Prepared in cooperation with the
National Park Service and the U.S. Department of Agriculture Forest Service

Rocky Mountain Snowpack Chemistry at Selected Sites, 2002

Open-File Report 2004–1027

U.S. Department of the Interior
U.S. Geological Survey

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By George P. Ingersoll, M. Alisa Mast, Leora Nanus, David J. Manthorne,
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Conversion Factors and Abbreviations

Multiply	By	To obtain
meter (m)	3.28084	foot
kilometer (km)	0.6213712	mile
centimeter (cm)	0.3937003	inch
liter (L)	0.2641721	gallon

To convert from microequivalents per liter to milligrams per liter for major ions, divide microequivalents by factors indicated for each ion:

To obtain milligrams per liter	For	Divide by
	hydrogen (H^+)	1,000
	calcium (Ca^{2+})	49.9
	magnesium (Mg^{2+})	82.26
	sodium (Na^+)	43.5
	potassium (K^+)	25.57
	ammonium (NH_4^+)	55.44
	chloride (Cl^-)	28.21
	sulfate (SO_4^{2-})	20.83
	nitrate (NO_3^-)	16.13

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8\times°C)+32$$

Sea level: In this report, “sea level” refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

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Abstract

During spring 2002, the chemical composition of annual snowpacks in the Rocky Mountain region of the Western United States was analyzed. Snow samples were collected at 75 geographically distributed sites extending from New Mexico to Montana. Near the end of the 2002 snowfall season, the snow-water equivalent (SWE) in annual snowpacks sampled generally was below average in most of the region. Regional patterns in the concentrations of major ions (including ammonium, nitrate, and sulfate), mercury, and stable sulfur isotope ratios are presented.

The 2002 snowpack chemistry in the region differed from the previous year. Snowpack ammonium concentrations were higher at 66 percent of sites in Montana compared to concentrations in the 2001 snowpack but were lower at 74 percent of sites in Wyoming, Colorado, and New Mexico. Nitrate was lower at all Montana sites and lower at all but one Wyoming site; nitrate was higher at all but two Colorado sites and higher at all New Mexico sites. Sulfate was lower across the region at 77 percent of sites. The range of mercury concentrations for the region was similar to those of 2001 but showed more variability than ammonium, nitrate, and sulfate concentrations. Concentrations of stable sulfur isotope ratios exhibited a strong regional pattern with values increasing northward from southern Colorado to northern Colorado and Wyoming.

Introduction

Snowfall that accumulates from October until March, April, or May provides much of the annual precipitation in headwater basins of the Rocky Mountains (Western Regional Climate Center, 2001). As these snowpacks accumulate during the winter and spring, chemicals deposited from the atmosphere are stored in the snow until snowmelt begins in spring. Because snowmelt supplies most of the freshwater in mountain lakes, streams, and wetlands, monitoring the water quality of snow is important to understanding the effects of atmospheric deposition to these systems.

In the Rocky Mountain region, population growth, water use, and energy development are increasingly affecting the quantity and quality of water resources at higher elevations. Identifying changes in water quality and processes leading to changes in water quality is important because alpine and subalpine environments in the region are sensitive to changes in chemical composition of the water. Thin alpine and subalpine soils and dilute water bodies in mountain ecosystems typically have limited capacity to buffer acidity that may be deposited with airborne contaminants such as nitrogen and sulfur. Atmospheric input of these and other chemicals, such as mercury, to these sensitive areas may harm aquatic and terrestrial plant and wildlife populations and has been documented in surface-water bodies in the study area (U.S. Environmental Protection Agency, 2001).

Although several watershed-scale studies have investigated anthropogenic deposition in small headwater basins in the Rocky Mountains (Turk and Campbell, 1987; Caine and Thurman, 1990; Baron, 1992; Reuss and others, 1993; Campbell and others, 1995; and Williams and others, 1996), regional-scale atmospheric deposition data are sparse. The National Atmospheric Deposition Program (NADP) (2001) provides nationwide estimates of atmospheric deposition (Nilles, 2000). Coverage for high-elevation areas (greater than 2,000 meters) in the Rocky Mountains, however, is limited. Although 10 NADP sites monitor atmospheric deposition above 2000 meters in Colorado, few sites are operated in high-elevation areas of Idaho, Montana, Wyoming, and New Mexico, where snowpacks persist with negligible melt through the snowfall season. These high-elevation snowpacks are important because they may accumulate 2 to 3 times the annual precipitation measured at lower elevations where regular monitoring is more feasible.

Purpose and Scope

To gain a better understanding of atmospheric deposition at high elevation in the Rocky Mountains, the U.S. Geological Survey, in cooperation with the National Park Service, U.S. Department of Agriculture Forest Service, the U.S.

Environmental Protection Agency, and other organizations established a network of more than 50 snow-sampling sites in the Rocky Mountain region. Sites in the network have been sampled annually since 1993. The purpose of this report is to present the 2002 snowpack-chemistry data for comparison to previous years (Ingersoll, 1999; Ingersoll and others, 2002, 2003; Mast and others, 2001; Turk and others, 2001).

