COAL MATURATION AND THE NATURAL GAS POTENTIAL OF WESTERN AND CENTRAL WASHINGTON

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Coal Maturation and the Natural Gas Potential of Western and Central Washington State[1]

Timothy J. Walsh and William S. Lingley, Jr.

ABSTRACT

Paleogene sedimentary and volcanogenic rocks ranging in thickness from 3.5 km (12,000 ft) to 11 km (36,000 ft) accumulated in five depocenters in the Puget trough. Eocene coals at shallow depths near these depocenters are mostly lignite and subbituminous, but rank generally increases to anthracite toward the Cascade Range. In mining districts where coal rank is greater than high volatile C bituminous, coal isorank contours cut across structural contours that are drawn by using detailed mine maps. These relations and regional geology suggest that coal rank in the eastern Puget trough results from thermal overprinting associated with Miocene igneous intrusion and metamorphism. Thermally mature rocks containing abundant coal and detrital Type-III kerogen are common in the eastern Puget trough and Cascade foothills. Wildcat wells in the Puget trough and Cascade foothills have median sandstone porosities of 32 percent and 14 percent, respectively. These data suggest that natural gas accumulations should be present in pre-middle Miocene structural traps.

INTRODUCTION

This paper describes coal data that provide a tool for interpreting maturation levels and structure of the fluvial and deltaic Eocene sequences of western and central Washington state. These data, together with cross-cutting relations of structure and isorank contours, constrain the timing of probable gas generation and suggest heat-flow mechanisms. The study area consists of the Puget trough, parts of the Cascade Range, and the western Columbia Basin (Fig. 1).

Oil and gas production in Washington has been insignificant (McFarland, 1983). Minor amounts of gas have been recovered from glacial deposits (Glover, 1935); from a Columbia River basalt flow in the southeastern portion of the state (Hammer, 1934); and from melange along the Pacific coast (Snavely and Kvenvolden, 1989; Palmer and Lingley, 1989). Most of the 58 wildcats that were drilled deeper than 1,500 m (5,000 ft) in Washington sought oil from Eocene strata within the Puget trough, where more than 11 km (36,000 ft) of Cenozoic sedimentary section is preserved (Danes and others, 1965).

In recent years, exploration emphasis has shifted to conventional gas and coalbed-methane. With the exception of the Mist Field in northwestern Oregon, where upper Eocene rocks have produced 39.5 billion cubic feet of gas (D. Olmstead, Oregon Dept. of Geology and Mineral Industries, oral commun., June 1990), exploration results have been discouraging. Poor permeability in locally derived lithic and volcanolithic sandstones, which are common throughout the Tertiary section (see Galloway, 1974), and the poor quality of seismic-reflection records in prospective areas have discouraged exploration. Type I

[1]This paper was prepared for the proceedings of the 1990 Circum-Pacific Energy Council Conference in Honolulu, Hawaii.

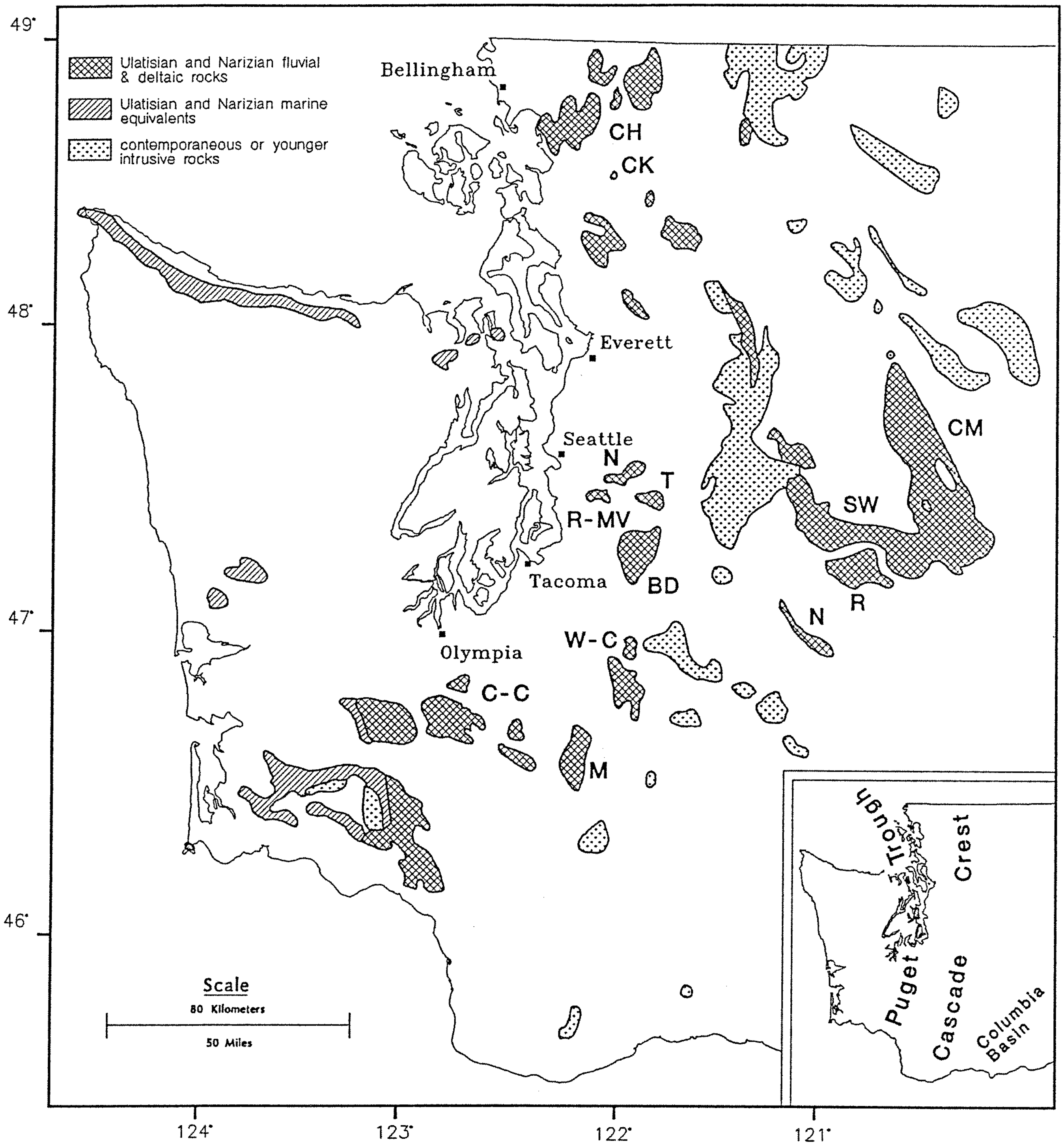

Figure 1. Distribution of Ulatisian and Narizian fluvial and deltaic rocks in western and central Washington (cross hatch), their marine equivalents (diagonal line pattern), and intrusive rocks the same age or younger (small crosses). Abbreviations for coalfields discussed in text: Ch, Chuckanut outcrop area; CK, Cokedale; R-MV, Renton-Maple Valley; N, Newcastle; T, Taylor; BD, Black Diamond; W-C, Wilkeson-Carbonado; C-C, Centralia-Chehalis; M, Morton; Ro, Roslyn; SW, Swauk outcrop area; CM, Chumstick outcrop area.

kerogen has not been identified in Washington, and few hydrogen indices greater than 250 have been recorded (Brown and Ruth Laboratories, Inc., 1984; Snavely and Kvenvolden, 1989). Paraffinic liquid in the Phillips State No. 1 at 2,152 m (7,200 ft) is the only geochemically verified oil show in the study area (Brown and Ruth Laboratories, Inc., 1984).

However, middle to upper Eocene feldspathic sandstones derived from extrabasinal sediments (Frizzell, 1979; Heller and others, 1985, 1987) commonly have greater than 15 percent porosity and greater than 100 millidarcies permeability (Fig. 2; Snavely and others, 1958; Wurden and Ford, 1977). For example, one late Eocene sandstone reservoir at the Jackson Prairie gas-storage facility at the south end of the Centralia-Chehalis coalfield (C-C, Fig. 1) is 43 m thick, averages 36 percent porosity, and has permeabilities ranging from 1 to 3 Darcies (Wurden and Ford, 1977). Anderson (1959) reports 16 separate Eocene sandstones in the vicinity of Black Diamond having an aggregate thickness of 550 m (1,800 ft). At least three are more than 100 m thick (Evans, 1912).

Structural traps may have developed during several periods of Paleogene deformation and during middle Miocene uplift of the central and southern Cascade Range in Washington. Numerous important local unconformities, folds, and faults that are only rarely exposed but are commonly depicted in subsurface maps of coal mines are evidence for these deformational events.

Coalbeds as much as 15 m (50 ft) thick are abundant in Eocene strata. Coals range from mostly lignite and subbituminous near the center of the Puget trough to anthracite at the Cascade crest. Additionally, Eocene fine-grained clastic rocks commonly contain from 0.5 to 2.0 percent detrital Type-III kerogen, indicating potential for gas generation (Brown and Ruth Laboratories, Inc., 1984; Core Laboratories, 1987a, 1987b; Jan Reichelderfer, U.S. Dept. of Energy, written commun., 1987; Hans von der Dick, Canadian Hunter, written commun., 1989). At least 30 significant gas shows have been logged in the Cascade foothills and Columbia Basin (McFarland, 1983; Lingley and Walsh, 1986). For example, the Lawson coal exploration test ("Flaming Geyser well") drilled near Black Diamond blew out in 1911 and has produced methane since that date.

Nine coalbed-methane wildcats have been drilled in western Washington. Twenty coalbed-methane desorption analyses from samples collected in the western foothills of the Cascades range from 217 to 563 (average 423) standard cubic feet of methane per ton (S. P. Pappajohn, GeoTrends, oral commun., 1990). Production modeling suggests an in-place reserve of 14 billion ft^3/mi^2 (Mitchell and Pappajohn, 1989). These data suggest a gas-generative environment and the potential for coalbed-methane production. However, dewatering operations have been attempted in only four wells.

