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RANK OF EOCENE COALS IN WESTERN AND CENTRAL WASHINGTON STATE: A REFLECTION OF CASCADE PLUTONISM?

by

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ABSTRACT

Coals ranging in rank from lignite to anthracite are contained in lower to upper Eocene strata of Washington. The coals crop out or are known from mine workings in the eastern and western foothills of the Cascade Mountains. Distribution of coal rank in six coalfields of the region was determined using trend-surface analysis of fixed carbon (dry, mineral-matter free) and BTU (moist, mineral-matter free) data from fresh, underground mine samples. For the Roslyn and Centralia-Chehalis fields, rank data are from single, areally extensive seams. For the Whatcom County, Newcastle, Green River, and Wilkeson-Carbonado fields, data are from stratigraphic sequences up to 1.2 km thick. Results of trend-surface analysis were similar for all fields: coal rank increases systematically toward the crest of the Cascades. On both flanks of the Cascades, zones 15-25 km wide are present in which lateral coal-rank gradients increase sharply toward the mountain crest. Within these zones, coal rank is independent of structural trends and stratigraphic position and rank gradients of up to 1.5% fixed carbon/km are observed.

Patterns of coal rank distribution imply sharply greater burial depths and/or higher geothermal gradients during burial time for Eocene sediments close to the Cascades. From Eocene through Miocene time, the Cascade range was the locus of igneous activity resulting in emplacement of numerous plutons and accumulation of 5-8.5 km of volcanic rocks. We propose that high regional geothermal gradients induced by Eocene-Miocene Cascade plutonism upgraded coal rank throughout much of the coal-bearing Eocene section of western and central Washington, well beyond the previously recognized extent of the Cascade thermal aureole. This model has important implications for fossil fuel exploration and interpretation of fission-track dates in the region.

INTRODUCTION

Coal-bearing rocks of Eocene age occur in both the eastern and western foothills of the Cascade Mountains in Washington State (figure 1). The coals were formed in interdistributary bogs and lakes in a broad, fluvial-deltaic lowland called the Weaver Plain (Mackin and Cary, 1965). The rivers that flowed across the plain emptied into a deep, narrow basin located where the Puget Lowlands exist today. Sporadic episodes of vulcanism deposited locally thick wedges of lahars and andesite flows, as well as numerous thin ash beds in the coal swamps. Throughout Oligocene and Miocene time, numerous Cascade plutons and batholiths intruded the coal-bearing section and covered much of it with their associated volcanic outpourings. In middle Miocene through Pliocene time, voluminous flood basalts poured westward from vents near the Washington-Idaho-Oregon border, lapping up against the then emergent Cascade Mountains. During Pliocene time, the locus of Cascade vulcanism shifted southeastward, continuing through the present. During the Pleistocene, continental glaciers filled Puget Sound and deposited thick till and drift on the western portion of the coal measures. The Eocene coal deposits were left exposed principally in narrow belts on either flank of the Cascade Mountains.

Coal was discovered in Washington as early as 1833 by the Hudson's Bay Company and the first mine was opened at Bellingham Bay in 1854 (Beikman et al, 1961). Eventually, five major coal-bearing areas were discovered and coal mining became a major industry in Washington, almost entirely by underground methods. By the time the last underground coal mine shut down in 1970 approximately 150 million tons had been produced. The advent of cheap oil from California and the switch by railroads to diesel fuel depleted the coal markets. In addition, the

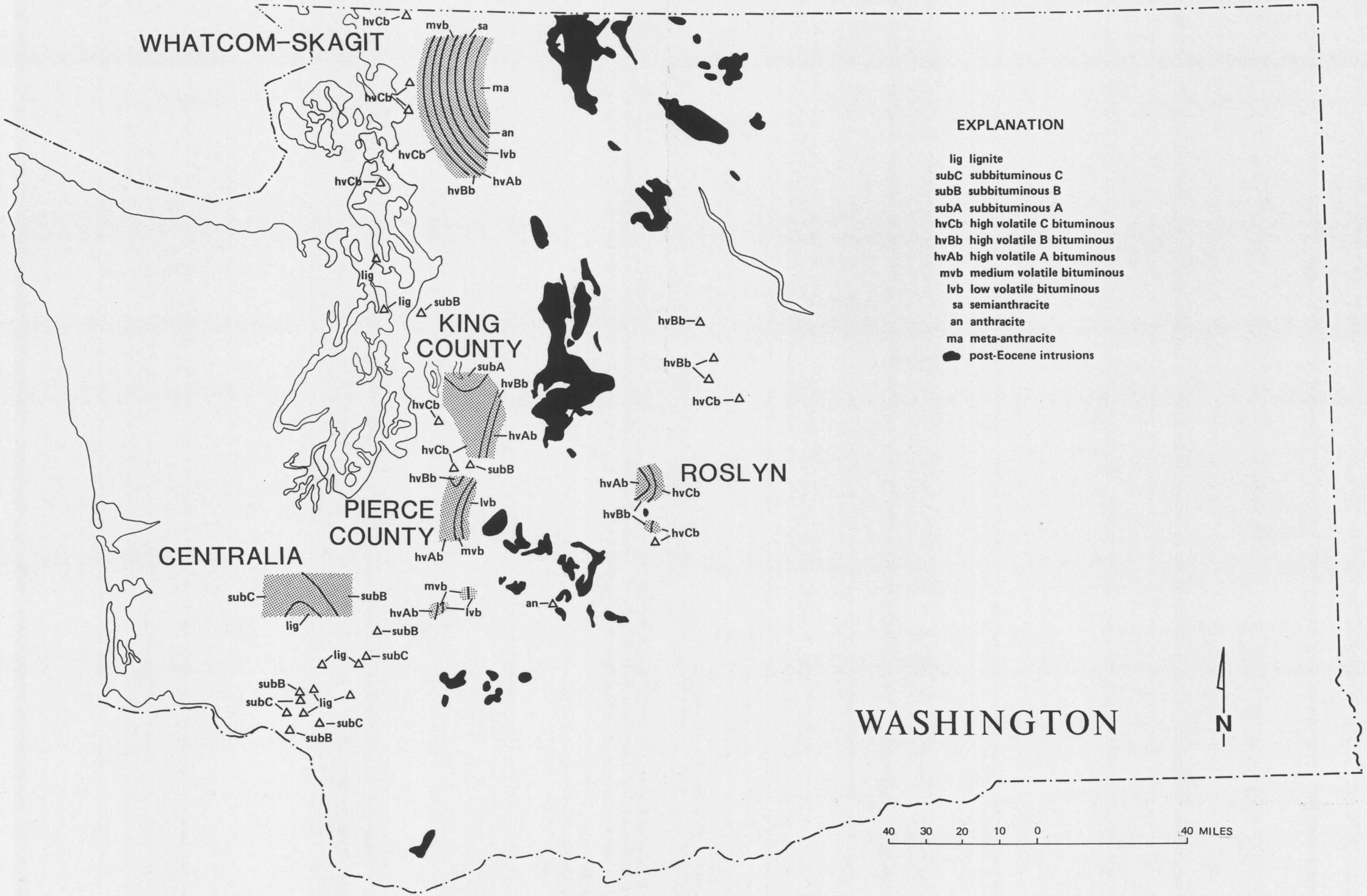

Figure 1. Location of coal-bearing areas discussed in text. Major faults shown by solid lines.

steep pitch of most coal in the state is not amenable to modern mechanized mining techniques. Today only one coal mine remains in the state, the Centralia mine, which is captive to a steam electric plant.

