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# ARSENIC IN STREAM SEDIMENTS OF NORTHERN ALABAMA

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## INTRODUCTION

### STATEMENT OF THE PROBLEM

Bituminous coal samples from Alabama locally have unusually high concentrations of arsenic (Goldhaber and others, 2000). Arsenic (As) in these coal samples is contained in the mineral pyrite ($FeS_2$) (Goldhaber and others, 1997). Furthermore, some gold occurrences in metamorphic rocks to the east of the coal fields also have elevated levels of arsenic in the form of the mineral arsenopyrite (FeAsS). For these reasons, it is important to evaluate the geochemical dispersion of arsenic from rocks associated with coal and ore deposits into the environment.

### Approach to the Problem

As a first step in this evaluation, a large suite of stream-sediment samples was analyzed for a number of elements including arsenic. Because these analyses indicated elevated arsenic concentrations in stream sediments of the Warrior and Cahaba coal fields (see below), some additional, more focused studies were undertaken to specifically evaluate the role of past coal mining in producing arsenic geochemical anomalies in stream sediments.

Figure 1 shows the location of bituminous coal fields in Alabama. The Warrior, Cahaba, and Coosa fields are labeled. Coal in these fields is hosted by the Pottsville Formation of Pennsylvanian age. The locations of coal mines are shown as black mine symbols. The locations of these mines are from the U.S. Bureau of Mines MRDS (Mineral Resource Data System) database, and have not been updated for many years; almost all mines are now closed, and current mines may not be shown. The same figure shows the location of small gold occurrences, which are indicated as purple mine symbols.

## SAMPLES AND CHEMICAL ANALYSIS TECHNIQUE

### NURE STREAM SEDIMENT SAMPLES

During the late 1970's, the U.S. Department of Energy undertook a comprehensive sampling of stream sediments of the United States with the idea of using the results to evaluate potential for uranium and thorium deposits. This program was called NURE for National Uranium Resource Evaluation. All stream sediments were analyzed for the elements U and Th, and a small subset of the samples was analyzed for additional elements. Splits of stream-sediment samples are in storage on the Denver Federal Center. Figure 2 shows the location of NURE stream-sediment samples collected in the northern part of Alabama. With funding from the Mineral Resources Program of the U.S. Geological Survey (USGS), a subset of these stream sediments (red dots on figure 2) was retrieved and submitted for chemical analyses during this study. Samples previously analyzed for arsenic during the original NURE program are shown as black dots.

### SAMPLING OF ABANDONED COAL MINES

As mentioned previously, Pennsylvanian coal of Alabama is locally enriched in arsenic. To evaluate this coal as a source of arsenic in stream sediments, a reconnaissance study was carried out. Sampling was conducted in the immediate vicinity of abandoned coal mines. The specific sites that were of interest to Alabama State government were chosen by Larry Barwick of the Abandoned Mine Land Reclamation Division, Department of Industrial Relations of the State of Alabama (fig. 3). Most of the sites have been closed for several decades. At sites labeled Black Branch, Gorgas, Pleasant Grove, and Blue Creek, samples of stream sediments, stream waters, and solid waste materials from the coal mining operations were collected. At sites labeled Newcastle, Short Creek, and Lost Creek, only coal waste materials were collected. Figures 4, 5, and 6 show part of the mine waste pile at Pleasant Grove, a small unnamed stream at the toe of the Pleasant Grove waste pile, and the Blue Creek site, respectively. Sampling protocols for stream sediments and waters were modified slightly from established USGS National Water-Quality Assessment Program (NAWQA) procedures (Shelton, 1994; Shelton and Capel, 1994). Stream sediments were collected and sieved to minus 80 mesh. Waters were filtered with a 0.44 mm filter using clean protocols in a mobile clean lab. The samples of coal waste pile materials were grab samples selected because they exhibited signs of weathering, such as the presence of orange or red iron-oxide sulfide-oxidation products. They are, therefore, not necessarily representative of the overall geochemistry of the coal mine wastes.

### CHEMICAL ANALYSIS TECHNIQUES

A contract laboratory performed the analyses of NURE stream-sediment samples, as well as the samples from coal mine dumps (these mine dumps are known as "gob piles"). Forty elements were analyzed by inductively coupled plasma-atomic emission spectroscopy following low temperature digestion of the rock or sediment sample by a combination of hydrochloric, hydrofluoric, perchloric, and nitric acids. In addition, each sample was analyzed for arsenic by hydride generation, atomic adsorption spectroscopy. Only the hydride generation arsenic data plus a limited suite of additional elements are reported here. Blind standards were submitted with each job to monitor lab precision and accuracy. In figure 2, the samples re-analyzed by these techniques are shown as red dots. A smaller suite of samples had been analyzed previously for arsenic during the NURE program and they were not re-analyzed. However, overlapping NURE analyses and new analyses indicate that the NURE arsenic data may be systematically low (J. Grossman, oral communication, 1999). Water samples were analyzed in the USGS laboratories, Denver, Colorado, by inductively coupled plasma-mass spectroscopy (analyst Al Meier). A limited suite of samples was analyzed using a selective leaching procedure to identify element associations. A four-step process was employed. The initial leach used 0.1M $KH_2PO_4$ to remove easily exchangeable ions. The second was 0.25M hydroxylamine hydrochloride in 0.25M HCl to remove easily reducible iron oxides. The third used 4N HCl at 95°C for 45 minutes to remove crystalline iron oxides. The final leach was a mixture of nitric, perchloric, and hydrofluoric acids, to dissolve the remaining phases.

## RESULTS

### OVERVIEW OF ARSENIC IN STREAM SEDIMENTS

The overall range of arsenic in the NURE stream sediments was from 0.3 to 44 mg/kg sediment (ppm) As in the sample data set. The mean value was 4.3 ppm with a standard deviation of 4.1 ppm. For comparison, the crustal abundance of arsenic is 1.8 ppm (Taylor, 1964). Shale is higher, with average values of 15 ppm. Coal samples from the entire USGS National Coal Resource Data System coal database (Finkelman, 1994) average 24 ppm arsenic. A study of stream sediments from throughout the U.S. by the USGS NAWQA program reported that the 75th percentile for arsenic in 541 stream sediments was 9.5 ppm (Rice, 1999). Given the relatively low crustal abundance of arsenic, a number of stream-sediment samples in this study may be considered geochemically anomalous in this element.

Figure 7 shows the arsenic concentration in stream sediments as variable-sized red circles, with each circle representing a range of concentration values; the larger the circle the higher the concentration range. The concentration ranges were selected using a mathematical method provided by the computer program ArcView. This method, termed "natural breaks," optimizes the breakpoints between classes using an algorithm that minimizes the variance within classes.

The arsenic data from the NURE stream sediments was also gridded using methodology built into the ArcView program. Gridding takes the point data and uses a mathematical algorithm to predict values in intervening areas. This grid was calculated with the Inverse Distance Weighted (IDW) interpolator that assumes each input point has a local influence that diminishes with distance. Points closer to the processing cell are weighted greater than those farther away. The results of the gridding calculation are shown as variably colored regions on figure 7. These colors indicate areas that are enriched in arsenic. A specified number of points, or optionally all points within a specified radius, can be used to determine the output value for each location. Grid values less than 4.5 ppm are not colored. Several areas stand out both as groupings of larger sized dots and as systematically enriched areas in the gridded data. One of these is the coal-bearing region of Alabama indicated by black mine symbols. This includes the Warrior coal field as well as the smaller Cahaba and Coosa coal fields (fig. 1). A second, smaller area of enrichment is associated with the gold occurrences (purple mine symbols). A third area of enrichment lies between the coal mining region and the gold occurrences. A fourth area of arsenic enrichment is in northwestern Alabama. For reference, these four areas are labeled 1-4 respectively.

In figure 8, parts of the four areas of stream-sediment arsenic enrichment shown in figure 7 are plotted on a map showing the type of rock exposed at the surface. There are two main geologic divisions represented in this figure based on the age of the surface rocks. The swath of light pink (gravel, sand, clay) together with dark blue "bricks" (chalk) on the western, south-western, and southern part of the map are the Tertiary and Quaternary rocks of the Gulf Coastal Plain. These rocks and sediments lap onto the older (Paleozoic) rocks shown in the remaining colors and patterns. Within the Paleozoic rocks, sandstone of the Pennsylvanian Pottsville Formation, host of the bituminous coal of Alabama, is colored yellow on figure 8. The Pottsville Formation consists of sandstone, shale, and minor coal. Carbonate rocks, including limestone and dolomite, are colored shades of blue and green, respectively, on figure 8.

