U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

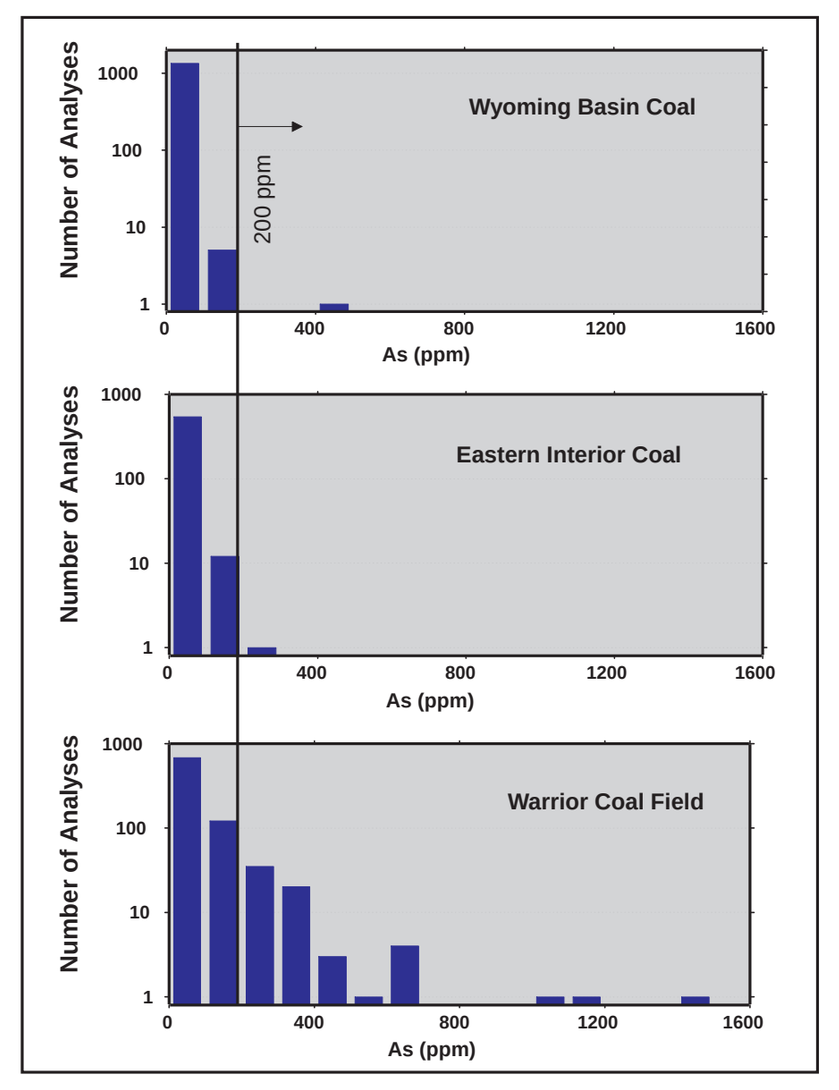


Figure 1. Histogram comparing concentration of arsenic in coal (whole coal basis) from three coal-bearing areas. Histogram A shows data for the Wyoming Basin. Histogram B shows data for Eastern Interior Coal including parts of Illinois, Indiana, western Kentucky, and Missouri. Histogram C shows data for the Warrior coal field. Note the exceptional number of data that fall above 200 parts per million (ppm) in the Warrior coal field.

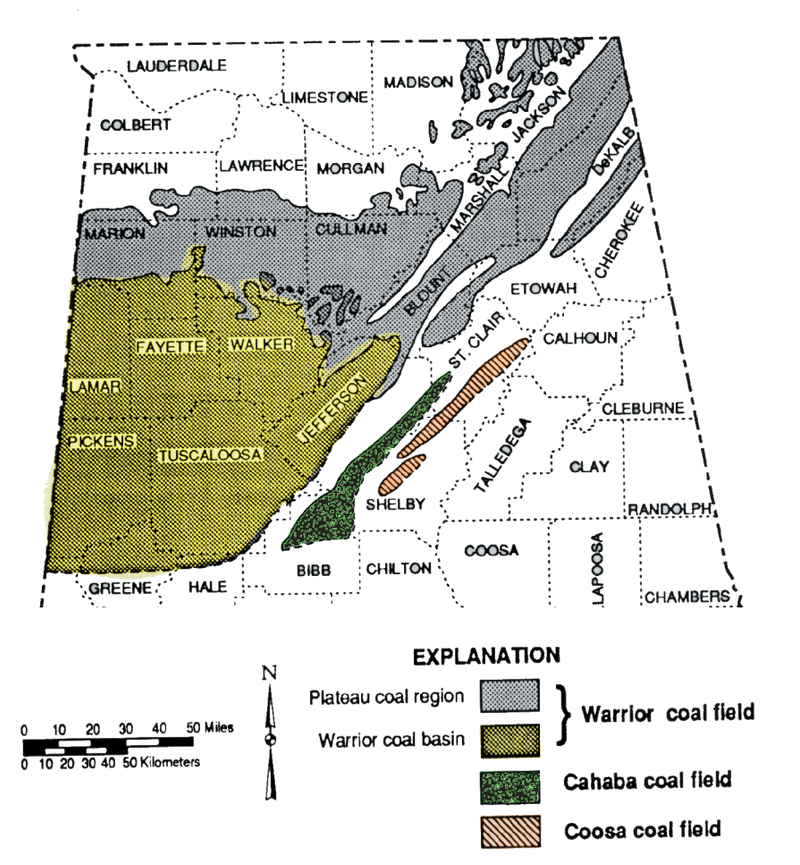


Figure 2. Index map showing the location of the Warrior coal field in northern Alabama. The Warrior coal field is comprised of the Warrior coal basin (yellow) and the Plateau coal region (gray). Two other coal-bearing areas, the Cahaba coal field (green) and the Coosa coal field (orange) are present to the southeast of the Warrior coal field. All coal-bearing areas shown in this figure are in the Pennsylvanian Pottsville Formation.

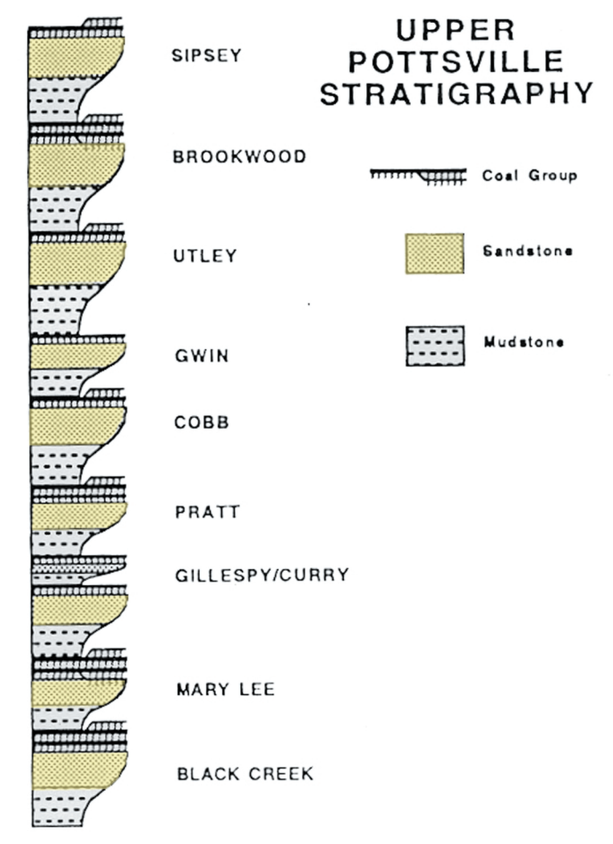


Figure 3. Stratigraphic column showing stratigraphy of the Pennsylvanian upper Pottsville Formation. Also shown are the coal groups referred to in the text. These groups consist of bundles of coal beds that can be traced for long distances in the Warrior coal field.

Arsenic in Warrior Field Coal
Shown with Sample Data Locations in Five Coal Groups

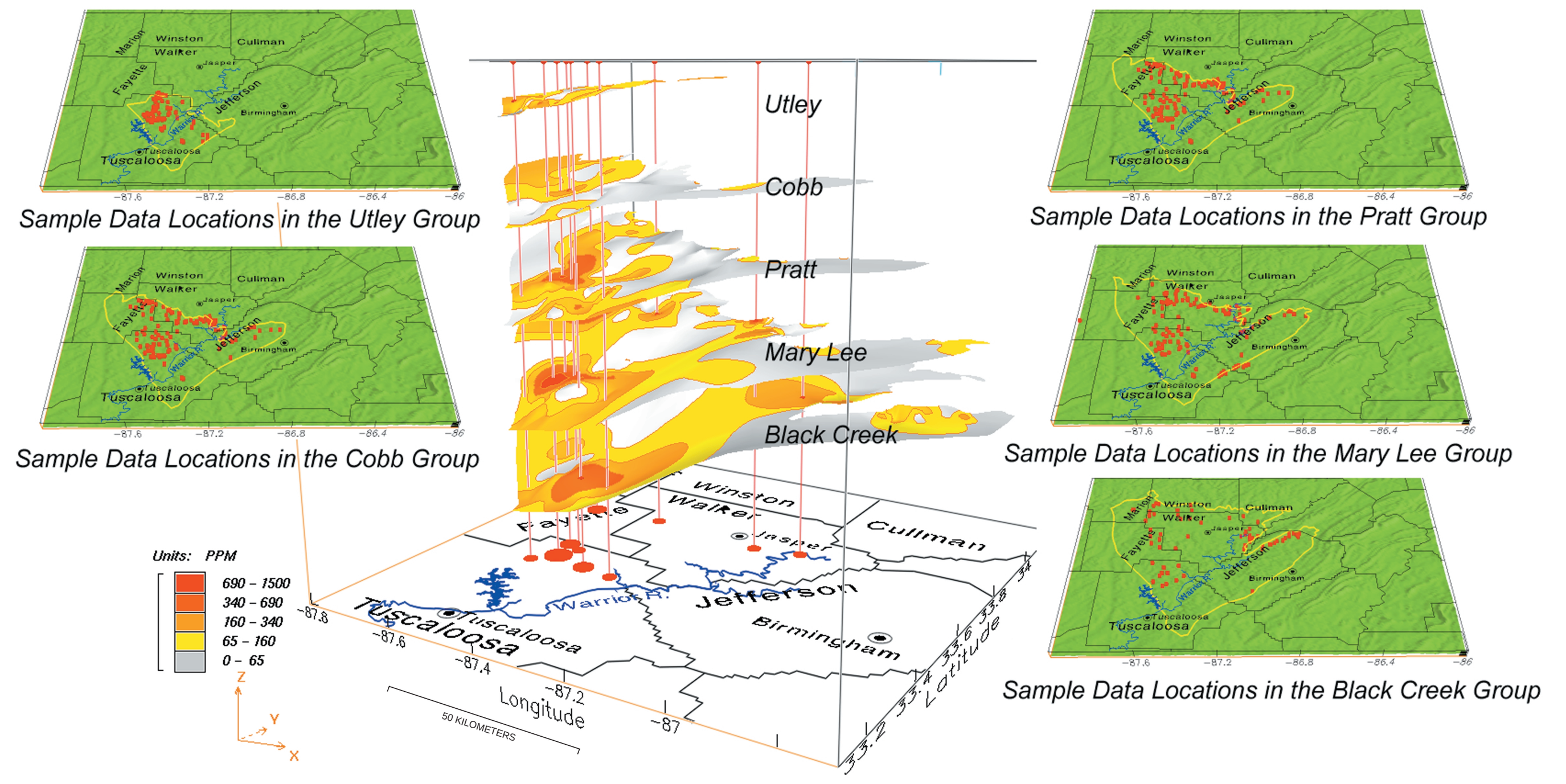


Figure 4. Arsenic concentration in the Warrior coal field. The three-dimensional view shows contoured concentrations of arsenic in ppm (parts per million) for five different coal groups. The view is toward the northwest. Vertical dimension is not drawn to scale. The two-dimensional views show sample control points for each coal group. The two-dimensional sample locations for figures 5-15 are the same as shown here. The vertical lines are drawn through areas with exceptionally high arsenic. The downward projection of the lines shows the geographic location of these high values. The lower intercept of these drop lines has an associated circle whose diameter is roughly proportional to the extent of the associated arsenic enrichment. See appendix for description of how this figure was constructed.

