulated in Georgia Basin due to an estimated 2.7 km of tectonic subsidence in the inner forearc region. The Nanaimo Group is succeeded by the late Paleocene to Eocene Chuckanut Formation and correlative sedimentary units (for example, Burrard and Kitsilano Formations). The Tertiary depocenters (Whatcom and Chuckanut basins) lay east and southeast of the Late Cretaceous depocenters (Comox and Nanaimo basins).

At about 45 Ma (middle Eocene), at least some of the Paleogene sedimentary units and the Nanaimo Group and its Wrangellian basement were contracted to form the Cowichan fold and thrust system, which comprises large northwest-trending folds and related thrust faults that appear to sole at mid-crustal depths under Georgia Strait (England and Calon, 1991). The fold and thrust system is well exposed in southwestern Georgia Basin, extending from the Gulf Islands to central Vancouver Island. Deformation in the Chuckanut basin appears to be slightly younger (middle to late Eocene; Johnson, 1984) but may be linked to the Cowichan deformation.

Potential reservoir rocks may exist in the Nanaimo Group in fluvial, deltaic, and deep marine sandstones and conglomerates. The majority of the sandstones are lithic to arkosic, although some quartzose sandstones occur, and porosity and permeability measurements of surface and core samples are generally poor to moderate. Good lateral and top seals are expected in the Nanaimo Group. In the Paleogene units, reservoir potential exists in fluvial sandstones, but seal potential is reduced due to the overall high sand content of the units.

Good oil source rocks have not been identified in Georgia Basin. Marine shales of the Nanaimo Group have generally less than 1 percent total organic carbon and moderate to low hydrogen indices and contain mainly dispersed Type III organic matter (Bustin and England, 1991). Some coals and coaly mudstones of the lower Nanaimo Group locally contain as much as 5 percent exinite and may have restricted potential for hydrocarbon liquids (England and others, 1989). In general, the substantial coal deposits in northwestern Georgia Basin are considered excellent gas sources, but these are probably absent in the central, deeper part of Georgia Basin. Better source rocks may exist in the central, undrilled part of the basin where euxinic conditions may have been developed in the deepest marine environment during sedimentation. Source rocks may also be present underlying Georgia Basin in the Triassic section of the Wrangellian basement; their maturity, however, has not been determined. A few gas and gas-condensate seeps occur on the western margin of Georgia Basin.

The Upper Cretaceous to Paleogene sedimentary succession is, in general, mature for hydrocarbon generation (England, 1990). Adjacent to late Eocene and Oligocene shallow intrusions of the Mount Washington Intrusive Suite on eastern Vancouver Island, the Nanaimo Group is overmature, locally attaining maturities (expressed as vitrinite reflectance values) as high as 4.6% R_o. In subthrust positions in southwestern Georgia Basin (and probably beneath some areas of the Tertiary depocenters), the Nanaimo Group is well into the gas window; vitrinite reflectance values are in excess of 1.3% R_o. The Paleogene section is mainly immature to early mature at the surface (0.29–0.66% R_o). Post-middle Eocene uplift and erosion ranges from about 1.6 to 6.6 km in western Georgia Basin, decreasing to about 1 km in eastern Georgia Basin.

In the context of hydrocarbon potential, the major structures and potential traps in Georgia Basin developed in the middle to late Eocene, whereas most of the sediment fill is Upper Cretaceous to lower Eocene. The primary hydrocarbon charge in the basin, initiated by normal burial metamorphism with low geothermal gradients prevailing, clearly *predated* trap formation. Only where special circumstances have created the possibility of a late or secondary hydrocarbon charge is there hydrocarbon potential, either beneath the Paleogene depocenters in eastern Georgia Basin or in subthrust positions in the Cowichan fold and thrust system (that is, where there has been tectonic burial).

References Cited

Armstrong, R. L., 1988, Mesozoic and early Cenozoic magmatic evolution of the Canadian Cordillera. *In* Clark, S. P., Jr.; Burchfiel, B. C.; Suppe, John, editors, Processes in continental lithospheric deformation: Geological Society of America Special Paper 218, p. 55–91.

Bustin, R. M.; England, T. D. J., 1991, Petroleum source rock potential of the Nanaimo Group, western margin of the Georgia Basin, southwestern British Columbia: Geological Survey of Canada Paper 91-1A, p. 143–145.

Dickinson, W. R., 1976, Sedimentary basins developed during evolution of Mesozoic–Cenozoic arc-trench system in western North America: Canadian Journal of Earth Sciences, v. 13, no. 9, p. 1268–1287.

Engebretson, D. C.; Cox, A.; Gordon, R. G., 1985, Relative motions between oceanic and continental plates in the Pacific Basin: Geological Society of America Special Paper 206, 59 p.

England, T. D. J., 1990, Late Cretaceous to Paleogene evolution of the Georgia Basin, southwestern British Columbia: Memorial University of Newfoundland Doctor of Philosophy thesis, 481 p.

England, T. D. J.; Calon, T. J., 1991, The Cowichan fold and thrust system, Vancouver Island, southwestern British Columbia: Geological Society of America Bulletin, v. 103, no. 3, p. 336–362.

England, T. D. J.; Piggott, N.; Douglas, T. R., 1989, Hydrocarbon charge control on the prospectivity of the Georgia Basin, Vancouver Island, British Columbia [abstract]. *In* Exploration update '89: CSEG/CSPG annual Meeting Program with Abstracts.

Haggart, J. W., 1991, A new assessment of the age of the basal Nanaimo Group, Gulf Islands, British Columbia: Geological Survey of Canada Paper 91-1E, p. 77–82.

Johnson, S. Y., 1984, Stratigraphy, age, and paleogeography of the Eocene Chuckanut Formation, northwest Washington: Canadian Journal of Earth Sciences, v. 21, no. 1, p. 92–106.

Muller, J. E., 1977, Evolution of the Pacific margin, Vancouver Island, and adjacent regions: Canadian Journal of Earth Sciences, v. 14, no. 9, p. 2062–2085.

Muller, J. E.; Jeletzky, J. A., 1970, Geology of the Upper Cretaceous Nanaimo Group, Vancouver Island and Gulf Islands, British Columbia: Geological Survey of Canada Paper 69–25, 77 p., 1 plate.

Sedimentation and Tectonic Setting of the Chuckanut Formation, Northwest Washington

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The latest Paleocene(?) to Eocene Chuckanut Formation of northwest Washington comprises about 5,700–6,000 m of alluvial strata and is one of the thickest nonmarine sequences in North America. It is exposed in several disconnected outcrop belts that are remnants of what was probably an extensive fluvial system in western Washington. Six stratigraphic members are defined in the main outcrop belt of the Chuckanut near Bellingham (Figs. 1, 2; stratigraphic nomenclature after Johnson, 1984). Their ages, based on fission-track dates, palynologic studies, and correlation by mapping, range from latest Paleocene(?) to late(?) middle Eocene. Six phases of deposition and (or) deformation are inferred from stratigraphic, sedimentologic, lithologic, and structural data.

The 2,700- to 3,300-m-thick Bellingham Bay Member (Figs. 2, 3A) forms the lowest part of the Chuckanut and consists of vertically stacked, fining-upward cycles of meandering-river origin. The cycles comprise a lower coarser grained unit consisting of sandstone and minor conglomerate and an upper fine-grained unit consisting of mudstone. Mean cycle and coarse-unit thicknesses are 25.6 m and 8.6 m, respectively. Paleocurrent data indicate that sediment transport was to the west-southwest.

The 1,960-m-thick Slide Member overlies the Bellingham Bay Member in the eastern part of the outcrop belt (Figs. 2, 3B, 3C) and similarly consists of east-derived fining-upward cycles of inferred meandering-river origin. Slide Member cycles are much finer grained and thinner (mean cycle and coarse-unit thickness are 14.4 m and 3.8 m, respectively) than those of the Bellingham Bay Member, suggesting an abrupt major decrease in the size and competence of the fluvial system entering the basin from the east. This abrupt change probably reflects a tectonically induced change in the size of the drainage basin.

The transition from the Bellingham Bay Member to the Slide Member coincided with deposition of the Governors Point Member in the western part of the outcrop belt (Figs. 2, 3B). The Governors Point Member consists of sandstone and conglomerate interpreted as braided-river deposits. It has a maximum thickness of 375 m and thins and pinches out to the east. Paleocurrent data indicate that sediment transport was to the southwest. Graywacke, greenstone, and serpentinite detritus indicate that sediments were derived locally from an uplifted block on the north side of the Lummi Island fault.

Similar to the Governors Point Member, the 3,000-m-thick Padden Member (Figs. 2, 3C) is present only in the western part of the outcrop belt. It conformably overlies the Governors Point Member south of Bellingham and, at least locally, unconformably overlies pre-Tertiary bedrock to the north. The Padden Member consists of sandstone, mudstone, and conglomerate interpreted as the deposits of braided rivers and flanking floodplains. Paleocurrent data indicate that sediment transport was to the southeast and southwest. The distinctive petrology and sediment-dispersal patterns for the Padden Member indicate progradation of a second major fluvial system into the basin from the north.

The 800-m-thick Maple Falls Member and the 1,000-m-thick Warnick Member are present at the top of the section in the eastern part of the main outcrop belt (Figs. 2, 3D). These units were probably laterally continuous, but intervening strata have been eroded or cut out by the Boulder Creek fault (Fig. 1). The Maple Falls and Warnick Members consist of conglomerate, sandstone, and mudstone interpreted as the deposits of small, interfingering alluvial fans. Paleocurrent directions are southerly. Conglomerate clasts are as large as 70 cm, and their similarity to local greenstone and chert

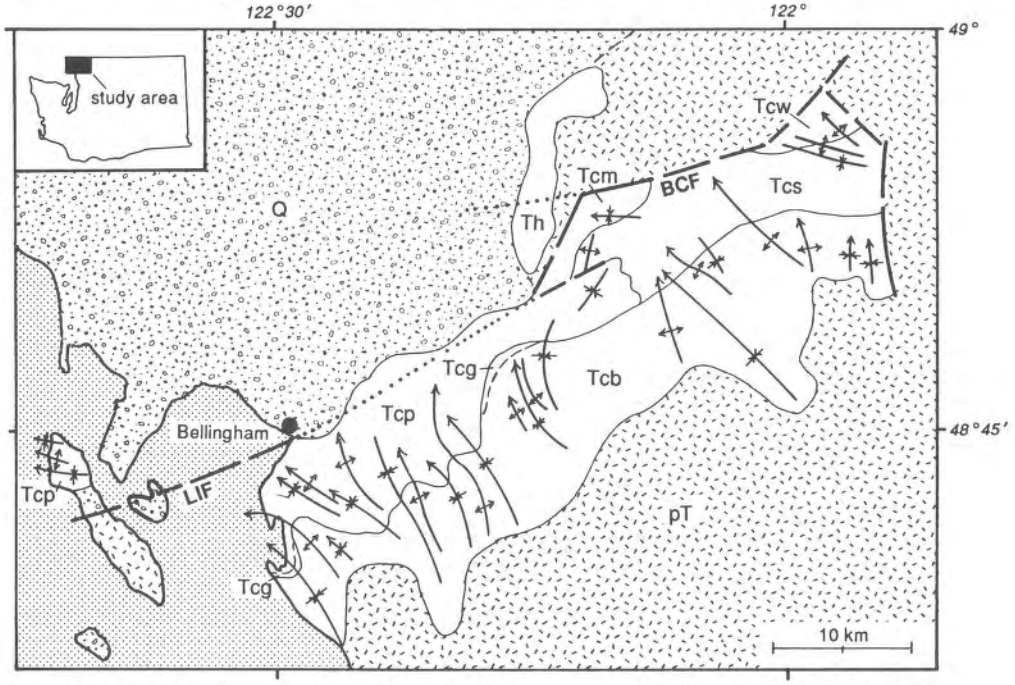

Figure 1. Schematic geologic map of the main outcrop belt of the Chuckanut Formation. BCF, Boulder Creek fault; LIF, Lummi Island fault; Q, Quaternary deposits; pT, pre-Tertiary rocks; Tcb, Bellingham Bay Member; Tcg, Governors Point Member; Tcm, Maple Falls Member; Tcp, Padden Member; Tcs, Slide Member; Tcw, Warnick Member; Th, Huntingdon Formation. Bold lines show locations of faults. Lines with arrows show trend and plunge of folds.

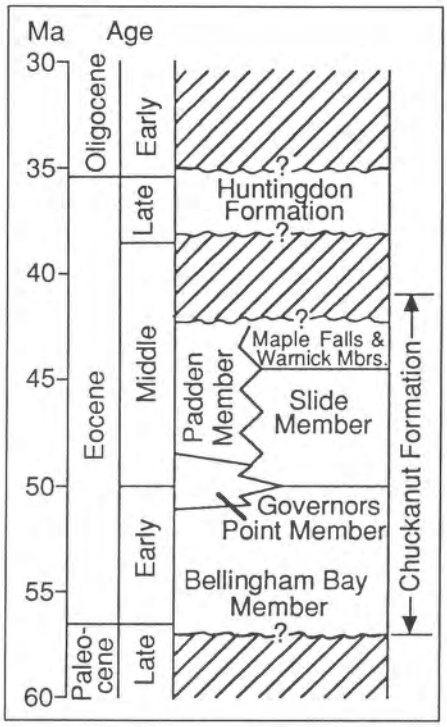

Figure 2. Inferred stratigraphy and age of the Chuckanut and Huntingdon Formations.

sources north of the east-northeast-trending Boulder Creek fault strongly suggests that this fault was active during sedimentation. Previous correlation of the Maple Falls and Warnick Members with a third unit, the Bald Mountain Member or Formation, is now regarded as tentative.

Following deposition, the Chuckanut Formation was deformed into northwest-trending folds in the late middle to late Eocene (Fig. 3E). The Chuckanut fold belt is synchronous with and represents a southeastern extension of the Cowichan fold and thrust system, recognized by England and Calon (1991) in the Nanaimo basin. However, the amount of shortening documented for the Nanaimo basin (20–30% or more) in this contractional event is much larger than that inferred for the Chuckanut.

The Chuckanut folds and the Boulder Creek fault were draped by the upper Eocene Huntingdon Formation (Figs. 1, 2, 3F). South of the main outcrop belt, the Chuckanut is interbedded with and (or) intruded by rhyolitic rocks (52.7 Ma and 38–45 Ma) and basaltic dikes (41–50 Ma).

From a regional perspective, the Chuckanut is one of several Paleogene basins in central and western Washington that formed between a network of active and inferred dextral strike-slip faults (Johnson, 1985). Strike-slip influence on Chuckanut basin evolution is indicated by several features: (1) rapid subsidence rates (about 56 cm/10^3 years for the Bellingham Bay Member and about 27 cm/10^3 years for younger Chuckanut strata); (2) abrupt facies and thickness changes; (3) basin-margin unconformities; (4) evidence for fault-induced(?) drainage reorganizations; (5) interbedded and intrusive relations with extension-related(?) volcanic rocks; and (6) characteristic fault and fold patterns. On a larger scale, strike-slip control on regional deposition is also supported by local and diachronous deformation, rapidly alternating pulses of uplift and subsidence, and petrographic mismatches in coeval strata across inferred master faults.

References Cited

England, T. D. J.; Calon, T. J., 1991, The Cowichan fold and thrust system, southwestern British Columbia: Geological Society of America Bulletin, v. 103, no. 3, p. 336–362.

Johnson, S. Y., 1984, Stratigraphy, age, and paleogeography of the Eocene Chuckanut Formation, northwest Washington: Canadian Journal of Earth Sciences, v. 21, no. 1, p. 92–106.

Johnson, S. Y., 1985, Eocene strike-slip faulting and nonmarine basin formation in Washington. *In* Biddle, K. T.; Christie-Blick, Nicholas, editors, Strike-slip deformation, basin formation, and sedimentation: Society of Economic Paleontologists and Mineralogists Special Publication 37, p. 283–302.

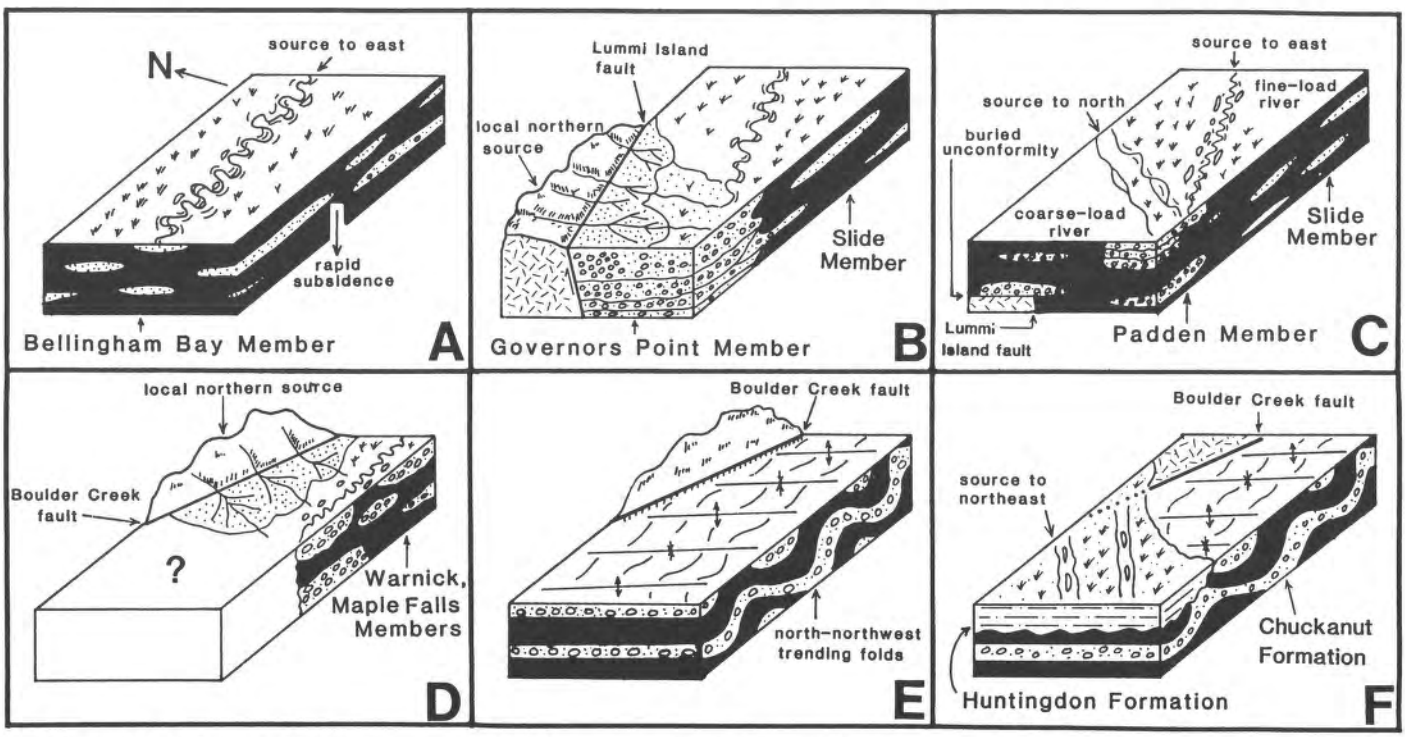

Figure 3. Schematic block diagrams showing six stages in the evolution of the Chuckanut Formation. See text for discussion.

The Rocks of Bulson Creek—Eocene through Oligocene Sedimentation and Tectonics in the Lake McMurray Area, Washington

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Upper Eocene to lower Oligocene sedimentary rocks in the Lake McMurray area of Skagit County, Washington, consist of approximately 1,500 m of interbedded conglomerate, sandstone, shale, and siltstone that were deposited in fluvial and nearshore environments along the continental margin (Fig. 1). The rocks are informally known as the rocks of Bulson Creek, and they crop out in the area east and south of Mount Vernon. These rocks represent one of the thick sediment packages that occur in the foreland or forearc basins of the western flank of the Cascades. Stratigraphic evidence suggests that the Bulson Creek rocks were initially deposited quickly in a deep depression and that only small amounts of organic matter accumulated. Other units within this sediment package, such as the Chuckanut Formation (Fig. 2), contain abundant coal and noncommercial quantities of natural gas. Coal-bearing and fossiliferous zones are also evident in the Bulson Creek rocks (Fig. 3) but are not economically significant.

Two main lithofacies can be recognized in the Bulson Creek sequence. The lower is nonmarine and consists of poorly sorted, thick, structureless conglomerate with interbedded sandstone, siltstone, shale, and a few thin lenses of coal. The lower lithofacies rocks unconformably overlie paleosols developed on pre-Tertiary rocks. The rocks of the upper lithofacies indicate a gradation upward from a lacustrine environment to a shallow-water marine environment. These marine rocks are well-sorted, fossiliferous, pebbly sandstone, sandstone, and siltstone (Fig. 3). The contact between the lower and upper lithofacies is not exposed but is inferred to be an angular unconformity. The change in depositional environment across this contact is clear.

At least three periods of tectonism and two periods of deposition are recognized in the study area. The Devils Mountain fault is a major west-trending feature along which there has been a long and complex history of displacement. The deformation of the rocks in the Lake McMurray area can be

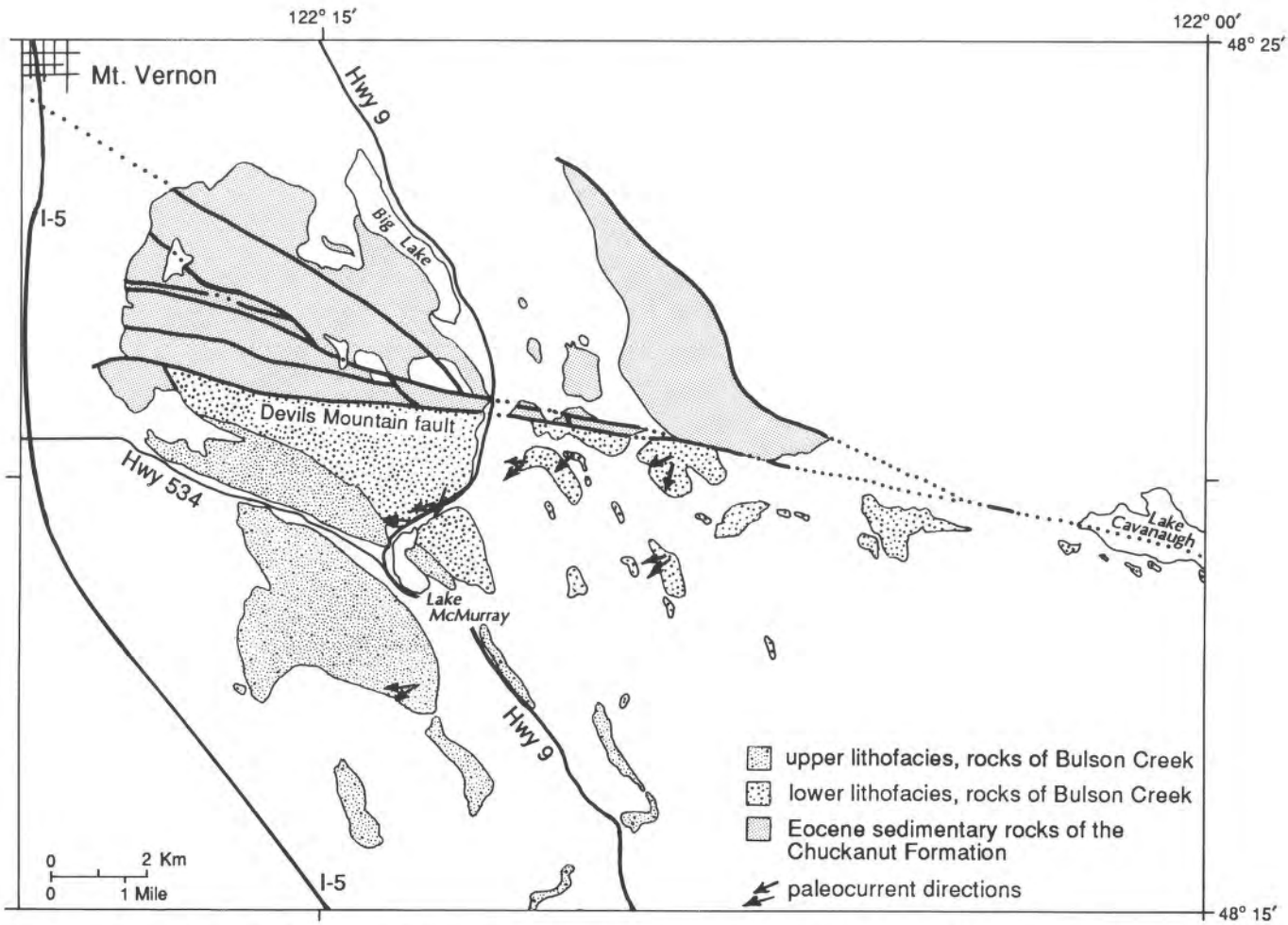

Figure 1. Distribution of outcrops of the two lithofacies of the rocks of Bulson Creek and of the Chuckanut Formation.

Age	Stages	Weaver 1937	Danner 1957 & 1966	Lovseth 1975	Miller 1979	Author
Miocene	Saucesian		Bryant Formation Frailey Mt. Formation			
Oligocene	Zemorrian					
Eocene	Ref.			Rocks of Bulson Creek	Sedimentary Rocks	Upper & Lower lithofacies of Bulson Ck. Rhyolithic volcanic intrusives and extrusives
	Nar.				Silicic to basic volcanic and sedimentary rocks, undif.	
	Ula.					
	Pn.			Chuckanut Formation	Chuckanut Formation	Chuckanut Formation
Paleocene	Bul.		Chuckanut Formation			
	Ynez.	Chuckanut Formation				
Cretaceous				Rocks of Frailey Mt.		

Figure 2. Development of stratigraphic nomenclature in the Lake McMurray area. Foraminiferal stages: Ynez., Ynezian; Bul., Bulitian; Pen., Penutian; Ula., Ulatisian; Nar., Narizian; Ref., Refugian.

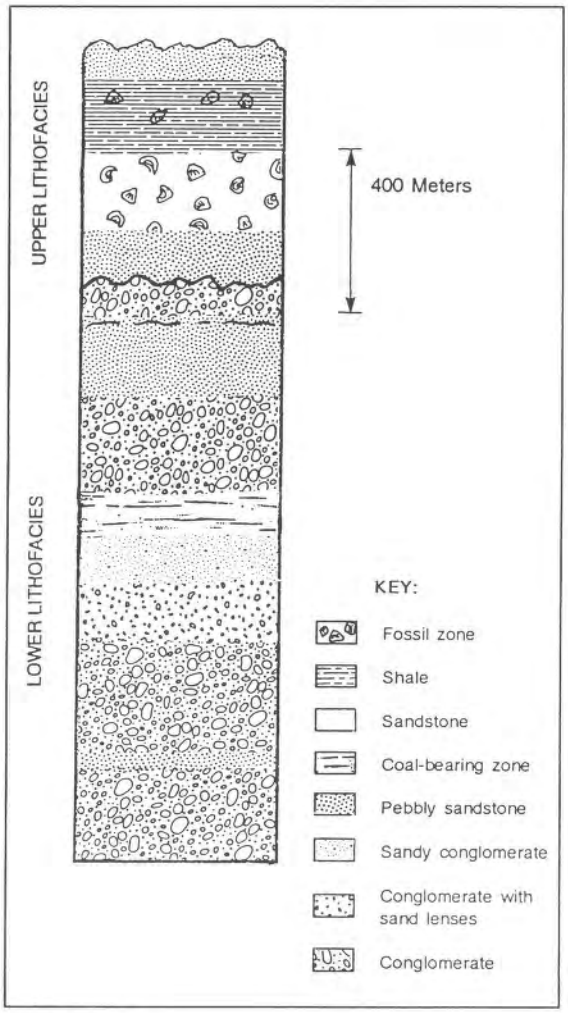

Figure 3. Generalized stratigraphic column of the rocks of Bulson Creek.

attributed to movement along this fault, which truncates the rocks of Bulson Creek on the north (Fig. 1). Deposition of the lower lithofacies followed compressional folding associated with normal faulting. The interpreted angular unconformity between the two lithofacies units indicates that the lower unit was folded prior to deposition of the upper lithofacies. Activity on the Devils Mountain fault subsequently tilted both units to the south.

References Cited

Danner, W. R., 1957, Stratigraphic reconnaissance in the northwestern Cascade Mountains and San Juan Islands of Washington State: University of Washington Doctor of Philosophy thesis, 2 v., 562 p.

Danner, W. R., 1966, Limestone resources of western Washington: Washington Division of Mines and Geology Bulletin 52, 474 p.

Lovseth, T. P., 1975, The Devils Mountain fault zone, northwestern Washington: University of Washington Master of Science thesis, 29 p.

Miller, G. M., 1979, Western extent of the Shuksan and Church Mountain thrust plates in Whatcom, Skagit, and Snohomish Counties, Washington: Northwest Science, v. 52, no. 4, p. 229–240.

Weaver, C. E., 1937, Tertiary stratigraphy of western Washington and northwestern Oregon: Washington University Publications in Geology, v. 4, 266 p.

Galley proof responses not received by press time.

Petroleum Geology of the Bellingham Basin, Washington, and Evaluation of the AHEL and Partners Birch Bay No. 1 Well

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A preliminary evaluation of well logs, drill and core samples, gas samples from seeps, and geophysical data from the Bellingham basin in 1986 by American Hunter Exploration Ltd. (AHEL) revealed the significant hydrocarbon potential of this frontier basin. In 1986 and 1987, a seismic and gravity program was completed to further delineate structural highs (Fig. 1). The Birch Bay No. 1 well was drilled by AHEL and partners in 1988 to test a large anticlinal structure in the western part of the basin (Fig. 1). The total depth of this well was 9,125 ft, and it penetrated nonmarine Tertiary Huntingdon and Chuckanut Formation sedimentary rocks. The well was drilled both to test the structure for commercial hydrocarbons and to provide pertinent data for basin evaluation.

Fourteen cores were cut, and 14 drillstem tests were performed to evaluate the structure for hydrocarbons and reservoir quality. In addition, multiple sets of cutting samples were collected to determine the source rock potential and the biostratigraphic age of the rocks. Figure 2 is a north-south seismic section across the Birch Bay structure. Regional correlation of a middle Eocene seismic reflector suggests a structural closure of approximately 8 mi^2. The Birch Bay No. 1 well, located near the crest of the anticline, tested water that contained solution gas from numerous sandstones. The salinity of the water increased from 800 ppm chlorides at 800 ft to 23,000 ppm at 3,500 ft. Three sandstone intervals had good mud gas responses and tested gas to surface at low rates. Both post-Eocene faulting and the near-surface subcropping of Oligocene sedimentary rocks may have permitted the deep flushing of meteoric water and the breaching of the structural trap. Reinterpretation of the seismic data shows that the well may not be in the optimum structural location on this faulted anticline. If the Mist field in Oregon is used as an analogue for exploration, numerous gas pools of less than 8 billion ft^3 of recoverable gas reserves may be present in small faulted blocks in the Birch Bay structure.