Study Area

Snow-sampling sites in Montana, Idaho, Wyoming, Colorado, and New Mexico generally are located near the Continental Divide in National Forests or National Parks (fig. 1). Sampling sites were chosen at locations with limited human activity or emissions from local residential, commercial, or industrial activities to enable detection of regional emissions signals that may affect deposition hundreds of kilometers downwind. Sites were located at least 30 meters away from plowed roadways to minimize contamination from vehicular traffic. Colorado and New Mexico sites range in elevation from about 2,700 to 3,400 meters; sites in Idaho, Wyoming, and Montana typically are at about 1,800 to 2,700 meters. At these elevations, seasonal snowpacks accumulate throughout the winter, and substantial snowmelt does not occur until spring runoff begins in March, April, or May. The seasonal snowpacks melt entirely each summer at sites in the network, so resampling snowfall from previous years is avoided. As latitude increases along the Continental Divide, the elevation at which seasonal snowpacks develop generally decreases.

Acknowledgments

The authors are grateful for the cooperation from numerous individuals from many organizations including Colorado Department of Public Health and Environment; National Park Service; Public Service Company of Colorado; Routt County, Colorado; Tri-State Generation and Transmission Association; U.S. Department of Agriculture Forest Service, and the U.S. Environmental Protection Agency; all made this study possible. The authors also thank the many individuals who assisted with logistical support, field work, and analytical processing, including Stan Bones, Cindy Bosco, Doug Cancilla, Bob Dixon, Jay Dorr, Dan Fagre, Mike Gillespie, Ben Glass, Bob Hammer, Val Hancock, Mary Hektner, Karen Holzer, Nan Ingersoll, Larry Kawanabe, Cyndi Kester, Tarry King, Craig McClure, Pat McKay, Lisa McKeon, Rick Neam, Gary Nelson, Ted Porwoll, Blaze Reardon, Don Rosenberry, Orville Rosenberry, John Sacklin, Tom Schwartz, Mark Story, Terry Svalberg, Corky Ward, and Art Weir. Special thanks also to the generous logistical support from the following ski areas: The Big Mountain, Big Sky, Loveland, Showdown, Snow Bowl, Taos Ski Valley, and Teton Village.

Study Methods

The USGS has developed methods for measuring physical and chemical properties of seasonal snowpacks. Detailed descriptions of sample-collection and analytical methods are reported in Ingersoll and others (2002).

Data Collection

Where feasible, snow-sampling sites were collocated with snowpack-telemetry (SNOTEL) instrument sites where measurements of snow-water equivalence were recorded daily by the USDA, Natural Resources Conservation Service (National Resources Conservation Service, 2002). Samples were collected from late February to early April just before the time of the annual maximum snow depth. Samples were collected from snowpits (fig. 2) in small clearings in forests where uniform snowcover appeared to be free of human disturbance, excessive tree litter, or animal activity. Snow samples were collected and placed in 8-liter Teflon bags that were sealed and frozen until analyzed at USGS laboratories in Boulder and Denver, Colorado. An additional 60-liter snow sample was collected in a plastic container for determination of stable sulfur isotope ratios.

Analytical Methods

Concentrations of major ions and trace constituents were determined from snow melted in the 8-liter Teflon bag containing a single, depth-integrated, composite sample from a single snowpit. High-quality deionized water (DI) was used for all blanks and was transported to the field in acid-rinsed Teflon bottles. Field-replicate snow samples were collected in Teflon bags and processed separately in the laboratory for analyses of major ions, dissolved organic carbon (DOC), and mercury. Stable sulfur isotope ratios were determined from the separate, 60-liter container snow sample. Analytical laboratory methods, detection limits, and quality-assurance procedures for analyses of major-ion concentrations and stable sulfur isotope ratios are described in Ingersoll and others (2002), Mast and others (2001), and Turk and others (2001). Total mercury analyses were done by potassium-dichromate digestion of whole-water samples using cold-vapor atomic fluorescence spectrometry (Roth, 1994). The laboratory reporting limit for mercury analyses was 0.1 nanogram per liter.

