Environmental Geochemistry in Yellowstone National Park—Natural and Anthropogenic Anomalies and Their Potential Impact on the Environment

By Maurice A. Chaffee, Robert R. Carlson, and Harley D. King

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Integrated Geoscience Studies in the Greater Yellowstone Area— Volcanic, Tectonic, and Hydrothermal Processes in the Yellowstone Geoecosystem

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Abstract

In cooperation with the National Park Service, the U.S. Geological Survey conducted a stream-sediment-based environmental geochemical study in and near Yellowstone National Park (the Park). The main goals of the study were to (1) determine background concentrations for as many as 49 elements in samples of rock and stream sediment, (2) establish a geochemical baseline during the 1990s for future reference, (3) identify the source(s) of anomalies for selected elements, and (4) identify potential chemical impacts on the Park environment, especially on wildlife.

Two areas of the Park containing identified environmental geochemical problems were selected for detailed study: (1) an area in the western part of the Park that includes the Gibbon, Firehole, and Madison River basins, and (2) an area in the northeastern part that includes the Soda Butte Creek and Lamar River basins and part of the Yellowstone River basin. The geology of the first area is characterized mainly by Quaternary felsic volcanic rocks. Localities with major geothermal activity are present in this area. The second area has more complex geology that consists primarily of Tertiary volcanic rocks of intermediate composition and Precambrian schists and gneisses. Also present are scattered exposures of Paleozoic clastic and carbonate rocks and Quaternary felsic volcanic rocks. Geothermal activity is very limited in this area. Both study areas contain extensive deposits of glacial, fluvial, or lacustrine origin.

Analyses for as many as 49 elements in 393 samples of stream sediment collected from throughout the Park were evaluated statistically, including factor analysis. A five-factor model classified the elements on the basis of two lithologic factors, one mineral-deposit-related factor, one geothermal-process-associated factor, and one "miscellaneous" factor.

Data from the factor analysis, when combined with the distributions of anomalies for the elements determined in this study, show that most (34) of the elements are best correlated with rock chemistry. Many of these elements can be used to discriminate between major lithologic units and can therefore be used to assist geologic mapping studies in the Park area.

Anomalies of As, Cs, F, Hg, Mo, S, Sb, Tl, and W were determined to be associated with areas of geothermal activity. Of these nine elements, cesium is the best discriminator between anomalies related to geothermal activity and those related to outcrops of mineralized rock and to past mining activity near the Park. The effects of mineralization and past mining activity in the Cooke City, Mont., area, outside but near the northeastern boundary of the Park, are defined by anomalies of Ag, As, Au, Cu, Fe, Hg, Mo, Pb, S, Sb, Se, Te, Tl, W, and Zn, and possibly F. The effects are delineated best by anomalies of Au, Cu, and Te. Relatively weak anomalies of some of these elements extend as far as 18 km inside the Park.

In the area of Slough Creek, in the northeastern area of the Park, the source for a high concentration of lead was determined to be anthropogenic because of the sample location and a lack of anomalies of other elements that commonly are associated with natural lead anomalies. This anomaly probably is related to past fishing activity.

In high concentrations, a number of the elements associated with geothermal activity in the Park are potentially toxic to animals. Currently, only one of the 49 elements determined (fluorine) is known to affect the health and longevity of wildlife in the Park. Additional studies are needed to determine whether other elements are impacting the Park environment, including wildlife.

Introduction

An important goal in the field of environmental geochemistry is to identify unusually high or low natural concentrations of elements in the surficial environment and to evaluate their potential impact on the environment. An equally important goal is to identify element concentrations that are related to human (anthropogenic) activity. In cooperation with the National Park Service, the U.S. Geological Survey (USGS) conducted a stream-sediment-based environmental geochemical study in and near Yellowstone National Park (the Park). The Park is
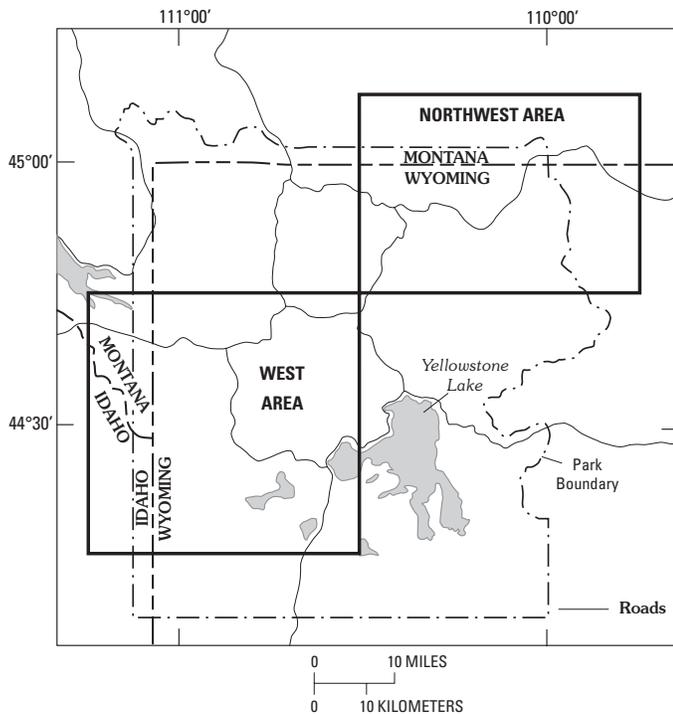

U.S. Geological Survey, Box 25046, Mail Stop 973, Denver Federal Center, Denver, CO, 80225.

Figure 1. Index map of Yellowstone National Park and vicinity showing locations of the two study areas. Road shown as thin solid line.

mostly located in northwestern Wyoming, with small portions in adjacent areas of Idaho and Montana (fig. 1).

As part of a regional environmental geochemical study of Yellowstone National Park, surficial materials were sampled throughout the Park and in the immediately adjacent area. The main goals of the study were to (1) determine background concentrations for as many as 49 elements in samples of rock and stream sediment, (2) establish a geochemical baseline during the 1990s for future reference, (3) identify the source(s) of anomalies for selected elements, and (4) identify potential chemical impacts on the Park environment, especially on wildlife.

Two areas of the Park containing identified environmental geochemical problem areas have been selected for discussion here (fig. 1). The West Study Area (West Area) includes streams above and below the major geyser basins along the Firehole, Gibbon, and Madison Rivers. The waters of many of these streams contain natural but elevated concentrations of elements such as arsenic, fluorine, and molybdenum (Miller and others, 1997), which may impact the health of animals in the Park.

The Northeast Study Area (Northeast Area) contains the Soda Butte Creek basin, which includes the New World mining district, north of Cooke City, Mont., and the Republic district, south of Cooke City. Soda Butte Creek drains runoff and ground water from predominantly gold- and copper-rich, base- and precious-metal mineral deposits and their associated dumps, tailings piles, and slag heaps in these two districts. That stream flow enters the Lamar and Yellowstone River basins in the Park.

Previous Investigations

Analyses of waters collected in Yellowstone National Park have been described and interpreted by a number of investigators (see, for example, Allen and Day, 1935; Gooch and Whitfield, 1888; Miller and others, 1997; Rowe and others, 1973; Stauffer and others, 1980; Thompson and DeMonge, 1996; Thompson and Hutchinson, 1981; Thompson and Yadav, 1979; Thompson and others, 1975; White and others, 1988). Water and stream-sediment samples were collected in the Park and analyzed (but never adequately evaluated) for the National Uranium Reconnaissance Evaluation Program (Bolivar, Hensley, and others, 1980; Bolivar, Sandoval, and others, 1980; Broxton and others, 1979; Shannon and others, 1980). Geochemical data and interpretations have been published by the U.S. Geological Survey for several of the national forests and wilderness areas surrounding Yellowstone National Park (Antweiler, Love, and others, 1989; Antweiler, Rankin, and others, 1985; Carlson and Lee, 2005; Elliott and others, 1983; Lee and Carlson, 1993; Love and others, 1975; Nelson and others, 1980; Simons and others, 1979; Wedow and others, 1975). A report by Shannon (1982) is the only one that describes the regional geochemistry of stream-sediment samples collected within any part of the Park.

Geologic Setting

The geology of Yellowstone National Park has been described by many workers (see, for example, Bond, 1978; Christiansen and Blank, 1972; Fournier and others, 1994; Keefer, 1972; Love and Keefer, 1975; Taylor and others, 1989; U.S. Geological Survey, 1972; Wilson and Elliott, 1997). Only a brief summary, based on these maps and reports, is included here.

Simplified geologic maps are shown for the two study areas (figs. 2*A* and 2*B*). In the West Area (fig. 2*A*), exposures are almost entirely Quaternary felsic (mostly rhyolitic) volcanic rocks. A few small basalt flows are exposed in the northwestern part of this area. Quaternary alluvial and lacustrine deposits and glacial moraines locally cover the older units.

In contrast, the Northeast Area (fig. 2*B*) is geologically complex. The oldest rocks in the area are in the Beartooth Mountains, in the extreme northeastern part of this area. These rocks are mostly Precambrian granitic gneisses and migmatites, with minor intrusions of mafic rocks (B.S. Van Gosen, written commun., 1998). Areas of Precambrian metasedimentary rocks and quartz monzonite and diorite are present at several localities in the west-central part of the area. Paleozoic sedimentary rocks, mostly quartzite, sandstone, and limestone, are present at scattered localities, mainly in the northeastern part of this area. Tertiary volcanic rocks of the Absaroka Volcanic Supergroup, primarily andesites of intermediate composition, are the most common rock types in the Northeast Area. Exposures of Quaternary felsic volcanic rocks are present in the southwestern part of this study area, mainly in the Yellowstone River basin. Deposits of Quaternary alluvium and glacial moraine locally cover the older rocks.

A

EXPLANATION

Quaternary unconsolidated sediment

Quaternary basalt flows

Quaternary felsic volcanic rocks

Tertiary volcanic rocks

Paleozoic sedimentary rocks

Precambrian metasedimentary and
meta-igneous rocks

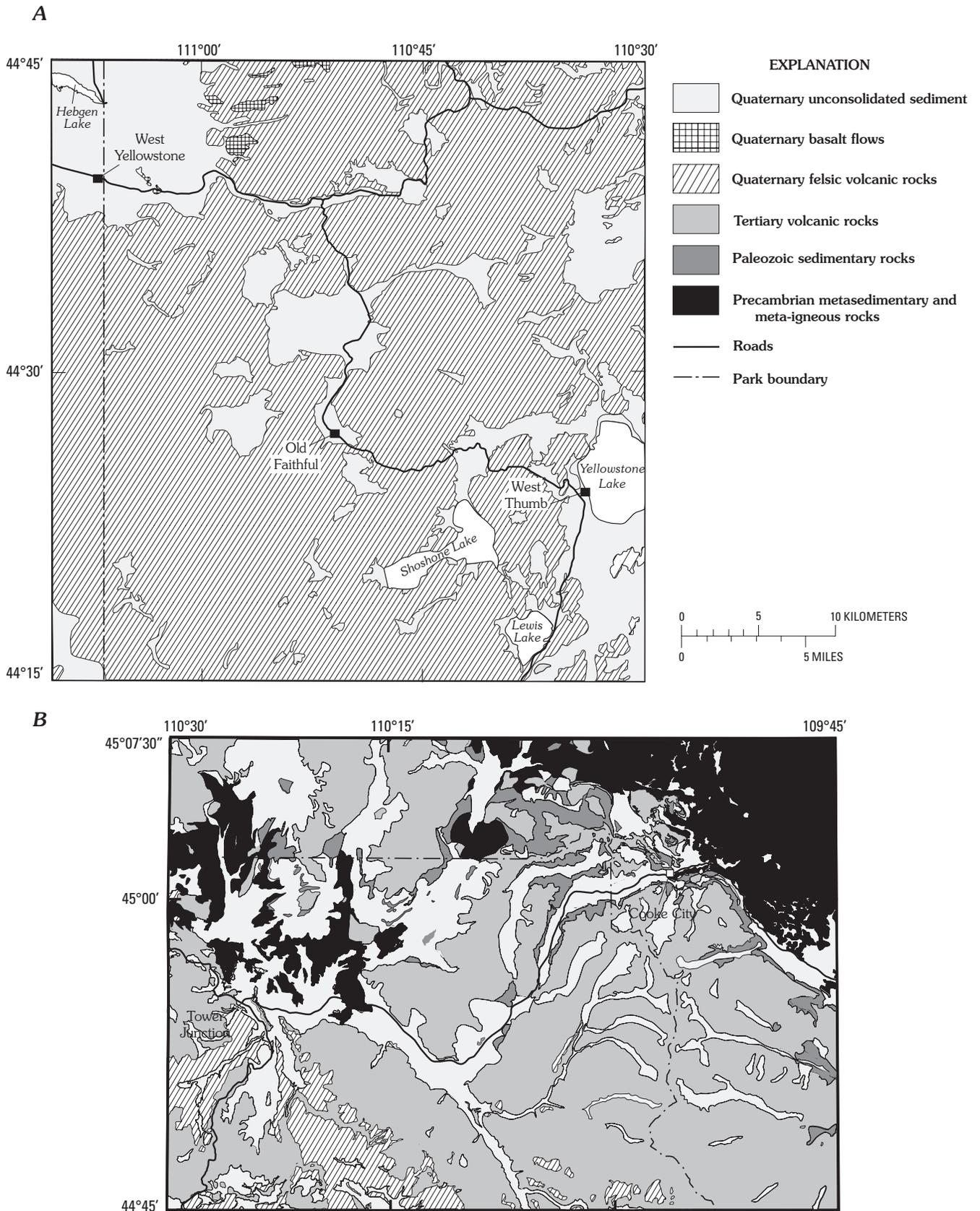——— Roads

—··— Park boundary

B

Figure 2. *A,* Generalized geologic map of the West Study Area. Geology modified from Taylor and others (1989), U.S. Geological Survey (1972), and Wilson and Elliott (1997). *B,* Generalized geologic map of the Northeast Study Area. Geology modified from Taylor and others (1989), U.S. Geological Survey (1972), and B.S. Van Gosen (written commun., 1998).