TERTIARY STRATIGRAPHY

Tertiary sedimentary rocks are present throughout a regional downwarp that extends from southern British Columbia to southwestern Oregon. In middle and early late Eocene time (equivalent to the Ulatisian and Narizian benthic foraminiferal stages of Rau, 1981), fluvial and deltaic coal-bearing sediments of the Puget Group and its equivalents (Fig. 3) were deposited on a coastal plain covering much of west-central Washington (Snavely and Wagner, 1963; Buckovic, 1979; Heller and others, 1987). This Eocene plain was interrupted by constructional volcanic hills of the Northcraft and Tukwila Formations (Buckovic, 1979) together with the volcanic rocks of Mt. Persis (Tabor and others, 1982) and the volcanic rocks of Grays River (Walsh, 1987; Phillips, 1987; also see Phillips and others, 1989). Deep-marine embayments along the margin of the plain resulted in deposition of areally restricted siltstone and turbidite sequences of the middle Eocene sandstone of Megler (Wells, 1979), the middle Eocene feldspatholithic sedimentary rocks of the McIntosh Formation, and their equivalents. The position of the irregular Eocene shoreline probably trended northwest (Heller and others, 1987).

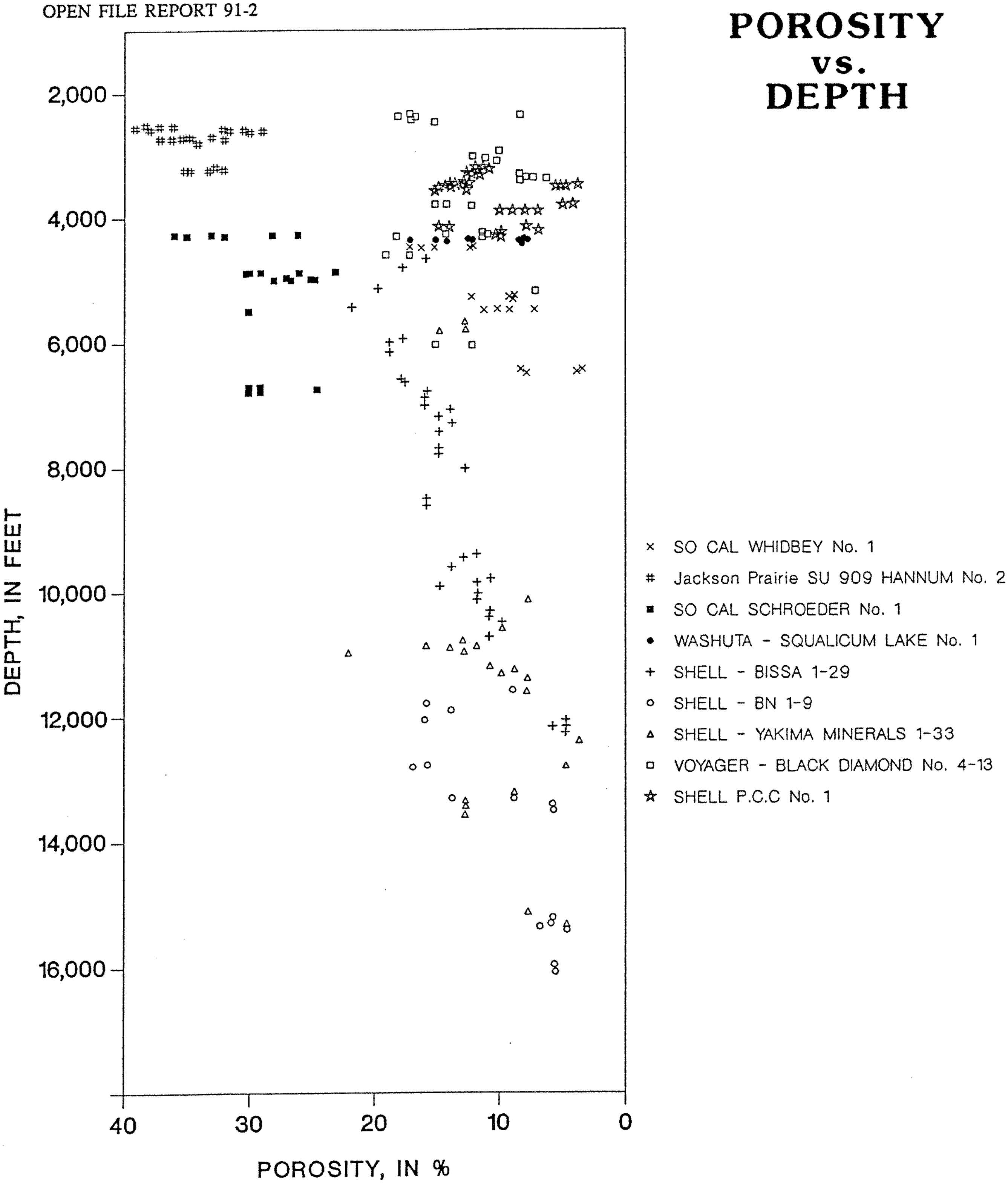

Figure 2. Plot of porosity versus depth for selected wells in the Puget and Columbia Basins. Data are from Washington Division of Geology and Earth Resources files.

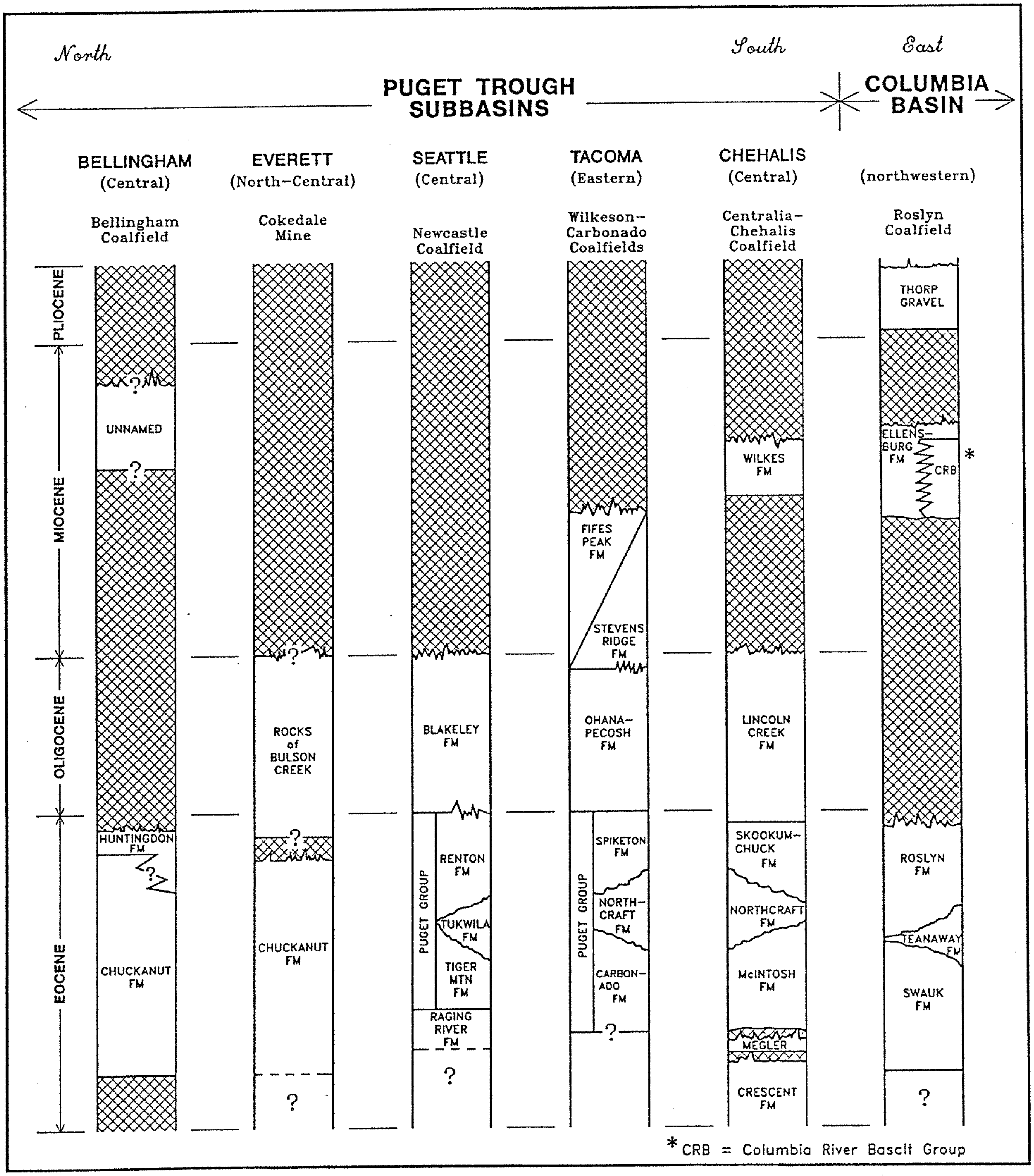

Figure 3. Correlation chart of Tertiary rocks and sediments of western and central Washington discussed in the text (modified from Hopkins, 1968; Walsh and Phillips, 1983b; Johnson, 1985; Walsh and others, 1987, and Whetten and others, 1988).

Figure 4 is an isopachous map of Ulatisian and Narizian rocks exclusive of Crescent Formation basaltic rocks. It was drawn on the basis of well control, measured sections, and seismic reflection, gravity, and magnetic data. The shapes of the contours are controlled mainly by gravity data (McLeod and others, 1977) and especially the long wave-length filtered data set of Finn and others (1986), which shows excellent correlation with isopachous trends where well control is available.