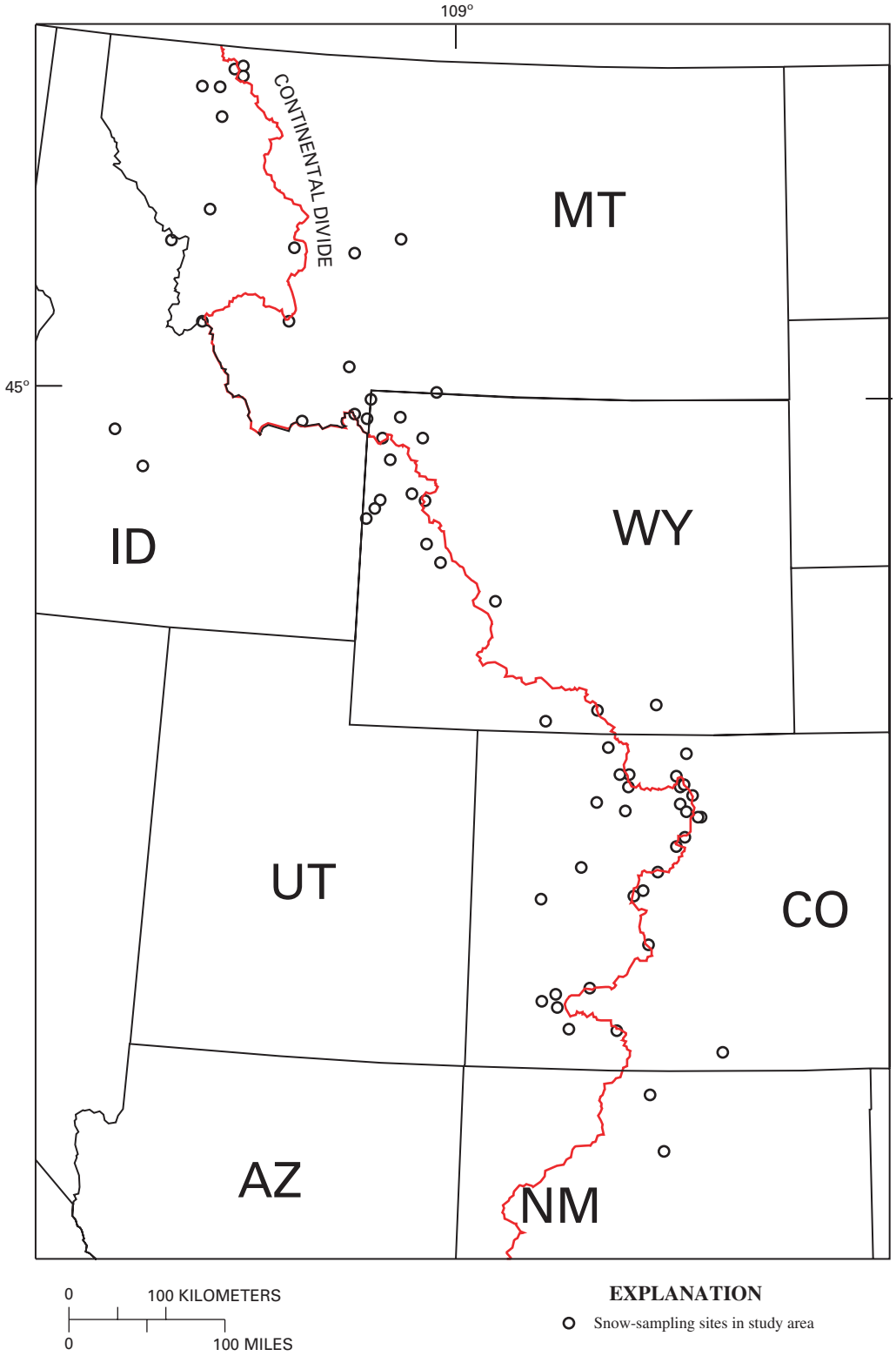

Figure 1. Snow-sampling sites in the study area.

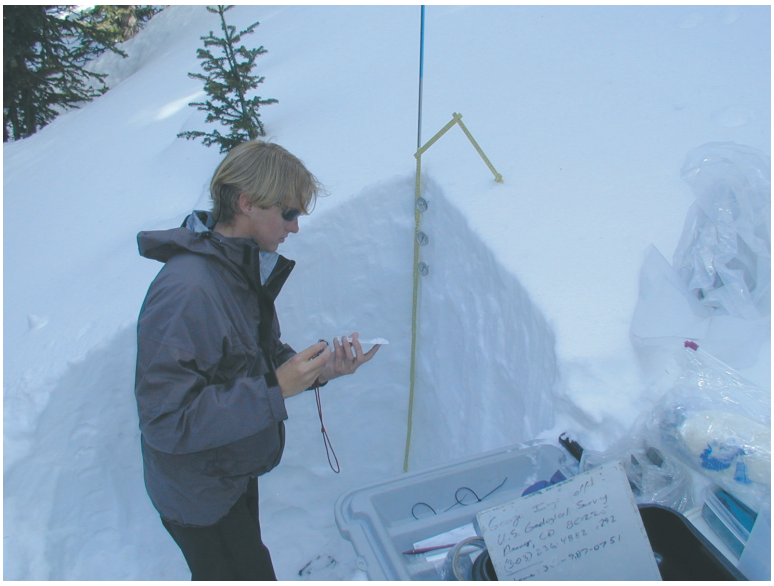

Figure 2. Snowpit face during sampling.

Snowpack Chemistry

Water Content

Snowpack samples were collected at 75 sites in 2002 including 50 long-term sampling sites in the network that have been sampled annually since 1993, and an additional 25 sites that were added since 1993 to expand the coverage of the network in Colorado, Idaho, and Montana. When snow samples were collected during February, March, and April, the snowpack water content, referred to as "snow-water equivalent (SWE)," was below average throughout much of the Rocky Mountain region. Snow depth at sampling sites ranged from 20 to 370 centimeters; SWE measured for full snowpacks ranged from about 4.8 centimeters to 133.8 centimeters. The majority of measured SWE values ranged from 20 to 80 centimeters. Snow depths in 2002 generally were similar to snow depths in 2001 but substantially less than average snow depths for 1993–2000.