Table 1.   Summary statistics for analyses of 49 elements in 393 stream-sediment and 68 rock samples, Yellowstone National Park and vicinity.

[Element symbols in bold identify elements discussed in detail in text. Concentrations for Au shown in ppb; all other values in ppm unless "(%)" shown after element symbol. N, not detected at the lower limit of determination shown in parentheses. Geom., Geometric. Mean values based on unqualified values only. HY, hydride analysis; NA, neutron-activation analysis; AA, atomic-absorption analysis; CVA, cold-vapor atomic-absorption analysis; INST, LECO furnace analysis; ION, specific-ion electrode analysis; no letters, ICP-AES analysis. "<" before a value in mean columns indicates estimated value]

| Element | Range of values | | Number unqualified | Percent unqualified | A Geom. mean 393 sediments | B Geom. mean 49 rhyolites | C Geom. mean 19 andesites | D Crustal[3] abundance |
	Minimum	Maximum						
Ag[1]	N(0.4)	7.8	27	7	<0.4	<0.4	<0.4	0.05
Al (%)	0.27	10	393	100	6.04	6.01	7.98	8.04
As-NA[1]	N(0.5)	670	375	95	6.1	4.5	2.1	1.5
Au-NA[1]	N(2.)	14,300	147	37	8.5	4.4	4.2	1.8
Ba-NA	N(50.)	4,000	390	99	760	460	1,000	550
Be	N(2.)	120	144	37	2.9	3.7	2.0	1.5
Br-NA[1]	N(0.5)	20	220	56	2.9	1.7	<0.5	2.5
Ca (%)	0.10	7.8	393	100	1.61	0.37	4.45	3.00
Cd	N(0.5)	7.7	64	16	0.60	0.60	0.77	0.098
Ce-NA	3	780	393	100	93	140	54	64
Co-NA	N(0.5)	52	370	94	9.1	1.8	23	10
Cr-NA	N(5.)	900	337	86	95	9.6	81	35
Cs-NA	N(1.)	870	348	89	3.6	2.9	2.6	3.7
Cu	1.0	630	393	100	8.5	3.4	27	25
Eu-NA	N(0.2)	3.4	388	99	1.2	0.96	1.4	0.88
F-ION	N(20.)	1,600	389	99	440	640	360	625
Fe-NA (%)	0.13	18.3	393	100	2.58	1.28	5.30	3.50
Hf-NA	N(1.)	67	391	99	8.2	9.1	3.6	5.8
Hg-CVA	N(0.02)	50	159	40	0.08	<0.02	<0.02	0.08
K (%)	0.12	5.41	393	100	2.13	4.07	1.51	2.80
La-NA	2.0	550	393	100	57	77	31	30
Lu-NA	N(0.05)	2.36	392	99	0.43	0.83	0.22	0.32
Mg (%)	0.01	5.69	393	100	0.62	0.03	1.81	1.33
Mn	16	11,800	393	100	530	240	720	600
Mo	N(2.)	29	220	56	3.4	4.1	<2.0	1.5
Na-NA (%)	0.10	3.16	393	100	1.92	2.46	2.41	2.89
Nd-NA	N(5.)	360	391	99	36	47	21	26
Ni	2.0	190	393	100	19	2.4	35	20
P (%)	0.003	0.22	393	100	0.04	0.008	0.11	0.07
Pb	N(5.)	190	388	99	20	32	15	12.5
Rb-NA	N(15.)	230	351	89	83	170	63	20
S-INST(%)	N(0.01)	4.25	341	87	0.03	0.02	0.04	0.03
Sb-NA	N(0.1)	150	287	73	0.68	0.38	0.21	0.2
Sc-NA	0.4	49	393	100	7.6	2.1	17	11
Se-HY[1]	N(0.2)	4.6	86	22	0.29	<0.2	<0.2	0.05
Sm-NA	0.20	43	393	100	6.3	9.5	4.3	4.5
Sr	5	1,500[2]	380	97	190	19	710	350
Ta-NA[1]	N(0.5)	8.6	221	56	2.4	3.4	1.2	2.2
Tb-NA	N(0.5)	5	203	52	1.3	1.5	0.60	0.64
Te-AA	N(0.1)	16	46	12	0.19	<0.1	<0.1	0.001
Th-NA	0.50	94	393	100	11	25	3.9	11
Ti (%)	0.01	1.13	393	100	0.24	0.09	0.42	0.30
Tl-AA	N(0.1)	21	343	87	0.45	0.76	0.23	0.75
U-NA[1]	N(0.5)	16	345	88	3.4	5.5	1.3	2.8
V	2	510	393	100	36	2.8	130	60
W-NA[1]	N(1.)	260	99	25	7.4	3.5	<1.0	2.0
Y	2	140	393	100	25	51	13	22
Yb-NA	0.2	15	393	100	2.9	5.7	1.4	2.2
Zn	5	350	393	100	70	63	70	71

[1]Lower limits vary. Lowest reported value shown.

[2]Excludes 13 samples reported as >750 ppm Sr.

[3]Values for Br and F from compilation by Levinson (1974). Value for S from compilation by Rose and others (1979). Value for Hg from Taylor (1964). Value for Te from Coakley (1975). Other elements from compilation by Taylor and McLennan (1995) for upper continental crust.

Sampling and Analysis

This study is based on 393 samples of active sediment from streams throughout the Park and in some of the areas bordering the Park. At each site, sample material was composited from multiple sample points to represent as closely as possible the typical chemical composition of material in the vicinity of the site. These compositions reflect a combination of (1) the chemistry of solid material eroded upstream and transported to the sampling site and (2) chemical elements carried in solution and precipitated on sediment grains at the site. Each sample was sieved to minus 0.18 mm (minus 80 mesh), and the material passing through the sieve was pulverized to less than 0.10 mm (minus 150 mesh).

The samples were submitted for analysis in a random order. Internal standards and duplicates were included to monitor the quality of the analyses. Most samples were analyzed for 49 elements that were included in commercial analytical packages. Concentrations of 25 of the elements were determined by instrumental neutron-activation analysis, and concentrations of 18 elements were determined by inductively coupled plasma atomic-emission spectroscopy. In addition, fluorine was determined by an ion-selective electrode technique, mercury by cold-vapor atomic-absorption analysis, total sulfur by a combustion method, selenium by a hydride technique, and tellurium and thallium by atomic-absorption spectroscopy. The analytical results, including analytical methods used for each element, are summarized in table 1.

Rock samples also were collected from outcrops at scattered localities in Yellowstone National Park and vicinity. For this report, only rock samples collected from relatively fresh, unaltered outcrops were evaluated. These samples first were hand-cobbed to remove surficial weathered material, and then they were crushed and pulverized prior to analysis. For comparison purposes, mean values for the rock analyses for two major rock units are included in table 1.

Description and Discussion of Chemical Differences by Media and Location

Table 1 summarizes concentration ranges, geometric mean values, and other information for 49 elements in 393 stream-sediment samples and 68 rock samples collected in, and in the vicinity of, Yellowstone National Park. Of particular importance in table 1 are columns A, B, C, and D. Column A lists the geometric mean values for all of the elements determined in the stream-sediment samples. These mean values are deemed to approximate the most typical value for each element in stream sediment for

Yellowstone National Park. Columns B and C list geometric mean values for 49 rhyolite and 19 andesite samples, respectively, that were collected in or near the Park. All of those samples were fresh rock that was not significantly affected by chemical weathering or by hydrothermal alteration. These means are deemed to represent estimates of regional background values for these two major rock types in the Park area. Column D lists published estimates of crustal abundances for the elements listed in columns A, B, and C (Coakley, 1975; Levinson, 1974; Rose and others, 1979; Taylor, 1964; Taylor and McLennan, 1995).

A comparison of mean values for the two types of unaltered rocks (columns B and C) with crustal abundance values (column D) indicates that at least five elements (As, Au, Be, Cd, and Rb) are relatively enriched in both of these rock types in the Park area, as compared to crustal abundances. Similarly, fresh Yellowstone-area rocks are relatively low in Br, Cs, and Hg. A comparison of the mean values for sediment samples (column A), which includes material derived from both fresh and altered rocks, with the mean values for unaltered rocks (columns B and C) indicates that the sediments are relatively enriched in at least nine elements (shown in bold type in table 2: As, Au, Br, Cs, Hg, Sb, Se, Te, and W) and are relatively depleted only in sodium. Our data indicate that all nine elements, except possibly Br, are enriched in the Yellowstone area as a result of past or current geothermal activity. The mean values for other elements in the sediment samples generally are between the extremes represented by the respective values for the two types of rock samples. In a few cases, no meaningful mean value could be calculated because an insufficient number of analyses has been reported, and an estimated value is given.

Figure 3 is a graphical representation constructed to emphasize concentration differences for selected elements collected in the two study areas. All values determined for this figure were calculated after replacing each qualified value with a value equal to 0.5 times the lower limit of determination. This figure shows that some elements occur within a relatively small range of values in both areas (F, Mo, and Tl, for example), whereas other elements tend to occur over a much wider range (As, Au, Hg, S, and W, for example). The plots also show that the elements As, Cs, F, Hg, La, Mo, Tl, and W are more enriched in the West Area, where geothermal activity is high and rhyolite is the dominant rock type, whereas the elements Au, Cu, and Te are more enriched in the Northeast Area, where contaminated material from mineralized outcrops and past mining activities in the vicinity of the New World and Republic mining districts has entered the Park. Lead and sulfur show similar distribution ranges for both areas, indicating that these two elements probably have multiple sources with similar concentration levels.
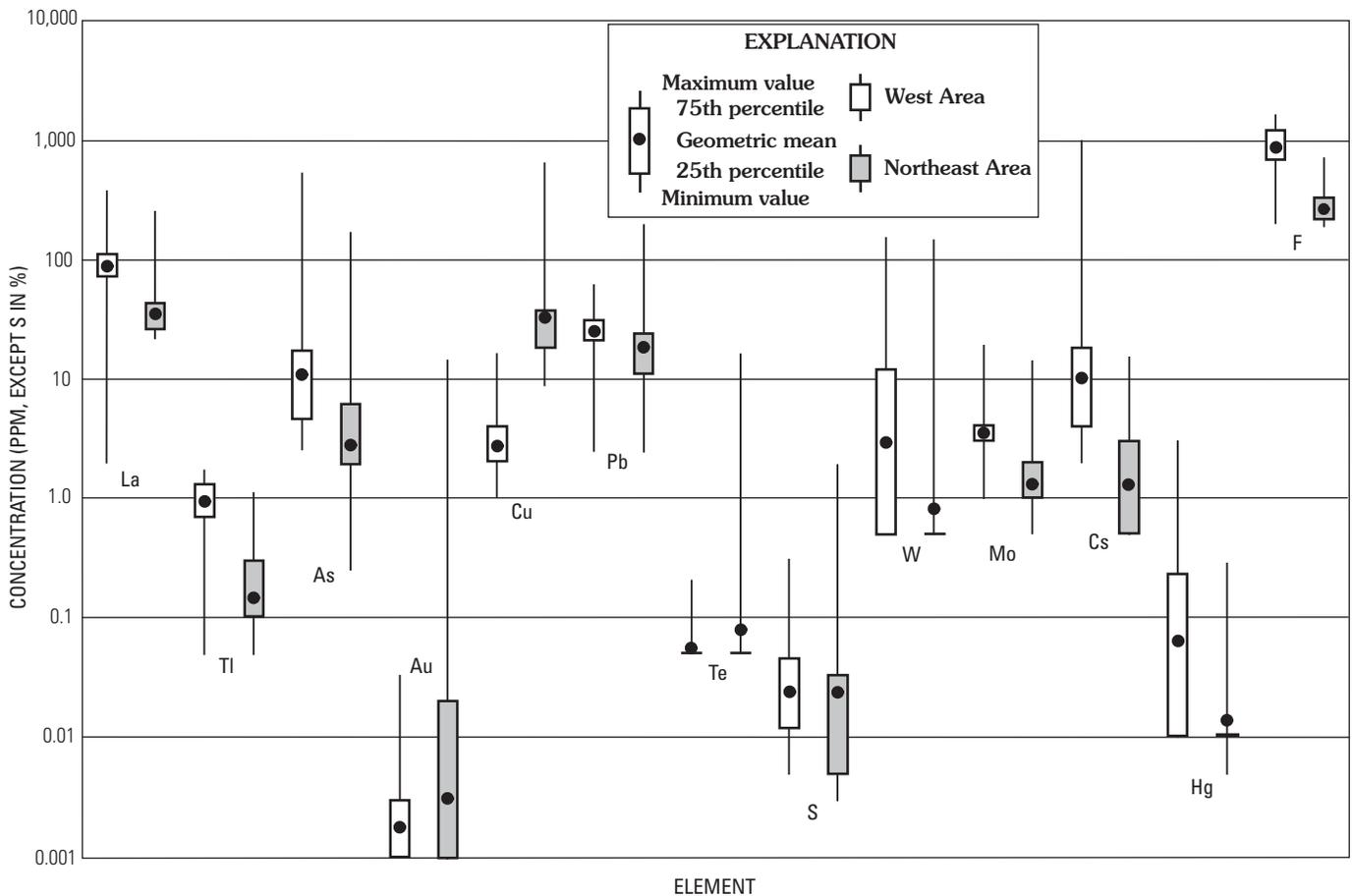
Figure 3.   Box plot comparing analytical ranges for 13 elements in the two study areas. The single horizontal line for tellurium in the West Area indicates that all values are below the lower limit of determination.