This isopach map shows five subbasins within the Puget trough, each of which contains more than 3,000 m (10,000 ft) of middle and upper Eocene rocks. From north to south, these are the Bellingham (B), Everett (E), Seattle (S), Tacoma (T), and Chehalis (C) subbasins as informally named in Danes and others (1965) and Deacon (1962). The configurations of these subbasins are modified herein on the basis of more extensive data. The eastern side of the map shows the west limb of the Columbia basin (Lingley and Walsh, 1986). The presence of several widely separated exposures of Eocene strata between the Puget trough and Columbia basin that range from 1,500 to 3,000 m (5,000 to 10,000 ft) in thickness suggests that Eocene rocks were deposited continuously across the area of the Cascade Range. This interpretation is supported by reflection-seismic data described in Gwilliam and others (1990). The subbasins and adjacent areas on their eastern flanks have been extensively mined for coal since 1853 when the Bellingham mine was opened (Walsh and Logan, 1989).

In latest Eocene (Refugian) and early Oligocene time, approximately synchronously with a marine transgression, the Cascade magmatic arc became active and choked the stream system(s) with tuffaceous debris (Heller and others, 1987; Phillips and others, 1989). The Oligocene section grades westward from nonmarine, sub-alkalic to calc-alkaline volcanic rock and impermeable volcaniclastic sedimentary rocks on the eastern margin of the trough, to deep-water marine tuffaceous siltstones in the subbasins (Walsh, 1984; Phillips, 1984; Lovseth, 1975; Fiske and others, 1963). These rocks are overlain by patches of Miocene and Pliocene volcanogenic rocks that commonly grade westward into conglomerates and then marine clastic rocks.

Figure 4. Isopach of Ulatisian and Narizian surface accumulated rocks in western and central Washington. Thicknesses are from measured sections, drilled depths, and cross-sections. Shapes of contours (in feet) are guided by potential field data, principally long-wavelength-filtered gravity anomalies. Data are from Brown and Gower, 1958; Brown and others, 1960; Bruer and others, 1984; Campbell and Banning, 1985; Catchings and Mooney, 1988; Danes, 1985; Danner, 1957; Evans, 1988; Finn and others, 1986; Fiske and others, 1963; Garling and others, 1965; Glover, 1985; Gower, 1960; Gresens and others, 1981; Hales, P. O., Weyerhaeuser Corp., 1988, written commun.; Heath, 1971; Henriksen, 1956; Huntting and others, 1961; Ise, T. F., 1988, written commun.; Johnson, 1984; MacLeod and others, 1977; Martin and others, 1985; McFarland, 1983; McKeel, 1983; McLean, 1977; Muller, 1982; Mullineaux, 1965, 1970; Newton and Van Atta, 1976; Palmer and Lingley, 1989; Phillips, 1987; Prieto and others, 1985; Rau, 1958, 1966, and personal commun.; Rau and McFarland, 1982; Rauch, 1985; Roberts, 1958; Schreiber, 1981; Sharp, 1988; Snavely and others, 1986; Spencer, 1983a, 1983b, 1984; Stine, 1987; Swanson, 1978; Tabor and Cady, 1978; Tabor and others, 1984; Vance, 1957; Vance and others, 1987; Walker, 1980; Walsh and others, 1987; Weaver, 1937; Wells, 1981; Whetten and others, 1988; Winters, 1984; Wise, 1970; Wolfe and McKee, 1968. Subbasins discussed in text are labeled: B, Bellingham; E, Everett; S, Seattle; T, Tacoma; and C, Chehalis.

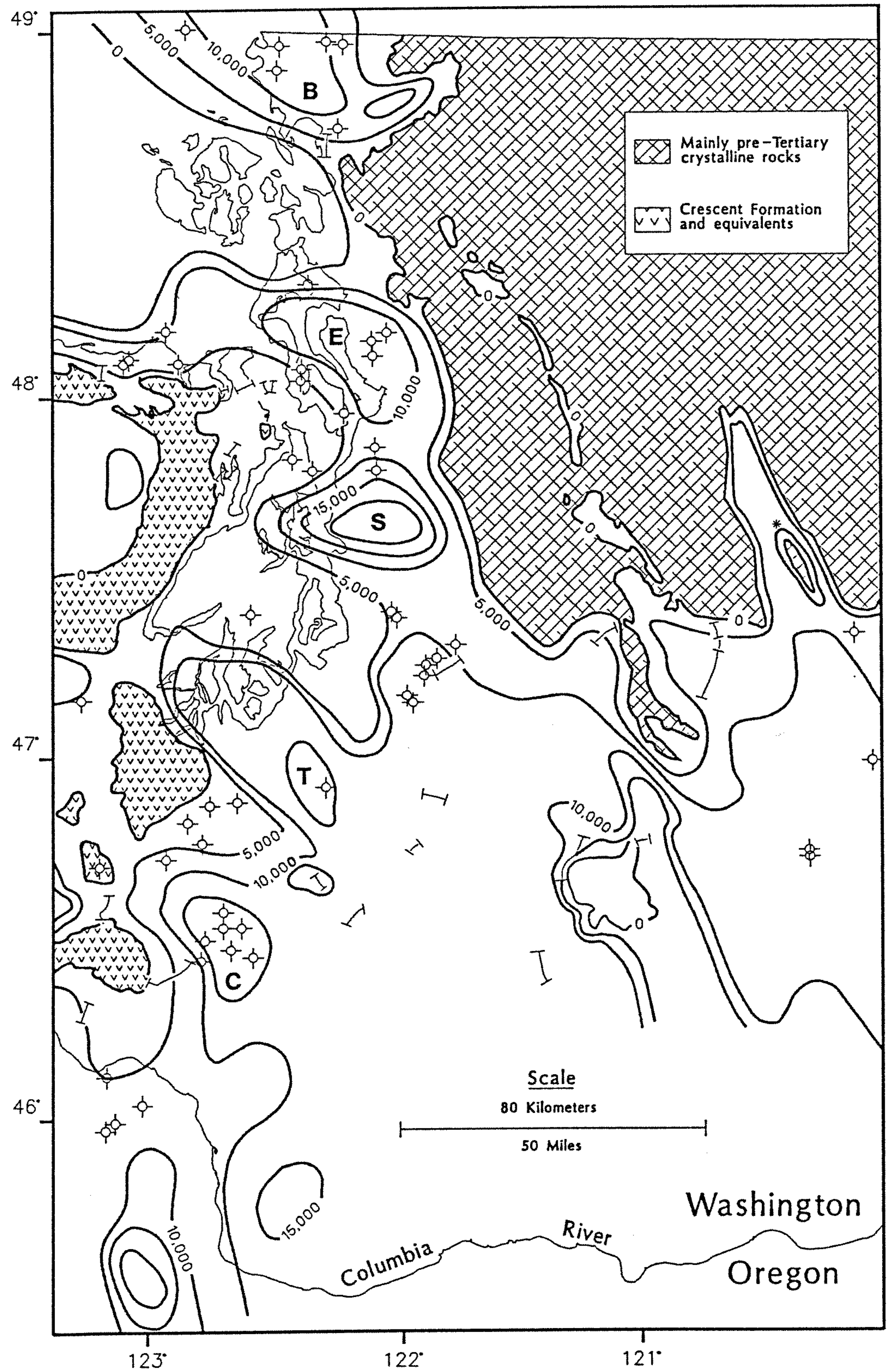

Figure 4. Isopach of Ulatisian and Narizian surface-accumulated rocks. (Caption on facing page.)

STRUCTURE AS DETERMINED FROM MINE MAPS

Magnetic and gravity data (Finn and others, 1986; Danes and others, 1965) and geologic mapping by Cheney (1987), Gower and others (1985), Harding and others (1988), Lovseth (1975), Walsh (1984), and Whetten and others (1988) indicate that the northern and southern margins of the Everett, Seattle, and Tacoma subbasins are controlled by west- and northwest-trending faults. On sedimentologic evidence, Johnson (1985) suggested that deposition in the Bellingham and Seattle subbasins was controlled by strike-slip faulting. The southern boundary fault of the Seattle subbasin was active during deposition of the lower middle Eocene Raging River Formation and the Oligocene Blakeley Formation (Walsh, 1986), and it may have had 1,100 m (3,500 ft) of Quaternary displacement (Gower and others, 1985).

Prospect-scale structures are difficult to map in Washington because of the poor quality of most seismic records and limited exposure due to the presence of Quaternary sediments and thick vegetation. However, subsurface maps of numerous coal mines in Eocene rocks provide a data set that can be used to define prospects. More than 1,100 maps of approximately 150 mines and coal prospects are available (Schasse and others, 1983). These mines were developed by driving major tunnels (gangways) at approximately one-half degree to strike in order to facilitate drainage and allow gravity movement of loaded coal cars. Chutes were then driven updip and connected by smaller tunnels called crosscuts, which commonly parallel strike (Walsh and Logan, 1989). Elevation, dip magnitude, and dip azimuth are displayed on coal mine maps. These mine maps illustrate structure in far greater detail than is generally available from surface studies or from geophysical methods. Although faulted anticlines similar to the traps at the Mist gas field can be interpreted from these maps, apparently few conventional gas exploration programs have used these data.

Many of these mine maps clearly illustrate fold styles. Plate 1 (at the end of this report) is a map of the Pacific Coast Coal Company Electric Mine; it shows two north-plunging chevron synclines and an intervening anticline, all of which are located in the south-central part of the Wilkeson-Carbonado coalfield (Fig. 1). An interpretation of several mine maps in the field shows west- and northwest-trending chevron folds and high-angle faults (Fig. 5). Chevron folds also are present in the Ashford area at the southern end of the Wilkeson-Carbonado coalfield (Beeson, 1980) and in the Black Diamond area (Anderson, 1959). At Black Diamond, open folds having essentially concentric geometries are present adjacent to chevron folds in the same lithologies. Mine maps of the Roslyn coalfield show open concentric folding, as do the maps of the Centralia coalfield (Snavely and others, 1958).