During the mining heyday, U.S. Geological Survey and U.S. Bureau of Mines personnel collected hundreds of face-channel samples from operating coal mines for proximate and ultimate analyses (Daniels et al, 1958; Yancey and Geer, 1941; Fieldner et al, 1931). For each area in which sufficient coal analyses were available, we have modeled the distribution of coal rank calculated according to ASTM standard D388-77, by the method of trend surface analysis. The trend surface program was developed by R. D. LeFever and is patterned after the program in Davis (1973). It is a least squares model which fits polynomial surfaces to map data. The first order surface is planar and is the same as a multiple linear regression with two independent variables. The second order, or quadratic surface, is a simple fold or a saddle; higher order surfaces have progressively more complex geometric forms. The goodness-of-fit is expressed by the percentage of variation explained, which is analagous to the coefficient of determination in linear regression. The significance is expressed as the F-statistic for the order chosen, which is the ratio of the mean squares of the model and the deviation from the model. The degrees of freedom for the model and the deviation, respectively, are given as (df = x/y). All models reported herein are significant at the 99% level.

RESULTS

In Whatcom and Skagit Counties, coal is principally contained in the Chuckanut Formation of early through late Eocene age (Johnson, 1982; Frizzell, 1979). Chuckanut Formation was deposited with profound unconformity on Mesozoic schists and sedimentary rocks (Figure 2). It grades from meandering river facies upward

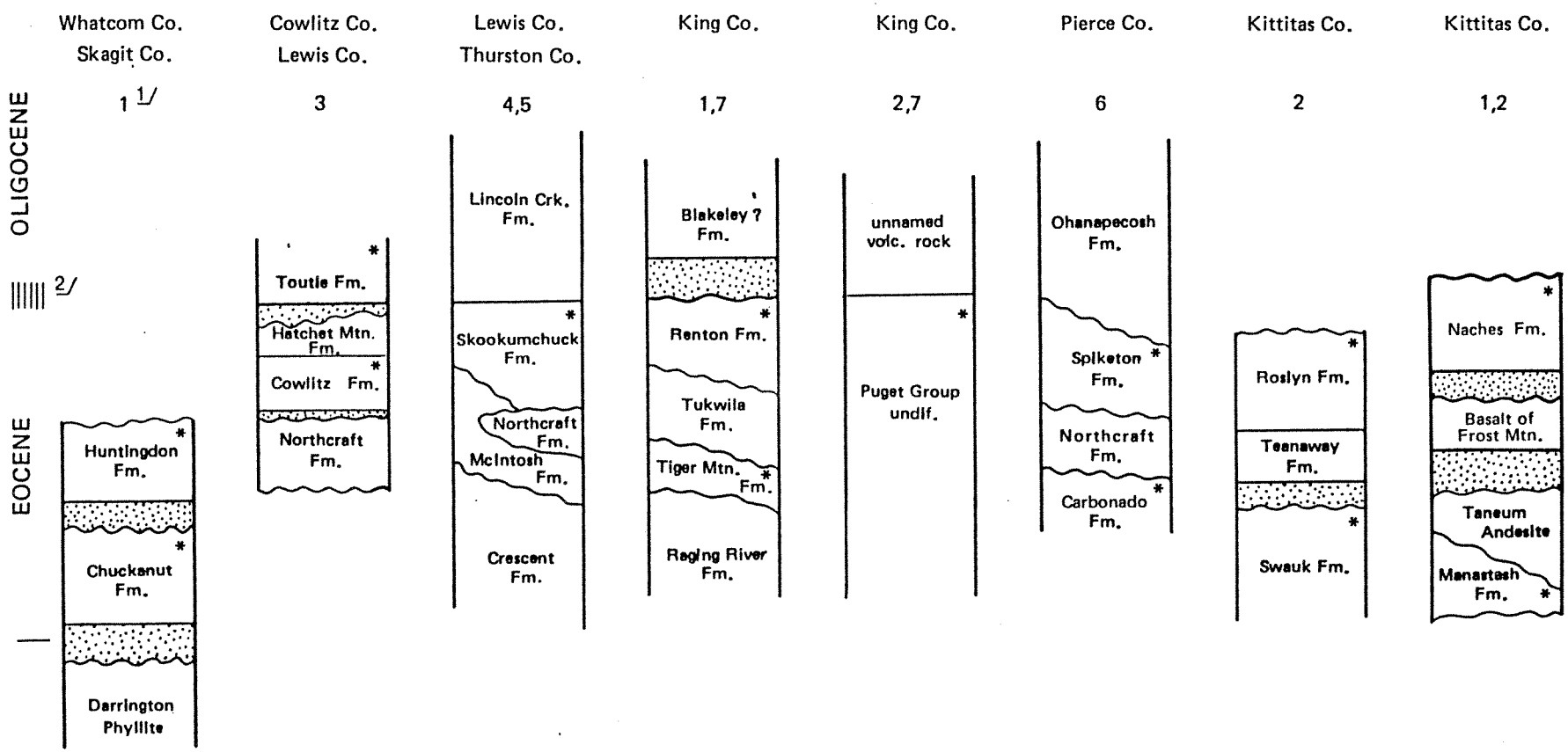

FIGURE 2. – Age and suggested correlations of some lower Tertiary rock units in Washington (asterisks indicate coal-bearing formations; stippled areas represent unconformities).

1/ Each column is modified from the following sources: 1 - Frizzell (1979); 2 - Newman (1981); 3 - Roberts (1958); 4 - Rau (1981); 5 - Snavely and others (1958); 6 - Gard (1968); 7 - Vine (1969).

2/ The broad Eocene-Oligocene boundary represents the evolving views of its placement by the various authors whose conventions are followed in this table.

into braided river and alluvial fan deposits (Johnson, 1982). A much-prospected coal-bearing section called the Blue Canyon Zone (Jenkins, 1923) occurs in the lowermost 1,000 feet of the formation, in the meandering river facies. Johnson (1982) measured a thickness of more than 20,000 feet in this area, which combined with the overlying Huntingdon Formation of at least 1,400 feet (Hopkins, 1966), and yields a burial depth of at least 20,000 feet for Blue Canyon Zone coal.

Trend-surface analysis was performed on 21 coal analyses from the Blue Canyon Zone. The resulting model (Figure 3) satisfied 92% of the total variability in the data with an F-statistic of 29.2 (df = 5/15). The strong easterly gradient is approximately 1.5% Fixed Carbon/km. The rank increases systematically from high volatile B bituminous to anthracite within approximately 15 miles (24 km). Other occurrences of coal farther to the west are approximately 13,000 BTU/lb on a moist, mineral-matter-free basis, which is the boundary between high volatile B and high volatile C bituminous coal. These miscellaneous occurrences of coal were not included in the trend-surface calculation because they occur more than 8,000 feet higher in the section. Extrapolation of the trend to include these coals would correctly classify them, suggesting that burial depth is not the primary factor controlling coal rank. The coal rank contours also bear no obvious relation to structural trends (Figure 4).