From this figure, several important features are apparent: (1) Not all of the streams flowing over the Pottsville Formation contain sediment with elevated levels of arsenic. Note, for example, the area in the Pottsville Formation to the north of area 1. This northern part of the formation represents the lower Pottsville that contains only sporadic coal seams. Area 1 in figure 8 also encompasses an area of carbonate (mostly dolomitic) rocks with elevated levels of arsenic in stream sediments. As shown on figures 1 and 8, these carbonate rocks are between the main Warrior coal field on the west and the smaller Cahaba and Coosa coal fields to the east, and coincide with a geologic feature known as the Birmingham Anticlinorium. (2) Also included in area 1 is the large urban area of Birmingham, which is a possible source of industrial pollution. (3) Area 3 of figure 7 coincides with carbonate (mostly dolomitic) rock types. (4) Area 4 of figure 7 coincides with rocks that are dominantly limestone.

### STUDIES OF ABANDONED COAL MINES

The stream-sediment data from samples collected near abandoned underground coal mines are presented in table 1. The sediments are locally enriched in As, Fe, Cu, Zn, and Se. Arsenic concentrations range from 4 to 180 ppm. The arithmetic mean of this data is 48 ppm. For comparison, the arithmetic mean of all of the subset of NURE samples analyzed by the contract lab is 5.0 ppm (n=1,899 total samples) as noted above. Based on these results, stream sediments from the immediate vicinity of old abandoned coal mines contain significantly elevated concentrations of arsenic compared to stream sediments from the NURE data set. This enrichment in arsenic is further illustrated by a histogram (fig. 9) comparing the stream-sediment samples from near coal mines with the overall Alabama NURE data set. Over half of the coal mine samples have higher arsenic concentrations than are present in the much larger NURE sample suite. Furthermore the highest value in the NURE data set (44 ppm As) is exceeded by at least one analysis from stream sediments collected in the vicinity of each abandoned coal mine.

Most samples of the coal mine waste materials (gob-pile samples) were enriched in arsenic compared to average shale and coal values. The overall range for the coal waste samples was 7–472 ppm arsenic with an arithmetic mean of 122 ppm (table 2). It should be kept in mind that these coal mine waste samples are not necessarily representative of the overall waste pile, and are instead surface oxidized materials from the dumps. However, the data indicate that both altered (oxidized) wastes from abandoned coal mines and stream sediments close to the abandoned mines are elevated in arsenic.

In contrast to solid phase materials, water samples contain only low levels of dissolved arsenic (table 2). Concentrations of arsenic are below the proposed (lowered) drinking water standard of 5 ppb, with the exception of a single sample collected from the Gorgas site that had 89 mg/l (ppb) arsenic. This sample was collected by digging down to the water table in a plume of sediments that had slumped off a coal mine waste pile. Therefore, the sample represents shallow groundwater, not stream water. The low arsenic concentrations found in water in this study are important, because the concentration of arsenic in drinking water has the most direct impact on human health (Anonymous, 1999).

## DISCUSSION

### ARSENIC IN WARRIOR, CAHABA, AND COOSA STREAM SEDIMENTS

#### Potential Relationship of Pyrite Oxidation to Arsenic Release

The enrichment of arsenic in coal mine waste samples and in stream sediments adjacent to abandoned coal mines is consistent with the hypothesis that arsenic from coal mine waste is being released into stream sediments. We suggest that arsenic dominantly resides in coal strata pyrite and is released during weathering. Figure 10 (left side) is a geochemical model constructed using the computer program Geochemist's Workbench (Bethke, 1996). This figure illustrates the weathering (oxidation) of arsenic-bearing pyrite by atmospheric oxygen. As pyrite oxidizes, the pH drops dramatically, and sulfur (as sulfate), iron (as aqueous ferric iron), and arsenic (as the arsenate ion) are released to solution. However, as water pH is neutralized (in the example by reaction with calcite), arsenic in solution once again drops. This is because the rising pH causes iron oxyhydroxides to precipitate. Arsenic adsorbs strongly to this iron phase (Cullen and Reimer, 1989). This calculation predicts adsorption of arsenic in the solid fraction of the weathering products, and low arsenic in solution. A similar mechanism could explain the association of arsenic with arsenic-bearing gold deposits and occurrences (area 2 of figure 8); however, arsenopyrite may be the arsenic-bearing sulfide rather than arsenic-bearing pyrite.

An independent indication that pyrite oxidation has taken place over time in the coal fields of Alabama is the presence of stream waters with elevated sulfate concentrations. Sulfate, as shown by the equation at the top of figure 10, is a product of pyrite oxidation. Unlike iron that tends to precipitate as iron oxide, sulfate remains in solution. Typical streams world-wide have low sulfate concentrations. A world-wide average (not corrected for additions due to pollution) is 11.5 ppm (Berner and Berner, 1987). As can be seen in figure 11, high sulfate concentrations are locally present throughout the coal mining region, but rare elsewhere in the part of Alabama under study. These high sulfate concentrations are a further indication that pyrite oxidation impacts the stream environment. Note that many of the sites with high sulfate concentrations have been analyzed repeatedly over a considerable period of time (in some cases decades), and only the highest sulfate concentration at each site is shown. Thus figure 11 presents a picture of the maximum effect of pyrite oxidation on stream waters rather than a geochemical baseline at one time.

To test the prediction from figure 10 that arsenic is associated with an iron-rich phase, a limited number of selective leaching experiments were carried out on stream sediments from the NURE sample suite. The results of these leaching studies are shown in figures 12*A* and 12*B*. These figures show data for iron and arsenic respectively. Figure 12*A* shows the partitioning of iron into four operationally defined fractions as described in the Chemical Analysis Techniques section. This figure shows that the majority of the iron is removed during the third (HCL leach) step. Iron leached in this step corresponds to iron residing in 'well crystalline' iron oxides. The majority of the arsenic (fig. 12*B*) is removed with iron in this HCL leach step. These results are consistent with the mechanism presented above which hypothesized that arsenic was adsorbed on iron oxides produced during pyrite oxidation, provided that the iron oxides "age" to form well crystalline precipitates after initially forming and adsorbing arsenic.

### ARSENIC ELSEWHERE IN NORTHERN ALABAMA

Arsenic is present in elevated concentrations in stream sediments in specific areas outside of the coal fields of Alabama. Three such areas are identified on figure 7. Area 2 is associated with arsenic-bearing gold deposits and occurrences. Arsenic enrichment in stream sediments of this area is likely due to oxidation of the mineral arsenopyrite, which is often associated with these gold deposits.

The origin of elevated stream-sediment arsenic in area 3 is not known. As stated previously, carbonate rocks predominantly underlie this area. It is possible that this is a naturally occurring arsenic enrichment related to high arsenic concentrations in these rocks. The origin of arsenic in area 3 is still being investigated.

The origin of arsenic enrichment in stream sediments of area 4 in northwestern Alabama is also not well understood. This part of the State is extensively farmed for cotton, and the possibility exists that agricultural chemicals utilized in cotton farming have contributed to the higher arsenic concentrations in stream sediments. This possibility is reinforced by data showing the rate of application of the arsenic-bearing herbicide DSMA (Disodium metharsenate; fig. 13). A similar plot could be made for the related compound MSMA (Monosodium metharsenate). The possible link between application of agricultural chemicals and stream-sediment arsenic is presently being investigated.

## CONCLUSIONS

Geochemical data indicate that arsenic is enriched in stream sediments collected from parts of northern Alabama. In bituminous coal mining areas, this enrichment can be linked to oxidation of arsenic-bearing pyrite that is present locally in the coal beds and mine waste materials. Dissolved arsenic in these coal mining areas is not elevated in the waters contacting the stream sediments. Dissolved arsenic in drinking water supplies is of most concern to human health (Anonymous, 1999); however, this study suggests that there is presently no reason to believe that human health impacts will result from environmental enrichment of arsenic in northern Alabama.