Cumulative SWE in 2001 and 2002 reported at SNOTEL sites in basins near snow-sampling sites as of April 1, 2002, ranged from below average to much below average at most sampling sites except in northwestern Montana. Compared to 30-year averages (1971–2000), SWE accumulations at SNOTEL sites were 78–120 percent in Montana, 83–95 percent in Idaho, 64–88 percent in Wyoming, 33–66 percent in Colorado, and 45–50 percent in New Mexico (National Resources Conservation Service, 2002).

Chemistry

Chemical data for 2002, including alkalinities, laboratory pH, concentrations of major ions, dissolved organic carbon, total mercury, stable sulfur isotope ratios, and ionic charge balances, are presented in table 1. Snow-sampling sites shown alphabetically by State in table 1 also are referenced by their site numbers in figures 3–6, and site numbers appear in parentheses directly after the first mention of site names in the following text.

Concentrations of ammonium ranged from less than 0.5 microequivalent per liter at Brumley, Colorado (44), and Vallecito, Colorado (72), to 13.8 microequivalents per liter at Lionshead, Montana (12) (fig. 3, table 1), and tended to be lowest at sites surrounded by mountain forests with limited agricultural land use and highest near areas of large-scale agricultural activity in lower elevation plains. The second highest ammonium concentration was found at Monida Pass, Montana (13) (12.6 μeq/L), about 90 kilometers west of Lionshead. This pattern of high ammonium concentrations in southwestern Montana is consistent with previous years. Both the Lionshead and Monida Pass sites are located near mountain passes where prevailing westerly winds funnel airmasses over the Continental Divide (Thompson and others, 1993). Storms originating out of the southwest travel over large agricultural areas of Idaho, where large-scale application of fertilizer occurs, before reaching the two sites.

Comparing results for 2002 to 2001, ammonium concentrations were higher at 66 percent of sites in Montana (Ingersoll and others, 2003). In contrast, concentrations were

lower at 74 percent of sites sampled in Wyoming, Colorado, and New Mexico. Concentrations of ammonium were elevated at two sites near the Denver area and adjacent agricultural areas of northeastern Colorado: Niwot SNOTEL (65) (10.8 μeq/L) and University Camp (71) (11.3 μeq/L).

Concentrations of nitrate ranged from 2.7 microequivalents per liter at Granite Pass, Montana (10), to 24.5 microequivalents per liter at Loveland Pass, Colorado (61) (fig. 4, table 1). Similar to previous years, the highest concentrations were detected at several sites in Colorado and northern New Mexico and the lowest were at sites in Wyoming, Idaho, and Montana. The exception was Monida Pass, Montana (13), which had a nitrate concentration of 17.3 microequivalents per liter possibly because of the very thin snowpack (20 centimeters) and proximity to agricultural land use in Idaho. Compared to 2001 data, nitrate in 2002 decreased at all Montana and Wyoming sites (except Brooklyn Lake ([24]), and increased at all but two Colorado and two New Mexico sites.

Concentrations of sulfate ranged from 1.8 microequivalents per liter at Granite Pass, Montana (10), to 15.5 microequivalents per liter at South Pass, Wyoming (35) (fig. 5, table 1). Sulfate concentrations in 2002 decreased across the region at 77 percent of sites compared to 2001 snowpacks. Whether this finding is consistent with other nationwide research that indicates sulfur dioxide emissions have decreased in the past decade (U.S. Environmental Protection Agency, 1999; Nilles and Conley, 2001), or is influenced by the recent drought conditions or other factors, is unclear. Sulfate concentrations at all sites in Idaho and Montana were equal to or below the average concentration for 2002 for the region (5.9 μeq/L). The highest concentration of sulfate detected in the region at South Pass (35) possibly was affected by emissions from coal-burning powerplants located in southern Wyoming and northwestern Colorado.

Nitrate and sulfate concentrations generally were lower in less developed areas of the region such as in central Idaho and northwestern Montana than in more developed areas such as northern New Mexico, Colorado, and southern Wyoming. As observed in the 2001 snowpack chemistry, the sites in northwestern Colorado that are west of the highly developed Denver metropolitan area and east or south of coal-fired powerplants in northwestern Colorado or southern Wyoming, respectively, had higher concentrations of nitrate (fig. 4, table 1) and sulfate (fig. 5, table 1) than other sites in Colorado. Substantial emissions of both nitrogen oxides and sulfur dioxide have been reported for 1999 from several powerplants in this area (U.S. Environmental Protection Agency, 2003).