In King County, coal is found in the Eocene Puget Group, which is at least 6,000 feet thick (the base is not exposed). In the southern part of the county, the mined coal was all found in the upper 4,000 feet of the section. In the northern part of the field, Puget Group is divisible into three formations (Figure 2), the Tiger Mountain Formation and the Renton Formation, which are fluvio-deltaic, separated by the Tukwila Formation, a wedge-shaped accumulation of lahars, andesite flows, and minor tuffs and sedimentary rocks. The upper unit, the Renton Formation, is approximately 3,000 feet thick, and contains all the

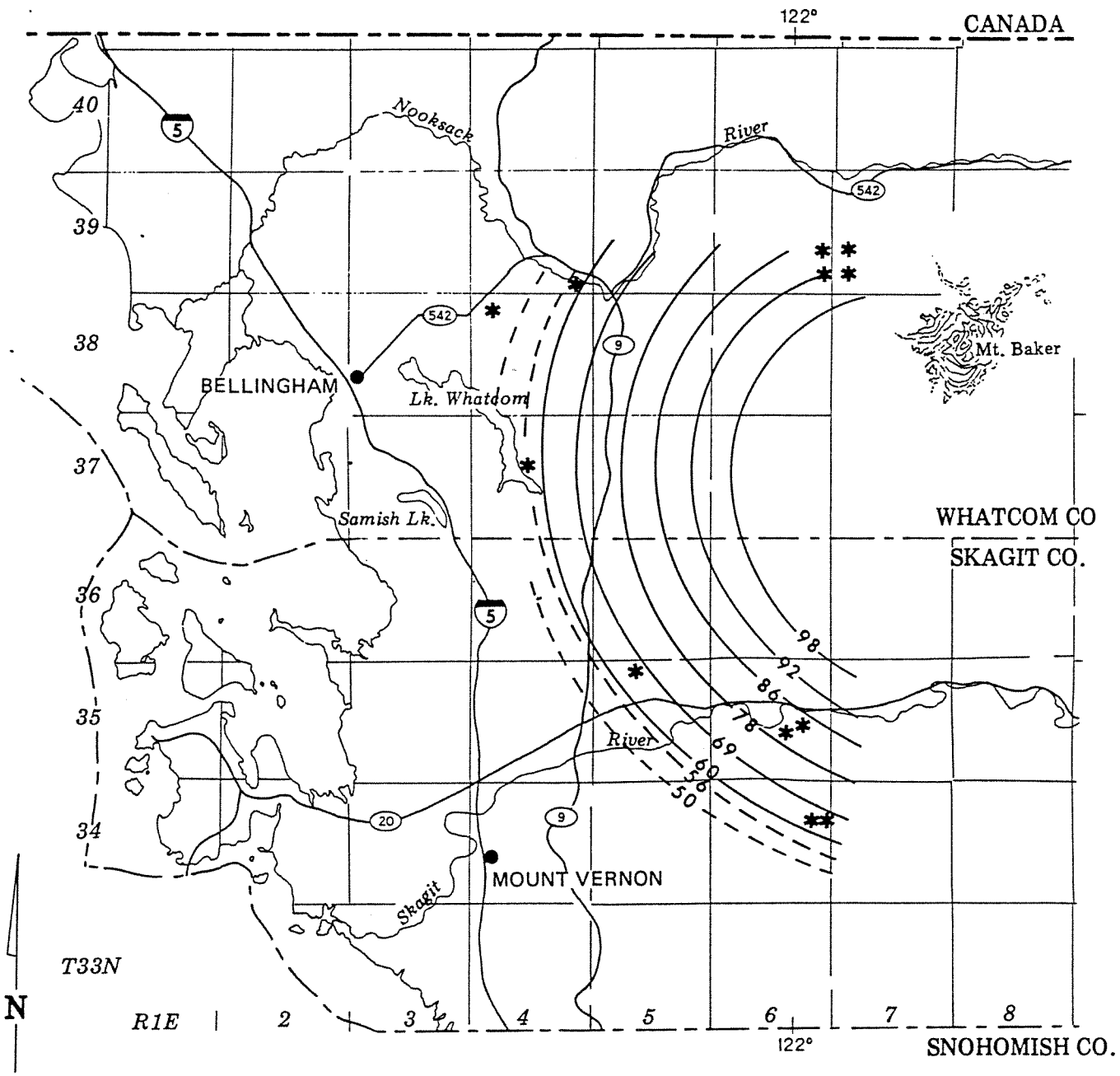

Figure 3. — Second order trend surface model of coal rank distribution in the Whatcom-Skagit study area. Asterisks show location of sampling sites in the Blue Canyon coal zone of the Chuckanut Formation. Contours are labelled with percent fixed carbon on a dry, mineral-matter-free basis. The trend model explains 92.4% of the total sample variance. F-statistic is 29.2 (df = 5/15).

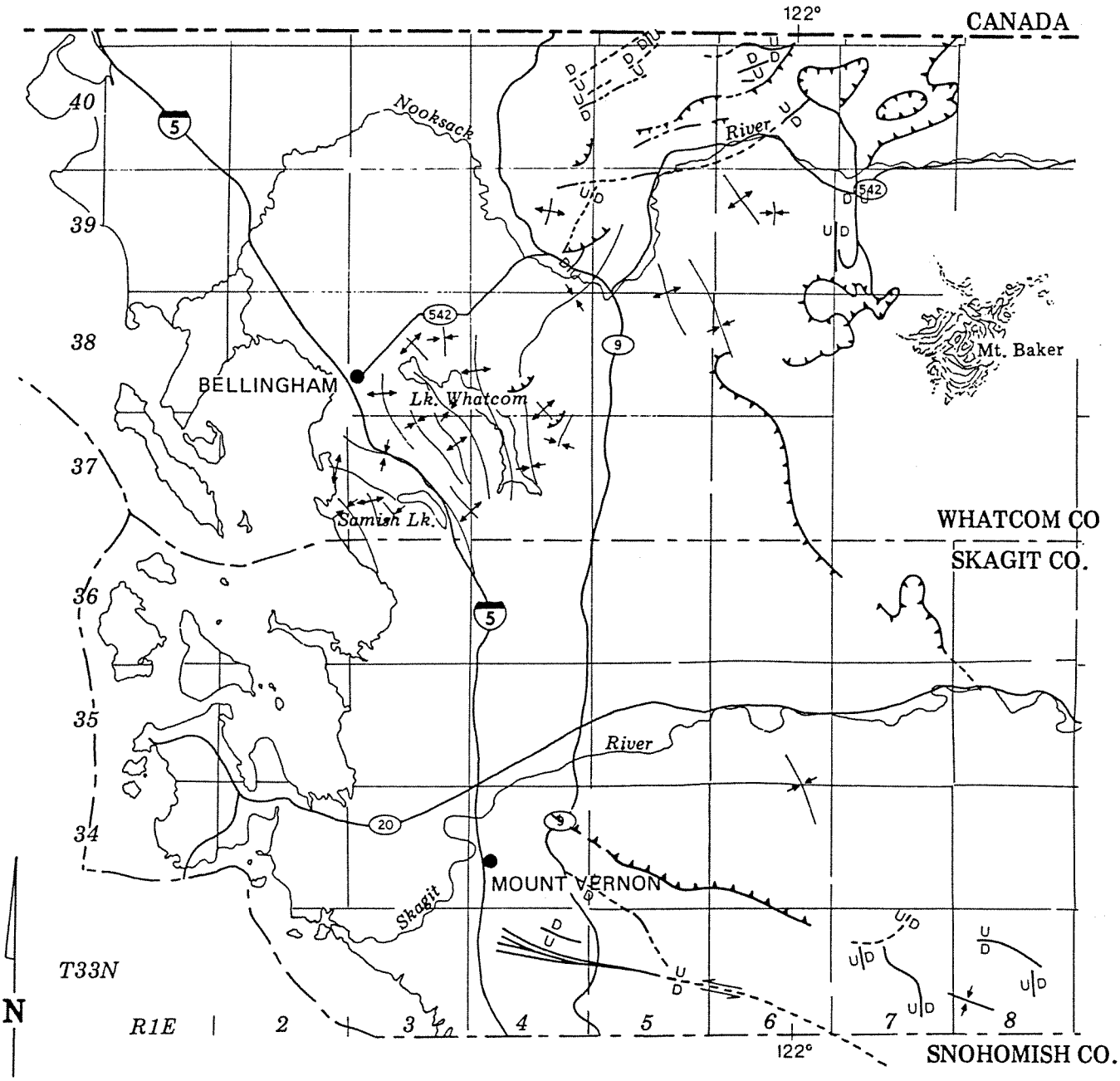

Figure 4. — Map of the Whatcom-Skagit study area showing generalized structural features, from Gower, 1978.

coal that was mined in the northern part of the King County coalfields. To the east, the Puget Group was covered by approximately 5,000 feet of epiclastic volcanic rocks with subordinate flows, ashfalls, and sediment (Vine, 1969). To the west, these rocks interfinger with conglomerates, tuffs, tuffaceous sandstones, and shales which are at least 4,000 feet thick, and may be as much as 8,000 feet thick (Warren et al, 1945).