Results of Factor Analysis

To provide a better understanding of the interrelationships of the group of elements determined for this study, we ran factor analysis. Factor analysis is a mathematical technique that groups variables (in this case, chemical elements) according to how they vary in relation to each other in the samples. As used here, the technique helps to identify suites of elements that have been enriched or depleted in the region (1) as a result of a common process or (2) because the elements are present in a common mineral or suite of minerals. Prior to running the analysis, two elements (cadmium and silver) were deleted from the data set because either there were too few reported values above the lower limit of determination (silver) or there was insufficient analytical variation (cadmium) for proper evaluation by this technique. For the remaining 47 elements, arbitrarily selected values were substituted for all qualified determinations. A value equal to half the lower limit of determination was substituted for each element for all values below the respective lower limit(s) of determination for each element. For values reported as being above an

upper limit of determination, a new value equal to the upper limit divided by 0.7 was substituted. Because most of the elements displayed log-normal distributions, logarithms of the analyses were used in the factor analysis. A five-factor model with varimax rotation was selected as best fitting observed geologic conditions. This model accounts for 78 percent of the variance in the data. The loading values for each element, which identify the elements most strongly associated with each factor, are shown for the model in table 2. Factor scores, which rank the samples in each factor and thus show which samples most closely correlate with a given factor, were determined as part of the factor analysis, but they are not included in this report.

Factor 1 is a lithology factor. The factor scores indicate that the elements loaded on this factor are mostly from samples containing minerals commonly associated with felsic igneous rocks, such as rhyolite. These rocks contain sodium- and potassium-rich feldspars and rock-forming accessory minerals that commonly are enriched in uranium and thorium and (or) in lanthanide-series elements, including Ce, Eu, La, Lu, Nd, Sm, and others. Note that molybdenum, an element commonly associated with

Table 2.   Factor loading values for 47 elements in 393 samples of stream sediment, Yellowstone National Park and vicinity.

[Five-factor model, varimax loading, based on log-normalized values. Elements in italic indicate secondary loading values]

Factor 1 (Felsic rocks)		Factor 2 (Mafic rocks)		Factor 3 (Geothermal)		Factor 4 (Mineral deposit)		Factor 5 (Miscellaneous)	
La	0.96	Sc	0.91	Sb	0.81	Te	0.85	Zn	0.59
Ce	0.95	Ti	0.90	As	0.77	Se	0.73	Be	0.59
Nd	0.94	Mg	0.89	Hg	0.73	Au	0.71	*Mn*	0.50
Sm	0.94	V	0.88	Cs	0.67	Pb	0.65	F	0.43
Th	0.87	Sr	0.88	S	0.65	*Cu*	0.46	*Br*	0.21
Lu	0.83	Cr	0.87	W	0.61	*S*	0.39		
Yb	0.81	Fe	0.87	*Hf*	0.41	*Zn*	0.33		
Hf	0.80	Ni	0.85	*Tl*	0.33	*W*	0.27		
K	0.78	Co	0.85	*Mo*	0.31	*Fe*	0.21		
Y	0.76	Ca	0.82	*Be*	0.29				
Ta	0.63	Ba	0.78						
Rb	0.63	Cu	0.69						
Tb	0.62	P	0.65						
U	0.61	Mn	0.61						
Mo	0.60	Al	0.60						
Tl	0.51	Eu	0.59						
Pb	0.50								
Na	0.49								
Zn	0.42								
F	0.42								
Br	0.22								

Percent variability explained				
48%	13%	8%	5%	4%

mineral deposits, has its primary loading on this factor, suggesting that it is mainly associated with felsic-rock lithology in the study areas, rather than with geothermal activity or mineral deposits. Molybdenum is known to occur in many major and accessory rock-forming minerals, as well as in tungsten minerals (Manheim and Landergren, 1978).

Factor 2 also is a lithology factor. The scores indicate that the elements loaded on this factor are mostly from samples containing minerals that commonly are associated with intermediate to mafic igneous rocks, such as andesites, which commonly contain dark minerals such as calcium- and magnesium-rich feldspars, hornblende, biotite, and magnetite. Note that copper, an element sometimes enriched in one or more of these dark minerals, has its highest loading on this factor, emphasizing a moderately strong lithologic affinity for this element.

Factor 3 is a geothermal-process-associated factor. Factor scores indicate that the elements loaded on this factor are associated with samples of altered material from areas of past or present geothermal activity. Note that Mo and Tl have secondary loading values on this factor, indicating more than one source for these elements.

Factor 4 is a mineral-deposit-related factor. The factor scores indicate that the elements loaded on this factor are associated with sample material from the Cooke City, Mont., area, outside the northeast corner of the Park. Much of this material has been eroded from outcrops altered by hydrothermal mineralization or from dumps, tailings piles, or slag heaps related to past mining. Note that Cu, Fe, S, W, and Zn, elements associated with the mineral deposits near Cooke City, have secondary loading values on this factor, indicating their association with more than one source.

Factor 5 is a "miscellaneous" factor containing primary loadings for three elements (Be, F, and Zn) that do not seem to fit well into any of the other factors. By default, they have been mathematically forced into this last factor grouping, and they may or may not have a common natural association. The factor scores indicate that samples associated with this factor are composed mostly of felsic tuffs, Precambrian granites, or strongly altered, geothermally related sinter deposits that commonly are strongly enriched in one or more of the elements in this factor. The manganese-zinc association may be related to manganese scavenging, a natural process that enriches some trace elements when they co-precipitate with manganese as coatings on sediment grains or when they are adsorbed onto manganese-oxide coatings or nodules.
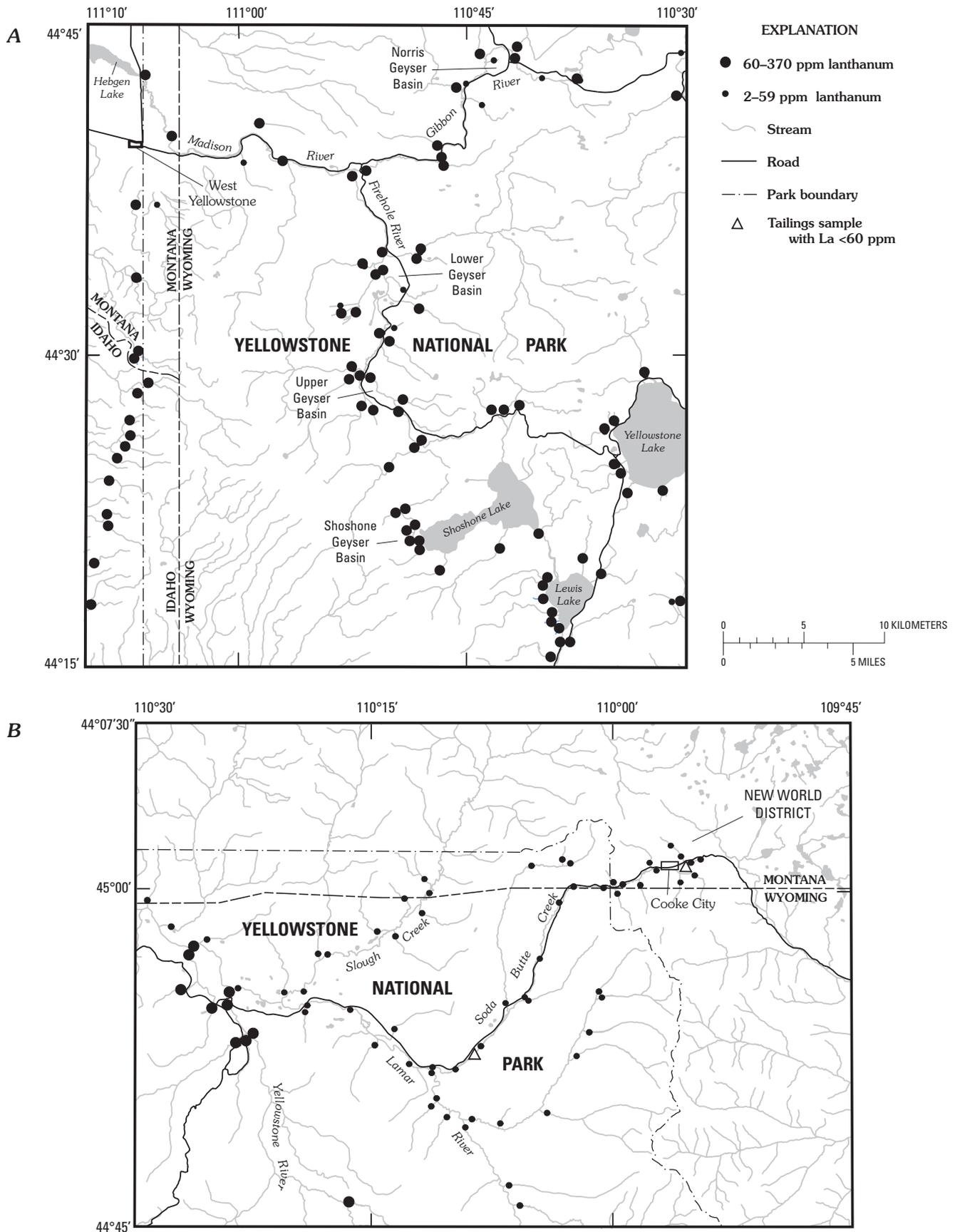
Figure 4. *A,* Distribution of lanthanum in stream sediment, West Area. *B,* Distribution of lanthanum in stream sediment, Northeast Area.

Descriptions of the Geochemical Maps

The distributions of anomalies for 15 elements in 152 of the 393 stream-sediment samples are described in this section. Some elements were selected to illustrate different sources and distribution patterns for the respective anomalies. Others were selected because they could be toxic to plants or animals, or both. The ranges of values shown on each map are for the plotted samples only and not for the complete data set. Sites whose samples fell in the range of values deemed to represent background concentrations for each element are shown as small filled circles on each map. The highest background value (threshold value) for each element was selected after studying (1) the frequency-distribution plots for each element and (2) the spatial distribution for each element plotted on a geologic base map. Anomalous samples are shown as filled squares or large filled circles. In addition to stream-sediment sites, maps for the Northeast Area show the locations of two samples of sediment that consist mostly of mill tailings. The northern one is from near the large tailings pile of the long-abandoned McLaren mine, one of the larger mines in the New World district. The southern one is from a flood-plain deposit adjacent to Soda Butte Creek that is composed of sediment derived from erosion of some of the McLaren mill tailings during a flash flood in 1950 (Meyer, 1993).

Lanthanum.—Lanthanum, the most strongly loaded element on factor 1 (table 2), is an element whose concentration is strongly correlated with lithology. This element is most common in rock-forming accessory minerals. Anomalies for lanthanum (60–370 ppm) are present in most of the West Area (fig. 4A) and in the Yellowstone River drainage in the western part of the Northeast Area (fig. 4B). The anomalies correlate well with the distribution of Quaternary felsic volcanic rocks in the two areas. Shannon (1982) noted that a number of elements in stream-sediment samples collected by the Department of Energy in the Ashton, Idaho-Montana-Wyoming 1°×2° quadrangle were useful for identifying provenances in parts of the Park. Our study confirms Shannon's observations and suggests that lanthanum, and also many of the other elements listed in factors 1 and 2 of the factor analysis (table 2), should be useful in mapping and correlating selected geologic formations in the region.

Thallium.—Thallium also is loaded on factor 1 (table 2), indicating that its strongest affinity is to lithology, especially to felsic volcanic rocks. However, it has two distinct sources. As a lithology-associated element, thallium is most abundant in potassium-rich minerals such as orthoclase feldspar, micas, and clay minerals. Thallium also occurs in sulfide minerals in some mineral deposit environments (de Albuquerque and Shaw, 1972). In the West Area (fig. 5A) and in the Yellowstone River drainage in the Northeast Area (fig. 5B), the widespread distribution of anomalous thallium (0.3–1.7 ppm) is similar to that of lanthanum (figs. 4A and 4B). Anomalous thallium in samples from the Slough Creek area and the stream northeast of Slough Creek probably are related to potassium-rich, Precambrian, felsic intrusive rocks or to glacial deposits containing material derived from these rocks. Thallium also is anomalous (0.3–1.1 ppm) in the New World mining district upstream from Cooke City, Mont., and in the two samples of tailings-rich sediment (0.3 and 0.8 ppm in fig. 5B), indicating a weak secondary affinity of this element in mineralized rocks of the district. The specific mineral residence of thallium in the district is not known.

Arsenic and antimony.—Arsenic commonly forms its own minerals, but it also may occur in more complex minerals. Both arsenic and antimony are strongly loaded only on the geothermal factor (table 2). However, arsenic also has two other, less significant, sources. In the West Area (fig. 6A), arsenic is strongly anomalous (15–670 ppm) in sediment from many streams. Note that the overall concentrations of arsenic in this area (represented by a relatively high percentage of filled-square and large-circle symbols) are much higher than in the Northeast Area (fig. 6B). Many of the weakly anomalous (6–14 ppm) samples in the West Area may be related to fossil geothermal areas, or they may simply represent unusually high background values in some of the felsic volcanic rocks. Arsenic is strongly anomalous (27 ppm) in the Madison River at the western boundary of the Park. The downstream extent of anomalous arsenic in sediment from this stream is not known, but anomalous arsenic in Madison River water is present at least to the junction of this stream with the Jefferson River, about 140 km downstream from the Park boundary at West Yellowstone, Wyo. (Sonderegger and Ohguchi, 1988).