Flow directions of surface winds in the Rocky Mountains are variable and may fluctuate hourly, but prevailing westerly winds dominate in this region, especially during winter (Banta and Cotton, 1981; Barry, 1992). In contrast, springtime snow storms in Colorado often originate from other directions with an easterly influence. Three northwestern Colorado sites at Arapaho Creek (41), Dry Lake (49), and Phantom Valley (66) are located between local coal-fired powerplants (Turk and Campbell, 1997) and the Denver metropolitan area. This is noteworthy because the lowest pH values (4.82–4.90) detected in the 2002 snowpacks in the Rocky Mountain region were observed at these sites. Nitrate concentrations also were among the highest in the network at these three sites (ranging from 19.0 to 21.5 μeq/L) where byproducts of fossil-fuel combustion such as nitrate would be expected to be found in air masses passing over the area during snowstorms.

Heuer and others (2000) determined that nitrogen concentrations measured during 1992–97 in precipitation at NADP sites that are mostly within 200 kilometers of Denver were consistently higher than those at NADP sites farther from Denver. Other work has shown similarly elevated levels of nitrogen deposition to mountain ecosystems within this distance from Denver (Williams and others, 1996; Campbell and others, 2000). These findings are consistent with the regional spatial patterns of snowpack nitrate shown in figure 4.

Total mercury detected is reported for all mercury concentrations in these results. Mercury concentrations in 2002 snowpacks ranged from 0.4 nanograms per liter at Galena Summit, Idaho (23), to 11.9 nanogram per liter at Taos Ski Valley, New Mexico (75) (fig. 6, table 1), and showed more complex spatial variability than observed with ammonium, nitrate, and sulfate. The second highest concentration of mercury was found at South Pass, Wyoming (35) (11.5 ng/L). Other areas in the region where total mercury concentrations were highest were in northwestern Montana at Granite Pass (10) (11.1 ng/L) and nearby Snow Bowl (17) (11.0 ng/L). Elevated concentrations also were detected at site E6 (located on the east side of Glacier National Park), Montana (8) (7.8 ng/L); Lionshead, Montana (12) (8.2 ng/L); Grand Mesa, Colorado (54) (9.4 ng/L); and Monarch Pass, Colorado (64) (9.6 ng/L). The lowest concentrations of mercury found in the 2002 snowpack were in southern Idaho, northwestern Wyoming, and southwestern Montana (excepting Lionshead).

The distribution of both high and low concentrations of mercury in snowpacks near sites where mercury emissions would be expected is perplexing. At many sampling sites located farther away (greater than 100 kilometers) from large point sources of mercury emissions (relative to other sites in the network) concentrations were low. However, several snow samples from sites near likely sources of mercury, such as coal-fired powerplants, were lower than the 2002 mean mercury concentration (3.7 ng/ L), while concentrations at two sites near similarly large emissions sources–South Pass, Wyoming (35) and Taos Ski Valley, New Mexico (75)–were elevated (11.5 and 11.9 ng/L, respectively). The spatial variability of mercury concentrations possibly is due other factors (in addition to the proximity of sites to likely emissions sources) including snowstorm trajectories during the snowfall season and the potential for long-distance transport (>1,000 km) of airborne mercury from several emissions sources (U.S. Environmental Protection Agency, 1998, 2002). Because limited total-mercury data have been collected in the Rocky Mountain region, and most data available are from samples collected since October 1998 or later, spatial or temporal trend analyses of mercury concentrations are not

Table 1. Alkalinity and laboratory pH; concentrations of major ions, dissolved organic carbon, mercury, and sulfur-34; and ionic charge balances from analysesof the 2002 snowpack.
[Alkalinity (Alk), hydrogen (H^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), potassium (K^+), ammonium (NH_4^+), chloride (Cl^-), sulfate (SO_4^{2-}), nitrate (NO_3^-) are in microequivalents per liter; dissolved organic carbon (DOC) values expressed in milligrams per liter. Mercury (Hg) expressed as nanograms per liter from whole-water samples. Sulfur-34 ($\delta^{34}S$), per mil; "--", not analyzed. Ionic balances are percentages. NP, National Park; na, not applicable.]