The trend-surface analysis for King County was performed on 255 sample analyses from the Renton Formation and from the undifferentiated Puget Group. Because of uncertainties in location and the large number of samples, coals were only located to 1/4 section accuracy, so that as many as 10 samples have the same location. A total of 79 unique locations are represented. The trend-surface model portrayed here (Figure 5) is the third order surface. It satisfied 66.4% of the variability and had an F-statistic of 53.7 (df = 9/245). The rather low percent variation explained is apparently due to the variability built in by so many overlapping locations. As in Whatcom-Skagit Counties, coal rank shows a pronounced positive gradient toward the Cascade Mountains, and the gradient is oblique to structural trends (Figure 6).

In Pierce County (Figure 1), coal is also found in rocks of the Puget Group. As in northern King County, Puget Group is divisible into lower and upper coal-bearing deltaic sequences separated by a wedge of volcanic rocks (Figure 2). All of the coal examined here occurs in a 2,000 foot thick sequence of Carbonado Formation, the lowermost unit of the Puget Group in Pierce County (Beikman et al, 1961). This sequence is overlain by 2,000 feet of non-coal-bearing Carbonado Formation, approximately 1,000 feet of Northcraft Formation, 3,600 feet of Spiketon Formation (the upper sedimentary unit), and 5,500 feet of Ohanapecosh Formation, an Oligocene volcanic unit (Gard, 1968).

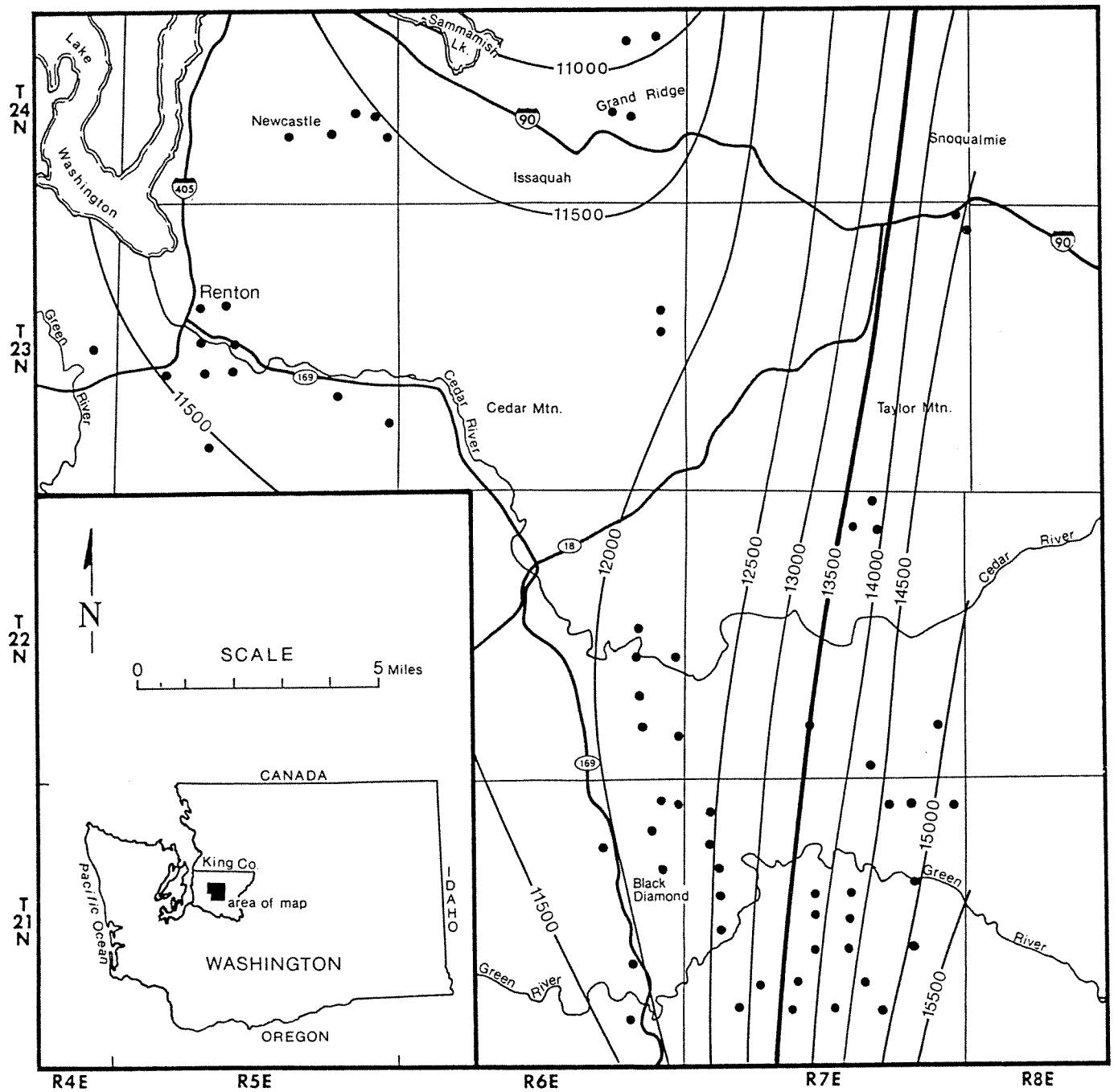

Figure 5. — Third-order trend-surface model of coal-rank distribution in the King County study area. Dots show location of sampling sites in the Puget Group. Contours are labeled with B.T.U. on a moist, mineral-matter free basis. The trend model explains 66.4% of the total sample variance. F-statistic is 53.7 (df = 9/245).