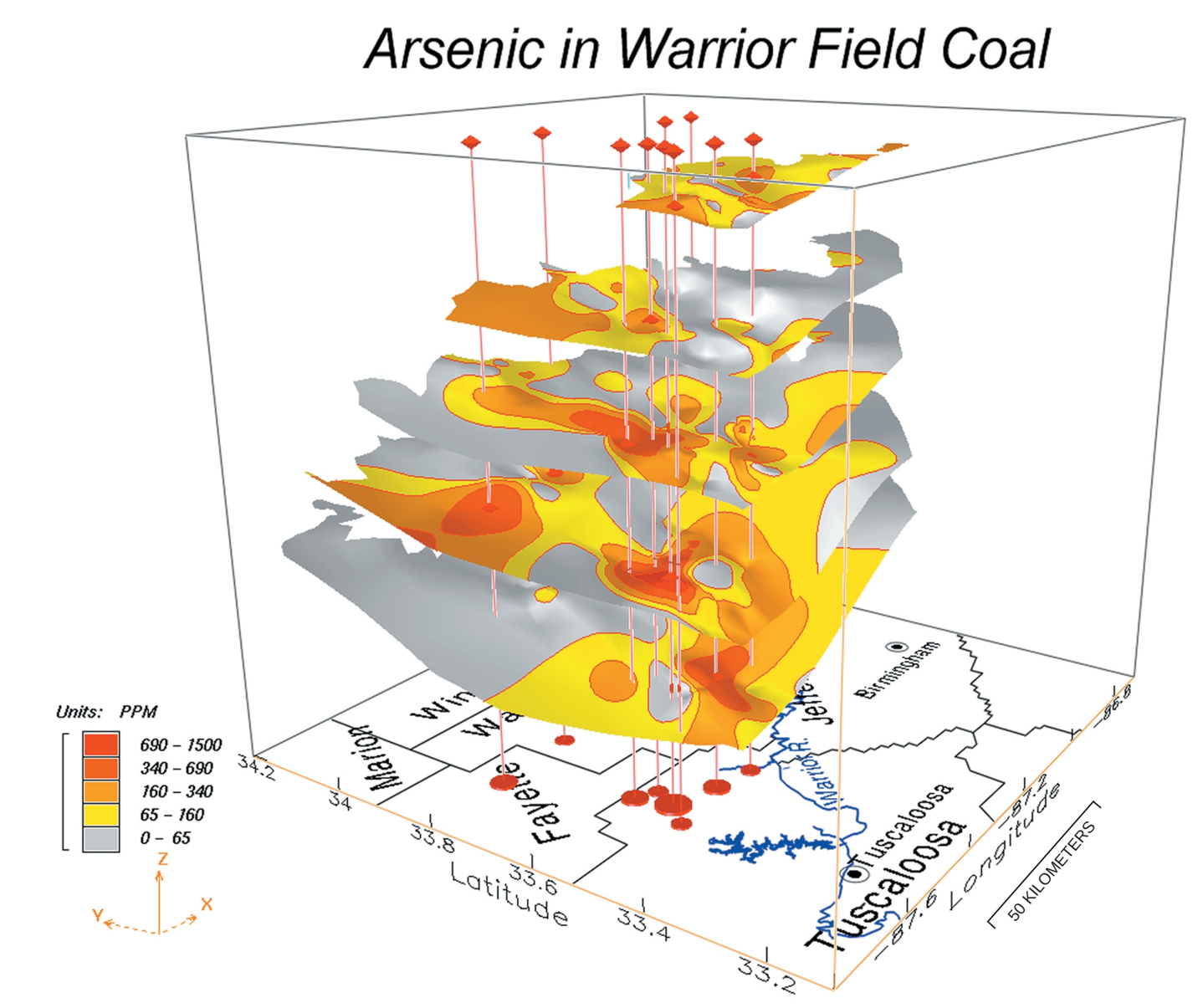
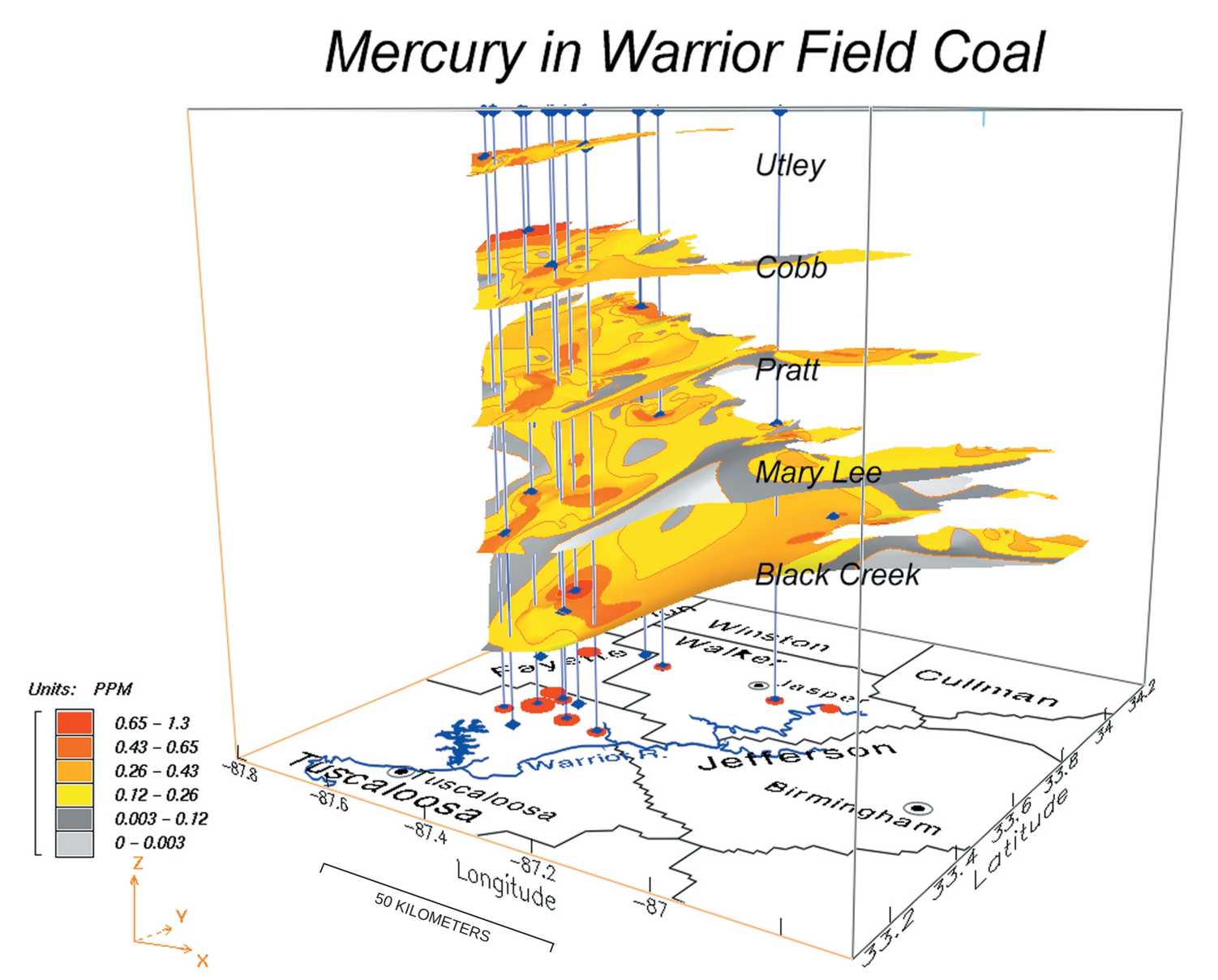
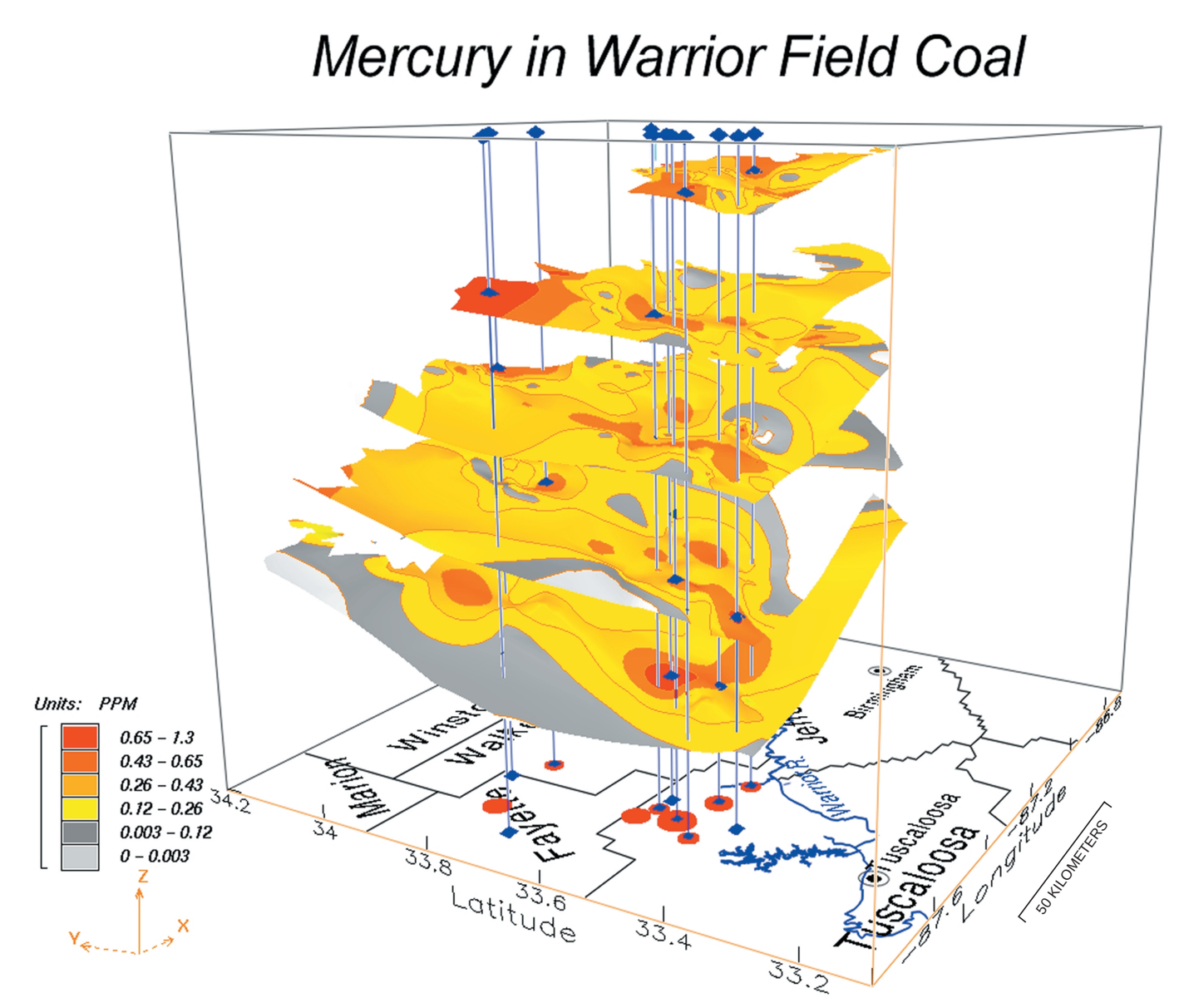
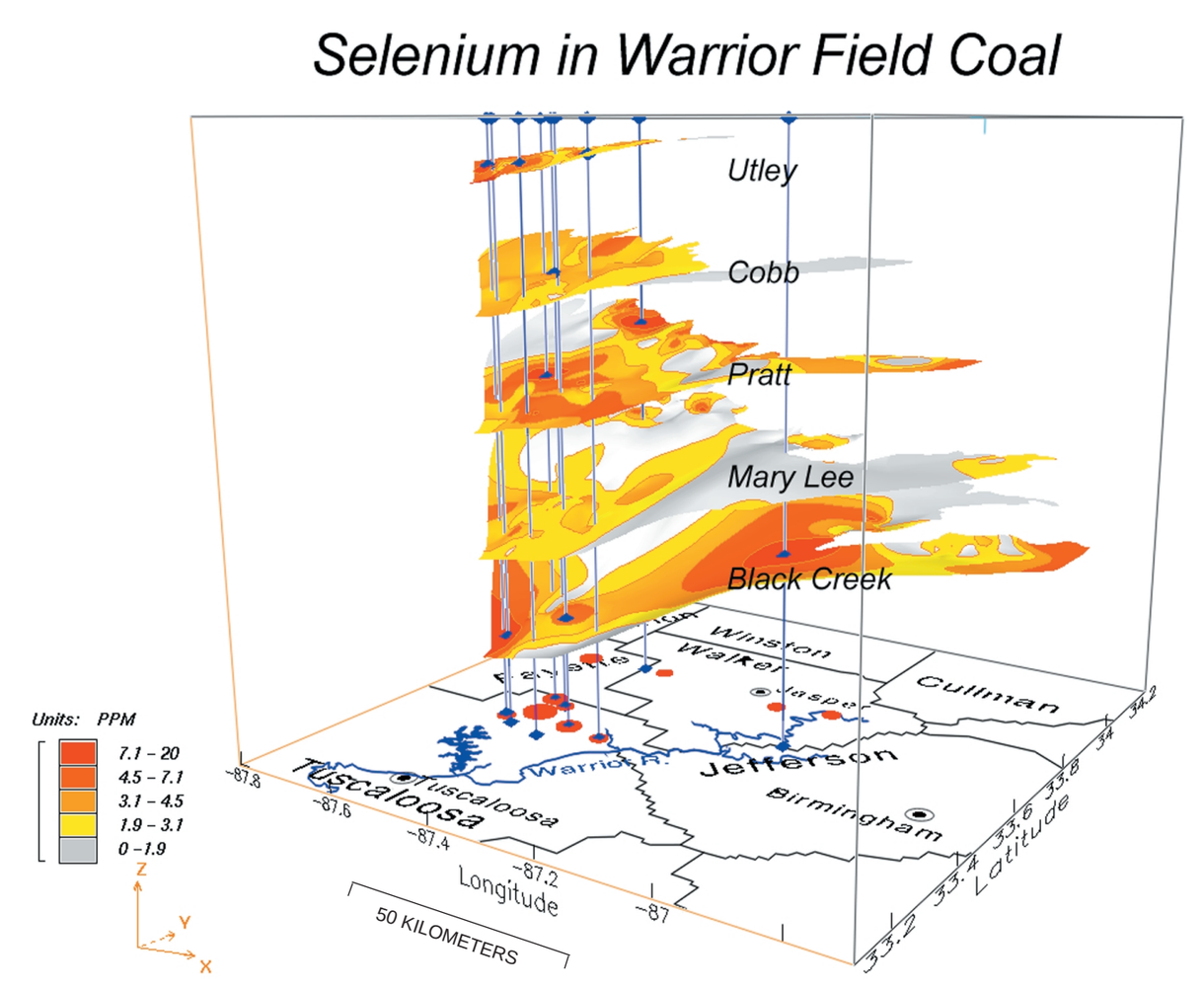
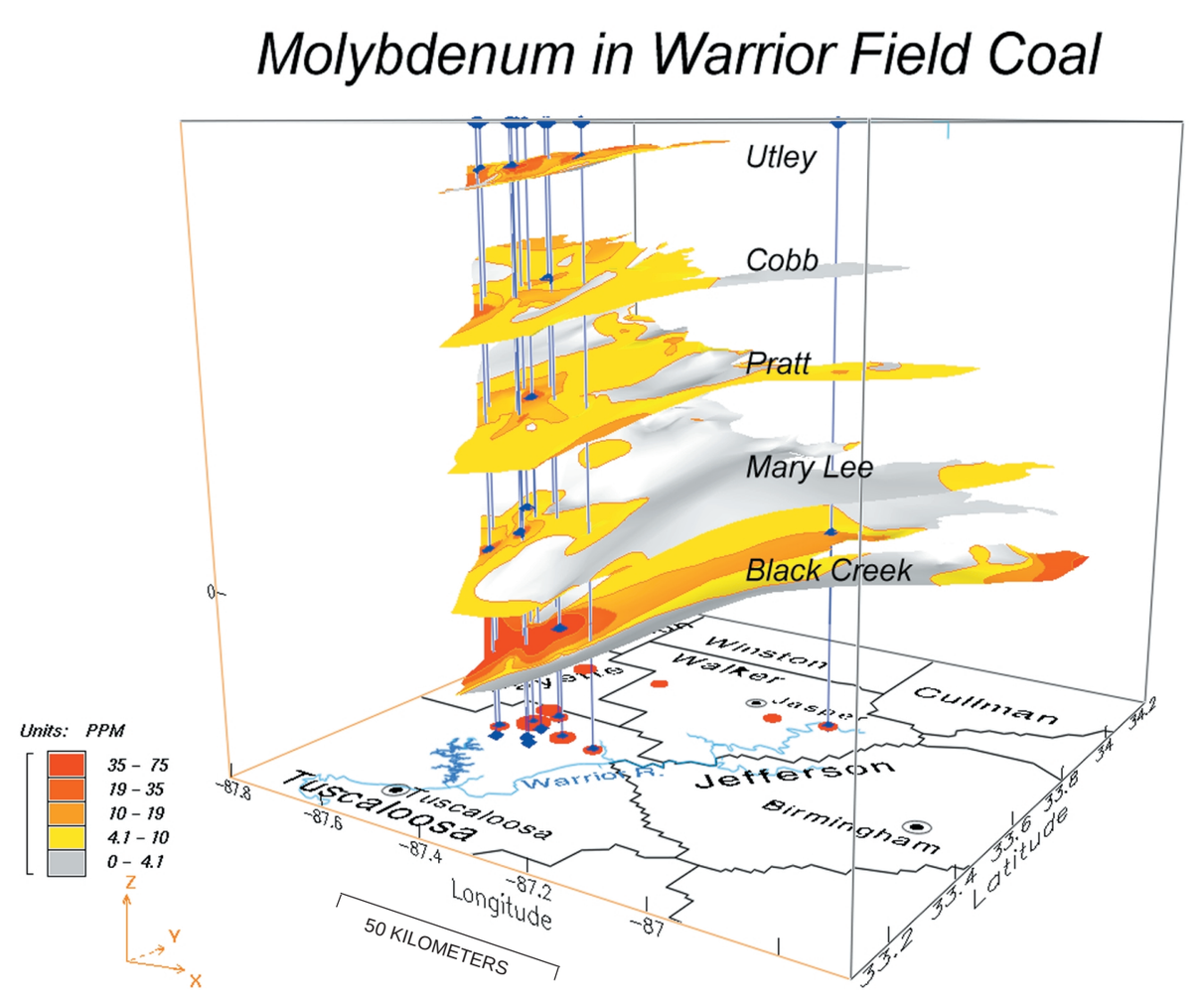