Site number shown in figures	Site name	Alk	pH	H^+	Ca^{2+}	Mg^{2+}	Na^+	K^+	NH_4^+	CL^-	SO_4^{2-}	NO_3^-	DOC	Hg	$\delta^{34}S$	ionic balance[1,2]
1	Apgar Lookout, Mont.	-8.65	5.24	5.75	1.3	<0.5	<0.5	<0.5	5.2	0.9	3.1	6.6	0.4	1.0	-	7.3
2	Big Mountain, Mont.	-7.5	5.29	5.13	1.5	<0.5	5.3	<0.5	4.9	0.6	2.6	4.9	0.3	1.1	5.9	35.0
3	Big Sky, Mont.	-2.4	5.54	2.88	4.9	0.8	<0.5	0.5	4.4	0.6	2.9	4.7	0.6	2.0	-	24.4
4	Chief Joseph Pass, Mont.	-4.1	5.44	3.63	1.5	<0.5	<0.5	<0.5	3.4	<0.5	2.0	3.7	0.3	1.4	6.3	19.9
5	Daisy Pass, Mont.	-4	5.43	3.72	3.4	0.8	0.6	0.7	4.6	0.5	3.4	5.9	0.4	1.6	-	17.0
6	E3 (Glacier NP), Mont.	-8.4	5.23	5.89	2.0	<0.5	1.1	0.7	3.9	0.6	3.5	6.8	0.3	2.1	-	11.0
7	E5 (Glacier NP), Mont.	-6.2	5.27	5.37	1.0	<0.5	<0.5	<0.5	2.3	0.6	2.1	4.1	0.2	1.4	-	12.1
8	E6 (Glacier NP), Mont.	-7	5.27	5.37	1.5	0.8	0.5	0.6	2.1	0.7	2.4	4.5	0.3	7.8	-	17.7
9	Granite Park, Mont.	-7	5.25	5.62	0.5	<0.5	0.5	<0.5	3.4	0.5	2.5	4.8	0.1	0.6	-	12.5
10	Granite Pass, Mont.	-3.2	5.49	3.24	1.5	0.8	0.6	0.6	1.3	0.6	1.8	2.7	0.4	11.1	-	22.4
11	Kings Hill, Mont.	-1.7	5.60	2.51	9.9	1.6	0.6	1.5	7.8	0.8	4.5	8.8	0.8	5.0	-	25.8
12	Lionshead, Mont.	-3.4	5.40	3.98	3.4	0.8	0.5	1.0	13.8	0.9	5.9	10.7	0.4	8.2	-	14.6
13	Monida Pass, Mont.	-4.4	5.55	2.82	10.9	4.1	1.4	0.7	12.6	1.9	5.5	17.3	0.6	0.6	-	13.7
14	Mount Belmont, Mont.	-8.2	5.15	7.08	4.9	1.6	0.6	4.2	6.5	1.0	5.0	9.5	1.4	1.7	-	23.2
15	Noisy Basin, Mont.	-5.9	5.24	5.75	1.5	0.8	0.6	0.6	5.0	0.8	3.1	6.1	0.4	2.3	-	17.5
16	Red Mountain, Mont.	-4.6	5.27	5.37	4.4	0.8	<0.5	0.5	4.6	<0.5	2.4	6.1	0.7	3.7	-	29.7
17	Snow Bowl, Mont.	-6.4	5.27	5.37	1.5	0.8	<0.5	0.6	3.0	0.7	3.3	4.4	0.5	11.0	-	14.6
18	Spring Gulch, Mont.	-0.2	5.62	2.40	13.4	1.6	<0.5	1.2	7.6	0.7	3.2	11.9	0.6	5.3	-	24.8
19	Swiftcurrent Creek, Mont.	-7.7	5.18	6.61	1.5	<0.5	0.7	0.5	4.9	0.9	4.0	7.1	0.2	3.1	-	8.4
20	W10 (Glacier NP), Mont.	-8.25	5.21	6.17	1.8	0.8	0.8	<0.5	3.9	0.8	3.6	6.6	0.4	2.0	-	10.0
21	West Yellowstone, Mont.	-4.1	5.40	3.98	3.4	0.8	1.7	0.6	10.3	0.9	5.5	10.7	0.3	2.2	-	9.7
22	Banner Summit, Idaho	-3.6	5.48	3.31	1.5	<0.5	1.4	<0.5	3.5	<0.5	2.5	3.4	0.2	1.5	6.5	24.4
23	Galena Summit, Idaho	-4.6	5.38	4.17	2.0	<0.5	8.2	<0.5	1.2	5.6	2.7	3.7	0.5	0.4	6.1	12.9
24	Brooklyn Lake, Wyo.	10.1	6.00	1.00	24.4	4.9	5.5	2.2	4.2	1.5	11.8	13.4	1.5	5.9	6.6	6.8
25	Canyon, Wyo.	-7.8	5.34	4.57	2.9	0.8	1.2	<0.5	6.7	1.1	3.0	7.3	0.2	0.7	-	17.3
26	Divide Peak, Wyo.	-1.3	5.51	3.09	15.4	3.2	4.8	0.5	6.3	1.7	9.7	16.9	0.7	4.5	-	8.1
27	Elkhart Park, Wyo.	-8.3	5.27	5.37	5.9	0.8	1.7	0.8	5.4	1.2	5.2	7.5	0.5	1.1	7.6	17.9
28	Four Mile Meadow, Wyo.	-4.6	5.49	3.24	6.9	1.6	2.8	1.1	8.4	1.5	5.0	9.9	0.8	1.2	6.9	18.9
29	Garnet Canyon, Wyo.	-4.9	5.39	4.07	5.4	1.6	1.6	0.9	6.1	1.5	6.9	8.4	0.4	3.4	-	7.9
30	Gypsum Creek, Wyo.	-8.6	5.29	5.13	6.4	1.6	3.0	0.5	7.2	1.5	6.7	10.9	0.2	1.0	-	11.0
31	Lewis Lake Divide, Wyo.	-1.7	5.53	2.95	3.9	0.8	1.5	<0.5	5.7	0.9	4.2	6.0	0.3	1.2	-	14.5
32	Old Battle, Wyo.	-5.3	5.25	5.62	8.9	1.6	2.7	<0.5	5.1	1.1	7.4	13.0	0.3	2.3	-	5.3
33	Old Faithful, Wyo.	-4.5	5.41	3.89	4.4	0.8	2.0	0.6	7.9	1.2	5.9	9.1	0.3	0.9	-	9.5
34	Rendezous Mountain, Wyo.	-7.1	5.47	3.39	3.9	0.8	1.6	<0.5	6.6	0.7	4.9	5.8	0.2	0.6	-	17.7
35	South Pass, Wyo.	-4.7	5.33	4.68	14.9	3.2	5.0	2.6	7.1	1.9	15.5	12.5	1.1	11.5	-	11.2
36	Sylvan Lake, Wyo.	-3.6	5.44	3.63	2.9	0.8	1.1	<0.5	5.4	0.9	3.3	6.3	0.2	1.8	-	13.7
37	Teton Pass, Wyo.	-0.6	5.70	2.00	8.4	2.4	2.5	1.7	9.3	1.4	6.8	9.2	0.8	4.8	-	20.4
38	Togwotee Pass, Wyo.	-2.8	5.64	2.29	6.4	1.6	2.1	0.9	5.3	1.2	4.7	6.7	0.5	3.8	-	19.2
39	Twenty-one Mile, Wyo.	-5.5	5.33	4.68	2.5	0.8	0.9	<0.5	6.8	1.2	3.0	7.9	0.3	2.6	-	12.9
40	Andrews Buttress, Colo.	-9.8	5.10	7.94	10.4	2.4	2.1	0.8	4.1	1.6	5.5	17.1	0.5	1.5	-	6.8
41	Arapaho Creek, Colo.	-18.5	4.82	15.14	7.4	1.6	2.3	0.7	2.2	1.3	5.0	21.2	0.6	1.4	-	3.2

