Chemical Analyses of Middle and Upper Pennsylvanian Coals from Southeastern Kansas

Lawrence L. Brady[1] and Joseph R. Hatch[2]

[1]Kansas Geological Survey, 1930 Constant Avenue, Lawrence, KS 66047-3726

[2]U.S. Geological Survey, Box 25046, MS 939, Denver Federal Center, Denver, CO 80225-0046

Abstract

Elemental and chemical analyses and physical tests were conducted on 36 samples of Middle and Upper Pennsylvanian coals from southeastern Kansas. Concentrations of 35 minor and trace elements in these coals were statistically compared with concentrations in coals of similar rank and age from other areas in the western region of the Interior Coal Province, showing that Kansas coals have significantly higher concentrations of copper, arsenic, and lead. The zinc content in Kansas coal samples ranges from 160 to 51,000 ppm (whole-coal basis), the maximum value being the highest zinc value reported for U.S. coals. Cadmium content also has an extreme range, from less than 1.0 to 160 ppm (whole-coal basis), the maximum value being one of the highest cadmium values reported in U.S. coals. The apparent ranks of these coal samples range from high-volatile B to high-volatile A bituminous coal. Most samples of Middle Pennsylvanian coals from the major coal-mining area in Bourbon, Crawford, and Cherokee counties are high-volatile A bituminous coal. Arithmetic mean values for proximate analyses of coals (as-received basis; n = 25) show these coals to be 15.5% ash, 35.3% volatile matter, 45.9% fixed carbon, and 3.3% moisture and to have a heat of combustion of 11,910 Btu/lb. Arithmetic mean values for ultimate analyses of the coals show these coals to be 4.9% percent hydrogen, 65.3% carbon, 1.2% nitrogen, 5.5% sulfur, and 7.7% oxygen. The geometric mean values of these Kansas coals are 3.03% pyritic sulfur, 1.25% organic sulfur, and 0.2% sulfate sulfur.

Kansas coal has been an important contributor to the heat and power generation required by the developing Kansas economy. Commercial production of coal in Kansas started in the 1850's with the first shallow mines near Fort Leavenworth in Leavenworth County (Schoewe, 1958, p. 369–371). Subsequent development of coal mines in eastern Kansas has resulted in total historic bituminous coal production of slightly over 300 million tons through 1996. Most of this production was from the Weir-Pittsburg coal bed that was deep-mined in Cherokee and Crawford counties. Kansas coal production was highest in 1917 and 1918 when approximately 7.25 million tons were produced annually. Since those early days, coal production has declined to a low of 232 thousand tons in 1996 (based on production figures from the Mining Section, Kansas Department of Health and Environment). Kansas coal production reached 2.02 million tons in 1987 for a recent high, but production declines since that time are due mainly to recent Environmental Protection Agency standards for SO_2 emissions and the subsequent import of Wyoming coal into Kansas.

The U.S. Geological Survey, with cooperation from state governments and industry, has made characterization of the chemical composition of coal a significant part of the assessment of the nation's coal resources. The Kansas Geological Survey contributed to this program by collecting 36 samples of Middle and Upper Pennsylvanian coals between 1974 and 1977 from Franklin, Wilson, Bourbon, Crawford, and Cherokee counties. These samples are representative of nine Kansas coal beds that are presently mined or were mined in the recent past (table 1). Thirty-one of these samples were collected from active mines, one from a construction excavation, and four samples are from mine tipples after coal cleaning. The information from the chemical and physical tests helps to characterize the most important coal beds with significant reserves remaining in the state.

Stratigraphic distribution of Kansas coals

A generalized stratigraphic distribution of the bituminous coals in Kansas is shown in fig. 1, whereas areal distribution of the strippable Pennsylvanian coals by group is shown in fig. 2. The general distribution of Pennsylvanian coal in Kansas relative to the coal areas of the western and the eastern regions of the Interior Coal Province is shown in fig. 3. Coal from the Middle Pennsylvanian (Desmoinesian) Cherokee Group (including the nine coals

TABLE 1—Location and identification of coal samples.

Sample no.	County	Location	Bed	Bed thickness	Sample type (inches)
D176058	Franklin	NW sec 30, T18S, R18E	U. Williamsburg	12	Grab (5” thick)
D176055	Wilson	SW sec 21, T29S, R17E	Thayer	10	Channel (upper bed)
D176056	Wilson	SW sec 21, T29S, R17E	Thayer	11	Channel (upper bed)
D176057	Wilson	SW sec 21, T29S, R17E	Thayer	5	Channel (lower bed)
D189091	Bourbon	SE sec 26, T26S, R25E	Mulky	14	Channel (lower bed)
D189704	Bourbon	SE sec 26, T26S, R25E	Mulky	14	Channel (lower bed)
D189705	Bourbon	SE sec 26, T26S, R25E	Mulky	14	Channel (lower bed)
D196196	Bourbon	NW sec 28, T26S, R25E	Mulky	14	Channel (lower bed)
D196197	Bourbon	NW sec 28, T26S, R25E	Mulky	13	Channel (lower bed)
D196198	Crawford	SE sec 2, T31S, R22E	Bevier	18	Channel (lower bed)
D196199	Crawford	SE sec 2, T31S, R22E	Bevier	13	Channel (lower bed)
D183114	Bourbon	SW sec 25, T26S, R25E	Croweburg	14	Channel (lower bed)
D183115	Crawford	NE sec 16, T28S, R25E	Croweburg	14	Channel (lower bed)
D176045	Crawford	SW sec 5, T28S, R25E	Croweburg	12	Channel (lower bed)
D176046	Crawford	SW sec 5, T28S, R25E	Croweburg	13	Channel (lower bed)
D176047	Crawford	SW sec 5, T28S, R25E	Croweburg	11	Channel (lower bed)
D183120	Crawford	NE sec 16, T28S, R25E	Croweburg	—	Tipple
D183112	Bourbon	SW sec 25, T26S, R25E	Mineral	16	Channel
D183113	Bourbon	SW sec 25, T26S, R25E	Mineral	15	Channel
D176048	Crawford	NW sec 15, T28S, R25E	Mineral	17	Channel
D176049	Crawford	NW sec 15, T28S, R25E	Mineral	17	Channel
D183116	Crawford	NE sec 16, T28S, R25E	Mineral	16	Channel
D183119	Crawford	NE sec 16, T28S, R25E	Mineral	—	Tipple
D180072	Crawford	SE sec 10, T31S, R25E	Dry Wood	12	Channel
D180074	Crawford	SW sec 11, T31S, R25E	Dry Wood	12	Channel
D183118	Crawford	sec 10-11, T31S, R25E	Dry Wood	—	Tipple
D176050	Crawford	NE sec 10, T31S, R25E	Rowe	18	Channel
D176051	Crawford	NE sec 10, T31S, R25E	Rowe	18	Channel
D176052	Crawford	NE sec 10, T31S, R25E	Rowe	20	Channel
D180069	Crawford	SE sec 10, T31S, R25E	Rowe	18	Channel
D180071	Crawford	SE sec 10, T31S, R25E	Rowe	17	Channel
D180073	Crawford	SE sec 11, T31S, R25E	Rowe	16	Channel
D183117	Crawford	sec 10-11, T31S, R25E	Rowe	—	Tipple
D189706	Cherokee	NW sec 18, T32S, R25E	Rowe	12	Channel
D176053	Cherokee	NW sec 20, T32S, R25E	Unnamed	14	Channel
D176054	Cherokee	NW sec 20, T32S, R25E	Unnamed	14	Channel

sampled for this study plus the Weir-Pittsburg and Fleming coals) represents 90% of the historical production in Kansas. Stratigraphic descriptions of the important coal beds in the Cherokee Group are to be found in Pierce and Courtier (1938), Howe (1956), and Brady et al. (1976). Past production from the Middle Pennsylvanian (Desmoinesian) Marmaton Group (Mulberry coal) represents about 5% of the state’s production, and coals in the Upper Pennsylvanian (Virgilian) Wabaunsee Group (mainly the Nodaway coal) account for nearly 4%. Production from the Upper Pennsylvanian (Missourian) Kansas City Group (mainly Thayer coal), the Upper Pennsylvanian (Virgilian) Douglas Group (mainly Williamsburg coals), and the Early Cretaceous lignites of the Dakota Formation together represent less than 1% of cumulative Kansas coal production.

Brady et al. (1976) estimated strippable coal resources of 2.8 billion tons in 17 different Middle and Upper Pennsylvanian coals; Brady and Livingston (1989) and Brady (1990) estimated deep coal resources (30 m, 100 ft) in Kansas to be at least 50 billion tons in 32 coal beds. The present study includes samples from nine coal beds with significant strippable resources. These coals include the Rowe, Dry Wood, Mineral, Croweburg, Bevier, Mulky, Thayer, Upper Williamsburg, and an unnamed but extensively mined coal that is present a short distance beneath the Rowe coal.

Previous investigations of chemical composition of Kansas coals

Except for those elements commonly reported in the ultimate analysis of coal (S, C, H, O, and N), previous analyses of the chemical composition of Kansas coals are limited. Schleicher and Hambleton (1954) analyzed 24 samples from six Middle Pennsylvanian Kansas

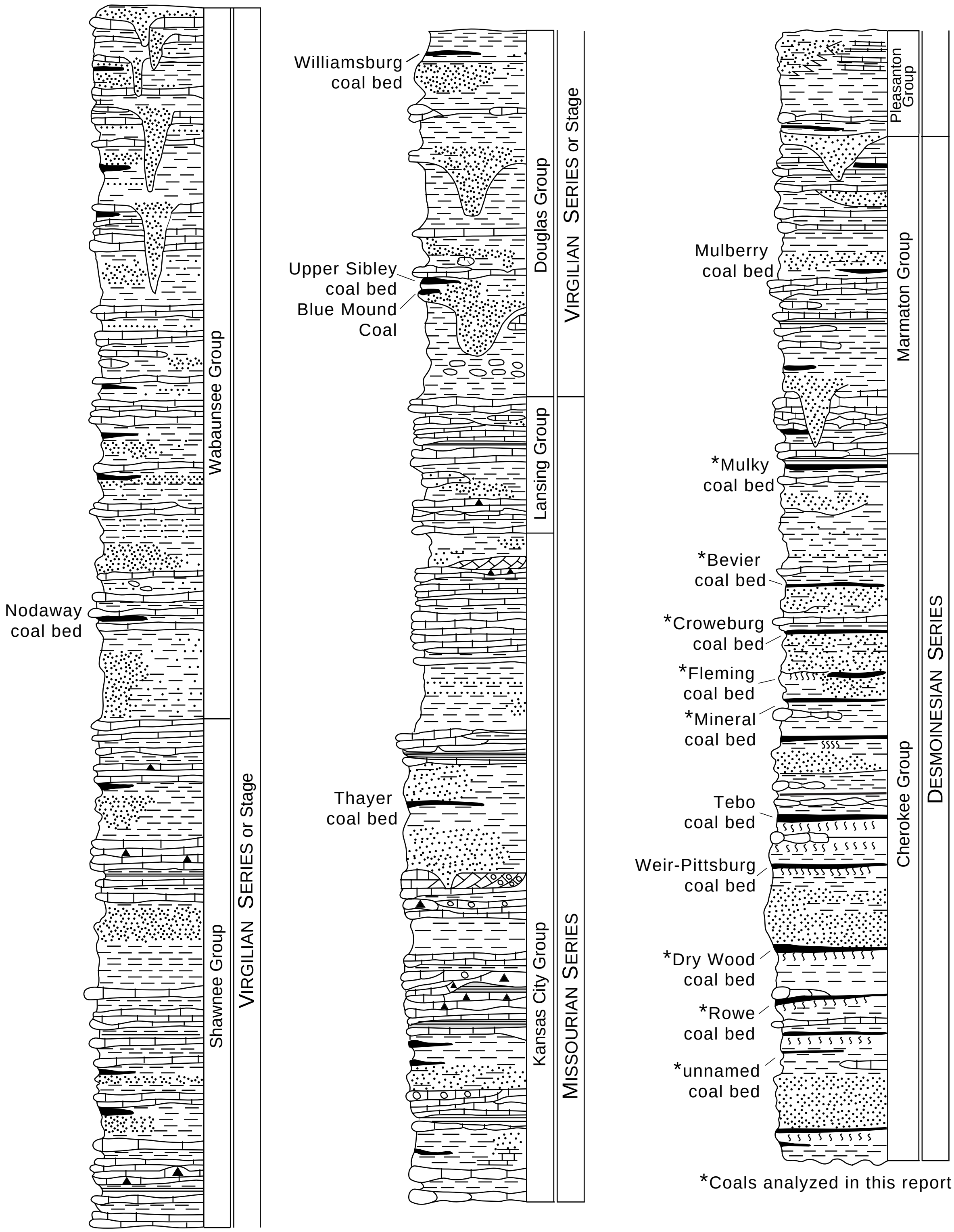

FIGURE. 1. Stratigraphic position of coal beds discussed in this report (column modified from Zeller, 1968).

coals—Tebo, Mineral, Croweburg, Bevier, Mulky, and Mulberry coals (see fig. 1 for relative stratigraphic positions)—for germanium (Ge) content. They found germanium content ranging from 6.9 to 48 ppm, with the Mulky coal sample in Bourbon County and a Mulberry coal sample in Linn County having the highest concentrations (41 ppm and 48 ppm, respectively). A later study by Schleicher (1959) on 20 different Middle and Upper Pennsylvanian Kansas coal beds showed germanium content to range from 6 to 116 ppm. These analyses showed generally higher germanium content in those coals higher in the stratigraphic section; for example, the 23