THERMAL MATURATION AS DETERMINED FROM COAL DATA

Since 1911, the Washington Division of Geology and Earth Resources, the U.S. Geological Survey, and the U.S. Bureau of Mines have systematically sampled coals from Washington mines and performed proximate and ultimate analyses (Smith, 1911; U.S. Bureau of Mines, 1931, 1941; Daniels and others, 1958; Phillips and others, 1982). Coal rank determined from these analyses provides an accurate means of mapping thermal maturity in the Puget trough (Walsh and Phillips, 1982, 1983a, 1983b).

Coal rank is generally described according to ASTM Standard D388-88, which specifies classification by moist, mineral matter-free British thermal units per pound (mmmf-BTU) if this value is less than 14,000 <u>and</u> dry, mineral-matter-free fixed carbon (dmmf-FC) is less than 69 percent. If dmmf-FC is greater than 69 percent and/or mmmf-BTU is greater than 14,000, then dmmf-FC is used for classification. For mines that contain coals that are both higher and lower than 14,000 mmmf-BTU, one classification system is used for the entire area.

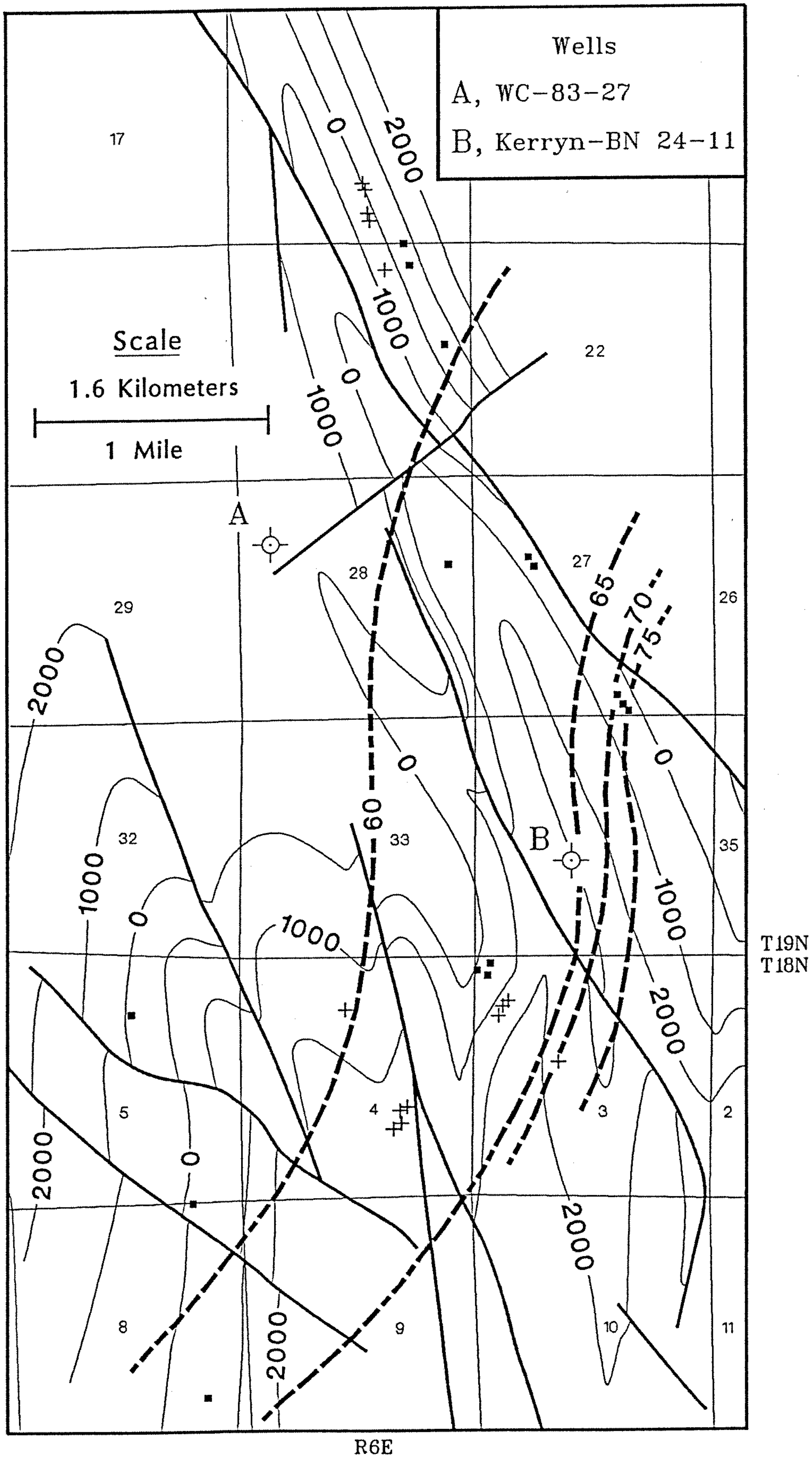

Figure 5. Isorank contours (dmmf-FC; dashed lines) plotted on structure contours (fine solid lines) on the Wingate seam for the Wilkeson-Carbonado coalfield. Structure contours (in feet) are modified from Daniels (1914) and Gard (1968). Coal rank data points are from the Wingate seam (crosses) and the Wilkeson #3 seam (boxes).

Figure 6 shows coal-rank mapping of most commercially mined coalfields of western and central Washington. This figure is a composite of maps depicting trend-surface models fitted to more than 1,000 coal analyses (Walsh and Phillips, 1983b). For the Roslyn and Centralia-Chehalis fields, sufficient data are available to map regional coal rank from single coal seams. In order to build the trend-surface models for the King County coalfields, it was necessary to aggregate 1,800 m (6,000 ft) of section. The trend-surface analyses used to generate Figure 6 are statistically significant at the 0.999 level, and, with the exception of the King County coalfields, all correlation coefficients are greater than 0.9. The correlation coefficient for King County coalfields is 0.82, reflecting variation resulting from the use of the 1,800-m stratigraphic interval, from local igneous intrusions into the coal-bearing section, and from juxtaposition of differing fold geometries. Vitrinite reflectance values from outcrop samples (Table 1; Koesters, 1984; Walsh, 1984)) closely match coal-rank values predicted by the trend-surface models.

Figure 6 shows that coal rank increases from the Puget trough and Columbia Basin toward the Cascade crest. These trends closely coincide with trends of increasing present-day geothermal gradients. (See Blackwell and others, 1985.) Gradients in the central Puget trough range from 10° to 38°C/km and average 23°C/km (Barnett, 1986; Barnett and Korosec, 1989; Blackwell and others, 1985; Korosec and others, 1981). The lowest gradients coincide with the thickest sedimentary sections. Gradients increase eastward to an average of 44°C/km in the south Cascades. Gradients in the western Columbia basin average 36°C/km. However, coal rank in the eastern Puget trough and Cascade foothills is generally higher than would be produced solely by present-day heat flow (Walsh, 1985; Summer and Verosub, 1989).

Figure 7 is a map of the depths to vitrinite reflectance (R_o)=0.5% on the basis of analyses of coal samples from outcrop (Table 1; Evans, 1988; Koesters, 1984; Snavely and Kvenvolden, 1989; Walsh, 1984) and subsurface data (Table 2; Brown and Ruth Laboratories, Inc., 1984; Armentrout and Suek, 1985; Lingley and Walsh, 1986). The depth-to-R_o=0.5% contours were constructed using the coal-rank contours from Figure 6 as guides in areas of sparse control. The 0.5% reflectance value was used to approximate onset of peak dry-gas generation (Kontorovich, 1984).

In general, Figure 7 shows that depth to R_o=0.5% increases westward and eastward away from the crest of the Cascade mountains. Detailed mapping of the Wilkeson-Carbonado field confirms the regional trends (Fig. 5): dmmf-FC here increases southeastward toward the Cascade front, and the shape and trends of present geothermal gradient contours match depth-to-R_o=0.5% contours.

Four exceptions to the trend of increasing rank toward the Cascades are noteworthy:

(1) Only coals above high volatile C bituminous increase in rank toward the Cascade crest. Rank contours on low-rank coals in the Newcastle coalfield near Seattle, for instance, strike eastward, increase to the south, and parallel structural contours (Fig. 8), implying that Hilt's law (i.e., coal rank increases down section) is applicable there and that these coals reached their present rank prior to folding (Walsh, 1986). At the New Black Diamond mine directly south of Newcastle, rank increases westward, away from the mountains. At Centralia, coal rank contours are synformal (Fig. 6).

(2) Between the Tacoma and Chehalis subbasins, depth-to-R_o=0.5% contours bulge northwestward, corresponding to an area in which middle and upper Eocene rocks are interbedded with calc-alkaline flows and tuffs of the Northcraft Formation. The Northcraft there is propylitically and argillically altered (Walsh and others, 1987), and Puget Group sandstones are mineralized with mercury (Mackin, 1944), suggesting that coal rank in the Morton area has been upgraded by convective heat flow.

Table 1. Vitrinite reflectance data from western and central Washington outcrops. All analyses are mean random reflectance and represent at least 50 points counted. Data from Amoco Production Company and from Washington Division of Geology and Earth Resources files.