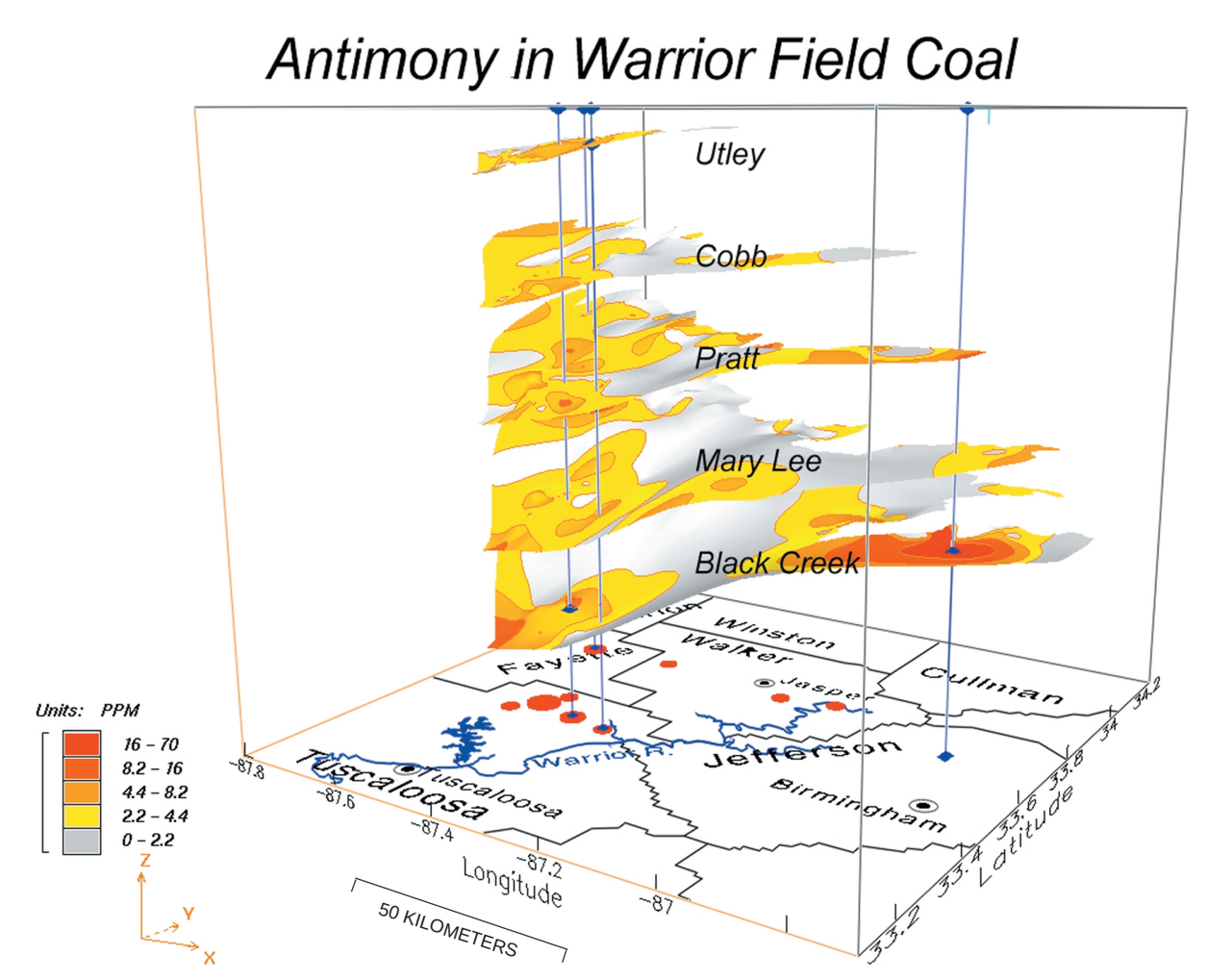
Figure 5. Arsenic in the Warrior coal field. The 3D view shows contoured concentrations of arsenic in ppm (parts per million) for five different coal groups. The contours in this figure are the same as those in figure 4, but in this figure they are viewed looking toward the northeast.