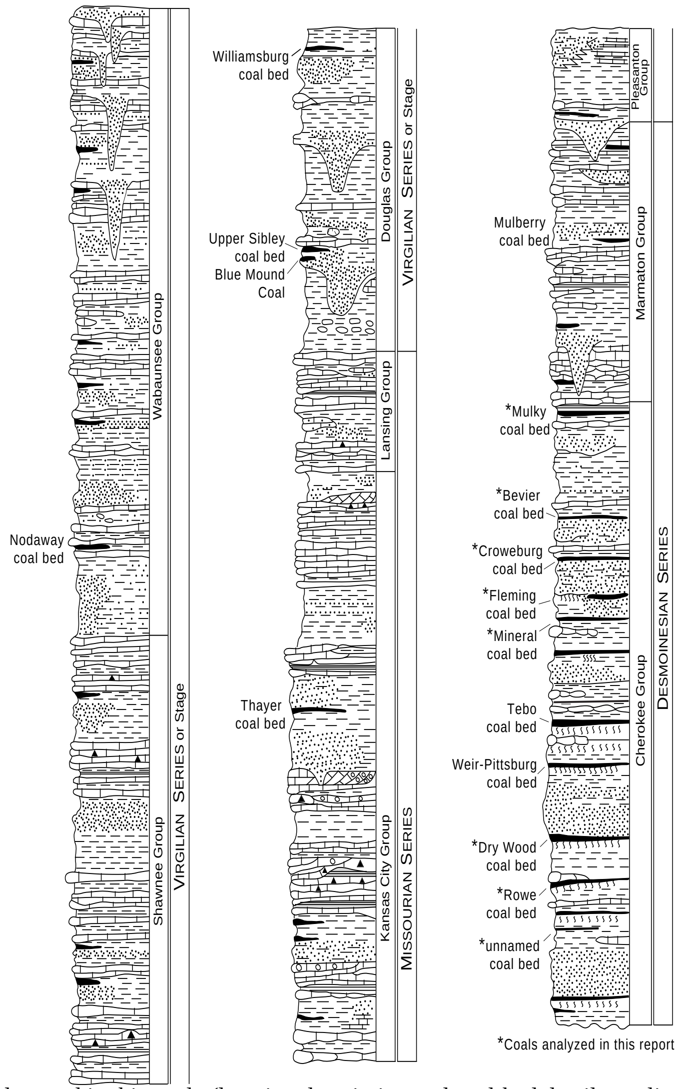

FIGURE 2. Location of coal samples used in this study (location description and coal-bed details are listed in table 1), and the general distribution of strippable coal resources by geologic group for coals under 30 m (100 ft) of overburden or less. Map is modified from Brady and others (1976).

samples of Nodaway coal from the Upper Pennsylvanian (Virgilian) Wabaunsee Group had a mean germanium content of 51 ppm, and seven samples of Upper Williamsburg coal from the Upper Pennsylvanian (Virgilian) Douglas Group had a mean germanium content of 52 ppm.

Analyses of the major and minor oxide composition of two Kansas coal ash samples were included in a summary report on major ash constituents in U.S. coals by Abernethy et al. (1969, p. 4). Information on the major and minor elements of the Mulberry, Mulky, Croweburg, Fleming, Mineral, Tebo, Weir-Pittsburg, Drywood (spelled Dry Wood in Kansas), and Rowe coals in southwestern Missouri and the Bevier, Croweburg, and Rowe coals in northeastern Oklahoma that have stratigraphic continuity into Kansas is presented in Zubovic et al. (1967), Swanson et al. (1976), Wedge et al. (1976), Wedge and Hatch (1980), Burchett (1977), Finkelman et al. (1990), and Tewalt and Finkelman (1990). The Mulberry coal analyses obtained from samples collected in Bates County, Missouri by Wedge and Hatch (1980) are relevant to the characterization of Kansas coals because the locations are within 2 mi (3.2 km) of the Linn County, Kansas, area where the Mulberry coal has been extensively mined.

Mineral content in Kansas coals was discussed as part of a larger study by Hambleton (1953, p. 50–61) on the petrography of the Mineral, Croweburg, and Bevier coals. Detrital minerals determined in that study included quartz, clay minerals, and apatite with authigenic minerals consisting of calcite, aragonite, pyrite, marcasite, and minor amounts of sphalerite. Hatch, Avcin et al. (1976) and Cobb (1981) identified sphalerite in the Mineral, Croweburg, and Mulky coals in Kansas after preliminary sample analyses of these beds indicated high zinc contents. Sphalerite was also identified in the Mineral and Mulberry coals a few miles from the Kansas border in Vernon and

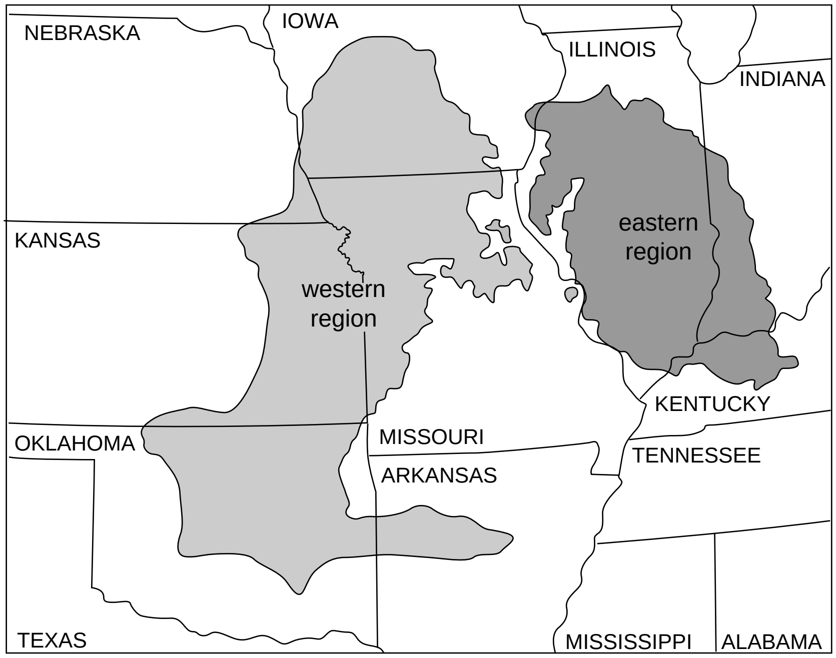

Figure 3. Location of western and eastern regions of the Interior Coal Province as discussed in the report. Map is modified from Wood and Bour (1988).

Bates counties, Missouri. Based on X-ray diffraction work, Finkelman et al. (1990, p. 36) characterized the mineralogy of eight coal samples (including samples from the Mineral, Croweburg, and Bevier coals), showing the main minerals to be calcite and pyrite.

Part of the data listed in this report were published in three earlier reports. These include analyses of 14 samples in Swanson et al. (1976, p. 279–287), zinc and cadmium analyses for 16 samples in Hatch, Avcin et al. (1976), and proximate, ultimate, and trace element analyses of six samples of Rowe and Dry Wood coals in Welch and Brady (1982, p. 22–25). A summary paper of analytical data on coals from the western region of the Interior Coal Province by Finkelman and Tewalt (1990) included a summary of Kansas coal samples in addition to summaries of samples from Arkansas, Iowa, Missouri, Nebraska, and Oklahoma.

Location of sampled coal beds

Of the 36 samples reported in this study, 32 are from Middle Pennsylvanian (Desmoinesian) coals from the Cherokee Group (table 1). The other four coal samples are from Upper Pennsylvanian rocks, three of these from the Missourian Thayer coal and one from the Virgilian Upper Williamsburg coal. Sample locations and number of samples collected at each locality are shown in fig. 2. Listed in table 1 are the sample identification numbers, locations, names and thicknesses of beds, and sample types.

All samples except one were collected from active strip mines. The one exception is a grab sample from the Upper Williamsburg coal, which was collected from a new pond excavation. A total of 31 channel samples representing the full thickness of the bed, one grab sample, and four tipple samples (from coal that passed through the coal cleaning plant) are included in this study.

Analytical methods

Analyses performed on the coal samples from southeastern Kansas are listed by laboratory in fig. 4. Determinations of proximate and ultimate analyses, heat of combustion, air-dried loss, forms of sulfur, ash-fusion temperatures, and free-swelling index were supplied by the U.S. Bureau of Mines, Pittsburgh, Pennsylvania. Analytical procedures for these analyses are described in the U.S. Office of Coal Research (1967). The analytical procedures used by the U.S. Geological Survey for elemental analyses are described in Swanson and Huffman (1976). A flow chart showing the sequence of sample preparation and chemical analyses is shown in fig. 5. Listed in table 2 are those additional elements for which coals were analyzed, but whose values were below the detection limits of the six-step spectrographic methods. Changes in the X-ray fluorescence technique to determine phosphorus content in ash resulted in variable lower detection limits. For samples D176045–D176058, the lower detection limit is 0.04% phosphorus (0.1% P_2O_5). For samples analyzed later (D196196–D196199), the lower detection limit is 0.004% phosphorus (0.01% P_2O_5). For the other samples, however, the lower detection limit is 0.4% phosphorus (1.0% P_2O_5). Thorium content of samples D189091, D189704–D189706, and D196196–D196199 was determined by instrumental neutron activation analysis and this method

U.S. Geological Survey		U.S. Bureau of Mines	
Major and minor elements (percent) [1]		**Proximate analysis (percent)**	
Silicon (Si)	Potassium (K)	Moisture	Fixed carbon
Aluminum (Al)	Iron (Fe)	Volatile matter	Ash
Calcium (Ca)	Titanium (Ti)	**Ultimate analysis (percent)**	
Magnesium (Mg)	Phosphorous (P)	Hydrogen (H)	Oxygen (O)
Sodium (Na)	Sulfur (S)	Carbon (C)	Sulfur (S)
Trace elements (ppm) [2]		Nitrogen (N)	Ash
Antimony (Sb)	Mercury (Hg)	Heat of combustion (Btu/pound; Kcal/kg)	
Arsenic (As)	Molybdenum (Mo)	**Forms of sulfur (percent)**	
Barium (Ba)	Neodymium (Nd)	Pyritic	
Beryllium (Be)	Nickel (Ni)	Organic	
Boron (B)	Niobium (Nb)	Sulfate	
Cadmium (Cd)	Scandium (Sc)	**Fusibility of ash (Temperature °C)**	
Cerium (Ce)	Selenium (Se)	Initial deformation	
Chromium (Cr)	Silver (Ag)	Softening temperature	
Cobalt (Co)	Strontium (Sr)	Fluid temperature	
Copper (Cu)	Thorium (Th)	**Free-swelling index**	
Fluorine (F)	Uranium (U)		
Gallium (Ga)	Vanadium (V)		
Germanium (Ge)	Ytterbium (Yb)		
Lanthanum (La)	Yttrium (Y)		
Lead (Pb)	Zinc (Zn)		
Lithium (Li)	Zirconium (Zr)		
Manganese (Mn)			

1 Reported as oxides in 525°C laboratory ash as well as on a whole-coal basis.

2 Reported as parts per million on a whole-coal basis and/or in 525°C laboratory ash.

FIGURE 4. Analyses and physical tests performed by goverment laboratories.

provides a lower detection limit of 0.1 ppm; the remaining 28 samples were analyzed by delayed-neutron activation analysis and have a lower detection limit of 3.0 ppm.

Statistical methods

In this report, the geometric mean (GM) is used as the estimate of the most probable concentration (mode). The geometric mean was calculated by taking the logarithm of each analytical value, summing the logarithms, dividing the sum by the total number of values, and obtaining the antilogarithm of the result. The geometric deviation (GD), which is the antilog of the standard deviation of the logarithms of the analytical values, was used to measure scatter about the mode. These statistics were used because quantities of trace elements in natural materials commonly exhibit positively skewed frequency distributions; such distributions are normalized by analyzing and summarizing trace-element data on a logarithmic basis. If the frequency distributions are log-normal, the geometric mean is the best estimate of the mode, and the estimated range of the central two-thirds of the observed distribution has a lower limit equal to GM/GD and an upper limit equal to $GM \times GD$. The estimated range of the central 95% of the observed distribution has a lower limit equal to GM/GD^2 and an upper limit equal to $GM \times GD^2$ (Conner et al., 1976).

Although the geometric mean is generally an adequate estimate of the most common analytical value in log-normal populations, it is nevertheless a biased estimate of the arithmetic mean. The estimates of the arithmetic means, as listed in the summary tables (tables 3–7), are Sichel's *t* statistic (Miesch, 1967). The common problem of a "censored" distribution arises in statistical summaries of trace-element data when the element content of one or more of the samples is below or greater than the limits of analytical detection. Procedures developed by Cohen (1959) were used to compute unbiased estimates of the geometric mean, geometric deviation, and arithmetic mean when the data are censored.

Because lower detection limits vary, data summaries for P_2O_5 in coal ash (table 6) and phosphorous and thorium in whole coal were not calculated (table 7; see table 9). Five elements (Ce, La, Nb, Nd, and Yb) were detected in some samples, but not in enough samples to calculate meaningful statistics. To be consistent with the precision of the semiquantitative emission spectrographic technique, arithmetic and geometric means of elements determined by this method are reported as the midpoint of the enclosing six-step brackets. The tipple samples D183117–D183120 were excluded from all the data summaries.

Results and discussion

Chemical analyses of coal samples

Proximate and ultimate analyses, heat of combustion, air-dried loss, forms of sulfur, free-swelling index, and ash-fusion temperatures were determined for 29 Kansas coal samples (appendix A). The 29 samples include 19

TABLE 2—Elements looked for but not detected in Pennsylvanian-age coal samples from southeastern Kansas. (Approximate lower detection limits in coal ash as determined by the six-step spectrographic method of the U.S. Geological Survey are included for all elements.)