Coal Name	Formation	County	TWP	Range	Section	Part of Section	Reflectance (R_o), in %
Van Zandt	Chuckanut	Whatcom	38N	4E	12	Center	0.74
unnamed	Chuckanut	Whatcom	39N	6E	22	N/2 N/2	1.44
unnamed	Chuckanut	Whatcom	39N	6E	21	SE/4 SE/4	1.81
unnamed	Chuckanut	Whatcom	39N	5E	11	NE/4 NE/4 NE/4	0.81
unnamed	Chuckanut	Whatcom	39N	7E	30	W/2	2.88
Cumberland #1	Chuckanut	Skagit	35N	6E	23	N/2 SE/4	1.63
Cumberland #3	Chuckanut	Skagit	35N	6E	23	N/2 SE/4	1.71
unnamed	Chuckanut	Skagit	35N	5E	13	C. NW/4	1.01
Cashman	Puget Group	King	22N	7E	33	E/2 NE/4	0.58
Cashman	Puget Group	King	22N	7E	33	E/2 NE/4	0.58
unnamed	Puget Group	King	21N	7E	11	SW/4 SW/4	0.80
Peters Prospect	Tiger Mtn.	King	24N	7E	32	Center NW/4	1.13
Taylor	Renton	King	22N	7E	3	Center	0.63
Tiger Mtn. 3	Renton	King	23N	6E	13	SE/4 NW/4	0.64
Tiger Mtn. 2	Renton	King	23N	6E	13	SE/4 NW/4	0.48
Tiger Mtn. 1	Renton	King	23N	6E	13	SE/4 NW/4	0.42
Taylor	Renton	King	22N	7E	3	Center	0.55
Franklin #2	Puget Group	King	21N	7E	18	SE/4 NE/4	0.53
McKay	Puget Group	King	21N	7E	18	SE/4 NE/4	0.51
McKay	Puget Group	King	21N	7E	18	SE/4 NE/4	0.51
Gem	Puget Group	King	21N	7E	18	SW/4 NE/4	0.41
Gem	Puget Group	King	21N	7E	2	NW/4 NW/4	0.46
Primrose	Renton	King	24N	6E	31	NE/4 NE/4	0.39
Issaquah #4	Renton	King	24N	5E	36	NW/4 NW/4	0.41
unnamed	Puget Group	King	21N	6E	1		0.36
Durham #2	Puget Group	King	21N	7E	2	Center W/2	0.74
Durham #2	Puget Group	King	21N	7E	2	Center W/2	0.73
unknown	Puget Group	King	21N	7E	19		0.51
Kummer #0	Puget Group	King	21N	7E	31	NW/4	0.30
Pittsburgh #6	Spiketon	Pierce	19N	6E	15	SW/4 SE/4	0.93
unnamed	Carbonado	Pierce	18N	6E	26	C. S/2 N/2	1.69
unnamed	Spiketon	Pierce	17N	7E	19	NW/4	.095
unnamed	Spiketon	Pierce	17N	7E	19	S/2 NW/4	2.19
unnamed	Spiketon	Pierce	17N	7E	19	S/2 SW/4	1.97
unnamed	Carbonado?	Pierce	15N	6E	22	SE/4	0.72
unnamed	Carbonado	Pierce	15N	6E	9		0.68
Wilkeson #6	Carbonado	Pierce	18N	6E	2	NW/4 SW/4	1.21
Wilkeson #7	Carbonado	Pierce	18N	6E	2	NW/4 SW/4	1.17
Wilkeson #1	Carbonado	Pierce	18N	6E	2	NW/4 SW/4	1.14
Wilkeson #2	Carbonado	Pierce	18N	6E	2	NW/4 SW/4	0.99
Wilkeson #3	Carbonado	Pierce	18N	6E	2	SW/4 NW/4	1.07
Wilkeson #4	Carbonado	Pierce	18N	6E	2	SW/4 NW/4	1.15
unnamed	Carbonado	Pierce	18N	6E	4	Center	0.70
unnamed	Carbonado	Pierce	18N	6E	4?	Center?	0.98
unnamed	Carbonado	Pierce	18N	6E	34	N/2 NW/4	1.01
unnamed	Carbonado	Pierce	18N	6E	27	SW/4 SE/4	0.73
unnamed	Carbonado	Pierce	19N	6E	22	C. SE/4	0.73
Summit Creek	Puget Group	Lewis	14N	10E	13	N/2	2.60
Summit Creek	Puget Group	Lewis	14N	10E	13	N/2	2.77
unnamed	McIntosh equiv.	Lewis	14N	4E	12	SW/4 SE/4	0.97
unnamed	McIntosh equiv.	Lewis	14N	4E	29	SW/4	0.87
unnamed	McIntosh equiv.	Lewis	14N	4E	24		0.76
unnamed	McIntosh equiv.	Lewis	14N	4E	25		0.98
Big Dirty	Skookumchuck	Lewis	15N	1W	18?		0.35
Smith	Skookumchuck	Lewis	15N	1W	18?		0.40
unnamed	McIntosh equiv.	Lewis	12N	4E	13	NE/4	0.61
unnamed	McIntosh equiv.	Lewis	13N	4E	25	SE/4 SE/4	0.61
unnamed	Puget Group	Lewis	13N	4E	14	SW/4 NE/4	0.73
unnamed	Puget Group	Lewis	14N	2E	11	NW/4	2.80
unnamed	Cowlitz	Cowlitz	7N	2W	12	SW/4 NE/4	0.23
unnamed	Ohanapecosh	Skamania	4N	9E	27	SW/4 NE/4	0.40
unnamed	Ohanapecosh	Clark	5N	4E	4	SE/4 NE/4	0.32

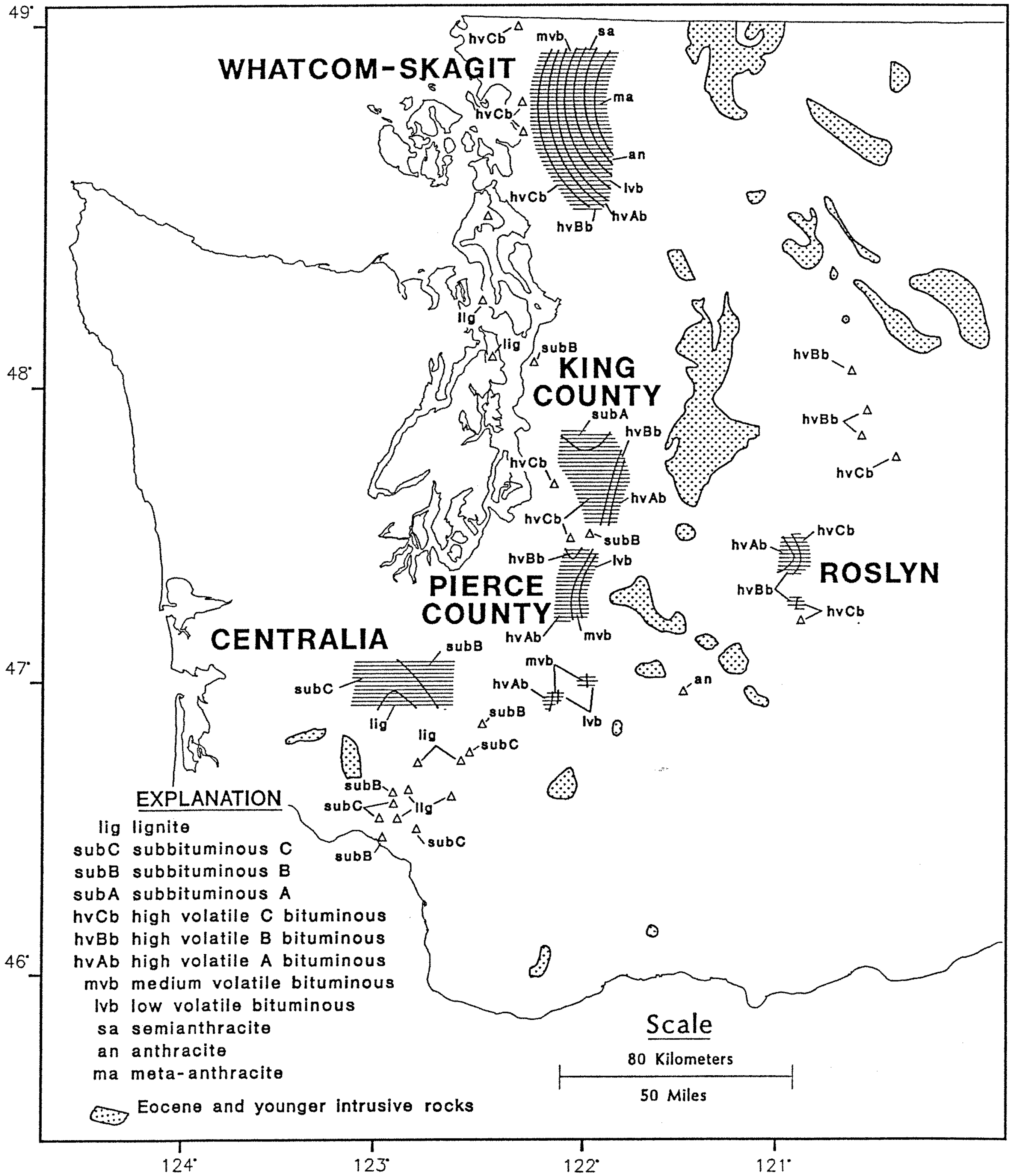

Figure 6. Map of trend-surface models of coal rank parameters of Eocene coals of western and central Washington. Coal fields are represented by areas of horizontal-line pattern. Modified from Walsh and Phillips (1983b).