Reservoir rock penetrated in the well consists of medium- to coarse-grained arkosic sandstones and bimodal or polymodal conglomerates. The sandstones coarsen downward, a character typical of fluvial meander channels. Several conglomerate/sand channel deposits have the blocky electric-log profile of braided streams. Porosity decreases with depth from 26 percent at 1,000 ft to less than 10 percent below 6,000 ft. This decrease is caused by feldspar degradation, an increase in silica cement, and compaction. Permeability-feet (Kh) calculations from core analyses indicate permeable reservoir rock down to at least 4,500 ft. However, flow capacity (in situ Kh) calculations suggest that laboratory permeability measurements may be optimistic. Laboratory analyses could be affected by clay dehydration and (or) removal of net overburden pressure. Despite the more pessimistic in situ Kh calculations, good quality (>100 md/ft) reservoir rock ca-

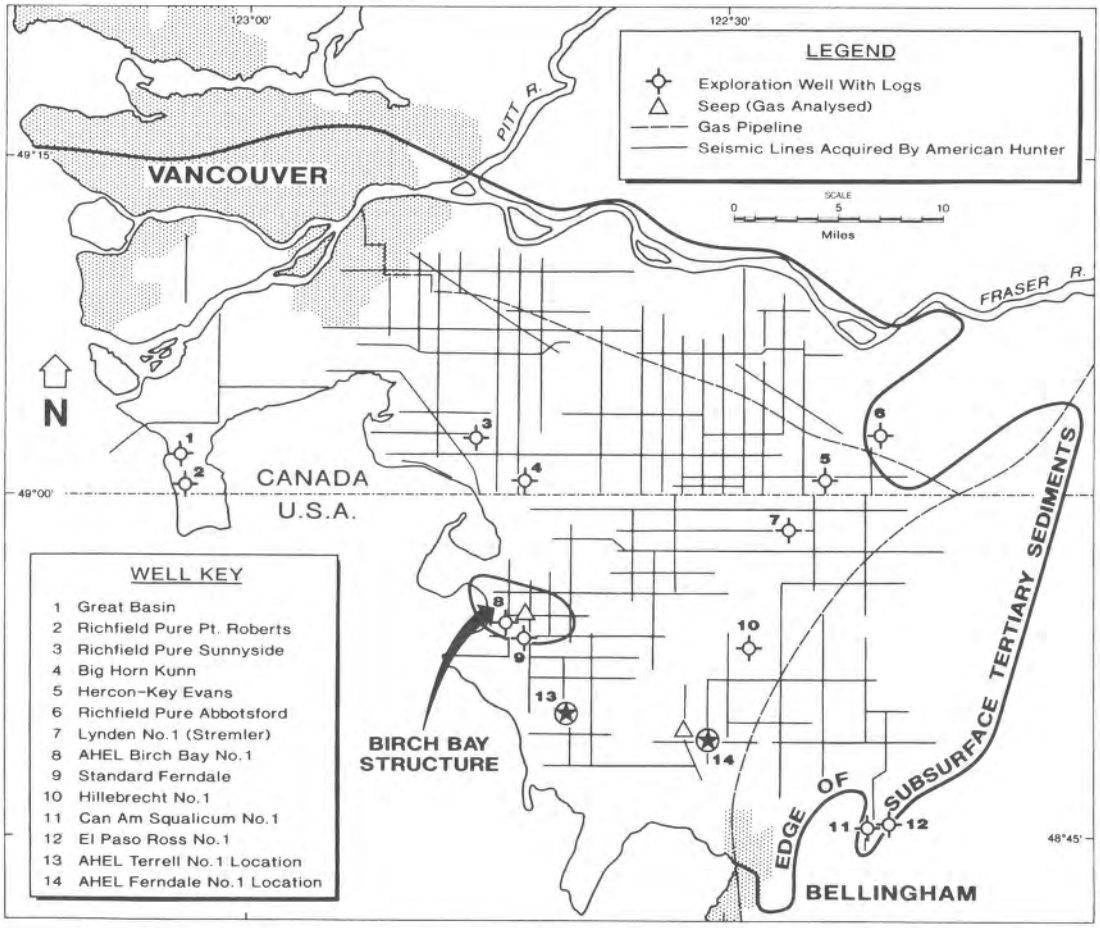

Figure 1. Bellingham Basin Project area. AHEL and partners have licensed two new drilling locations, Terrell No. 1 and Ferndale No. 1; these wells will test the Chuckanut Formation in two subsurface structures.

pable of storing and producing hydrocarbons is present in the well above 4,500 ft.

An unconformity may be present at 6,000 ft where shale changes color from gray-brown above this depth to bluish gray, orange, and maroon. Below 6,000 ft the sands are impermeable and fractured, and they have a high lithic content. A saltwater flow at 7,925 ft and good gas shows from cemented impermeable sands below 6,000 ft attest to the presence of fractures. A 200-ft-thick diorite sill was penetrated at 7,000 ft. Its age has yet to be determined.

Palynological analyses by J. Lentin of L. I. B. Consultants Ltd. indicate lower Oligocene deposits at 130 ft, upper Eocene at 600 ft, middle Eocene at 1,800 ft, and lower Eocene at 3,600 ft. Samples between 3,600 ft and 6,500 ft contained undiagnostic material. Below 6,500 ft, samples were barren of spores or pollen. On the basis of the stratigraphic sequence proposed by Johnson (1982), this would place the Padden Member of the Chuckanut Formation between 600 ft and 3,600 ft, the Bellingham Bay Member from 3,600 ft to the proposed unconformity at 6,000 ft, and possibly Paleocene or Cretaceous sedimentary rocks below 6,000 ft.

Source rock evaluation shows that coals and shales down to a depth of 6,000 ft have high concentrations of Type IIB kerogen (liquid hydrocarbon prone); numerous rocks in this interval contain more than 6 percent total organic carbon (TOC). Rocks below 6,000 ft contain Type III kerogen (humic) and have low TOC values. Pyrolysis data show that "early-mature" maturation conditions prevail below 6,000 ft, and vitrinite reflectance data indicate that early mature conditions occur below 4,200 ft. Thus the kerogen-rich Type IIB rocks are immature, and the kerogen-poor Type III rocks are within the oil window on the structure. From this it can be concluded that in order to generate significant quantities of hydrocarbons, the kerogen-rich Type IIB rocks must be buried significantly deeper or located closer to a high heat-flow regime.

Gas seeps from old well casings (Fig. 1) have been sampled and analyzed by American Hunter. Isotope analyses

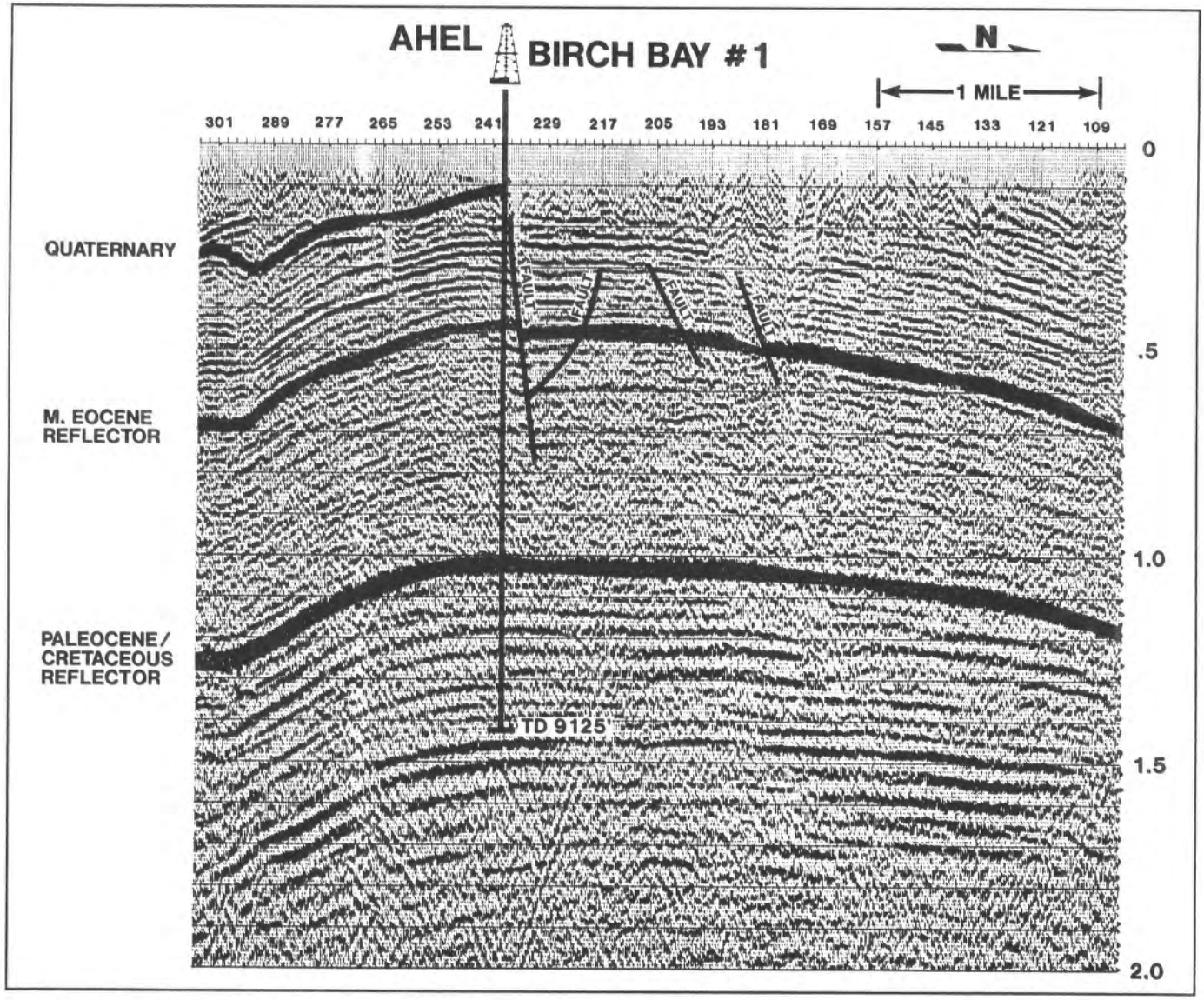

Figure 2. Seismic section across the Birch Bay structure. The middle Eocene reflector was mapped regionally across the basin. The Birch Bay anticline has 5,000 acres of structurally closed area mapped on the Eocene reflector. Vertical scale is two-way time in seconds.

indicate a thermal origin with some biogenic mixing for the gases. This substantiates that hydrocarbons have been generated at depth and that there is a potential for commercial accumulations of gas in the basin.

In summary, the Bellingham basin has all the characteristics that contribute to commercial hydrocarbon accumulations. The Chuckanut Formation contains rich source rocks that should be mature east or southwest of the Birch Bay No. 1 well. Thick, porous, and permeable channel sandstone reservoirs are common in the Chuckanut Formation. Furthermore, large fault-related structures, adequate shale seals, and numerous thermogenic gas shows are present in the basin. The basin's potential could be confirmed by drilling more wells.

Reference Cited

Johnson, S. Y., 1982, Stratigraphy, sedimentology, and tectonic setting of the Eocene Chuckanut Formation, northwest Washington: University of Washington Doctor of Philosophy thesis, 221 p., 4 pl.

Northwest Pipeline Corporation Expands into the '90s

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The Federal Energy Regulatory Commission's (FERC) program, commonly referred to as "open access", completely changed the character of the natural gas industry. Beginning in the mid-1980s with the issuance of Orders 436 and 500, the FERC directed interstate pipeline companies to provide natural gas service to all parties on a nondiscriminatory basis. Access to such transportation services combined with market-based wellhead pricing allowed gas to become competitive with alternative fuels and more cost effective for all end-users. The subsequent impact on Pacific Northwest natural gas markets in industrial, commercial, and residential applications has been dramatic. The volume of gas transported annually through Northwest Pipeline Corporation's (Northwest) system has grown from 432 trillion Btu (TBtu) in 1985 to 555 TBtu in 1990, an increase of 28 percent.

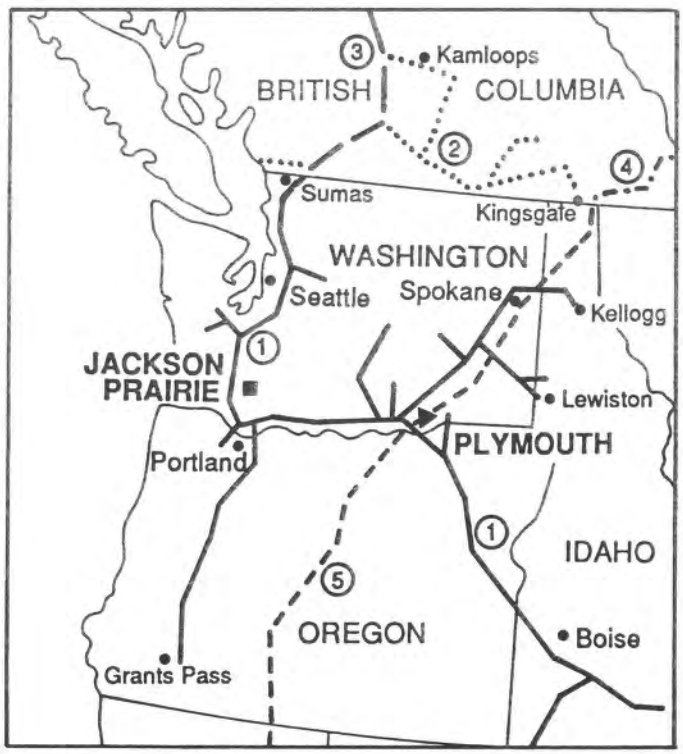

Figure 1. Natural gas transmission lines and storage facilities in Washington and adjacent areas. 1, Northwest Pipeline Corp.; 2, B.C. Gas Inc.; 3, Westcoast Energy, Inc.; 4, Alberta Natural Gas Co., Ltd.; 5, Pacific Gas Transmission Co.

This increase in demand has been driven by several factors that include competitive pricing, demand for electricity, population and industrial growth in the region, and air-quality concerns. This growth spurred natural-gas producers, marketers, local distribution companies, and end-users to request additional firm (or guaranteed on a 365-days-per-year basis) transportation capacity on Northwest to serve their expanding markets. By early 1990, Northwest's firm transportation capacity queue had grown to include 47 shippers requesting more than 3 TBtu per day of additional firm capacity.

In response to those requests, Northwest filed an application with the FERC on December 31, 1990, requesting authority to construct and operate facilities capable of delivering an additional 534,007 million Btu per day (MMBtu/d). The application was amended on October 7, 1991, to reduce the volume to its current 433,415 MMBtu/d. This would effectively increase the system's capacity by approximately 20 percent. The FERC's final order authorizing construction is expected in the first quarter of 1992. Upon receipt of that order, construction would begin in the second quarter of 1992, with commencement of service in the first quarter of 1993.

The expansion project includes the installation of approximately 42 miles of pipeline and 42,000 horsepower of compression at various places throughout the state of Washington. These additions will bolster the existing system that

Mainline Capacities	1990 Performance
Design day: 2.0 Bcf/day	Total deliveries: 555 TBtu
Record delivery: 2.4 Bcf/day	Average daily delivery: 1.5 TBtu
System receipts (in MMcf/day):	Service activity:
Canadian - 790	92% transmission; 8% sales
Domestic - 580	Sources of gas:
Jackson Prairie - 450	51% domestic
Plymouth LNG - 300	49% Canadian

serves the state, which includes 1,348 miles of transmission lines, 53,000 horsepower of compression, a liquefied natural gas (LNG) storage facility, and the Jackson Prairie underground storage field (Fig. 1).

The LNG storage plant in Plymouth, Washington, has a total storage capacity equivalent to 2.4 billion ft^3 (Bcf) of natural gas. The gas is liquefied at -258°F and then stored in two double-walled tanks, each holding 348,000 barrels (42 gal) of LNG. The plant is capable of liquefying 12 million cubic feet (MMcf) per day and can vaporize and deliver as much as 300 MMcf per day during extreme peaks in demand.

The Jackson Prairie facility, located near Chehalis, Washington, uses a natural aquifer to store as much as 34.4 Bcf of natural gas underground. The project is currently authorized to operate with 18.8 Bcf of cushion gas, which maintains the pressure needed to retrieve the gas, and 15.1 Bcf of working gas, which is readily recoverable and capable of heating a million western Washington homes for a year. A volume of 450 MMcf of natural gas per day can be withdrawn on a firm basis, and as much as an additional 72 MMcf per day can be withdrawn on a best-effort basis.

After the expansion, the system should be capable of meeting requirements into the mid-1990s. However, the factors responsible for the recent increase in the Pacific Northwest gas market are expected to contribute to future growth as well. To keep pace with the growing energy needs of the region, Northwest has tentatively outlined plans for a second expansion project. This is in response to existing requests for additional firm capacity beginning in 1995 and beyond. Pending the disposition of the current application and assuming a sufficient level of market interest, the next expansion project would begin with a solicitation for participants in the second quarter of 1992. The FERC application would follow in the first quarter of 1993, with commencement of service in the first quarter of 1995.

Northwest Pipeline Corporation is one of The Williams Companies, owners and operators of more than 25,000 miles of pipelines for natural gas and petroleum products in 20 western and midwestern states, as well as a nationwide digital communications network. The Williams Companies has its headquarters in Tulsa, Oklahoma.

Coalbed Methane Potential of Vancouver Island, British Columbia

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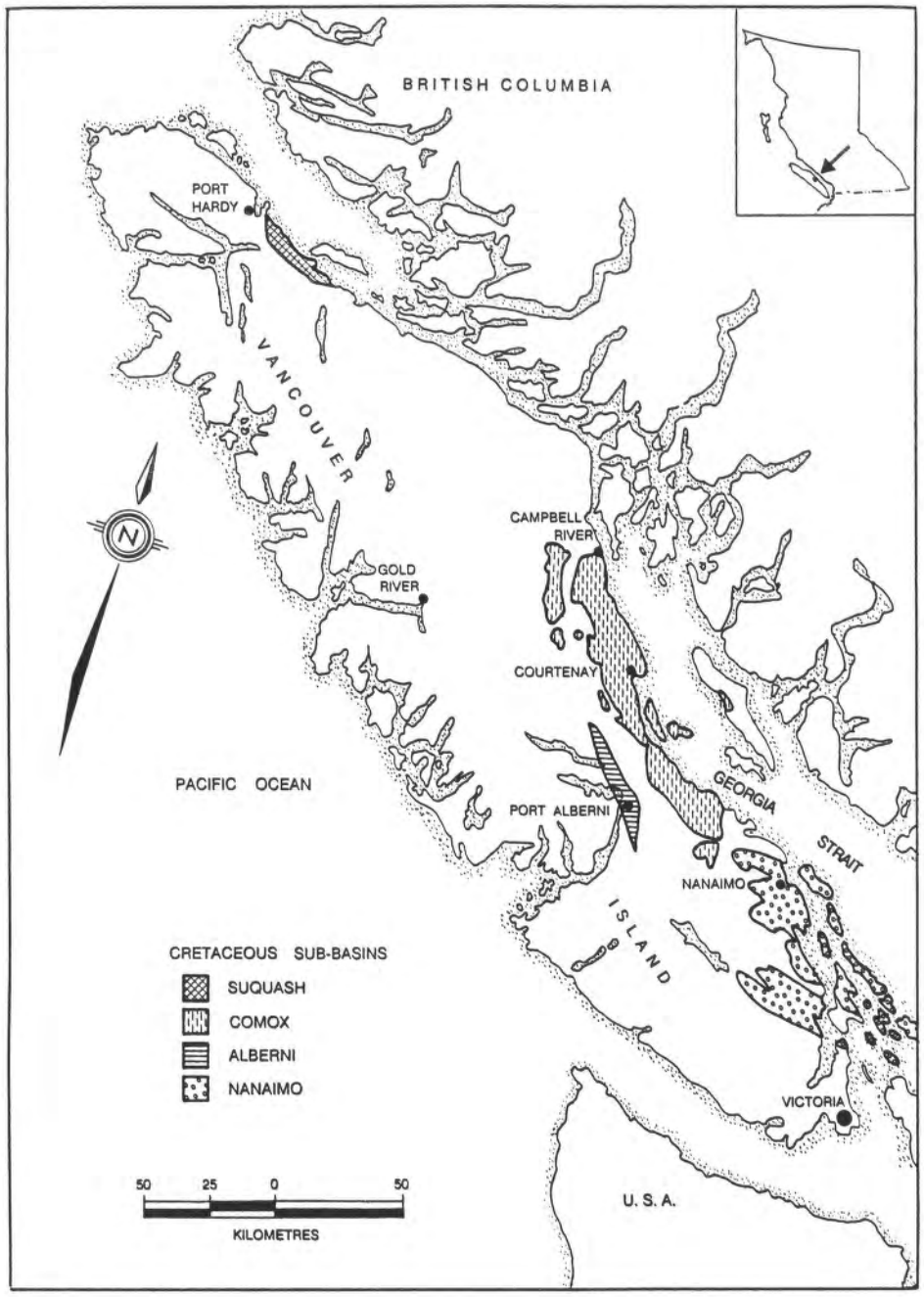
Exploration and production activity of coalbed methane in the United States has generated much interest in Canada, in particular the Province of British Columbia, which has large coal resources. Commercially attractive quantities of coalbed gas on Vancouver Island are indicated from recent studies by the provincial Geological Survey Branch and independent consultants. Interest has further been fueled by the construction (nearing completion) of a gas pipeline across Georgia Strait.

Coals along the east coast of Vancouver Island have been prospected and mined from 1849 to the present. Large amounts of data concerning drilling, mining, and coal quality, as well as reserve information, are available through provincial government records. "Gassy" occurrences mentioned in drill records and surface venting of gas have been noted in various reports on file with the Ministry of Energy, Mines and Petroleum Resources. The presence of methane in the coals of Vancouver Island is further corroborated by numerous gas-related disasters and fires in virtually all of the underground mines.

The Upper Cretaceous coal measures of Vancouver Island are in Nanaimo Group sedimentary rocks within the Georgia successor basin, which covers approximately 1,000 mi^2. These rocks consist of cyclically graded sequences of conglomerate, sandstone, shale, and coal. Strata dip to the north-northeast at an average of 11 degrees. Unconformably underlying the coal measures are crystalline basement rocks of Triassic and Jurassic age. Basement lithologies range from basalt, gabbro, and volcanic breccia to coarsely crystalline marble, calcareous siltstone, skarn, and granodiorite. Basement rocks were strongly folded and faulted and subsequently uplifted and eroded, prior to deposition of the coal measures. The irregular topography of basement rocks strongly influenced the deposition of the coal-bearing sediments. Post-Cretaceous faulting involves significant thrusting, in addition to dextral separation.

The Georgia basin is divided into the Comox, Nanaimo, Suquash, and Alberni sub-basins (Fig. 1). In the Comox sub-basin, the coal-bearing interval is in the Comox Formation, which can vary from 600 to 1,500 ft (thickening to the north) and contains as many as ten coal beds. The seams attain aggregate thicknesses greater than 40 ft, with a maximum seam thickness of 15 ft. In the Nanaimo sub-basin, the coal-bearing interval encompasses a number of formations and ranges from 1,800 to 2,600 ft in thickness. The maximum aggregate thickness of five coal beds above the Haslam Formation in the Nanaimo sub-basin is 30 to 60 ft; maximum seam thickness is 30 ft. The deep coals in the Nanaimo sub-basin need further exploration. Results of current research involving coal quality and regional rank distribution, as well as desorption testing, indicate a potential economic gas resource in the coal seams of these two sub-basins.

Vancouver Island coals are generally high-volatile-A to -B bituminous in rank. Vitrinite reflectance data place the coals in the window of coalbed methane generation, with $R_{o\ max}$ values ranging from 0.59 to 3.21%. Anomalous values are found close to Tertiary intrusions or in coals quite high in the section. Maceral determinations indicate very high vitrinite counts. Well-defined cleat systems are seen in almost all



outcrops and drill core. Throughout most of the coal measures, there are large-scale fractures and joint systems that would likely result in structurally enhanced permeability.

Test well desorption data from the Nanaimo coalfield have indicated that coals can contain as much as 380 ft^3 of gas per short ton at a depth of 1,230 ft. Gas samples are of pipeline quality: 95 percent methane, 4.5 percent heavier hydrocarbons, and 0.5 percent carbon dioxide. Limited desorption testing has been done on other coal seams on Vancouver Island, and the results from those at shallow depths show promise. However, these data remain confidential.

A conservative in-place methane resource estimate of 1 trillion ft^3 was determined for Vancouver Island using preliminary desorption test data, coal quality information, and results of recent mapping. This resource estimate took into account mined-out areas and areas where no coal is present because of intrusive bodies, paleohighs, and complex structure. Further exploration work is necessary on the island before the resource potential can be accurately determined.

Figure 1. Cretaceous coal-bearing sub-basins of Vancouver Island.

Coalbed Methane Potential of Whatcom and Skagit Counties, Washington

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Coal was discovered on Bellingham Bay in western Washington in 1852. The coal-bearing rocks of both Whatcom and Skagit Counties are found on the west side of the Cascade Range in the Chuckanut and Huntingdon Formations of early to late Eocene age (Fig. 1).

Jenkins (1923, 1924) identified 15 Whatcom County coalbeds that range up to approximately 25 ft thick (Fig. 2). Two main coal zones are recognized in Whatcom and Skagit Counties. The Blue Canyon coal zone at the base of the Chuckanut Formation is present at the Blue Canyon and Glacier coal mining districts in Whatcom County and at the Cokedale district in Skagit County (where it is known as the Klondike coal zone) (Fig. 1). Approximately 10,000 ft higher stratigraphically, below the base of the Huntingdon Forma-

tion, is the Bellingham coal zone, which occurs in both the Bellingham coal district and to the north and east in the Van Wyck syncline area. Other coal beds are present throughout the Huntingdon and Chuckanut Formations; these are generally interbedded with carbonaceous shale and arkosic sandstone. All underground coal mines in both counties have been inactive since 1955 when the Bellingham mine closed after 38 years in operation.

Coal-bearing rocks of Eocene age underlie approximately 1,200 mi^2 in Whatcom and Skagit Counties (Beikman and others, 1961). From a combination of direct measurements at outcrops and abandoned mines and in exploration wells and coreholes and from assumptions regarding the lateral continuity of coal seams, the estimated coal reserves in Whatcom County total more than 381 million tons and nearly 507 million tons in Skagit County (Choate and Johnson, 1980). Coal quality is generally high (mineral matter <15%) for both the Blue Canyon and Bellingham coal zones and poor (mineral matter >25%) for most other coalbeds in the section. Coal rank, however, expressed as either percent fixed carbon, Btu value, or percentage vitrinite reflectance, generally increases both with depth of burial (Hilt's law) and with proximity to post-Eocene (primarily Miocene) igneous intrusive bodies and metamorphism associated with emplacement of Cascade Range terrains to the east (Fig. 3).

Encouraging factors for the exploration of coalbed methane in Whatcom and Skagit Counties include: (1) the presence of sufficient thicknesses of high volatile bituminous coal at suitable depths to host potentially significant volumes of methane; (2) reports of methane in coal mining records; (3) gas shows from oil and gas exploration wells drilled through the coal-bearing Eocene section; and (4) gas produced from very shallow water wells in the Ferndale Gas Field northwest of Bellingham, where naturally degassing methane from deeper coalbeds is thought to have been trapped in the glacial overburden. While little nonproprietary information about gas desorption isotherms and gas-per-ton values is available for the Whatcom–Skagit area, modest assumptions concerning coal reserves and rank-based coal contents indicate more than 350 billion ft^3 of methane may potentially be in place. The intense folding and faulting throughout the trend of the Chuckanut Formation may act to enhance permeability in seams. Gassy conditions in Whatcom County's Blue Canyon mine (sec. 15, T37N, R4E) may have

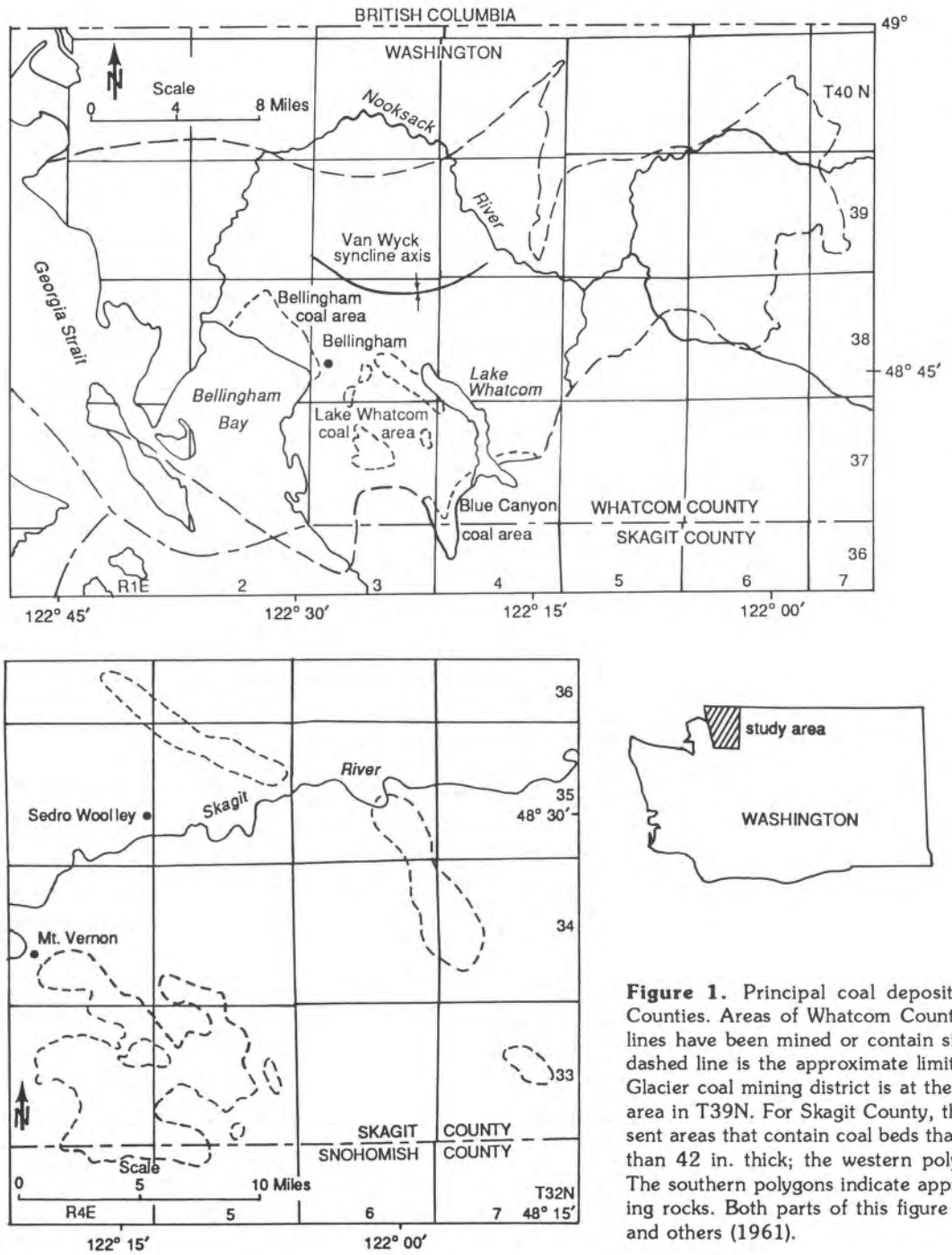


Figure 1. Principal coal deposits of Whatcom and Skagit Counties. Areas of Whatcom County enclosed by short dashed lines have been mined or contain significant reserves; the long dashed line is the approximate limit of coal-bearing rocks. The Glacier coal mining district is at the eastern margin of the map area in T39N. For Skagit County, the northern polygons represent areas that contain coal beds that range from 28 in. to more than 42 in. thick; the western polygon is the Cokedale area. The southern polygons indicate approximate limits of coal-bearing rocks. Both parts of this figure are redrawn from Beikman and others (1961).