Element name	Symbol	Lower limit of detection (ppm) in ash
Gold	Au	50
Bismuth	Bi	20
Dysprosium	Dy	100
Erbium	Er	100
Europium	Eu	200
Gadolinium	Gd	100
Hafnium	Hf	200
Holmium	Ho	50
Indium	In	20
Lutetium	Lu	70
Palladium	Pd	5
Praseodymium	Pr	200
Platinum	Pt	100
Rhenium	Re	100
Smarium	Sm	200
Tin	Sn	20
Tantalum	Ta	1,000
Terbium	Tb	700
Tellurium	Te	5,000
Thallium	Tl	100
Thulium	Tm	50
Tungsten	W	200

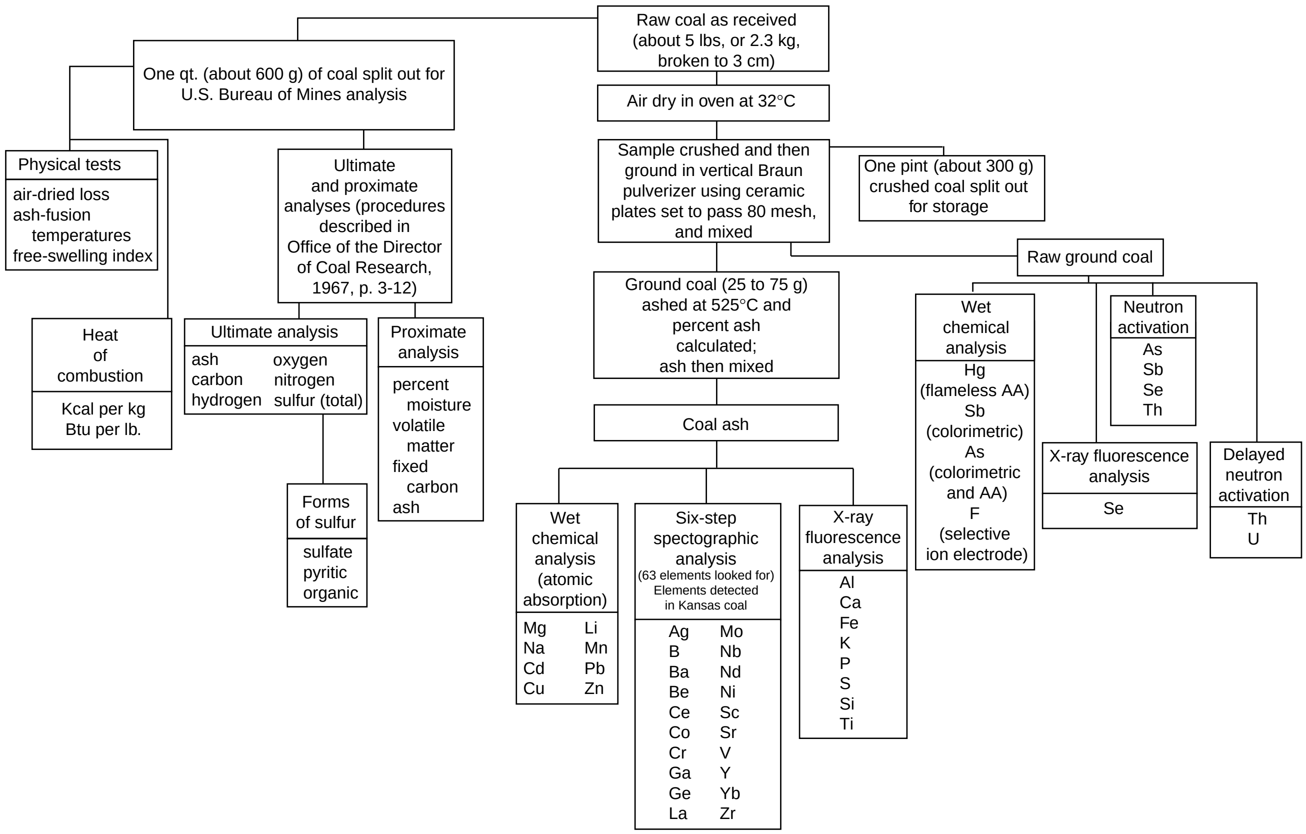

FIGURE 5. Flow chart showing sequence of sample preparation and chemical analysis. Modified from Swanson and Huffman (1976, fig. 1).

individual channel coal samples, six samples that are composites (where two or three channel samples collected from the same coal bed in the same mine were combined), and the four tipple samples (samples D183117–D183120). The laboratory ash of all 36 coal samples was analyzed for major- and minor-oxide and trace-element composition (appendix B). Thirty-six samples of coal were also analyzed for 42 elements (appendix C). Unweighted statistical summaries of the analytical data for the 31 channel samples and one grab sample listed in appendices A, B, and C (excluding the four tipple samples) are listed in tables 3–7.

Proximate analyses for the individual coal beds (on an as-recieved basis) are summarized in table 8. All values are arithmetic means. The concentration of volatile matter ranges from 30.1% in the Dry Wood bed to 39.7% in the Upper Williamsburg coal, averaging 35.3% for the 25 Kansas coals listed in appendix A (tipple samples excluded). Fixed-carbon composition ranges from 41.3% for the Dry Wood and Thayer coals to 50.4% for the samples from the unnamed coal bed in the lower part of the Cherokee Group, the mean value for all 25 coal samples being 45.9%. Ash content can be quite variable within a coal bed as well as between coal beds. The lowest ash content is 6.7% for the grab sample from the Upper Williamsburg coal. This sample, however, did not represent the full thickness of the bed. Where the entire thickness of the coal was sampled, the Mulky coal has the lowest mean ash content (11.4 percent), and the Dry Wood coal has the highest (25.6%). The mean ash content for all 25 channel samples of coal is 15.5%. Mechanical coal-cleaning plants can greatly reduce the percentage of ash present in mined coal. The tipple samples of coal from four different coal beds—Rowe (D183117), Dry Wood (D183118), Mineral (D183119), and Croweburg (D183120)—that had passed through a coal-cleaning plant have 16–38% less ash than the uncleaned samples from the same coal bed. The mean moisture content for different coal beds ranges from 2.7% in the Croweburg coal up to 6.8% in the Thayer coal. The mean moisture content for the 25 samples is 3.3%. Moisture content of coal samples is dependent on coal rank and to a lesser extent on the sampling technique. Exposure of the coal to the atmosphere after sampling strongly affects the measured moisture content (American Society for Testing and Materials, 1993, standard D2234). Of the samples collected, only the Upper Williamsburg coal sample was air-dried before analysis.

Heat of combustion for individual Kansas coal beds is also summarized in table 8. The mean heat of combustion (as-received basis) ranges from 10,310 Btu/lb for the Dry Wood coal to 12,695 Btu/lb for the Mulky coal and

TABLE 3—Results of proximate and ultimate analyses of 25 Pennsylvanian-age coal samples from southeastern Kansas. (All values are reported on the as-received basis.)

	Arithmetic mean (%)	Observed range (%) Minimum	Maximum	Geometric mean (%)	Geometric deviation
Moisture	3.3	1.7	8.1	3.1	1.4
Volatile matter	35.3	28.2	39.9	35.1	1.1
Fixed carbon	45.9	37.0	52.6	45.8	1.1
Ash	15.5	6.7	31.1	14.7	1.4
Hydrogen	4.9	3.8	5.6	4.9	1.1
Carbon	65.3	47.8	71.3	65.0	1.1
Nitrogen	1.2	0.8	1.9	1.2	1.2
Oxygen	7.7	3.7	13.3	7.3	1.4
Sulfur	5.5	1.6	12.8	4.9	1.6

TABLE 4—Heat of combustion results for 25 Pennsylvanian-age coal samples from southeastern Kansas. (All values are reported on the as-received basis. Kcal/kg = 0.556 Btu/lb.)

	Arithmetic mean	Observed range Minimum	Maximum	Geometric mean	Geometric deviation
Kcal/kg	6,620	5,160	7,100	6,600	1.1
Btu/lb	11,910	9,290	12,780	11,870	1.1

averages 11,910 Btu/lb for all 25 channel samples. Heat of combustion is related to coal rank and is also significantly affected by moisture and ash content. For a moisture- and ash-free basis, heat of combustion ranges from 13,940 Btu/lb for the Upper Williamsburg coal to 14,980 Btu/lb for Mineral coal samples.

Ultimate analyses of the 25 coal samples show arithmetic means (as-received basis) of 4.9% hydrogen, 65.3% carbon, 1.2% nitrogen, 7.7% oxygen, and 5.5% sulfur (table 3). The sulfur content of Kansas coal is generally high (greater than 2.0%). As table 8 shows, the samples with the lowest sulfur content were Bevier coal (arithmetic mean of 2.7%) and Upper Williamsburg coal (1.6%). The highest sulfur content was in samples of the Dry Wood coal (10.4%) and Rowe coal (8.8%). Where these coals were sampled, considerable pyrite was observed along bedding planes and cleats, with pyrite bands along bedding planes as thick as 0.4 inches (1 cm). The mean pyritic sulfur content in the Dry Wood coal is 7.4%; in the Rowe coal, it is 6.9% (based on sample data in appendix A). The relatively low sulfur content (for Kansas coals) of the Upper Williamsburg (one grab sample) and Bevier coal (two channel samples) is similar to analyses published by Hamilton et al. (1975, p. 292). Their compilation of all available sulfur sample values showed that 22 samples of Bevier coal from Cherokee County (on an as-received basis) averaged 2.6% sulfur, whereas 133 Bevier coal samples from Crawford County averaged 2.0%. Five Upper Williamsburg samples listed in Hamilton et al. (1975) averaged 1.7% sulfur (moisture-free basis). In analyses listed by Bowsher and Jewett (1943, p. 57) for Upper Williamsburg coal from three different mines (as-received basis), sulfur content averaged 1.6%.

Coal rank

Apparent ranks for the 25 coal samples were calculated using the approximation Parr formulas (American Society for Testing and Materials, 1993, p. 202, standard D-388). Calculated apparent rank (moist, mineral-matter-free Btu values) for these samples range from high-volatile B bituminous to high-volatile A bituminous coal. Except for composite sample D196198–D196199, all coal samples from the Cherokee Group in southeastern Kansas (Cherokee, Crawford, and Bourbon counties) have an apparent rank of high-volatile A bituminous coal; whereas samples of younger coals (Thayer and Upper Williamsburg) from Wilson and Franklin counties have an apparent rank of high-volatile B bituminous coal.

Trace elements in Kansas coal

Table 9 summarizes the geometric means and the geometric deviations for 35 minor and trace elements in coals from southeastern Kansas. For comparison, this information is also listed for equivalent-aged coal samples from Oklahoma, Iowa, and Missouri. The Oklahoma coals were associated with a rapidly subsiding basin, whereas the Kansas, southwest Missouri, and Iowa samples were from coals associated mainly with shelf deposits. Also included in table 9 are geometric mean values of the trace elements in Interior Province (Swanson et al., 1976, p. 223) and U.S. coals (Finkelman and Tewalt, 1990, p. 213).

TABLE 5—Forms of sulfur in 25 Pennsylvanian-age coal samples from southeastern Kansas. (All values are reported on the as-received basis.)

	Arithmetic mean (%)	Observed range (%) Minimum	Maximum	Geometric mean (%)	Geometric deviation
Pyritic	3.82	0.57	10.7	3.03	2.0
Organic	1.42	0.50	2.95	1.25	1.6
Sulfate	0.50	0.01	0.96	0.20	4.0

TABLE 6—Concentrations of ash and nine major and minor oxides in the laboratory ash of 32 Pennsylvanian-age coal samples from southeastern Kansas. All samples were ashed at 525°C.

Oxide	Arithmetic mean (%)	Observed range (%) Minimum	Maximum	Geometric mean (%)	Geometric deviation
(Ash)	16.2	7.6	32.3	15.6	1.3
SiO_2	26	13	42	25	1.3
Al_2O_3	11	1.6	21	9.4	1.7
CaO	9.6	0.31	30	4.8	4.1
MgO	0.68	0.29	1.53	0.63	1.5
Na_2O	0.28	0.07	0.77	0.25	1.7
K_2O	1.5	0.50	3.1	1.3	1.6
Fe_2O_3	34	11	59	31	1.5
TiO_2	0.49	0.09	1.0	0.42	1.7
SO_3	6.9	1.4	16	5.2	2.1

Geometric means of minor- and trace-element values in the samples from Kansas were compared with those in coal samples from Oklahoma (Arkoma basin area, Hildebrand, 1981, p. 42), Iowa (Hatch et al., 1984, p. 101), and southwestern Missouri (Wedge and Hatch, 1980, p. 98–99). Based on the *t*-test (99% confidence level), when compared to coals from adjacent states and the Interior Province coals, Kansas coals have significantly higher concentrations of As, Cu, and Pb and lower concentrations of V. Compared to Interior Province coals (Swanson et al., 1976), Kansas coals also have higher concentrations of F, Ga, Mn, Ni, Sr, Y and Zn and a lower concentration of B. Additionally, the Iowa coals have higher concentrations of B, Cr, Ga, Ge, Li, Mn, Ni, V, Zn, and Zr. Compared with coals from the Arkoma basin in eastern Oklahoma, Kansas coals have higher concentrations of Fe, B, F, Ga, Mn, Ni, Se, Y, and Zn and lower Ba content. Kansas coals also have significantly higher concentrations of Ge, Mn, Sr and lower concentrations of Co, Cr, F, Ga, Ni, Zn, and Zr than coals from the southwest mining district of Missouri. As table 9 shows, Kansas coals have more than 16 times the lead content of U.S. coals and five or more times more Ag, Cd, Ge, and Zn.