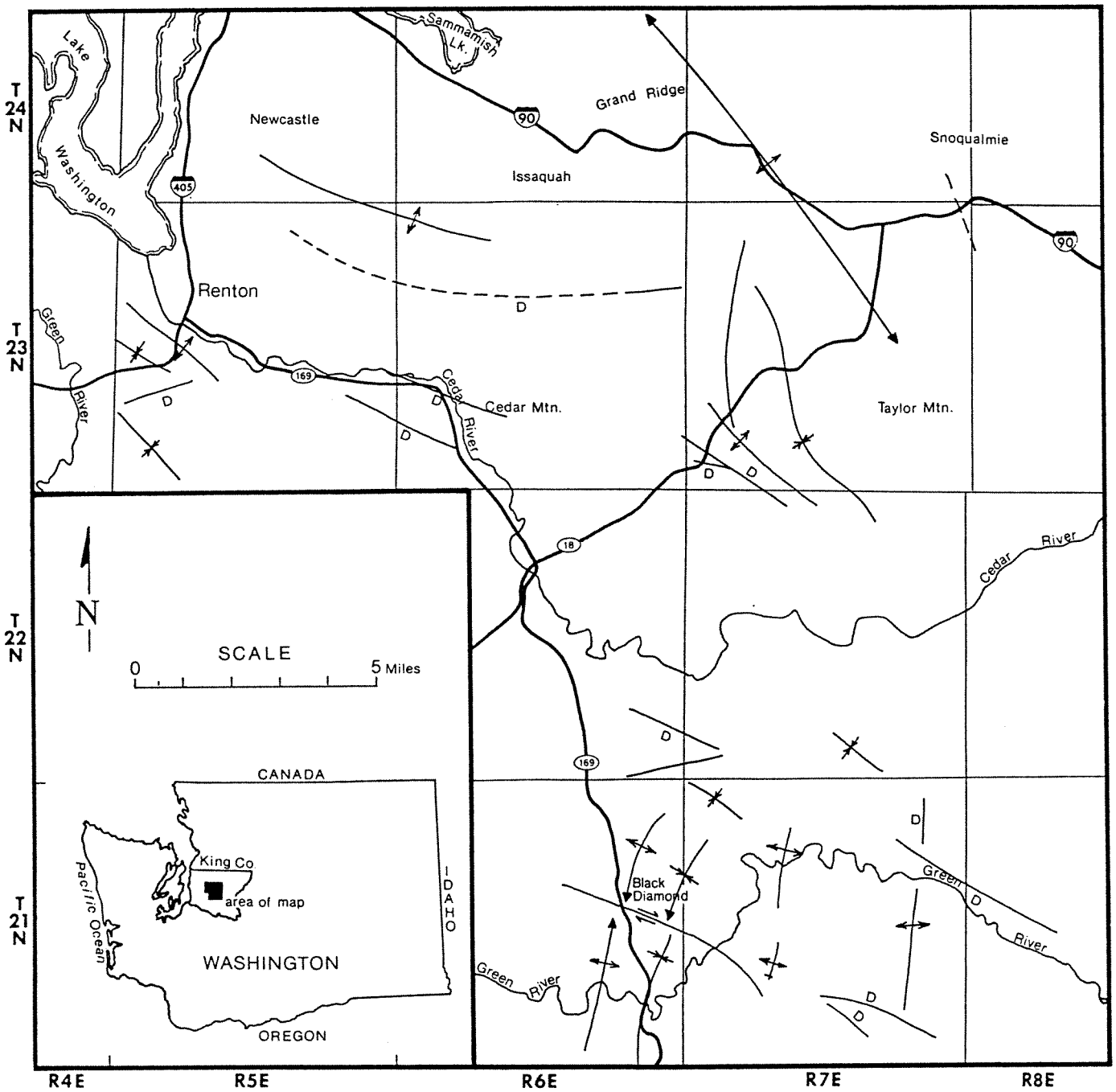

Figure 6. — Map of the King County study area showing generalized structural features (after Walsh and Phillips, 1982).

The trend-surface analysis for Pierce County was performed on 65 samples from the Carbonado Formation. Coal samples from this area but geographically removed from the main portion of the field were excluded to avoid patchiness of the data. The trend-surface shown here, the third order, satisfied 91.3% of the variation in the data, with an F-statistic of 64.1 (df = 9/55). (Figure 7). As in the preceding cases, the trend-surface shows a steep gradient toward the Cascades and is oblique to structural trends (Figure 8).

In the Centralia field (Figure 1), coal occurs in the Skookumchuck Formation of late Eocene age. Skookumchuck Formation overlies the volcanic rocks of Northcraft Formation and is therefore considered correlative with the Spiketon Formation of Pierce County, and is the uppermost unit of the Puget Group in southwest Washington. The Centralia field is farther west than the other fields, and so is more removed from the Cascade axis. There is no evidence that it was ever covered by Ohanapecosh Formation. It was, however, probably not buried by much more than 1,000 feet of Oligocene Lincoln Creek Formation (Rau, personal communication). Portions of the field may also have been covered by relatively thin Quaternary units. Trend-surface analysis in the Centralia field was performed on a single, areally extensive coal seam, as correlated by Snavely et al (1959). This seam, the Tono No. 1, lies within 200 feet of the top of the Skookumchuck Formation, and so was probably never more deeply buried than 1,500 feet. Trend-surface analysis was performed on 48 samples of Tono No. 1 and satisfied 82% of the variation with an F-statistic of 38.2 (df = 5/42) (Figure 9). In contrast to the fields previously examined, the rank gradient, which increases toward the Cascades, is roughly parallel to structural trends (Figure 10), although it is not clearly related to structure.

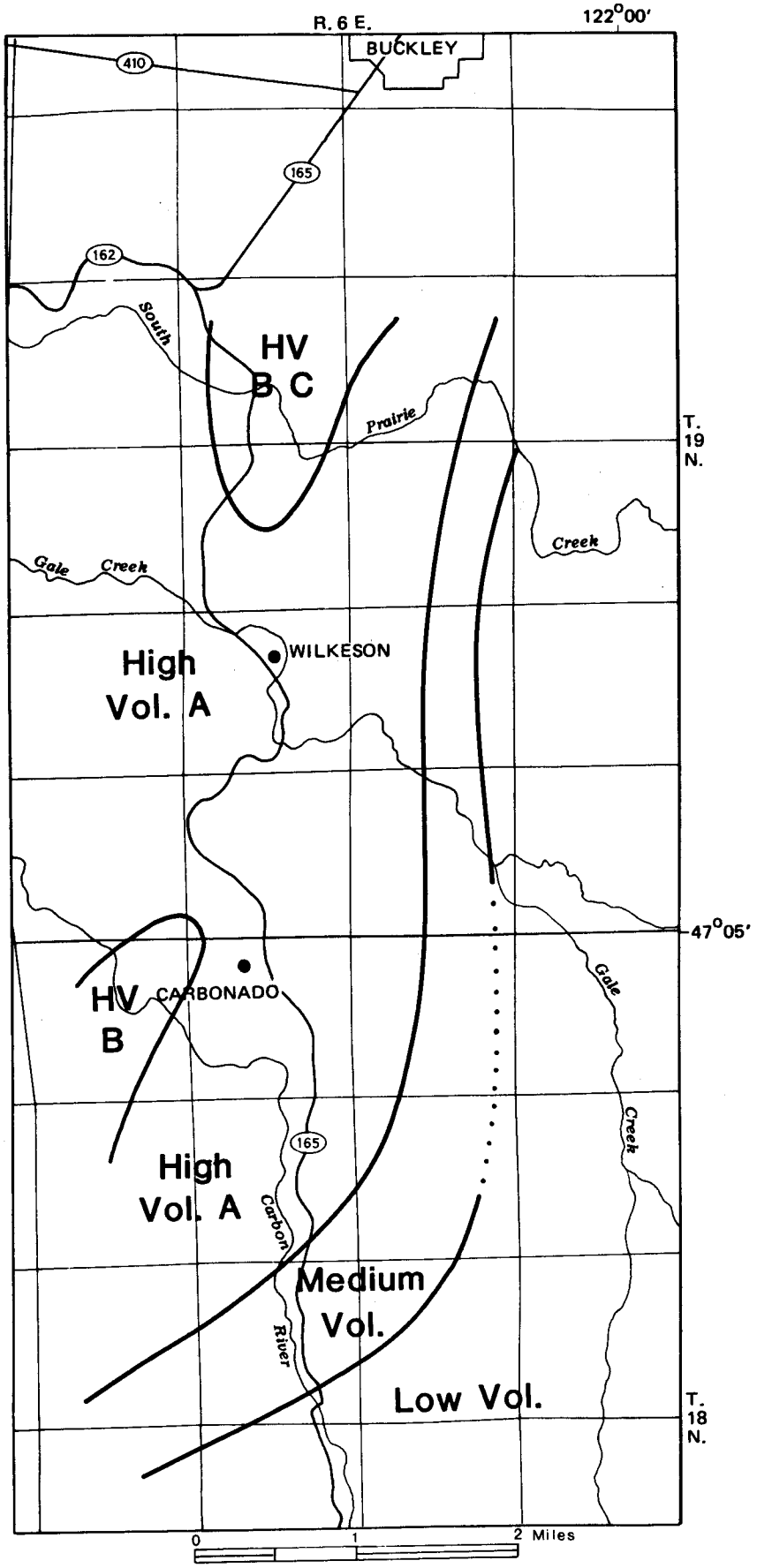

Figure 7. — Third-order trend-surface model of coal-rank distribution in the Pierce County study area. Data from coal samples contained in the Carbonado Formation of the Puget Group. The trend model explains 91.3% of the total sample variatio F-statistic is 64.1 (df = 9/55), HVBC denotes ASTM rank class high volatile B and C bituminous coal. High Vol. A denotes ASTM rank class high volatile A bituminous coal. Medium and Low Vol. denotes ASTM rank class medium and low volatile bituminous coal, respectively.