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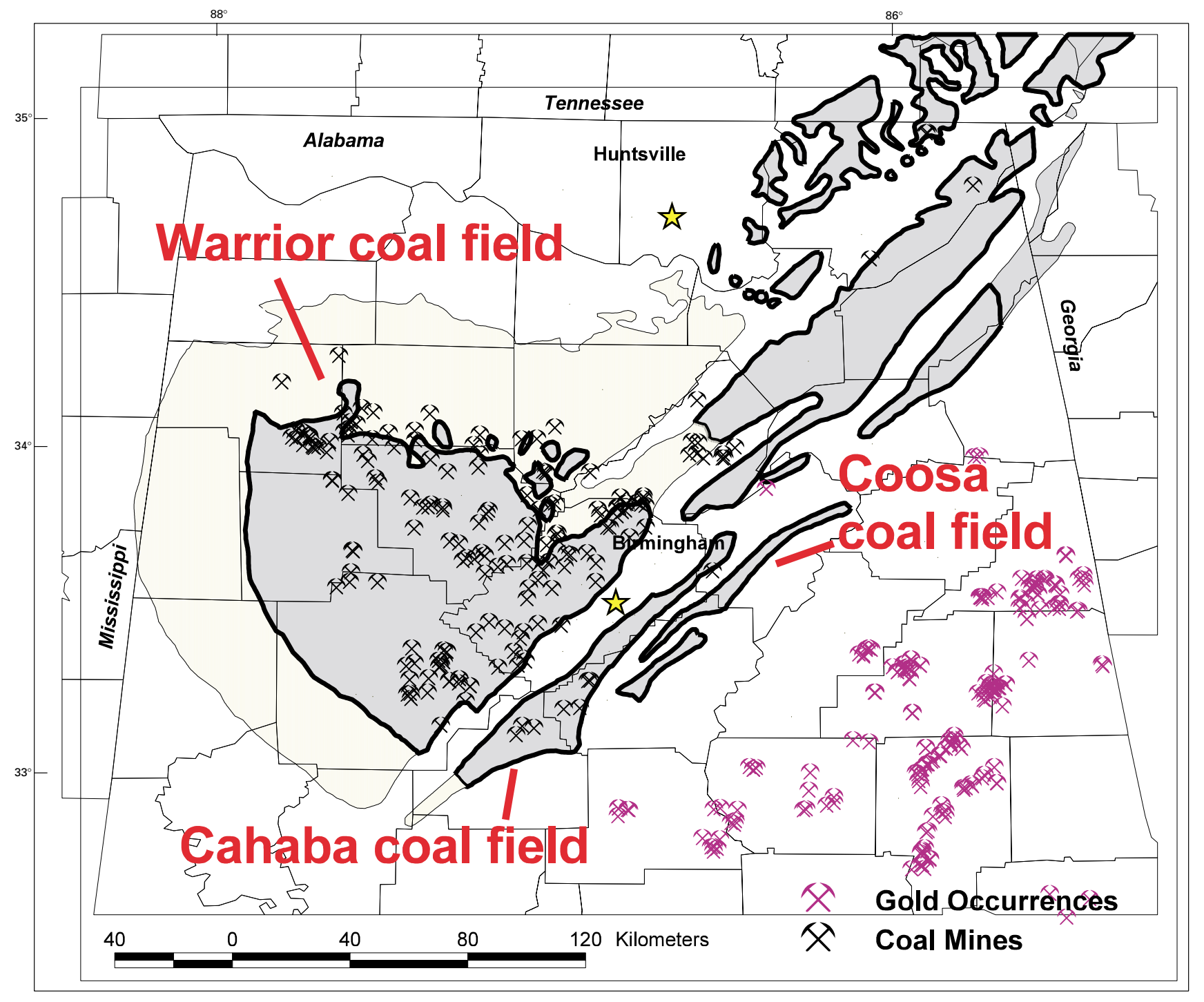


**Figure 1.** Map of the northern part of Alabama showing the locations of economic coal fields (gray areas outlined in black), along with some of the larger cities (stars). Coal mines are shown as black mine symbols, and gold shows and deposits are shown as purple mine symbols. Light-yellow areas are typically subeconomic coal fields.

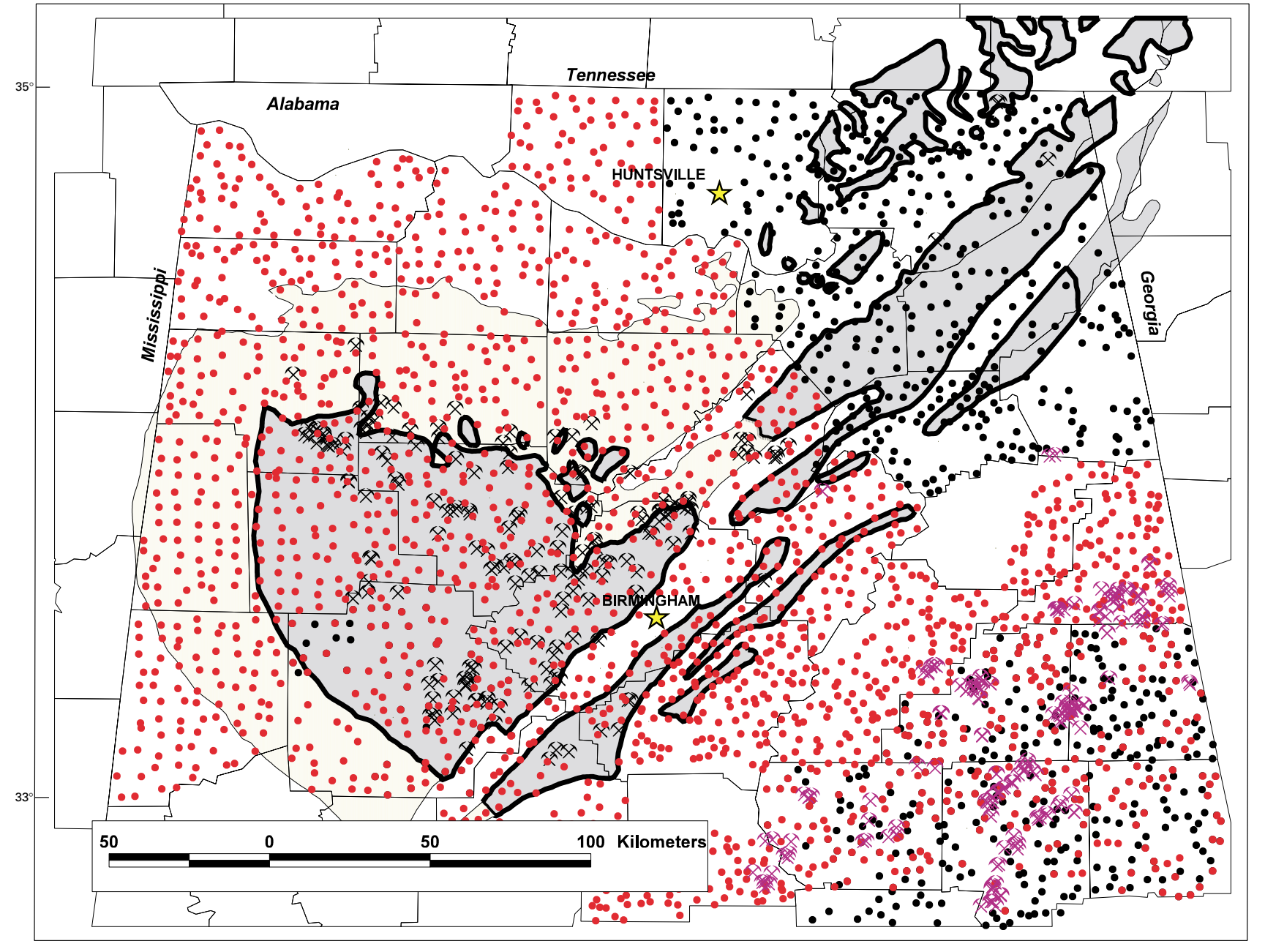


**Figure 2.** Map of the same area of Alabama as shown in figure 1. The dots show NURE stream-sediment sample localities. The red dots indicate samples analyzed during this study; the black dots indicate samples previously analyzed during the NURE program. Coal mines are shown as black mine symbols, and gold shows and deposits are shown as purple mine symbols. Economic coal fields are shown in gray and are outlined in black. Light-yellow areas are typically subeconomic coal fields.