In the Northeast Area (fig. 6B), arsenic is weakly to moderately anomalous (6–20 ppm) in most samples of active stream sediment collected from Soda Butte Creek. The highest concentrations (11–20 ppm As) are associated with mineralized outcrops or contaminated material in the New World district. The concentrations decrease rapidly downstream, and they reach background levels (<6 ppm) about 8 km downstream from the Northeast Entrance Park boundary. The moderately to strongly anomalous (15–170 ppm As) samples collected from the Yellowstone River, on the west side of this area, are not mining related. They are mainly enriched as a result of solfataric (geothermal) activity, but some of the enrichment may be related to the local lithology. The sample from the vicinity of the McLaren tailings pile contains 28 ppm As. Note that the downstream flood-plain tailings sample is anomalous (46 ppm As), whereas the adjacent active stream-sediment sample (2.5 ppm) is not. This relationship, which also is true for other elements, clearly indicates the anthropogenic nature and origin of the downstream tailings sample.

Antimony is nearly always closely associated in the natural environment with arsenic, and it commonly proxies for arsenic in arsenic-rich minerals. Because of its close association with arsenic, the distribution of antimony is not shown here. Antimony is the most strongly loaded element on the geothermal factor (table 2). The distributions of anomalies of this element in both study areas (0.5–150 ppm Sb) are generally similar to those of arsenic. In the Northeast Area, antimony is anomalous (1.5 and 1.0 ppm) in the two tailings samples. Unlike arsenic, however, antimony is only anomalous in Soda Butte Creek in the immediate area upstream from Cooke City.
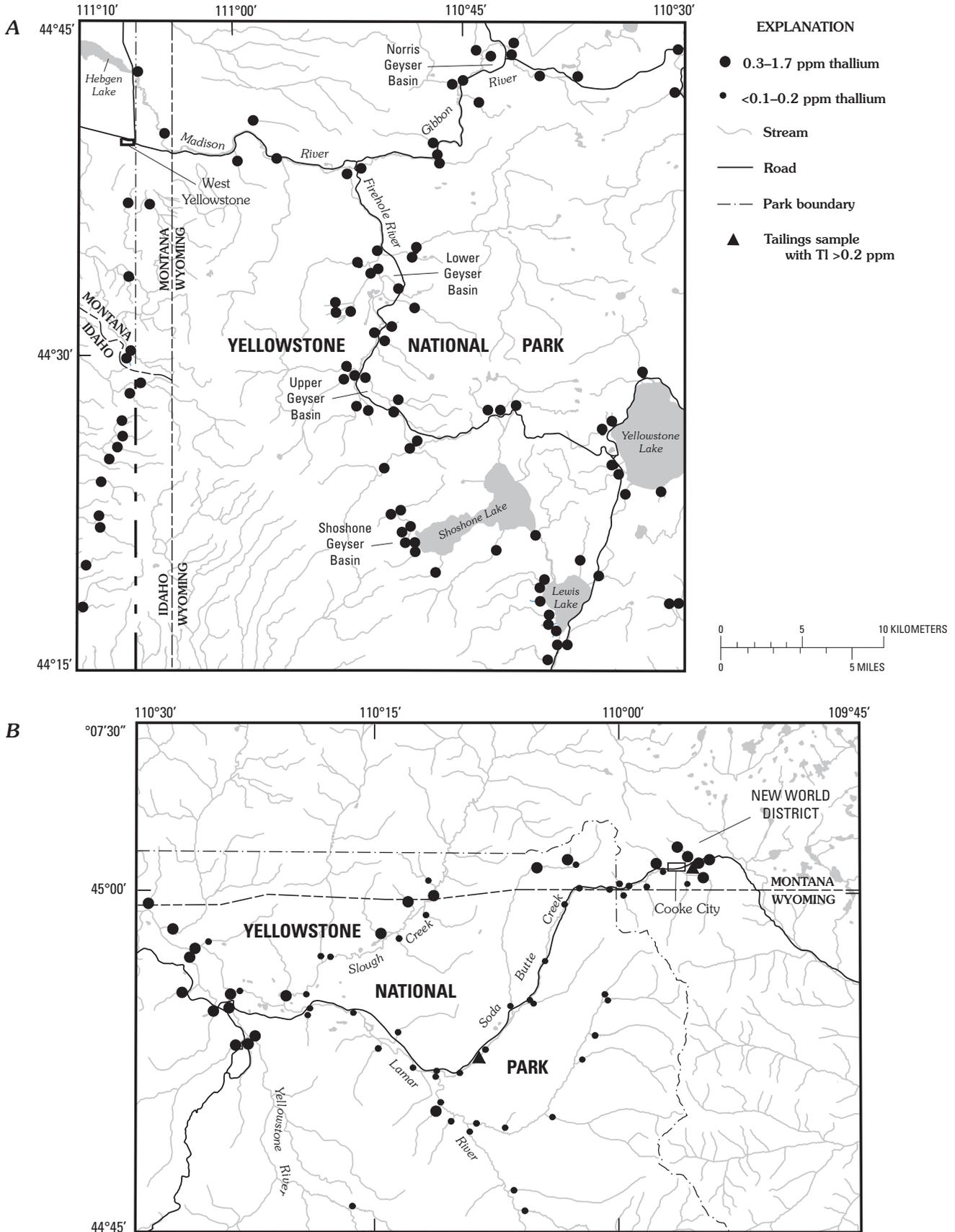
Figure 5. *A,* Distribution of thallium in stream sediment, West Area. *B,* Distribution of thallium in stream sediment, Northeast Area.
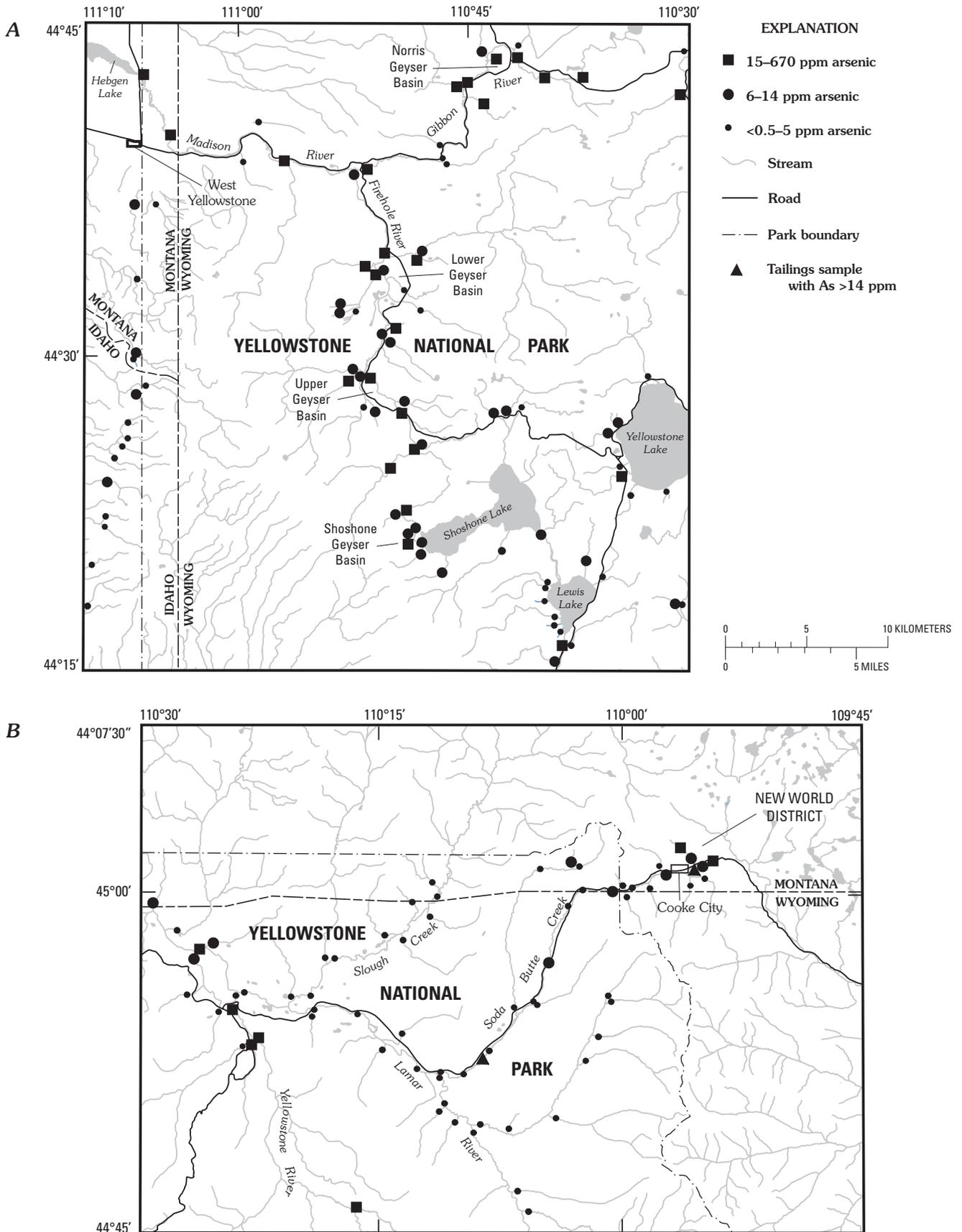
Figure 6. *A,* Distribution of arsenic in stream sediment, West Area. *B,* Distribution of arsenic in stream sediment, Northeast Area.

Gold.—Gold is strongly loaded only on the mineral deposit factor (table 2). However, a second, less significant source for this element exists. In the West Area (fig. 7*A*), anomalous gold (7–33 ppb) related to geothermal processes is present at scattered localities, particularly in the Norris and Shoshone Geyser Basins. The mineral form of this gold is not known.

In the Northeast Area (fig. 7*B*), gold is one of the elements enriched in the mineralized New World district. This element may occur as free gold, or it may be present in the structures of other ore-related minerals, such as pyrite or chalcopyrite. Anomalous gold (7–14,300 ppb) is present in stream-sediment samples collected in the New World district and in samples collected downstream from there in Soda Butte Creek. The anomaly continues to the junction of Soda Butte Creek with the Lamar River, where sediments with low gold concentrations from sources in the upper Lamar River watershed dilute anomalous sediments from Soda Butte Creek to background levels. Four additional samples collected downstream from this junction also are anomalous. The source of the gold in the sample from below the junction of the Lamar and Yellowstone Rivers (27 ppb) is not known. This anomaly, which may represent the "nugget effect" sometimes present in gold-rich sediment samples, may be an additional manifestation of contamination from the Cooke City area. The anomalous (7 ppb Au) sample from the Yellowstone River above its junction with the Lamar River probably is related to geothermally altered rocks. The sources of the gold anomalies in lower Slough Creek and the small stream south of there are not known. Note that both tailings samples are anomalous (5,000 and 730 ppb Au), again emphasizing that most of the anomaly in Soda Butte Creek probably is associated with naturally mineralized rock outcrops or with past mining activity in the New World district.

Copper.—Copper is loaded on two factors (table 2). The primary loading is on factor 2, the mafic rock factor, emphasizing the probable association of copper with dark accessory minerals that are common in the intermediate to mafic volcanic rocks in the Northeast Area (fig. 2*B*). The secondary loading is on factor 4, the mineral deposit factor. Anomalous copper in the Northeast Area is present mainly as chalcopyrite or its weathering products. In this same area, copper (fig. 8) is moderately to strongly anomalous (40–630 ppm) in the highly mineralized areas upstream from Cooke City. A small part of the copper content of samples from the Northeast Area probably is a contribution from the dark-mineral-rich volcanic rocks of the area. However, most of the high copper concentrations are in material eroded from the copper-rich mineral deposits and their associated dumps and tailings and slag piles. The anomaly extends downstream from the Cooke City area and into the Park along Soda Butte Creek to a point past the junction of that stream and the Lamar River. Both tailings samples also are strongly anomalous in copper (530 and 260 ppm).

No copper anomalies are associated with geothermal activity or with the distribution of felsic rocks in either study area. Thus, a copper map for the West Area shows no anomalies and is not shown here. These observations indicate that copper

is a good geochemical indicator of both mineralized rock and mining activity in the northeastern part of the Park.

Lead.—Lead is strongly loaded on the mineral deposit factor (table 2). It also has a secondary loading on the felsic-rock factor. We speculate that the lead represented by the loading on the felsic-rock factor probably is related to lead substituting for potassium in potassium-rich feldspars.

In the Northeast Area (fig. 9), lead is anomalous (50–190 ppm) in sediment from streams draining the mineralized New World mining district and adjacent Republic district. However, this anomaly does not extend into the Park in Soda Butte Creek. In the Northeast Area, anomalous lead is mainly associated with galena or oxidation products of this mineral. The anomalous sample collected near the tailings pile contains 86 ppm Pb. Note that the downstream, flood-plain tailings sample is anomalous (100 ppm), whereas the nearby active stream-sediment sample (24 ppm) is not, indicating that anomalous lead in sediment has migrated downstream in the past from the original tailings pile, but it is not currently moving downstream in significant amounts in active sediment.

The anomalous (110 ppm Pb) sample collected in lower Slough Creek is from a site below the Slough Creek Campground. Because of its location and the absence of other anomalous elements in this sample, this anomaly is deemed to be anthropogenic in origin. It might represent contamination from lead fishing weights. In the West Area, a single lead anomaly (61 ppm) is present in a sample collected below Lewis Falls, at the outlet to Lewis Lake, a popular tourist stop. Unlike the sample from Slough Creek, this sample also is anomalous for several elements that compose the geothermal suite (table 2). However, because lead is not an element associated with the geothermal suite, this isolated lead anomaly may be anthropogenic in origin. Because only one sample with anomalous lead was identified in the West Area, no map for that area is included.