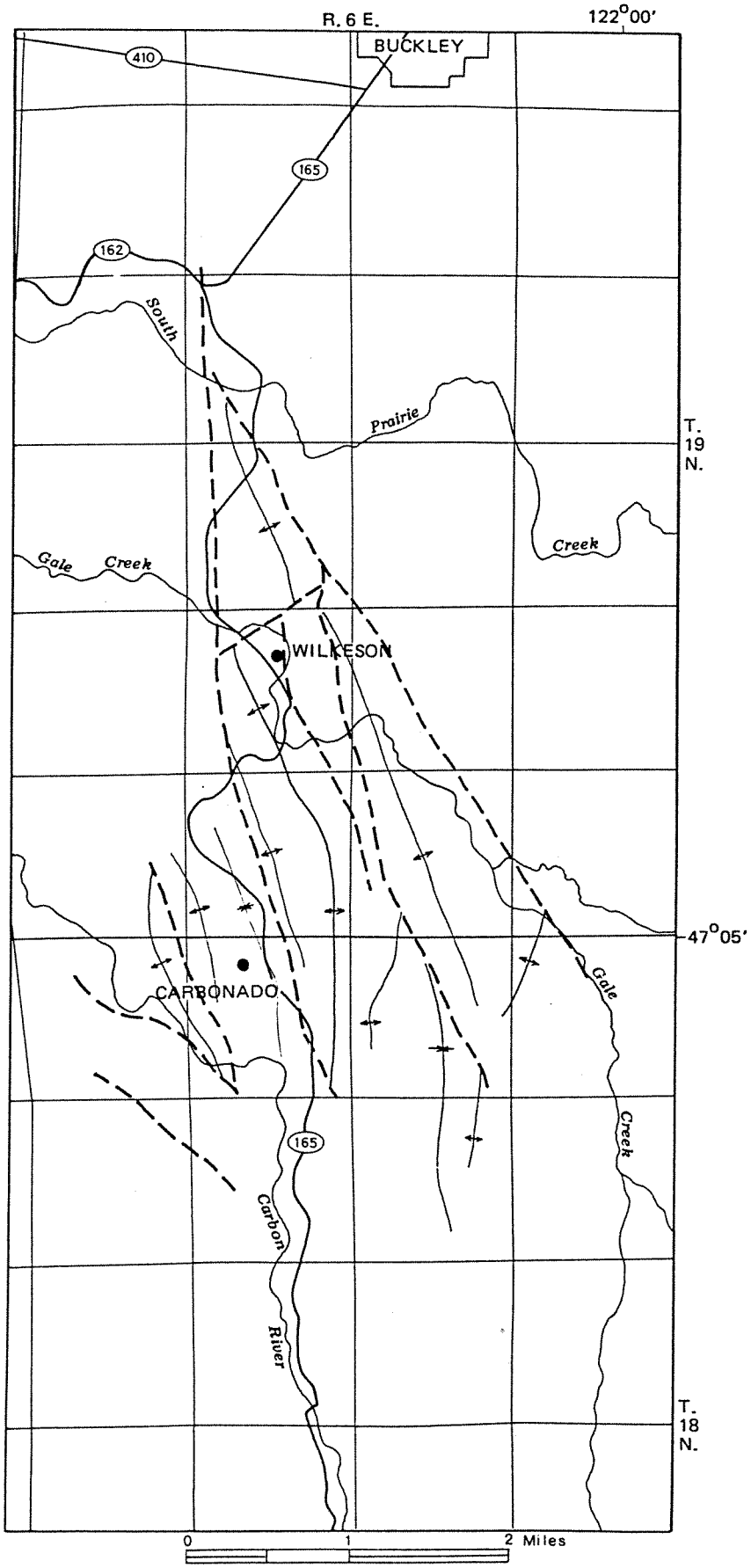

Figure 8. — Map of the Pierce County study area showing generalized structural features. From Beikman et al, 1961.

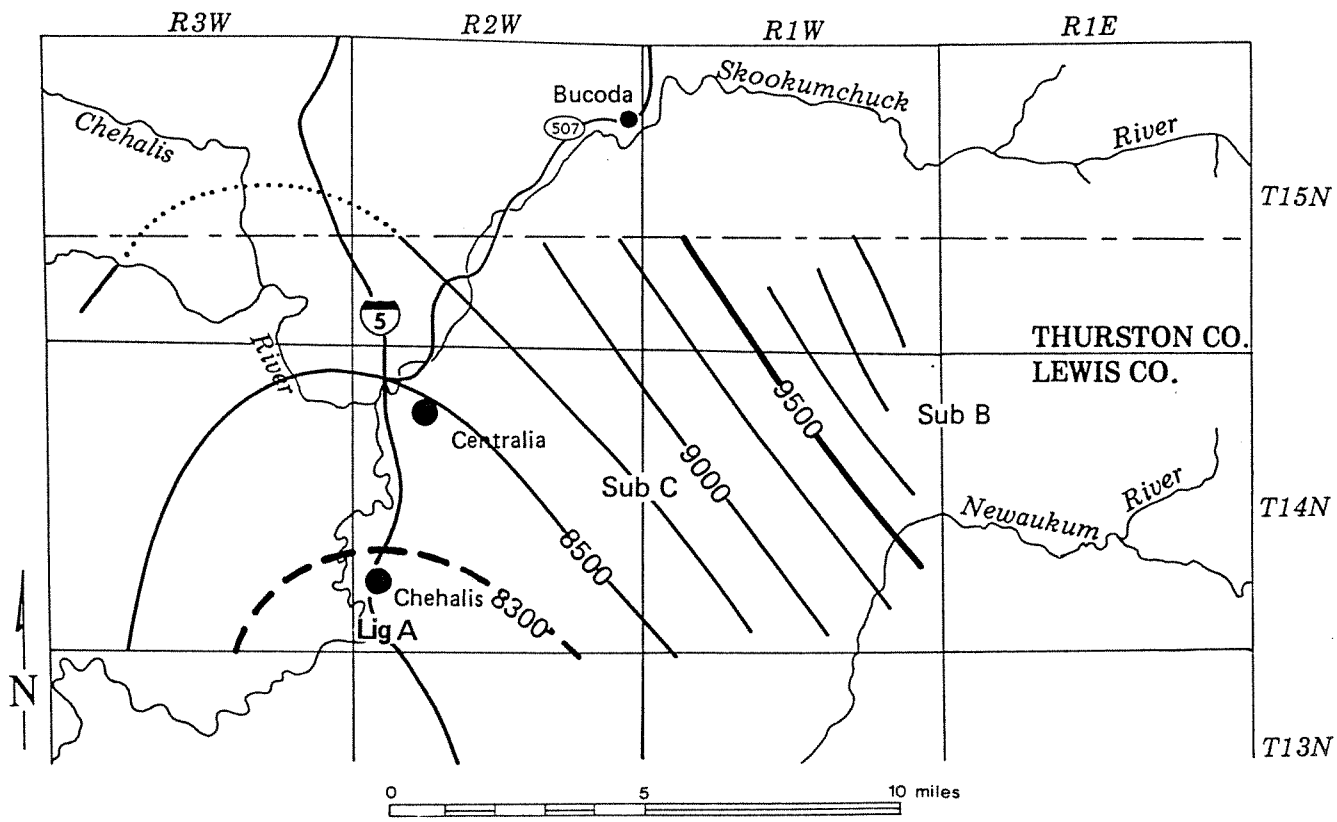

Figure 9. — Second-order trend-surface model of coal-rank distribution in the Centralia study area. Data from the Tono No. 1 seam of the Skookumchuck Formation. Contours are labeled with B.T.U. values on a moist, mineral-matter-free basis. Sub B denotes ASTM rank class sub-bituminous B. The trend model explains 82% of the total sample variation. F-statistic is 38.2 (df = 5/42).