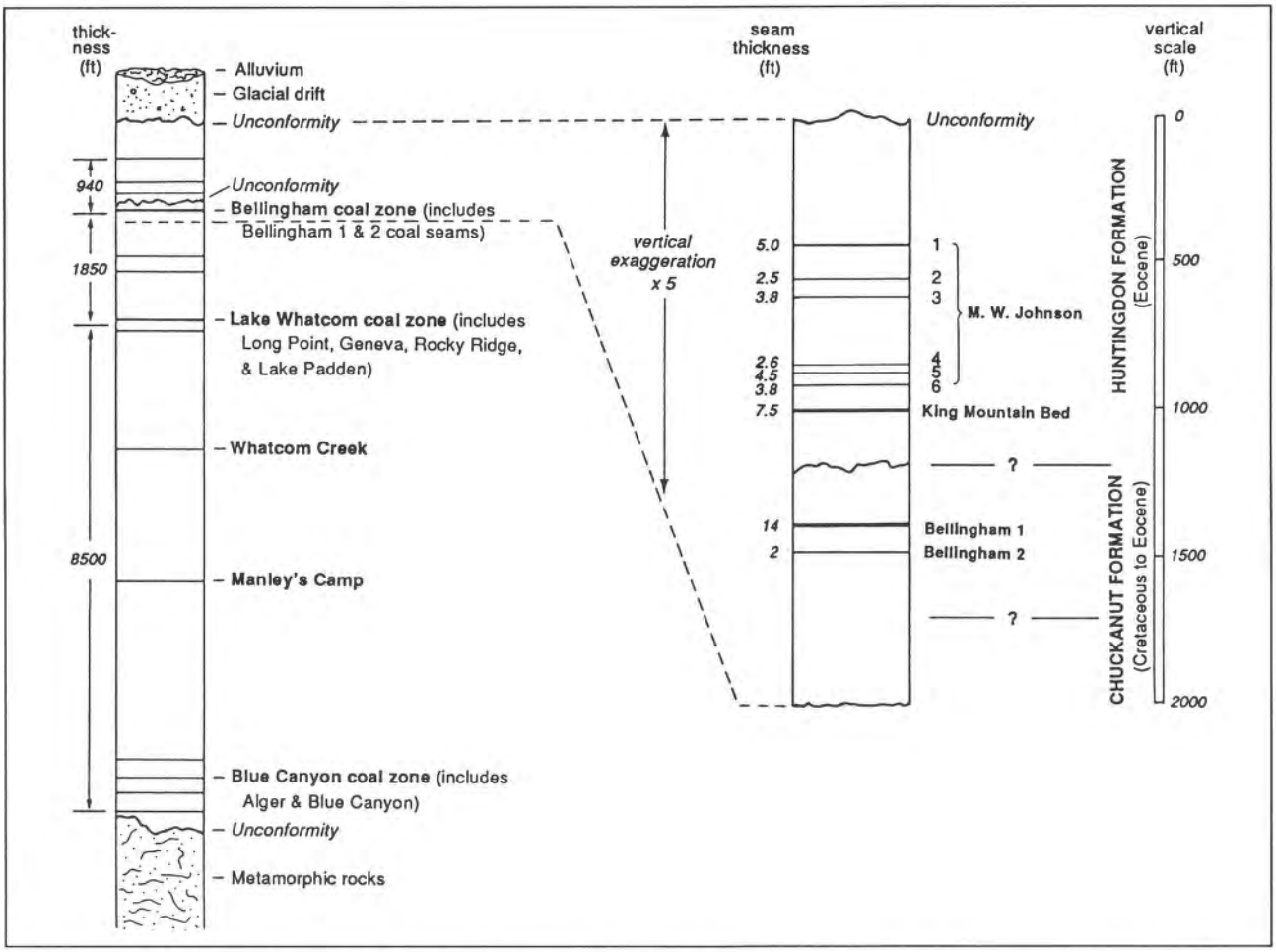
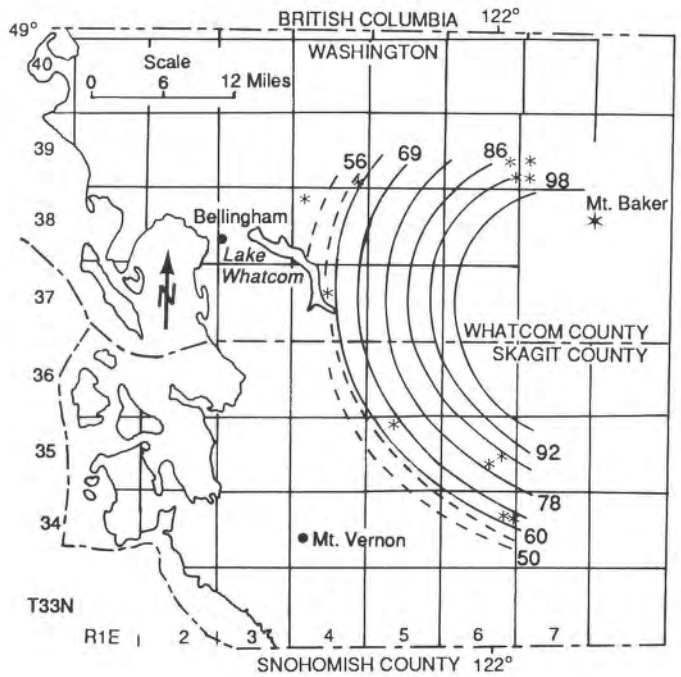


Figure 2. Generalized sections of coal-bearing rocks in Whatcom and Skagit Counties. Modified from Jenkins (1924).



been a direct result of structurally enhanced permeability. Though structural deformation in the Huntingdon Formation is not as intense as indicated by dips measured in the old Bellingham mine and from drilling records for the Van Wyck syncline, movement of methane gas upward through the sandstones of generally low porosity and permeability in the Eocene section in the Ferndale area may also have been facilitated by faulting or other structural features.

References Cited

Beikman, H. M.; Gower, H. D.; Dana, T. A. M., 1961, Coal reserves in Washington: Washington Division of Mines and Geology Bulletin 47, 115 p.

Choate, Raoul; Johnson, C. A., 1980, Western Washington coal region report—A study of early Tertiary geology, coal and coalbed methane regions in western Washington: TRW Energy Systems Group (Lakewood, Colo.), 1 v.

Jenkins, O. P., 1923, Geological investigation of the coal fields of western Whatcom County, Washington: Washington Division of Geology Bulletin 28, 135 p.

Figure 3. Distribution of coal rank in Whatcom and Skagit Counties. The asterisks indicate locations of sampling sites, and the numerals on the isorank contours indicate the percentage of fixed carbon on a dry mineral-matter-free basis. Redrawn from Walsh and Phillips (1983).

Jenkins, O. P., 1924, Geological investigation of the coal fields of Skagit County, Washington: Washington Division of Geology Bulletin 29, 63 p.

Walsh, T. J.; Phillips, W. M. 1983, Rank of Eocene coals in western and central Washington State–A reflection of Cascade plutonism?: Washington Division of Geology and Earth Resources Open File Report 83-16, 21 p.

Petroleum Geochemistry of Washington—A Summary

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Although Washington is commonly thought of as an impoverished gas-prone province, some data do not support this view. These data include: (1) gas, condensate, and oil seeps and shows associated with Tertiary sedimentary sections throughout the state, (2) a dearth of wells drilled into petroleum-generative thermal environments, and (3) Type II kerogens in Tertiary sections of the continental margin and coal-bearing strata within the Puget trough that have gas- and liquids-generative potential.

Organic-rich shales and coals, which range from a few millimeters to about 15 m thick, are present in a variety of depositional settings, including turbidites of the western Olympic core complex (Snavely, 1987), graben-fill sequences of northeastern Washington (Gaylord, 1986), and tropical lower-floodplain deposits of eastern Puget trough. (See Beikman and others, 1961.) The area from which information for this article is taken is shown in Figure 1.

Figures 2 and 3 summarize some geochemical characteristics of these rocks as determined from analyses of 1,312 samples from 16 wells and seven measured sections (Brown and Ruth, 1984; Grady, 1985; U.S. Dept. of Energy, 1985; Sidle and Richers, 1985; Lingley and Walsh, 1986; Kvenvolden and others, 1989b; Palmer and Lingley, 1989; Bustin, 1990; Walsh and Lingley, 1991; this study). Measured organic carbon contents of these rocks are generally less than 1.5 percent, but enriched zones are present in most wells and measured sections. In general, Cenozoic nonmarine rocks of central Washington have better carbon preservation than coeval marine sections. S_2 pyrolysis values are generally less than 2.0, indicating fair kerogen preservation. (See Peters, 1986, for criteria.) Visual assessments and pseudo van Krevelen diagrams (Fig. 3) indicate that both marine and continental strata contain mainly Type III (gas-generative) and IV (inert) kerogens. However, rocks deposited along the Puget trough in continental environments have significant amounts of Type II (light-liquids- and gas-prone) kerogen (Fig. 3). The continental rocks appear to be hydrogen enriched relative to coeval marine and paralic rocks. Many of these kerogens have an amorphous appearance.

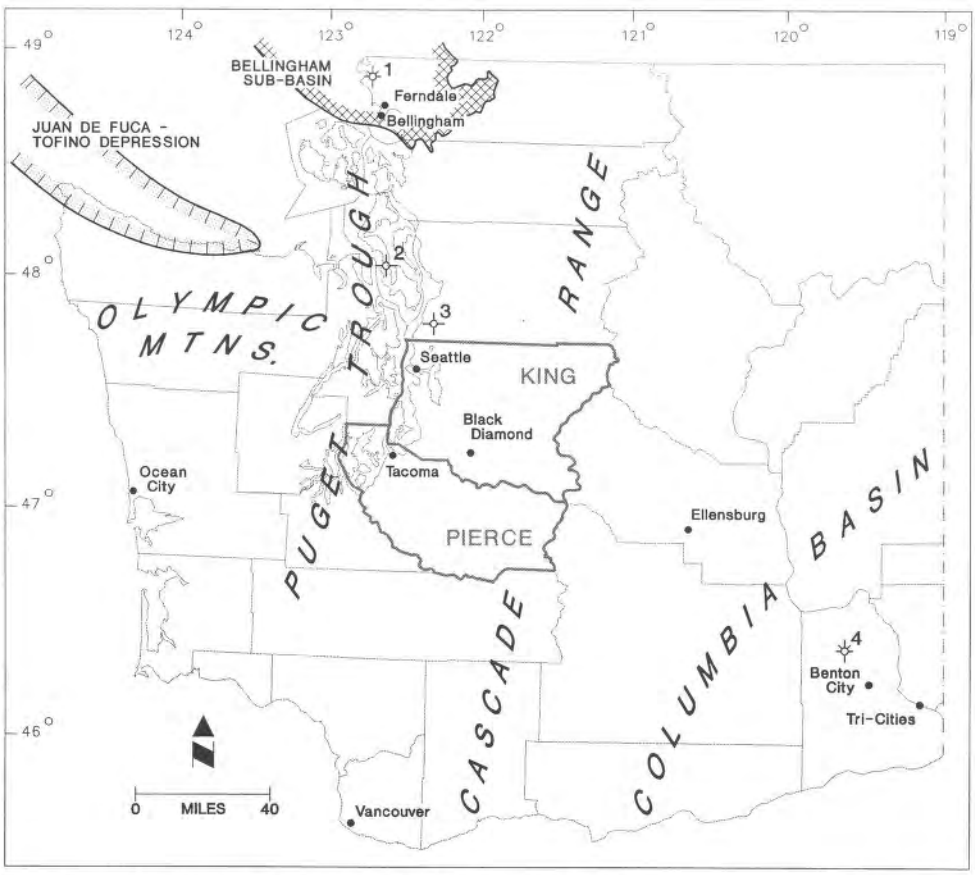

Figure 1. Western and central Washington. 1, Birch Bay No. 1 well; 2, Engstrom Community Well No. 1; 3, Alderwood No. 1; 4, Rattlesnake Hills gas field. Tri-Cities, Richland, Pasco, Kennewick.

Hydrous pyrolysis of Type II coals and adjacent shales penetrated in the Birch Bay No. 1 well, drilled by American Hunter and others, indicates that both shales and coals have potential to generate light hydrocarbons (Fig. 4). Figure 5 indicates that these rocks are rich in liptinitic coal macerals. Brown and Ruth (1984) noted the presence of exinitic material in several other Puget trough wells, but data from Cohen (1983) show that coals from eastern King and Pierce Counties do not contain Type II

kerogen. These King and Pierce County coals fluoresce.

Geothermal gradients in the Puget trough average a remarkably low 23°C/km (Blackwell and others, 1985). The Birch Bay No. 1, drilled in the Bellingham sub-basin (central Puget trough), has a 14.4°C/km gradient, as determined from numerous drillstem test measurements. However, Puget trough geothermal gradients increase eastward abruptly across the foothills to the crest of the Cascade mountains, where gradients average 44°C/km and where anthracite is present. Vitrinite reflectance mapping (Walsh and Lingley, 1991) indicates that geothermal paleogradients conform closely to present-day gradients. In general, geothermal paleogradients in the central Puget trough were equal to or less than the present gradients. Best-fit linear regressions of Puget trough geothermal gradient indicators versus depth are unusually steep. Samples from many wells display little increase in vitrinite reflectance (R_o), thermal alteration indices (TAI), and T_{max} pyrolysis values as depth increases (Brown and Ruth, 1984; Summer and Verosub, 1987; Bustin, 1990; Walsh and Lingley, 1991). Consequently, the apparent oil-generative window commonly appears to be 3,000 m long but lies below the total depth of most Washington wildcats. Mature values of R_o, TAI, and T_{max} in outcrop samples do not necessarily condemn underlying prospects.

Petroleum seeps and shows are present in many parts of the state. Stripper thermogenic-gas production has been achieved at Ocean City (Palmer and Lingley, 1989); near Ferndale (McFarland, 1983; Hurst, this issue); and at Benton City (Hammer, 1934). The last produced a total of 1.3 billion ft^3 of methane from the Rattlesnake Hills field. Twelve-thousand barrels of paraffinic oil were produced at Ocean City. Oils from the Olympic Peninsula (Kvenvolden and others, 1989b; Palmer and Lingley, 1989) and condensates from the Columbia Basin are paraffinic and range from 37° to 52° API gravity. Saturate-fraction chromatography indicates that all of these oils are immature and have carbon preference indices mostly greater than 1.2. Although bona fide shows are rare in the center of the Puget trough and the Fuca–Tofino basin, few wells have been drilled into the oil-generative window (Walsh and Lingley, 1991). Apparent live-oil shows were logged in Tertiary sections in the Engstrom Community No. 1, the Alderwood No. 1, and the Phillips State No. 1. Gas seeps are present near Bellingham, Benton City, and Black Diamond. These have been ascribed to glacial, biogenic, or low-temperature coal alteration origins because of the great depths to thermogenic gas-generative zones in these areas. However, analyzed gases contain significant fractions of methane having delta-C^{13} heavier than -55, suggesting a thermal origin (Hurst, this issue; Kvenvolden and others, 1989a; this study).

Little information is available to link seeps and shows with corresponding source rocks. Kvenvolden and others (1989b) identified rare biomarkers in both Olympic coast oils and organic detritus from adjacent turbidites of the Olympic core complex. Oils from Ocean City have bulk chemistries and triterpane (m/z 191) distributions that are essentially

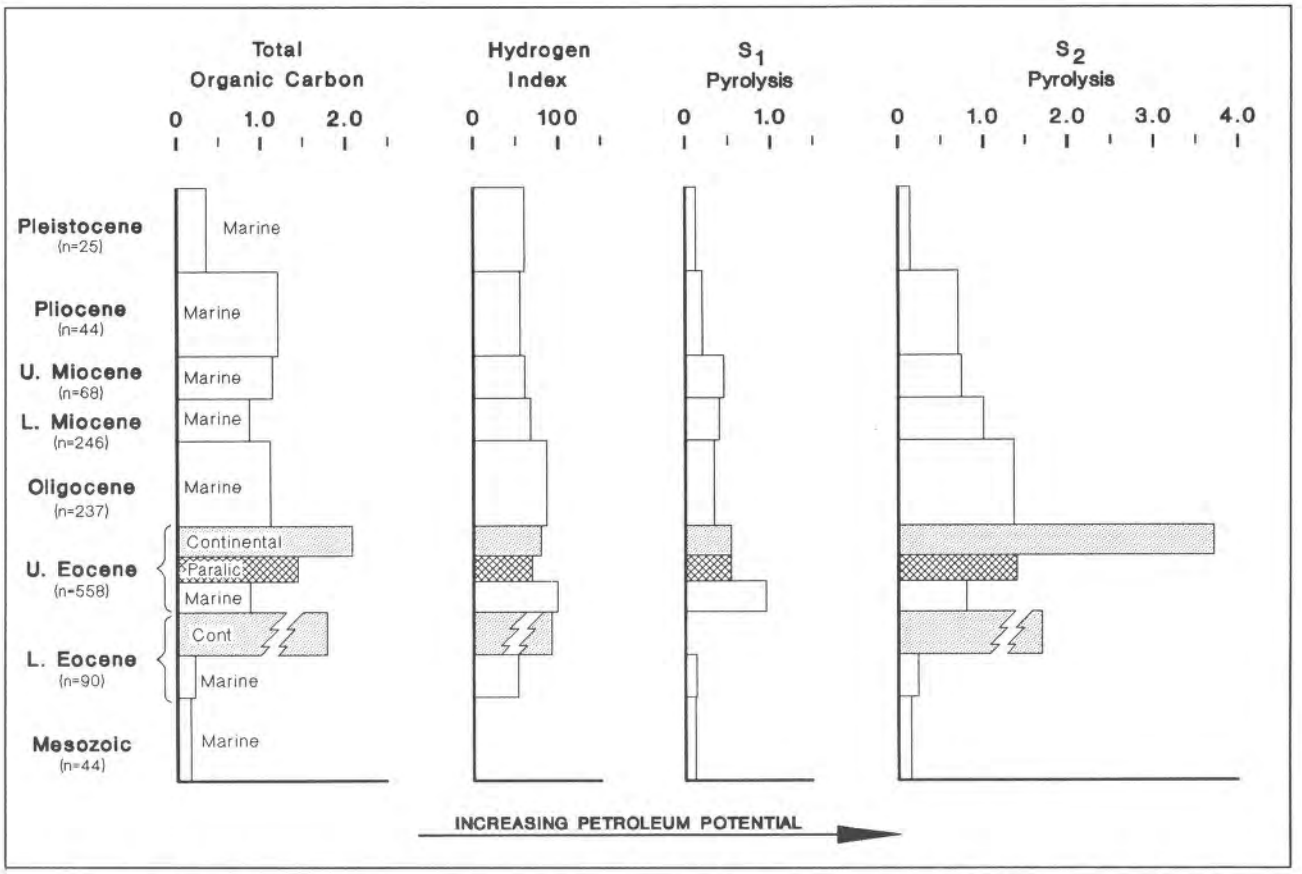

Figure 2. Some organic geochemical characteristics of selected sedimentary rocks in Washington. The dominant depositional environments for each time-stratigraphic interval are: marine, paralic, and continental. Data from coals are not shown except for lower Eocene rocks where broken bars indicate that the mean values are off-scale but not enriched relative to other time-stratigraphic intervals.

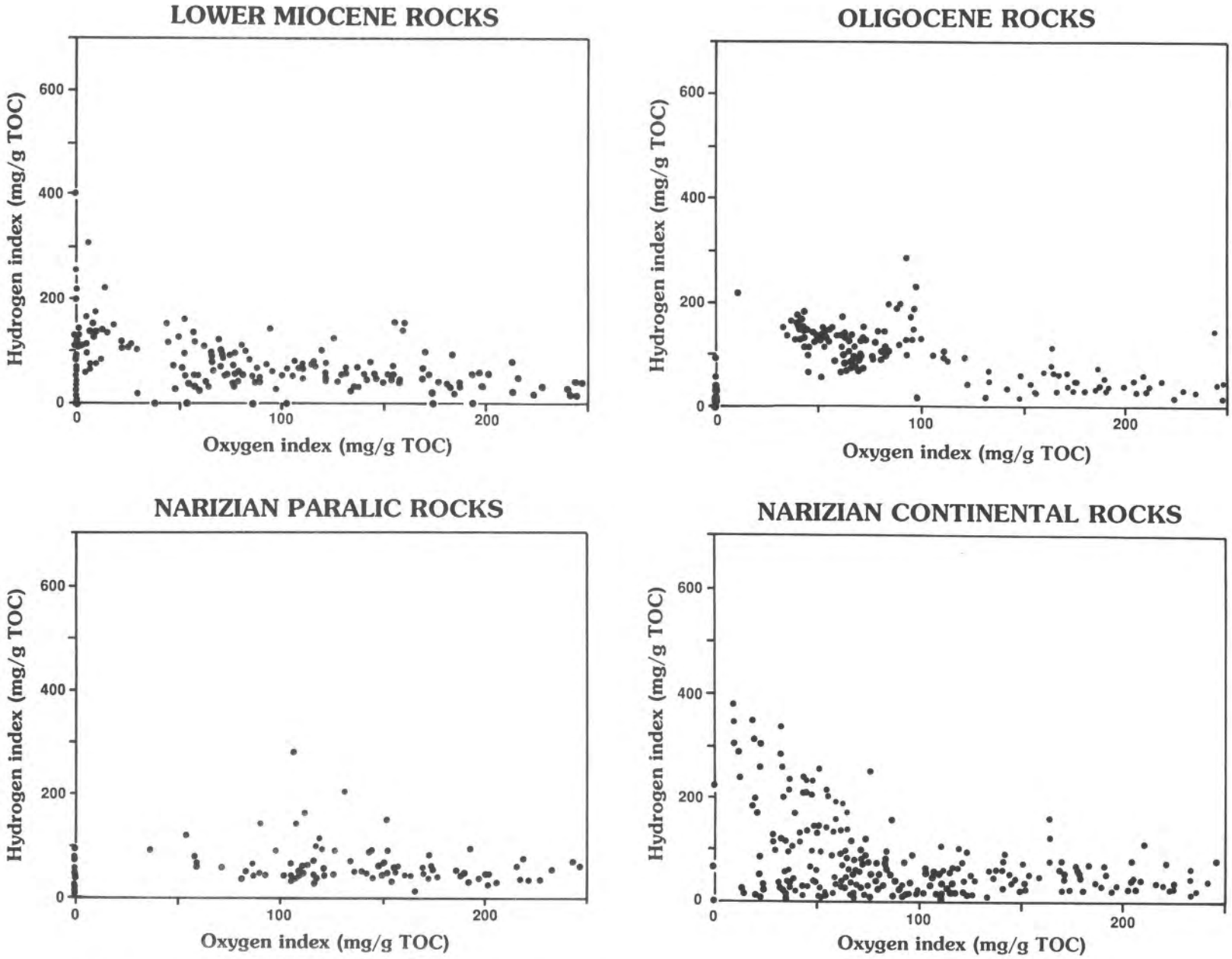

Figure 3. Pseudo van Krevelen diagrams for various stratigraphic intervals sampled in Washington wells and measured sections. All four diagrams indicate that gas-prone Type III kerogen predominates. However, Narizian-stage rocks deposited in continental environments show significant Type II (light-liquids- and gas-prone) kerogen, as well as hydrogen enrichment relative to coeval marginal-marine rocks and rocks in other stratigraphic intervals. Data sources are cited in text. TOC, total organic carbon.

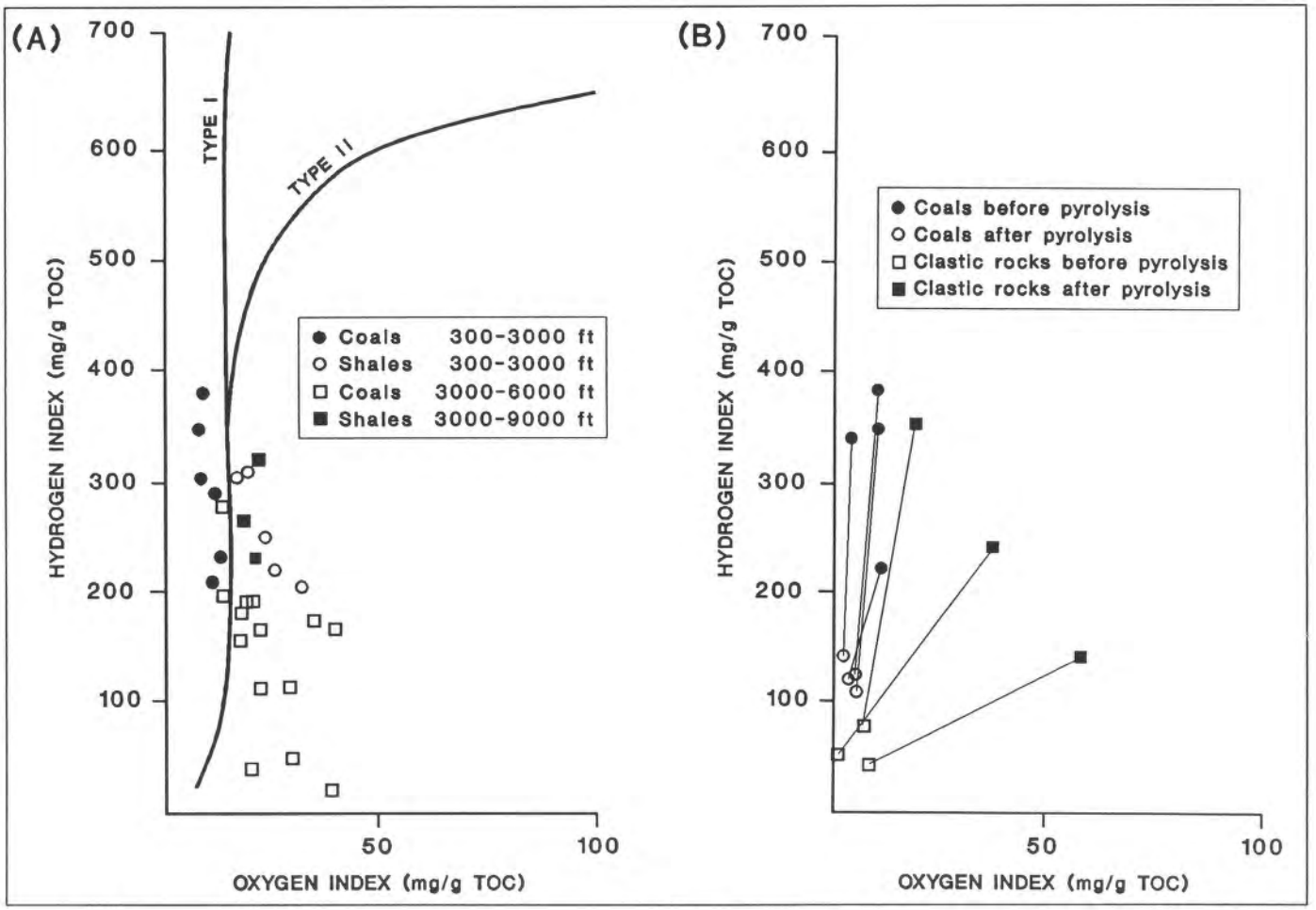

Figure 4. Pseudo van Krevelen diagrams for Birch Bay No. 1 samples. **A.** Results from Rock-Eval analysis. **B.** Results before and after hydrous pyrolysis. TOC, total organic carbon.

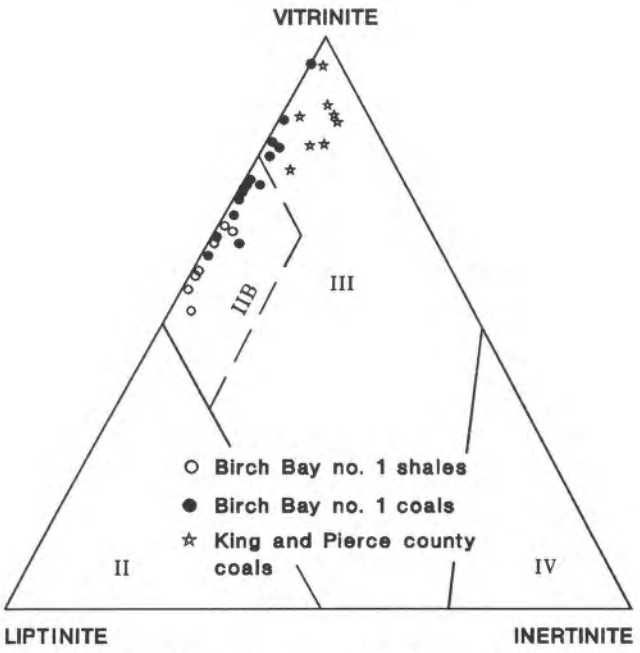

Figure 5. Maceral composition of some Washington coals (Cohen, 1984; this study). Kerogen types are indicated by roman numerals.

identical to those of oils tested from wells and seeps near Forks, which is located about 62 mi to the north. This suggests a cogenetic relation for coastal oils (Palmer and Lingley, 1989). C_{20} diterpane in Puget trough wells such as the Engstrom Community No. 1 and Alderwood No. 1 (Brown and Ruth, 1984) indicates a terrestrial source for minor shows logged in these wells.

From this body of data, we conclude that Washington has potential for gas, condensate, and light-oil accumulations. In order to explore for such pools, operators should map areas with potential to preserve Types II and III kerogen (reducing depositional environments) and be certain that peak-generative conditions will be present within the depths to be drilled.

References Cited

Beikman, H. M.; Gower, H. D.; Dana, T. A. M., 1961, Coal reserves of Washington; reprinted 1984 with addendum by H. W. Schasse, T. J. Walsh, and W. M. Phillips: Washington Division of Geology and Earth Resources Bulletin 47, 134 p.

Blackwell, D. D.; Steele, J. L.; Kelley, S. A., 1985, Heat flow and geothermal studies in the State of Washington: Washington Division of Geology and Earth Resources Open File Report 85-6, 68 p., 2 appendices.

Brown and Ruth Laboratories, Inc., 1984, Regional petroleum geochemistry of Washington and Oregon: Brown and Ruth Laboratories, Inc., 1 v., looseleaf.

Bustin, R. M., 1990, Stratigraphy, sedimentology, and petroleum source rock potential of the Georgia Basin, southwest British Columbia and northwest Washington State. *In* Geological Survey of Canada, Current research, Part F: Geological Survey of Canada Paper 90-1F, p. 103–108.

Cohen, M. L., 1983, The petrography of variously ranked Puget Lowlands coals: Southern Illinois University Master of Science thesis, 96 p.

Gaylord, D. R., 1986, Cenozoic sedimentation in the Republic graben, north-central Washington—Economic implications [abstract]: Society of Economic Paleontologists and Mineralogists Annual Midyear Meeting Abstracts, v. 3, p. 42.

Grady, M. T., 1985, Stratigraphy, sedimentology, and hydrocarbon potential of the Hoh turbidite sequence (Miocene), western Olympic Peninsula, Washington: University of Idaho Master of Science thesis, 192 p.