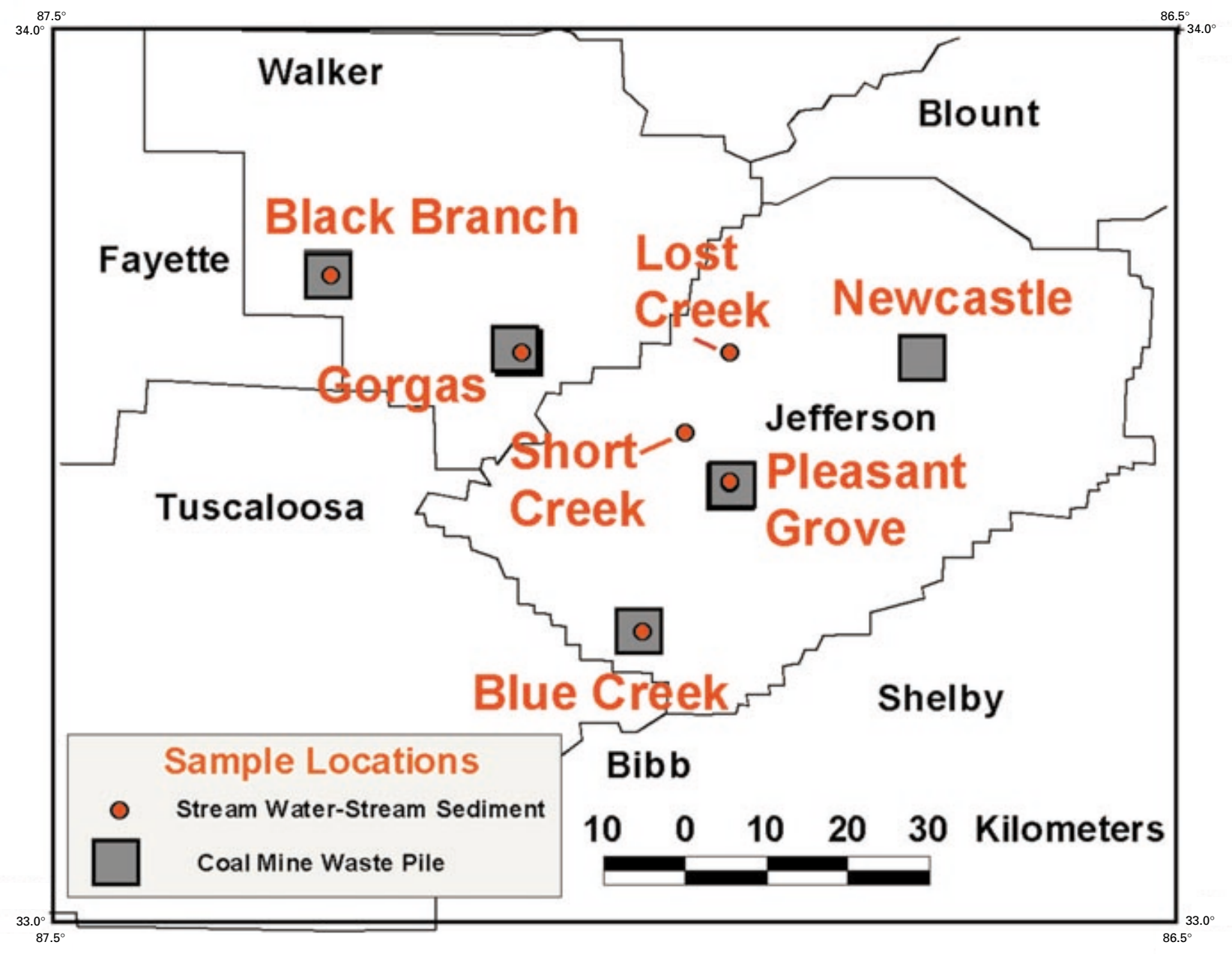


**Figure 3.** Map showing the locations of stream-sediment/stream-water sample localities and abandoned coal mine waste sample localities visited during this study. County names are in black type.

**Figure 4.** Photograph of a part the Pleasant Grove mine waste (gob) pile. The white and orange colors are oxidation products formed by the oxidation of pyrite.

**Figure 5.** Photograph of a small unnamed stream at the toe of the Pleasant Grove gob pile shown in figure 4. The brown color is due to iron oxides formed by pyrite oxidation. The pH of this stream was 3.4.

**Figure 6.** Photograph of Blue Creek adjacent to a gob pile.

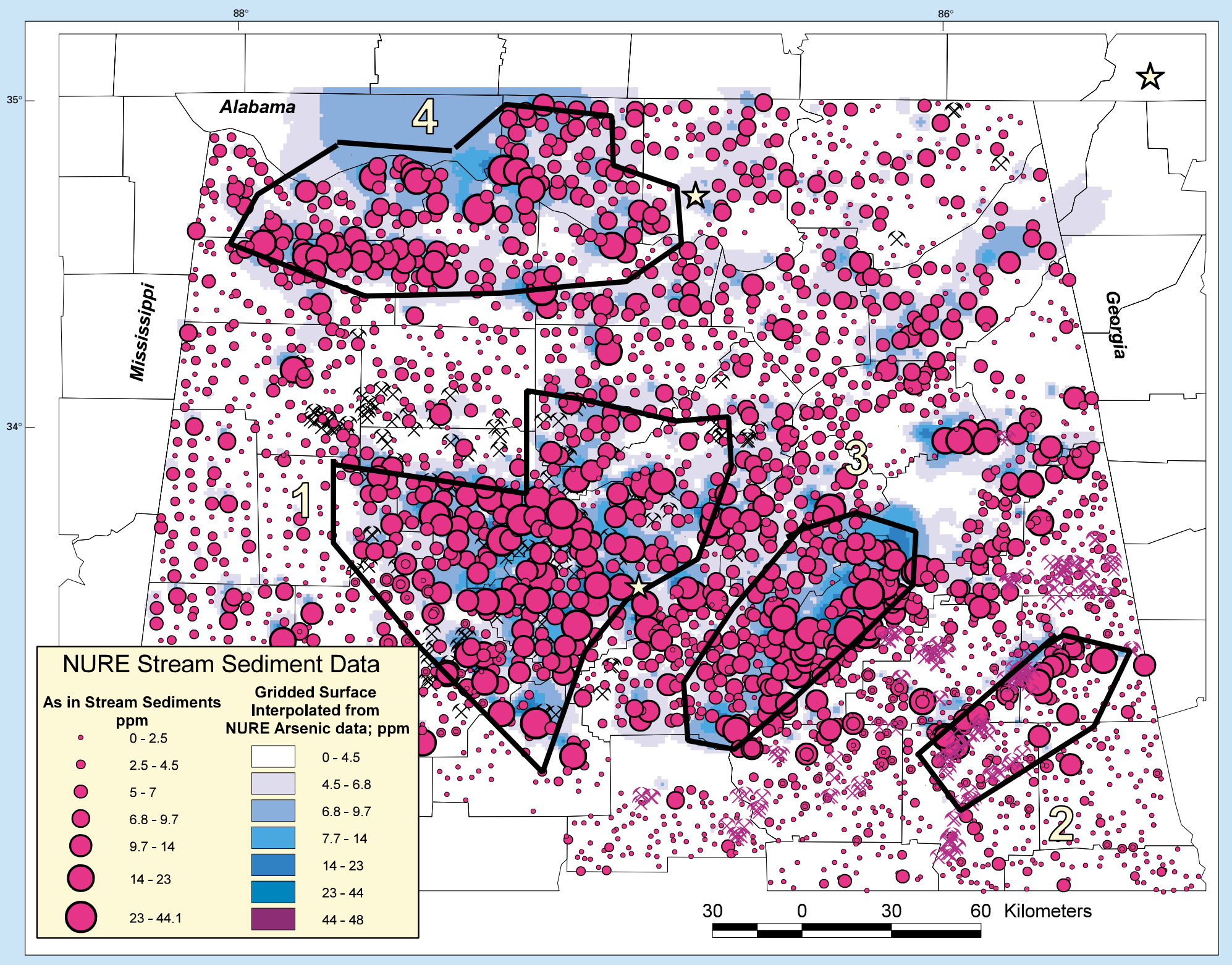


**Figure 7.** Map showing the distribution of arsenic in stream sediments. The size of the dot is proportional to the abundance of arsenic. Four areas with systematically elevated arsenic concentrations are outlined by thick black lines.