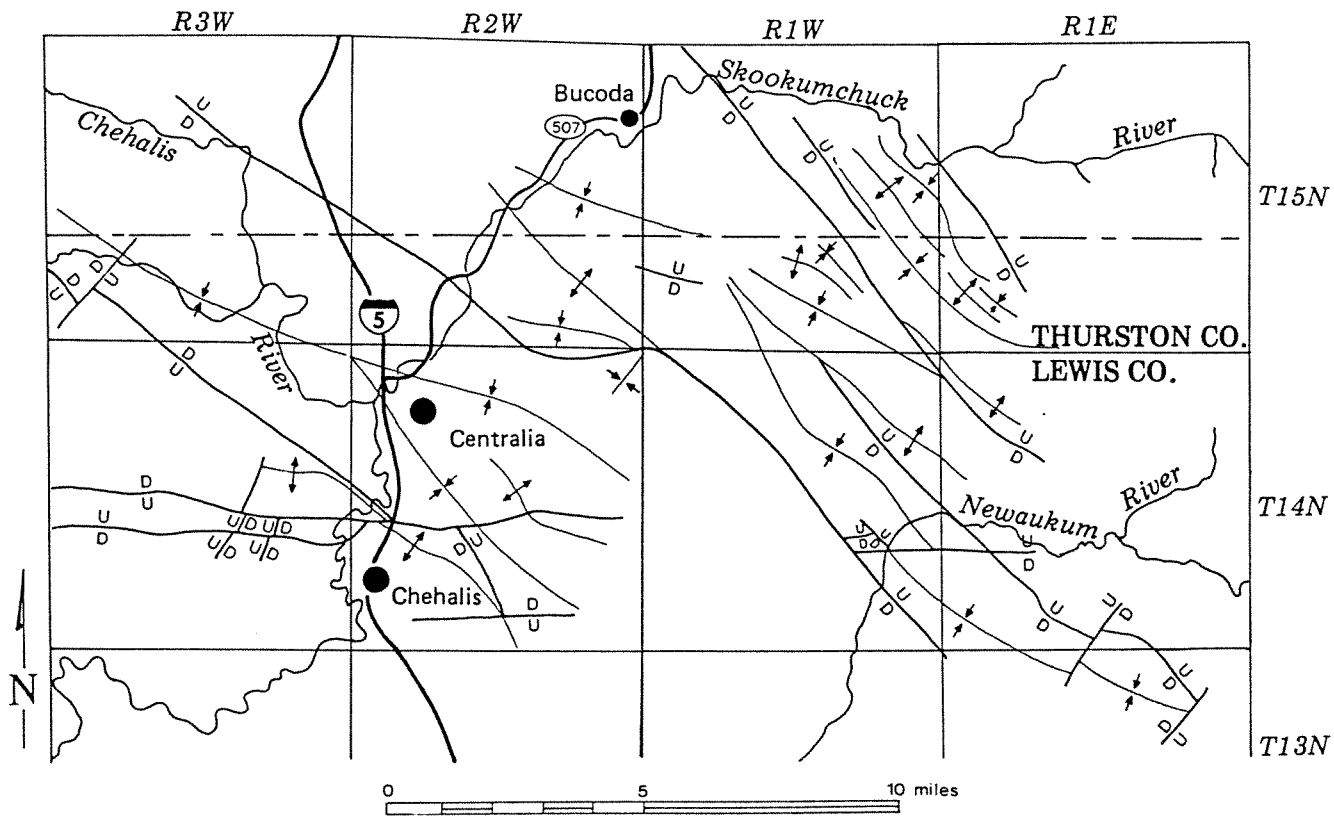

Figure 10. — Map of the Centralia study area showing generalized structural features. From Beikman et al, 1961.

The final major coalfield in Washington is the Roslyn field in the eastern foothills of the Cascades. The coal occurs in the upper 2,500 feet of the Roslyn Formation of Late Eocene age. As in the Centralia field, the coal-rank analysis was performed on a single, areally extensive seam, the Roslyn No. 5. The Roslyn No. 5 was covered by at least 1,700 feet of Roslyn Formation (Walker, 1980), and probably was also covered by approximately 500 feet of Yakima Basalt. The trend-surface analysis was performed on 45 samples. The second-order surface (Figure 11) satisfied 88.7% of the variation and had an F-statistic of 61.3 (df = 5/39). In this field, as at Centralia, the coal rank trends are subparallel to the structural trends (Figure 12), but are not easily explained by them.

CONCLUSIONS

The strong gradients of coal-rank imply sharply greater heating of the coal toward the Cascade crest (Teichmuller and Teichmuller, 1968). While more rapid subsidence and subsequent greater depth of burial in the Cascade region could account for the observed pattern, stratigraphic evidence does not support such an occurrence. The overburden on the coal measures has not been observed to thicken toward the Cascades within the area of this study. An alternative explanation is that geothermal gradients increased sharply toward the Cascades through much of Tertiary time. Hartman (1973) documented steep gradients of low grade metamorphic isograds that were discordant to the strata in the Greenwater River area, which is 10 to 20 miles east of the Pierce County coal area. He attributed these gradients to Miocene granitic intrusives in that area.

We propose that high regional geothermal gradients induced by Eocene to Miocene Cascade plutonism upgraded coal rank throughout the coal-bearing Eocene