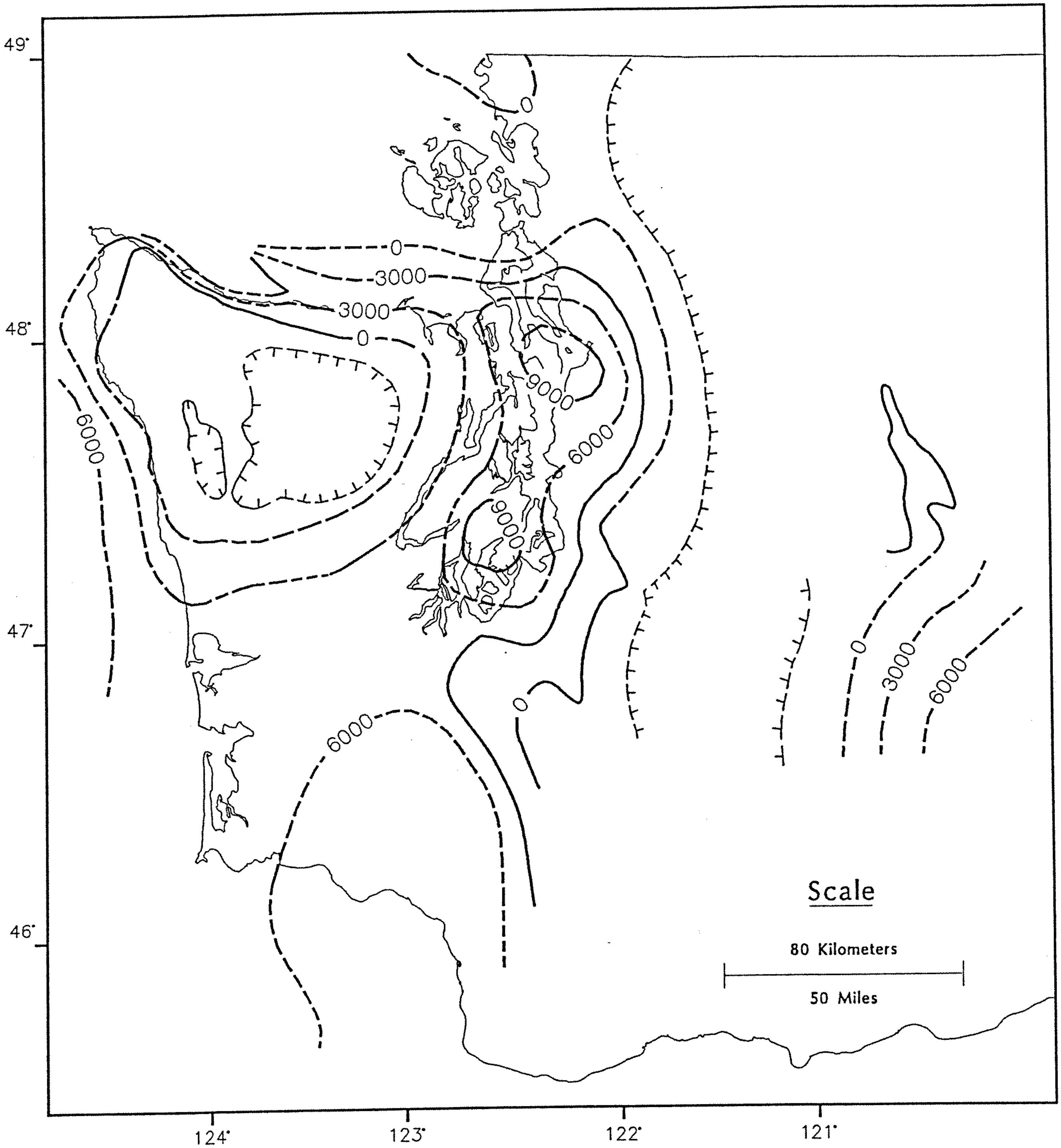

Figure 7. Contour map of depth (in feet) to vitrinite reflectance R_o=0.5%. The end of oil generation ("oil deadline"), herein taken as R_o=1.4%, is shown for reference, with hatchures on the R_o>1.4% side. Data from Tables 1 and 2; Fig. 5; Brown and Ruth (1984); Evans (1988); Snavely and Kvenvolden (1989); and Walsh (1984).

Table 2. Vitrinite reflectance data from oil and gas tests in western and central Washington. All analyses are mean random reflectance. Data from Amoco Production Company and from Washington Division of Geology and Earth Resources files.

Well name	Depth interval (ft)	Mean reflectance (%)	Median reflectance (%)	Standard deviation	Number of observations
Stremler No. 2	1390-1450	0.55	0.55	0.051	50
Whatcom County	1500-1510	0.56	0.56	0.048	50
SW/4 SW/4 sec. 4 (40N-3E)	1510-1520	0.51	0.51	0.048	50
	1640-1660	0.54	0.55	0.063	50
	1660-1670	0.51	0.52	0.068	50
	1670-1680	0.57	0.58	0.063	50
	1860-1870	0.50	0.49	0.055	51
	1870-1880	0.50	0.51	0.042	50
	1880-1890	0.54	0.54	0.052	50
	4040-4050	0.54	0.55	0.058	50
	4710-4720	0.52	0.51	0.066	50
Socal Schroeder No. 1	4740-4760	0.43	0.44	0.05	75
Snohomish County	5940-5960	0.40	0.36	0.10	71
850'FSL, 1400'FWL, sec. 26	6320-6340	0.50	0.51	0.05	75
(27N-4E)	6960-6980	0.52	0.52	0.07	76
	7520-7540	0.51	0.51	0.06	75
	7980-8000	0.61	0.61	0.06	75
	9580-9600	0.60	0.59	0.11	76
KSD No. 1	1220-1260	0.59	0.59	0.044	26
King County	3200-3240	0.58	0.57	0.061	31
330' FSL, 1220'FEL, sec. 4	4200-4240	0.60	0.59	0.070	20
(22N-5E)	4600-4640	0.60	0.60	0.065	49
	4800-4840	0.59	0.60	0.079	31
	5400-5440	0.63	0.64	0.075	27
	6000-6040	0.68	0.68	0.074	23
	6200-6240	0.69	0.69	0.055	34
	6400-6440	0.69	0.72	0.086	31
	6600-6640	0.70	0.73	0.057	13
	7000-7040	0.76	0.75	0.078	4
	8600-8640	0.71	0.73	0.066	13
	9000-9040	0.72	0.72	0.114	15
	9200-9240	0.76	0.77	0.072	40
Piel No. 34	3910-3940	0.51	0.53	0.052	50
King County	4100-4200	0.50	0.52	0.074	50
2468'FNL, 2104'FWL, sec. 10	4500-4600	0.53	0.54	0.074	47
(22N-5E)	4700-4800	0.48	0.47	0.053	19
	5300-5400	0.57	0.57	0.056	45
	5740-5780	0.60	0.59	0.069	49
	6160-6190	0.57	0.57	0.058	42
	6700-6800	0.60	0.59	0.058	25
Bachmann No. 1	950-1000	0.55	0.55	0.046	50
King County	1590-1610	0.59	0.59	0.061	50
2640'FNL+380'FWL, sec. 26,	2385-2395	0.71	0.72	0.059	50
(21N-6E)	2840-2900	0.64	0.65	0.060	50
	2950-3000	0.64	0.64	0.074	50
	3200-3250	0.68	0.70	0.068	50
	3280-3290	0.71	0.73	0.049	50
	3290-3315	0.61	0.62	0.059	50
	3380-3415	0.68	0.70	0.055	50
	3495-3500	0.74	0.75	0.054	50
	3515-3540	0.62	0.62	0.064	49
	3545-3560	0.60	0.62	0.057	50
	3595-3600	0.65	0.66	0.080	50
	3640-3700	0.63	0.64	0.052	50
	3825-3840	0.66	0.73	0.213	55
	3865-3900	0.67	0.67	0.075	50
	3955-3980	0.65	0.65	0.052	50
Brandt No. 1	1500-1600	0.49	0.47	0.071	41
King County	1900-2000	0.52	0.52	0.050	40
2203'FNL, 312'FEL, sec. 34	2200-2300	0.54	0.55	0.068	42
(21N-6E)	2300-2400	0.55	0.55	0.059	33
	3100-3200	0.60	0.60	0.061	50
	3200-3300	0.57	0.57	0.061	50
	3300-3400	0.62	0.62	0.090	30
	3400-3500	0.60	0.59	0.074	31

Table 2. Vitrinite reflectance data, oil and gas tests (Continued)

Well name	Depth interval (ft)	Mean reflectance (%)	Median reflectance (%)	Standard deviation	Number of observations
McCulloch-Krainick No. 1 King County 493'FNL, 642'FWL, sec. 10 (20N-6E)	1280-1290	0.43	0.44	0.052	49
	2920-2940	0.51	0.52	0.065	50
	3040-3060	0.52	0.54	0.057	50
	3440-3450	0.55	0.57	0.075	38
	4870-4890	0.64	0.64	0.057	50
Blessing Siler Community No. 1 Pierce County 740'FSL, 136'FWL, sec. 31 (20N-6E)	870	0.67	0.67	0.06	78
	1230	0.54	0.55	0.06	78
	1890	0.52	0.52	0.07	76
	2100	0.63	0.62	0.05	79
	2370	0.62	0.61	0.06	75
	2910	0.62	0.60	0.07	75
	3660	0.67	0.67	0.05	75
	3960	0.61	0.61	0.05	76
	4380	0.67	0.66	0.09	80
	4590	0.67	0.68	0.06	81
	4800	0.66	0.66	0.05	82
	5220	0.72	0.72	0.05	79
	5640	0.78	0.79	0.06	80
	6000	0.74	0.74	0.05	84
	6030	0.73	0.74	0.05	75
	6480	0.88	0.88	0.05	83
	7170	0.81	0.82	0.05	83
	7420	1.75	1.75	0.09	84
Everett Trust and Savings Bank Trustee No. 1 Lewis County 960'ESL, 440'FWL, sec. 23 (13N-1E)	210-240	0.24	0.25	0.024	8
	1800-1830	0.63	0.64	0.070	17
	1830	0.37	0.35	0.083	29
	2007	0.49	0.50	0.052	46
	2280	0.49	0.48	0.074	50
	2430-2460	0.51	0.52	0.069	15
	2457	0.57	0.57	0.129	14
	2551	0.61	0.62	0.072	14
	3101	0.53	0.54	0.085	9
Rosa Meyer No. 1 Lewis County 350'FNL, 415'FWL sec. 8 (12N-2E)	1607-1698	0.40	0.41	0.086	19
	2034-2065	0.49	0.51	0.081	50
	2307-2337	0.59	0.58	0.082	14
	3435-3465	0.55	0.54	0.076	50
	3649	0.53	0.54	0.061	50
	3805-3836	0.57	0.56	0.136	50
	4050-4080	0.60	0.57	0.109	50
Roscoe B. Perry et ux No. 1 Lewis County 1783'FSL, 991'FWL, sec. 12 (12N-1W)	120-150	0.86	0.90	0.182	23
	1320-1350	0.31	0.32	0.047	49
	1500-1530	0.52	0.53	0.061	50
	1800-1830	0.75	0.75	0.098	50
	2160-2190	0.71	0.72	0.132	20
	2310-2340	0.71	0.72	0.082	32
	4440-4470	0.47	0.47	0.056	50
	4620-4650	0.50	0.49	0.096	34
	4710-4740	0.48	0.46	0.077	51
	4920-4950	0.49	0.48	0.090	50
	5100-5130	0.48	0.48	0.041	50
	5310-5340	0.46	0.46	0.054	50
	5910-5940	0.52	0.49	0.133	18
	6120-6150	0.43	0.44	0.064	50
	6510-6540	0.53	0.53	0.100	15
	6720-6750	0.51	0.52	0.097	50
	7110-7230	0.59	0.60	0.048	50
	7320-7350	0.49	0.48	0.091	11
	7500-7530	0.65	0.66	0.066	15
	7440-7560	0.64	0.65	0.097	50
	7620-7740	0.64	0.64	0.047	50
	7920-7950	0.57	0.56	0.132	22
	7950-8040	0.87	0.87	6.056	48
	8190-8310	0.79	0.82	0.105	10
	9060-9150	0.56	0.55	0.058	17
	9510-9540	0.52	0.50	0.133	18
John Brown et al. No. 1 Lewis County 1,800 FSL, 925 FWL sec. 15, (11N-1E)	40-70	0.47	0.46	0.076	50
	250-280	0.37	0.38	0.063	28
	1630-1660	0.44	0.44	0.048	13
	3424-3454	0.48	0.48	0.105	10