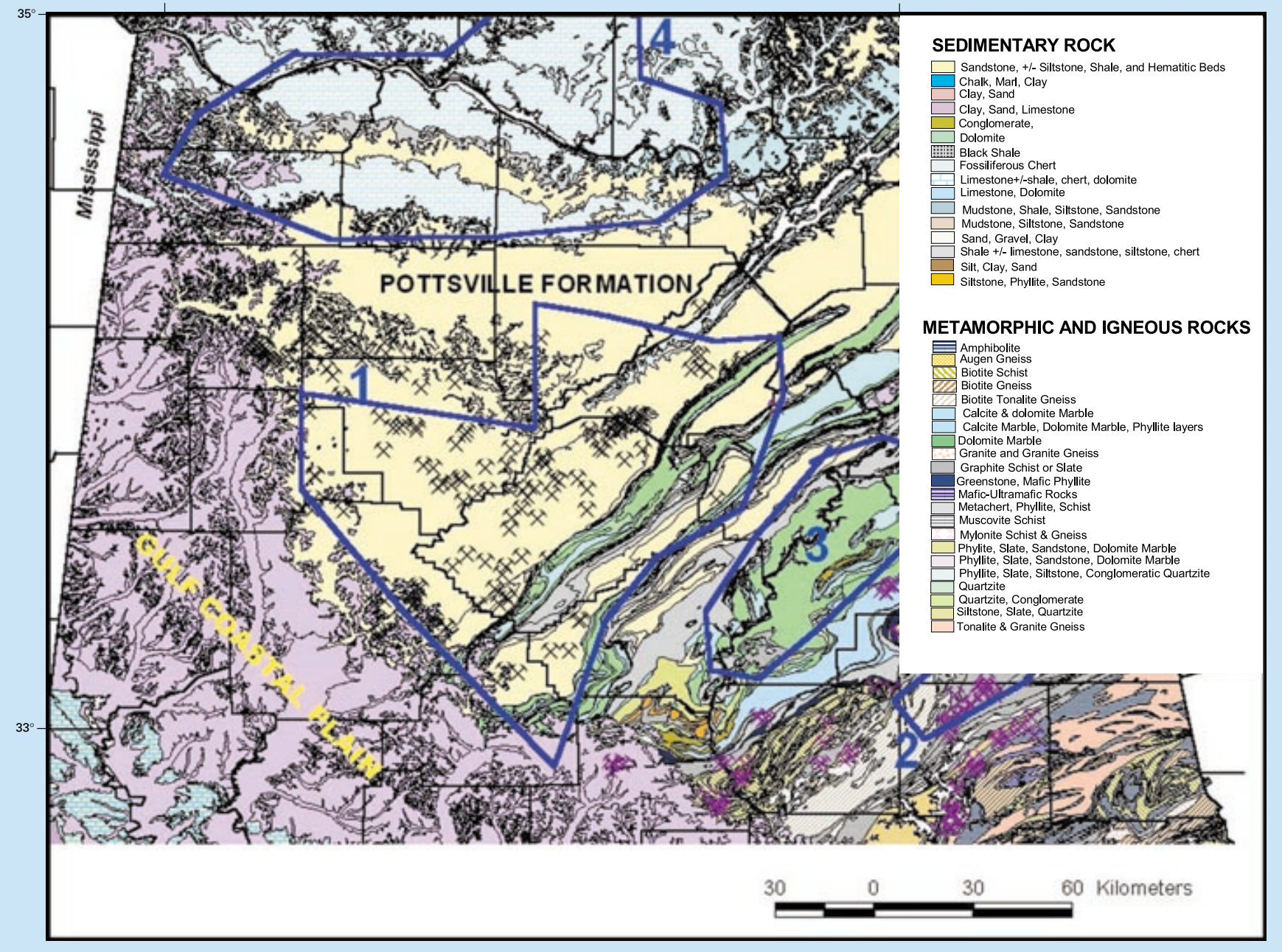


**Figure 8.** Map showing the geology of part of Alabama. The Pottsville Formation that hosts the bituminous coal of Alabama is yellow. Dolomite ($CaMgCO_3$) is shown in green. All or parts of four areas with elevated arsenic concentrations are outlined in blue. Coal mines are shown as black mine symbols, and gold shows and deposits are shown as purple mine symbols.

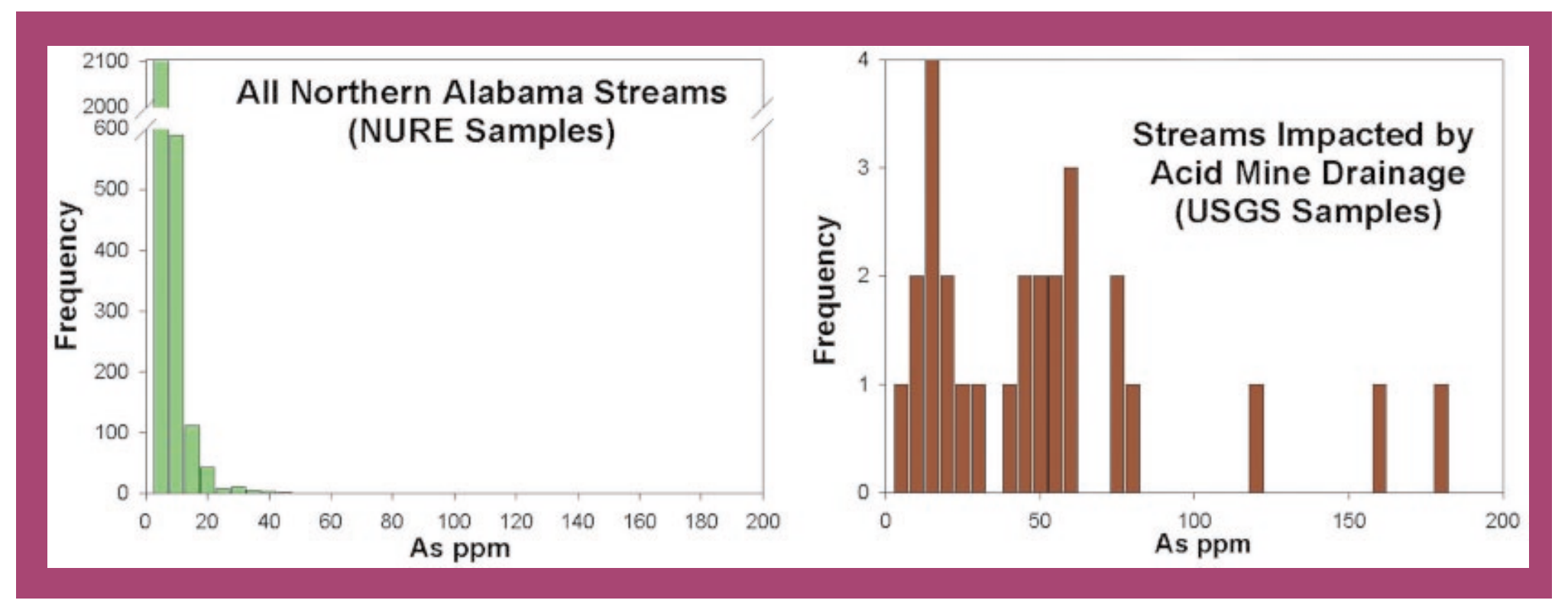


**Figure 9.** Histograms showing the concentration of arsenic in stream sediments. The histogram on the left depicts the data from NURE stream-sediment samples and is the same data as that shown in figure 7. The histogram on the right shows data for stream sediments immediately adjacent to abandoned coal mines (see figure 3 for the location of the sample localities). The two histograms have the same horizontal scale. Note the elevated arsenic concentrations immediately adjacent to coal mines as compared to the NURE samples.