Table 1. Alkalinity and laboratory pH; concentrations of major ions, dissolved organic carbon, mercury, and sulfur-34; and ionic charge balances from analysesof the 2002 snowpack. [Alkalinity (Alk), hydrogen (H^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), potassium (K^+), ammonium (NH_4^+), chloride (Cl^-), sulfate (SO_4^{2-}), nitrate (NO_3^-) are in microequivalents per liter; dissolved organic carbon (DOC) values expressed in milligrams per liter. Mercury (Hg) expressed as nanograms per liter from whole-water samples. Sulfur-34 ($\delta^{34}S$), per mil; "–", not analyzed. Ionic balances are percentages. NP, National Park; na, not applicable.]–Continued

Site number shown in figures	Site name	Alk	pH	H^+	Ca^{2+}	Mg^{2+}	Na^+	K^+	NH_4^+	CL-	SO_4^{2-}	NO_3^-	DOC	Hg	$\delta^{34}S$	ionic balance[1,2]
42	Bear Lake, Colo.	-5.1	5.36	4.37	13.4	2.4	1.9	1.3	7.3	1.2	8.2	16.0	0.8	3.2	-	9.4
43	Berthoud Pass, Colo.	-6.3	5.23	5.89	10.4	1.6	2.4	0.7	3.6	2.8	4.8	13.4	0.6	3.1	-	7.9
44	Brumley, Colo.	21.5	6.37	0.43	31.9	9.8	1.1	7.1	<0.5	1.7	5.9	10.5	3.4	6.4	-	11.9
45	Buffalo Pass, Colo.	-8.9	5.17	6.76	11.4	2.4	1.8	0.6	5.7	1.1	9.3	15.2	0.5	2.0	7.0	5.6
46	Cameron Pass, Colo.	-6.1	5.29	5.13	10.9	2.4	3.6	0.8	4.0	1.6	8.0	12.6	0.6	2.6	-	9.4
47	Culebra, Colo.	6	6.00	1.00	21.4	2.4	2.9	2.1	6.3	1.5	8.1	15.9	0.7	3.9	5.2	6.8
48	Deadman Pass, Colo.	-6.6	5.38	4.17	13.9	2.4	2.7	1.4	6.6	1.3	9.5	16.0	1.0	5.8	-	7.5
49	Dry Lake, Colo.	-16.8	4.85	14.13	8.9	2.4	3.1	0.7	6.3	2.2	8.8	21.5	0.3	0.9	-	4.4
50	Dunckley Pass, Colo.	-2.1	5.58	2.63	12.9	2.4	1.2	1.9	3.8	1.0	6.9	14.0	0.7	4.0	-	6.3
51	Elk River, Colo.	-7.3	5.27	5.37	12.4	2.4	6.6	<0.5	5.6	2.3	9.8	16.2	0.3	1.5	-	6.7
52	Forest Canyon Pass, Colo.	-6.4	5.23	5.89	9.4	1.6	0.9	0.9	2.8	1.1	5.8	12.3	0.8	6.3	-	5.6
53	Fremont Pass, Colo.	-1.9	5.58	2.63	10.4	1.6	<0.5	1.5	1.9	1.1	3.3	9.8	0.7	3.0	-	11.9
54	Grand Mesa, Colo.	25.5	6.40	0.40	34.4	5.7	2.0	3.8	3.7	1.9	7.4	15.7	1.6	9.4	-	-0.5
55	Green Ridge, Colo.	32.7	6.64	0.23	41.9	14.8	2.7	6.9	4.5	1.7	8.2	23.2	0.7	1.8	-	3.8
56	Halfmoon Creek, Colo.	2.9	5.78	1.66	19.9	4.1	1.7	1.9	3.3	1.6	6.9	15.0	1.9	3.6	-	10.4
57	Lake Irene Forest, Colo.	-1.9	5.61	2.48	16.9	2.4	1.9	1.0	5.1	1.3	7.3	14.6	0.5	2.9	-	12.6