(3) East of the Tacoma subbasin, coals of the Wilkeson-Carbonado field have substantially higher ranks than corresponding coals in the Black Diamond fields directly to the north along the same structural trend (Fig. 6). This discontinuity is approximately 0.3% R_o, corresponding to an increase from high volatile B bituminous to medium volatile bituminous coal. Reflectance values in the Phillips State No. 1 wildcat, located between these coalfields (Fig. 1), show a linear increase from R_o=0.45% at the surface to 0.6% at 2,200 m (7,200 ft), where reflectance jumps to 1.1%, and then increases linearly at the same slope to R_o=1.4% at the 3,938-m (12,920 ft) total depth (Brown and Ruth Laboratories, Inc., 1984). A similar discontinuity in the reflectance vs. depth curve appears to be present at approximately the same depth in the Blessing Siler Community No. 1 wildcat, located 1 km (0.6 mile) to the southwest (Fig. 1, Table 2). This discontinuity probably results from right-lateral offset along a northwest-trending fault separating the two coalfields and two wells. A mid-Eocene unconformity is a less likely explanation for the non-linear reflectance-depth profiles.

(4) Mine and drillhole data in the central and western Bellingham subbasin reveal little lateral or vertical increase in coal rank. In the Birch Bay No. 1 well, reflectance increases only 0.1% in 2,450-m (8,000 ft) (H. von der Dick, Canadian Hunter, written commun., 1990). Vitrinite data from the Daymont Stremler No. 2 well (Table 2) and the Point Roberts No. 1 well (Bustin, 1990) also show little reflectance increase with increasing depth, indicating essentially isothermal conditions. Summer and Verosub (1989) note anomalously steep maturation profiles in several other Pacific Northwest wells.

TIMING OF THERMAL MATURATION

Present coal maturation levels in the Wilkeson-Carbonado area resulted from a post-early Miocene thermal event. A map of the coalfield shows that rank contours cut at a high angle across structural contours mapped on the Eocene Puget Group (Fig. 5). These same folds coaxially deform Oligocene and lower Miocene rocks in the central Cascades near Wilkeson-Carbonado, constraining the time at which present coal rank was developed to post-early Miocene (Gard, 1968; Fiske and others, 1963; Walsh and others, 1987). Evarts and others (1987) note that upper Miocene sedimentary rocks have not been affected by this thermal event in the Mount St. Helens area.

Rank contours that cut structural contours in the Wilkeson-Carbonado coalfield could have developed in response to a post-folding regional thermal event or, alternatively, to differential burial and subsequent uplift. To test these two hypotheses, geometric relations of structure, stratigraphy, and rank on the Wingate seam in the Wilkeson-Carbonado coalfield were examined. An increase of 15 percent dmmf-FC is observed over a 1-km (3,200-ft) distance southeastward along strike between sections 21 and 27 (Fig. 5). There is no observed repetition of the isorank surface in the Wingate, despite one intervening fault. The slope of the vitrinite-depth relation from the nearby Phillips State No. 1 wildcat (Brown and Ruth Laboratories, Inc., 1984) shows that between 2,500 and 4,000 m (8,200 and 13,000 ft) of burial would be required to cause a 15 percent dmmf-FC rank increase in this 1-km (3,200-ft) wide area. Furthermore, there is no evidence for deposition of a thick section of post-lower Miocene rocks at Wilkeson-Carbonado. Therefore, the hypothesis that the observed rank-increase patterns at the Wilkeson-Carbonado field were caused by differential burial and subsequent uplift requires unreasonable geometries.

At the Rosyln coalfield, isorank contours cut across structure and increase westward from high volatile C bituminous to high volatile A bituminous (Beikman and others, 1961). Moderately folded Eocene rocks at Roslyn are unconformably overlain by gently dipping, poorly indurated, Pliocene Thorp and Miocene Ellensburg gravels, constraining the age of coal maturation as Miocene or Oligocene.

However, the age of folding cannot be constrained with sufficient accuracy to compare deformation and timing of maturation at Roslyn with those of the Wilkeson-Carbonado area. Rank contours also cut across structural contours on Eocene rocks in the Bellingham subbasin and at Morton, east of the Chehalis subbasin.

In the subbasin depocenters where rank in outcrop is lower than high volatile C bituminous, coal reached its present rank prior to folding (Walsh, 1986). Figure 8, for instance, shows an area where rank contours are folded together with the strata.

MECHANISMS OF HEAT FLOW

The regional increase in coal rank toward the Cascade crest coincides with the late Oligocene to middle Miocene development of the Cascade arc plutons. Zeolite-facies burial metamorphism along the Cascade crest accompanied emplacement of these calc-alkaline to sub-alkalic plutons and probably peaked during the early Miocene (Evarts and others, 1987). Evarts and others (1987) observed that upper Miocene rocks are not regionally metamorphosed.

Contact metamorphism probably affected coal rank for a distance of several miles from these plutons. Evarts and others (1987) observed contact-metamorphic mineral assemblages 1,500 to 4,000 m (5,000 to 13,000 ft) from the Spirit Lake pluton south of Morton. Westward-increasing coal rank at the New Black Diamond mine was probably caused by contact effects of Oligocene intrusive rocks 2 km (1.25 miles) to the south and west.

Heating by regional or contact metamorphism probably cannot account for the near-isothermal conditions described in exception (4) above. Summer and Verosub (1989) suggest that steep vitrinite and thermal alteration index vs. depth profiles noted in Oregon and Washington are caused by convective heating. In order to test this hypothesis, inherent ash and sulfur content were plotted against dmmf-FC. Good correlation between ash or sulfur and coal rank could suggest that minerals and/or ions had been precipitated or removed by convective fluids. This is apparently the case in the area between the Tacoma and Chehalis subbasins, as noted in exception (2) above. Analyses from the Wilkeson No. 5 seam show a moderate correlation between dmmf-FC and ash (correlation coefficient = 0.8, n = 26) and dmmf-FC and sulfur (correlation coefficient = 0.74, n = 26). These correlation coefficients are reduced to 0.4 and -0.38, respectively, if three statistical outliers are removed from the data set. In the Wilkeson-Carbonado coalfield, local fluid movement probably occurred around these data points, but elsewhere there is little evidence for convection. Data from the Roslyn No. 5 seam show no correlation between ash and dmmf-FC (correlation coefficient = -0.07, n = 61). This suggests that increasing rank at Roslyn was due to conductive heating.

EXPLORATION SIGNIFICANCE

The configuration of the contours shown on Figure 7 together with gas shows in the Black Diamond area and high coalbed-methane desorption values indicate that gas generation has occurred along the foothills of the Cascade Range, probably at depths of less than 1,800 m (6,000 ft). Within the subbasins, peak gas generation probably took place at depths between 1,800 m (6,000 ft) and 2,750 m (9,000 ft). In the foothills, pre-middle Miocene folds are potential traps because they formed prior to gas generation.