Hammer, A. A., 1934, Rattlesnake Hills gas field, Benton County, Washington: American Association of Petroleum Geologists Bulletin, v. 18, no. 7, p. 847–859.

Kvenvolden, K. A.; Golan-Bac, Margaret; Snavely, P. D., Jr., 1989a, Composition of natural gases in seeps, outcrops, and a test well. Chapter C *In* Preliminary evaluation of the petroleum potential of the Tertiary accretionary terrane, west side of the Olympic Peninsula, Washington: U.S. Geological Survey Bulletin 1892, p. 37–45.

Kvenvolden, K. A.; Rapp, J. B.; Hostettler, F. D.; Snavely, P. D., Jr., 1989b, Comparison of molecular markers in oil and rock extracts. Chapter B *In* Preliminary evaluation of the petroleum potential of the Tertiary accretionary terrane, west side of the Olympic Peninsula, Washington: U.S. Geological Survey Bulletin 1892, p. 19-35.

Lingley, W. S., Jr.; Walsh, T. J., 1986, Issues relating to petroleum drilling near the proposed high-level nuclear waste repository at Hanford: Washington Geologic Newsletter, v. 14, no. 3, p. 10–19.

McFarland, C. R., 1983, Oil and gas exploration in Washington, 1900–1982: Washington Division of Geology and Earth Resources Information Circular 75, 119 p.

Palmer, S. P.; Lingley, W. S., Jr., 1989, An assessment of the oil and gas potential of the Washington outer continental shelf: University of Washington, Washington Sea Grant Program, Washington State and Offshore Oil and Gas, 83 p., 12 plates.

Peters, K. E., 1986, Guidelines for evaluating petroleum source rock using programmed pyrolysis: American Association of Petroleum Geologists Bulletin, v. 70, no. 3, p. 318–329.

Sidle, W. C.; Richers, D. M., 1985, Geochemical reconnaissance of Cretaceous inliers in north-central Oregon: American Association of Petroleum Geologists Bulletin, v. 69, no. 3, p. 412–421.

Snavely, P. D., Jr., 1987, Tertiary geologic framework, neotectonics, and petroleum potential of the Oregon–Washington continental margin. *In* Scholl, D. W.; Grantz, A.; Vedder, J. G., editors, Geology and resources potential of the continental margin of western North America and adjacent ocean basins—Beaufort Sea to Baja California: Circum-Pacific Council for Energy and Mineral Resources, Earth Science Series, v. 6, p. 305–335.

Snavely, P. D., Jr.; Kvenvolden, K. A., 1988, Preliminary evaluation of the petroleum potential of the Tertiary accretionary terrane, west side of the Olympic Peninsula, Washington [abstract]. *In* Northwest Petroleum Association, Symposium—Program and abstracts: Northwest Petroleum Association, 1 p.

Snavely, P. D., Jr.; Kvenvolden, K. A., 1989, Geology and hydrocarbon potential. Chapter B *In* Preliminary evaluation of the petroleum potential of the Tertiary accretionary terrane, west side of the Olympic Peninsula, Washington: U.S. Geological Survey Bulletin 1892, p. 1–18, 1 plate.

Summer, N. S.; Verosub, K. L., 1987, Extraordinary maturation profiles of the Pacific Northwest: Oregon Geology, v. 49, no. 11, p. 135–140.

U.S. Department of Energy Morgantown Energy Technology Center, 1985, Deep source gas project, METC—Use of geochemical and paleobasin reconstruction studies of the Methow Basin, Washington, to investigate the hydrocarbon generating potential of deep sedimentary basins in the Pacific Northwest—FY 85 status report; draft: U.S. Department of Energy Morgantown Energy Technology Center, 1 v.

Walsh, T. J.; Lingley, W. S., Jr., 1991, Coal maturation and the natural gas potential of western and central Washington: Washington Division of Geology and Earth Resources Open File Report 91-2, 26 p.

Geology and Preliminary Hydrocarbon Evaluation of the Tertiary Juan de Fuca Basin, Olympic Peninsula, Northwest Washington

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The Juan de Fuca basin (JDFB) extends from near Striped Peak northwestward to Cape Flattery along the northern margin of the Olympic Mountains (Fig. 1). This Tertiary deep marginal basin continues north and northwest beneath the Strait of Juan de Fuca and the Pacific Ocean to the Canadian shelf and slope and is referred to as the Tofino basin (TB) by Shouldice (1971) and the Tofino–Fuca basin by Snavely and others (1980). The northern flank of the JDFB–TB is exposed in a narrow belt of shallow- and deep-marine Paleogene and early Neogene strata that crop out along the southern coast of Vancouver Island (Snavely and others, 1980; Cameron, 1971, 1979; Bream, 1987). The JDFB may have extended farther east at times (De Chant, 1989) and (or) may have been connected with other deep-marine basins that had different sediment source areas (Snavely and others, 1980).

The southern flank of the JDFB consists of more than 6,000 m of homoclinal north-dipping strata of middle Eocene to early Miocene age (Brown and others, 1960; Gower, 1960; Snavely, 1983; Snavely and others, 1986, 1989). Lithic arkosic to lithic turbidite sandstone, deep-marine mudstone, and subordinate polymict conglomerate and sedimentary breccias unconformably overlie lower Eocene oceanic

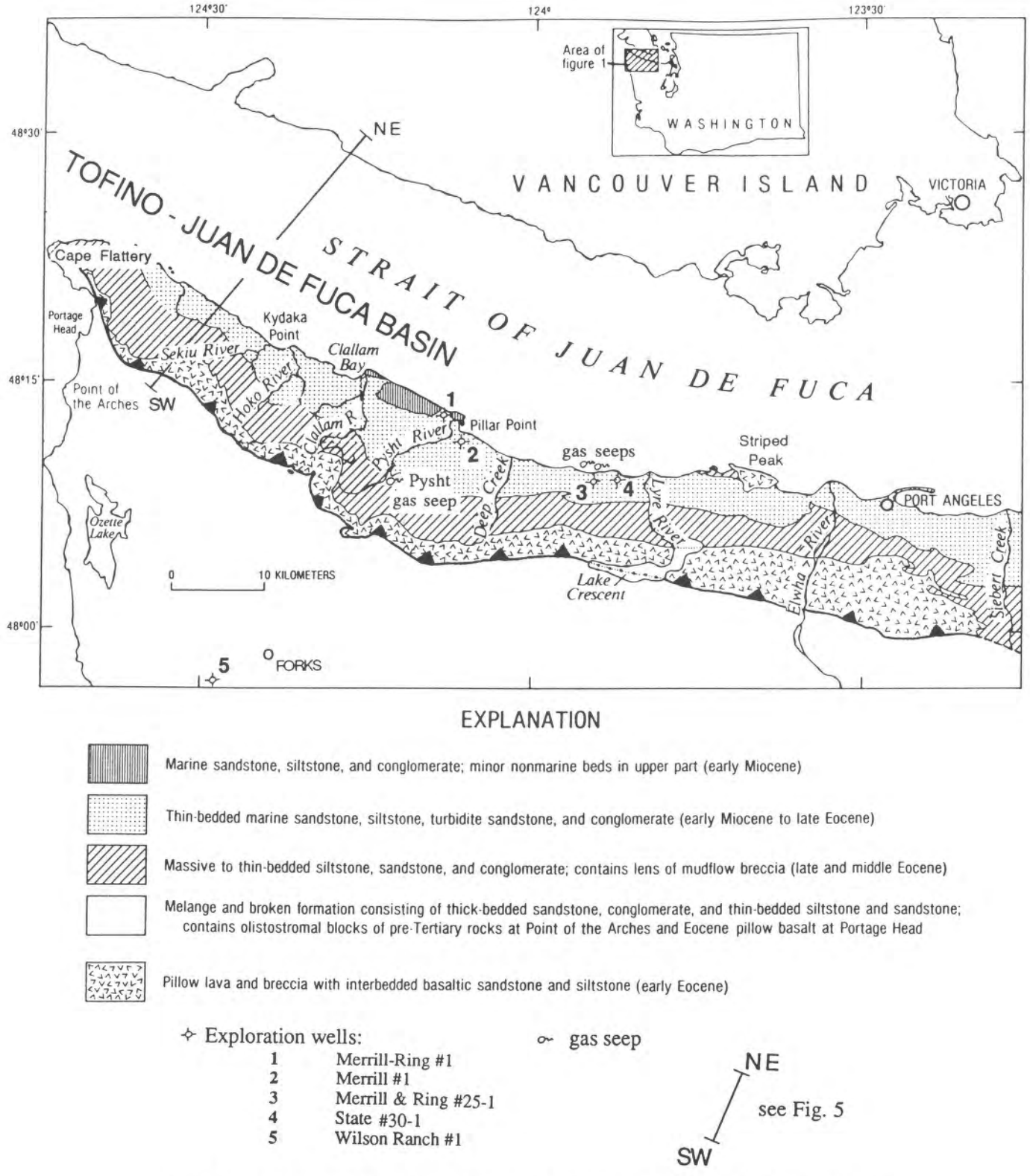

Figure 1. Location map of the Juan de Fuca area (redrawn from Snavely and others, 1980).

basalt of the Crescent Formation (Fig. 2). The sedimentary sequence is capped by a prograding, wave-dominated, deltaic facies of the coal-bearing lower Miocene Clallam Formation that filled this largely deep-marine basin (Gower, 1960; Anderson, 1985; Addicott, 1976). To the south, the Crescent basalt and marginal JDFB strata are underplated by several terranes of mélange and broken formation of the Olympic core rocks (Tabor and Cady, 1978), including the middle to upper Eocene Ozette terrane, the Jurassic to upper Eocene Sooes terrane, and the unnamed terrane between the

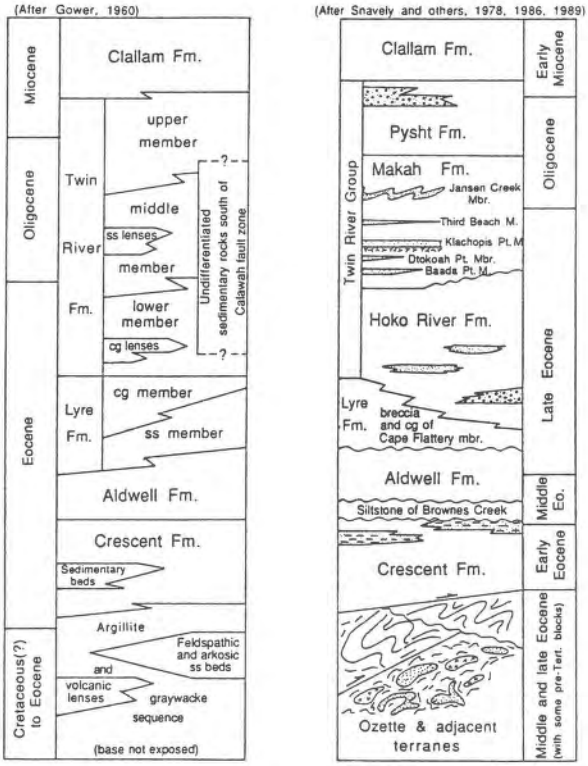

Figure 2. Stratigraphic columns for Juan de Fuca basin. The eastern part of the basin is represented by a column modified from Gower (1960); the western part of the basin is shown as interpreted by Snavely and others (1978, 1986, 1989).

Calawah fault and the Crescent thrust fault (Snavely and others, 1986; Snavely and Kvenvolden, 1989).

Depositional environments represented by the JDFB sedimentary rocks include (a) bathyal slope, outer fan, and basin-plain environments, indicated by thick mudstone deposits with minor thin distal turbidites and (or) locally derived debris flows (middle and upper Eocene Aldwell Formation – Snavely, 1983; Marcott, 1984; Oligocene and lower Miocene Pysht Formation – Snavely and others, 1978), (b) submarine fan cones or gravel slope wedges (upper Eocene Cape Flattery breccia and Lyre Formation – Brown and others, 1956; Ansfield, 1972; Alice Shilhanek, Western Wash. Univ., oral commun., 1991), (c) intraslope basin debris flows and middle to outer fan conglomerate channels (upper Eocene Hoko River Formation – Ansfield, 1987; De Chant, 1989), (d) depositional lobes in an outer- to mid-fan environment (upper Eocene and Oligocene Makah Formation – Snavely and others, 1980; and upper Eocene to lower Miocene Twin River Group – Brown and Gower, 1958, and Rau, 1964), and (e) submarine slumps (Jansen Creek Member of the Makah Formation – Snavely and others, 1980; Niem and others, 1989). Some Eocene shallow-marine basaltic sandstones fringe and are derived from and interbedded with flows associated with Crescent volcanic highs (for example, Striped Peak; Brown and others, 1960). The JDFB strata were largely derived from Mesozoic and Paleozoic low-grade metamorphic, granitic, volcanic, and recycled sedimentary source terranes on southern Vancouver Island (Snavely and others, 1980; Pearl, 1977; Ansfield, 1972; De Chant, 1989; Anderson, 1985) and from local Crescent/Metchosin volcanic paleohighs (Snavely, 1983; Brown and others, 1960; Marcott, 1984).

Few data have been published regarding the organic richness, maturation, porosity, and permeability of JDFB sedimentary units. (See Snavely, 1987; Snavely and Kvenvolden, 1989; Kvenvolden and others, 1989). Thus, these data may not be representative of the hydrocarbon potential of the entire basin. Total organic carbon (TOC) values for several outcrop samples of mudstone from these formations are typical of poor to fair source rocks (Table 1) (Peters, 1986). The oil and gas generative potential ($S_1 + S_2$) falls in the non-source rock category (Fig. 3A). These mudstones also display low hydrogen and oxygen indices (HI and OI, respectively, Table 1), and most samples plot on a van Krevelen diagram in a nondiagnostic area near the convergence of the Type III (gas-prone, terrestrial) and Type II (oil-prone, marine) kerogen curves (Fig. 3B). Low vitrinite reflectance (R_o), thermal alteration index (TAI), production index (PI), T_{max}, and transformational ratio (TR) values (Table 2) indicate that these samples are also thermally immature to marginally mature with respect to the peak oil generation window and immature with respect to the thermogenic wet and dry gas

Table 1. Source rock analyses of Tertiary siltstone, Juan de Fuca basin. TOC, total organic carbon; HI, hydrogen index = (S_2/TOC)x100; S_1+S_2 = oil or gas potential; OI, oxygen index = (S_3/TOC)x100

		Rock-Eval mg/g rock					
Formation	TOC	S_1	S_2	S_3	HI	OI	S_1+S_2
Pysht-1	0.87	0.02	0.47	0.21	54	24	0.49
Pysht-2	0.41	0.00	0.25	0.09	61	22	0.25
Pysht-3	0.45	0.04	0.37	0.01	82	2	0.41
Makah-4	0.34	0.01	0.18	0.07	52	20	0.19
Aldwell-5	0.44	0.04	0.28	0.06	64	14	0.32
Aldwell-6	0.34	0.00	0.20	0.13	59	38	0.20
Range	0.34	0.00	0.18	0.01	52	2	0.19
	0.87	0.04	0.47	0.21	82	38	0.49
Av. (n = 6)	0.48	0.02	0.29	0.10	62	20	0.31

Table 2. Maturation analyses of Tertiary siltstone, Juan de Fuca basin. R_o, vitrinite reflectance; PI, production index; TAI, thermal alteration index; TR, transformation ratio = $S_1/(S_1+S_2)$. (From Snavely and Kvenvolden, 1989)

			Rock-Eval		
Formation	R_o	TAI	PI	T_{max} (°C)	TR
Pysht-1	0.42	2.4	0.04	428	0.04
Pysht-2	0.48	2.5	0.00	430	0.00
Pysht-3	0.52	2.5	0.10	428	0.10
Makah-4	0.61	2.55	0.06	432	0.05
Aldwell-5	0.51	2.5	0.00	441	0.13
Aldwell-6	0.53	2.5	0.00	436	0.00
Range	0.42	2.4	0.00	428	0.00
	0.61	2.55	0.10	441	0.13
Av. (n=6)	0.51	2.5	0.03	433	0.05
Olympic core rocks					
Av. (n = 26)	0.75				

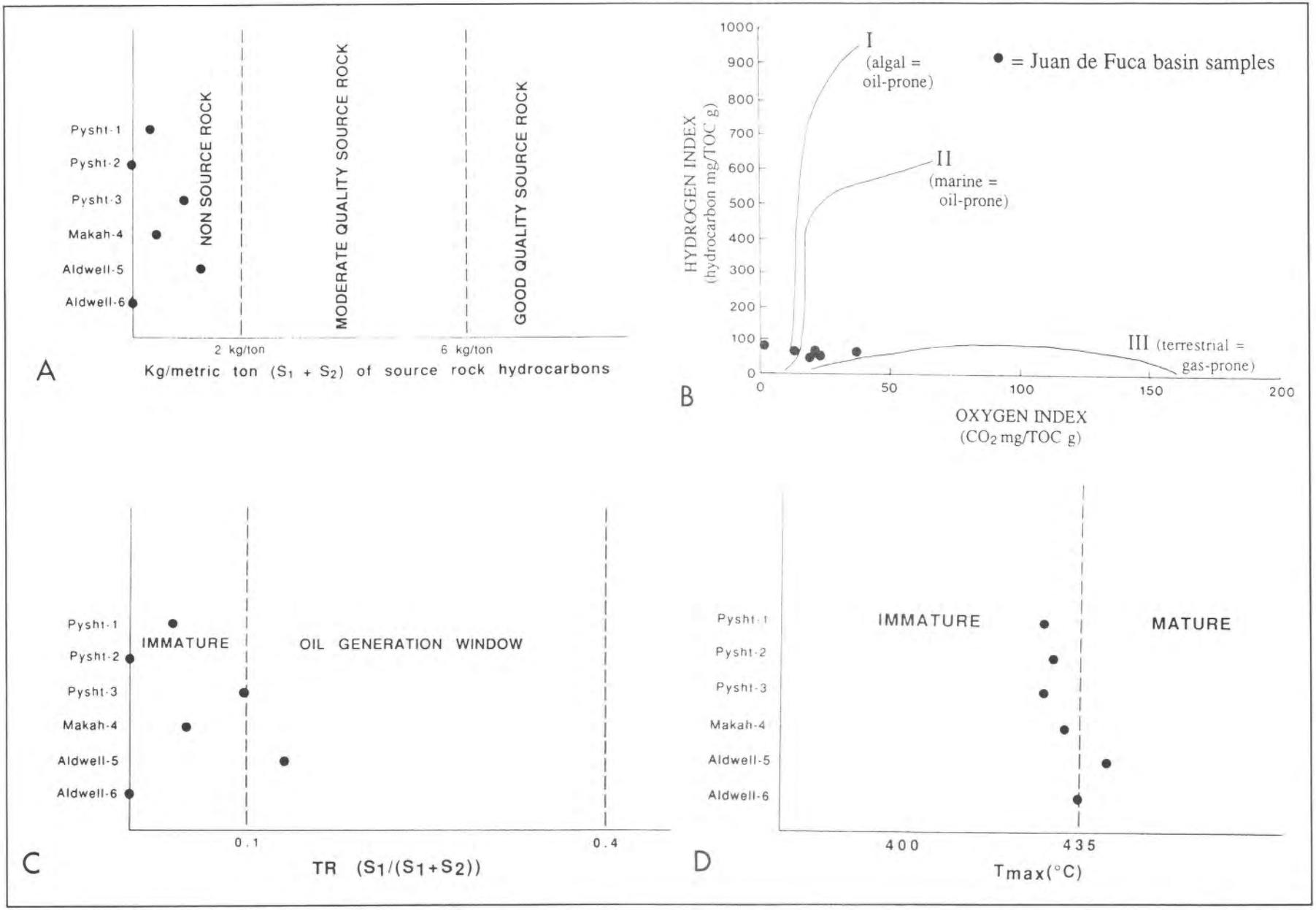

Figure 3. A. Classification of source rock quality of Juan de Fuca basin samples based on kilograms per metric ton ($S_1 + S_2$) of source rock hydrocarbons. (Bounding values from Tissot and Welte, 1978). **B.** Van Krevelen diagram (after Tissot and Welte, 1978) for Juan de Fuca basin samples reported in Snavely and Kvenvolden (1989). **C.** Source rock maturity evaluation diagram for Juan de Fuca basin samples based on transformation ratio (TR = $S_1/(S_1 + S_2)$) (oil generation window as defined by Tissot and Welte, 1978). **D.** Classification of source rock maturity for Juan de Fuca basin samples based on T_{max} (°C) (temperature ranges as shown by Espitalié and others, 1977). Sample values reported in Snavely and Kvenvolden (1989).

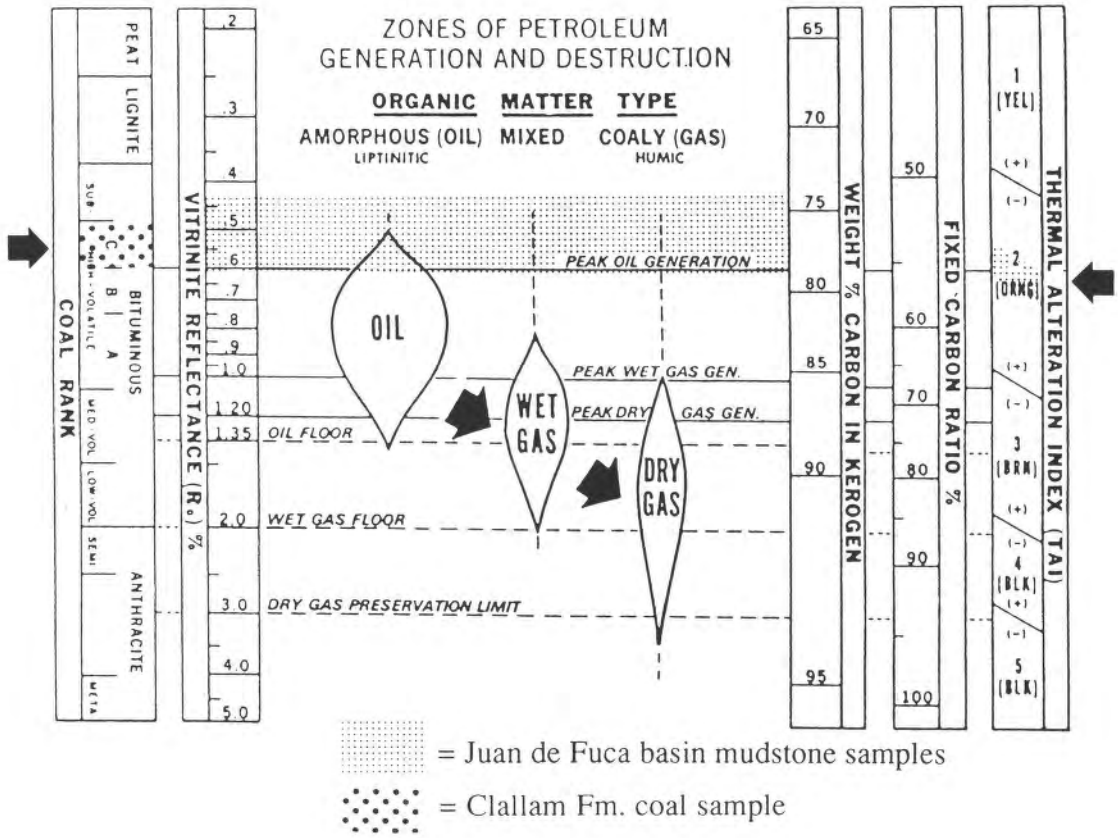

Figure 4. Correlation of various maturation indices (for example, R_o and TAI) with coal rank and zones of petroleum generation and destruction (modified from Dow, 1978). Juan de Fuca basin mudstone samples (reported by Snavely and Kvenvolden, 1989) plot in the stippled area on this diagram. Coal rank of the Clallam Formation was calculated by T. J. Walsh, Wash. Div. of Geol. and Earth Res., from an earlier published analysis by Smith (1911).

generation window (Figs. 3C, 3D, and 4) (Tissot and Welte, 1978; Dow, 1978). The HI, OI, S_1, S_2, S_3, PI, TR, T_{max} values, derived by Rock-Eval pyrolysis, however, can be affected by low TOC values, outcrop weathering, or adsorption of pyrolyzate on clay mineral matrix (Peters, 1986). The high volatile C bituminous rank of a Clallam Formation coal sample is consistent with the thermal immaturity of these mudstone samples (Fig. 4). In contrast, the more highly deformed middle and upper Eocene broken formation and mélange terranes of the northwest Olympic core rocks (that is, Ozette, Sooes, and unnamed terranes) exposed immediately south of the JDFB are generally thermally more mature (that is, an R_o average of 0.75 for 26 samples) (Table 2).

A natural seep in fractured Hoko River turbidite lithic sandstone and siltstone (lower Twin River Formation of Gower, 1960) along the Pysht River (Fig. 1) emits thermogenic gas (Snavely, 1987). The hydrocarbon and isotopic compositions of this gas are similar to those in thermogenic gas from the Wilson Ranch well in the Ozette mélange and broken formation to the south near Forks (Kvenvolden and others, 1989) (Table 3, and no. 5 on Fig. 1). This suggested to Snavely (1987) and Kvenvolden and others (1989) that the Pysht River gas may be sourced via deep-seated faults from the underlying Ozette mélange and broken formation and adjacent core rock terranes that have been underplated beneath the Crescent volcanic rocks and overlying JDFB fill (Fig. 5). The middle and upper Eocene Ozette mélange also includes oil-prone "smell muds" that contain thermogenic gas (Snavely and Kvenvolden, 1989). Thermogenic gas seeps in the JDFB have also been reported immediately offshore in the Strait of Juan de Fuca (Northwest Oil Report, 1986; Lingley, 1986) (Fig. 1).

Four exploration wells (as much as 8,519 ft total depth) have been drilled onshore in the eastern part of the JDFB (Nos. 1 through 4 on Fig. 1), mostly in the Eocene and Oligocene Twin River Group. Some oil and gas shows were reported (Northwest Oil Report, 1986, 1987; McFarland, 1983; unpub. drillers' logs from Dept. of Nat. Res. files). Hydrocarbon and isotopic analysis of a gas sample from the Twin River Oil and Gas State No. 30-1 well (drilled in 1986) showed that the gas is thermogenic (W. S. Lingley, Jr., Wash.

Table 3. Gas analyses for a natural seep and a test well, Juan de Fuca basin and Olympic core rocks (From Snavely and Kvenvolden, 1989)

Gas (volume %)	Pysht gas seep	Wilson Ranch well
Methane	94.33	95.8
Ethane	3.50	2.7
Propane	1.54	0.90
Butanes	0.43	0.30
Pentanes+	0.19	0.27
Methane Delta ^{13}C per mil	-31.5	-34.7
Hydrogen Delta D per mil	—	-135

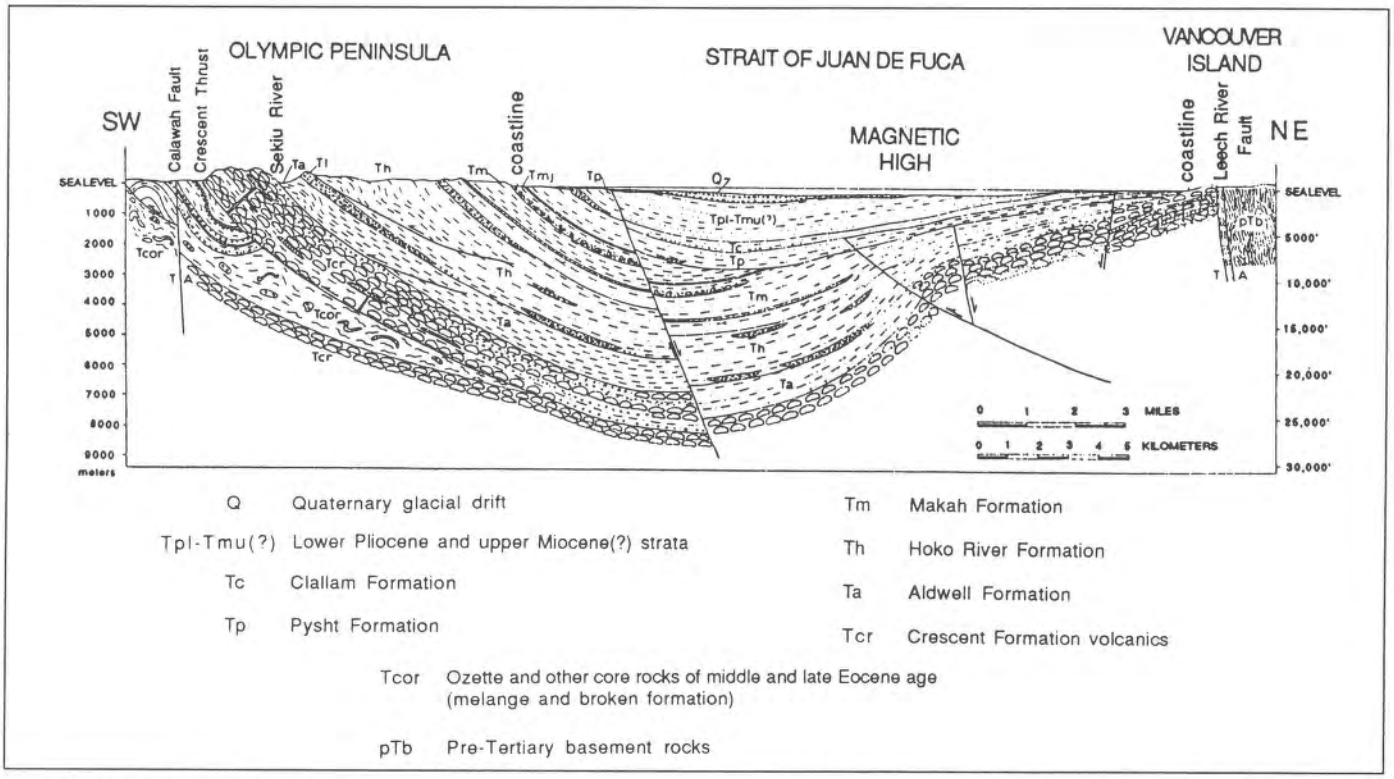

Figure 5. Generalized southwest-northeast cross section of the Juan de Fuca basin from the Olympic Peninsula beneath the Strait of Juan de Fuca to southern Vancouver Island (after Snavely, 1983). Location of cross section is shown on Figure 1.

Div. of Geol. and Earth Res. [DGER], oral commun., 1991). These shows may be sourced from underplated Ozette mélange and broken formation and adjacent core rocks or may have migrated updip from the more deeply buried, offshore part of the JDFB.

In general, the reservoir potential of the matrix-rich turbidite sandstone and conglomerate beds in the JDFB is low to moderate because abundant diagenetic and detrital clays, calcite, and minor zeolite and siliceous cements clog primary pores and pore throats (Pearl, 1977; Snavely and others, 1980; Ansfield, 1972; Anderson, 1985). Only a few values of porosity and permeability have been published for outcrop samples of members of the Makah Formation (Fig. 2; Snavely and others, 1980; Snavely, 1987). These values are lowest in the matrix-rich lithic and lithic arkosic wackes (for example, Baada Point Member, 20.4% and 20.7%, 2.0–7.5 md) but are moderately high in some cleaner micaceous arkosic sandstone units (for example, Klachopis Point Member, 24.6% and 657 md). These members represent thickening-upward, thick-bedded, sheet-like sandstones of mid- to outer-fan depositional lobes that can be traced laterally as much as 32 km in the western part of the JDFB (Snavely and others, 1980, 1986). Preliminary analysis of wireline logs from the Merrill–Ring No. 1 and Merrill No. 1 wells suggests that the penetrated section is dominantly siltstone, claystone, and minor thin, tight, distal turbidite sandstone (W. S. Lingley, Jr., DGER, oral commun., 1991). No significant reservoir sandstone was penetrated. Minor secondary fracture porosity in JDFB formations may have been created by faulting and jointing.