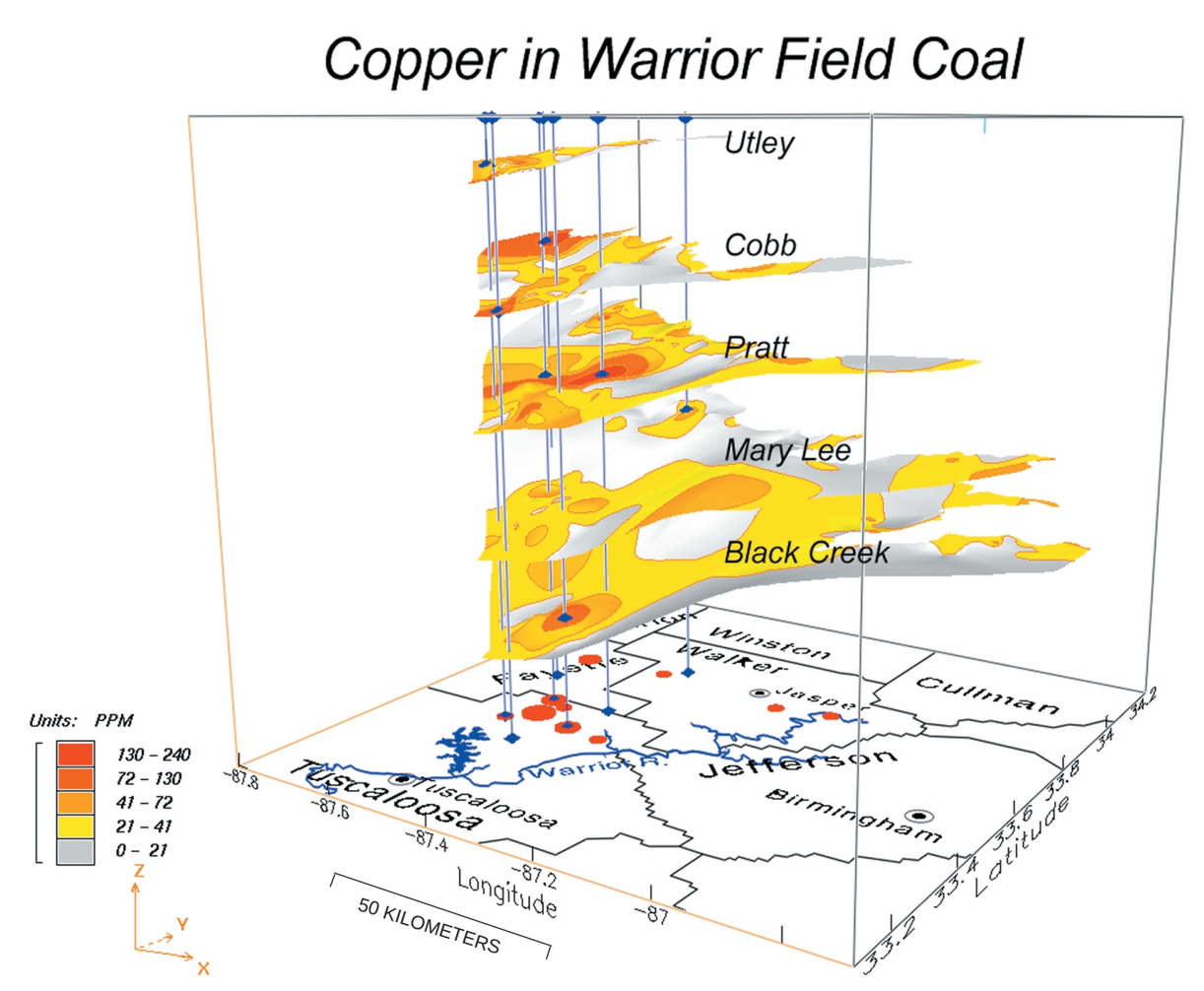


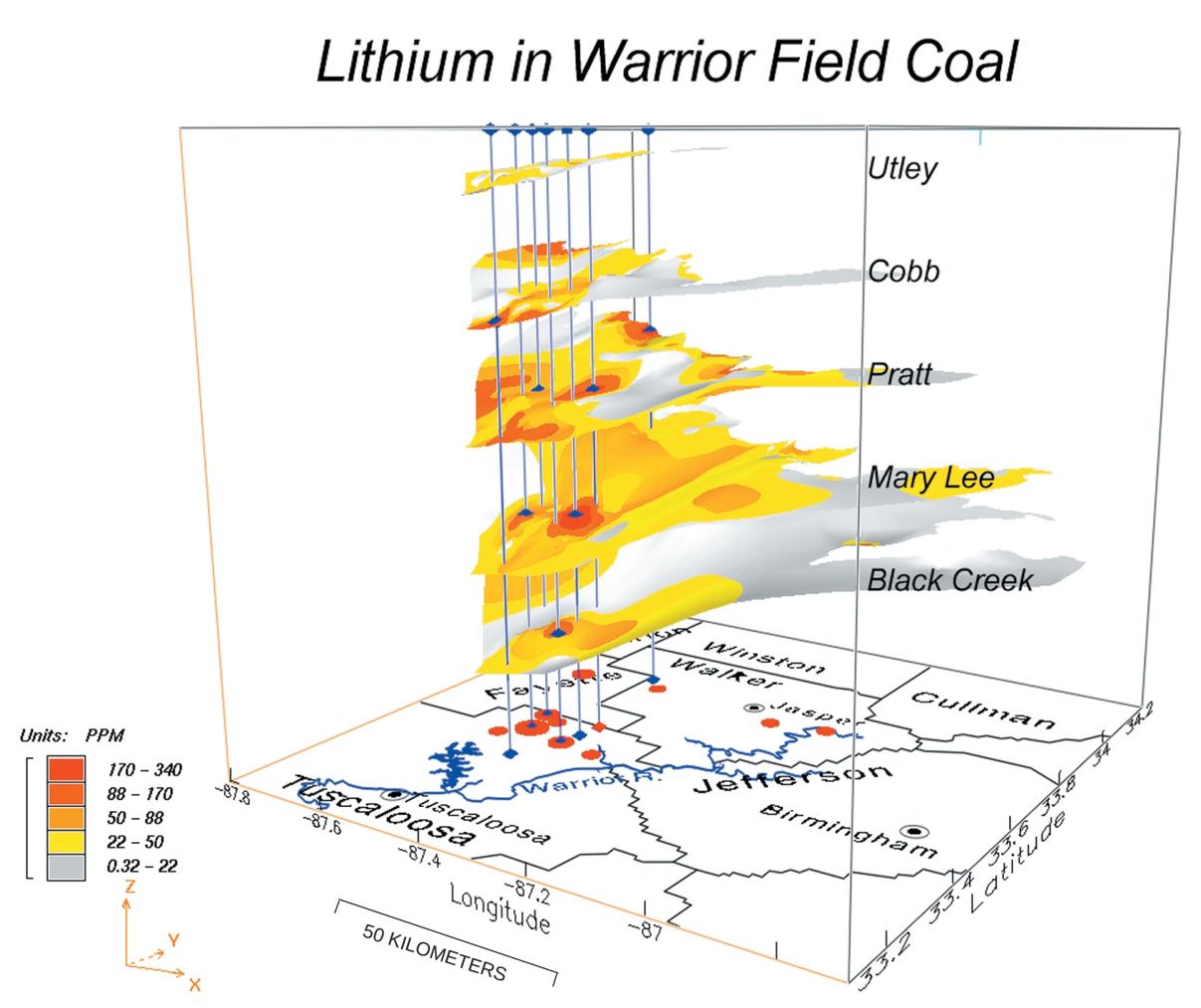


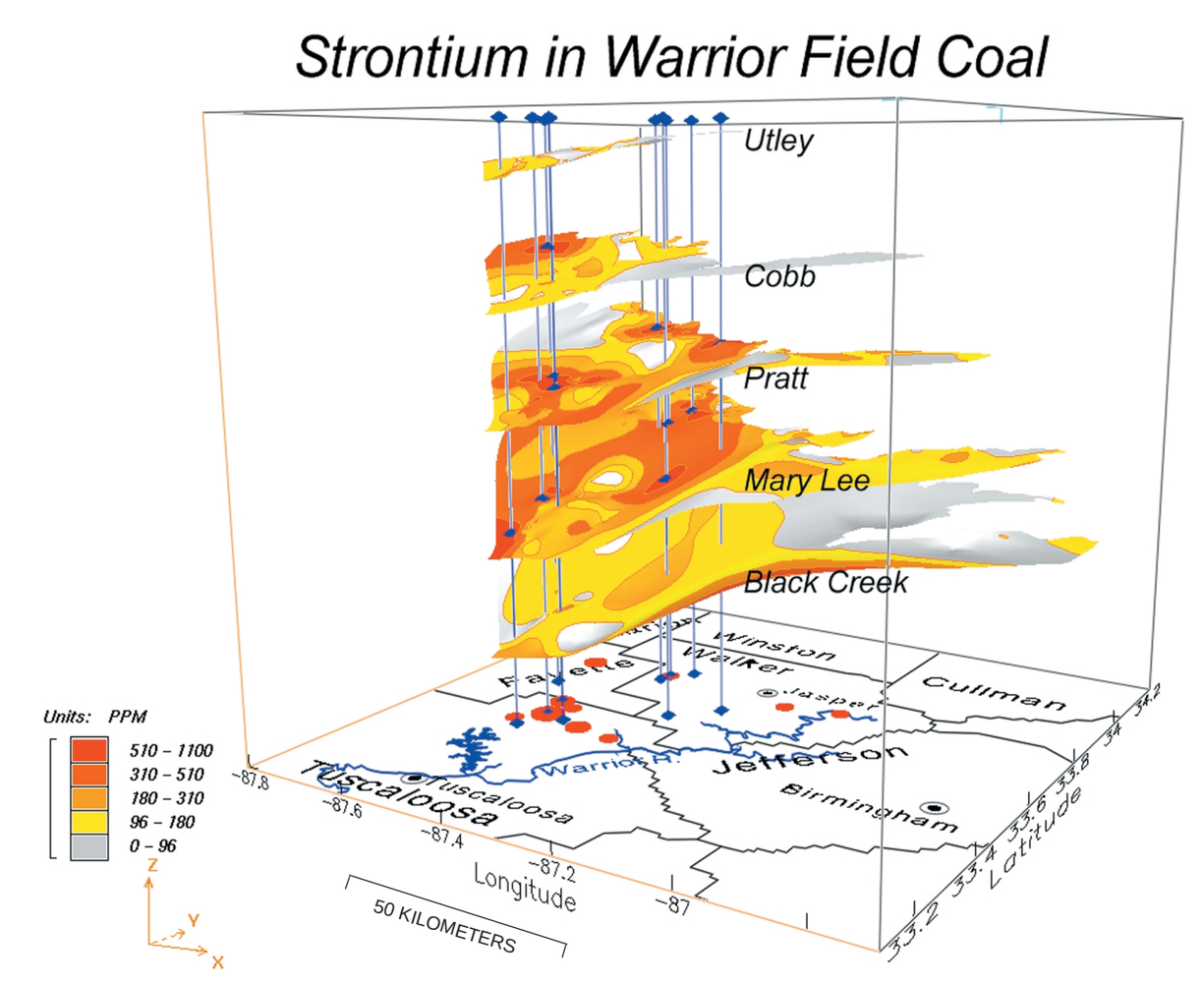


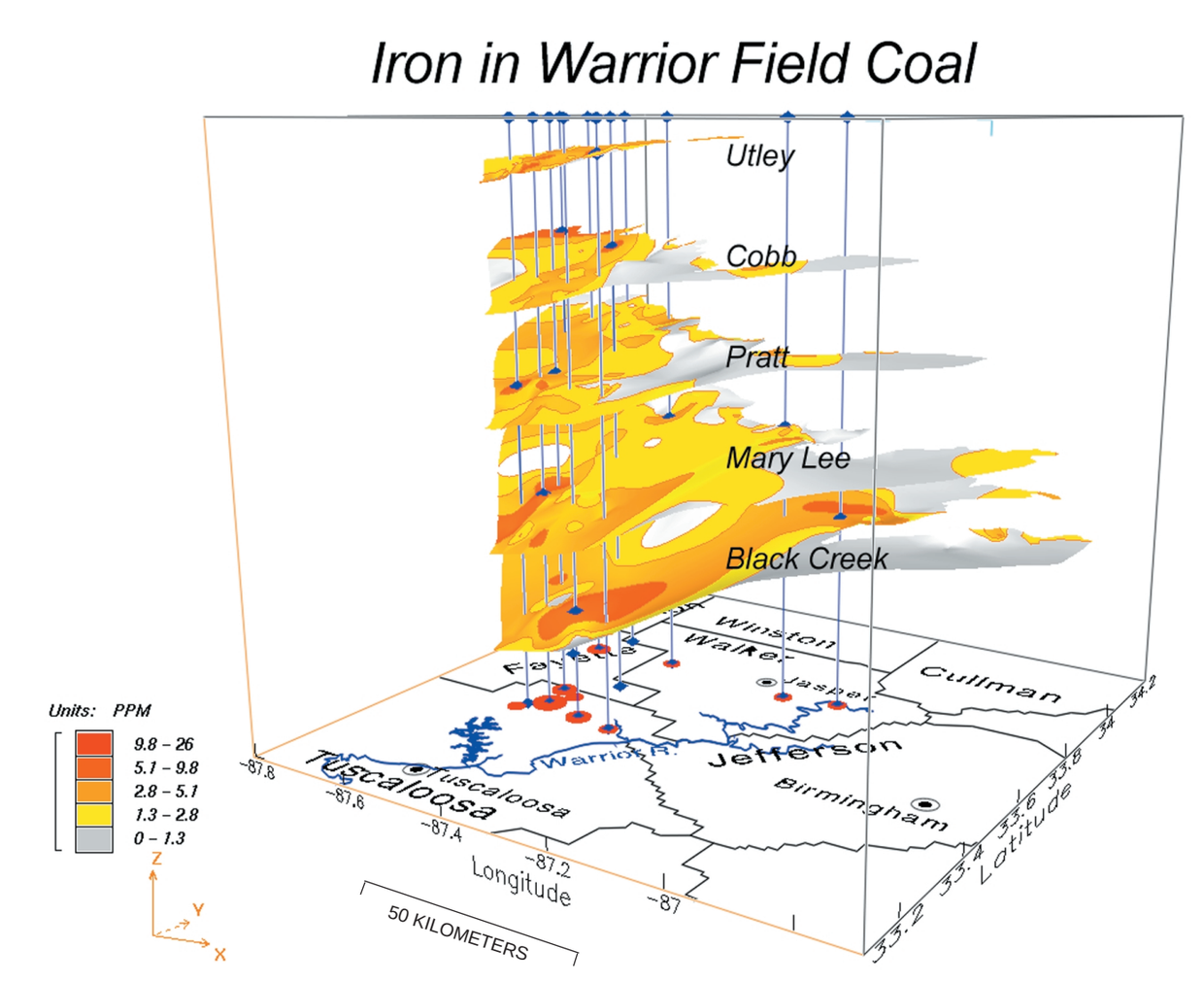


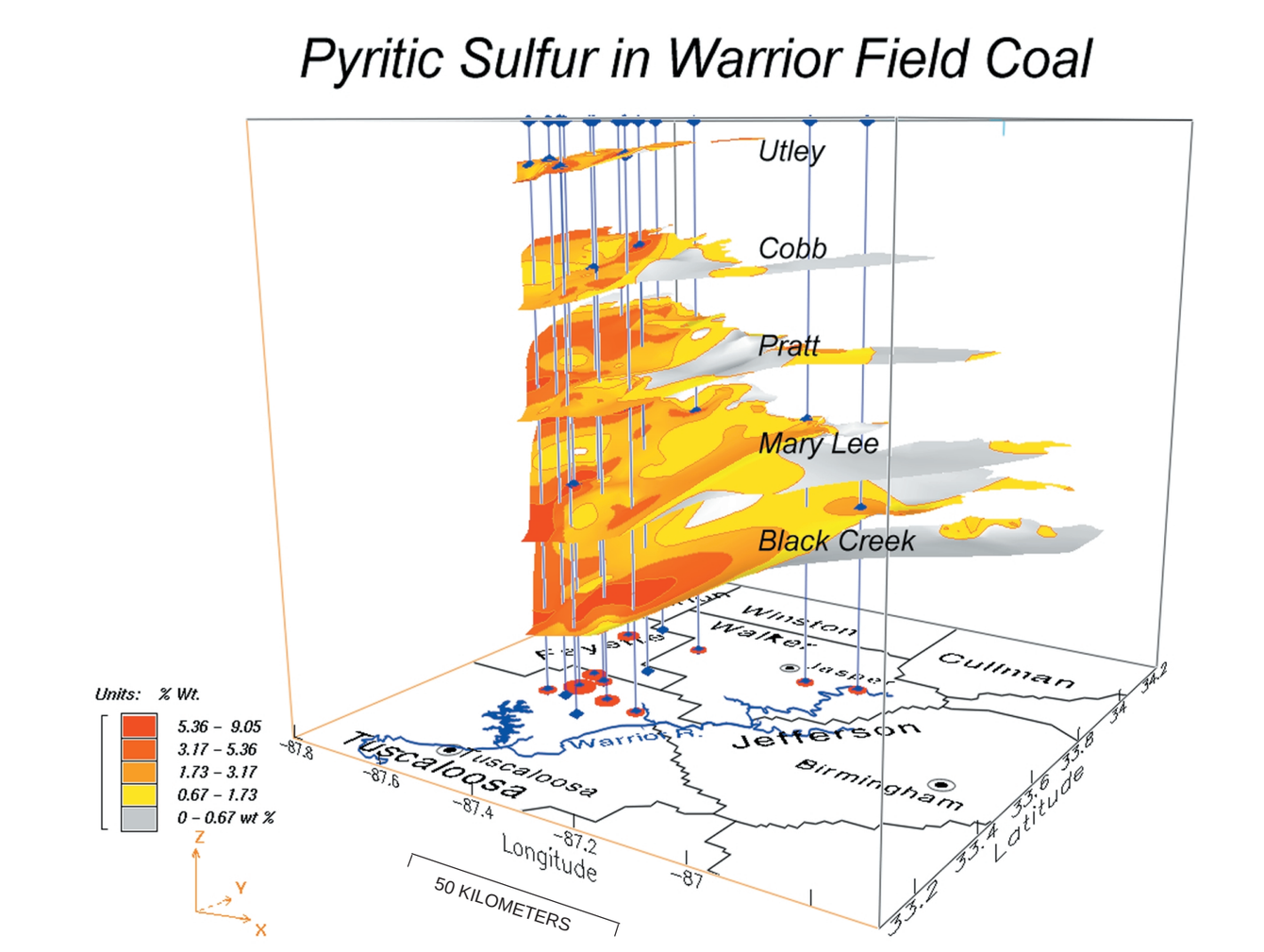