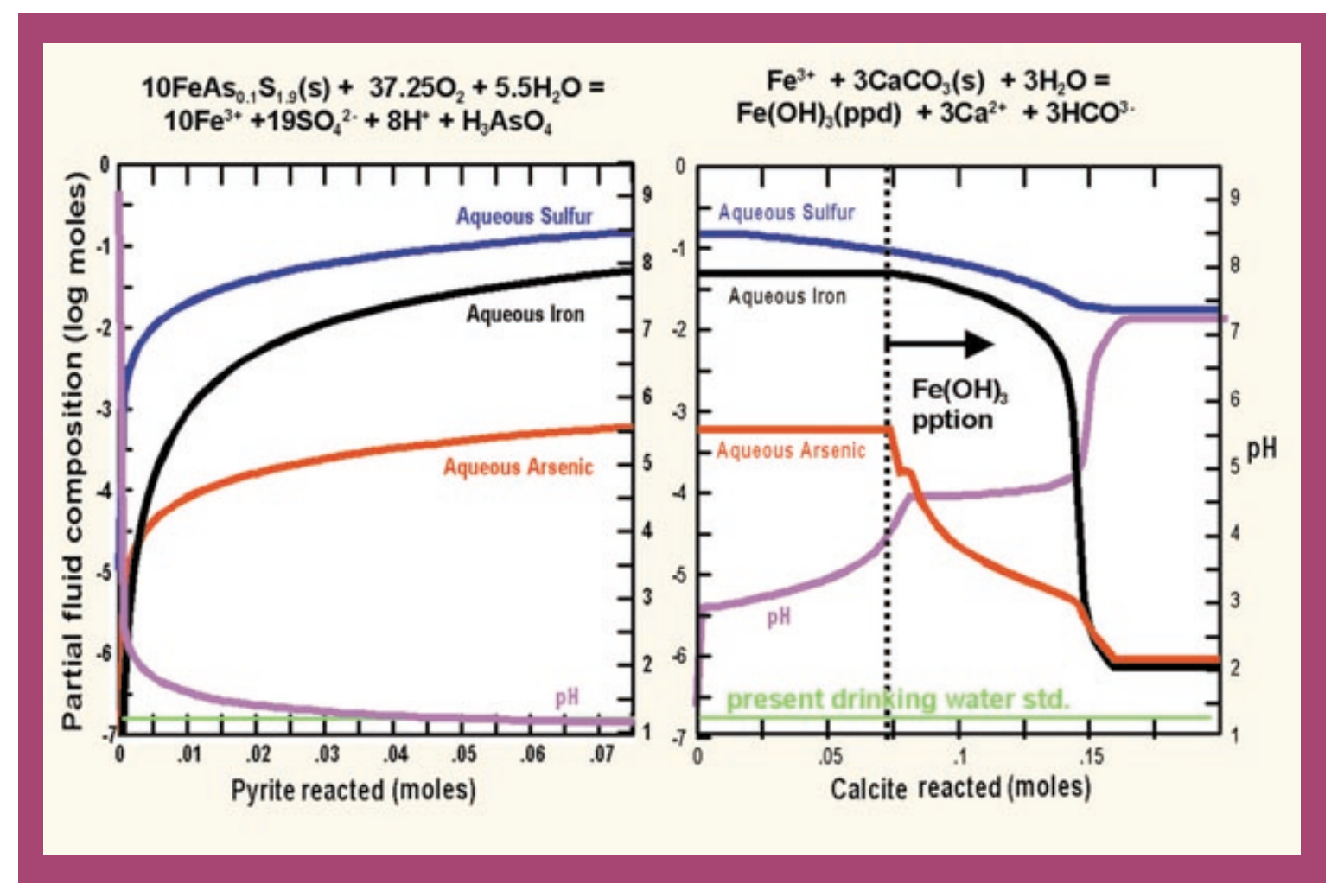


**Figure 10.** Geochemical models of pyrite oxidation produced by the computer program "Geochemists Workbench." The left panel shows a model of the oxidation of arsenic-bearing pyrite in the presence of an infinite supply of atmospheric oxygen. The products of this process are aqueous sulfur (in the form of sulfate), aqueous iron (in the form of $Fe^{3+}$), and aqueous arsenic (in the form of the arsenate ion). Note the rapid drop in pH (leading to acid mine drainage). The right panel shows the consequences of neutralizing the low pH waters produced by pyrite oxidation by reaction with calcite ($CaCO_3$). The pH rises until the dissolved iron starts to precipitate as the mineral ferrihydrite ($Fe(OH)_3$). The dissolved arsenic drops rapidly when this happens due to adsorption of arsenate on the ferrihydrite surface.

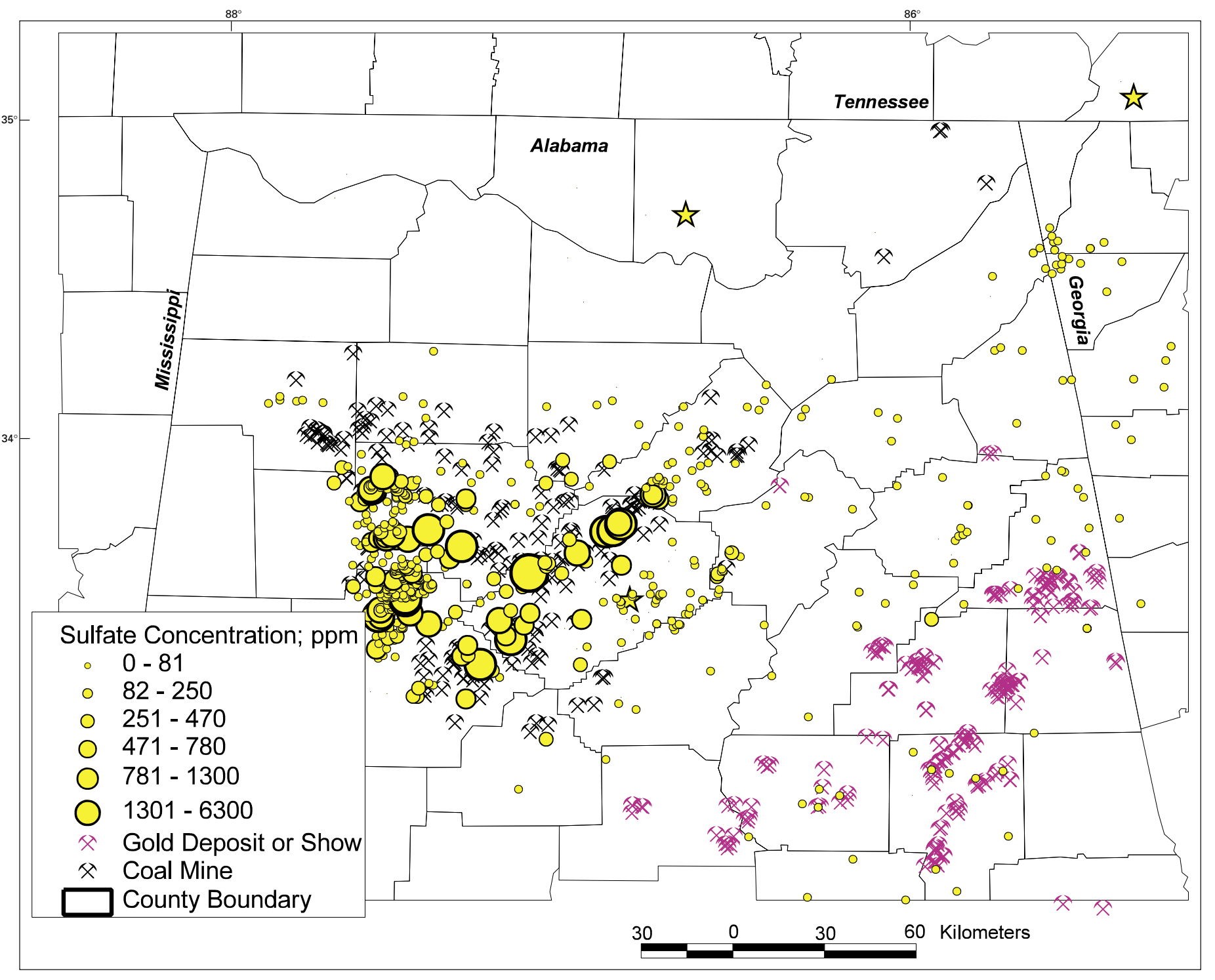


**Figure 11.** Distribution of dissolved sulfate in stream waters of Alabama. The concentrations are shown as a series of proportionally sized dots, with larger dots representing higher concentrations. For comparison, world average river water has about 11 ppm sulfate. Note the concentration of high values in the Warrior coal field.