Sulfur.—Total sulfur, as determined for this study, consists of the sum of sulfide sulfur, sulfate sulfur, elemental sulfur, and probably minor amounts of other sulfur compounds. Sulfur is primarily loaded on the geothermal factor (table 2). It is secondarily loaded on the mineral deposit factor, indicating more than one source for this element. Sulfide minerals are common in the mineralized New World district. Native sulfur and other sulfur minerals are common in many geothermal areas in the Park.

The strongest sulfur anomalies in the West Area (fig. 10*A*) all are related to geothermal activity. Some of the strong anomalies, such as those for samples collected at sites north of Shoshone Lake, near the Park road and downstream from geothermally altered rhyolite outcrops (0.06–0.07 percent S), are related to fossil geothermal activity. The weak anomalies along the west boundary of the Park, in fresh rhyolitic rocks, probably represent the high end of the background range of values for sulfur. Most of the other anomalies (0.05–0.30 percent S) are related to active geothermal localities. Note that none of the samples collected in the Shoshone Geyser Basin and only one collected in the Upper Geyser Basin are anoma-
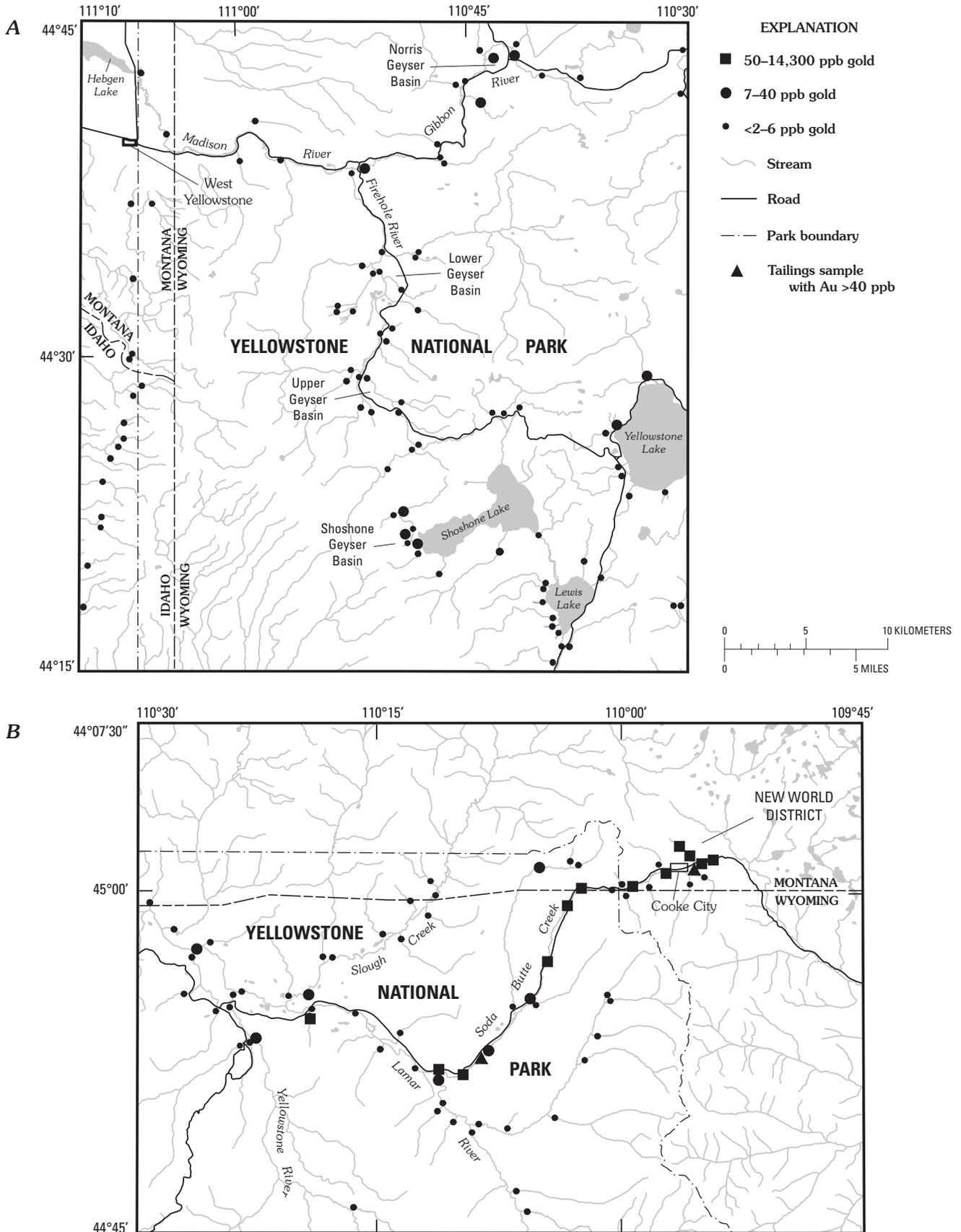
Figure 7.   *A*, Distribution of gold in stream sediment, West Area. *B,* Distribution of gold in stream sediment, Northeast Area.
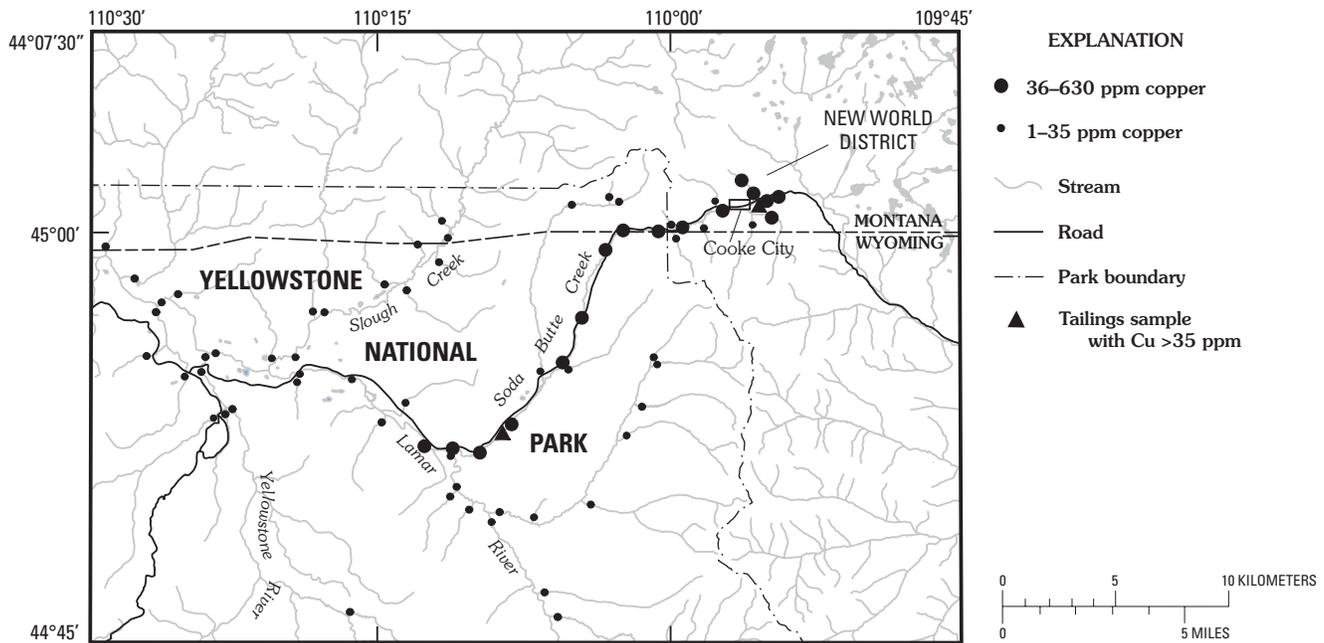
Figure 8.   Distribution of copper in stream sediment, Northeast Area.

lous. We speculate that sulfur in these active geothermal areas is still in solution, and it tends to precipitate, mainly in the form of sulfates, only farther downstream where temperatures are lower and (or) evaporation of sulfur-rich water is occurring.

In the Northeast Area (fig. 10*B*), sulfur is weakly to strongly anomalous (0.04–1.86 percent) in the New World mining district and is intermittently anomalous (0.03–0.07 percent) along Soda Butte Creek. Most of this sulfur is derived from the sulfide-rich mineral deposits near Cooke City. Both of the tailings-related samples contain significant concentrations (1.86 percent and 0.27 percent) of sulfur. These observations indicate that sulfides (mainly pyrite) were transported downstream during the 1950 flood and that sulfur is a good geochemical indicator of the effects of the flooding.

The weakly anomalous (0.03 percent) sulfur in the sample from the Lamar River upstream from its junction with Soda Butte Creek and the strongly anomalous (0.05–1.33 percent) sulfur from the samples along the Yellowstone River near its junction with the Lamar River are related to local areas containing sulfur-rich hot springs; they are not related to the sulfides in the Cooke City area. The isolated, anomalous (0.07 percent S) sample collected near the southwest corner of the Northeast Area is from Wrong Creek, downstream from an area of hot springs.

Tellurium and selenium.—Tellurium, which is common in sulfide minerals (especially pyrite), is the most strongly loaded element on the mineral deposit factor (table 2). This association corroborates the distribution of anomalous (0.1–16 ppm) tellurium in the Northeast Area (fig. 11*B*), in the New World district area, and downstream in Soda Butte Creek to its junction with the Lamar River. The two tailings-related samples also are strongly anomalous (16 and 3.6 ppm Te). In

the West Area (fig. 11*A*), weakly anomalous (0.01–0.02 ppm) tellurium is present in samples collected in the southeastern corner of the area, near Heart Lake, and in several samples of rhyolite-rich sediment collected along the western boundary of the Park. These anomalies probably represent concentrations that are in the high end of the background range for this element, and thus they have no relationship to any mineral deposits. These observations indicate that tellurium in concentrations >0.2 ppm is a good indicator element for delineating the distribution of mineral-deposit-related material in the Northeast Area.

Selenium is another element that is strongly loaded on the mineral deposit factor (table 2). This element also commonly proxies for sulfur in mineral structures. The distribution of selenium (not shown) is very similar to that of tellurium. It shows only a very restricted anomaly (0.5–4.6 ppm) in the immediate area of the New World district, with no anomaly extending downstream into the Park. Both of the tailings-related samples also are anomalous (3.7 and 1.0 ppm Se). As is the case for tellurium, the selenium anomalies in the West Area are weak (0.04 ppm), and they are confined to three rhyolite-rich sediment samples collected along the western boundary of the Park.

Tungsten.—Tungsten is loaded primarily on the geothermal factor and secondarily on the mineral deposit factor (table 2), emphasizing its association with both the geothermal systems and the mineralized New World district. Although not reflected in the factor analysis, a minor lithologic component also may be present locally. This element commonly occurs as tungstate minerals. However, its mineral residence in the study areas is not known. In the West Area (fig. 12*A*), tungsten is weakly to strongly enriched (1–150 ppm) in stream-sediment samples.
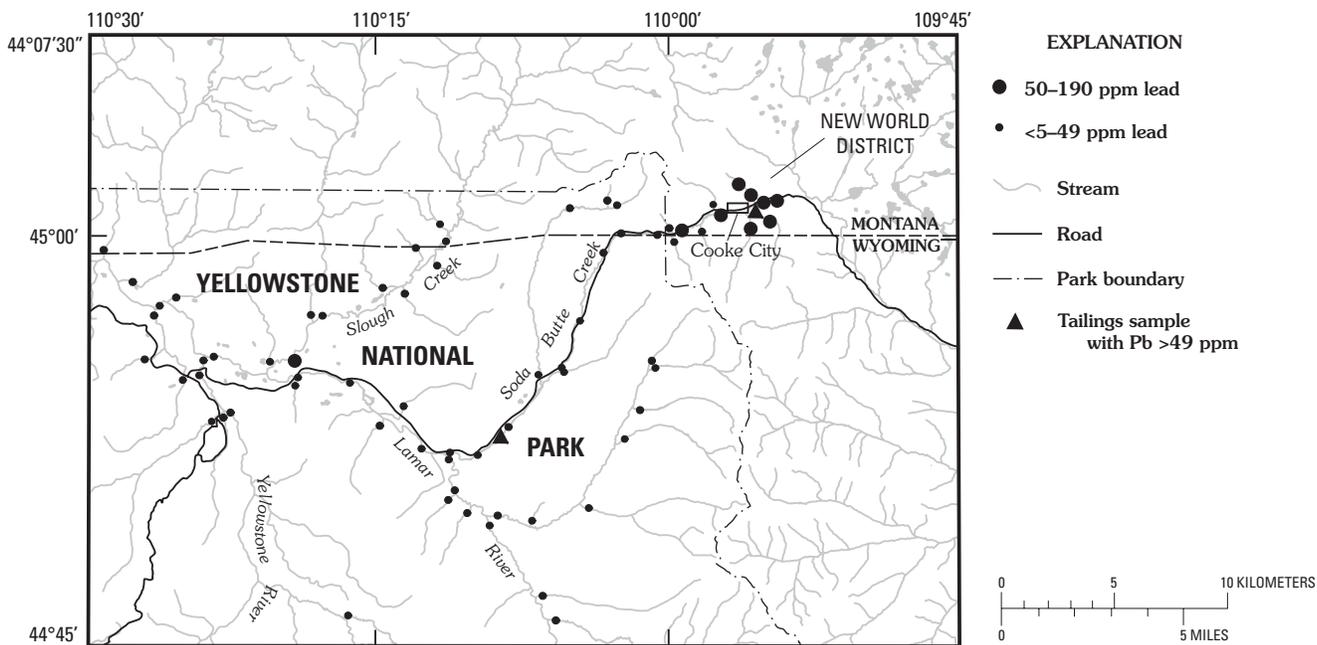
Figure 9. Distribution of lead in stream sediment, Northeast Area.