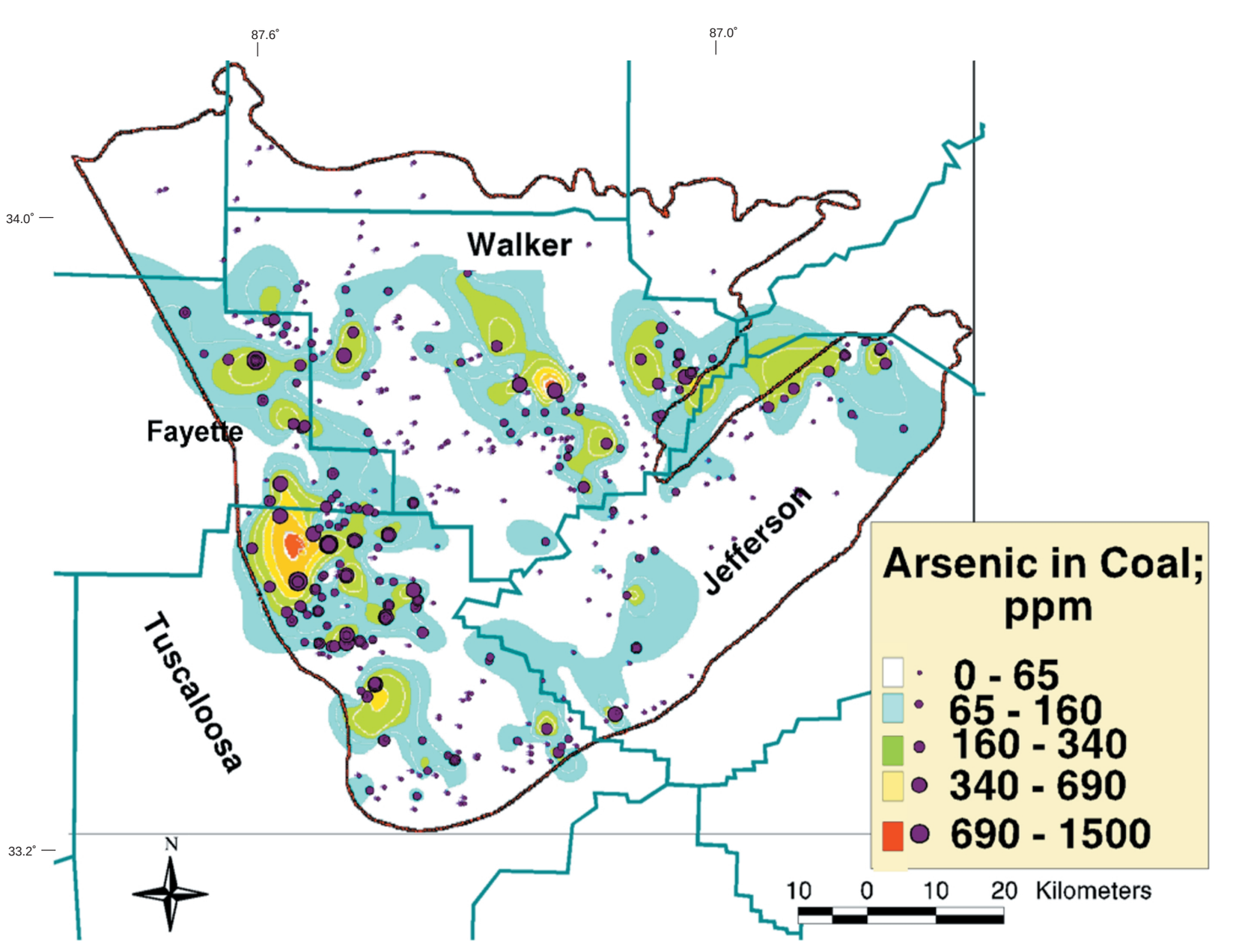


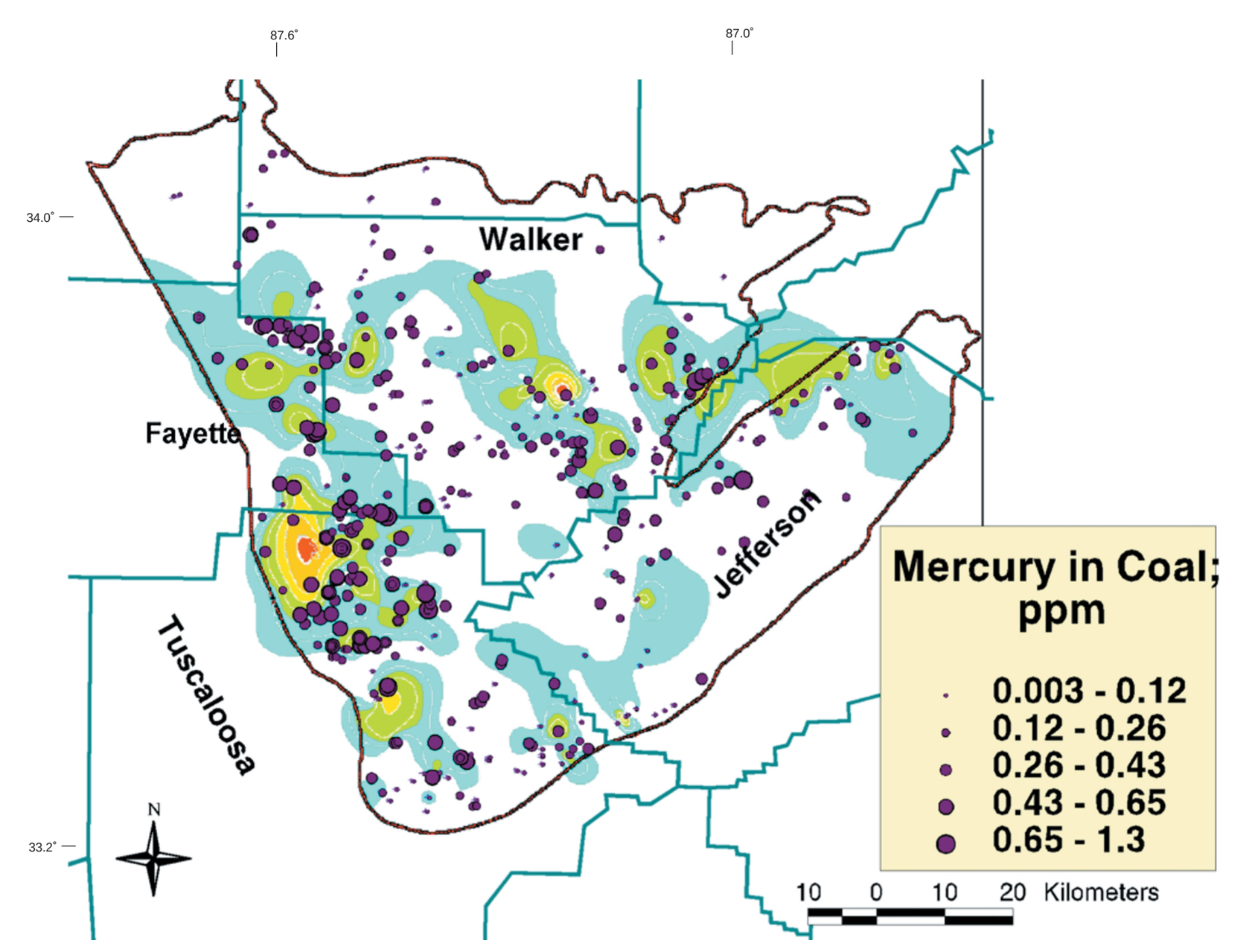


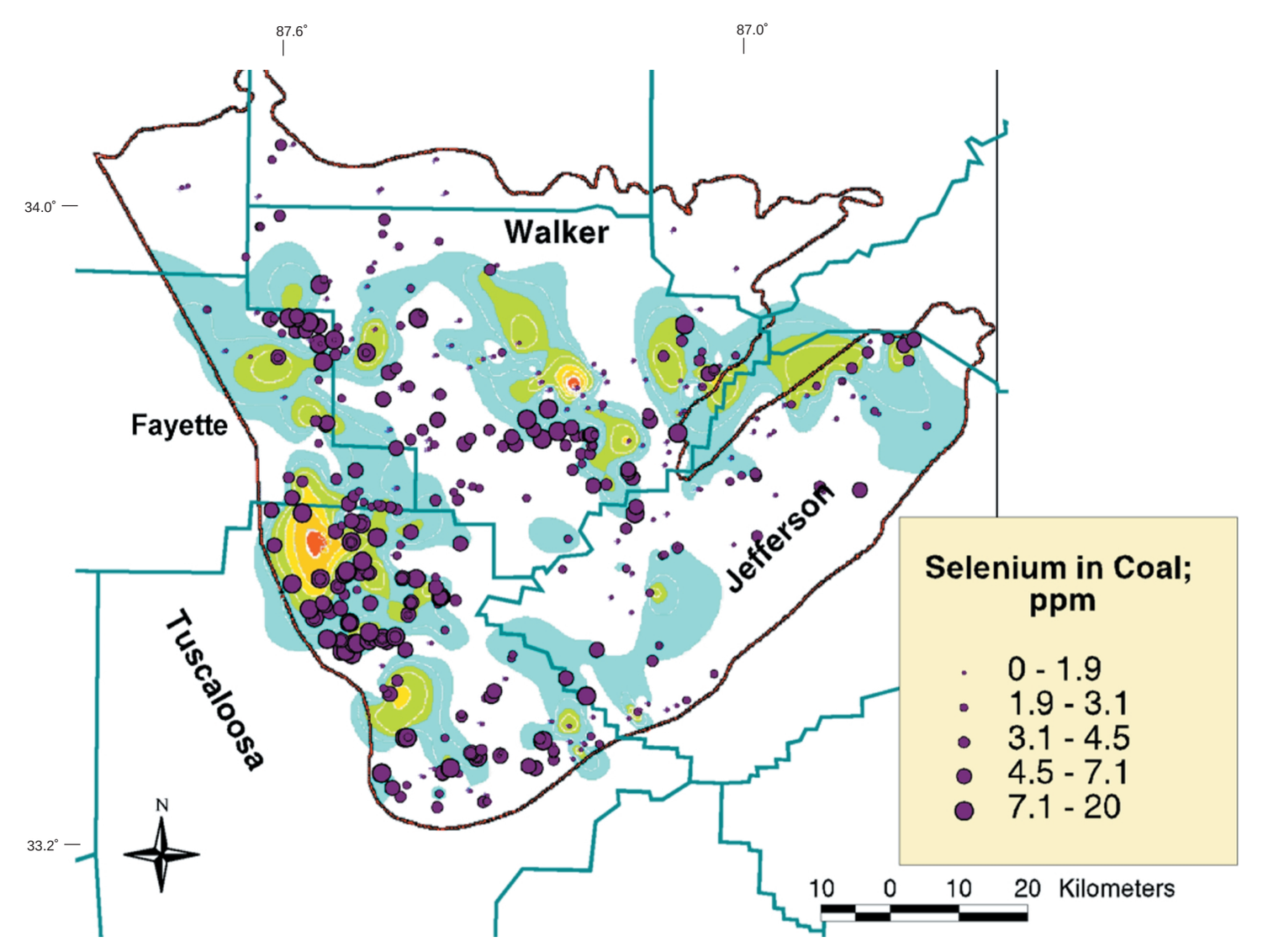


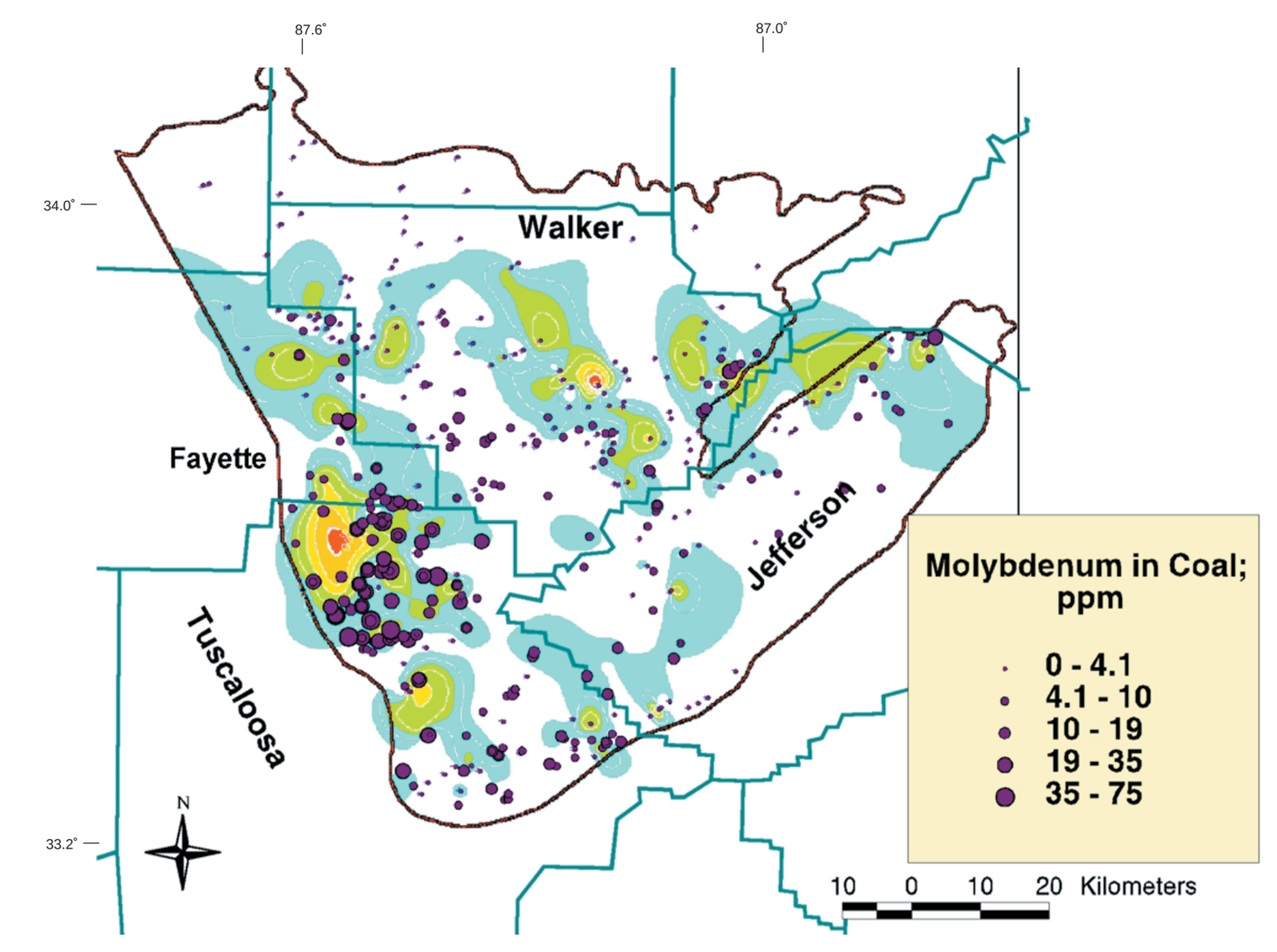


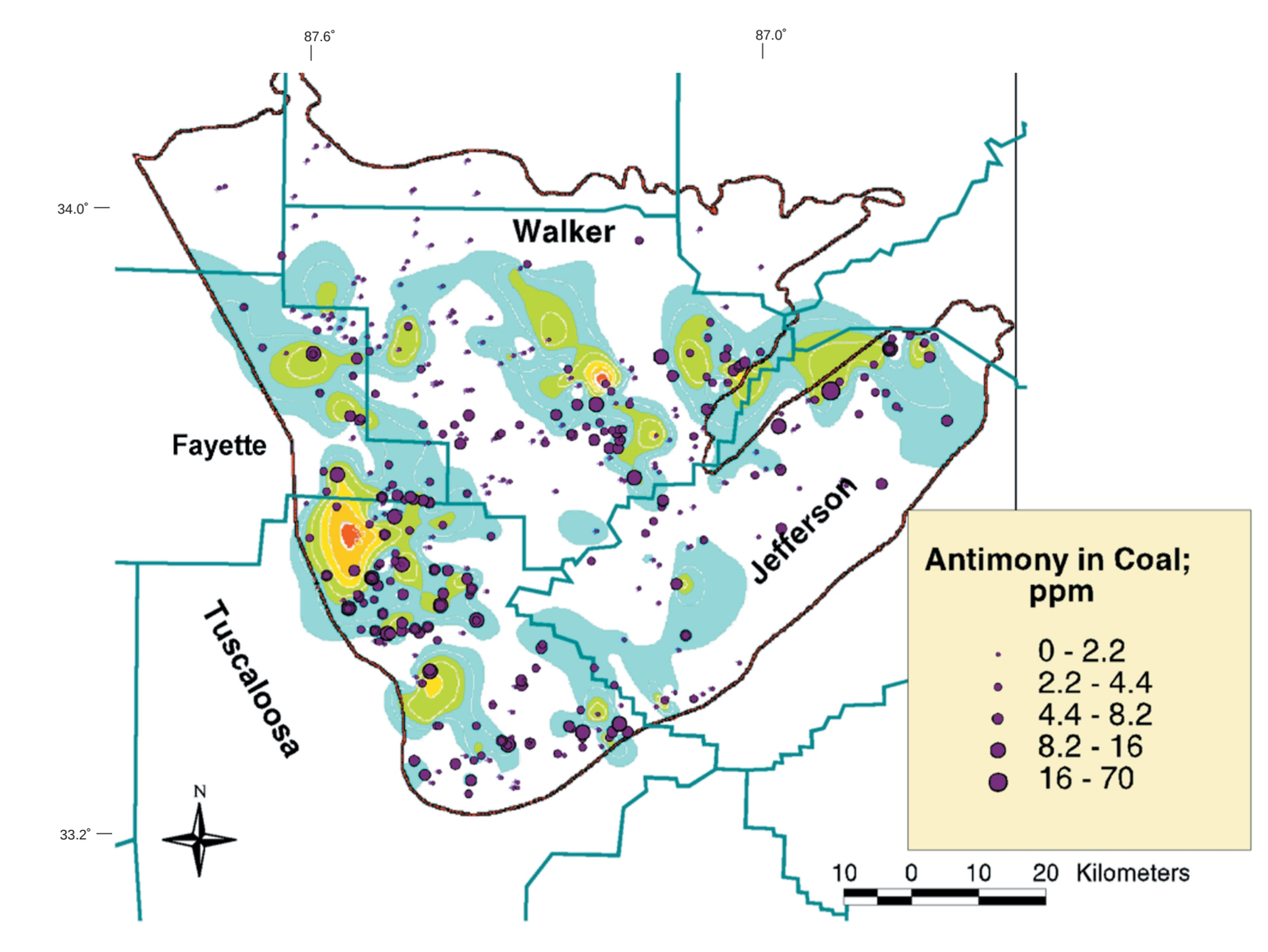












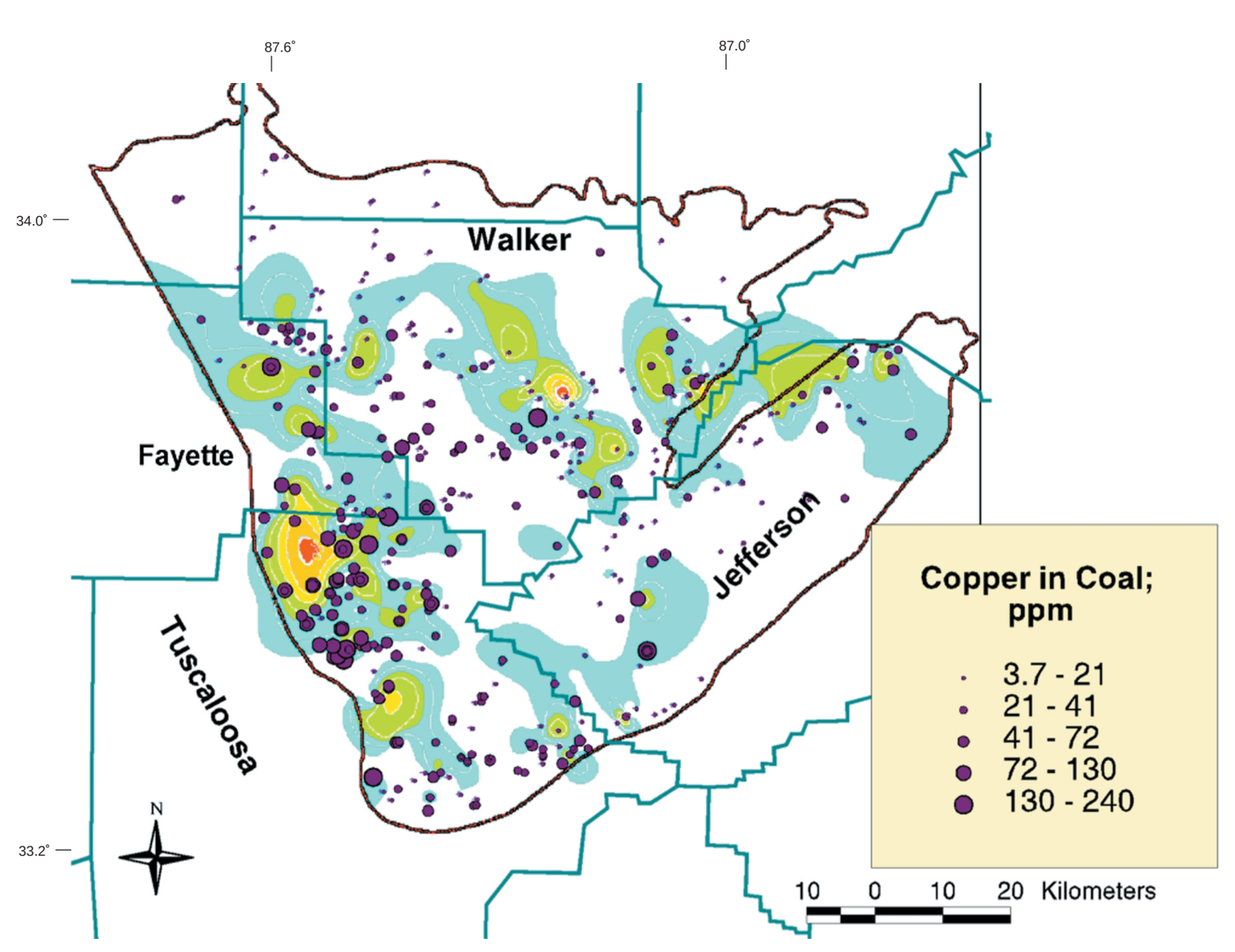