Correlation analysis

To relate the variation of 42 minor and trace elements in the 31 channel samples, correlation coefficients were calculated from the data in appendix C. These are shown in appendix D. No less than eight analytical values were used in the correlation analyses. The number of pairs used to calculate each correlation coefficient is also listed in appendix D.

Eleven elements in Kansas coals show strong correlation with ash content (appendix D). At the 99% confidence level, ash shows significant positive correlation with Co, Cu, Fe, Ga, Si, and Y. At the 95% confidence level, ash is also correlated with Ba, Li, Mg, Sc, and Zr.

Elements found in high concentrations in Kansas coal

Silver (Ag). Limited information is available about silver content in U.S. coals. In their study of Interior Province coals, Swanson et al. (1976) did not list average silver content. For Missouri coals, Wedge and Hatch (1980) showed silver values for four separate coal-mining districts. Seventeen samples from coal beds in the southwest district of Missouri, which are continuous with coal deposits of southeastern Kansas, show a geometric mean of 0.15 ppm with a range of less than 0.15 to 0.3 ppm (Wedge and Hatch, 1980, p. 98). This concentration is similar to that seen in southeastern Kansas coals, where geometric mean silver content is 0.2 ppm and ranges from less than 0.2 ppm to 0.7 ppm. Silver shows no positive correlation at the 95% confidence level with other elements analyzed in this study (appendix D).

TABLE 7—Concentrations of 35 elements in 32 Pennsylvanian-age coal samples from southeastern Kansas (tipple samples listed in Appendix B are not included). Concentrations of the first 8 elements are given in percentages; the rest are in parts per million. All analyses are reported on a whole coal basis. As, F, Hg, Sb, Se, Th, and U values used to calculate the statistics were determined directly on whole coal. All other values used were calculated from determinations made on coal ash. L = less than the value shown; G = greater than the value shown.

Element	Arithmetic mean	Observed range Minimum	Observed range Maximum	Geometric mean	Geometric deviation
percentages					
Si	1.9	0.75	4.6	1.8	1.5
Al	0.91	0.22	2.4	0.77	1.8
Ca	1.4	0.046	4.2	0.54	4.0
Mg	0.065	0.029	0.22	0.059	1.6
Na	0.032	0.017	0.13	0.029	1.6
K	0.19	0.057	0.53	0.17	1.6
Fe	3.9	0.60	7.5	3.4	1.7
Ti	0.046	0.008	0.14	0.040	1.7
parts per million					
Ag	0.3	0.2	0.7	0.2	1.9
As	26	6.8	60	22	1.8
B	30	7	200	20	2.0
Ba	30	7	150	30	1.9
Be	1.5	0.7	3	1.5	1.4
Cd	20	0.1L	160	0.15	53
Co	10	1.5	70	7	2.6
Cr	10	2	30	10	1.6
Cu	27	5.5	75	26	1.6
F	88	30	330	76	1.7
Ga	5	1.5	30	5	2.3
Ge	15	5	50	15	1.5
Hg	0.16	0.06	0.83	0.14	1.6
Li	8.9	1.5	25	6.1	2.4
Mn	140	21	460	90	2.5
Mo	3	1	10	2	2.9
Ni	50	2	150	20	2.6
Pb	97	27	210	84	1.7
Sb	1.8	0.2	5.0	1.3	2.2
Sc	2	1L	5	2	1.6
Se	3.3	0.5	9.7	2.7	2.0
Sr	70	10	5,000 G	50	3.0
U	3.2	0.2L	25	1.6	3.4
V	20	2	150	15	2.1
Y	15	2	70	10	2.1
Zn	600	13	51,000	77	8.0
Zr	10	3	30	10	1.8

Lead (Pb). Lead content in Kansas coals ranges from 27 to 210 ppm and has a geometric mean of 84 ppm, as compared to a geometric mean of 19 ppm in coals from the Interior Province (table 9). Coals from the southwest district of Missouri have a geometric mean content of 64 ppm and a range of 23 to 280 ppm (Wedge and Hatch, 1980, p. 99), similar to the range and mean lead content in Kansas coals. In Kansas coals, lead has a strong positive correlation (99% or greater confidence level) with iron and copper; at the 95% confidence level, lead has a positive correlation with molybdenum.

Germanium (Ge). The relatively high germanium content in some Kansas coals was first recognized by Schleicher and Hambleton (1954) and Schleicher (1959), who found germanium concentrations ranging from 6 to 116 ppm. In this study, germanium content ranges from 5 to 50 ppm, with a geometric mean of 15 ppm (table 7). In coals from the southwestern district of Missouri, germanium content ranges from 5 to 20 ppm, with a geometric mean of 10 ppm (Wedge and Hatch, 1980, p. 98). For the Kansas coal analyses reported here, germanium has a strong positive correlation with boron (99% or

TABLE 8—Arithmetic means and standard deviations of the results of proximate analyses, heat of combustion, and sulfur analyses by coal bed. (*Moisture and mineral-matter free.)

Coal bed	n	% Moisture		% Volatile matter		% Fixed carbon		% Ash		% Sulfur		As-received (Btu)		m & mm free* (Btu)	
		mean	SD	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD
U. Williamsburg	1	3.3	—	39.7	—	50.3	—	6.7	—	1.6	—	12,550	—	13,940	—
Thayer	2	6.8	1.8	33.7	3.9	41.3	0.6	18.3	2.7	3.85	0.78	10,675	685	14,250	60
Mulky	5	3.0	0.3	38.3	2.7	47.4	3.0	11.4	0.7	4.60	0.29	12,695	100	14,820	115
Bevier	2	3.9	0.1	36.1	1.1	48.6	0.2	11.5	1.1	2.70	0.42	12,250	270	14,480	100
Croweburg	4	2.7	0.9	35.4	2.7	43.7	2.6	18.3	4.4	4.28	0.8	11,680	725	14,785	95
Mineral	3	2.8	0.6	36.1	0.7	47.8	1.9	13.2	0.9	4.70	0.10	12,575	155	14,980	140
Dry Wood	2	3.1	0.9	30.1	2.6	41.3	6.1	25.6	7.9	10.35	3.46	10,310	1,440	14,435	260
Rowe	5	3.0	1.1	34.1	0.9	46.1	2.7	16.9	3.7	8.77	2.50	11,725	555	14,615	205
Unnamed	1	3.3	—	31.2	—	50.4	—	15.1	—	4.1	—	12,060	—	14,780	—
All beds	25	3.3	1.3	35.3	3.1	45.9	3.6	15.5	5.2	5.36	2.54	11,910	895	14,655	390

greater confidence level) and calcium (95% confidence level).

Zinc (Zn) and Cadmium (Cd). These two elements are present in high amounts in coals from the Interior Coal Province, with a geometric mean content of 58 ppm for zinc and 0.12 ppm for cadmium. These values are nearly five times higher than in U.S. coals, where zinc averages 13 ppm and cadmium 0.02 ppm. Of the four states reviewed (table 9), the Oklahoma samples have the lowest zinc and cadmium content. Wide ranges of zinc and cadmium content are indicated by the large geometric deviation values in Kansas, southwest Missouri, and Iowa (table 9). These extreme values in the Kansas samples are discussed below. Zinc shows a strong positive correlation with cadmium and mercury at the 99% confidence level or higher, and with gallium and molybdenum at the 95% confidence level. Cadmium shows a positive correlation with arsenic, chromium, gallium, and antimony at the 95% confidence level, and with mercury and zinc at the 99% or higher confidence level.

Arsenic (As). Arsenic content in Kansas coals is significantly higher than in coals from surrounding states, the Interior Province, and the U.S. as a whole (table 9). At the 99% confidence level, arsenic shows a strong positive correlation with Al, Cr, Cu, Fe, Li, Ti, and V and with K and Zr at the 95% confidence level.

Copper (Cu). Copper content in Kansas coal is also higher than in coal samples from states adjacent to Kansas, the Interior Province, and the U.S. In Kansas coals copper has a strong positive correlation with Al, As, Co, Cr, Fe, Hg, Li, Pb, V, and Y at the 99% confidence level and with Ga, Ni, Ti, and Zr at the 95% confidence level.

Outlier occurrences of trace and minor elements in Kansas coals

High concentrations of minor and trace elements are considered to be statistical outliers when those element quantities in individual coal analyses exceed the 95% central distribution range of $GM \times GD^2$ for the given element. A total of 31 outlier occurrences of trace or minor elements were present in 13 different Kansas coal samples (table 10). Coals from the Thayer and Dry Wood beds had the most outliers, 13 and nine, respectively.

The highest zinc and cadmium content (51,000 ppm and 160 ppm, respectively) is present in sample D180074 from the Dry Wood coal. According to Hatch (1983, p. 90), this sample has the highest zinc content reported in U.S. coal samples. The maximum cadmium content reported for U.S. coals listed by Hatch (1983) is 170 ppm from a sample of the Bevier coal from Howard County, Missouri. These high concentrations of zinc and cadmium exceed the expected values (geometric mean) for Kansas by about 1,000 times for cadmium and about 600 times for zinc. Five other coal samples—one from the Dry Wood coal, two from the Mineral coal, and two samples from the Mulky coal—show zinc concentrations exceeding 900 ppm and cadmium concentrations exceeding 5 ppm (appendix C). These two values were picked because they appear to mark distinct lower values for the samples containing high amounts of cadmium and zinc. The strongly skewed distributions indicate two different populations of zinc and cadmium occurrences, the first one of mineralized coals, the second, unmineralized. Field observations and limited X-ray work show that sphalerite (ZnS) occurs primarily along small fractures and along cleats in the mineralized coals. Hatch, Avcin et al. (1976), Hatch, Gluskoter, and Lindahl (1976), and Cobb (1981) studied sphalerite occurrences in coal from the Interior Coal Province. They also found sphalerite filling small fractures and cleats in the coal.

The correlation coefficient of zinc with cadmium for 14 channel samples is 0.94, indicating a significant positive correlation of the two elements at the 99.9% confidence level. Only 14 pairs were used in the correlation analysis because, in the other 18 samples, the cadmium content was below the detection limit. This correlation of cadmium with zinc is probably related to the presence of cadmium

TABLE 9—Concentrations of 35 elements in coal samples from Kansas, Iowa, the southwest coal region of Missouri, the Arkoma basin of Oklahoma, the Interior Coal Province, and the U.S. (n = number of samples). Geometric mean (GM) and geometric deviation (GD) values are shown for all the samples except for those from the U.S. coal database, for which only the geometric mean is given. Concentrations of the first 8 elements are given in percentages; the rest are in parts per million.

Element	Kansas		Oklahoma[1]		Iowa[2]		Missouri[3]		Interior Province[4]		U.S.[5]
	GM	GD	GM	GD	GM	GD	GM	GD	GM	GD	GM
percentages											
Si	1.8	1.5	1.1	2.7	1.7	1.9	2.4	1.5	1.4	2.3	—
Al	0.77	1.8	0.74	2.7	0.78	2.0	0.97	1.7	0.77	2.0	—
Ca	0.54	4.0	0.38	3.1	1.2	2.3	0.39	4.1	0.50	3.8	—
Mg	0.059	1.6	0.12	2.6	0.045	2.0	0.069	1.4	0.063	2.3	—
Na	0.029	1.6	0.031	2.6	0.026	1.8	0.024	1.6	0.026	2.2	—
K	0.17	1.6	0.1	2.9	0.10	2.1	0.19	1.7	0.11	2.4	—
Fe	3.4	1.7	1.4	2.3	4.0	2.0	2.8	1.3	2.3	2.4	—
Ti	0.040	1.7	0.033	2.4	0.040	2.0	0.051	1.8	0.04	2.1	—
parts per million											
Ag	0.2	1.9	—	—	0.05	8.1	0.15	1.5	—	—	0.01
As	22	1.8	11	4.2	15	2.5	14	1.9	12	2.9	6.5
B	20	2.0	15	3.0	100	1.6	20	1.6	50	3.4	30
Ba	30	1.9	50	2.1	30	3.6	30	1.7	30	2.6	90
Be	1.5	1.4	0.5	4.0	2	1.5	1.5	1.5	1.5	3.1	1
Cd	0.15	53	—	—	0.4	17	0.37	52	0.12	18.3	0.02
Co	7	2.6	—	—	7	2.5	10	1.6	7	2.3	4
Cr	10	1.6	10	2.6	15	2.1	15	1.8	10	2.0	11
Cu	26	1.6	13	1.9	19	2.0	24	1.3	16.3	1.9	12
F	76	1.7	61	2.0	65	1.8	78	1.6	58	1.9	35
Ga	5	2.3	3	2.4	7	1.8	7	1.8	3	2.0	5
Ge	15	1.5	—	—	20	1.7	10	1.4	—	—	0.6
Hg	0.14	1.6	0.08	4.6	0.14	1.7	0.14	1.6	0.10	2.3	0.10
Li	6.1	2.4	7.4	3.5	7.9	2.8	7.1	2.6	7.0	2.7	9.2
Mn	90	2.5	59	2.7	170	2.0	71	2.4	72	3.1	19
Mo	2	2.9	3	3.1	3	3.7	2	3.2	2	2.8	1
Ni	20	2.6	15	2.0	30	2.3	30	1.5	18	2.4	9
Pb	84	1.7	3.3	3.1	44	2.5	64	2.0	19	4.3	5.0
Sb	1.3	2.2	0.3	2.4	0.8	4.0	1.1	2.9	0.8	3.4	0.61
Sc	2	1.6	2	2.5	5	2.1	3	1.4	3	2.1	3
Se	2.7	2.0	1.2	2.5	2.8	2.7	4.1	2.6	2.8	2.7	1.8
Sr	50	3.0	50	2.3	50	2.6	20	1.6	30	2.8	90
U	1.6	3.4	0.7	4.3	2.4	3.1	2	2.9	1.4	3.8	1.1
V	15	2.1	20	2.6	20	2.4	20	1.8	20	2.1	20
Y	10	2.1	7	2.3	10	1.7	10	1.6	7	1.9	7
Zn	77	8.0	23	2.1	150	7.5	170	12	58	6.9	13
Zr	10	1.8	—	—	15	2.0	15	1.6	10	2.0	19
n	32		51		105		22		143		*

[1] Data from Hildebrand, 1981, p. 42.
[2] Data from Hatch et al., 1984, p. 101.
[3] Data from Wedge and Hatch, 1980, p. 98–99.
[4] Data from Swanson et al., 1976, p. 223.
[5] Data from Finkelman and Tewalt, 1990, p. 213.
* U.S. sample number varies by element, 5,000> to <8,000

in solid solution in the sphalerite. Similar strong correlation of cadmium with zinc is reported by Hatch, Gluskoter, and Lindahl (1976) and Gluskoter et al. (1977) in Illinois basin coals, by Wedge and Hatch (1980) in Missouri coals, and Hatch et al. (1984) in Iowa coals.