Potential seals occur in thick slope mudstone units and thin-bedded outer fan and basinal turbidite sandstone and siltstone facies (for example, Pysht, Makah, and Hoko River Formations of Snavely and others, 1978, 1980, and Twin River Formation of Gower, 1960). However, most of the homoclinal north-dipping potential reservoir units are breached by erosion. Possible stratigraphic traps include buried pinchouts of turbidite sandstone and conglomeratic inner-fan channel deposits in the Hoko River and Lyre Formations and depositional lobes of the Makah Formation that wedge out on Crescent paleohighs. (See Snavely and others, 1980.) Structural traps onshore are few and include local normal, strike-slip, and thrust faults as well as minor closure on faulted anticlines mapped by Snavely and others (1986, 1989), Gower (1960), and Brown and others (1960). These faults formed mainly in the late Eocene and late middle Miocene during periods of active underplating (Snavely, 1987). The timing of generation and migration of potential hydrocarbons relative to the timing of formation of potential structural and stratigraphic traps will require further investigation.

The Eocene and Oligocene turbidite units and lower Miocene deltaic Clallam Formation, which represent potential reservoirs, also extend offshore to the north and northwest. A thick lower Pliocene and upper Miocene(?) sedimentary sequence and Pleistocene glacial fill unconformably overlie these Paleogene and lower Neogene units beneath the Strait of Juan de Fuca and could act as possible seals (Fig. 5). Interpretation of U.S. Geological Survey seismic-reflection profiles (Snavely, 1987; Wagner and Tomson, 1987) and magnetic anomaly maps (MacLeod and others, 1977) (Fig. 5) suggests that structural traps (for example, thrusts and normal faults) may occur in this area. However, agreements between Canada and the United States currently preclude drilling in these environmentally sensitive waters. Exploration of these units on land may merit further study.

References Cited

Addicott, W. O., 1976, Neogene molluscan stages of Oregon and Washington. *In* Fritsche, A. E.; Ter Best, Harry, Jr.; Wornardt, W. W., editors, The Neogene symposium—Selected technical papers on paleontology, sedimentology, petrology, tectonics and geologic history of the Pacific coast of North America: Society of Economic Paleontologists and Mineralogists Pacific Section, 51st Annual Meeting, p. 95–115.

Anderson, K. S., 1985, Sedimentology, sedimentary petrology, and tectonic setting of the lower Miocene Clallam Formation, northern Olympic Peninsula, Washington: Western Washington University Master of Science thesis, 135 p.

Ansfield, V. J., 1972, The stratigraphy and sedimentology of the Lyre Formation, northwestern Olympic Peninsula, Washington: University of Washington Doctor of Philosophy thesis, 131 p., 1 plate.

Ansfield, V. J., 1987, Late Eocene multi-event debris flows in the Hoko River Formation, NW Olympic Peninsula, Washington [abstract]: Geological Society of America Abstracts with Programs, v. 19, no. 6, p. 355.

Bream, S. E., 1987, Depositional environment, provenance, and tectonic setting of the upper Oligocene Sooke Formation, Vancouver Island, B.C.: Western Washington University Master of Science thesis, 228 p.

Brown, R. D., Jr.; Gower, H. D., 1958, Twin River Formation (redefinition), northern Olympic Peninsula, Washington: American Association of Petroleum Geologists Bulletin, v. 42, no. 10, p. 2492–2512.

Brown, R. D., Jr.; Gower, H. D.; Snavely, P. D., Jr., 1960, Geology of the Port Angeles–Lake Crescent area, Clallam County, Washington: U.S. Geological Survey Oil and Gas Investigations Map OM-203, 1 sheet, scale 1:62,500.

Brown, R. D., Jr.; Snavely, P. D., Jr.; Gower, H. D., 1956, Lyre Formation (redefinition), northern Olympic Peninsula, Washington: American Association of Petroleum Geologists Bulletin, v. 40, no. 1, p. 94–107.

Cameron, B. E. B., 1971, Tertiary stratigraphy and microfaunas from the Hesquiat–Nootka area, west coast, Vancouver Island (92E): Geological Survey of Canada Paper 71-1, Part B, p. 91–94.

Cameron, B. E. B., 1979, Early Cenozoic paleogeography of Vancouver Island, British Columbia [abstract]. *In* Armentrout, J. M.; Cole, M. R.; Ter Best, Harry, Jr., editors, Cenozoic paleogeography of the western United States: Society of Economic Paleontologists and Mineralogists Pacific Section Pacific Coast Paleogeography Symposium 3, p. 326.

De Chant, J. H., 1989, Sedimentary petrology, depositional environment and paleogeographic significance of the upper Hoko River Formation, northern Olympic Peninsula, Washington: Western Washington University Master of Science thesis, 195 p., 6 plates.

Dow, W. G., 1978, Petroleum source beds on continental slopes and rises: American Association of Petroleum Geologists Bulletin, v. 62, no. 9, p. 1584–1606.

Espitalié, J.; Laporte, J. L.; Madec, M.; Marquis, F.; Leplat, P.; Paulet, J.; Boutefeu, A., 1977, Rapid method of source rock characterization and for evaluating their petroleum potential and their degree of evolution [English translation]: Institut Français du Petrole, v. 32, p. 23–42.

Gower, H. D., 1960, Geology of the Pysht quadrangle, Washington: U.S. Geological Survey Geologic Quadrangle Map GQ-129, 1 sheet, scale 1:62,500.

Kvenvolden, K. A.; Golan-Bac, Margaret; Snavely, P. D., Jr., 1989, Composition of natural gases in seeps, outcrops, and a test well. Chapter C *In* Preliminary evaluation of the petroleum potential of the Tertiary accretionary terrane, west side of the Olympic Peninsula, Washington: U.S. Geological Survey Bulletin 1892, p. 37–45.

Law, B. E.; Anders, D. E.; Fouch, T. D.; Pawlewicz, M. J.; Lickus, M. R.; Molenaar, C. M., 1984, Petroleum source rock evaluations of outcrop samples from Oregon and northern California: Oregon Geology, v. 46, no. 7, p. 77–81.

Lingley, W. S., Jr., 1986, Twin River Oil and Gas, Inc. drilling near Port Angeles: Washington Geologic Newsletter, v. 14, no. 3, p. 24–26.

MacLeod, N. S.; Tiffin, D. L.; Snavely, P. D., Jr.; Currie, R. G., 1977, Geologic interpretation of magnetic and gravity anomalies in the Strait of Juan de Fuca, U.S.–Canada: Canadian Journal of Earth Sciences, v. 14, no. 2, p. 223–238.

Marcott, Keith, 1984, The sedimentary petrography, depositional environment and tectonic setting of the Aldwell Formation, northern Olympic Peninsula, Washington: Western Washington University Master of Science thesis, 78 p.

McFarland, C. R., 1983, Oil and gas exploration in Washington, 1900–1982: Washington Division of Geology and Earth Resources Information Circular 75, 119 p.

Northwest Oil Report, 1986, Clallam County, Washington wildcat planned: Northwest Oil Report, v. 28, no. 7, p. [1].

Northwest Oil Report, 1987, Twin River well reported flowing gas: Northwest Oil Report, v. 29, no. 5., p. [1].

Niem, A. R.; Snavely, P. D., Jr.; Chen, Ying; Niem, W. A., 1989, Jansen Creek Member of the Makah Formation—A major Oligocene submarine landslide or slump deposit from the Vancouver shelf in the Juan de Fuca deep margin basin, NW Olympic Peninsula, Washington [abstract]: Geological Society of America Abstracts with Programs, v. 21, no. 5, p. 123.

Pearl, J. E., 1977, Petrology of Tertiary sedimentary rocks in the northwesternmost part of the Olympic Peninsula, Washington: San Jose State University Master of Science thesis, 91 p.

Peters, K. E., 1986, Guidelines for evaluating petroleum source rock using programmed pyrolysis: American Association of Petroleum Geologists Bulletin, v. 70, no. 3, p. 318–329.

Rau, W. W., 1964, Foraminifera from the northern Olympic Peninsula, Washington: U.S. Geological Survey Professional Paper 374-G, 33 p., 7 plates.

Shouldice, D. H., 1971, Geology of the western Canadian continental shelf: Canadian Petroleum Geology Bulletin, v. 19, no. 2, p. 405–436.

Smith, E. E., 1911, Coals of the State of Washington: U.S. Geological Survey Bulletin 474, 206 p.

Snavely, P. D., Jr., 1983, Peripheral rocks—Tertiary geology of the northwestern part of the Olympic Peninsula, Washington. *In* Muller, J. E.; Snavely, P. D., Jr.; Tabor, R. W., The Tertiary Olympic terrane, southwest Vancouver Island and northwest Washington: Geological Association of Canada Field Trip Guidebook 12, p. 6–31.

Snavely, P. D., Jr., 1987, Tertiary geologic framework, neotectonics, and petroleum potential of the Oregon–Washington continental margin. *In* Scholl, D. W.; Grantz, A.; Vedder, J. G., editors, Geology and resources potential of the continental margin of western North America and adjacent ocean basins—Beaufort Sea to Baja California: Circum-Pacific Council for Energy and Mineral Resources, Earth Science Series, v. 6, p. 305–335.

Snavely, P. D., Jr.; Kvenvolden, K. A., 1989, Geology and hydrocarbon potential. Chapter A *In* Preliminary evaluation of the petroleum potential of the Tertiary accretionary terrane, west side of the Olympic Peninsula, Washington: U.S. Geological Survey Bulletin 1892, p. 1–17, 1 plate.

Snavely, P. D., Jr.; MacLeod, N. S.; Niem, A. R.; Minasian, D. L., 1986, Geologic map of the Cape Flattery area, northwestern Olympic Peninsula, Washington: U.S. Geological Survey Open-File Report 86-344B, 1 sheet, scale 1:48,000, with 10 p. text.

Snavely, P. D., Jr.; Niem, A. R.; MacLeod, N. S., 1989, Geology of the coastal area between Cape Flattery and Cape Alava, northwest Washington: U.S. Geological Survey Open-File Report 89-141, 1 sheet, scale 1:24,000.

Snavely, P. D., Jr.; Niem, A. R.; MacLeod, N. S.; Pearl, J. E.; Rau, W. W., 1980, Makah Formation—A deep-marginal-basin sedimentary sequence of late Eocene and Oligocene age in the northwestern Olympic Peninsula, Washington: U.S. Geological Survey Professional Paper 1162-B, 28 p.

Snavely, P. D., Jr.; Niem, A. R.; Pearl, J. E., 1978, [1979], Twin River Group (upper Eocene to lower Miocene)—Defined to include the Hoko River, Makah, and Pysht Formations, Clallam County, Washington. *In* Sohl, N. F.; Wright, W. B., Changes in stratigraphic nomenclature by the U.S. Geological Survey, 1977: U.S. Geological Survey Bulletin 1457-A, p. 111–120.

Tabor, R. W.; Cady, W. M., 1978, Geologic map of the Olympic Peninsula, Washington: U.S. Geological Survey Miscellaneous Investigations Series Map I-994, 2 sheets, scale 1:125,000.

Tissot, B. P.; Welte, D. H., 1978, Petroleum Formation and Occurrence: Springer-Verlag Publishing Co., 538 p.

Wagner, H. C.; Tomson, J. H., 1987, Offshore geology of the Strait of Juan de Fuca, State of Washington and British Columbia, Canada: Washington Division of Geology and Earth Resources Open File Report 87-1, 16 p., 7 plates.

Washington Geologic Newsletter, 1989, Oil and gas wells permitted in 1988 and 1989: Washington Geologic Newsletter, v. 17, no. 3, p. 8.

Geothermal Projects at Mount Meager, British Columbia—History, Geology, Power Marketing, and Implications for the U.S. Cascades

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During the years 1973–1984, the British Columbia Hydro and Power Authority (B.C. Hydro), a Crown corporation, explored for geothermal resources at Mount Meager, 160 km (100 mi) north of Vancouver, B.C. (Fig. 1). The Geological Survey of Canada (GSC) and its parent, Energy, Mines and Resources Canada, also conducted seminal research, drilled several holes, and financially assisted B.C. Hydro.

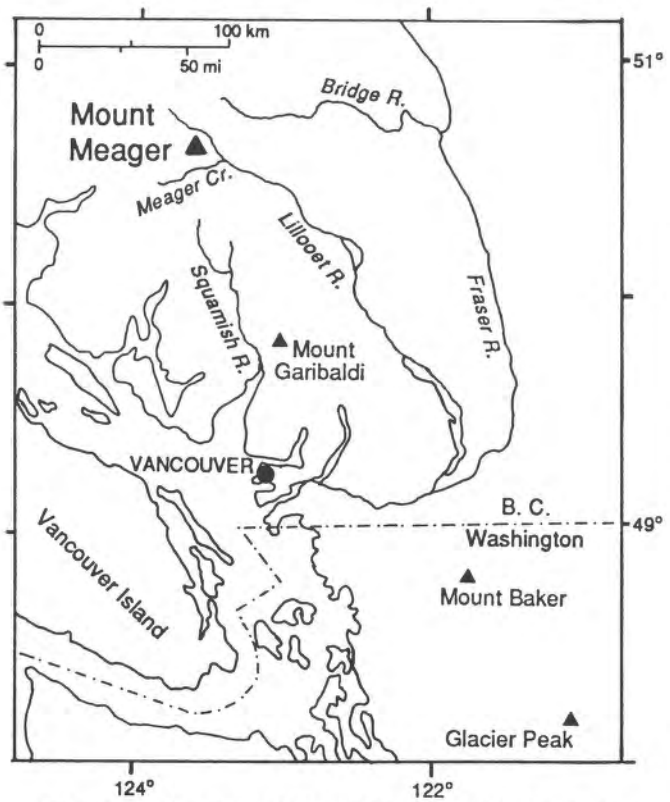

Figure 1. Location of Mount Meager, British Columbia.

The work discovered two high-temperature geothermal reservoirs, on the north and south flanks of Mount Meager. However, B.C. Hydro abandoned the project in the mid-1980s, during a period of diminished load growth, low energy prices, and high borrowing costs, and returned its geothermal tenure to the Province.

Interest in geothermal energy has picked up during the past few years, and private sector independent power producers (IPP) have resumed work where B.C. Hydro left off.

Geography and Physiography

Mount Meager is one of the northernmost volcanic complexes of the belt that extends from Mounts Lassen and Shasta in California through the Cascade chain of Oregon and Washington. In British Columbia, these volcanic rocks are called the Garibaldi belt.

The physiography of Mount Meager differs from that of Mount Baker, Mount St. Helens, and the other central volcanoes. Mount Meager was extruded on and among the rugged granitic peaks of the Coast Range. At Meager, the circular ramp of lava flows, lahars, and fanglomerates that surrounds most of the Cascade volcanoes has been dissected and removed by erosion, including glaciation. This has exposed the crystalline basement rocks on three sides. About 100 km^2 (40 mi^2) of volcanic rocks are exposed. Elevations in the area are from 400 to 2,800 m (1,300–8,790 ft).

Valleys are filled with alluvium, landslide debris, and till. Lower slopes are covered with first-growth fir, currently being logged. Treeline is at about 1,500 m (5,000 ft).

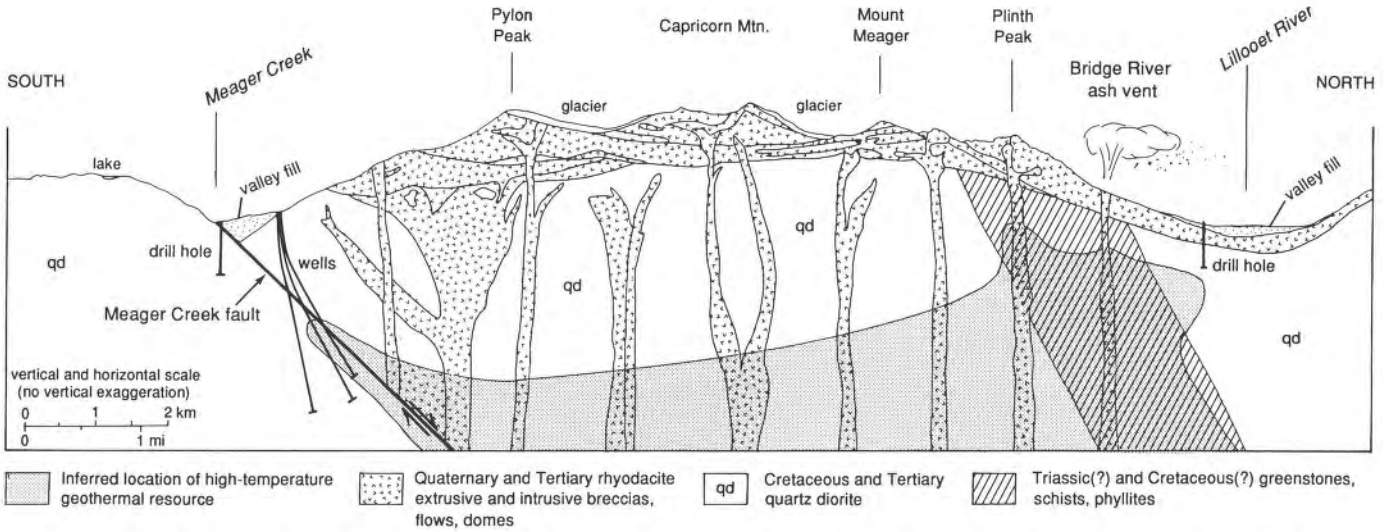

Figure 2. Conceptual cross section of the Mount Meager volcanic and geothermal system along a meridian at 123°31′22″W. Some features are projected a short distance onto the plane of the section. Redrawn from Nevin Sadlier-Brown Goodbrand Ltd. (unpub. report, 1979).

The broad, high passes are covered by permanent ice caps. The high central part of the volcanic edifice is not economically accessible for well siting.

Annual precipitation is as much as 250 cm (100 in.). The high precipitation has two practical effects—one bad, one good. The bad: detecting thermal features in shallow drill holes is difficult because large volumes of cold ground water continuously seep down the hydrologic gradient, suppressing, mixing with, and sweeping aside upwelling thermal waters. The cold ground water also distorts the already complex conductive geothermal gradient. The good: most geothermal feed or recharge water is of meteoric origin, and a producing geothermal field in this region would not overdraw its fluid as readily as one located in a drier climate.

Exploration Methods

The work done by B.C. Hydro and the GSC consisted mainly of the following:

- Geologic mapping at 1:20,000 and larger scales, petrography, and geochemical studies of rocks, soils, and waters. The geochemical studies included mercury surveys, radon surveys, major and minor ion studies, and stable isotope studies;
- Electrical resistivity studies over 250 km^2 (100 mi^2) of rough country and other geophysical work including magnetotelluric, microearthquake, and refraction seismic surveys;
- 26 shallow wells, generally to depths of 400 to 1,200 m (1,300–4,000 ft), using light, helicopter-portable, diamond core drills of the type used in metals exploration; thermal gradient and heat flow studies in these wells;
- Supporting the early camps and most of the diamond drilling by helicopter; later building roads and bridges;
- Drilling three exploratory wells with rotary tools to 3,000 to 3,500 m (9,800–11,500 ft) total depths (TD) and flow testing them.

The total spent was about $30 million (Canadian).

The most fruitful methods for siting the exploratory wells were (a) detailed geologic mapping, (b) electrical resistivity using dipole-dipole, pole-pole, and Schlumberger arrays, and (c) shallow temperature gradient wells.

Volcanic Geology

The age of volcanism at Mount Meager is Pliocene to Recent. Nine distinct volcanic assemblages range in age from 1.9 ± 0.2 Ma and to 2,340 ± 50 yr (Read, 1979, 1990). The geology is generalized in Figure 2.

Eruptions started at the south edge of the complex and progressed northward. Rock assemblages tend to overlap northward like shingles.

Composition is generally rhyodacite or quartz dacite, but some andesites and one basalt unit are present. Fragmental rocks—lahars, flow breccias, vent breccias, and tuffs—predominate over flows.

The units have highly irregular thicknesses; a maximum thickness for the volcanic assemblage could be estimated at about 1,000 m (3,300 ft) under Plinth Peak on the north edge of the complex. A complete treatment is given by Read (1979, 1990).

Basement Rocks and Structure

The volcanic rocks are underlain mainly by quartz diorite of Cretaceous age. Within this batholith are (a) pendants and septa of Triassic(?) and early Cretaceous(?) greenstones, phyllites, greywackes, and schists, (b) three smaller and younger stocks of quartz monzonite and quartz diorite composition, and (c) swarms of younger aphanitic volcanic dikes.

The south edge of the volcanic complex is cut by a caldera-boundary fault, the Meager Creek fault, that strikes east, dips about 45° to 50° north, and has a normal displacement of about 1,000 m (3,300 ft). Other regional faults are known or inferred to cut through the prospect area.

The quartz diorite has no intrinsic permeability, except in the networks of interconnected fractures (including parts

of the Meager Creek fault), the regional faults, and along the dikes.

Meager Creek (South) Reservoir

The Meager Creek (south) resource occupies the quartz diorite, and in this respect it resembles the Roosevelt geothermal field in Utah and other fracture-controlled reservoirs. The deep geothermal waters are dilute sodium chloride brines (less than 4,000 ppm), with a slightly alkaline pH of 8 to 9, and contain 240 to 440 ppm silica.

A geologic interpretation of stable isotope and ion geothermometry and temperature modeling (Ghomshei and others, 1986) suggests that the Meager Creek reservoir is a distal reservoir in which mixed geothermal and cold ground water equilibrated with the rocks at temperatures of about 210°C (410°F). This reservoir is fed from another that is closer to the heat source and probably located under the central volcanic edifice, where the rocks and fluids equilibrated at temperatures on the order of 280°C (536°F). The system almost certainly consists of high-pressure hot water lacking any steam cap.

As with most fracture-controlled geothermal reservoirs, the anomalous pressure derives from self-generated mineral precipitates that plug up the fractures. Lateral and vertical flow in and out are restricted. At Meager Creek the hydrothermal precipitates and alteration minerals observed in well cuttings and cores include secondary quartz, epidote, garnet, K-feldspar, albite, chlorite, allophane, smectite, sericite, wairakite, chalcedony, dolomite, anhydrite, calcite, and laumontite.

All three of the deep exploratory wells were drilled in the Meager Creek reservoir, angled in different directions from the same site. The highest directly measured down-hole temperature was 272°C (522°F).

Only one well has a sustainable flow. The flow is 17,000 kg/hr at 220 kPa (37,000 lb/hr at 32 psi) at a temperature of about 170°C (338°F) (B.C. Hydro and Barber-Nichols, 1987). This comes from a low-temperature zone at a shallow depth. A fraction of this water flashes to steam upon release to atmospheric pressure; however, the well does not meet commercial requirements.

The fracture-controlled reservoir is better understood now, and informed geologists believe that future wells could produce commercial-class geothermal fluids.

Pebble Creek (North) Reservoir

The geology suggests that the Pebble Creek resource directly overlies the hottest part of the volcanic system and that permeability is not likely to be a critical problem.

The Pebble Creek resource lies in and near at least five of the youngest volcanic vents. The wall rock consists of Triassic(?) and early Cretaceous(?) greenstones, phyllites, greywackes, and schists.

Inherent rock permeability is inferred to be greater than that of the quartz diorite. For example, the phyllites and schists are highly fractured in outcrop, and one of the volcanic vents was the conduit for an explosive pumice eruption, the well-known Bridge River Ash formation (2,340 ± 50 yr ago) and is probably a breccia pipe consisting of pumice blocks.

The only exposed thermal spring is a dilute sodium carbonate water; however, at least one concealed acid-sulfate spring is present. The evidence for this is hydrogen sulfide gas discharging into the atmosphere from underneath a small, stagnant valley glacier.

Drill-hole measurements of thermal gradients, below the obvious ground-water effects, range from 90°C/km (5°F/100 ft) to 200°C/km (11°F/100 ft). The higher values imply that commercial temperatures are within easy reach of wells. However, the area has not yet been drilled deeply enough to form an opinion on reservoir temperature.

Current Canadian Agenda

Private-sector IPPs are a fairly new enterprise in British Columbia, brought about by new legislation and B.C. Hydro's new policy of buying new energy. A lease on the Meager Creek property is now held by Canadian Crew Energy Corporation (CCEC), of Vancouver, B.C., under the B.C. Geothermal Resources Act. CCEC has responded to a recent request for proposals from B.C. Hydro to develop a geothermal demonstration plant, and the two parties are currently in negotiations over plant size, energy price, and other terms.

At industry request, the B.C. Ministry of Energy, Mines and Petroleum Resources recently announced a competitive sale of a geothermal exploration permit on the Pebble Creek area. Awarding of the permit is not determined at the time this was written, but it will probably be acquired by an IPP with experience in the geothermal business.

The current agenda starts with marketing—for a good reason. At present, a geothermal energy project aimed at electric power production must start with a power purchase agreement. During the high and volatile energy prices of the 1970s, geothermal developments were driven by acquisition and exploration. The prevailing notion was that any energy that could be found could be marketed. Geothermal steam producers and IPPs regularly accepted the risks of several millions of dollars for drilling wells prior to making marketing arrangements.

Since then a sea change has taken place in the North American geothermal business. It is currently market-driven. An IPP cannot accept the risk of drilling exploratory or production wells prior to having a conditional sales agreement from a utility company.

The two Canadian projects are technically the most advanced in the Northwest. Once marketing arrangements are made, they are expected to be developed rapidly.

Issues in the U.S. Cascades

Geothermal energy is one of the cleanest sources of electric power. It is nonpolluting, and it produces negligible carbon dioxide. It does not flood valleys, nor does it affect salmon or trout. It is efficient and has low operating costs. A geothermal electric plant does not disturb a very large area.

However, a geothermal plant must be located at the resource; unlike a coal-fired generating plant, there is no choice of sites. This has led to special problems in the U.S. Cascades, where recreational values are high and the U.S. Forest Service is the principal administrator of public lands.

Despite thousands of square miles of geothermal lease applications in the Cascades during the 1970s, no leases were issued and no private-sector exploration or development took place because the Forest Service did not set environ-

mental standards for exploration, and that window of opportunity passed.

At present, the geothermal industry views the U.S. Cascades as having enormous geothermal energy potential. However, specific reserves have not been measured, resource characteristics are not known, and extra compliance and permitting costs will add to the already expensive front-end charges and risks.

These extra costs, specific to the U.S. Cascades, will result from resolving competing land uses, coping with expenses and delays brought about by environmental and no-growth lobbies, and complying with the various requirements of dozens of agencies at all levels of government.

In order to afford the inherent and extra front-end costs, an IPP's investors and bankers will require a commitment of a high price for the first increments of energy, perhaps 8 to 10 cents per kWh, a price higher than the Northwest's utilities are used to paying for new power.

Current U.S. Work

The Northwest still has the lowest cost energy in the U.S. Avoided costs (costs of new energy increments) are in the range of 4.5 to 5.5 cents per kWh, but the economics are changing rapidly.

The factors converging on higher prices to be paid by utilities and energy users include the lack of any more rivers to dam, measures to protect the sockeye and other salmon species, return of Columbia River Downstream Benefits to British Columbia in the late 1990s, high regional load growth, and the Clean Air Act.

Terms for entry of geothermal energy into the Northwest's energy mix are succinctly analyzed by Sifford (1990). The utilities are aware of geothermal energy and its economics. Puget Sound Power and Light recently executed a power purchase agreement with a California producer, Trans Pacific Geothermal Corporation, and the Bonneville Power Administration recently initiated a program to support three 10-megawatt geothermal demonstration plants within its service area (Darr, 1990).

More than 20 U.S. geothermal fields have been developed to nearly 3,000 megawatts of generating capacity in four states, California, Nevada, Utah, and Hawaii. The growth rate has been 13 percent annually since 1975.

Acknowledgment

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References Cited

B.C. Hydro and Power Authority; Barber-Nichols Engineering Company, 1987, Meager Creek geothermal project: Electric Power Research Institute, Palo Alto, California, AP-5118, Research Projects 1196-4, -90, 88 p.

Darr, G. D., 1990, The Bonneville Power Administration's geothermal program—Pilot projects in the Pacific Northwest: Geothermal Resources Council Bulletin, v. 19, no. 11, p. 308–310.

Ghomshei, M. M.; Croft, S. A. S.; Stauder, J. J., 1986, Geochemical evidence of chemical equilibria in the south Meager Creek geothermal system, British Columbia: Geothermics, v. 15, no. 1, p. 49–61.

Read, P. B., 1979, Geological map of Meager Creek geothermal area, southwestern British Columbia: Geological Survey of Canada Open File 603, 1 sheet, scale 1:20,000.

Read, P. B., 1990, Mount meager complex, Garibaldi belt, southwestern British Columbia: Geoscience Canada, v. 17, no. 3, p. 167–170.

Sifford, Alex, 1990, Geothermal power in the Pacific Northwest—Market prospects for the 1990's: Geothermal Resources Council Bulletin, v. 19, no. 11, p. 302–306.

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With the theme "Integrating mining, metallurgical and environmental innovations for survival in demanding times", the main focus of the forum will be on improving productivity in gold plants. However, papers are also invited on resource trends and innovative emerging mining technologies that will have an impact on selection of metallurgical processes and environmental management. Significant new technological advances and ways of improving productivity will be covered in the technical program; the trade exhibition will highlight metallurgical and environmental management products and services.

Submittals of papers are invited on extraction and recovery of gold, silver, and platinum group metals that reduce costs, improve productivity, and (or) facilitate environmental management. Topics of interest include: integrated systems to match resource trends; backfill, undercut, and fill; hydraulic hoisting; fine blasting; improving comminution productivity; sorting, gravity, and flotation preconcentration; refractory ore treatment options and results; leaching, heap leaching, in-situ leaching; oxygen and peroxide leach supercharging; cyanide optimization; heap vs. dump vs. agitation leaching—economic comparison; ion exchange system advances, resins, fibers; improved carbon management byproducts recovery; reagent cost optimization; heap, mine and tailings reclamation; and cyanide recovery.

For more information and (or) submittal of papers contact: Hans von Michaelis, Conference Program Chairman, Randol International Ltd., 21578 Mountsfield Drive, Golden, CO 80401 USA; 303/526-1626; FAX: 303/526-1650.

Surface Mining and Surface Mining Law in Washington

by William S. Lingley, Jr., and David K. Norman

Introduction

In this article, we describe surface mining and surface mining law in Washington. We also introduce proposed amendments to the Surface Mine Reclamation Act (Chapter 78.44 RCW).

Washington is among the largest producers of sand and gravel (round-rock aggregate) and magnesium (from dolomite) in the United States. At present, there are about 1,750 surface mines in Washington. Of the permitted operations, 930 are sand and gravel pits, 332 are quarries, nine sites are permitted for clay extraction, eight for dolomite, and six for silica. There are also four permitted sites at which diatomite can be mined, two coal mines, and two metal mines (Schasse, 1991; Joseph, 1991). The remainder are unpermitted borrow pits. Borrow pits are exempt from state permitting because they are in remote areas and used mainly for forest or agricultural road construction, or because they are smaller than the 3-acre statutory permitting threshold.