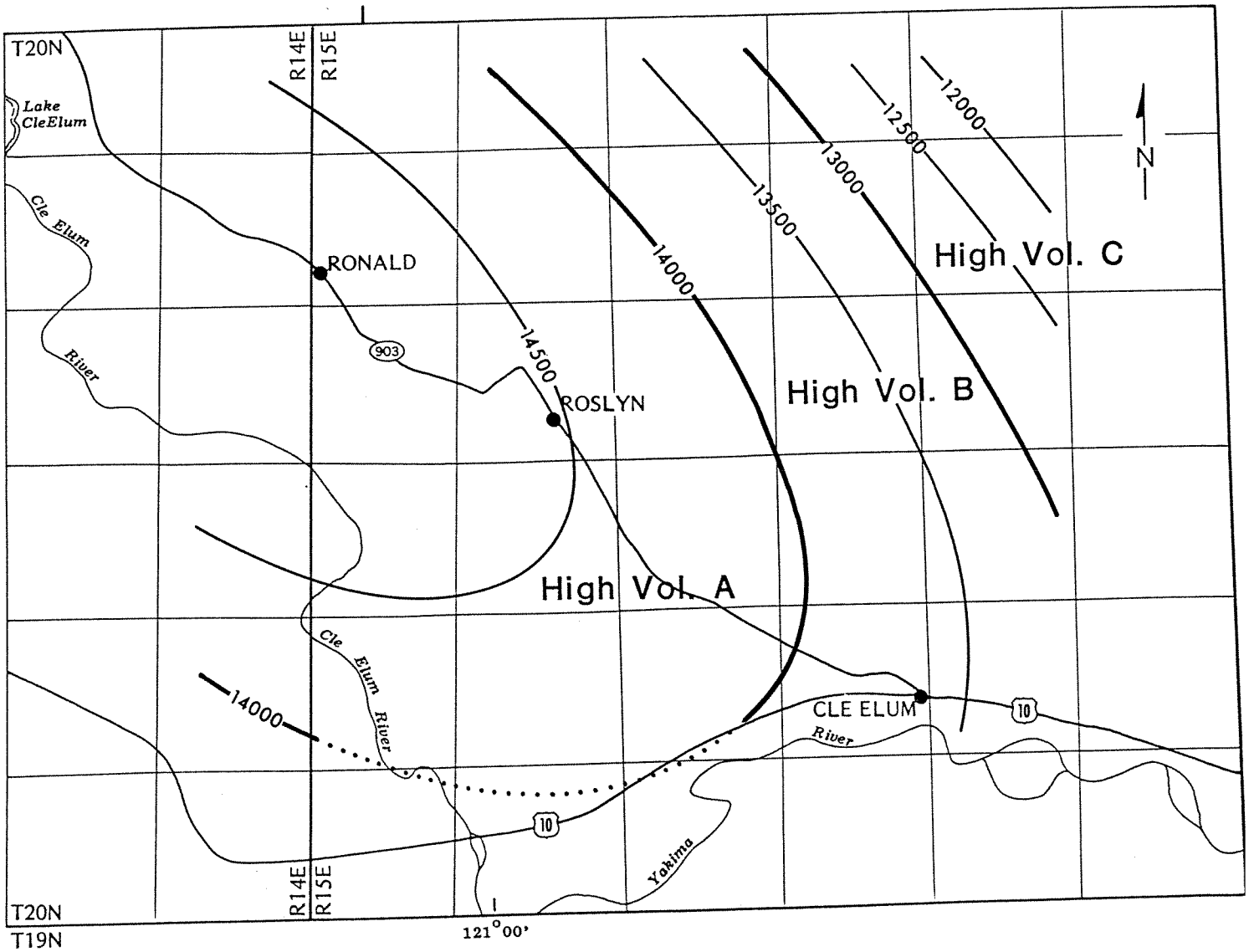

Figure 11. — Second-order trend-surface model of coal rank distribution in the Roslyn study area. Data from the Roslyn No. 5 seam of the Roslyn Formation. Contours are labeled with B.T.U. values on a moist, mineral-matter-free basis. The trend model explains 88.7% of the total sample variance. F-statistic is 61.3 (df = 5/39). High Vol. A, High Vol. B, and High Vol. C refer to ASTM high volume A, B, and C bituminous coal-rank classes.

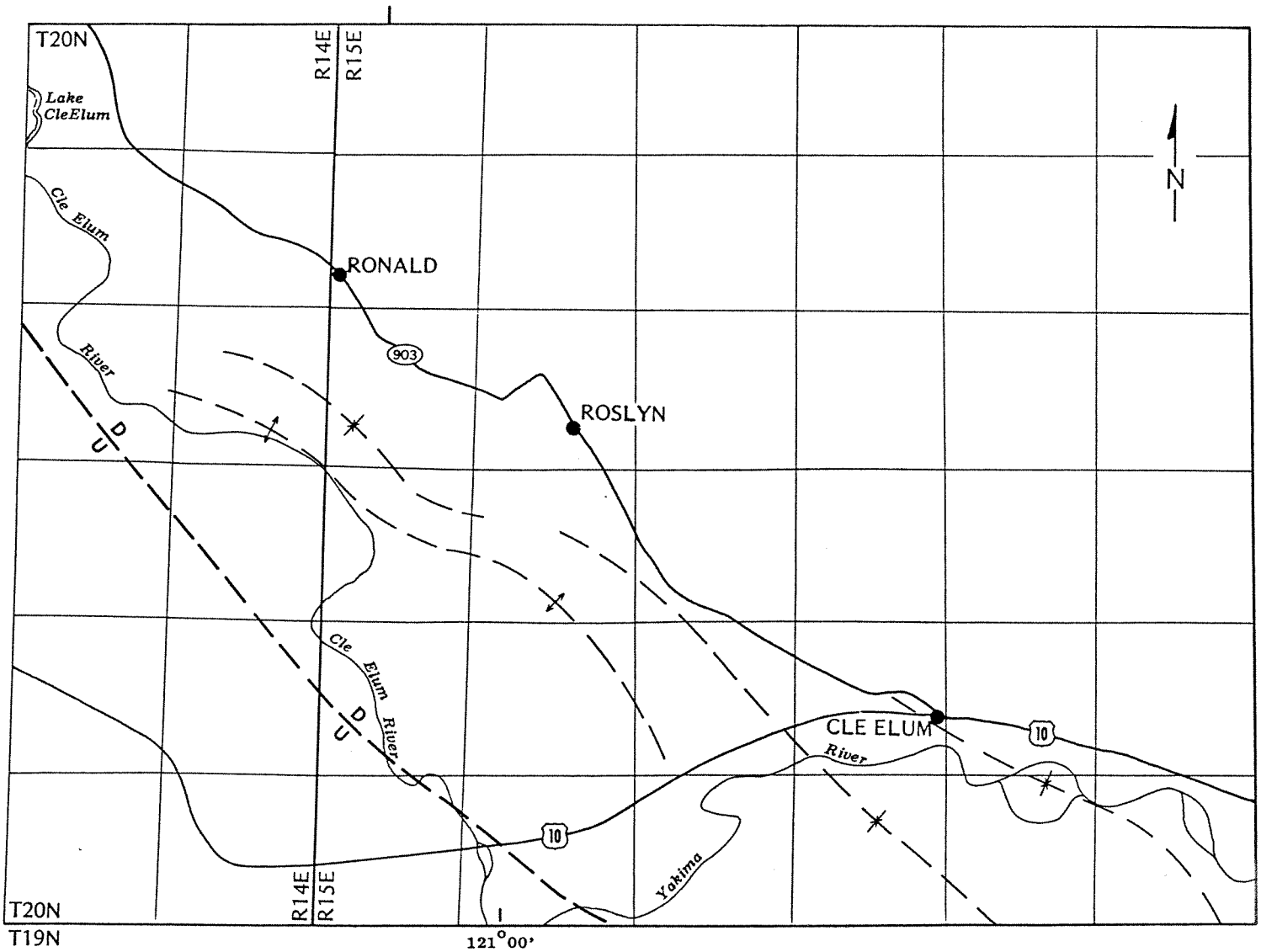

Figure 12. — Map of the Roslyn study area showing generalized structural features. From Beikman et al, 1961.

section of western and central Washington. The coal-rank contours are roughly parallel to the Tertiary plutons and are apparently affected by plutons for a distance of at least 40 miles (65 km), well beyond any previously recognized Cascade thermal aureole. Because oil and gas accumulations are produced by thermal metamorphism, coal-rank patterns can be useful in predicting the type of hydrocarbon that might be present in an oil or gas reservoir (see, for instance, Bostick and Damberger, 1971; Staplin, 1969; Walsh and Phillips, 1982).

Furthermore, because the coal-rank gradients imply higher geothermal gradients in the past, caution is in order in the interpretation of radiometric dates which may have been close to closing temperatures during the Cascade orogeny (see, for instance, Naeser, 1979).

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