Hatch, Avcin et al. (1976) suggest a relationship between sphalerite in midcontinent coals and the proximity to major lead-zinc mining districts or major structural features. The six Kansas coal samples with high cadmium and zinc content were collected in southeastern Bourbon County and southeastern Crawford County relatively close to the old Tri-State zinc-lead mining district of southeastern Kansas, northeastern Oklahoma, and southwestern Missouri. The Dry Wood coal samples (with very high

TABLE 10. Anomalous individual minor- and trace-element occurrence (statistical outliers) in Kansas coal samples when compared with the estimated upper distribution of the samples. (* Interior Province data (Swanson et al., 1976, p. 223) was used for calculating Cd 95% limit because of wide range of Cd values in Kansas samples would not allow a meaningful 95% limit to be developed on Kansas Cd data alone.)

Element	Upper limit 95% range	Samp. value	Sample no.	Coal bed
percentages				
Si	4.1	4.6	D183114	Croweburg
Mg	0.15	0.22	D176057	Thayer
Na	0.07	0.089	D176055	Thayer
		0.13	D176057	Thayer
K	0.44	0.53	D176057	Thayer
Ti	0.12	0.14	D176057	Thayer
parts per million				
B	80	200	D176058	U. Williamsburg
Ba	108	150	D176057	Thayer
Be	2.9	3	D180069	Rowe
		3	D180071	Rowe
Cd	40*	44	D183112	Mineral
		160	D180074	Dry Wood
Co	47	70	D180072	Dry Wood
Cr	26	30	D176057	Thayer
Cu	67	75	D180074	Dry Wood
F	220	295	D176056	Thayer
		330	D176057	Thayer
Ga	26	30	D180074	Dry Wood
Ge	34	50	D176058	U. Williamsburg
Hg	0.36	0.83	D180074	Dry Wood
Sr	450	5,000G	D176055	Thayer
		700	D176056	Thayer
		1,000	D176057	Thayer
U	18	22	D176056	Mulky
		25	D196197	Mulky
V	66	150	D176057	Thayer
Y	44	70	D180072	Dry Wood
		50	D180074	Dry Wood
Zn	4,930	5,800	D183112	Mineral
		5,300	D180072	Dry Wood
		51,000	D180074	Dry Wood

zinc and cadmium content) in southeastern Crawford County came from locations approximately 6 miles (10 km) from areas of past zinc and lead mining. The four other samples with high zinc and cadmium content came from approximately 36 miles (60 km) north of past zinc-lead mining. Zinc and lead ores in the Tri-State district are present mainly in rocks of Mississippian age, with some mineralization present in Middle Pennsylvanian shales (Brockie et al., 1968, p. 413; McKnight and Fisher, 1970, p. 154–155; Hagni, 1982, p. 105).

As table 10 shows, uranium content in two Mulky coal samples is anomalously high (22 ppm and 25 ppm). The other three samples from the Mulky coal (appendix C, samples D189704, D189706, and D189091), though lower (3.4, 5.1, and 6.3 ppm), still greatly exceed the geometric mean of 1.6 for uranium in Kansas coals. This coal bed is directly overlain in the mine areas by a marine black shale (Excello Shale Member of the Fort Scott Limestone). The anoxic marine environment in which this shale was deposited probably represents the source of the uranium.

Summary

The results of the elemental and chemical analyses and physical tests on Kansas coals are summarized below:

1. Apparent rank for all southeastern Kansas coal samples ranges from high-volatile A to high-volatile B bituminous coal. Most of the samples in the principal coal-mining area of southeastern Kansas are high-volatile A bituminous coal.
2. Proximate analyses show the average (arithmetic mean) composition of Kansas coals to be 15.5% ash, 35.3% volatile matter, 45.9% fixed carbon, and 3.3% moisture and the average heat of combustion to be

11,910 Btu/lb. Ultimate analyses show average composition of Kansas coals to be 4.9% hydrogen, 65.3% carbon, 1.2% nitrogen, 5.5% sulfur, and 7.7% oxygen. These Kansas coal samples also contain 3.03% pyritic sulfur, 1.25% organic sulfur, and 0.2% sulfate sulfur (geometric mean).
3. In Kansas coals, the arsenic, copper, and lead concentrations are significantly higher and the vanadium content is significantly lower than in coals from other areas of the central U.S. Mean concentrations of Ag, Ge, Pb, Zn, and Cd are at least five times higher in southeastern Kansas coals than in U.S. coals as a whole.
4. Of 31 anomalously high element concentrations, 13 were from the Thayer coal, and nine were from the Dry Wood coal. Those elements having anomalously high occurrences in more than one Kansas coal sample include Be, Cd, F, Na, Sr, U, Y, and Zn.
5. Zinc concentrations of 51,000 ppm and cadmium concentrations of 160 ppm are among the highest values reported from any coal bed in the U.S.
6. Sphalerite has been observed in fracture fillings and cleats in coal beds near the location of the samples with high cadmium and zinc concentrations. The presence of zinc and lead ores in the Tri-State mining district within 40 miles (65 km) suggests a similar source for these metals in the Kansas coals.

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Apppendix A. Proximate and ultimate analyses, heat-of-combustion, forms-of-sulfur, free-swelling index, and ash-fusion-temperature determinations for 29 Pennsylvanian coal samples from southeastern Kansas. For each sample number, the analyses are reported three ways: first, as-received; second, moisture-free; and third, moisture and ash free. All analyses by Coal Analysis Section, U.S. Department of Energy, Pittsburgh, Pennsylvania. Kcal/kg = 0.556 (Btu/lb); °F = (°C x 1.8) + 32. (*D176055 is a composite of samples D176055 and D176056; D176046 of samples D176046 and D176047; D183112 of samples D183112 and D183113; D176048 of samples D176048 and D176049; D176050 of samples D176050, D176051, and D176052; and D176053 of samples D176053 and D176054.)