Most of this enrichment is deemed to be a result of past or present geothermal activity. In a few cases, such as in the two samples southeast of Shoshone Lake and the sample north of Lewis Lake, anomalous tungsten possibly is related locally to elevated background concentrations in felsic volcanic rocks.

With one exception, the distribution of anomalous (3–60 ppm) tungsten in stream-sediment samples in the Northeast Area (fig. 12B) is restricted to Soda Butte Creek, mainly upstream from Cooke City. The sample from near the McLaren tailings pile in the New World district is strongly anomalous (140 ppm W). The lower flood-plain tailings sample also is anomalous (21 ppm); however, nearby sediment samples in lower Soda Butte Creek are not anomalous, again emphasizing the tailings-related origin of material in that flood-plain sample. The single anomalous sample on the west side of the area is related to geothermally altered rocks.

Molybdenum.—Molybdenum is loaded on two factors (table 2). Its primary loading is on factor 1, the felsic igneous rock factor. It is secondarily loaded on the geothermal factor, emphasizing at least two sources for this element. Like tungsten, molybdenum forms its own minerals, the most common of which is the sulfide, molybdenite; however, the mineral form of molybdenum in the study areas has not been identified. In the West Area (fig. 13A), molybdenum anomalies (3–19 ppm) are widespread. Field observations indicate that some of these anomalies are not related to geothermal activity and that some samples containing geothermally altered material are not anomalous. These observations corroborate the results of the factor analysis and strongly suggest that, in the West Area, molybdenum is enriched both as a result of naturally high background concentrations related to the rhyolite lithology and as a result of geothermal activity.

In the Northeast Area (fig. 13B), molybdenum is anomalous (8–14 ppm) in two samples from the New World district, but it shows only background concentrations along Soda Butte Creek. Note that, unlike tungsten, neither tailings-related sample is anomalous. In the Northeast Area, molybdenum also is anomalous in a cluster of samples along the Yellowstone River, near its junction with the Lamar River, and in the isolated sample collected in the southwestern part of the area. These anomalies are deemed to be related to a combination of lithologic and geothermal sources.

Cesium.—Cesium is strongly loaded on the geothermal factor (table 2). Unlike most other elements studied, anomalous cesium is associated solely with geothermal activity. We speculate that this element probably is substituting for potassium in potassium-rich alteration minerals. The highest concentrations of cesium (7–870 ppm) are in sediments collected in the West Area (fig. 14A) from smaller streams in the Upper, Lower, and Norris Geyser Basins that drain areas of active geothermal systems. Anomalous concentrations extend downstream from these geyser basins to the Madison River, and thence all the way to the western boundary of the Park. Anomalous cesium also is present in sediments from streams draining hydrothermally altered rocks near Shoshone, Lewis, and Heart Lakes.

In the Northeast Area (fig. 14B), anomalous cesium concentrations (10–18 ppm) are only in samples collected along the Yellowstone River, near its junction with the Lamar River. As noted previously, these anomalies are associated with solfataric alteration and hot springs in that area. The absence of anomalous cesium in the Soda Butte Creek drainage emphasizes that this element is not associated with mineralized rock in the Cooke City area. Thus, anomalous cesium is a good
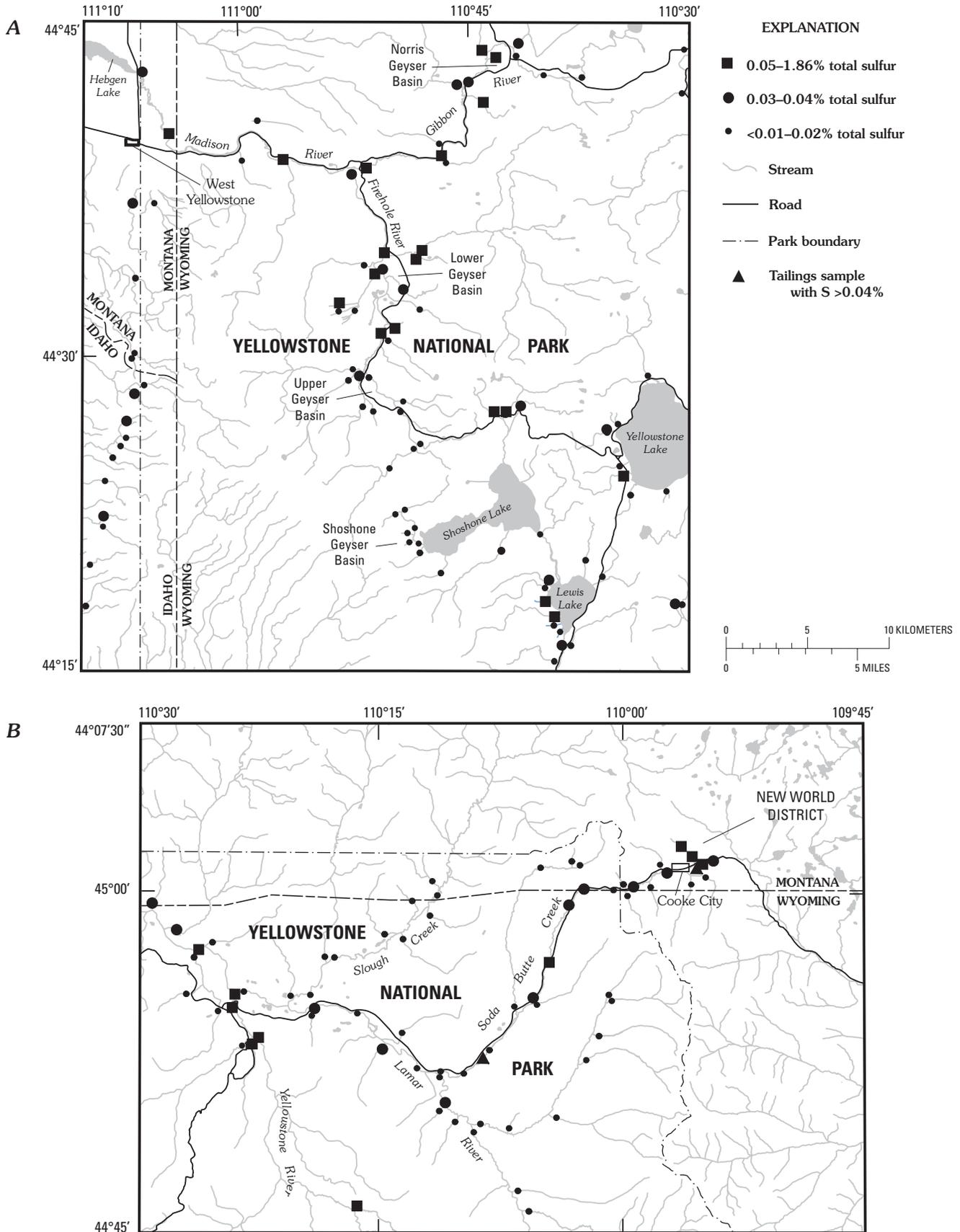
Figure 10. *A,* Distribution of sulfur in stream sediment, West Area. *B,* Distribution of sulfur in stream sediment, Northeast Area.
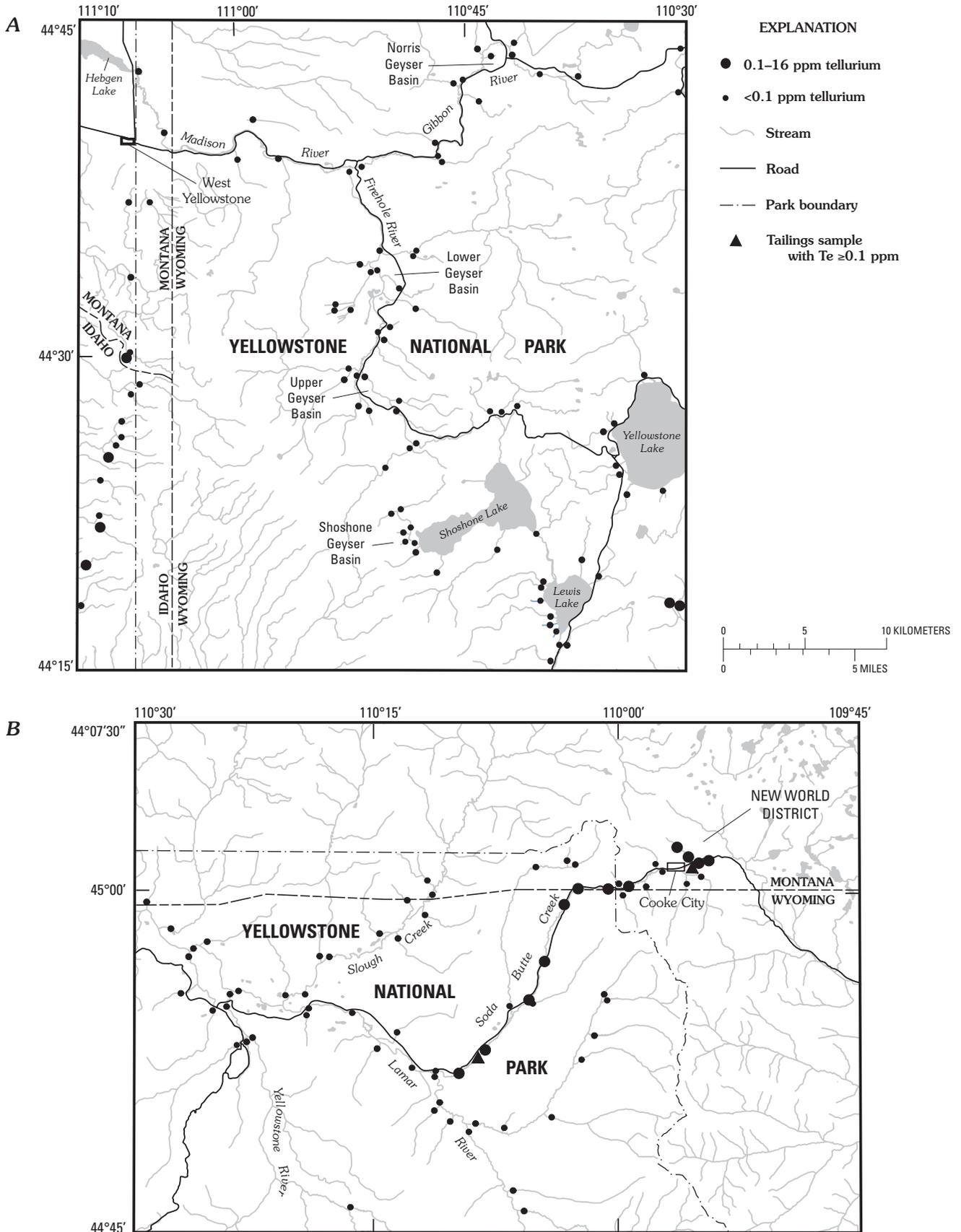
Figure 11. *A,* Distribution of tellurium in stream sediment, West Area. *B,* Distribution of tellurium in ystream sediment, Northeast Area.
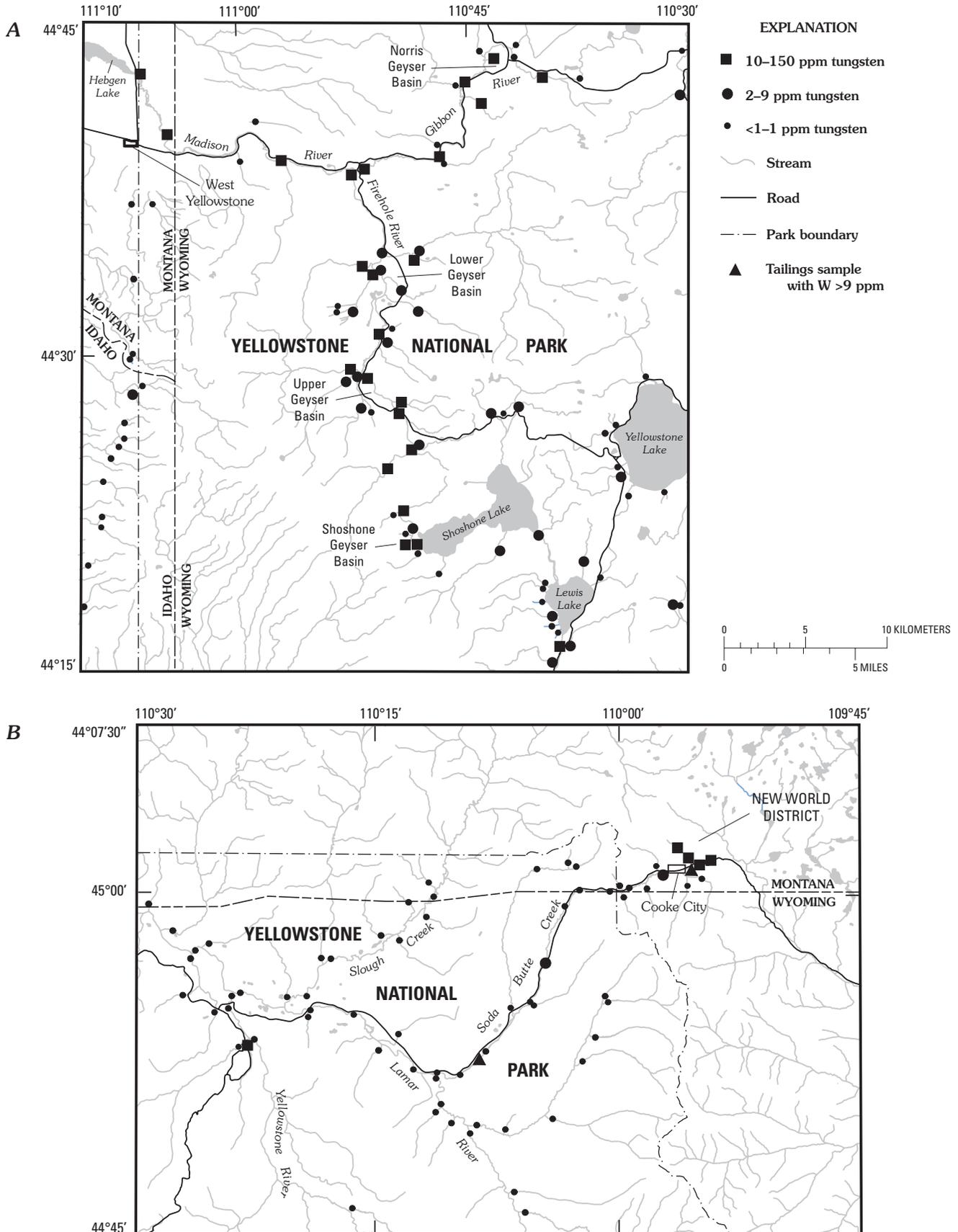
Figure 12. *A,* Distribution of tungsten in stream sediment, West Area. *B,* Distribution of tungsten in stream sediment, Northeast Area.