Mines currently operating under Surface Mining Permits issued by the Department of Natural Resources include 400

Figure 1. The Lonestar Northwest, Inc., Steilacoom gravel pit, the fifth largest sand and gravel mine in the United States. This view (from the northwest) shows mineral processing, stockpiling, and barge loading facilities. Mining at the site commenced in 1896, but intense residential building did not impinge on the site until 1960. The photo also shows reclamation in progress, including sediment slurries that are pumped from retention ponds in the center of the photo to reestablish soil in areas mined prior to adoption of RCW 78.44. Photo courtesy of Ron Summers.

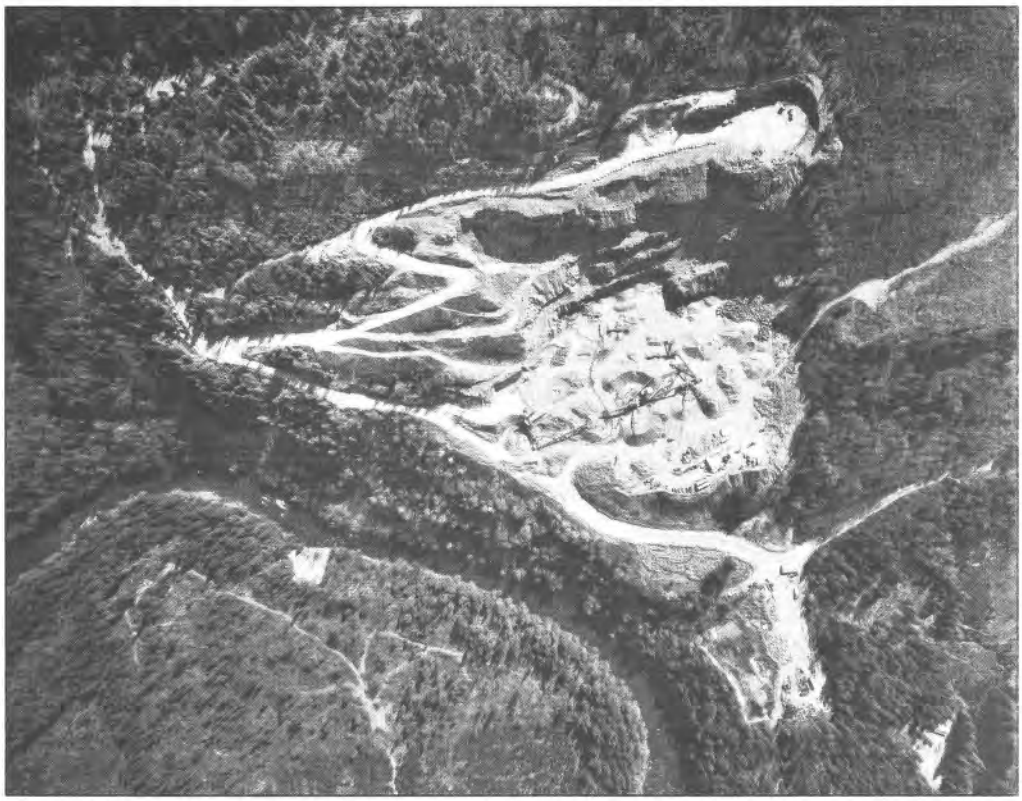

Figure 2. The Meridian Aggregates Company Granite Falls quarry in Snohomish County, one of the largest in Washington. The site was opened in 1905 by the Wayside Copper Company for use as an underground copper and gold mine. Today, the rock is used primarily for railroad ballast and construction applications. Mining is likely to continue for another 75 years. View is to the south; photo courtesy of Dave Piper.

mines owned by the Washington Department of Transportation or local governments and 893 privately owned mines.

Mine Economics

The primary uses of round-rock aggregate are for the manufacture of concrete (batching) and for drainage applications. Crushed oversize gravel and crushed quarried rock are used for roadbase and as asphalt aggregate. Both round-rock aggregate and asphalt aggregate displace relatively expensive ingredients in concrete and asphalt, respectively. Cement used in concrete is expensive because it is made from powdered limestone that has been heated to 2,700°F. Tar used in asphalt is an expensive petroleum product. Aggregate also adds strength to concrete and asphalt.

In Washington, the annual per capita demand is approximately 8 tons of sand and gravel and about 3 tons of quarried rock for all uses.

The concrete and asphalt aggregate mining businesses are intensely competitive. Typical returns on capital invested are 12 percent, and typical gross profits are $1.00/ton. Approximate per-ton mine operating costs are $0.50 for landowner royalties, $1.00 for loading (by front-end loaders or conveyor belts), $2.00 for processing (sorting and crushing), and $0.25/ton/mile for transportation. The cost of transportation controls the price of rock products: a moderate increase in the distance from mine to market markedly increases the cost of the rock. Revenues from Washington's sand and gravel and quarried rock businesses were about $200 million during 1990 (Joseph, 1991).

The economics of other surface-mined commodities is controlled, to a large degree, by national or international markets that are subject to large fluctuations, and profits vary accordingly. Metal mining is capital intensive.

Resource Geology

Western Washington has been rich in round-rock aggregate owing to production from 30 ice-age deltaic deposits. The Fraser continental glacier carried strong and durable granitic gravel from the Coast Mountains of British Columbia and other rock types from local sources. These were deposited from periglacial streams in deltas built out into lakes covering parts of the Puget Lowland between 18,000 and 12,000 years ago. Most of these ice-age lakes were located along the Cascade and Olympic foothills. Mining complexes in Steilacoom (Fig. 1), Issaquah, and Auburn are extracting gravel from these deposits. In the last few decades, the abundance of aggregate and intense competition contributed to the low cost of housing and public works. However, these deposits are nearly depleted, and other sources are of poorer quality, are farther from the market, and (or) require disturbing larger areas to produce the same volume of aggregate.

As with many resources, round-rock aggregate and rock suitable for quarrying are not evenly distributed or of similar quality throughout the state. Southern and eastern Washington rely on river deposits for much of their sand and gravel. The Spokane River valley contains abundant high-quality gravel, but these resources are coincident with the sole-source aquifer. Eastern and north-central Washington have abundant quarried rock resources because of the granitic or nonmarine basaltic rocks that crop out in many areas. Figure 2 shows the Granite Falls quarry, which is typical of large operations in northern Washington. On the other hand, quarried rock that will meet specifications for strength and durability is rare in southwestern Washington and on the Olympic Peninsula. Igneous rocks in these areas are mainly marine basalts that were subjected to weakening alteration by seawater as they were extruded.

Environmental Impacts of Mining

The chief environmental impacts of round-rock mining are dust and truck traffic. Less common problems that are of great concern are river avulsion or other river bed damage and potential degradation of ground-water quality and (rarely)

quantity. A major detrimental post-mining impact has been backfilling of sand and gravel pits with garbage (for example, the Midway landfill south of Seattle). In quarries, surface-water quality is commonly a problem because the quarry floors are generally impermeable and none of the rain that falls on the site enters the ground. Consequently, large precipitation events may overwhelm poorly designed discharge systems and carry sediment or pollutants into adjacent drainages. (One untapped, potentially beneficial aspect of low-permeability quarries is their suitability as landfill sites.) Social impacts from all mining are locally intense and include truck traffic, noise, dust, glare, back-up alarms, blasting vibrations, and flyrock from blasting. However, noise and air pollution commonly remain below the statutory definitions of infractions.

Compounding these social impacts is the fact that miners sometimes provide rock at odd hours. Maintenance of busy roads is generally performed at night. Early-morning and (or) 24-hour concrete pours produce stronger and more durable products. Longer lasting products help conserve the limited rock resources. At least one concrete plant on Seattle's Duwamish waterway must be supplied with aggregate at night because of road-use restrictions.

Mine Regulation and Laws

The present mine regulatory scheme is complex and unwieldy. Land-use decisions and many operating restrictions are imposed by local governments during the mine zoning or land-use permitting processes. Counties and municipalities must now consider mining in the context of growth management planning (Chapter 36.70A RCW). King County has a mine regulatory program that is comparable in size and budget to the State program. Restrictions are generally applied under the authority of the State Environmental Policy Act (Chapter 43.21C RCW, often referred to as SEPA). Such restrictions may be enforced only if these are part of an environmental impact statement or are regulated under written local SEPA policies. Local government also regulates some types of mine-related solid waste and shoreline management (Chapters 70.95 and 90.58 RCW, respectively). Other operating standards are regulated by the Department of Labor and Industries (Chapter 70.74 RCW) and the Federal Mine Safety and Health Administration (or MSHA, Public Laws 91-173 and 95-164).

Environmental impacts of mining are regulated by a variety of agencies. The Department of Ecology regulates ground- and surface-water quality and (or) quantity under Chapters 90.44, 90.48, and 90.54 RCW. They also regulate solid waste disposal and air quality (Chapters 70.95 and 70.94 RCW). The Department of Fisheries regulates mining in river channels as part of its Hydraulics Permit process (Chapter 75.20 RCW). The federal Environmental Protection Agency regulates processed mine waste and chemical mining (such as gold heap-leaching) under Public Law 95-510 (also known by its acronym, CERCLA). Each federal land owner (such as the Bureau of Land Management, the Forest Service, the National Park Service, or the Bureau of Reclamation) and Native American nations regulate mining under its applicable regulations (for example, Public Laws 94-579 and 96-479 and other chapters for the Bureau of Land Management). Coal mines are partly regulated by the federal Office of Surface Mining under Public Law 95-87 as amended.

Each of these laws was written by a legislative body, and each is accompanied by state rules (the Washington Administrative Code, or WAC) or federal regulations (Code of Federal Regulations or CFR). Rules and regulations are written by the agency administering each law.

The Washington surface mining law (Chapter 78.44 RCW), administered by the Department of Natural Resources, was adopted in 1970 in order to assure that a "reasonable" level of reclamation occurred in all surface mines. A key aspect of the existing State surface mining law is that it was broadly written so as to regulate effectively all types of mining. The law, in its present form, is characterized by imprecise statutes, inconsistencies resulting from prior incomplete amendment of the statute, and a lack of compliance tools for regulators. Consequently, it is difficult to force recalcitrant miners to comply, and our staff has been embroiled in numerous and costly legal actions.

Mine Reclamation

While 753 mines have been reclaimed to the standards set forth in the statute, some of this reclamation would not meet present standards because the reclaimed slopes have rectilinear appearances and many revegetation efforts have been unsuccessful. The Department currently encourages miners to implement our administrative reclamation standards. Initially, RCW 78.44 contemplated progressive reclamation, wherein a mine would expand in annual segments and each segment of the mine would have a reclamation plan. This approach, adopted from coal mine law, was difficult to implement. Progressive reclamation is commonly impractical for sand and gravel operations because material is blended from many segments of the mine in order to produce various rock products. Furthermore, SEPA mandates that all impacts of any mine must be analyzed at the time the permit is initially issued.

Recent Court Cases

Judicial decisions have alternately clarified and confounded regulatory efforts. In *Reid v King County,* 35 Wn. App. 720, 669 P. 2d 502 (1983), the Department and King County argued and prevailed in our assertion that mining vertical cliffs contiguous with neighboring properties is inconsistent with the statutory requirement for slope stability maintenance. In *Valentine v Board of Adjustment for Kittitas County,* 51 Wn. App. 366, 370, 753 P. 2d 988 (1988), the Court agreed with the assertion of Kittitas County, supported by the Department, that mineral processing is properly regulated by counties and municipalities. However, with *In re Anderman,* No. 70-012066-1 (Department of Natural Resources, May 14, 1991), an administrative law judge found that the Department could not regulate water quality where damage had not occurred. In *Valentine v Board of Adjustment for Kittitas County, Fjetland v Pierce County,* No. 12448-3-II (Wash. Ct. App. May 4, 1990), and *Browning v Clark County,* No. 90-2-00184-2 (Clark County Super. Ct. Nov. 30, 1990), the Courts found that, to various degrees, the State surface mining law preempts mine regulation by counties and municipalities. Paradoxically, these preemption decisions, which limit the regulatory authority of local government, were rendered at the same time local government was assigned comprehensive new responsibility to plan and protect land uses under the Growth Management Act.

Proposed Changes to Surface Mining Law

Despite myriad applicable laws, the regulatory scheme is not working well: reclamation is not occurring with statewide consistency, environmental impacts are not always mitigated, local governments have been stripped of their authority to address land-use issues, and confrontations between miners and their neighbors are escalating. The unwieldy regulatory scheme may be partially responsible for some small mines being forced out of business and the short supply of quality rock products in some areas. For these reasons, the Department believes that a careful revision of the State surface mining law and the accompanying rules would be in the best interest of the citizens of Washington.

During the 1990 legislative session, the Senate Environment and Natural Resources Committee formed a subcommittee to prepare amendments to Chapter 78.44 RCW. Subcommittee members are Senators Neil Amondson, Linda Smith, and Dean Sutherland. They, in turn, asked the Department of Natural Resources, Division of Geology and Earth Resources to draft a set of proposed amendments. In order to accomplish this work, the Division formed a working group composed of 14 persons representing key interest groups involved in, or affected by, surface mining.

Several divisive issues faced this working group. A central problem is partitioning regulatory authority between state and local jurisdictions. The working group considered assigning all responsibility to a single agency but dismissed this option after failing to resolve the conflicting necessities of achieving a reasonable level of statewide environmental consistency and allowing local control over land-use determinations. In order to avoid costly and unnecessary bureaucracy, we settled on assigning the authority to regulate mining operations such as truck traffic, public safety, and noise to county government. Under the proposed amendments, counties may also be authorized by the Department to be the sole regulator of mine reclamation if they meet certain statutory criteria.

Other important issues are the low level of accountability of various agencies regulating mining and apparent mismanagement of many regulatory programs. We estimate that more than 200 city, county, state, and federal regulators spend at least 5,000 person-days per year regulating mines in Washington. We reasoned that eliminating redundant regulation would reduce the number and increase the effectiveness and accountability of regulatory personnel.

The proposed amendments to the State surface mining law developed by the working group are given below. These amendments are designed to:

(1) Prevent redundant regulation.
(2) Assure that mine regulators and appeals officers are experts in their field.
(3) Isolate specific regulatory responsibilities within individual agencies in order to assure accountability.
(4) Improve environmental protection by:
  (a) codifying our administrative reclamation standards;
  (b) greatly strengthening enforcement provisions; and
  (c) removing overlapping regulatory responsibilities.

These proposed amendments were presented to the Senate Subcommittee on October 7, 1991. The Subcommittee has held public hearings on these proposals. The Department welcomes the comments of our readers received by January 1, 1991. These should be addressed to the authors at the Division of Geology and Earth Resources.

Acknowledgments

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References Cited

Joseph, N. L., 1991, Washington's mineral industry—1990: Washington Geology, v. 19, no. 1, p. 3–24.

Schasse, H. W., 1991, Coal activity in Washington during 1990: Washington Geology, v. 19, no. 1, p. 26–27.

Proposed Amendments to RCW 78.44

[Expressions in double parentheses and overstruck are to be deleted; wording underscored is to be added to the statute.]

BE IT ENACTED BY THE LEGISLATURE OF THE STATE OF WASHINGTON:

Sec. 1. Legislative finding. RCW 78.44.010 and 1970 ex.s. c 64 s 2 are each amended to read as follows:

The legislature recognizes that the extraction of minerals by surface mining is ((~~a basic and~~)) an essential activity making ((~~an important~~)) a vital contribution to the ((~~economic~~)) well-being of the state and nation. ((~~At the same time, proper reclamation of surface~~)) It is not possible to extract minerals required by our society without producing some environmental impacts and the very character of surface mining operations precludes restoration of the land to its original condition. However, comprehensive regulation of mining and thorough reclamation of mined lands is necessary to prevent ((~~undesirable land and water~~)) or mitigate conditions that ((~~would be~~)) are detrimental to the environment and to protect the general welfare, ((~~health,~~)) safety, and property rights of the citizens of the state. ((~~Surface mining takes place in diverse areas where the geologic, topographic, climatic, biologic, and social conditions are significantly different, and reclamation specifications must vary accordingly. It is not practical to extract minerals required by our society without disturbing the surface of the earth and producing waste materials, and the very character of many types of surface mining operations precludes complete restoration of the land to its original condition. However, the legislature finds that reclamation of surface mined lands as provided in this chapter will allow the mining of valuable minerals and will provide for the protection and subsequent beneficial use of the mined and reclaimed land.~~)) Therefore, the legislature finds that a balance between appropriate environmental regulation and encouragement of the production and conservation of minerals is in the best interests of the citizens of the state.

Sec. 2. Purpose. RCW 78.44.020 and 1970 ex.s. c 64 s 3 are each amended to read as follows:

The purposes of this chapter ((~~is~~)) are to:

(1) Provide that the usefulness, productivity, and scenic values of ((~~all~~)) lands and waters involved in surface mining within

the state will receive the greatest practical degree of ((~~protection and restoration. It is a further purpose of this chapter to provide a means of cooperation between private and governmental entities in carrying this chapter into effect~~)) reclamation at the earliest opportunity following excavation;

(2) Provide for local regulation of mining operations in order to mitigate or prevent some environmental and social impacts of surface mining operations;

(3) Provide for the greatest practical degree of state-wide consistency in the regulation of surface mines;

(4) Apportion regulatory authority between state and local authorities in order to eliminate redundant regulation of mining; and

(5) Ensure the right of local government to regulate land use.

NEW SECTION. **Sec. 3. Definitions.** Unless the context clearly indicates otherwise, the definitions in this section apply throughout this chapter.

(1) "Authorized county" means a county that has accepted the criteria and has received written delegation to regulate surface mining from the department.

(2) "Completion of surface mining" means the cessation of mining in any segment of a surface mine that occurs when all minerals identified in the permit application have been depleted except minerals required to accomplish reclamation according to the approved reclamation plan.

(3) "Department" means the department of natural resources.

(4) "Determination" means any action by the department or authorized county including delegation of administration of this chapter to counties, permit issuance, reporting, reclamation plan approval or modification, permit transfers, bond calculation, orders, fines, or refusal to issue permits.

(5) "Disturbed area" means any place where activities clearly in preparation for, or during, surface mining physically disrupt, cover, compact, move, or otherwise alter the characteristics of soil, bedrock, or topography that existed prior to such activity. Disturbed areas may include but are not limited to: Working faces, water bodies created by mine-related excavation, pit floors, the land beneath processing plant and stock pile sites, spoil pile sites, and equipment staging areas.

Disturbed areas do not include:

(a) Mine access roads unless these have characteristics of topography, drainage, slope stability, or ownership that, in the opinion of the department or an authorized county, require reclamation, and

(b) Lands that have been reclaimed to all standards outlined in this chapter, the SEPA environmental impact statement, and the approved reclamation plan.

(6) "Miner" means any person or persons, any partnership, limited partnership, or corporation, or any association of persons, either natural or artificial, including every public or governmental agency engaged in any surface mining.

(7) "Minerals" means clay, coal, gravel, metallic substances, sand, stone, topsoil, and any other similar solid material or substance to be excavated from natural deposits on or in the earth for commercial, industrial, or construction use.

(8) "Operations" means mine-related activities, exclusive of reclamation, that may generate noise, air quality, surface and ground water quality and quantity, glare, pollution, and/or public safety impacts commonly regulated under provisions of land use permits, or other state laws. Operations include:

(a) Blasting, equipment maintenance, sorting, crushing, and loading;

(b) On-site mineral processing including heap leaching, asphalt or concrete batching, concrete recycling, and other aggregate recycling; and

(c) Transporting minerals to and from the mine, road maintenance, traffic safety, and traffic control.

(9) "Overburden" means the earth, rock, soil, and topsoil that lie above mineral deposits.

(10) "Permit holder" means any person or persons, any partnership, limited partnership, or corporation, or any association of persons, either natural or artificial, including every public or governmental agency engaged in surface mining, whether individually, jointly, or through subsidiaries, agents, employees, or contractors who holds a state reclamation permit.

(11) "Qualified mine regulatory personnel" means a mine regulatory staff composed of at least fifty percent mining engineers, civil engineers, geologists, geophysicists, hydrologists, reclamationists, or mine operators with a minimum of four years of professional experience. Advanced university degrees shall not be considered as professional experience.

(12) "Reclamation" means reasonable rehabilitation of disturbed areas resulting from surface mining including areas under associated mineral processing equipment and stockpiled materials. Although both the need for and the practicability of reclamation will control the type and degree of reclamation in any specific mine, the basic objective shall be to reestablish on a continuing basis the vegetative cover, soil stability, and water conditions appropriate to the proposed subsequent use of the minesite and to mitigate or prevent future environmental degradation.

(13) "Reclamation setbacks" include those lands along the margins of surface mines wherein rocks and sediments are preserved in sufficient volumes to accomplish reclamation according to the approved plan and the minimum reclamation standards. Maintenance of reclamation setbacks shall not preclude other mine-related activities within the reclamation setback.

(14) "Screening" consists of vegetation, berms or other topography, fencing, and/or other screens that may be required to mitigate impacts of mining on adjacent properties and/or the environment.

(15) "Segment" means contiguous portions of the permit area that must be reclaimed within two years of completion of surface mining in that area. Segments shall include those portions of the mine that have characteristics of topography, drainage, slope stability, ownership, mining development, or mineral distribution that, in the opinion of the department or authorized county, require reclamation and are not in use as part of mining and related activities as determined by the department.

(16) "SEPA" means the state environmental policy act, chapter 43.21C RCW and rules adopted thereunder.

(17) "Surface mining" means all or any part of the processes involved in mining from the surface which collectively result in more than three acres of disturbed area or that result in mined slopes greater than thirty feet high and steeper than 1.0 foot horizontal to 1.0 foot vertical.

(a) Surface mining also includes mineral extraction from the surface:

(i) By the auger method or from mining refuse when these exceed the size or height thresholds listed in this subsection; or

(ii) As part of prospecting and exploration activities when these are of such nature and extent as to disturb one acre in eight. The department or authorized county shall expedite issuing permits for exploration purposes.

(b) Surface mining shall not include:

(i) Excavation or grading conducted on site primarily for construction, road maintenance, forestry, or farming on site or on contiguous lands; or

(ii) Excavations or grading for the purpose of restoring the land following an emergent natural disaster.

(18) "Topsoil" means the naturally occurring upper part of a soil profile, including the soil horizon that is rich in humus and capable of supporting vegetation together with other sediments within four vertical feet of the ground surface.

NEW SECTION. **Sec. 4. Administration of chapter——Delegation to counties.** The department is charged with the administration of this chapter, except that:

(1) Administration of this chapter may be delegated to a county if the county agrees to meet the following criteria:

(a) The authorized county shall administer this chapter and the rules of the department;

(b) The authorized county shall employ sufficient qualified mine regulatory personnel to achieve the purposes of this chapter and the rules of the department;

(c) The authorized county shall assume full responsibility for all aspects of mine reclamation regulation;

(d) The authorized county shall not adopt any reclamation ordinances nor exceed the reclamation regulation standards set forth in this chapter and the department's rules;

(e) The authorized county shall set forth in ordinance a fee schedule and a process for timely action on all determinations pursuant to this chapter; and

(f) The authorized county shall report all permit determinations to the department.

In order to be empowered as an authorized county, a county shall make written petition to the department. The department shall then determine whether the county meets the criteria listed in this section and, if so, shall delegate administration of this chapter to the county. The department shall not regulate nor have any responsibility for any aspect of surface mine regulation in authorized counties, except those that relate to the department's proprietary responsibilities on public lands. The department shall, from time to time, audit the performance of approved counties for compliance with this section. In the event that an approved county fails to comply with this section, the department shall seek a remedy with the county. If the county continues to fail to meet these criteria, the department may revoke the authorization.

(2) Any county or municipality may regulate surface mining operations and mine siting pursuant to local zoning control.

Sec. 5. Administration of chapter——Rule-making authority. RCW 78.44.040 and 1984 c 215 s 2 are each amended to read as follows:

((~~The department of natural resources is charged with the administration of this chapter.~~)) In order to implement ((~~the chapter's terms and provisions~~)) this chapter, the department, under the ((~~provisions of the~~)) administrative procedure act (chapter 34.05 RCW), ((~~as now or hereafter amended,~~)) may from time to time ((~~promulgate~~)) adopt those rules ((~~and regulations~~)) necessary to carry out the purposes of this chapter.

Sec. 6. Chapter cumulative and nonexclusive——Other laws not affected. RCW 78.44.050 and 1970 ex.s. c 64 s 6 are each amended to read as follows:

The department or authorized county shall have the exclusive authority to regulate surface mine reclamation. All counties and municipalities shall have the authority to zone mines and regulate mine siting pursuant to local zoning control and mining operations as provided in section 15 of this act, except that county or municipality operating ordinances may be preempted for a period of three weeks by the department during the emergencies outlined in section 23 of this act and related rules.

This chapter shall not ((~~affect~~)) preempt any ((~~of the~~)) provisions of the state fisheries laws (Title 75 RCW), the state water pollution control laws (Title 90 RCW), the state ((~~game~~)) wildlife laws (Title 77 RCW), ((~~or any other state laws, and shall be cumulative and nonexclusive~~)) state noise laws or air quality laws (Title 70 RCW), shoreline management (chapter 90.58 RCW), the state environmental policy act (chapter 43.21C RCW), state growth management (chapter 36.70A RCW).

Sec. 7. Investigations, research, etc.——Dissemination of information. RCW 78.44.060 and 1970 ex.s. c 64 s 7 are each amended to read as follows:

The department shall have the authority to conduct ((~~or~~)), authorize, and/or participate in investigations, research, experiments, and demonstrations, and to collect and disseminate information relating to surface mining and reclamation of surface mined lands.

Sec. 8. Cooperation with other agencies——Receipt and expenditure of funds. RCW 78.44.070 and 1970 ex.s. c 64 s 8 are each amended to read as follows:

The department may cooperate with other governmental and private agencies ((~~in this state and other states~~)), native American nations, and agencies of the federal government, and may reasonably reimburse them for any services the department requests that they provide. ((~~The department may also receive any federal funds, state funds and any other funds and expend them for reclamation of land affected by surface mining and for purposes enumerated in RCW 78.44.060.~~))

NEW SECTION. **Sec. 9. Surface mining reclamation account.** The surface mining reclamation account is created in the state treasury. Annual mining fees, funds received by the department from state, local, or federal agencies for research purposes, as well as other mine-related funds received by the department shall be deposited into this account. The surface mine reclamation account may be used by the department only to:

(1) Administer its regulatory program pursuant to this chapter;

(2) Undertake research relating to surface mine regulation and related issues; and

(3) Cover costs arising from administrative appeals to determinations made under this chapter.

Fines collected under the provisions of this chapter shall be used to reclaim surface mines abandoned prior to 1971.

Only the commissioner of public lands or the commissioner's designee may authorize expenditures from the account. The account is subject to chapter 43.88 RCW, but no appropriation is required for expenditures. The disposition of fees, fines, and other funds collected or received by authorized counties shall be determined by the authorized county.

NEW SECTION. **Sec. 10. Reclamation permits required——Applications.** After July 1, 1992, a person may not engage in surface mining without having first obtained a reclamation permit from the department or from an authorized county. Operating permits issued by the department between January 1, 1971, and June 30, 1992, shall be considered reclamation permits. A separate permit shall be required for each noncontiguous surface mine. The reclamation permit shall consist of the permit forms and any exhibits attached thereto. The permit holder shall comply with the reclamation permit unless otherwise waived in writing by the department.

Prior to receiving a reclamation permit, a miner must submit an application on forms provided by the department that shall contain the following information and shall be considered part of the reclamation permit:

(1) Name and address of the legal landowner, or purchaser of the land under a real estate contract;

(2) The name of the applicant or, if the applicants are corporations or other business entities, the names and addresses of their principal officers and resident agent for service of process;

(3) A reasonably accurate description of the minerals to be surface mined;

(4) Type of surface mining to be performed;

(5) Expected starting date of surface mining;

(6) Size and legal description of the permit area and maximum lateral and vertical extent of the disturbed area;

(7) Expected area to be disturbed by surface mining during the next twelve months;

(8) Final SEPA declarations; and

(9) Other pertinent data as required by the department.

The reclamation permit shall be granted for the period required to deplete essentially all minerals identified in the reclamation permit on the land covered by the reclamation plan. The reclamation permit shall be valid until the reclamation is complete unless the permit is canceled by the department or the authorized county.

The department or authorized county shall issue a SEPA threshold determination within one hundred eighty days of receipt of a complete permit application including the reclamation plan acceptable to the department or authorized county. Reclamation permits shall not be issued until SEPA review of the entire proposal is complete.

NEW SECTION. **Sec. 11. Reclamation plans.** An applicant shall provide a reclamation plan and copies acceptable to the department prior to obtaining a reclamation permit. The department or an authorized county shall have the sole authority to approve reclamation plans. Reclamation plans or modified reclamation plans submitted to the department or authorized county after June 30, 1992, shall meet or exceed the minimum reclamation standards set forth by the department by rule. The reclamation plan shall include:

(1) A written narrative describing the proposed mining and reclamation scheme with:

(a) A statement of a proposed subsequent use of the land after reclamation. Approval of the reclamation plan shall not vest the proposed subsequent use of the land;

(b) If the permit holder is not the sole landowner, a copy of the conveyance or a written statement that expressly grants or reserves the right to extract minerals by surface mining methods;

(c) A simple and accurate legal description of the permit area and disturbed areas;

(d) The maximum depth of mining;

(e) A reasonably accurate description of the minerals to be mined;

(f) A description of the method of mining;

(g) A description of the sequence of mining that will provide, within limits of normal procedures of the industry, for completion of surface mining and associated disturbance on each segment of the permit area so the reclamation can be initiated at the earliest possible time on each segment of the mine;

(h) A schedule for progressive reclamation of each segment of the mine;

(i) Where mining on flood plains or in river or stream channels is contemplated, a thoroughly documented hydrogeologic evaluation that will protect against or mitigate avulsion and erosion;

(j) Where mining is contemplated within critical aquifer recharge areas, special protection areas as defined by chapter 90.48 RCW and implementing rules, public water supply watersheds, sole source aquifers, wellhead protection areas, and designated aquifer protection areas as set forth in chapter 36.36 RCW, a thoroughly documented hydrogeologic analysis of the reclamation scheme; and

(k) Additional information including but not limited to: The positions of reclamation setbacks and screening, conservation of topsoil, interim reclamation, revegetation, postmining erosion control, drainage control, slope stability, disposal of mine wastes, control of fill material, development of wetlands, ponds, lakes, and impoundments, and rehabilitation of topography.

(2) Maps of the surface mine showing:

(a) All applicable data required in the narrative portion of the reclamation plan;

(b) Existing topographic contours;

(c) Contours depicting specifications for surface gradient restoration appropriate to the proposed subsequent use of the land and meeting the minimum reclamation standards;

(d) Locations and names of all roads, railroads, and utility lines on or immediately adjacent to the area;

(e) Locations of proposed access roads to be built in conjunction with the surface mining;

(f) Detailed and accurate boundaries of the permit area, screening, reclamation setbacks, and maximum extent of the disturbed area; and

(g) Estimated depth to ground water and the locations of surface water bodies and wetlands both prior to and after mining.

(3) At least two cross sections of the mine including all applicable data required in the narrative and map portions of the reclamation plan.