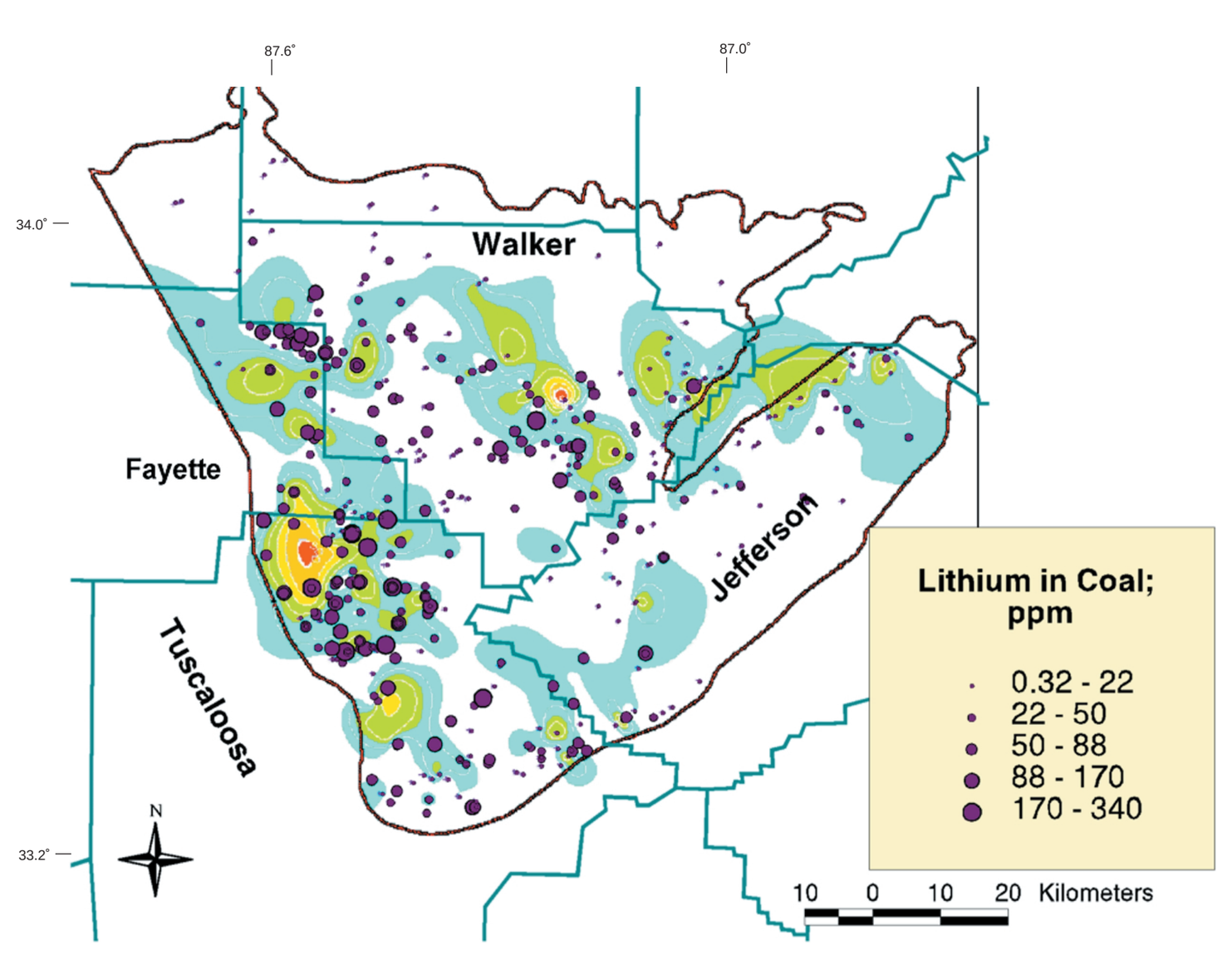


Figure 21. Map comparing point concentration data for copper with contoured concentration data for arsenic. The arsenic contours are the same as those in figure 16.