	Proximate Analysis (%)				Ultimate Analysis (%)					Heat of Combustion			Forms of Sulfur (%)				Ash Fusion Temp. °C		
Sample number	Moisture	Volatile matter	Fixed Carbon	Ash	H	C	N	O	S	Kcal/kg	Btu/lb	Air-dried loss	Sulfate	Pyritic	Organic	Free-swelling Index	Initial deform.	Soften.	Fluid
D176058	3.3	39.7	50.3	6.7	5.2	71.3	1.9	13.3	1.6	6,970	12,550	0.6	0.03	0.57	0.97	2.5	1,120	1,150	1,175
	—	41.1	52.0	6.9	5.0	73.7	2.0	10.7	1.7	7,210	12,980	—	0.03	0.59	1.00				
	—	44.1	55.9	—	5.4	79.2	2.1	11.5	1.8	7,750	13,940	—	0.03	0.63	1.08				
D176055*	5.5	36.4	41.7	16.4	4.8	62.1	1.5	10.8	4.4	6,200	11,160	2.3	0.52	2.92	1.00	4.0	1,055	1,080	1,110
	—	38.5	44.1	17.4	4.4	65.7	1.6	6.3	4.7	6,560	11,810	—	0.55	3.09	1.06				
	—	46.6	53.4	—	5.4	79.5	1.9	7.6	5.6	7,940	14,290	—	0.67	3.74	1.28				
D176057	8.1	30.9	40.8	20.2	4.8	57.3	1.4	13.0	3.3	5,660	10,190	3.7	0.54	1.66	1.15	2.5	1,065	1,095	1,120
	—	33.6	44.4	22.0	4.2	62.4	1.5	6.3	3.6	6,160	11,090	—	0.59	1.81	1.25				
	—	43.1	56.9	—	5.4	79.9	2.0	8.1	4.6	7,900	14,210	—	0.75	2.32	1.60				
D189091	2.7	33.5	52.6	11.2	5.5	69.6	1.3	7.9	4.4	7,090	12,760	0.1	0.36	1.63	2.45	8.5	1,070	1,125	1,175
	—	34.4	54.1	11.5	5.3	71.5	1.3	5.7	4.5	7,290	13,110	—	0.37	1.68	2.52				
	—	38.9	61.1	—	6.0	80.8	1.5	6.4	5.1	8,230	14,820	—	0.42	1.89	2.85				
D189704	3.2	38.8	46.5	11.5	5.6	69.0	1.3	8.1	4.5	7,070	12,720	0.2	0.01	2.02	2.43	8.5	1,040	1,100	1,140
	—	40.1	48.0	11.9	5.4	71.3	1.3	5.4	4.6	7,300	13,140	—	0.01	2.09	2.51				
	—	45.5	54.5	—	6.1	80.9	1.5	6.2	5.3	8,280	14,910	—	0.01	2.37	2.85				
D189705	2.8	39.9	45.5	11.8	5.4	68.8	1.3	7.9	4.8	7,100	12,780	0.3	0.01	2.26	2.55	9.0	1,015	1,070	1,120
	—	41.0	46.8	12.1	5.2	70.8	1.3	5.6	4.9	7,300	13,150	—	0.01	2.33	2.62				
	—	46.7	53.3	—	6.0	80.6	1.5	6.3	5.6	8,310	14,960	—	0.01	2.65	2.99				
D196196	3.4	39.5	46.8	10.3	5.3	69.7	1.3	9.0	4.3	7,050	12,690	0.1	0.38	1.86	2.06	8.0	1,015	1,040	1,060
	—	40.9	48.4	10.7	5.1	72.2	1.3	6.2	4.5	7,300	13,140	—	0.39	1.93	2.13				
	—	45.8	54.2	—	5.7	80.8	1.5	6.9	5.0	8,170	14,700	—	0.44	2.16	2.39				
D196197	2.8	39.6	45.5	12.1	5.3	67.9	1.3	8.4	5.0	6,960	12,530	0.2	0.41	2.75	1.89	8.5	1,050	1,070	1,095
	—	40.7	46.8	12.4	5.1	69.9	1.3	6.1	5.1	7,160	12,890	—	0.42	2.83	1.94				
	—	46.5	53.5	—	5.9	79.8	1.5	6.9	5.9	8,180	14,720	—	0.48	3.23	2.22				
D196198	3.8	36.8	48.7	10.7	5.1	69.6	1.3	10.2	3.0	6,910	12,440	0.6	0.40	1.39	1.25	8.5	1,230	1,260	1,305
	—	38.3	50.6	11.1	4.9	72.3	1.4	7.1	3.1	7,190	12,930	—	0.42	1.44	1.30				
	—	43.0	57.0	—	5.5	81.4	1.5	8.0	3.5	8,090	14,550	—	0.47	1.63	1.46				
D196199	4.0	35.3	48.4	12.3	5.0	67.7	1.3	11.4	2.4	6,700	12,060	0.5	0.27	1.05	1.04	8.0	1,100	1,115	1,130
	—	36.8	50.4	12.8	4.7	70.5	1.4	8.2	2.5	6,980	12,570	—	0.28	1.09	1.08				
	—	42.2	57.8	—	5.4	80.9	1.6	9.4	2.9	8,010	14,410	—	0.32	1.25	1.24				
D183114	3.9	31.5	41.0	23.6	4.5	59.2	1.0	7.0	4.8	5,990	10,780	1.3	0.55	3.75	0.50	8.0	1,070	1,140	1,190
	—	32.8	42.7	24.6	4.2	61.6	1.0	3.7	5.0	6,230	11,220	—	0.57	3.90	0.52				
	—	43.4	56.6	—	5.6	81.7	1.4	4.9	6.6	8,260	14,870	—	0.76	5.17	0.69				
D183115	2.6	35.8	42.9	18.7	4.7	65.3	1.1	6.4	3.8	6,490	11,680	0.9	0.21	2.53	1.05	8.5	1,075	1,120	1,165
	—	36.8	44.0	19.2	4.5	67.0	1.1	4.2	3.9	6,660	12,000	—	0.22	2.60	1.08				
	—	45.5	54.5	—	5.6	83.0	1.4	5.2	4.8	8,250	14,850	—	0.27	3.21	1.33				
D176045	1.9	36.2	43.7	18.2	4.7	65.5	1.2	5.3	5.1	6,510	11,710	0.4	0.10	4.34	0.64	6.0	1,050	1,065	1,080
	—	36.9	44.5	18.6	4.6	66.8	1.2	3.7	5.2	6,630	11,940	—	0.10	4.42	0.65				
	—	45.3	54.7	—	5.6	82.0	1.5	4.5	6.4	8,140	14,660	—	0.13	5.43	0.80				
D176046*	2.2	37.9	47.1	12.8	5.0	70.4	1.3	7.1	3.4	6,970	12,550	0.6	0.13	2.52	0.80	7.5	1,120	1,150	1,175
	—	38.8	48.2	13.1	4.9	72.0	1.3	5.3	3.5	7,130	12,830	—	0.13	2.58	0.82				
	—	44.6	55.4	—	5.6	82.8	1.5	6.1	4.0	8,200	14,760	—	0.15	2.96	0.94				
D183120	2.6	38.3	47.6	11.5	5.2	70.4	1.3	7.7	3.9	7,160	12,880	0.8	0.39	2.15	1.33	8.0	1,045	1,100	1,165
	—	39.3	48.9	11.8	5.0	72.3	1.3	5.5	4.0	7,350	13,230	—	0.40	2.21	1.37				
	—	44.6	55.4	—	5.7	82.0	1.5	6.3	4.5	8,330	15,000	—	0.45	2.50	1.55				
D183112*	3.5	36.6	46.2	13.7	5.1	67.3	1.1	8.2	4.6	6,890	12,400	1.1	0.05	3.53	0.98	9.0	1,045	1,100	1,165
	—	37.9	47.9	14.2	4.9	69.7	1.1	5.3	4.8	7,140	12,850	—	0.05	3.66	1.02				
	—	44.2	55.8	—	5.7	81.3	1.3	6.1	5.6	8,320	14,980	—	0.06	4.26	1.18				
D176048*	2.6	35.3	49.9	12.2	5.0	70.1	1.3	6.7	4.7	7,020	12,640	0.6	0.21	3.19	1.34	8.0	1,045	1,060	1,075
	—	36.2	51.2	12.5	4.8	72.0	1.3	4.5	4.8	7,210	12,980	—	0.22	3.28	1.38				
	—	41.4	58.6	—	5.5	82.3	1.5	5.2	5.5	8,240	14,840	—	0.25	3.74	1.57				
D183116	2.3	36.5	47.4	13.8	5.1	69.3	1.2	5.9	4.8	7,050	12,690	0.4	0.20	3.26	1.38	8.0	1,180	1,240	1,290
	—	37.4	48.5	14.1	5.0	70.9	1.2	3.9	4.9	7,210	12,990	—	0.20	3.34	1.41				
	—	43.5	56.5	—	5.8	82.6	1.4	4.6	5.7	8,400	15,120	—	0.24	3.89	1.64				
D183119	3.1	35.9	49.3	11.7	5.2	70.1	1.2	8.3	3.4	7,110	12,800	1.1	0.35	1.97	1.09	8.5	1,065	1,120	1,180
	—	37.0	50.9	12.1	5.0	72.3	1.2	5.7	3.5	7,340	13,210	—	0.36	2.03	1.12				
	—	42.1	57.9	—	5.7	82.3	1.4	6.5	4.0	8,350	15,020	—	0.41	2.31	1.28				
D180072	2.5	31.9	45.6	20.0	4.5	60.8	1.0	5.9	7.9	6,290	11,330	0.5	0.48	5.97	1.41	8.5	1,175	1,215	1,265
	—	32.7	46.8	20.5	4.3	62.4	1.0	3.8	8.1	6,450	11,620	—	0.49	6.12	1.45				
	—	41.2	58.8	—	5.4	78.5	1.3	4.7	10.2	8,120	14,620	—	0.62	7.70	1.82				
D180074	3.7	28.2	37.0	31.1	3.8	47.8	0.8	3.7	12.8	5,160	9,290	0.1	0.96	8.88	2.95	4.0	1,070	1,125	1,175
	—	29.3	38.4	32.3	3.5	49.6	0.8	0.4	13.3	5,360	9,650	—	1.00	9.22	3.06				
	—	43.3	56.7	—	5.2	73.3	1.2	0.6	19.6	7,910	14,250	—	1.47	13.62	4.52				
D183118	2.8	34.5	45.1	17.6	4.8	63.0	1.0	6.6	7.0	6,450	11,610	1.0	0.78	4.94	1.28	8.0	1,125	1,260	1,325
	—	35.5	46.4	18.1	4.6	64.8	1.0	4.2	7.2	6,640	11,940	—	0.80	5.08	1.32				
	—	43.3	56.7	—	5.6	79.1	1.3	5.2	8.8	8,100	14,590	—	0.98	6.21	1.61				
D176050*	1.7	35.3	45.8	17.2	4.6	64.6	1.1	4.2	8.3	6,630	11,940	0.3	0.29	6.64	1.38	6.0	1,105	1,130	1,160
	—	35.9	46.6	17.5	4.5	65.7	1.1	2.7	8.4	6,750	12,150	—	0.30	6.75	1.40				
	—	43.5	56.5	—	5.4	79.7	1.4	3.3	10.2	8,180	14,720	—	0.36	8.19	1.70				
D180069	2.3	33.4	43.3	21.0	4.1	57.6	0.9	4.1	12.3	6,090	10,970	0.7	0.70	10.73	0.86	7.5	1,315	1,375	1,420
	—	34.2	44.3	21.5	3.9	59.0	0.9	2.1	12.6	6,240	11,230	—	0.72	10.98	0.88				
	—	43.5	56.5	—	5.0	75.1	1.2	2.7	16.0	7,940	14,300	—	0.91	13.99	1.12				
D180071	2.5	33.9	43.8	19.8	4.7	59.9	1.0	4.4	10.2	6,290	11,320	0.5.	0.71	8.43	1.07	8.5	1,270	1,325	1,380
	—	34.8	44.9	20.3	4.5	61.4	1.0	2.2	10.5	6,450	11,610	—	0.73	8.65	1.10				
	—	43.6	56.4	—	5.7	77.1	1.3	2.8	13.1	8,100	14,570	—	0.91	10.85	1.38				
D180073	3.9	34.6	48.2	13.3	4.9	65.6	1.0	8.4	6.7	6,740	12,130	1.8	0.69	5.18	0.85	9.0	1,170	1,225	1,290
	—	36.0	50.2	13.8	4.6	68.3	1.0	5.1	7.0	7,010	12,630	—	0.72	5.39	0.88				
	—	41.8	58.2	—	5.4	79.2	1.2	6.0	8.1	8,140	14,650	—	0.83	6.26	1.03				
D183117	3.7	33.4	48.7	14.2	4.8	64.7	1.0	7.7	7.6	6,660	11,980	1.7	0.74	5.38	1.47	8.5	1,130	1,180	1,220
	—	34.7	50.6	14.7	4.6	67.2	1.0	4.6	7.9	6,910	12,440	—	0.77	5.59	1.53				
	—	40.7	59.3	—	5.3	78.8	1.2	5.4	9.3	8,110	14,600	—	0.90	6.55	1.79				
D176053*	3.3	31.2	50.4	15.1	4.6	68.1	1.2	6.9	4.1	6,700	12,060	1.3	0.36	3.17	0.57	7.5	1,055	1,080	1,110
	—	32.3	52.1	15.6	4.4	70.4	1.2	4.1	4.2	6,930	12,470	—	0.37	3.28	0.59				
	—	38.2	61.8	—	5.2	83.5	1.5	4.9	5.0	8,210	14,780	—	0.44	3.88	0.70				
D189706	4.4	33.2	49.4	13.0	5.0	66.8	1.1	7.8	6.3	6,810	12,260	1.4	0.01	3.56	2.73	5.5	1,080	1,140	1,180
	—	34.7	51.7	13.6	4.7	69.9	1.2	4.1	6.6	7,120	12,820	—	0.01	3.72	2.86				
	—	40.2	59.8	—	5.5	80.9	1.3	4.7	7.6	8,240	14,840	—	0.01	4.31	3.31				

Appendix B. Major- and minor-oxide and trace-element composition of the laboratory ash of 36 Pennsylvanaian coal samples from southeastern Kansas. Coal ashed at 525°C. S following element (e.g., Ag-S) indicates determinations by semiquantitative emission spectrography. (The spectrographic results are to be identified with geometric brackets whose boundaries are part of the ascending series 0.12, 0.18, 0.26, 0.38, 0.56, 0.83, 1.2, etc., but reported as midpoints of the brackets 0.1, 0.15, 0.2, 0.3, 0.5, 0.7, 1.0, etc. Precision of the spectrographic data is plus-or-minus one bracket at 68% or plus-or-minus two brackets at 95% confidence level.) L = less than the value shown; N = not detected; B = not determined.

Sample number	Ash %	SiO_2 %	Al_2O_3 %	CaO %	MgO %	Na_2O %	K_2O %	Fe_2O_3 %	TiO_2 %	P_2O_5 %	SO_3 %	Ag-S ppm	B-S ppm	Ba-S ppm	Be-S ppm	Cd ppm	Ce-S ppm	Co-S ppm	Cr-S ppm	Cu ppm	Ga-S ppm	Ge-S ppm	La-S ppm	Li ppm	Mn ppm	Mo-S ppm	Nb-S ppm	Nd-S ppm	Ni-S ppm	Pb ppm	Sc-S ppm	Sr-S ppm	V-S ppm	Y-S ppm	Yb-S ppm	Zn ppm	Zr-S ppm
D176058	7.6	21	9.5	27	0.64	0.55	1.3	11	0.48	0.51	5.0	N	3,000	200	30	1.0L	N	30	100	72	50	700	N	20	1,340	15	20L	B	300	350	30	300	150	70	7	172	70
D176055	19.4	21	9.3	14	1.21	0.62	1.4	28	0.40	0.46	10	N	300	300	7	1.0L	N	15	50	168	20	150	N	72	370	30	20L	B	70	900	15	20,000G	100	50	B	98	70
D176056	16.3	30	16	8.3	0.70	0.36	2.4	23	0.68	0.58	6.5	N	300	300	7	1.0L	500L	15	70	146	30	150	100L	34	595	30	20	150	70	530	15	5,000	300	70	B	86	70
D176057	23.4	36	16	7.9	1.53	0.77	2.7	16	1.0	0.27	6.5	N	300	700	7	1.0L	500L	50	150	118	30	70	100L	60	510	30	20	150L	200	200	15	5,000	700	50	B	166	150
D189091	10.9	41	12	4.5	0.80	0.32	2.3	31	0.56	1.0L	3.4	2	200	150	15	9.0	N	50	70	162	15	200	N	36	225	70	N	B	200	885	15	200	70	50	B	214	50
D189704	11.8	30	10	7.7	0.80	0.28	2.0	32	0.51	1.0L	4.3	2	150	150	10	1.0L	N	15	50	177	N	150	N	27	440	30	N	B	70	850	7	200	50	20	B	169	50
D189705	12.1	29	8.8	8.6	0.88	0.28	1.9	34	0.44	1.0L	6.7	5	150	150	10	261	N	15	150	169	N	150	N	29	360	70	N	B	100	810	7	200	200	20	B	12,500	30
D196196	10.8	32	12	6.0	0.64	0.28	1.5	32	0.50	0.010L	7.2	3	200	200	10	210	N	20	100	216	B	300	N	31	410	30	N	B	100	740	10L	200	100	30	B	15,000	50
D196197	12.1	42	12	3.7	0.66	0.29	1.8	33	0.50	0.010L	4.8	3	200	200	15	2.0	N	30	50	188	B	300	N	31	260	70	N	B	150	1,100	15	200	70	50	B	300	70
D196198	13.7	16	5.5	25	0.58	0.18	0.50	16	0.10	0.010	15	N	150	50	7	1.0	N	N	15	61	15	150	N	18	2,490	7	N	B	20	460	10L	500	15	30	3	300	20
D196199	15.4	24	9.3	23	0.78	0.27	1.1	13	0.40	0.090	7.2	N	150	200	5	1.0	N	15	30	165	15	70	N	43	2,040	15	N	B	70	350	15	500	70	30	3	300	50
D183114	25.7	38	1.6	14	0.60	0.12	0.51	27	0.088	1.0L	10	1.5	100	100	N	1.0L	N	50	15	79	B	70	N	10L	1,480	7	20	B	150	440	10L	100	30	70	B	83	30
D183115	19.5	17	2.2	30	0.55	0.18	0.62	22	0.20	1.0L	14	N	150	300	7	1.0L	N	70	30	89	B	100	N	12	2,360	N	20	B	150	300	15	300	70	100	B	293	70
D176045	20.0	20	5.8	19	0.65	0.26	1.2	28	0.23	0.33	9.4	N	150	200	7	1.0	N	50	30	158	B	70	N	17	1,780	N	20L	B	10	400	15	300	70	70	7	256	30
D176046	17.4	13	4.9	25	0.55	0.24	1.0	24	0.21	0.41	16	N	150	150	5	1.0L	N	50	50	158	B	150	N	17	1,920	10	20L	B	100	480	20	300	70	70	B	146	30
D176047	13.6	18	6.7	19	1.06	0.32	1.3	26	0.31	0.34	12	N	200	150	7	1.0L	N	70	50	164	B	150	N	22	1,840	7	20L	B	150	410	15	300	100	70	B	174	70
D183120	12.3	28	8.2	13	0.81	0.40	1.8	32	0.45	1.0L	7.5	N	300	200	10	1.0	N	70	70	169	B	150	N	33	1,170	10	30	B	200	540	20	300	150	100	B	507	150
D183112	14.4	23	7.7	12	0.65	0.20	1.4	36	0.44	1.0L	9.2	3	200	150	10	309	N	70	100	181	30	70	N	22	895	70	30	B	300	400	15	200	150	70	B	40,600	70
D183113	14.8	17	5.8	12	1.08	0.19	1.2	44	0.33	1.0L	9.2	2	150	150	7	42.0	N	70	50	215	B	70	N	20	1,370	50	30	B	300	565	15	150	70	70	B	6,680	70
D176048	13.2	25	10	8.6	0.60	0.28	1.6	34	0.54	0.15	6.3	3	150	150	7	1.0L	500L	50	70	194	30	70	100	34	770	20	20L	150	150	580	20	300	100	70	B	298	70
D176049	13.2	22	9.7	6.7	0.51	0.67	1.4	44	0.48	0.13	5.7	3	150	150	7	1.0	N	50	70	204	10	70	N	31	545	20	20L	B	200	710	20	300	100	50	B	348	100
D183116	13.2	24	8.0	13	0.63	0.22	1.5	36	0.47	1.0L	8.3	3	200	500	10	3.0	N	70	70	160	30	100	100L	34	1,070	20	30	N	200	445	20	300	150	100	B	902	100
D183119	12.8	35	11	9.2	0.98	0.36	2.2	28	0.69	1.0L	5.6	3	200	300	10	18.0	N	70	150	190	B	100	N	41	910	30	30	B	300	440	20	200	150	70	B	3,760	150
D180072	20.9	36	21	0.31	0.42	0.11	1.2	36	0.58	1.0L	2.6	2	50	150	10	77.0	200	300	70	200	50	20	70	60	115	N	N	200	500	230	20	150	150	300	30	25,500	100
D180074	32.3	21	9.5	2.6	0.40	0.07	0.85	31	0.29	1.0L	15	N	N	100	5	490	N	100	50	232	100	20	70	30	320	N	N	N	300	450	10	300	100	150	B	158,000	50
D183118	18.9	30	12	2.6	0.48	0.15	1.6	42	0.54	1.0L	2.9	1.5	150	200	10	5.0	N	300	70	169	B	70	N	56	600	15	30	B	700	500	20	150	150	200	B	1,630	100
D176050	16.4	22	13	0.73	0.43	0.22	1.3	52	0.62	0.10L	1.6	1.5	150	150	10	1.0L	500L	70	70	210	B	70	100L	132	310	7	20L	150L	300	830	15	70	100	100	B	120	70
D176051	16.6	23	13	0.64	0.42	0.24	1.3	51	0.55	0.10L	1.5	1.5	150	150	10	1.0L	N	100	70	200	B	70	100L	107	280	15	20L	150L	500	660	20	70	150	50	B	184	70
D176052	18.2	18	11	0.60	0.29	0.22	1.0	59	0.48	0.10L	1.4	1.5	100	150	7	1.0L	500L	100	70	300	B	70	100	108	640	N	20L	150	200	1,060	15	70	150	70	B	183	70
D180069	18.8	21	11	0.47	0.32	0.14	0.97	57	0.47	1.0L	1.6	N	50	100	15	1.0L	N	70	70	213	B	50	N	51	740	N	N	B	300	900	10	300	100	50	B	204	50
D180071	17.9	27	13	0.46	0.42	0.16	0.93	50	0.63	1.0L	1.6	N	70	150	15	1.0L	N	30	70	176	30	70	N	137	135	N	N	B	150	1,200	10	200	100	70	B	89	100
D180073	13.9	26	15	1.4	0.46	0.19	0.82	50	0.53	1.0L	3.3	N	70	500	15	1.5	N	70	100	306	30	100	N	90	340	N	N	B	200	1,200	15	300	200	100	B	1,020	100
D183117	15.4	21	10	1.1	0.32	0.18	1.3	54	0.49	1.0L	2.1	1.5	150	200	15	1.0L	N	70	70	311	B	70	100	77	160	30	30	100	300	1,300	20	150	150	150	B	352	70
D176053	16.1	33	18	2.3	1.01	0.30	2.8	30	0.81	0.10L	3.7	2	150	300	7	1.0L	500L	70	70	110	30	30	N	129	420	7	20	N	300	190	20	150	150	50	B	88	150
D176054	16.1	35	20	0.85	0.94	0.23	3.1	27	0.93	0.10L	1.9	3	150	300	7	1.0L	500L	70	100	136	50	N	100L	156	155	7	20L	150L	300	170	30	150	200	50	B	90	150
D189706	12.9	24	12	1.4	0.45	0.25	1.4	46	0.45	1.0L	2.1	2	50	100	10	1.0L	500L	100	70	241	B	30	100L	82	160	15	N	150L	500	835	20	1,500	150	50	B	376	50