A

EXPLANATION

■ 6–19 ppm molybdenum

● 3–5 ppm molybdenum

• <2–2 ppm molybdenum

〜 Stream

— Road

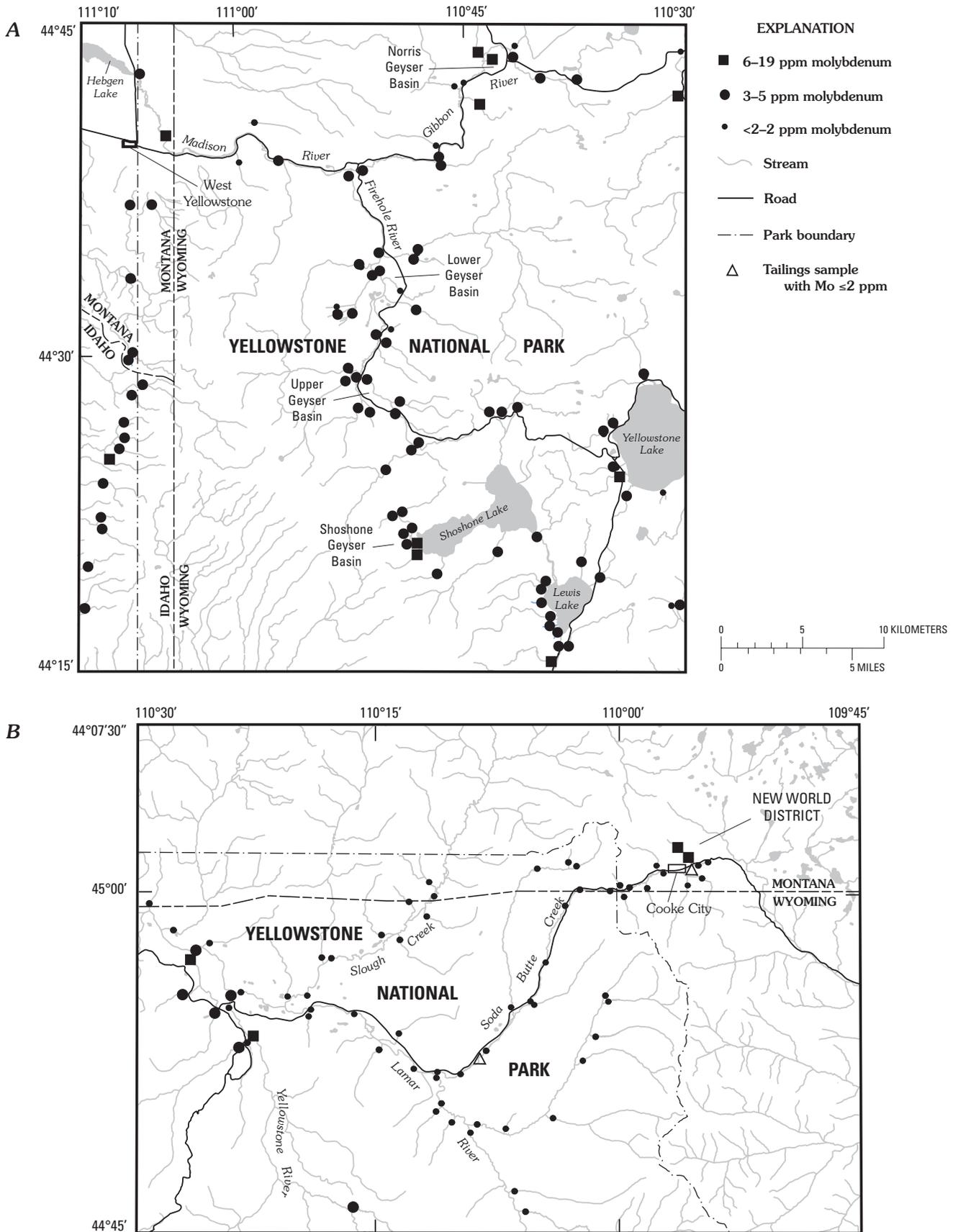–·– Park boundary

△ Tailings sample
    with Mo ≤2 ppm

Figure 13. *A,* Distribution of molybdenum in stream sediment, West Area. *B,* Distribution of molybdenum in stream sediment, Northeast Area.

indicator of both past and present geothermal activity in the Yellowstone area.

Mercury.—Mercury is strongly loaded only on the geothermal factor (table 2). However, this element probably has two additional, less significant, sources. The mineral form of mercury in the Yellowstone area has not been determined. It possibly occurs as free mercury or some other mercury mineral, or possibly it is within the structure of one or more sulfide minerals.

Samples with anomalous mercury (0.06–2.85 ppm) are widespread in the West Area (fig. 15*A*) in areas of both active geothermal activity and fossil geothermal systems. Some anomalous samples do not seem to be related to geothermal features. They are thus thought to represent high background concentrations in unaltered rhyolites, as seems to be the case for lead, molybdenum, and tungsten.

In the Northeast Area (fig. 15*B*), mercury is anomalous (0.06–0.28 ppm) in the stream-sediment samples from the immediate area of the New World mining district. The up-stream tailings-related sample also is anomalous (0.16 ppm Hg). These observations suggest that this element possibly is a previously unreported minor component of the mineral deposits in the district or, more likely, it was added to the ores during treatment. Low concentrations of mercury also have been detected in areas where mercury-bearing fungicides were applied during reseeding experiments conducted in the New World district. Anomalous (0.07–0.25 ppm) geothermally or lithologically related mercury is also present in the area of active hot springs found along the Yellowstone River near its junction with the Lamar River.

Fluorine.—Fluorine is primarily loaded on the miscellaneous factor (factor 5) (table 2), and it has a secondary loading on the felsic-rock factor. Factor scores indicate that fluorine is closely associated with both fresh and geothermally altered igneous rocks, primarily rhyolites. Kornitnig (1972) noted that fluorine commonly is enriched in rocks with high silica content. This relationship seems to hold in the two study areas. Fluorine can proxy for other elements in silicate structures, and it also may occur in accessory minerals, such as fluorite, topaz, and micas. The mineral residence(s) for fluorine in the Yellowstone area has not been identified.

In the West Area (fig. 16*A*), fluorine is anomalous (450–1,600 ppm) in sediments from streams draining nearly all parts of the area, including localities of fresh rhyolites along the western boundary of the Park and elsewhere and localities of geothermally altered rocks. Fluorine is only anomalous in four of the samples analyzed from the Northeast Area (fig. 16*B*). Three, including two regular sediment samples (480–560 ppm F) and one tailings-related sample (600 ppm F), are from the mineralized area in the New World district upstream from Cooke City. The one other anomalous sample (480 ppm F) is from a tributary of upper Slough Creek. These four samples are from streams that drain areas of either Precambrian metamorphic rocks, Tertiary andesitic rocks, or, in the area upstream from Cooke City, material mined in the New World district.

Environmental Concerns

Concentrations of many of the elements described here may impact the surficial environment of the Park in a variety of ways. Widespread, although generally low-level, concentrations of a number of potentially toxic elements are present in sediments in many parts of the Park. Weakly anomalous, high background levels of As, F, Hg, Mo, Pb, Sb, and (or) W have been identified in stream sediments derived from relatively unaltered felsic volcanic rocks in several parts of the Park. We do not know whether elevated levels of any of these elements are also present in stream waters near these high-background, but anomalous, stream-sediment sample sites. However, our observations suggest that any water stored in the Park for public water supplies should be carefully monitored for quality.

The evaluation of water samples from the Soda Butte Creek drainage by Miller and others (1997) indicates that neither strongly acidic nor strongly basic conditions are currently present in Soda Butte Creek within the Park. Consequently, the leaching into this basin of sulfide minerals from the tailings and dumps of the New World district is not presently significant in terms of impact on water pH.

This study of stream sediment, and that of Miller and others (1997) for water, together suggest that anthropogenic activities in and near the Park, such as mining and recreation, have had only a localized, minimal impact on the surficial environment. When compared to the distributions and concentration levels created by natural processes, such as geothermal features, the distributions and concentration levels of elements enriched by anthropogenic activity are not pronounced.

Little is known about how the health and longevity of wildlife are affected by the naturally occurring surficial chemistry of the Yellowstone-area environment. Anomalous concentrations of many elements in plants and water consumed by animals have been shown to cause health problems (Adriano, 1986; Gough and others, 1979; Lepp, 1981; Speidel and Agnew, 1982; Winston and others, 1973; and references in these publications). Discussion of the many parameters related to the potential toxicity of the elements determined for this study and their impact on wildlife is beyond the scope of this paper. However, an example follows to illustrate one instance in which surficial geochemistry has impacted wildlife.