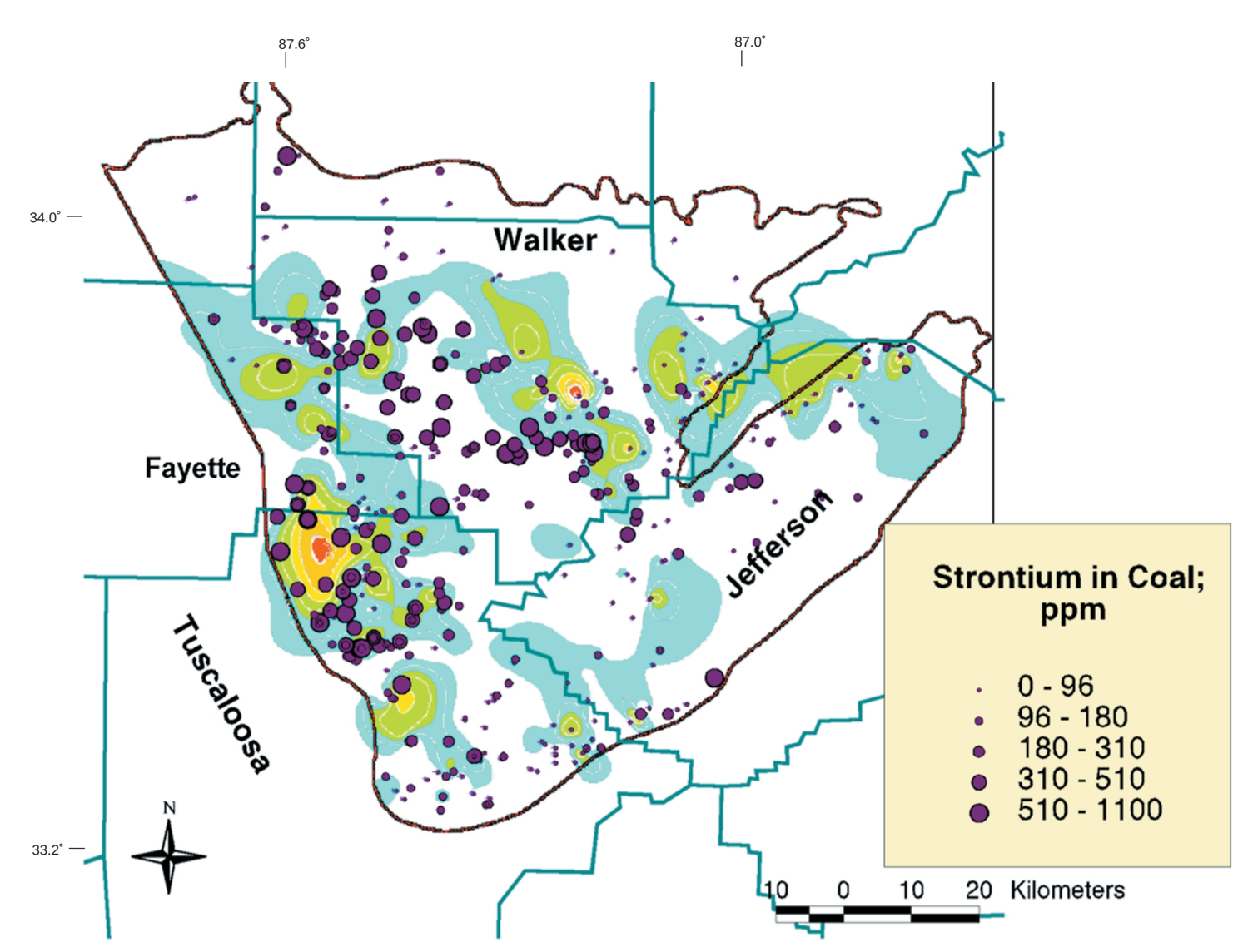


Figure 23. Map comparing point concentration data for strontium with contoured concentration data for arsenic. The arsenic contours are the same as those in figure 16.

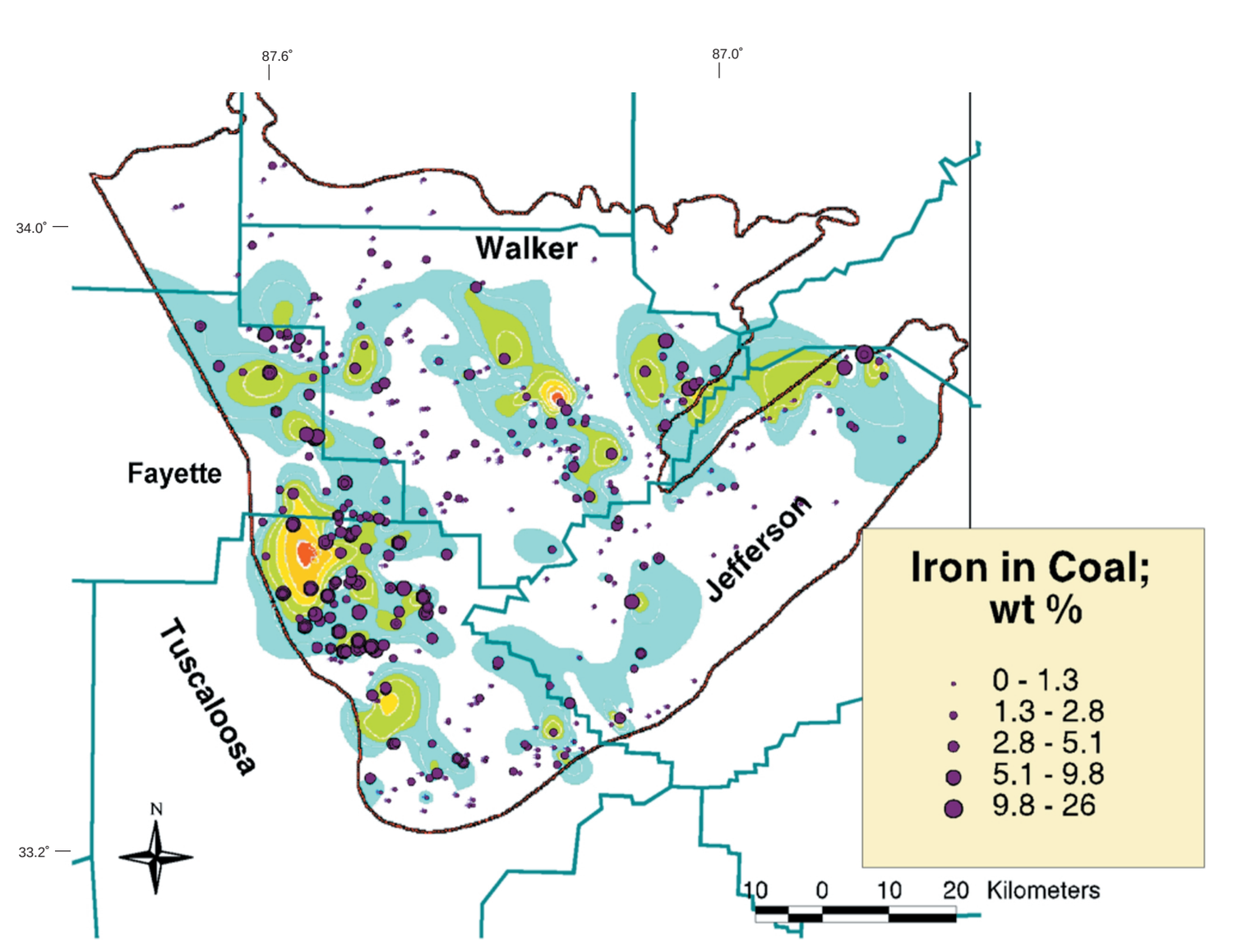
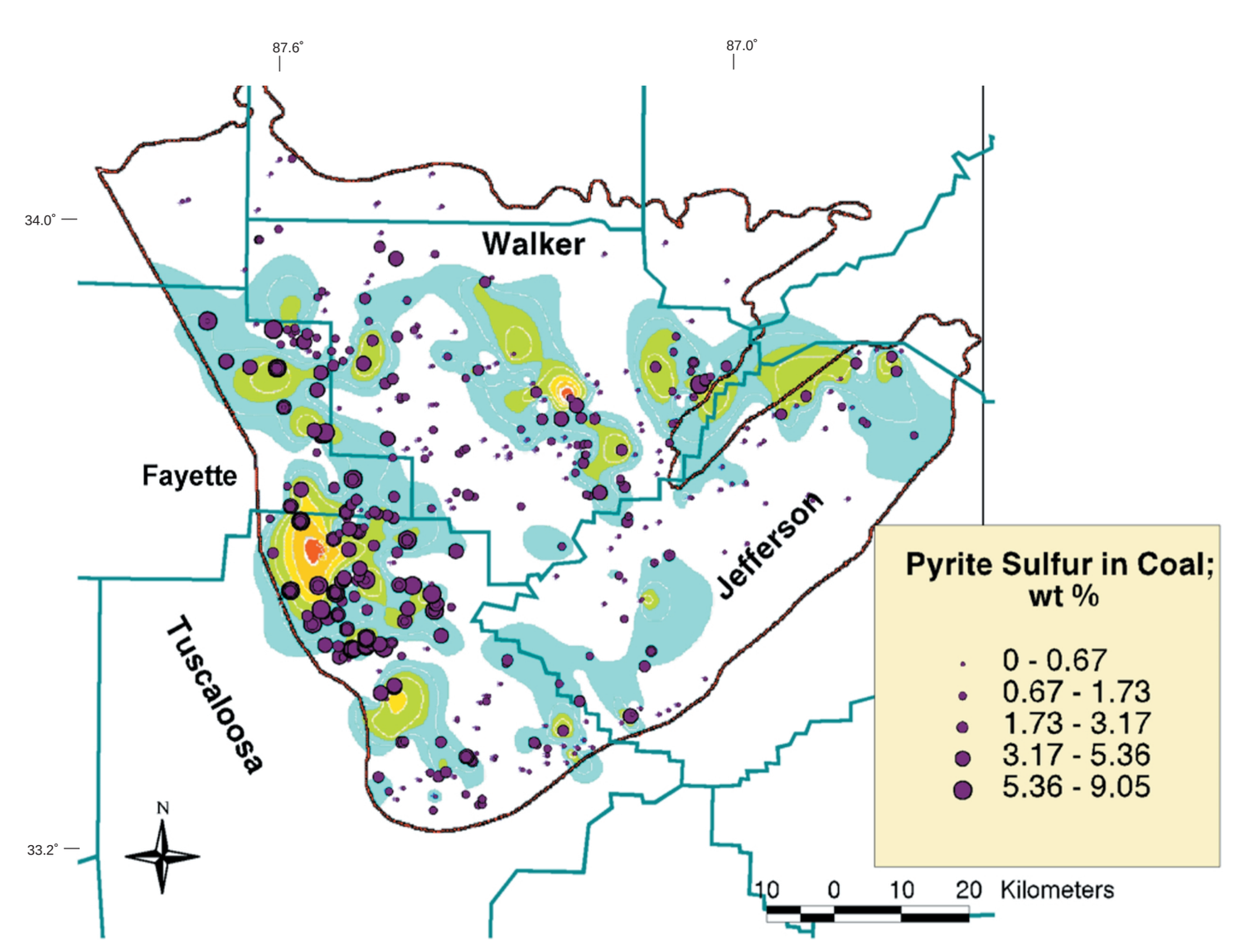


Figure 24. Map comparing point concentration data for iron with contoured concentration data for arsenic. The arsenic contours are the same as those in figure 16.



DISTRIBUTION OF A SUITE OF ELEMENTS INCLUDING ARSENIC AND MERCURY IN ALABAMA COAL

By
M.B. Goldhaber, R.C. Bigelow, J.R. Hatch, and J.C. Pashin
2000

INTRODUCTION

Arsenic and other elements are unusually abundant in Alabama coal. This conclusion is based on chemical analyses of coal in the U.S. Geological Survey's National Coal Resources Data System (NCRDS; Bragg and others, 1994). According to NCRDS data, the average concentration of arsenic in Alabama coal (72 ppm) is three times higher than is the average for all U.S. coal (24 ppm). Of the U.S. coal analyses for arsenic that are at least 3 standard deviations above the mean, approximately 90% are from the coal fields of Alabama. Figure 1 contrasts the abundance of arsenic in coal of the Warrior field of Alabama (histogram C) with that of coal of the Powder River Basin, Wyoming (histogram A), and the Eastern Interior Province including the Illinois Basin and nearby areas (histogram B). The Warrior field is by far the largest in Alabama. On the histogram, the large 'tail' of very high values (> 200 ppm) in the Warrior coal contrasts with the other two regions that have very few analyses greater than 200 ppm.

In addition to arsenic, Warrior field coal is enriched in a suite of trace elements including (but not limited to) molybdenum, antimony, copper, mercury, lithium, selenium, thallium, and gold. Data for the first seven of these elements are found in the NCRDS database. These elements are enriched relative to other U.S. coal. For example the mean value of molybdenum for Warrior field coal is twice as high (6 ppm) as for all U.S. coal (3 ppm); for antimony, the means are 3 ppm, and 1.2 ppm, respectively. Data on thallium and gold enrichments are based on fewer samples collected during recent field studies and will be published separately (J. R. Hatch, unpublished data, 1999). Several other elements, including strontium, iron, and pyritic sulfur, are also of interest in Alabama coal. Pyritic sulfur (that is that portion of the total sulfur in the mineral pyrite, FeS_2) is of concern because preliminary investigations indicate that the arsenic resides in pyrite (Goldhaber and others, 1997). Strontium is included in this study because it exhibits a different geographic distribution from many of the other elements chosen for this study.

In this report, we first briefly describe the geologic context of Warrior field coal and then focus on the geographic distribution of arsenic and other trace elements in the coal. The reason for investigating this geographic variability is to determine whether specific parts of the Warrior field are systematically enriched in the suite of trace elements listed above. Arsenic and mercury in particular are known to be potentially harmful to plants and animals; defining their geographic distribution is a first step to investigating possible environmental impacts of natural and mining-related dispersion of elements from the coal. Furthermore, the geographic distribution of elements may provide clues as to the processes that introduced the elements into the coal beds. Note, however, that coal-mining practices are designed to avoid coal beds with high pyrite content, and thus produced coal from a given area will be lower in arsenic and mercury than indicated by the figures.