Appendix C. Major-, minor-, and trace-element composition of 36 Pennsylvanian coal samples from southeastern Kansas (whole coal basis). As, F, Hg, Sb, Se, Th, and U values are from direct determinations on air-dried (32°C) coal; all other values were calculated from analyses of coal ash. S following element (Ag-S) indicates analysis by emission spectrography. L = less than the value shown; N = not detected; B = not determined.

Sample number	Si %	Al %	Ca %	Mg %	Na %	K %	Fe %	Ti %	Ag-S ppm	As ppm	B-S ppm	Ba-S ppm	Be-S ppm	Cd ppm	Ce-S ppm	Co-S ppm	Cr-S ppm	Cu ppm	F ppm	Ga-S ppm	Ge-S ppm	Hg ppm	La-S ppm	Li ppm	Mn ppm	Mo-S ppm	Nb-S ppm	Nd-S ppm	Ni-S ppm	P ppm	Pb ppm	Sb ppm	Sc-S ppm	Se ppm	Sr-S ppm	Th ppm	U ppm	V-S ppm	Y-S ppm	Yb-S ppm	Zn ppm	Zr-S ppm
D176058	0.75	0.38	1.5	0.029	0.031	0.082	0.60	0.022	N	12	200	15	2	0.08L	N	2	7	5.5	100	3	50	0.08	N	1.5	100	1	1.5L	B	20	170	27	4.3	2	0.5	20	3.0L	0.2L	10	5	0.5	13	5
D176055	1.9	0.95	1.9	0.14	0.089	0.23	3.8	0.046	N	50	70	70	1.5	0.19L	N	3	10	33	205	5	30	0.09	N	14.	72	7	5L	B	15	390	170	2.5	3	2.6	5,000G	3.0L	2.9	20	10	B	19	15
D176056	2.3	1.4	0.97	0.069	0.043	0.33	2.6	0.066	N	60	50	50	1	0.16L	70L	2	10	24	295	5	20	0.07	15L	5.5	97	5	3	20	10	410	86	2.3	2	2.3	700	3.0L	4.7	50	10	B	14	10
D176057	3.9	2.0	1.3	0.22	0.13	0.53	2.7	0.14	N	35	70	150	1.5	0.23L	100L	10	30	28	330	7	15	0.06	20L	14.	120	7	5	30L	50	280	47	1.9	3	2.8	1,000	16.0	7.1	150	10	B	39	30
D189091	2.1	0.69	0.35	0.052	0.026	0.21	2.4	0.037	0.2	16	20	15	1.5	0.98	N	5	7	18	100	1.5	20	0.13	N	3.9	25	7	N	B	20	480L	96	5.0	1.5	7.4	20	1.1	6.3	7	5	B	23	5
D189704	1.7	0.62	0.65	0.057	0.024	0.20	2.6	0.036	0.2	13	15	15	1	0.12L	N	1.5	7	21	70	N	15	0.10	N	3.2	52	3	N	B	10	520L	100	3.1	1	3.1	20	1.2	3.4	7	2	B	20	7
D189705	1.6	0.56	0.74	0.064	0.025	0.19	2.9	0.032	0.7	22	20	20	1	32	N	2	20	20	110	N	20	0.20	N	3.5	44	10	N	B	10	530L	98	4.7	1	9.7	20	1.1	22.	20	2	B	1,500	3
D196196	1.6	0.69	0.46	0.042	0.022	0.13	2.4	0.032	0.3	19	20	20	1	23	N	2	10	23	75	B	30	0.13	N	3.3	44	3	N	B	10	5L	80	3.7	1L	5.9	20	1.0	5.1	10	3	B	1,600	5
D196197	2.4	0.77	0.32	0.048	0.026	0.18	2.8	0.036	0.3	21	20	20	2	0.24	N	3	7	23	85	B	30	0.12	N	3.8	31	10	N	B	20	5L	130	3.4	2	8.3	20	1.1	25.	10	7	B	36	10
D196198	1.0	0.40	2.4	0.048	0.018	0.057	1.5	0.008	N	6.8	20	7	1	0.14	N	N	2	8.4	50	2	20	0.14	N	2.5	340	1	N	B	3	6	63	0.2	1.5L	1.6	70	0.5	0.2L	2	5	0.5	41	3
D196199	1.7	0.76	2.5	0.072	0.031	0.14	1.4	0.037	N	7.6	20	30	0.7	0.15	N	2	5	25	115	2	10	0.10	N	6.6	310	2	N	B	10	61	54	0.4	2	2.4	70	1.2	1.2	10	5	0.5	46	7
D183114	4.6	0.22	2.6	0.093	0.023	0.11	4.9	0.014	0.5	14	20	20	N	0.26L	N	15	5	20	50	B	20	0.11	N	2.6L	380	2	5	B	50	1,100L	110	1.2	2L	0.8	20	9.2	0.2L	7	20	B	21	7
D183115	1.5	0.23	4.2	0.065	0.026	0.10	3.0	0.023	N	17	30	70	1.5	0.20L	N	15	7	17	65	B	20	0.12	N	2.3	460	N	5	B	30	850L	59	0.7	3	0.9	70	14.5	0.2L	15	20	B	57	15
D176045	1.8	0.61	2.7	0.078	0.039	0.19	3.9	0.028	N	15	30	50	1.5	0.20	N	10	7	32	55	B	15	0.12	N	3.4	360	N	5L	B	2	290	80	0.8	3	1.5	70	3.0L	0.7	15	15	1.5	51	7
D176046	1.0	0.45	3.1	0.058	0.031	0.14	2.9	0.022	N	20	20	20	1	0.17L	N	10	10	27	55	B	20	0.11	N	3.0	330	1.5	3L	B	15	310	84	0.8	3	1.4	50	3.0L	1.5	15	15	B	25	5
D176047	1.1	0.48	1.8	0.087	0.032	0.15	2.5	0.025	N	15	30	20	1	0.14L	N	10	7	22	80	B	20	0.12	N	3.0	250	1	3L	B	20	200	56	0.6	2	2.3	50	3.0L	0.4	15	10	B	24	10
D183120*	1.6	0.53	1.1	0.060	0.036	0.18	2.8	0.033	N	9.0	30	20	1.5	0.12L	N	10	10	21	55	B	20	0.13	N	4.1	140	1.5	3	B	20	540L	66	0.7	2	1.0	30	3.0L	1.0	20	15	B	62	20
D183112	1.5	0.59	1.2	0.056	0.021	0.17	3.6	0.038	0.5	16	30	20	1.5	44	N	10	15	26	65	5	10	0.23	N	3.2	130	10	5	B	50	630L	58	2.1	2	4.9	30	8.5	5.4	20	10	B	5,800	10
D183113	1.2	0.45	1.3	0.096	0.021	0.15	4.6	0.029	0.3	28	20	20	1	6.2	N	10	7	32	75	B	10	0.17	N	3.0	200	7	5	B	50	650L	84	2.5	2	2.5	20	3.0L	1.6	10	10	B	990	10
D176048	1.5	0.71	0.81	0.048	0.027	0.17	3.1	0.043	0.5	10	20	20	1	0.13L	70L	7	10	26	80	5	10	0.11	15	4.5	100	3	3L	20	20	87	77	0.8	3	0.9	50	3.0L	2.4	15	10	B	39	10
D176049	1.4	0.67	0.63	0.041	0.066	0.15	4.0	0.038	0.5	15	20	20	1	0.13	N	7	10	27	70	1.5	10	0.14	N	4.1	72	3	3L	B	30	75	94	1.2	3	2.3	50	3.0L	1.1	15	7	B	46	15
D183116	1.5	0.56	1.2	0.050	0.022	0.16	3.3	0.037	0.5	8.0	30	70	1.5	0.40	N	1	10	21	70	5	15	0.12	15L	4.5	140	3	5	N	30	580L	59	1.4	3	1.7	50	3.0L	1.4	20	15	B	120	15
D183119*	2.1	0.74	0.84	0.076	0.034	0.23	2.5	0.053	0.5	6.0	20	50	1.5	2.3	N	10	20	24	65	B	15	0.14	N	5.2	120	5	5	B	50	560L	56	1.3	2	2.8	20	3.0L	3.6	20	10	B	480	20
D180072	3.5	2.4	0.046	0.053	0.017	0.21	5.2	0.073	0.5	27	10	30	2	16	50	70	15	42	75	10	5	0.23	15	13.	24	N	N	50	100	910L	48	1.7	5	4.5	30	3.0L	1.6	30	70	7.	5,300	20
D180074	3.1	1.6	0.61	0.078	0.017	0.23	7.0	0.056	N	31	N	30	1.5	160	N	30	15	75	65	30	7	0.83	20	9.7	100	N	N	N	100	1,400L	150	1.5	3	3.0	100	3.0L	1.7	30	50	B	51,000	15
D183118*	2.6	1.2	0.35	0.055	0.021	0.25	5.5	0.061	0.3	27	30	30	2	0.95	N	70	15	32	65	B	15	0.18	N	11	110	3	7	B	150	830L	95	1.2	3	2.5	30	4.6	1.5	30	30	B	310	20
D176050	1.7	1.1	0.085	0.042	0.027	0.18	6.0	0.061	0.2	30	20	20	1.5	0.16L	70L	10	10	34	75	B	10	0.18	15L	22	51	1	3L	20L	50	72L	140	0.6	2	4.6	10	3.0L	1.4	15	15	B	20	10
D176051	1.8	1.1	0.076	0.042	0.030	0.18	5.9	0.055	0.2	35	20	20	1.5	0.17L	N	15	10	33	60	B	10	0.17	15L	18	46	2	3L	20L	100	73L	110	0.9	3	3.5	10	3.0L	0.8	20	10	B	31	10
D176052	1.5	1.0	0.078	0.032	0.030	0.15	7.5	0.052	0.3	60	20	30	1.5	0.18L	100L	20	15	55	45	B	15	0.26	20	20	120	N	3L	30	30	80L	190	0.7	3	4.2	15	3.0L	1.0	30	15	B	33	15
D180069	1.8	1.1	0.063	0.036	0.020	0.15	7.5	0.053	N	41	10	20	3	0.19L	N	15	15	40	40	B	10	0.21	N	9.6	140	N	N	B	70	820L	170	0.9	2	3.1	70	3.0L	0.9	20	10	B	38	10
D180071	2.3	1.3	0.059	0.045	0.021	0.14	6.2	0.068	N	39	15	30	3	0.18L	N	5	15	32	55	5	15	0.20	N	25	24	N	N	B	30	780L	210	0.6	2	2.7	30	3.0L	0.6	20	15	B	16	20
D180073	1.7	1.1	0.14	0.038	0.020	0.095	4.8	0.044	N	25	10	70	2	0.21	N	10	15	43	30	5	15	0.14	N	13	47	N	N	B	30	610L	170	0.6	2	3.3	50	3.0L	0.8	30	15	B	140	15
D183117*	1.5	0.81	0.12	0.030	0.021	0.17	5.8	0.045	0.2	33	20	30	2	0.15L	N	10	10	48	35	B	10	0.19	15	12	25	5	5	15	50	670L	200	0.9	3	3.6	20	3.0L	12.	20	20	B	54	10
D176053	2.5	1.5	0.26	0.098	0.036	0.38	3.4	0.078	0.3	35	20	50	1	0.16L	70L	10	10	18	90	5	5	0.11	N	21	68	1	3	N	50	70L	31	1.5	3	3.3	20	6.8	0.6	20	7	B	14	20
D176054	2.7	1.7	0.098	0.091	0.027	0.42	3.1	0.090	0.5	25	20	50	1	0.16L	70L	10	15	22	105	7	N	0.16	15L	25	25	1	3L	20L	50	70L	27	1.5	5	3.5	20	3.0L	1.1	30	7	B	14	20
D189706	1.4	0.82	0.13	0.035	0.024	0.15	4.1	0.035	0.2	40	7	15	1.5	0.13L	70L	15	10	31	30	B	5	0.14	15L	11	21	2	N	20L	70	560L	110	1.7	2	2.8	200	1.6	5.4	20	7	B	49	7