The health and longevity of elk (*Cervus elaphus*) in the Park recently were studied (Garrott and others, 2002). Elk in the Lamar Valley area live longer than those in the Madison-Firehole area, where geothermal activity has markedly affected surficial chemistry. The longevities of elk in the two areas are closely associated with chemical differences in available food. The food chemistry, in turn, is related to differences in the chemistry of rock, soil, and stream waters of these two areas—differences that are due partly to local geology and partly to the presence or absence of geothermal features. Water, as well as plants and their substrates, is enriched in fluorine and silica in many parts of the Madison-
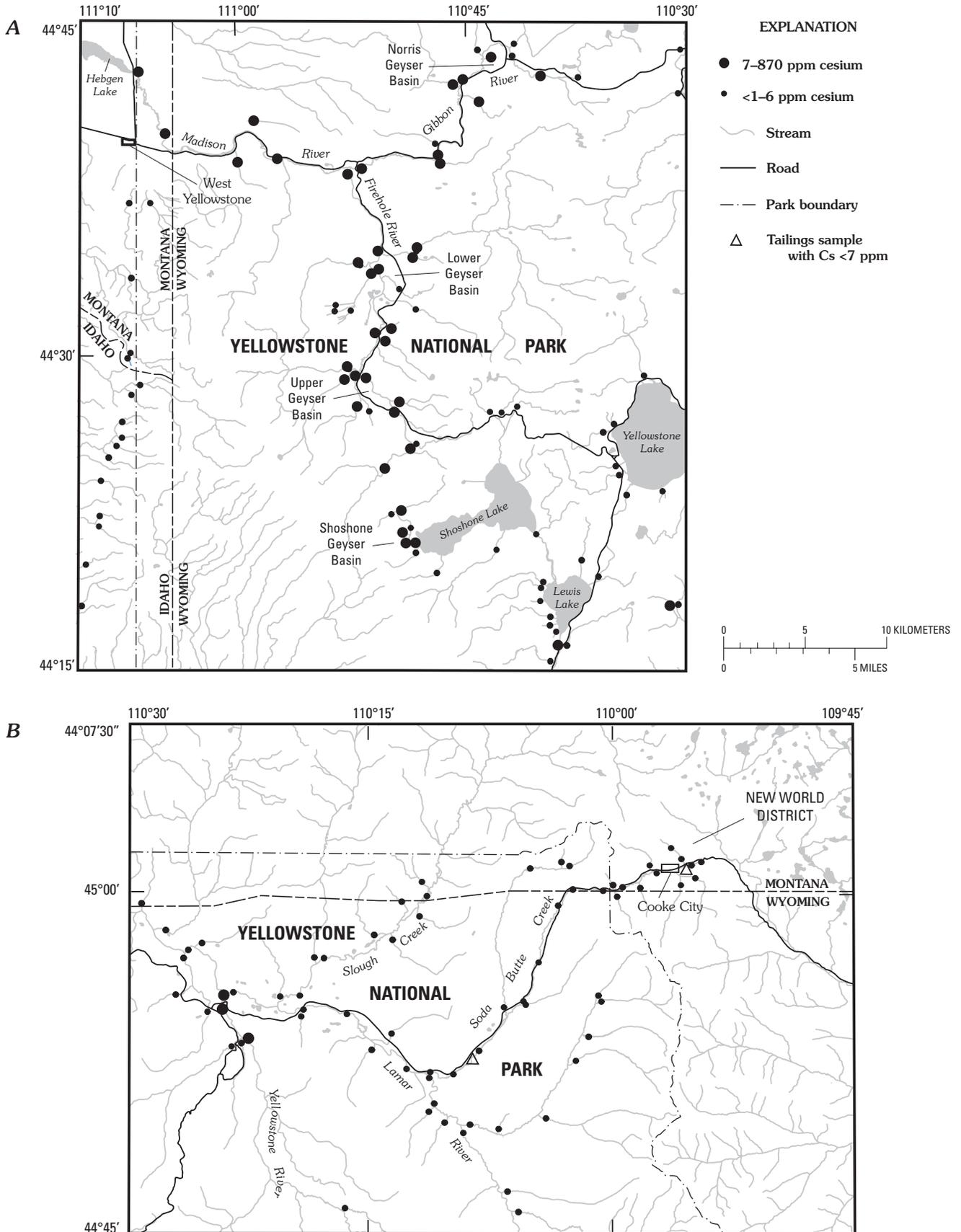
Figure 14. *A*, Distribution of cesium in stream sediment, West Area. *B*, Distribution of cesium in stream sediment, Northeast Area.
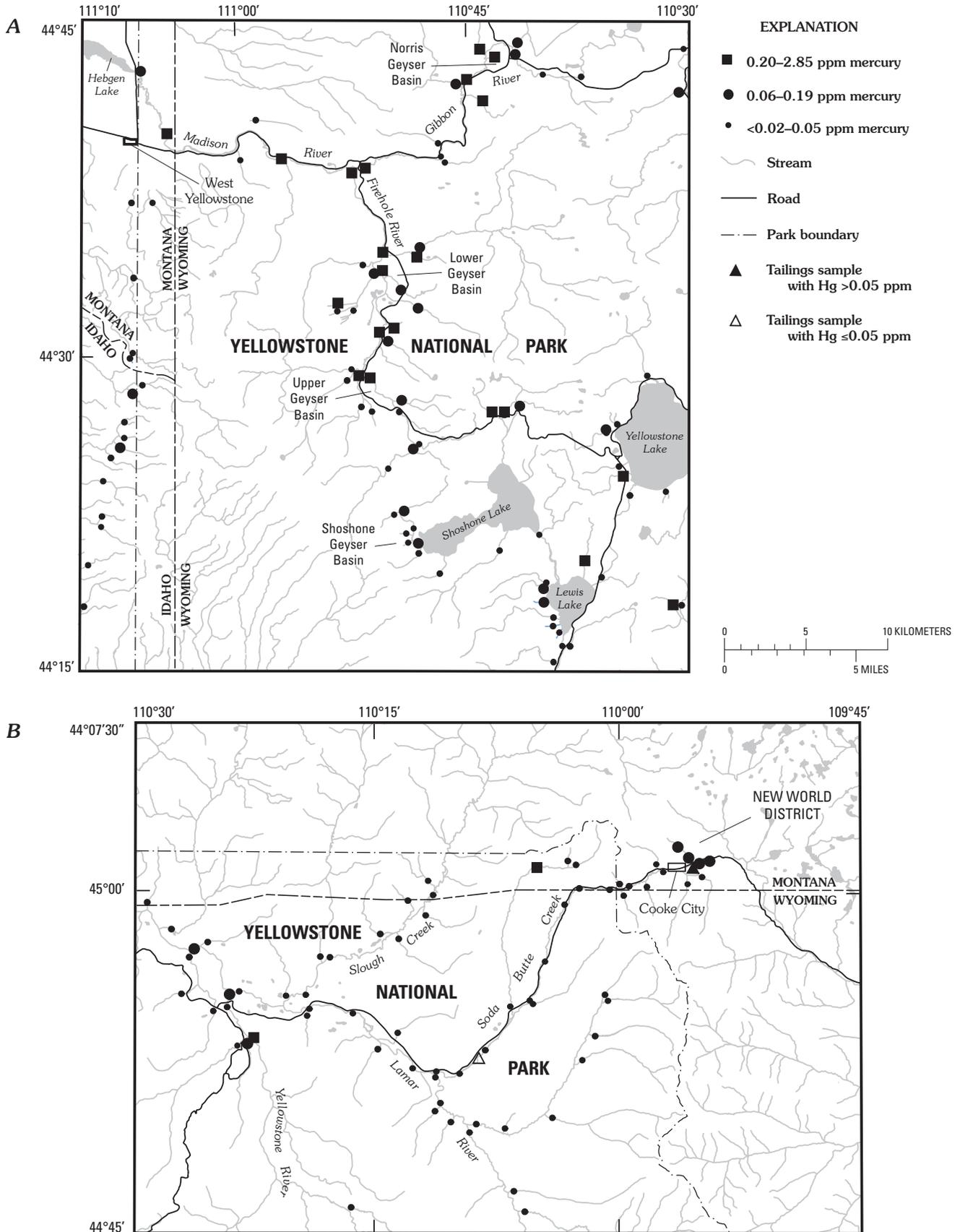
Figure 15. *A,* Distribution of mercury in stream sediment, West Area. *B,* Distribution of mercury in stream sediment, Northeast Area.
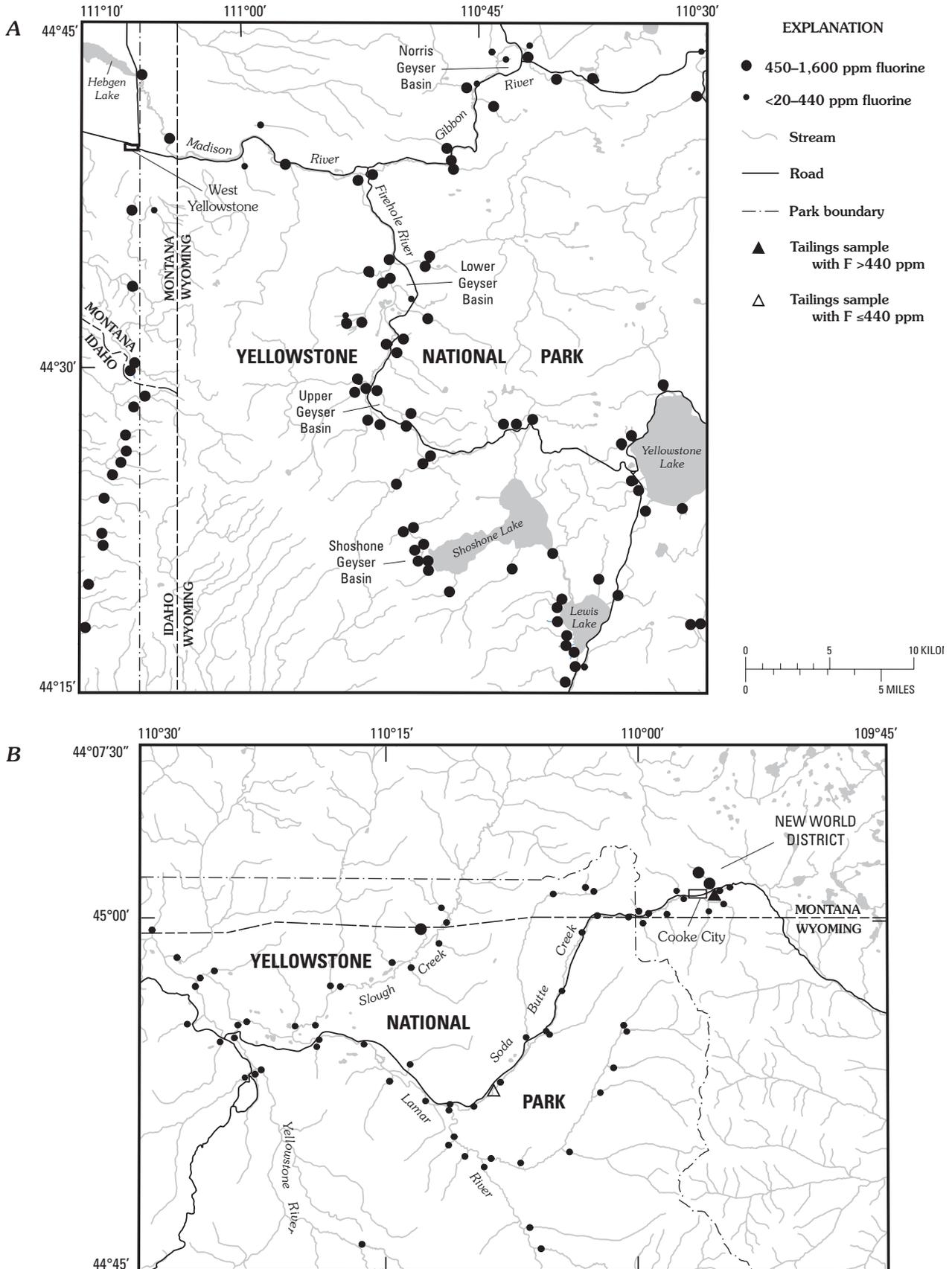
Figure 16. *A,* Distribution of fluorine in stream sediment, West Area. *B,* Distribution of fluorine in stream sediment, Northeast Area.

Firehole area, as compared to the Lamar River valley (Miller and others, 1997; Garrott and others, 2002). Excessive fluorine in the food chain causes severe fluorosis in elk and other ungulates (Shupe and others, 1984), weakening their tooth structure and ultimately destroying their teeth. Additionally, abrasive silica in plants eaten by elk causes abnormal wear of teeth. This fluorine-silica combination causes early loss of teeth and eventual starvation. Our fluorine data clearly show that this element is enriched in samples from many areas of rhyolite outcrops or geothermal features.

Of the elements determined for this study, arsenic, molybdenum, fluorine, and silicon probably have the greatest potential for affecting the health of Park animals. To the best of our knowledge, the effects of arsenic and molybdenum on elk (*C. elaphus*), bison (*Bison bison*), moose (*Alces americana*), or other animals living in or near the Park have not been documented. The impacts of other potentially toxic elements, such as mercury, thallium, selenium, tungsten, and lead, on the health of wildlife in the Park also are not known.

We have also determined the content of selected elements in samples of elk and bison scat collected at localities throughout the Park. The distributions of anomalous elements in these samples closely reflect the chemistry of the underlying rocks. This observation indicates that animals grazing in or near geothermal areas are ingesting plant material (and probably water) that is high in potentially toxic elements such as fluorine, arsenic, and molybdenum. Except for fluorine and silicon, we do not know what elements are being accumulated in Park animals and the effects of any such accumulation. Low levels of potentially toxic elements may not kill animals, but may stress their systems to a point at which they are more susceptible to disease. Further studies of the effects of trace elements on wildlife are clearly needed.

Summary and Conclusions

This study indicates that many elements are relatively enriched in rock, stream-sediment, and water samples collected from localities in and near Yellowstone National Park. Of the elements described here, many have multiple sources, whereas some have only one. The source(s) of many of these elements can be determined by examining their respective distributions on maps and their multivariate statistical associations as determined by factor analysis. Different suites of elements can be used to characterize and differentiate anomalies related to natural causes (such as rock lithology, undisturbed mineral deposits, and geothermal activity) and those related to anthropogenic causes (such as mining and recreation). For many of the elements examined, the strongest anomalies in the Park are related to natural causes rather than to anthropogenic activities. When compared to anomalies caused by geothermal activity, those related to past mining are relatively minor.

Spatial differences in concentrations of 34 of the 49 elements determined for this study are primarily associated with differences in rock type. Many of these elements can be used to discriminate between major lithologic units and thus can be used to assist geologic mapping in the Park area.

Elements discussed in this study that are most closely associated spatially with areas of geothermal activity or source rocks for geothermal waters include As, Cs, Hg, S, Sb, Tl, and W. Of these, cesium, which is enriched only in sediment from geothermal areas, is the best geochemical indicator of geothermal activity. Elements associated with mineral deposits near Cooke City, Mont., include Ag, As, Au, Cu, Fe, Hg, Mo, Pb, S, Sb, Se, Te, Tl, W, Zn, and possibly F. Of these, Au, Cu, and Te are especially useful for identifying the dispersion of mineral-deposit-related contamination, which extends from the New World and Republic districts near Cooke City downstream into the extreme northeastern corner of the Park. Relatively weak anomalies of some of these elements extend as far as 18 km inside the Park, as measured from the Northeast Entrance.

In the area of Slough Creek, in the northeastern part of the Park, a high concentration of lead in one sample was deemed to be anthropogenic because of a lack of anomalies of other elements that commonly are associated with natural lead anomalies. This anomaly probably is related to past fishing activity.

The present-day, active geothermal waters in the Park probably are modern analogs to those that formed certain types of gold deposits in many parts of the world. Studies of Yellowstone's geothermal features can help geologists to better understand the genesis of gold deposits, and possibly other types of mineral deposits.

Many of the elements in stream sediment studied here are also known to be present in anomalous concentrations in the stream waters draining geothermal areas. Some of these elements also are concentrated in plants in these areas; thus, they are in the food chain for wildlife that feed in the geothermal areas of the Park. The impact on Park animals and plants of high chemical concentrations in water, soil, or sediment is not well understood, and it needs to be addressed by scientists. Weakly anomalous concentrations of elements such as As, Mo, Pb, and W occur locally in relatively unaltered felsic rocks and also in stream sediments. In some cases, they occur in stream water, suggesting that water stored in the Park for public water supplies should be carefully monitored for quality.

Significant amounts of As, Cs, Hg, Mo, Sb, W, and probably other elements, are being carried out of the Park in sediment (and, in many cases, in water) in the Madison River and possibly in other streams that exit the Park. Although the downstream environmental effects of a number of elements in the waters of the Madison River have been documented, the chemical contents and effects of sediment downstream from the Park have not been investigated in any detail. Further investigations may be warranted.

Acknowledgments

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