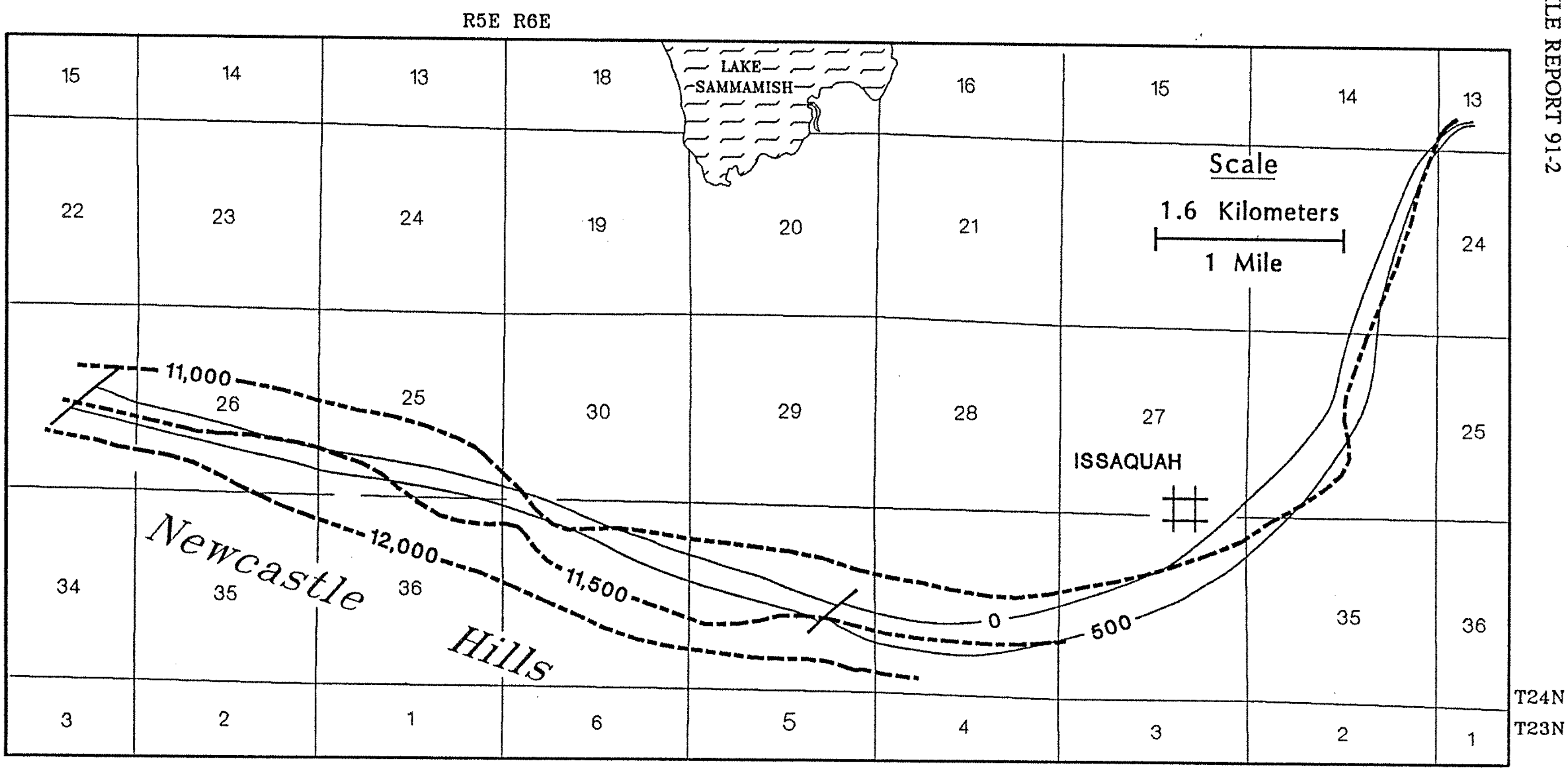

Figure 8. Isorank contours (heavy dashed lines; mmmf-BTU) plotted on structure contours (fine solid lines; in feet) for the Newcastle coalfield of central King County. Structure contours are drawn on the most extensively mined coal seam in the field, the Muldoon. Mine map control from Walsh (1983). All eight of the mined seams are represented in the isorank contours.

Near the Cascade crest, Eocene rocks are thoroughly indurated and have poor reservoir properties. Sandstones in the Columbia Basin, which are derived from extrabasinal rocks, show a linear decrease in porosity and permeability with increasing depth (Bissa 1-29, Yakima Minerals 33-1, and BN 1-9 on Fig. 2). Core analyses from the Squalicum Lake No. 1, the Socal-Whidbey No. 1, the Socal-Schroeder No. 1, and the Jackson Prairie SU 909 Hannum No. 2 (Fig. 2) drilled in the Puget trough, as well as the Voyager Black Diamond 4-13 and the Shell P. C. C. No. 1 drilled in the western Cascade foothills (McFarland, 1983), show no porosity-depth trends above 2,100 m (7,000 ft) depth. Core porosities range from 24 percent to 39 percent in the subbasin depocenters and 5 percent to 22 percent in the western Cascade foothills. Therefore, adequate porosity may be preserved above 1,800 m drilled depth in most of the study area.

These observations suggest that the best prospects are located in the western Cascade foothills, where porosity preservation is coupled with favorable timing of trap development and gas generation. Analogy to the Mist Gas Field, located in a terrain similar to that of the central Puget trough, suggests two models for gas accumulation in the subbasins. Armentrout and Suek (1985) mention possible avenues for migration of deeply generated gas at Mist. Interpretation of reflection seismic profiles (Ise, 1985) suggests that similar migration routes and possible reservoirs may be present below the McIntosh and equivalent sections. The oil show in the Phillips State No. 1 suggests that petroleum has migrated from depth in the east Tacoma subbasin (Brown and Ruth Laboratories, Inc., 1984). Summer and Verosub (1989) suggest that gas at Mist may have formed in response to contact metamorphism and related hydrothermal effects, although strata in the Mist field analyzed to date are submature (Armentrout and Suek, 1985). If, however, Summer and Verosub are correct, areas near depocenters where elevated reflectance values are observed, such as the New Black Diamond mine, may have potential for gas accumulation.

CONCLUSIONS

The constraints imposed by depth of maturation, timing of migration, and reservoir quality suggest that the most prospective areas are at depths less than 2,100 m (7,000 ft) (Fig. 2) and lie between the eastern Puget trough and Cascade foothills where porous and permeable rocks are probably preserved. The most favorable maturation trends within the Eocene rocks of western Washington resulted from thermal overprinting accompanying the Cascade orogen, probably during the Miocene epoch. In the eastern Puget trough and Cascade foothills where thermal overprinting by igneous intrusion is interpreted to have occurred, pre-Miocene structures offer attractive exploration targets. These areas are characterized by coal ranks of high volatile B bituminous or higher, and consequently lie within the peak gas-generative window.

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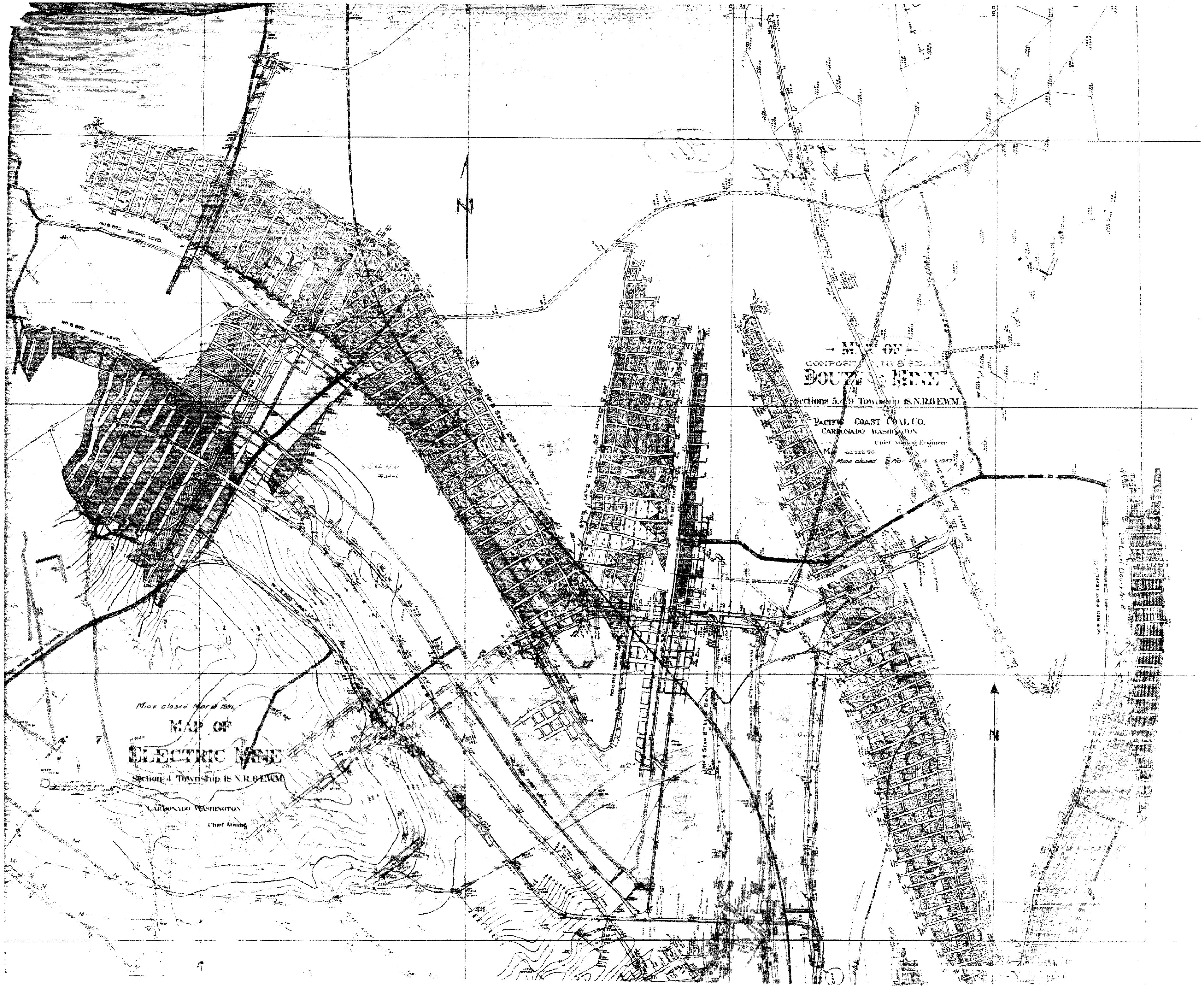

Plate 1. Map of parts of the Electric and Douty mines in the Wilkeson-Carbonado field, T. 18 N., R. 6 E., sec. 4, reproduced from a 1937 blueprint. This map shows two chevron synclines that were extensively mined and an intervening anticline. The grid spacing is 300 m (1,000 ft).