* Tipple sample

APPENDIX D. Correlation matrix for trace and minor elements in Kansas coals. Correlation coefficients and number of pairs are shown in the lower half of the array.

	Si	Al	Ca	Mg	Na	K	Fe	Ti	Ag-S	As	B-S	Ba-S	Be-S	Cd	Co-S	Cr-S	Cu	F	Ga-S	Ge-S	Hg	Li	Mn	Mo-S	Ni-S	Pb	Sb	Sc-S	Se	Sr-S	U	V-S	Y-S	Zn	Zr-S	Ash
%	%	%	%	%	%	%	%	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
Si (%)	—	0.50	-0.26	0.49	0.13	0.59	0.43	0.52	0.21	0.35	-0.17	0.44	0.22	0.38	0.31	0.37	0.41	0.27	0.62	-0.29	0.13	0.62	-0.25	0.26	0.38	0.10	0.15	.032	0.27	0.18	0.16	0.44	0.39	0.14	0.50	0.66
Al (%)	32	—	-0.68	0.12	0.18	0.68	0.39	0.88	-0.15	0.60	0.18	0.38	0.26	0.34	0.23	0.64	0.54	0.27	0.66	-0.49	0.25	0.83	-0.60	0.07	0.39	0.08	0.06	0.37	0.50	0.21	-0.14	0.67	0.25	0.13	0.60	0.31
Ca (%)	32	32	—	0.48	0.29	-0.21	-0.56	-0.58	0.39	-0.55	0.54	0.06	-0.50	-0.24	-0.33	-0.47	-0.44	0.30	-0.31	0.45	-0.43	-0.73	0.76	0.14	-0.54	-0.32	-.01	-0.12	-0.53	0.31	0.19	-0.29	-0.16	-0.02	-0.35	-0.02
Mg (%)	32	32	32	—	0.54	0.59	-0.04	0.24	0.31	0.10	0.33	0.55	-0.33	0.31	0.01	0.12	0.06	0.63	0.35	-0.01	-0.26	0.12	0.27	0.24	-0.02	-0.27	0.11	0.20	-0.04	0.38	0.07	0.32	0.09	0.01	0.33	0.50
Na (%)	32	32	32	32	—	0.49	-0.18	0.34	0.00	0.24	0.58	0.50	-0.19	-0.50	-0.25	0.22	-0.05	0.68	-0.18	0.20	0.58	0.13	0.09	0.20	-0.14	-0.13	0.14	0.18	-0.10	0.48	0.10	0.44	-0.15	-0.41	0.31	0.11
K (%)	32	32	32	32	32	—	0.20	0.81	0.02	0.48	0.11	0.54	-0.13	0.46	0.04	0.59	0.33	0.62	0.43	-0.32	-0.08	0.49	-0.35	0.27	0.26	-0.19	0.38	0.28	0.38	0.27	0.19	0.68	0.04	0.01	0.52	0.32
Fe (%)	32	32	32	32	32	32	—	0.39	-0.11	0.58	-0.60	0.17	0.39	0.45	0.65	0.46	0.85	0.39	0.56	-0.54	-0.60	0.62	-0.20	0.19	0.53	0.64	0.20	0.24	0.33	-0.12	-0.39	0.36	0.55	0.25	0.47	0.62
Ti (%)	32	32	32	32	32	32	32	—	-0.11	0.63	-0.03	0.58	0.24	0.40	0.18	0.79	0.51	0.40	0.54	-0.43	0.11	0.78	-0.54	0.20	0.50	0.01	0.19	0.37	0.42	0.19	-0.08	0.82	0.21	0.04	0.74	0.29
Ag-S (ppm)	18	18	18	18	18	18	18	18	—	-0.40	0.32	0.40	-0.20	0.26	0.11	0.44	-0.15	0.30	0.52	0.07	0.18	-0.22	0.32	0.23	-0.08	-0.40	0.01	0.29	-0.22	0.18	0.09	0.34	0.19	0.43	0.14	0.22
As (ppm)	32	32	32	32	32	32	32	32	18	—	-0.09	0.33	0.37	0.60	0.24	0.60	0.56	0.14	0.52	-0.22	0.22	0.66	-0.40	0.23	0.34	0.42	.18	0.14	0.37	0.14	-0.01	0.63	0.26	-0.01	0.45	0.38
B-S (ppm)	31	31	31	31	31	31	31	31	18	31	—	0.28	-0.06	-0.03	-0.39	-0.04	-0.52	0.66	-0.03	0.62	-0.60	-0.30	0.31	0.07	-0.25	-0.40	0.28	0.06	-0.41	0.20	0.17	0.14	-0.11	-0.23	0.01	-0.15
Ba-S (ppm)	32	32	32	32	32	32	32	32	18	32	31	—	0.18	-0.10	0.15	0.51	0.30	0.42	0.44	-0.03	-0.23	0.40	0.06	0.22	0.14	-0.12	0.00	0.46	-0.05	0.44	-0.16	0.74	0.35	-0.05	0.72	0.44
Be-S (ppm)	31	31	31	31	31	31	31	31	17	31	30	31	—	0.07	0.33	0.35	0.22	-0.30	0.31	0.03	0.26	0.12	-0.31	0.23	0.38	0.40	0.03	0.05	0.06	-0.05	-0.07	0.23	0.43	0.02	0.31	0.18
Cd (ppm)	14	14	14	14	14	14	14	14	9	14	13	14	14	—	0.28	0.62	0.43	0.22	0.80	-0.30	0.76	0.13	-0.29	0.58	0.51	0.00	0.55	-0.05	0.46	-0.29	0.33	0.43	0.21	0.94	0.04	0.35
Co-S (ppm)	31	31	31	31	31	31	31	31	18	31	30	31	30	13	—	0.28	0.54	0.44	0.64	-0.61	0.52	0.39	-0.10	0.28	0.67	0.03	-0.42	0.65	-0.07	0.02	0.45	0.33	0.81	0.31	0.49	0.62
Cr-S (ppm)	32	32	32	32	32	32	32	32	18	32	31	32	31	14	31	—	0.56	0.19	0.62	-0.27	0.27	0.10	-0.44	0.38	0.51	0.13	0.29	0.20	0.39	0.17	0.13	0.87	0.22	0.30	0.55	0.27
Cu (ppm)	32	32	32	32	32	32	32	32	18	32	31	32	31	14	31	32	—	-0.20	0.62	-0.53	0.57	0.56	-0.19	0.34	0.43	0.60	-0.14	0.26	0.40	0.09	-0.31	0.52	0.54	0.39	0.48	0.62
F (ppm)	32	32	32	32	32	32	32	32	18	32	31	32	31	14	31	32	32	—	0.03	0.29	-0.47	0.01	-0.03	0.38	-0.15	0.34	0.41	0.03	0.07	0.40	0.37	0.38	-0.19	-0.13	0.19	0.03
Ga-S (ppm)	17	17	17	17	17	17	17	17	8	17	16	17	17	9	16	17	17	17	—	-0.39	0.56	0.49	0.19	0.11	0.67	0.10	0.13	0.50	0.12	0.20	-0.06	0.61	0.80	0.62	0.59	0.75
Ge-S (ppm)	31	31	31	31	31	31	31	31	17	31	30	31	30	14	30	31	31	31	16	—	-0.45	-0.51	0.19	0.15	-0.55	0.01	0.24	-0.31	-0.20	-0.09	0.36	-0.27	-0.37	-0.31	0.10	-0.38
Hg (ppm)	32	32	32	32	32	32	32	32	18	32	31	32	31	14	31	32	32	32	17	31	—	0.26	-0.18	0.43	0.42	0.36	-0.11	0.11	0.36	-0.29	-0.16	0.04	0.42	0.68	0.11	0.37
Li (ppm)	31	31	31	31	31	31	31	31	17	31	30	31	31	14	30	31	31	31	17	30	31	—	-0.49	-0.19	0.53	0.27	-0.22	0.39	0.34	-0.04	-0.37	0.55	0.34	-0.13	0.64	0.51
Mn (ppm)	32	32	32	32	32	32	32	32	18	32	31	32	31	14	31	32	32	32	17	31	32	31	—	-0.21	-0.34	-0.17	-0.46	0.10	-0.62	0.24	-0.32	-0.23	0.17	-0.06	-0.19	0.28
Mo-S (ppm)	24	24	24	24	24	24	24	24	16	24	24	24	23	10	23	24	24	24	13	23	24	23	24	—	-0.03	0.43	0.60	-0.35	0.49	0.18	0.79	0.25	-0.15	0.52	0.05	0.03
Ni-S (ppm)	32	32	32	32	32	32	32	32	18	32	31	32	31	14	31	32	32	32	17	31	32	31	32	24	—	0.05	0.10	0.35	0.14	-0.11	-0.16	0.45	0.48	0.13	0.58	0.34
Pb (ppm)	32	32	32	32	32	32	32	32	18	32	31	32	31	14	31	32	32	32	17	31	32	31	32	24	32	—	-0.12	-0.30	0.30	-0.09	0.06	-0.01	0.15	0.04	-0.02	0.26
Sb (ppm)	32	32	32	32	32	32	32	32	18	32	31	32	31	14	31	32	32	32	17	31	32	31	32	24	32	32	—	-0.34	0.34	-0.11	0.77	0.14	-0.34	0.23	-0.11	-0.34
Sc-S (ppm)	29	29	29	29	29	29	29	29	16	29	28	29	29	12	29	29	29	29	16	28	29	29	29	21	29	29	29	—	-0.28	0.11	-0.44	0.43	0.68	0.25	0.65	0.52
Se (ppm)	32	32	32	32	32	32	32	32	18	32	31	32	31	14	31	32	32	32	17	31	32	31	32	24	32	32	32	29	—	-0.23	0.52	0.17	-0.22	0.33	0.04	-0.08
Sr-S (ppm)	31	31	31	31	31	31	31	31	18	31	30	31	30	14	30	31	31	31	16	30	31	30	31	23	31	31	31	28	31	—	0.15	0.48	0.15	-0.01	0.20	0.30
U (ppm)	28	28	28	28	28	28	28	28	17	28	27	28	28	13	28	28	28	28	15	27	28	28	28	21	28	28	28	27	28	27	—	-0.02	-0.44	0.22	-0.41	0.34
V-S (ppm)	32	32	32	32	32	32	32	32	18	32	31	32	31	14	31	32	32	32	17	31	32	31	32	24	32	32	32	29	32	31	28	—	0.37	0.13	0.70	0.42
Y-S (ppm)	32	32	32	32	32	32	32	32	18	32	31	32	31	14	31	32	32	32	17	31	32	31	32	24	32	32	32	29	32	31	28	32	—	0.29	0.55	0.72
Zn (ppm)	32	32	32	32	32	32	32	32	18	32	31	32	31	14	31	32	32	32	17	31	32	31	32	24	32	32	32	29	32	31	28	32	32	—	0.00	0.22
Zr-S (ppm)	32	32	32	32	32	32	32	32	18	32	31	32	31	14	31	32	32	32	17	31	32	31	32	24	8	32	32	29	31	31	28	32	32	18	—	0.50
Ash (ppm)	32	32	32	32	32	32	32	32	18	32	31	32	31	14	31	32	32	32	17	31	32	31	32	24	8	32	32	29	32	31	28	32	32	32	32	—