(4) Evidence that the proposed surface mine has been approved under local zoning regulations.

(5) Written approval of the reclamation plan by the landowner for mines permitted after June 30, 1992.

(6) Other supporting data and documents regarding the surface mine as reasonably required by the department or authorized county.

The applicant shall provide the department or authorized county with copies of the reclamation plan including maps and cross sections in order to facilitate SEPA processing.

If the department or authorized county refuses to approve a reclamation plan in the form submitted by an applicant or permit holder, it shall notify the applicant or permit holder stating the reasons for its determination and describe such additional requirements to the applicant or permit holder's reclamation plan as are necessary for the approval of the plan by the department or authorized county. If the department or authorized county refuses to approve a reclamation plan, the miner or permit holder may appeal this determination under the provisions of this chapter.

Mining may not significantly deviate from the approved reclamation plan without prior written approval for the proposed change.

NEW SECTION. **Sec. 12. SEPA declarations.** The department or the authorized county shall have exclusive authority with respect to reclamation plans. Prior to issuing a SEPA declaration, the lead agency other than the department or an authorized county shall submit a draft reclamation plan for preliminary approval by the department or the authorized county. Only draft reclamation plans approved by the department or the authorized county shall be incorporated in the SEPA declaration, regardless of the agency issuing the SEPA declaration. Information received by the SEPA lead agency during the SEPA comment period that relates to draft reclamation plans shall be considered by the department or the authorized county to develop a final reclamation plan. If the SEPA lead agency and the department or authorized county cannot reach agreement on a satisfactory reclamation plan, the failure to agree shall constitute grounds for denying the lead agency's permit and/or the reclamation permit. The department shall not regulate mine operations on behalf of other agencies.

NEW SECTION. **Sec. 13. Fees.** After June 30, 1992, the annual reclamation permit fee for mines regulated by the department or an authorized county shall be based on the size of the disturbed area and shall be set forth in rule or ordinance. Fees shall not exceed ten thousand dollars per year nor the approximate cost of administering the department's or, alternatively, the authorized county's surface mine regulatory program; except that:

(1) The total annual fee for each separate reclamation permit when the disturbed area is less than seven acres shall be five hundred dollars.

(2) There shall be no fee for permits held by state and local governmental agencies that are regulated by the department.

(3) Fees may be waived for a one-year period for recipients of a surface mine reclamation award as specified by the department.

The fee shall be payable with submission of the application and annually thereafter with submission of the report required in this chapter. Failure to pay the annual fee may constitute grounds for fines and/or an order to suspend surface mining or cancellation of the reclamation permit as outlined in this chapter. All fees collected by the department shall be deposited into the surface mining reclamation account. The disposition of fees collected by an authorized county shall be determined by that county.

NEW SECTION. **Sec. 14. Performance security.** The department or authorized county shall not issue a reclamation permit until

the applicant has deposited with the department or the authorized county an acceptable performance security on forms prescribed and furnished by the department or authorized county. A public or governmental agency shall not be required to post performance security nor shall a permit holder be required to post surface mining performance security with more than one state, local, or federal agency.

This performance security may be:

(1) Bank letters of credit acceptable to the department or authorized county;

(2) A cash deposit;

(3) Negotiable securities acceptable to the department or authorized county;

(4) An assignment of a savings account;

(5) A savings certificate in a Washington bank on an assignment form prescribed by the department or authorized county; or

(6) A corporate surety bond executed in favor of the department or authorized county by a corporation authorized to do business in the state of Washington under Title 48 RCW and authorized by the department or authorized county.

The performance security shall be conditioned upon the faithful performance of the requirements set forth in this chapter and of the rules and regulations adopted under it.

The department or authorized county shall have the authority to determine the amount of the performance security using a standardized performance security formula developed by the department. The amount of the security shall be determined by the department or authorized county and based on the estimated costs of completing reclamation according to the approved plan or minimum standards and related administrative overhead for the area to be surface mined during the next twelve-month period and any previously disturbed areas on which the reclamation has not been satisfactorily completed and approved.

The department or authorized county may increase or decrease the amount of the performance security at any time to compensate for a change in the disturbed area, the depth of excavation, a modification of the reclamation plan, or any other alteration in the conditions of the mine that affects the cost of reclamation.

The amount of the performance security shall not be subject to appeal. The department or authorized county for any reason may refuse any reclamation security not deemed adequate.

Liability under the performance security shall be maintained until reclamation is completed according to the approved reclamation plan to the satisfaction of the department or authorized county unless released as hereinafter provided. Liability under the performance security may be released only upon written notification from the department or authorized county. Notification shall be given upon completion of compliance or acceptance by the department or authorized county of a substitute performance security. In no event shall the liability of the surety exceed the amount of security required by this section and the department's reasonable legal fees to recover the security.

Any interest or appreciation on the performance security shall be held by the department or authorized county until reclamation is completed to their satisfaction. At such time, the interest shall be remitted to the permit holder; except that such interest or appreciation may be used by the department or authorized county to effect reclamation in the event that the permit holder fails to comply with the provisions of this chapter and the costs of reclamation exceed the face value of the performance security.

No other state or local agency shall require performance security for the purposes of reclamation and only one agency shall require and hold the reclamation security. If the permit area straddles the boundary of an authorized county and a county not regulating surface mining, the department only shall solicit and hold the reclamation security for the entire disturbed area. The department or authorized county may enter into written agreements with federal agencies in order to avoid redundant bonding of mines straddling boundaries between federally controlled and other lands within Washington state.

NEW SECTION. **Sec. 15. Operating standards.**

(1) Cities and counties may regulate surface mining operations in accordance with the standards and limitations of this section.

(2) Local zoning ordinances shall provide that surface mining operations are permitted uses within mineral resource lands identified pursuant to RCW 36.70A.170. Such ordinance may require site plan approval of mining operations to insure compliance with applicable standards.

(3) A county may by general ordinance adopt performance-based regulations governing surface mining operations that are more stringent than applicable state and federal standards.

(a) Examples of applicable state and federal regulations include the following:

(i) Washington state fisheries laws (Title 75 RCW);

(ii) Washington state wildlife laws (Title 77 RCW);

(iii) Washington state water pollution control laws (Title 90 RCW) and department of ecology rules;

(iv) Washington state noise standards (Title 70 RCW) and department of ecology rules;

(v) Washington state air quality standards (Title 70 RCW) and department of ecology rules;

(vi) Federal storm water and national pollutant discharge elimination system regulations and department of ecology rules;

(vii) Federal mine safety and health administration and the federal office of safety health administration rules.

(b) Any such local ordinance must:

(i) Consider provisions to:

(A) Vest historical permitted mining uses such as mineral processing;

(B) Insure that mines, especially small mines, are not forced out of business;

(C) Allow operations to accommodate emergency highway repairs, twenty-four-hour concrete and asphalt pours, early morning concrete pours as necessary to provide beneficial concrete strength;

(D) Provide adequate illumination for appropriate extended hours of operations;

(E) Allow on-site storage of replacement machinery and mining apparatus;

(F) Establish separate standards for rural and urban area mines;

(G) Encourage concrete and other recycled aggregate production; and

(H) Implement department of ecology best management practices for ground water protection at surface mines.

(ii) Be performance-based and generally applicable to other land use activities having similar impacts.

(iii) Limit exactions and other standards to those which are both authorized by state law and which are proportional to the direct operational impacts sought to be mitigated.

(iv) Require that exactions or special restrictions be based upon written findings of fact demonstrating compliance with locally adopted performance standards.

(v) Provide that approvals issued thereunder will be valid through completion of the subject surface mining.

(4) Control of blast-flyrock, fencing, and other public safety restrictions should be established during mine siting pursuant to local zoning control insofar as possible.

(5) All surface mines currently operating under land use permits issued by local government pursuant to local zoning ordinances shall be maintained and operated in conformance to the conditions set forth in the local permit.

NEW SECTION. **Sec. 16. Water control.** Water control as regulated by the department shall be limited to those provisions

necessary to effect mine reclamation and to protect ground and surface water resources after reclamation is complete. The department or authorized county shall solicit recommendations from all agencies with expertise in relevant water control laws when evaluating reclamation plans for mines in or near water. Control of mine site water pollution, water availability, and protection of fisheries and wildlife habitats shall be regulated under the provisions of ordinances of any local jurisdiction, fisheries laws (Title 75 RCW), water pollution control laws (Title 90 RCW), wildlife laws (Title 77 RCW), federal storm water regulations, and/or national pollutant discharge elimination system regulations, only.

NEW SECTION. **Sec. 17. Minimum reclamation standards.** The department shall establish by rule minimum reclamation standards. The need for, and the practicability of, reclamation shall control the type and degree of reclamation in any specific instance. The basic objective of the standards is to reestablish on a continuing basis the vegetative cover, slope stability, water conditions, and safety conditions suitable to the proposed subsequent use of the mine site.

Each permit holder, whether regulated by the department or by an authorized county, shall comply with the minimum reclamation standards in effect on the date the permit was issued and any additional reclamation standards set forth in the approved reclamation plan.

(1) The minimum standards shall provide that:

(a) Prior to surface mining, permit holders shall carefully stockpile all topsoil on the site for use in reclamation, except when the subsequent use of the land approved by the department or authorized county does not require replacing the topsoil. Topsoil needed for reclamation shall not be sold as a mineral nor mixed with sterile soils. Stockpiled materials used as screening shall not be used for reclamation until such time as the appropriate county or municipal government has given its approval.

(b) The department or authorized county may require that clearly visible, permanent monuments delineating the permit boundaries and maximum extent of the disturbed area be set at appropriate places around the mine site. The permit holder shall maintain the monuments until termination of the reclamation permit.

(c) Reclamation activities, particularly those relating to control of erosion and mitigation of impacts of mining to adjacent areas, shall, to the extent feasible, be conducted simultaneously with surface mining, and in any case shall be initiated at the earliest possible time after completion of mining on any segment of the permit area.

(d) All reclamation activities shall be completed not more than two years after completion or abandonment of surface mining on each segment of the area for which a permit is in force.

(2) Some or all minimum reclamation standards may be waived in writing by the department or authorized county in order to accommodate unique and beneficial reclamation schemes such as parks, swimming facilities, buildings, and wildlife reserves. Such waivers shall be granted only after written approval from the department or authorized county of a reclamation plan describing the variances to the minimum reclamation standards, receipt of a favorable SEPA declaration, and written approvals from the landowner and by the local land use authority.

(3) No surface mine permitted after July 1, 1992, may be reclaimed or used as a landfill or dump site without providing the department or authorized county with written approval from the appropriate regulatory agency including any revisions to the approval during the entire period the reclamation permit is in force.

(4) The minimum reclamation standards shall provide for reclamation of some working faces excavated in solid rock as cliffs in order to achieve topography harmonious with nearby or preexisting natural topography.

NEW SECTION. **Sec. 18. Permit transfers.** Reclamation permits shall be transferred to a subsequent permit holder and the department or authorized county shall release the former permit holder from the duties imposed by this chapter if:

(1) Both miners comply with all rules addressing requirements for transferring a permit; and

(2) Unless otherwise waived by the department or authorized county, the mine and all others operated by both the former and subsequent permit holders and their principal officers or owners are in compliance with this chapter and rules.

The department or authorized county shall not require that a reclamation permit be transferred without the written agreement of the permit holder; except that, in the event the legal interest or right of use of a permit holder expires and is not renewed in property owned by a public agency, the permit shall be transferred to the public agency provided that all other requirements for transferring the permit are satisfied by the former permit holder and the public agency. In such case, the department or an authorized county shall not require the consent of the former permit holder.

NEW SECTION. **Sec. 19. Modification of reclamation plans.** The department or authorized county and the permit holder jointly may modify the reclamation plan at any time during the term of the permit for any of the following reasons:

(1) To modify the requirements so that they do not conflict with existing laws;

(2) The previously adopted reclamation plan is impossible or impracticable to implement and maintain;

(3) The previously approved reclamation plan is not accomplishing the intent of this chapter; or

(4) When the permit holder and the department or authorized county mutually agree to change the reclamation plan.

Modified reclamation plans shall be reviewed under SEPA. Such SEPA analyses shall consider only those impacts relating directly to the proposed modifications.

Appeals from determinations made under this section shall be made under the provisions of RCW 78.44.910.

NEW SECTION. **Sec. 20. Reports.** Within thirty days after each annual anniversary date of the reclamation permit and each year thereafter until reclamation is completed and approved, the permit holder shall file a report of activities completed during the preceding year. The report shall be on a form prescribed by the department or authorized county.

NEW SECTION. **Sec. 21. Inspection of permit area.** Any time the department or authorized county may elect, the department or authorized county shall cause the permit area to be inspected to determine if the permit holder has complied with the reclamation permit, rules, and this chapter.

NEW SECTION. **Sec. 22. Order to rectify deficiencies.** The department or authorized county may issue an order to rectify deficiencies when a miner or permit holder is conducting surface mining in any manner not authorized by:

(1) This chapter;

(2) The rules adopted by the department;

(3) The authorized reclamation plan; or

(4) The reclamation permit.

The order shall describe the deficiencies and shall require that the miner or permit holder correct all deficiencies no later than sixty days from issuance of the order. The department or authorized county may extend the period for correction for delays clearly beyond the miner or permit holder's control, but only when the miner or permit holder is, in the opinion of the department or authorized county, making every reasonable effort to comply.

NEW SECTION. **Sec. 23. Emergency notice and order to rectify deficiencies; emergency order to suspend surface mining.** When the department or authorized county finds that a permit holder is conducting surface mining in any manner not authorized by:

(1) This chapter;

(2) The rules adopted by the department;

(3) The approved reclamation plan; or

(4) The reclamation permit;

and that activity has created a situation involving an immediate danger to the public health, safety, or welfare requiring immediate action, the department or authorized county may issue an emergency notice and order to rectify deficiencies, and/or an emergency order to suspend surface mining. These orders shall be effective when entered. The department or authorized county may take only such action as is necessary to prevent or avoid the immediate danger to the public health, safety, or welfare that justifies use of emergency adjudication. The department or authorized county shall give such notice as is practicable to the permit holder or miner who is required to comply with the order. The order shall comply with the requirements of the administrative procedure act.

Regulations of mining operations administered by other state and local agencies shall be preempted by this section to the extent that the time schedule and procedures necessary to rectify the emergency situation, as determined by the department, conflict with such local regulation.

NEW SECTION. **Sec. 24. Order to suspend surface mining.** The department or authorized county may issue an order to suspend surface mining when a miner or permit holder is conducting surface mining in any manner not authorized by:

(1) This chapter;

(2) The rules adopted by the department;

(3) The approved reclamation plan;

(4) The reclamation permit; or

(5) If the miner or permit holder fails to comply with any final order of the department or authorized county.

The order to suspend surface mining shall require the miner or permit holder to suspend part or all of the miner's or permit holder's surface mine until the conditions resulting in the issuance of the order have been mitigated to the satisfaction of the department or authorized county.

The attorney general or county prosecutor may take the necessary legal action to enjoin, or otherwise cause to be stopped, surface mining in violation of an order to suspend surface mining.

NEW SECTION. **Sec. 25. Declaration of abandonment.** The department or authorized county shall issue a declaration of abandonment when it determines that all surface mining has ceased for a period of one hundred eighty consecutive days not set forth in the permit holder's reclamation plan or when, by reason of inspection of the permit area, or by any other means, it becomes the opinion of the department or authorized county that the mine has in fact been abandoned by the permit holder. Abandonment shall not include normal interruptions of surface mining resulting from cyclical demand for minerals.

Following a declaration of abandonment, the department or authorized county may choose to require the permit holder to complete reclamation in accordance with this chapter. If the permit holder fails to do so within two years, the department or authorized county may proceed to do the necessary reclamation work pursuant to section 27 of this act.

If another miner applies for a permit on a site that has been declared abandoned, the department or authorized county may, in its discretion, cancel the reclamation permit of the permit holder and issue a new reclamation permit to the applicant. The department or authorized county shall not issue a new permit unless it determines that such issuance will be an effective means of assuring that the site will ultimately be reclaimed. The applicant must agree to assume the reclamation responsibilities left unfinished by the first miner, in addition to meeting all requirements for issuance of a new permit.

NEW SECTION. **Sec. 26. Cancellation of the reclamation permit.** When the department or authorized county determines that a mine has been illegally abandoned, it may cancel the reclamation permit. The miner or permit holder shall be informed of such actions with a notification of illegal abandonment and cancellation of the reclamation permit.

NEW SECTION. **Sec. 27. Order to submit performance security—— Reclamation by the department.** The department or authorized county may, with the staff, equipment, and material under its control, or by contract with others, reclaim the disturbed areas when it finds that reclamation has not occurred in any segment of a mine within two years of completion or of declaration of abandonment of mining.

If the department or authorized county intends to undertake the reclamation, the department or authorized county shall issue an order to submit performance security requiring the permit holder or surety to submit to the department the amount of moneys posted pursuant to section 11 of this act. If the amount specified in the order to submit performance security is not paid within twenty days after issuance of the notice, the attorney general or county prosecutor upon request of the department or authorized county, respectively, shall bring an action on behalf of the state in a superior court to recover the amount specified and associated legal fees.

The department or authorized county may proceed at any time after issuing the order to submit performance security with reclamation of the site according to the approved reclamation plan or according to a plan developed by the department or authorized county that meets or exceeds the minimum reclamation standards.

The department or authorized county shall keep a record of all expenses incurred in carrying out any reclamation project or activity authorized under this section, including:

(1) Reclamation;

(2) A reasonable charge for the services performed by the state's personnel and the state's equipment and materials utilized; and

(3) Administrative and legal expenses related to reclamation of the surface mine.

The department or authorized county shall refund to the surety or permit holder all amounts received in excess of the amount of expenses incurred. If the amount received is less than the expenses incurred, the attorney general or county prosecutor, upon request of the department or authorized county, may bring an action against the permit holder on behalf of the state or authorized county in the superior court to recover the remaining costs listed in this section.

NEWS SECTION. **Sec. 28. Fines.** Each order of the department or authorized county shall contain provisions for fines in the event that a miner or permit holder fails to obey the order of the department or authorized county. When a miner or permit holder fails to comply with an order of the department or authorized county, the miner or permit holder shall be subject to a civil penalty in an amount not more than ten thousand dollars for each violation based upon a schedule of fines set forth by the department or authorized county in rule. Each day on which a miner or permit holder continues to disobey any order of the department or authorized county shall constitute a separate violation. If the penalty is not paid to the department or authorized county after it becomes due and payable, the attorney general or prosecutor, upon the request of the department or authorized county, may bring an action in the name of the state of Washington to recover the penalty and associated legal fees.

All fines from mines regulated by the department shall be credited to the surface mining reclamation account.

NEW SECTION. **Sec. 29. Refusal to issue permits.** The department or authorized county may:

(1) Refuse to issue a reclamation permit if it determines during the SEPA process that the impacts of a proposed mine cannot be mitigated.

(2) Refuse to issue any other permit at any other location to any miner or permit holder who fails to rectify deficiencies set forth in an order of the department or authorized county within the requisite time schedule. However, the department or authorized county shall issue all appropriate permits when all deficiencies are corrected at each surface mining site.

Sec. 30. Operating without permit——Penalty. RCW 78.44.150 and 1970 ex.s. c 64 s 16 are each amended to read as follows:

Any ((~~operator~~)) miner conducting surface mining within the state of Washington without a valid ((~~operating~~)) reclamation permit shall be guilty of a gross misdemeanor. Mining outside of the permitted area shall constitute mining without a valid reclamation permit. Each day of ((~~operation~~)) mining shall constitute a separate offense.

Sec. 31. Appeals. RCW 78.44.170 and 1989 c 175 s 166 are each amended to read as follows:

Appeals from determinations under this chapter shall be made as follows:

(1) Appeals from determinations made under this chapter shall be made under the provisions of the Administrative Procedure Act (chapter 34.05 RCW), and shall be considered an adjudicative proceeding within the meaning of the Administrative Procedure Act, chapter 34.05 RCW. A fee of five hundred dollars shall be charged for each appeal under this section. This fee shall be refunded to the appellant if the department finds in favor of the appellant.

(2) Appeals from determinations of an authorized county and appeals to final decisions of the department under subsection (1) of this section shall be made to a surface mining appeals board composed of two surface mining hearings officers acting together as a quasi-judicial body hereby established within the environmental hearings office under chapter 43.21B RCW. The surface mining appeals board shall have hearings officers with the following qualifications:

(a) One officer shall be admitted to practice law in this state;

(b) Both officers shall have a minimum of five years of professional experience and/or training pertinent to surface mining reclamation, directly related environmental issues, mining law, or mining. Academic experience shall not be considered as professional experience for the purposes of this section; and

(c) Both officers shall have, or shall acquire, prior to administering any hearings, a thorough and detailed knowledge of surface mining and surface mining law in Washington.

Appeals from determinations of the department to the surface mining appeals board shall be de novo. Appeals from determinations of counties shall be on the record and not be de novo. If the hearings officers cannot reach consensus, the appellant shall appeal to the superior court as provided in this section.

Any person or agency aggrieved by an action of the department or authorized county pursuant to this chapter may seek review under this section by submitting a request in writing that is received by the environmental hearings office within thirty calendar days of the action.

(3) Appeals to decisions of the surface mining appeals board may be made to the superior court pursuant to the judicial review provisions of chapter 34.05 RCW, but only after all administrative remedies listed in this chapter have been exhausted.

Sec. 32. Previously mined land. RCW 78.44.910 and 1970 ex.s. c 64 s 22 are each amended to read as follows:

((~~This act shall not direct itself to the reclamation of land mined~~)) Neither miners nor permit holders may be required to reclaim any segment where all mining was completed prior to January 1, 1971.

NEW SECTION. **Sec. 33. Reclamation awards established.** The department shall create reclamation awards in any permitted mine in recognition of excellence in reclamation or reclamation research. Such awards shall be presented to individuals, companies, or government agencies performing exemplary surface mining in the state of Washington. The department may waive state annual fees as part of the award.

NEW SECTION. **Sec. 34. Reclamation service established.** The department shall establish a no-cost consulting service within the division of geology and earth resources to assist miners, permit holders, local government, and the public in technical matters related to mine regulation, mine operations, and reclamation. The department shall not be held liable for any negligent advice.

NEW SECTION. **Sec. 35.** The following acts or parts of acts are each repealed:

RCW 78.44.030 and 1987 c 258 s 1, 1984 c 215 s 1, & 1970 ex.s. c 64 s 4;

RCW 78.44.035 and 1987 c 258 s 3;

RCW 78.44.080 and 1970 ex.s. c 64 s 9;

RCW 78.44.090 and 1970 ex.s. c 64 s 10;

RCW 78.44.100 and 1984 c 215 s 3 & 1970 ex.s. c 64 s 11;

RCW 78.44.110 and 1987 c 258 s 2, 1984 c 215 s 4, & 1970 ex.s. c 64 s 12;

RCW 78.44.120 and 1984 c 215 s 5, 1977 c 66 s 1, & 1970 ex.s. c 64 s 13;

RCW 78.44.130 and 1970 ex.s. c 64 s 14;

RCW 78.44.140 and 1989 c 230 s 1, 1984 c 215 s 6, & 1970 ex.s. c 64 s 15;

RCW 78.44.160 and 1984 c 215 s 7 & 1970 ex.s. c 64 s 17; and

RCW 78.44.180 and 1970 ex.s. c 64 s 20.

NEW SECTION. **Sec. 36.** The code reviser may recodify, as necessary, RCW 78.44.150, 78.44.170, 78.44.175, and 78.44.910 within chapter 78.44 RCW to accomplish the reorganization of chapter 78.44 RCW as intended in this act.

NEW SECTION. **Sec. 37.** Captions used in this act do not constitute any part of the law.

NEW SECTION. **Sec. 38.** Sections 3, 4, 9 through 29, 33, and 34 of this act are each added to chapter 78.44 RCW.

NEW SECTION. **Sec. 39.** This act shall take effect July 1, 1992.

Division of Geology and Earth Resources Staff Activities—1991

During 1991, the Division reached a milestone with the release of the geologic map of the state's northeast quadrant. The Division also received much visibility in its regulatory role because of the conflicts between urban growth and extractive industries. Other Division activities and accomplishments cover a broad spectrum, and members of one section commonly collaborate on projects in other sections (Fig. 1). This article was prepared so as to provide our readers with an appreciation of the Division's efforts during the calendar year.

GEOLOGY AND RESOURCES SECTION

The focus of this section's work is providing current information about Washington's geology and mineral resources. Several long-term projects contribute to this effort.

- **The revised geologic map of the state.** The state map project has involved most of the staff geologists in study of a wide range of rock types and tectonic settings across the state. The first step in preparation of the four quadrant maps that will constitute the complete state map is compilation of the geology for each component 1:100,000-scale quadrangle. These maps are then reduced to 1:250,000 and prepared as a full-color map with accompanying explanatory materials. The map of the northeast quadrant was released in July 1991. The southeast quadrant is being prepared by Eric Schuster and by Charles Gulick of the Spokane field office; S. P. Reidel of Westinghouse Hanford Co. is also participating in this map compilation work. This quadrant's release is scheduled for 1993. Three geologists from the Geology and Resources section, two from the Regulatory section, and four from the Environmental Geology section (Fig. 1) are currently in various stages of quadrangle map compilation for the last quadrant, the northwest. Table 1 (p. 50) shows the quadrangle assignments. Plans call for this map to be released in 1995.
- **Information about precious and base metal and industrial mineral resources.** The Division's Spokane field office is the current center of economic geology and mineral-resource activity. Robert Derkey has been working, with Raymond Lasmanis (and Nancy Joseph of the Division of Lands and Minerals), on an update and redesign of the inventory of the state's metallic mineral resources. Open File Report 90-18 is the first step in this process. It contains brief descrip-

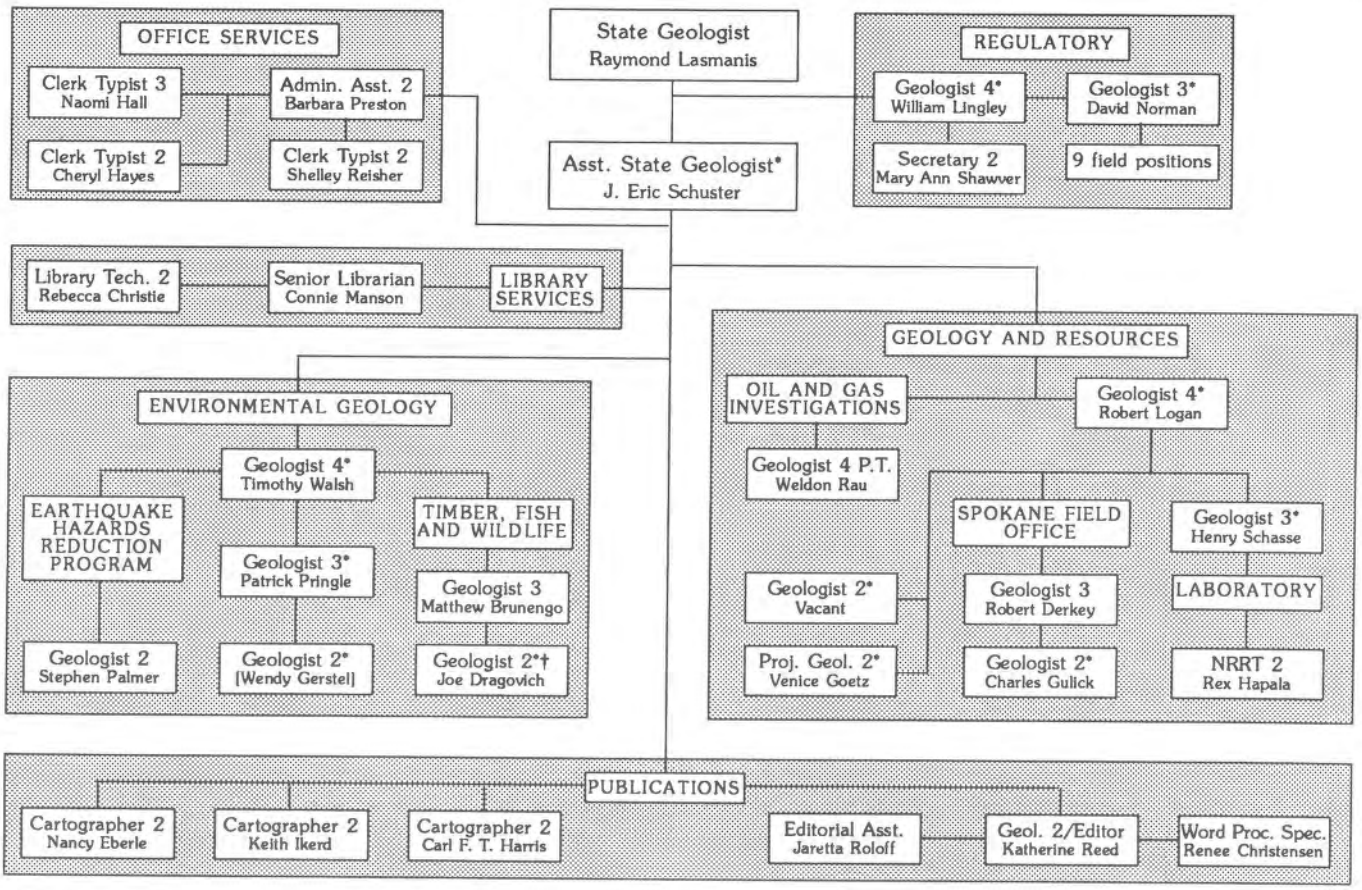

Figure 1. Organization chart, Division of Geology and Earth Resources, December 1991. PT, part-time; [ ], not yet on duty. * Duties include state geological map; † Dragovich will move to the vacant Geologist 2 position under Geology and Resources in April of 1992.

tions of 541 metal mines, some of which are currently producing; each formerly active mine listed produced at least $1,000 worth of ore. Gulick is focusing on Washington's industrial minerals (exclusive of sand and gravel).

Section geologists are also involved in many shorter term projects that contribute to other Division objectives. For example, a study of landslide-dammed lakes on the Olympic Peninsula was undertaken by Robert Logan in cooperation with R. L. Schuster of the USGS. The results have contributed to improved understanding of the local geology and have potential significance in studies of regional seismic history and geologic hazards.

Several grants are administered by the Geology and Resources section. A Minerals Management Service grant paid for 1991 mapping by Richard Stewart (Univ. of Wash.) in the western Olympic Mountains. A COGEOMAP program, through which the state provides funds to the U.S. Geological Survey (USGS), supported the continuation of mapping in the North Cascades. The Mapping Support Program offers financial help to faculty and graduate students for field and other work; in exchange, the Division obtains the resulting geologic maps. (See p. 55 for a summary of current support.)

The Division laboratory is an integral part of our service to citizens, public agencies, and industry. Rex Hapala prepares thin sections and x-ray diffraction samples and processes samples for study of conodonts and foraminifers. Weldon Rau and Katherine Reed identify the microfossils. Some zircon and other mineral extractions are being used to obtain radiometric and other dates.

ENVIRONMENTAL GEOLOGY SECTION

The principal focus of this section is evaluation of geologic hazards and mapping the associated geology. Section staff concentrate on hazards from volcanoes, earthquakes, and landslides, as well as on abandoned coal mine and flood hazards. Section geologists also worked cooperatively with the rest of the Division on oil and gas investigations and are involved in preparing the revised state geologic map. The following paragraphs outline accomplishments in 1991.