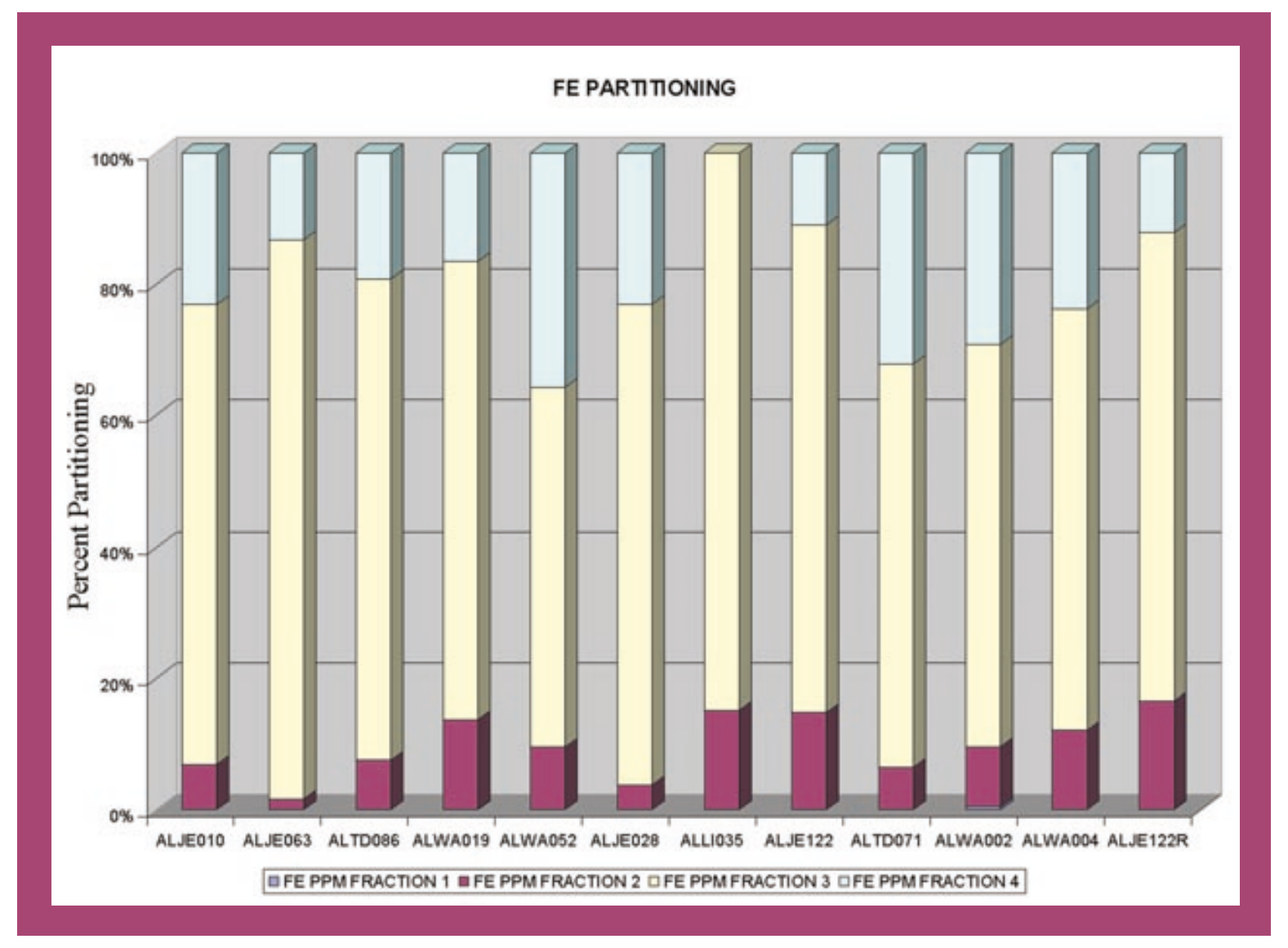


**Figure 12*A*.** Partitioning of iron in NURE stream-sediment samples. Fraction 1 is easily exchangeable ions, fraction 2 is easily reducible iron oxides, fraction 3 is crystalline iron oxides, and fraction 4 is the residual material after all the other fractions have been removed. See text in chemical analysis techniques section for details. Note that most Fe is removed in fraction 3. Samples labeled ALJE, ALTD, and ALWA are from Jefferson County, Talladega, and Walker Counties, respectively.

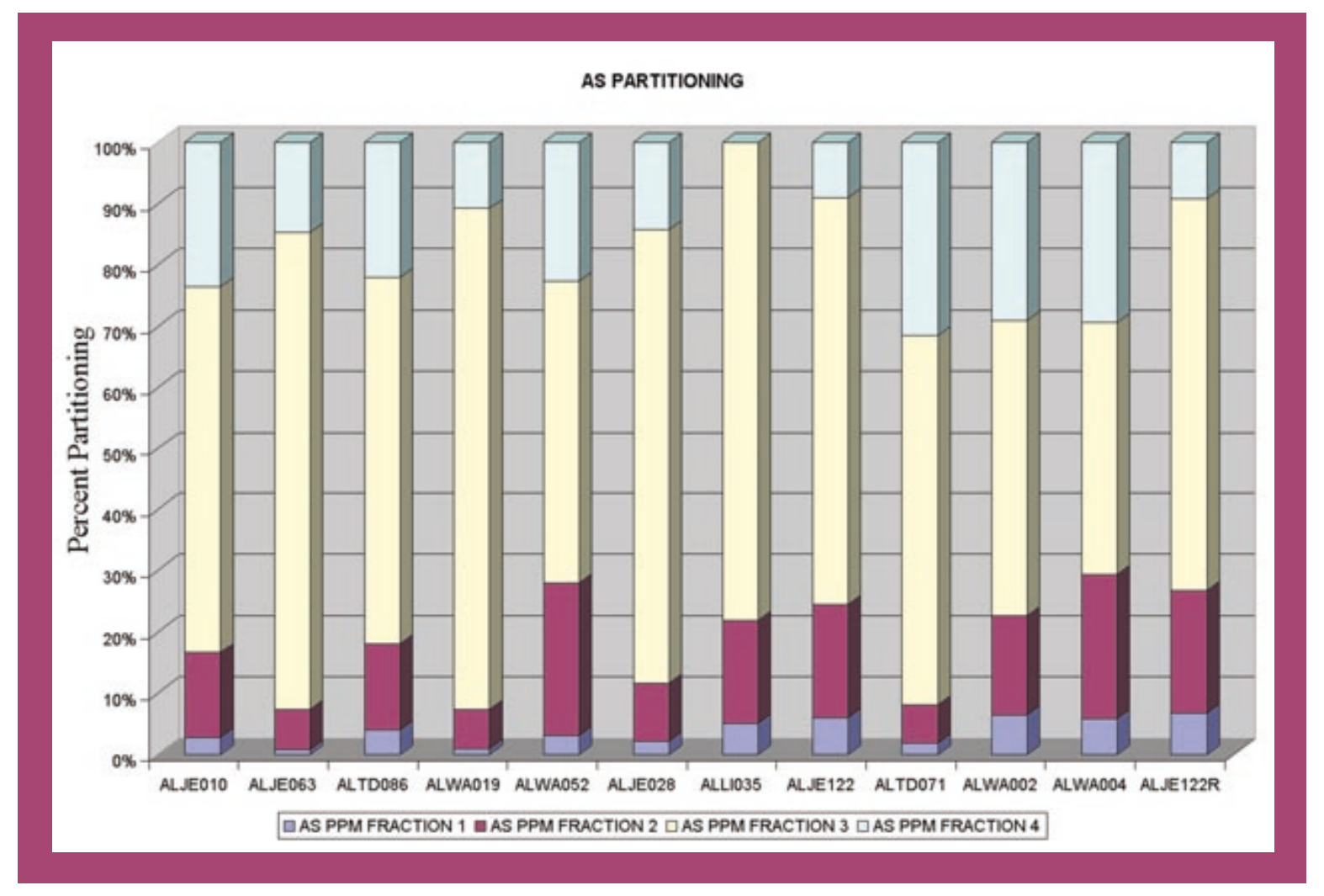
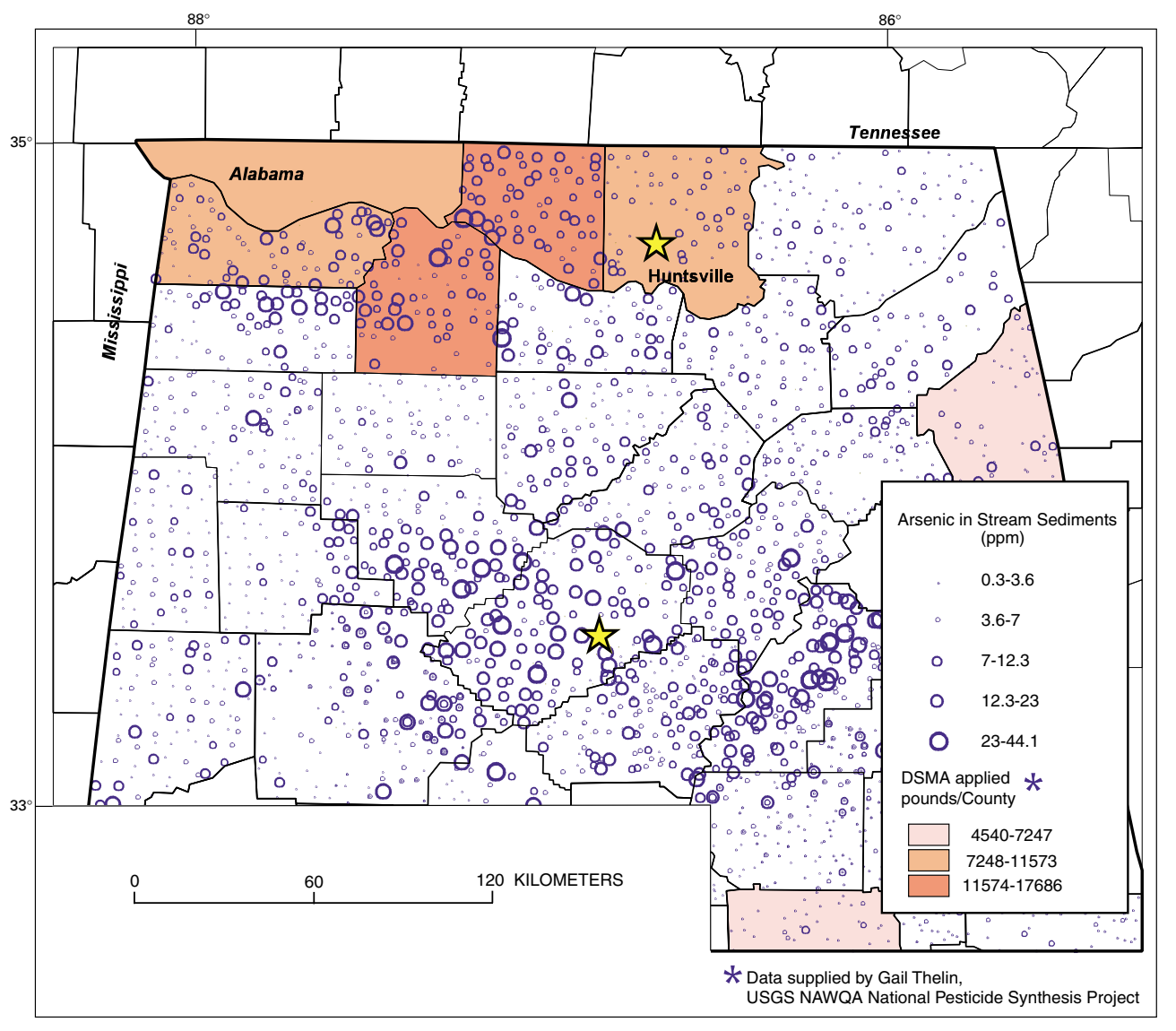


**Figure 12*B*.** Partitioning of arsenic in NURE stream-sediment samples. See figure 12*A* for an explanation of this graph. These are the same samples shown in figure 12*A*. Note that most arsenic is removed in the same fraction (3), as was the Fe in figure 12*A*. This is taken to be evidence that arsenic is associated with iron oxides in the stream sediments.