GEOLOGY OF ALABAMA COAL

The geology of Alabama coal has been described previously (for example, Pashin, 1991, and references therein), from which the following short overview is derived. Bituminous coal in Alabama is in the Warrior, Cahaba, and Coosa fields (figure 2). The majority of coal production has come from the Warrior field, which is the focus of this study. Coal in the Warrior exists in the lower Pennsylvanian Pottsville Formation. The Pottsville Formation is informally divided into two parts. The lower Pottsville is dominated by quartzose sandstone with only thin discontinuous coal beds. The upper Pottsville, shown schematically in figure 3, contains numerous economic coal beds. Major coal beds exist there in stratigraphic bundles called coal groups. Coal groups cap regressive, coarsening upward depositional cycles. As much as 110 meters (350 feet) of marine mudstone were deposited at the base of each cycle, followed by increasing amounts of sandstone and then interbedded mudstone-sandstone-coal at the top.

GEOGRAPHIC VARIABILITY OF TRACE ELEMENTS IN WARRIOR FIELD COAL

The distributions of trace elements are presented in two forms. The first is a series of three-dimensional visualizations of the elemental distributions in several of the coal groups shown in figure 3. The second is a series of two-dimensional plots that compare the smoothed (gridded and contoured) arsenic distribution with overlain data for the other elements. This dual approach provides two somewhat different pictures of the elemental distributions. The three-dimensional plots indicate whether or not the trace elements of interest are exceptionally enriched in specific coal groups, and whether geographic areas of trace element enrichment vary among the groups. The two-dimensional depictions are useful for directly comparing and contrasting elemental variability with that of arsenic.

THREE-DIMENSIONAL VISUALIZATION OF ELEMENTAL DISTRIBUTIONS

We have illustrated the distribution of a suite of coal chemistry parameters by means of three-dimensional plots of the coal beds that show contours of element abundance. The contours are based on data from over 900 coal samples from the NCRDS database that were each analyzed for approximately 80 parameters. We selected a subset of parameters for study and employed the computer program "EarthVision" (EV) to generate both the two and the three-dimensional contours in five coal groups. EV uses 'minimum tension gridding' to produce a surface from scattered data points. Where there was more than one sample at a single location in one coal group, we selected the maximum value of each element for plotting. This insured that the procedure would include the most significant concentrations of the elements. Details of preparation of the three-dimensional plots are given in the Appendix.

The views depict five coal groups with exaggerated vertical offsets between them so that the contours of elements for each coal group may be seen without being obscured by overlying and underlying coal groups. At this regional scale, each coal group appears as a layer of negligible thickness that dips to the southwest. Each view shows five coal groups: the Black Creek, Mary Lee, Pratt, Cobb, and Utley in sequence from deepest to most shallow. Two other coal groups, the Gwin and the Brookwood, are not represented because inadequate data were available to constrain the plots. The viewpoint of most of the plots is from the southeast looking across the coal group layers. For some elements, a second view looking from the west or southwest is presented to highlight otherwise obscured features.

Individual Element Plots

Arsenic

Figure 4 shows a plot of contoured arsenic concentration. Also on this figure are supplementary maps (also valid for figures 5-15) that show the sites where samples were collected. These maps have Digital Elevation Model (DEM, see appendix) data, which are overlain by political and hydrological features. The boundaries of investigation for each coal group, often referred to as an Area Of Interest (AOI), appear in yellow on the maps. For each coal group, the northern and eastern borders of its AOI were derived from published (Winston, 1990; Pashin, 1991) outlines of the outcrop of the coal group at the surface. In the west and southwest the AOI reflects the limits of the overlying Cretaceous sandstone. Figure 4 shows that there is a good distribution of sample control points over the study area.

The arsenic data in figure 4 are shown as a colored contour map, with contour intervals shown in the legend. The red intervals, which represent areas of the highest values of between 690 and 1,500 ppm, have a vertical "drop line" drawn through their centers. These lines are projected both upward and downward so that the geographic locations of the areas with high values are visible based on their intercepts with the counties. The lower intercept of the drop lines has an associated circle whose diameter is roughly proportional to the range of the arsenic enrichment with which it is associated (see appendix below for further discussion of the drop lines).

Several features of the arsenic plot in figure 4 are noteworthy. The first is that elevated arsenic concentrations, well above the average for all U.S. coal (24 ppm—see above), are present in all of the coal groups. There is also an apparent tendency for the highest values to cluster in the lower coal groups: the Black Creek, Mary Lee, and Pratt. High values of arsenic in all coal groups are not uniformly distributed throughout the Warrior field. Instead, high values are consistently present in northern Tuscaloosa, eastern Fayette, and western and eastern Walker Counties. Figure 5 is similar to figure 4 except that the viewpoint is from the southwest. The patterns of arsenic distribution in the Cobb and Utley groups are more easily seen from this position.

Mercury

Figures 6 and 7 show the distribution of mercury in Warrior field coal from two different perspectives. As was the case for arsenic, vertical drop lines have been provided to show the geographic position of the highest contour interval (0.65-1.3 ppm). The original intercepts from the arsenic figures (figures 4 and 5) have been retained (red circles) in this and subsequent illustrations (see appendix). The mercury intercepts are shown in blue. Generally, the areas with high mercury concentrations coincide with high arsenic areas. It does appear that relative to arsenic, mercury is concentrated in the upper two coal groups (Cobb and Utley).

Selenium

Figure 8 shows the distribution of selenium in Warrior field coal. High values are present in northern Tuscaloosa County in Black Creek, Pratt, Cobb, and Utley coal groups. A large area of elevated values is indicated along the Jefferson and Walker Counties border in the Black Creek group.

Molybdenum

Figure 9 shows the distribution of molybdenum in Warrior field coal. High concentrations are near the base and top of the coal-bearing section in the Black Creek and Utley groups, respectively. These highs are in northern Tuscaloosa County.

Antimony

Figure 10 shows the distribution of antimony in Warrior field coal. In contrast to arsenic and some other elements, the most prominent high is not in northern Tuscaloosa County. Instead, a concentration of antimony is found in northern Jefferson County. Antimony is apparently more concentrated in the Black Creek than in overlying coal groups.

Copper

Figure 11 shows the distribution of copper in Warrior field coal. High concentrations are found in the Black Creek, Pratt, Cobb, and Utley coal groups of northern Tuscaloosa County and the Utley coal group of eastern Fayette County.

Lithium

Figure 12 shows the distribution of lithium in Warrior field coal. Lithium concentrations are elevated in the lower four coal groups of northern Tuscaloosa County and in the Pratt coal group of western Walker County.

Strontium

Figure 13 shows the distribution of strontium in Warrior field coal. Strontium is highest in the middle three coal groups: Mary Lee, Pratt, and Cobb. The highest values extend northward from northern Tuscaloosa County into western Walker County.

Iron

Figure 14 shows the distribution of iron in Warrior field coal. The iron distribution is similar to that of arsenic.

Pyritic sulfur

Figure 15 shows the distribution of pyritic sulfur in Warrior field coal. The distribution of pyrite sulfur is very similar to that of arsenic.

TWO-DIMENSIONAL PLOTS OF ELEMENTAL ABUNDANCE

Two-dimensional plots are presented to supplement the three-dimensional plots described above. To construct these plots, the maximum arsenic concentration at a given location (regardless of coal group) was gridded and contoured using EV. The three-dimensional plots that show that arsenic concentrations are high throughout the coal-bearing strata justify this procedure. Maximum values for other elements are compared to arsenic contours using variable-sized dots. Within each concentration range shown in the legend of the figures, the diameter of the dot is proportional to the abundance of that element.

Arsenic

In figure 16 the colored As contours are compared to individual As analyses (dots). This comparison is indicative of the ability of the gridding and contouring procedures to reproduce the As data. This figure also has the legend for the contour intervals.

Mercury

In figure 17 the colored As contours are compared to individual Hg analyses (dots). There is generally good correspondence between areas with high As and high Hg. However, a part of northern Fayette County has systematically elevated Hg concentrations but low As.

Selenium

In figure 18 the colored As contours are compared to individual Se analyses (dots). There is generally good correspondence between areas with high As and high Hg. However, a part of northern Fayette County and of central Walker County has systematically elevated Se concentrations but low As.

Molybdenum

In figure 19 the colored As contours are compared to individual Mo analyses (dots). There is generally good correspondence between areas with high As and high Mo.

Antimony

In figure 20 the colored As contours are compared to individual Sb analyses (dots). There is generally good correspondence between areas with high As and high Sb.

Copper

In figure 21 the colored As contours are compared to individual Cu analyses (dots). There is generally good correspondence between areas with high As and high Cu.

Lithium

In figure 22 the colored As contours are compared to individual Li analyses (dots). There is generally good correspondence between areas with high As and high Li. However, a part of northern Fayette County has systematically elevated Li concentrations but low As.

Strontium

In figure 23 the colored As contours are compared to individual Sr analyses (dots). High As and Sr concentrations exist together in northern Tuscaloosa County. However, a band of high Sr values trending southeasterly through Walker County is in an area with systematically low As concentrations.

Iron

In figure 24 the colored As contours are compared to individual Fe analyses (dots). There is generally good correspondence between areas with high As and high Fe.

Pyritic Sulfur

In figure 25 the colored As contours are compared to individual S analyses (dots). There is generally good correspondence between areas with high As and high Fe.

CONCLUSIONS

Arsenic and a number of other elements are enriched in coal of the Warrior field in Alabama. The distribution of these elements within the Warrior field is illustrated using a series of two- and three-dimensional figures. In general, the stratigraphic and geographic distribution of arsenic, mercury, molybdenum, antimony, copper, lithium, iron, and pyrite sulfur are all generally similar. Elevated values of these elements in coal characterize parts of northern Tuscaloosa and eastern Fayette Counties. Systematically low concentrations of As are found over much of Walker and Jefferson Counties.

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APPENDIX
PREPARATION OF THE 3D FIGURES

Most of the modeling reported here was performed using EarthVision (EV) applications software. The sequence of tasks to build a three dimensional view in EV is to generate the surfaces necessary for the 3D view, color them with contours of element concentration, and assemble them into a composite view. The sample data were imported by EV as ASCII files containing 3-dimensional spatial coordinates (x, longitude; y, latitude; and z, depth) associated with the sample localities, together with corresponding element concentrations ("property values"). These data were taken from the NCRDS database (Bragg and others, 1994). From these values, three-dimensional "surfaces" were constructed using the minimum tension gridding algorithm of EV that represent either the distribution of a coal group in the subsurface or the depth distribution of property values versus x and y. Both these surfaces are 3D grids. The 3D grid files are assembled into "faces" files to create a surface colored with contours of elements; one physical surface file for the coal group and one element concentration file for each faces file. Each of these faces files is a single layer in the three dimensional views. The geographic extent of each single layer faces file is delimited by an Area of Interest (AOI) that limits the x and y extent of the display to those areas where data points and the coal groups themselves exist. Finally, several individual faces files are merged to form a composite faces file that is displayed as a 3D plot in Earth Vision. With some added annotation, these views are output to form the illustrations in this report.

The greatest challenge in data preparation was to determine depths of the coal groups throughout the study area. Approximately half of the NCRDS data lacked depth information. Many of the samples were taken from strip mines and so were essentially collected at the local surface. Thus, no specific depth information was included for them. For samples of this type, depth was approximated by a surface derived from 1-degree by 1-degree Digital Elevation Model (DEM) files. DEM files are available from the EROS Data Center, Sioux Falls, South Dakota. They represent the elevation of the surface of the earth at defined latitude and longitude intervals (see Elassal and Caruso, 1983). In contrast, about half the data came from drill-core samples and had sample depths included as part of the data set.

We generated a subset of the latitude, longitude, depth, and concentration data files for each of the coal groups. Maximum values of element concentration at each location were used as data for surface-modeling the element concentrations. From each of the individual coal groups we derived a second subset containing only samples with specific depth data. We used this second subset, along with graphical AOI's derived from Winston (1990), to generate surfaces that represent the physical location of the coal groups relative to the surface. Depths relative to the surface were converted to elevations above sea level. We merged four DEM files for northern Alabama. Using the formula processor in EV, we added arbitrary 1,500-foot offsets between each of the files to form "exploded" views such as those shown in figures 4-15. These offset grids were merged to show the distributions of elements in the coal beds. Generally, there are five, or in the case of mercury six, contoured concentration values. The ranges of the contours are shown in the legends of figures 4-15.

Annotation layers were prepared to show the county boundaries, larger cities, major rivers, and lakes. The annotation is provided to give spatial reference orientation for the viewer. Vertical "drop lines" were positioned through the centers of highest concentration ranges in each coal group in figures 4-15, and three sizes of red disks are shown on the annotation layers in figures 4-15 to roughly indicate the relative concentrations of arsenic above them. Each drop line is associated with only one coal group and, except for arsenic, the intersection of that drop line and its group is marked with a blue diamond. To highlight the coincidence between concentrations of arsenic with those of the other elements, those drop lines for arsenic which intersect the proper coal group near maxima of other elements are left in place and in some cases replace the other element drop lines. Generally, this was done if the location of the arsenic maximum overlapped the top two contours of another element. Iron is a good example; almost all the arsenic highs coincide with iron highs. Those element highs that do not coincide with an arsenic high have their own drop lines and terminate in diamond shapes on the annotated base; for example, see the copper views in figure 11.

For sale by U.S. Geological Survey Information Services
Box 25286, Federal Center, Denver, CO 80225

This map was produced on request, directly from digital files, on an electronic plotter. It is also available as a PDF file at http://greenwood.cr.usgs.gov

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Editing and digital layout by F.C. Brunstein