Volcanic Hazards

Patrick Pringle has nearly completed a draft of an interpretive road guide to Mount St. Helens geology. This project is being undertaken in cooperation with the U.S. Forest Service, Mount St. Helens National Monument, Friends of Mount St. Helens, and the USGS Cascades Volcano Observatory. Field work was conducted in July and August. The guide will be released in the spring of 1992 as a Division Information Circular and will also available through the Friends of Mount St. Helens.

Table 1. Quadrangle compilation responsibilities, Northwest quadrant map

Geologist	1:100,000 quadrangle(s)
Henry Schasse	Port Angeles, Port Townsend, Sauk River
David Norman	Mount Baker
Joe Dragovich	Robinson Mtn., Twisp, Chelan, Wenatchee
Wendy Gerstel	Forks, Mount Olympus
Patrick Pringle	Bellingham
Timothy Walsh	Seattle, Tacoma
Venice Goetz	Skykomish River, Snoqualmie Pass
William Lingley	Offshore areas

A draft of a field guide to mass-wasting processes at Mount Rainier is currently in peer review. This guide is planned for release as a Division Information Circular in early 1992. An earlier version of this field guide was prepared for the 1990 fall Pacific Northwest American Geophysical Union field trip to Mount Rainier but was not published. The guide will complement USGS Professional Paper 1447-C (in press): "Debris flows at Mount Rainier—Flow types, behavior, and hazards" by K. M. Scott, P. T. Pringle, and J. W. Vallance. That paper will appear initially as USGS Open-File Report 90-385.

Earthquake Hazards

A federally funded drilling program was completed in August 1991 in Puyallup. Locations for these borings were selected on the basis of soil changes in a sequence of hand-augered test holes drilled during this year. Four borings were drilled within 50–100 ft of sites of reported liquefaction during the 1949 and 1965 earthquakes. Standard penetration test values and disturbed samples, as well as piezo-cone penetrometer data were recovered at each site. Loose, dark-gray, clean sands that appear to be lahar runout deposits were found in each of the borings. An initial evaluation of these sediments by Stephen Palmer, Pringle, and John Shulene titled "Analysis of liquefiable soils in Puyallup, Washington" was published in the proceedings of the 4th International Conference on Seismic Zonation" held in California in August 1991. One of the liquefiable sand units was subsequently firmly identified as a lahar runout from Mount Rainier. The presence of Mount Rainier "C" tephra and a ^{14}C age of 2,320 ± 120 yr permit correlation of that unit with newly discovered lahars in the upper reaches of the Puyallup River and with coeval pyroclastic flows deposited on the west flanks of Mount Rainier. This discovery marks the first time that deposits from that eruptive episode have been found as far downstream as the city of Puyallup.

Palmer has compiled data for approximately 100 geotechnical borings in the Renton and Auburn 7½′ quadrangles, and a liquefaction analysis has been performed on approximately 80 borings. The remaining borings will be analyzed for liquefaction susceptibility, and the data and analyses will be released as a Division open-file report in a few months.

Timothy Walsh is collaborating with Al Rogers and William Kockelman of the USGS and George Priest of the Oregon Department of Geology and Mineral Industries in editing USGS Professional Paper 1560: "Assessing and Reducing Earthquake Hazards in the Pacific Northwest". The editors prepared the introduction to the volume, which will contain approximately 20 papers. Many of these papers are ready to be released as USGS open-file reports.

Landslides

Two major landslide projects are nearing completion. The first of these is a Slope-Hazard Zonation Pilot Project. Matthew Brunengo and Joe Dragovich have performed a detailed air-photo inventory of 1,500 landslides in 144 mi^2 in the southern Washington Cascades. To date, more than 1,000 landslides have been field-checked. Data are being collated for Geographic Information System (GIS) analysis; layers will include landslides, geology, landform, slope, slope aspect,

soils, and rain-on-snow susceptibility. The final product, due in draft form in April 1992, will be used to evaluate slope stability for forestry operations regulated by the Department of Natural Resources.

The second landslide project involves development of regulations to mitigate the cumulative effects of logging practices. Criteria are being developed for screening, prioritizing, and analyzing the sensitivity of forested basins to slope failure and erosion (both natural and logging-induced). Susceptibility to rain-on-snow events has been evaluated and mapped throughout the state. When available in June of 1992, these criteria will permit defensible regulation of cumulative effects of individual forest practices in an entire basin, rather than relying on the current practice of evaluating each practice in isolation.

Another landslide project completed earlier this year was an evaluation of potential sediment yield to mass-wasting processes in the Hoh River valley on the west side of the Olympic Peninsula. The report, currently an internal report by Robert Logan, Keith Kaler, and Philip Bigelow (the last two formerly with the Division) is being prepared for release as an open-file report.

Other Section Activity

Other activities have also required significant staff efforts. The Growth Management Act of 1990 requires that most Washington counties implement geologic hazard zonation in their land-use planning and zoning practices. The Environmental Geology Section staff provided advice and review of minimum guidelines for geologic hazards zonation to the Department of Community Development, the agency responsible for implementing the Growth Management Act. Section staff also gave information and advice to many local jurisdictions in delineating areas of significant geologic hazards, and suggested methods of mitigating these hazards.

Staff members from this section and the Geology and Resources section have provided information about the location of abandoned coal mines in the Seattle area to home owners, developers, and county officials. The historic mine maps in the Division collection are a major resource for this work.

The Legislature created the Washington State Seismic Safety Advisory Committee (SSAC) to evaluate earthquake preparedness in Washington; the SSAC is to report back to the Legislature at the end of 1991. The SSAC, of which Ray Lasmanis is chairman and Walsh is a member, created a technical subcommittee, of which Lasmanis, Walsh, and Palmer are members.

Walsh, assisted by Brunengo and Logan, also served on the state flood hazard committee, which drafted a State "Flood Hazard Mitigation Plan" now in review. This plan will be submitted to the Federal Emergency Management Agency and will provide the basis for continuing disaster assistance under federal law.

REGULATORY SECTION

The primary function of the Regulatory group is to administer the oil and gas, geothermal, gas storage, and surface mining programs. The Regulatory staff also have state mapping and research functions that overlap with those of other sections.

During 1991, most of the section's work focused on surface mine reclamation and amendment of the Surface Mine Reclamation Act (RCW 78.44), a draft of which is presented in this issue (p. 41–48). The accompanying surface mining rules (WAC 332-18) were also redrafted in order to provide a comprehensive package for appraising the proposed statutory amendments. Following submission of these amendments in October, section personnel made presentations throughout the state to provide background and justification to community action groups, legislative communities, and the Washington Association of Counties.

Division staff also inspected approximately 95 mines, provided training or consultation for Department of Natural Resources personnel, and participated in 20 days of sworn testimony during mine-related litigation. The staff also assisted in direction of nine reclamationists working in our Regional offices. In addition, the Regulatory section also provided assistance to several county planning departments for compliance with the mineral resource provisions of the Growth Management Act (Title 36.70A RCW).

David Norman completed a comprehensive draft of a procedures manual for mine reclamation of sand and gravel pits and rock quarries. He is currently preparing an open-file report expanding on some aspects of mine reclamation described in the manual.

Oil and gas activities consisted of issuing eight drilling permits for natural gas exploration wells and performing related inspections. This work included assessment of drilling prognoses, assuring compliance with the State Environmental Policy Act (RCW 43.21C), and examining engineering plans for blowout preventors, well casing, cementing, wireline logging, testing, and plugging wells. During 1991, staff spent about 20 days at various wellsites assuring compliance with the Oil and Gas Conservation Act (RCW 78.52).

During 1991, the Division completed a library of Washington geophysical data. Most public-record seismic reflection data have acquired and made available, on a limited basis, for public, commercial, and academic uses. An index of these data is available in DXF or AutoCad®-compatible disk formats.

Two proposals for gas-storage injection wells in the Jackson Prairie gas storage facility near Chehalis are in the process of evaluation. These wells will be drilled to assure that natural gas is available during periods of peak demand. Regulatory staff are also studying a borehole that will be used to evaluate experimental wireline logging tools.

A series of balanced cross sections of the Olympic Peninsula was developed with Steve Boyer from the University of Washington. Staff members gave a report of this work, which has implications for the origin of continental shelves and interplate slip mechanisms, at the annual meeting of the Geological Society of America. Regulatory staff also completed studies of the petroleum geochemistry of Washington with Hans von der Dick of Canadian Hunter Exploration Ltd., which are reported in this issue (p. 23–27), and studies of coal maturation and the potential for natural gas accumulations with Timothy Walsh. In addition, staff members presented a guest lecture on the geology of the Washington continental shelf to the federal Minerals Management Service at their offices in Camarillo, California.

LIBRARY SERVICES

The library staff (Connie Manson and Rebecca Christie) continue to provide reference and advisory services to staff members, other geologists, and the public. The most significant enhancement of library service during 1991 was the use of two reference databases on CD-ROM, GeoRef and Earth Science Database.

In the past year, about 700 books were added to the library collection. The bibliography grew by about 950 citations on Washington's geology. More than 500 citations covering Washington and adjacent areas were entered in the bibliography of materials on seismicity. An update of the seismic bibliography is nearing completion.

The bibliography of Washington citations added to the collection during 1990 was issued as an open-file report, continuing the bibliographic series. Further bibliographic service has been provided in the form of the cumulated indexes of geologic mapping and theses and thesis mapping, which are published annually as open-file reports, as well as monthly distribution to staff of bibliographies of additions to the Division's collection; announcement of selected acquisitions in *Washington Geology* continues. Six more reports were prepared in the series of bibliographies covering the geology and mineral resources of Washington counties, bringing the total to 24. The reports can assist planners and others with issues related to the Growth Management Act of 1990. More than 1,600 copies of these reports were distributed in 1991.

Manson has been investigating the types and uses of geologic literature and has prepared a statistical analysis of 100 years of citations about the geology of Washington; a report is scheduled for release in the Geoscience Information Society Proceedings (v. 22). She also described the Division library and its functions at a seminar in special librarianship held at the University of Washington.

Christie has completed archival-level conservation of four U.S. Geological Survey folios for Washington that were published between 1899 and 1906. These have been deacidified and encapsulated. This type of work is continuing.

OFFICE SERVICES

In the last year, the clerical staff has worked to improve the distribution of reports, as well as maintenance of the reports inventory. Mailing lists have been corrected with the assistance of the U.S. Postal Service. Furthermore, we have combined some mailings in order to reduce postage costs. The inventory process has been converted to a database.

From the start of the calendar year through mid-November, the office staff handled distribution of nearly 29,000 reports. Of these, about 4,800 were Bulletins, Information Circulars, Reports of Investigations, or releases in the Geologic Map series; 2,800 were open-file reports; and 3,800 were miscellaneous publications. About 16,000 copies of the newsletter were mailed or distributed over the counter. This level of activity is nearly 10 percent greater than that for 1990 and represents an average of 133 publications being distributed each working day.

The clerical staff has been gradually replacing or preparing master copies of older open-file reports and are now standardizing fold dimensions for maps in this series. Some open-file maps and nearly all of the open-file texts are now being reproduced and assembled in this office in an effort to keep costs as low as possible consistent with quality. The staff keeps the supply of reports at the office large enough to meet demand.

The office services staff do more than these statistics and reports activities suggest. Their primary goal is to serve the public, answering questions over the phone and assisting the many visitors in finding the help they seek. They also provide the traditional forms of support to the technical staff.

PUBLICATIONS

As noted earlier in this article, the three sheets and pamphlet for the geologic map of the northeast quadrant of the state (GM-39) and its companion topographic map (TM-2) were released in June. A major portion of the publications staff's work was devoted to editing and final cartographic preparation by Nancy Eberle, Keith Ikerd, and Carl Harris. These products constitute the second of four projected quadrant maps that will complete the 1:250,000-scale geologic and topographic maps of Washington. The base map and other materials for the third quadrant are now in preparation.

In addition, six open-file reports were released: two bibliographies, two geologic maps, a report about coal maturation and natural gas potential in Washington, and a compilation of seismic data for western Washington. In cooperation with the librarian, we have now made available bibliographies for 24 counties in both paper-copy and disk formats.

Our newsletter, which has nearly doubled in volume and circulation in five years, has been renamed *"Washington Geology"*. Many of the articles in this publication summarize recent Division work. In addition, we have worked with 20 authors from universities, industry, and federal or Canadian agencies in preparing other articles for this publication. Nearly 180 pages of information will have appeared in *Washington Geology* by the end of the calendar year.

We contributed a major portion of the graphics in the "Washington State" issue of *Rocks and Minerals* magazine, published in July. The publications staff also prepared material for geologists to use in displays, talks at schools, and professional meetings and for articles released in journals. One example of this work is the information about the geology of the Yacolt Burn State Forest on a map prepared by another division of the Department of Natural Resources.

The addition of our new Editorial Assistant, Jaretta Roloff, upgrade of computer hardware, and acquisition of software that will improve creation and transfer of graphic materials are enhancing preparation of our publications. ⚒

Geology of Seattle Available

A limited supply of copies of **Geology of Seattle, Washington, United States of America** (Bulletin of the Association of Engineering Geologists, v. 28, no. 3) has been made available to the Division through the generosity of the authors, R. W. Galster and W. T. Laprade. Requests for copies will be filled on a first come, first served basis. These copies are free, but please include $1.00 for postage and handling on each order.

Pacific Northwest Meeting—American Geophysical Union

by Venice L. Goetz

with Steven Reidel (Westinghouse Hanford Co.) *and* James Conca (Washington State University, Tri-Cities)

The 38th annual meeting of the Pacific Northwest chapter of the American Geophysical Union was held September 18–20 in Richland. It was sponsored by Washington State University Tri-Cities and the Sigma Xi Society in cooperation with Pacific Northwest Laboratory and Westinghouse Hanford Company. Symposium topics included climatology, atmospheric and ocean sciences, regional geology and geophysics, volcanology, geochemistry, and hydrology.

Topics of presented papers ranged from a report on ongoing archeological efforts in East Wenatchee (R. B. Waitt, U.S. Geol. Surv.) to studies of stable isotopes in ice and the atmosphere. Special session topics were vadose zone transport and characterization, surficial processes and Quaternary research, and environmental geology.

A highlight of the meeting was the special symposium and workshop, convened by P. R. Hooper (Wash. State Univ.) and E. D. Humphreys (Univ. of Ore.). The topic was magmatism in the tectonic framework of the Pacific Northwest. This session began with H. Lyatsky's (and others, Geol. Surv. Canada) presentation of a new interpretation of the continent–ocean boundary at the western margin of Canada. The authors propose a diffuse, nonconvergent continental margin north of central Vancouver Island. G. G. Goles (Univ. of Ore.), the next speaker, has been studying the fate of sediments in the Cascadia subduction zone; he suggested that these sediments may ooze landward into an underthrusting accretionary prism at a depth of about 30 km, become dewatered, and influence volcanism as a feedback loop. R. S. Babcock (and others, West. Wash. Univ.) has inferred that the Yellowstone Hotspot came on shore in Eocene time and contributed to extrusion of the Crescent Formation basalts of the Olympic Peninsula. Because the $^{3}He/^{4}He$ ratios in the Roseburg basalts are nearly identical to these ratios at Yellowstone, D. G. Pyle (and others, Ore. State Univ.) believe they have evidence for the Yellowstone Hotspot having come onshore in the Paleocene (ca. 64 Ma) in southwest Oregon. However, when Humphreys (and K. G. Dueker, Univ. of Ore.) presented alternatives to the popular mantle-plume hypothesis for the Colorado plateau uplift and mantle-derived magmas, the Columbia River Basalt Group, and the northeast trend of Yellowstone-related volcanic rocks, the intensity of the debates increased. D. D. Alt (and others, Univ. of Mont.) contended that the Pacific Northwest flood-basalt province includes the Snake River Plain and rocks in southeastern Oregon, and that the Glass Buttes area in southeastern Oregon is the granophyric rhyolitic center related to the Pacific Northwest flood-basalt province, just as other flood-basalt provinces world-wide have similar associated centers. Hooper's connection of Columbia River basalts to a mantle plume and D. Geist's (Univ. of Idaho) deflected-plume theory stimulated a lively discussion of plume longevity, timing of magmatism, rate of plate convergence, and plume geometries. Ideas about the origin of Cenozoic basaltic volcanism seem as numerous as the places it is found. D. S. Cowan (Univ. of Wash.) described his paleogeographic models of Late Jurassic to Early Cretaceous subduction in the northwestern Cordillera and California developed from geologic and paleomagnetic records.

Sixteen posters were presented for the special symposium. The two most controversial subjects were R. M. Conrey's (Wash. State Univ.) rift propagation in the Cascade Range and E. R. Rieken's (with R. L. Thiessen, Wash. State Univ.) new ideas about the geometry of the part of the Juan de Fuca plate that lies beneath western Washington. Conrey proposes a time-transgressive pie-shaped rift that has propagated from south to north and whose apex is Mount Adams. On the basis of his calculations and depth contours, Rieken postulates that the Juan de Fuca plate must be segmented below 55 km depth in order to account for a space problem caused by a disparity between the geometries of the slab and the subduction zone.

The meeting attracted more than 200 participants from 72 institutions in the Pacific Northwest, including Canada and Alaska, as well as Wyoming, Arizona, and California. One hundred and one abstracts were accepted.

Two field trips were held in conjunction with this meeting. A pre-meeting excursion to the Hanford site, led by S. P. Reidel and K. A. Lindsey (Westinghouse Hanford Co.), reviewed the geology, hydrology, climatology, and environment of the site (Fig. 1). A post-meeting field trip covering regional geology, tectonics and glaciology of south-central Washington was led by Reidel, Lindsey and T. L. Tolan (Tolan, Beeson and Assoc.).

Abstracts of presented papers and guides for the two field trips are available from James Conca, WSU Tri-Cities, 100 Sprout Road, Richland, WA, 99352; 509/375-3268.

Figure 1. Cross-bedded gravels of the Hanford formation. Field trip participants examine the internal structure of catastrophic flood deposits from the Spokane floods. The Hanford formation is the principal unit in the vadose zone on the Hanford Site and is the focus of studies concerning disposal practices. Photo by S. P. Reidel.

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

August 1991 through October 1991

THESES

Baron, Dirk, 1990, Analysis and numerical simulation of the ground water system at the Bonneville navigation lock site, Oregon: Portland State University Master of Science thesis, 117 p.

Desonie, Dana L., 1990, Geochemical expression of volcanism in an on-axis and intraplate hotspot—Cobb and Marquesas: Oregon State University Doctor of Philosophy thesis, 145 p.

Fassio, Joseph Michael, 1990, Geochemical evolution of ferruginous bauxite deposits in northwestern Oregon and southwestern Washington: Portland State University Master of Science thesis, 103 p.

Garver, John Irwin, 1989, Basin evolution and source terranes of Albian–Cenomanian rocks in the Tyaughton Basin, southern British Columbia—Implications for mid-Cretaceous tectonics in the Canadian Cordillera: University of Washington Doctor of Philosophy thesis, 227 p.

Hurban, Gary K., 1991, Fabric study and structural history of deformed plutonic and metamorphic rocks in the Holden area, North Cascades, Washington: Western Washington University Master of Science thesis, 106 p.

Johnson, Adelaide C., 1991, Effects of landslide–dam-break floods on channel morphology: University of Washington Master of Science thesis, 90 p.

Kehew, Alan E., 1977, Environmental geology of Lewiston, Idaho and vicinity: University of Idaho Doctor of Philosophy thesis, 211 p., 6 plates.

Muniz, Herminio R., 1991, Computer modeling of vadose zone groundwater flux at a hazardous waste site: Washington State University Master of Science thesis, 140 p.

Nowack, Robert L., 1985, Wave propagation in laterally varying media and iterative inversion for velocity: Massachusetts Institute of Technology Doctor of Philosophy thesis, 255 p.

Pettit, Don Joseph, 1990, Distribution of sand within selected littoral cells of the Pacific Northwest: Portland State University Master of Science thesis, 249 p.

Sharp, John L., 1991, Manganese and iron geochemistry in the Endeavour Ridge hydrothermal plume: Oregon State University Master of Science thesis, 88 p.

Smoot, John Leach, 1987, Hydrogeology and mathematical model of ground-water flow in the Pullman–Moscow region, Washington and Idaho: University of Idaho Master of Science thesis, 118 p.

Summers, Cathy A., 1990, Base and precious metal deposits in the western Cascades of Oregon and southern Washington—Mineralogy, fluid inclusions, and sulfur isotopes: Oregon State University Master of Science thesis, 144 p.

Wong, Anne B., 1978, The mineralogy, chemistry, and uranium distribution in the Spirit pluton, northeastern Washington: Bowling Green State University Master of Science thesis, 113 p.

U.S. GEOLOGICAL SURVEY REPORTS

Published Reports

Finn, Carol; Phillips, W. M.; Williams, D. L., 1991, Gravity anomaly and terrain maps of Washington: U.S. Geological Survey Geophysical Investigations Series Map GP-988, 5 sheets.

Shawe, D. R.; Ashley, R. P., editors, 1991, Epithermal gold deposits—Part II: U.S. Geological Survey Bulletin 1857-I, 48 p.

Shedlock, K. M.; Weaver, C. S., 1991, Program for earthquake hazards assessment in the Pacific Northwest: U.S. Geological Survey Circular 1067, 29 p.

Open-File Reports and Water-Resources Investigations Reports

Costa, J. E.; Schuster, R. L., 1991, Documented historical landslide dams from around the world: U.S. Geological Survey Open-File Report 91-239, 486 p.

Fuhrer, G. J.; Evans, Duane, 1990, Use of elutriate tests and bottom-material analyses in simulating dredging effects on water quality of selected rivers and estuaries in Oregon and Washington, 1980–1983: U.S. Geological Survey Water-Resources Investigations Report 89-4051, 54 p., 1 plate.

Gardner, J. V.; Sarna-Wojcicki, A. M.; Adam, D. P.; Dean, W. E.; Bradbury, J. P.; Rieck, H. J., 1991, Report of a workshop on the correlation of marine and terrestrial records of climate changes in the western U. S.: U.S. Geological Survey Open-File Report 91-140, 48 p.

Jacobson, M. L., compiler, 1991, National Earthquake Hazards Reduction Program, summaries of technical reports Volume XXXII: U.S. Geological Survey Open-File Report 91-352, 707 p.

Walsh, T. J.; Madin, Ian; Noson, L. L.; Yelin, T. S., 1990, Proceedings of Conference LX, 4th annual workshop on "Earthquake hazards in the Puget Sound and Portland areas": U.S. Geological Survey Open-File Report 90-703, 1 v.

Yount, J. C.; Gower, H. D., 1991, Bedrock geologic map of the Seattle 30′ by 60′ quadrangle, Washington: U.S. Geological Survey Open-File Report 91-147, 37 p., 4 plates.

GEOLOGY AND MINERAL RESOURCES OF WASHINGTON

(and related topics)

Iverson, R. M.; Martinson, H. A., editors, 1986, Mount St. Helens—American Geomorphological Field Group field trip guidebook and abstracts, 1986: American Geomorphological Field Group, 178 p., 1 plate.

Kennedy/Jenks/Chilton, 1991, Earthquake loss estimation for the City of Everett, Washington lifelines: Kennedy/Jenks/Chilton [Federal Way, Wash., under contract to U.S. Geological Survey], 1 v.

Pacific Northwest Metals and Minerals Conference, 1991, Abstracts: Pacific Northwest Metals and Minerals Conference, 1 v.

Continued on back page.

Support for Mapping Projects, Fiscal Year 1992

The Division's Mapping Support Program has three basic goals: (1) it seeks to stimulate generation of geologic mapping and map-related information to use in preparation and updating of the state geologic map; (2) it encourages graduate students to do mapping as part of the work toward advanced degrees; and (3) it promotes close working relations between the Division and the geology departments at colleges and universities.

This is the eighth year of the program. From Fiscal Years 1985 through 1991, the Division funded 76 projects for $112,712. The projects for Fiscal Year 1992 (July 1, 1991, through June 30, 1992) (tabulated below) bring the project total to 82 and total funding to $127,175.

Keith Brunstad (facing camera, center), M.S. candidate at Portland State University, led a field trip in October to the eastern part of the Fifes Peaks stratovolcano caldera. The caldera measures 5 by 6.5 km, elongate to the northeast, and lies between the American River and Crow Creek. Fifes Peaks, in the upper left background, are in the extreme southeast part of the caldera. Caldera fill deposits consist of interbedded tuffs, breccias, lava flows, and lahars and were intruded by plugs and dikes. Photo by H. W. Schasse.

Name	University	State Geologic Map Quadrant	Project focus
Keith A. Brunstad	Portland State University	SW	Geologic mapping of fill in the Fifes Peak caldera
Cynthia Carlstad	[Bothell, WA]	NW	Mapping of surficial geology from Partridge Point to Admiralty Head, Whidbey Island
Paul F. Hammond [faculty]	Portland State University	SW	Geologic map of the Mount Aix caldera
Peter R. Hooper [faculty] and Beth Gillespie	Washington State University	SE	Mapping of Columbia River basalt units in the Alpowa Ridge, Pomeroy, Rose Springs, Peola, and Potter Hill 7½′ quadrangles, southeastern Washington
Steven L. Kenitz	Portland State University	SW	Correlation of tuff beds in the Cowlitz Formation
Troy Rasbury	University of Texas, Austin	NW	Age, origin, and provenance of possible Precambrian rocks, North Cascades
Steven Reidel [faculty]	Wash. State University	SE	Geology of the western Saddle Mountains
Patrick K. Spencer [faculty]	Whitman College	SE	Reconnaissance geologic mapping of pre-Fraser loess and flood deposits, Harsha 7½′ quadrangle

LOCATION OF MAIN OFFICE

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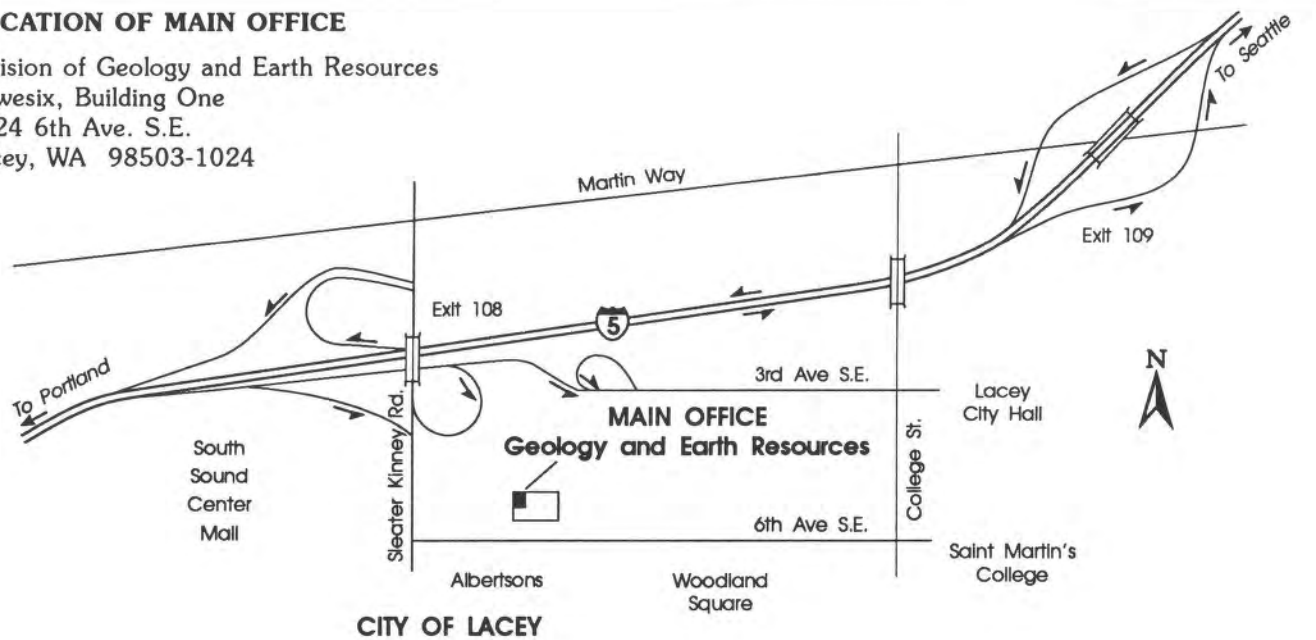
4224 6th Ave. S.E.
Lacey, WA 98503-1024



Selected Additions to the Library

Continued from p. 54.

U.S. Bureau of Land Management, 1991, [Mining claims microfiche—August 16, 1991]: U.S. Bureau of Land Management, 61 sheets microfiche.

U.S. Department of Energy, 1991, Overview of the Hanford cleanup five-year plan, September 1991: U.S. Department of Energy, 29 p.

University of Washington Geophysics Program, 1991, Quarterly network report 91-B on seismicity of Washington and northern Oregon, April 1 through June 30, 1991: University of Washington Geophysics Program, 22 p.

Weekes, D. C.; Luttrell, S. P.; Fuchs, M. R., 1987, Interim hydrogeologic characterization report and groundwater monitoring system for the nonradioactive dangerous waste landfill, Hanford site, Washington: Westinghouse Hanford Company WCH-EP-0021, 1 v.

Zoback, M. L.; Zoback, M. D.; Adams, J.; Bell, S.; Suter, M.; Suarez, G.; Jacob, K.; Estabrook, C.; Magee, M., 1991, Stress map of North America: Geological Society of America DNAG Continent-Scale Map 5, 4 sheets, scale 1:5,000,000.

MISCELLANEOUS TOPICS

Association of Engineering Geologists, 1987, Building over underground mines—Subsidence considerations: Association of Engineering Geologists Symposium Series 4, 127 p.

Gardiner, C. D., 1991, Canadian mines handbook, 1991–92: Southam Business Communications, 536 p.

World Organization of Volcano Observatories, 1991, Directory of volcano observatories 1990–1991: World Organization of Volcano Observatories/UNESCO, 99 p. ⚒

New Division Releases

Open File Report 91-6, **Geologic map of the Old Copper Hill–Butcher Mountain area, Stevens County, Washington**. This report by Moira T. Smith focuses on the structure and stratigraphy of the Lower Paleozoic Covada Group. The report has 9 pages and 1 plate (1:12,000 scale). The price is $1.39 + .11 = $1.50.

A new county bibliography of geologic information for **Grays Harbor County** (93k), in support of the Growth Management Act, brings the total number issued to 24. Copies are available on paper or disk (IBM-compatible). Paper copies are free, but please include $1 *with each order* for postage and handling. To obtain a disk copy, send us a 5.25-in. or 3.5-in. formatted disk. We will copy the file and return your disk. Please specify whether you want a WordPerfect 5.0 or 5.1 or an ASCII file. ASCII files will work with any word processing program. ASCII file users may want to order a paper copy as well, since it shows formatting lost in the conversion to ASCII.

Please add $1 to each order for postage and handling.

Our mailing address, on p. 2 of this publication, has recently been revised—we now have a Post Office Box number. In order to serve you as promptly as possible, we would appreciate having your Zip Code and the four-digit extension for your address with your correspondence. ⚒

A Note about Mailings

In an effort to economize on postage and reduce paper consumption, we are condensing mailing lists. Many of you who receive *Washington Geology* have also received separate notices of our new releases. Because all releases are announced in this publication, we are no longer mailing cards or letters for this purpose. *Washington Geology* will be sent to those who formerly received only the cards or letters.

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Natural Resources

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