* Data supplied by Gail Thelin,
USGS NAWQA National Pesticide Synthesis Project

**Figure 13.** Map showing the distribution of arsenic. Dot size is proportional to the abundance of arsenic in stream sediments. Shown in shades of pink and orange are county by county data on the rate of application of the arsenic-containing herbicide DSMA (Disodium metharsenate). Note the coincidence of high rates of application of DSMA and elevated stream-sediment arsenic concentrations in the northwest corner of Alabama.

**Table 1. Chemical analyses of stream sediments affected by acid mine drainage.**

| Field number | Fe (wt %) | As (ppm) | Cu (ppm) | Zn (ppm) | Se (ppm) |
|---|---|---|---|---|---|
| Gorgas1 | 17.4 | 180 | 44 | 54 | 4.8 |
| Gorgas2 | 26.4 | 79 | 24 | 39 | 2.4 |
| Gorgas3 | 10.4 | 43 | 42 | 85 | 1.6 |
| Lost Creek 1a | 3.5 | 14 | 27 | 139 | < 1 |
| Lost Creek 1b | 3.1 | 10 | 18 | 91 | < 1 |
| Lost Creek 2a | 10.5 | 75 | 40 | 46 | 4.3 |
| Lost Creek 2b | 4.2 | 45 | 38 | 47 | 2.6 |
| LostCreek 3a | 7.1 | 105 | 52 | 71 | 5.1 |
| Lost Creek 3b | 5.8 | 75 | 43 | 72 | 3.7 |
| Black Branch 1a | 10.6 | 60 | 35 | 59 | 5.0 |
| Black Branch 1b | 7.4 | 55 | 33 | 45 | 5.3 |
| Black Branch 2a | 43.7 | 55 | 9 | 26 | < 1 |
| Black Branch 2b | 33.8 | 42 | 19 | 29 | 1.5 |
| Black Branch 3 | 25.7 | 27 | 16 | 61 | 2.1 |
| Short Creek 1a | 3.2 | 10 | 29 | 114 | < 1 |
| Short Creek 1b | 1.5 | 5 | 14 | 41 | < 1 |
| Short Creek 2a | 4.4 | 17 | 51 | 141 | < 1 |
| Short Creek 2b | 4.1 | 16 | 47 | 126 | < 1 |
| Short Creek 3 | 12.2 | 150 | 48 | 49 | 5.6 |
| Goolsby-1 | 4.0 | 52 | 38 | 44 | 3.1 |
| Goolsby-A | 3.8 | 20 | 15 | 48 | 1.5 |
| Goolsby-B | 28.0 | 14 | 13 | 43 | 1.2 |
| Blue Creek-2 | 2.6 | 46 | 46 | 47 | 3.0 |
| Blue Creek-A | 7.9 | 56 | 38 | 77 | 1.9 |
| Blue Creek-B | 8.7 | 38 | 46 | 123 | 2.0 |

**Table 2. Chemical analyses of samples from coal mine waste materials.**

| Field number | Type | As (ppm) | Al (ppm) | Fe (ppm) | Cu (ppm) | Zn (ppm) | Se (ppm) |
|---|---|---|---|---|---|---|---|
| Cane_creek-1 | Gob Pile | 91 | 112,000 | 37,200 | 41 | 62 | 5 |
| Cane_creek-2 | Gob Pile | 81 | 80,600 | 35,700 | 63 | 25 | 5 |
| Cane_creek-3 | Gob Pile | 140 | 111,000 | 161,000 | 133 | 48 | 6 |
| Cane_creek-4 | Gob Pile | 472 | 21,800 | 229,000 | 19 | 12 | 31 |
| Cane_creek-7 | Gob Pile | 18 | 59,500 | 21,300 | 72 | 41 | 3 |
| Gorgas-1 | Gob Pile | 26 | 102,000 | 27,600 | 63 | 64 | 6 |
| Gorgas-2 | Gob Pile | 470 | 70,700 | 52,900 | 323 | 296 | 8 |
| Gorgas-3 | Slough | 43 | 53,400 | 15,600 | 43 | 27 | 5 |
| Gorgas-A | Gob Pile | 180 | 105,000 | 82,200 | 62 | 453 | 7 |
| Gorgas-B | Gob Pile | 224 | 108,000 | 70,600 | 61 | 208 | 5 |
| Plgrove-1 | Gob Pile | 134 | 60,400 | 30,500 | 91 | 366 | 3 |
| Plgrove-2 | Gob Pile | 40 | 86,000 | 30,000 | 60 | 82 | 5 |
| Plgrove-3 | Gob Pile | 7 | 42,900 | 24,200 | 15 | 52 | 1 |
| Plgrove-4 | Gob Pile | 77 | 112,000 | 47.300 | 87 | 136 | 3 |
| Plgrove-6 | Gob Pile | 24 | 50,100 | 20,500 | 292 | 967 | 3 |
| Plgrove-7 | Gob Pile | 85 | 60,200 | 116,000 | 469 | 143 | 16 |
| Newcastle-1 | Gob Pile | 136 | 72,400 | 46,800 | 42 | 53 | 2 |
| Newcastle-2 | Gob Pile | 116 | 62,700 | 159,000 | 56 | 40 | 2 |
| BlueCreek-1 | Gob Pile | 53 | 79,200 | 29,600 | 33 | 51 | 3 |
| Acmar-1 | Gob Pile | 196 | 81,700 | 38,600 | 35 | 34 | 6 |
| Acmar-2 | Slurry Pond | 45 | 58,800 | 26,500 | 45 | 36 | 3 |
| Gorgas-4 | Slurry Pond | 21 | 27,000 | 9,850 | 45 | 33 | 3 |

**Table 3. Water chemistry associated with acid mine drainage streams.**

| Sample description | Al ug/L | Fe ug/L | As ug/L | Cu ug/L | Zn ug/L | Se ug/L |
|---|---|---|---|---|---|---|
| Short Creek pH 6.9 water | <9 | <30 | 1 | <0.5 | 3 | 0.4 |
| Short Creek Mixing Zone | 2,400 | 62 | 0.5 | 5 | 99 | 0.4 |
| Short Creek Culvert | 79,000 | 380 | 0.3 | 84 | 640 | 0.2 |
| Black Branch Gob Pile | 7,100 | 17,000 | 2 | 1 | 95 | < 0.2 |
| Black Branch pond' | 15,000 | 950 | <0.2 | 2 | 110 | < 0.2 |
| Lost Creek Acid Mine Drainage | 91,000 | 3,400 | 0.4 | 23 | 1,300 | 2 |
| Lost Creek Receiving | <9 | <30 | 0.3 | 0.5 | 0.8 | 0.6 |
| Lost Creek Mixing Zone | 6,500 | 120 | 0.2 | 6 | 380 | < 0.2 |
| Gorgas Gob Pile | 38,000 | 35,000 | 4.1 | 13 | 440 | < 0.2 |
| Gorgas at river | 2,600 | 47,000 | 4.8 | 3 | 260 | 0.9 |
| Gorgas; small spring draining Gob Pile | 88,000 | 16,000 | 2.4 | 140 | 640 | 1 |
| Gorgas; water from water table in slough | >300,000 | 190,000 | 89 | 1,000 | 3,800 | 7.5 |

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[1] U.S. Geological Survey, Denver, Colo.
[2] U.S. Geological Survey, Auburn, Ala.
[3] U.S. Geological Survey, Montgomery, Ala.
[4] Auburn University, Auburn, Ala.
[5] Alabama Geological Survey, Tuscaloosa, Ala.
[6] Abandoned Mine Land Reclamation Division, State of Alabama, Birmingham, Ala.
[7] AML Project Coordinator, State of Alabama, Montgomery, Ala.
[8] U.S. Geological Survey, Reston, Va.