58	Lake Irene Meadow, Colo.	-7.05	5.23	5.89	10.9	1.6	1.4	0.6	3.7	1.2	5.9	14.5	0.3	0.9	-	5.6
59	Lizard Head Pass, Colo.	51.5	6.74	0.18	41.4	3.2	2.1	2.3	3.7	1.5	5.5	13.4	0.7	3.8	4.3	-15.2
60	Loch Vale Forest, Colo.	-7.1	5.21	6.17	13.4	2.4	2.1	0.9	5.7	1.6	7.8	19.2	0.7	3.8	-	3.5
61	Loveland Pass, Colo.	0.0	5.72	1.91	24.9	7.4	4.7	0.7	6.1	6.9	7.4	24.5	0.7	2.8	-	8.2
62	Lynx Pass, Colo.	-11.8	5.04	9.12	9.9	1.6	1.6	<0.5	3.5	1.0	5.6	16.6	0.4	1.0	-	5.2
63	Molas Lake, Colo.	15.8	6.33	0.47	25.4	2.4	3.7	1.2	2.5	3.6	4.3	10.7	0.3	3.6	4.7	1.8
64	Monarch Pass, Colo.	30.4	6.47	0.34	51.4	6.5	2.8	3.8	5.7	3.0	8.2	22.8	1.8	9.6	5.8	4.5
65	Niwot SNOTEL, Colo.	-5.9	5.22	6.03	14.9	3.2	1.8	2.4	10.8	1.7	9.6	20.4	1.8	3.3	-	10.5
66	Phantom Valley, Colo.	-15.9	4.90	12.59	7.4	1.6	1.7	0.6	5.2	1.1	7.4	19.0	0.4	1.1	-	2.8
67	Rabbit Ears, Colo.	-13.2	5.02	9.66	7.4	2.0	1.2	0.6	5.1	1.1	8.2	14.3	0.6	1.4	8.0	4.8
68	Red Mountain Pass, Colo.	36.8	6.51	0.31	37.9	3.2	2.9	1.3	3.5	2.7	5.1	13.6	0.5	4.6	4.9	-8.5
69	Slumgullion Pass, Colo.	42	6.52	0.30	45.4	4.9	2.6	3.3	2.4	2.2	6.5	12.8	1.2	6.5	4.3	-3.8
70	Sunlight Peak, Colo.	38.7	6.47	0.34	49.4	4.1	1.6	1.2	5.3	1.2	6.7	14.2	0.5	3.7	5.7	0.9
71	University Camp, Colo.	0.5	5.71	1.95	15.4	2.4	1.0	1.6	11.3	1.0	7.7	16.2	0.9	2.1	-	14.0
72	Vallecito, Colo.	17.35	6.30	0.50	28.7	4.9	2.5	6.1	<0.5	2.3	8.1	15.0	2.3	6.2	4.7	-0.1
73	Wolf Creek Pass, Colo.	3.7	5.91	1.23	22.9	3.2	2.6	3.2	3.7	2.3	8.1	15.4	1.2	6.0	4.8	11.1
74	Hopewell, N. Mex.	2.8	5.81	1.55	24.4	4.1	2.9	1.4	5.0	2.4	8.3	17.4	0.5	3.6	5.4	12.0
75	Taos Ski Valley, N. Mex.	8.7	5.95	1.12	29.4	4.1	4.0	4.4	7.1	3.2	12.7	20.1	1.8	11.9	5.2	5.7
	Summary statistics															
	minimum	-18.5	4.82	0.18	0.5	0.8	<0.5	<0.5	<0.5	<0.5	1.8	2.7	0.1	0.4	4.3	-15.2
	maximum	51.5	6.74	15.14	51.4	14.8	8.2	7.1	13.8	6.9	15.5	24.5	3.4	11.9	8.0	35.0
	mean[3]	-0.2	5.38	4.2	12.4	2.6	2.2	1.6	5.4	1.5	5.9	11.8	0.7	3.7	5.8	10.8
	standard deviation	14.0	na	3.0	12.5	2.3	1.5	1.5	2.5	1.0	2.7	5.5	0.6	3.0	1.1	8.2

Footnotes: 1 Percentages for ionic balances are mean values of individual annual calculations of charge balance of [(total cations - total anions)/(total cations + total anions)] x 100.

2 Positive alkalinities are included in total anions; negative values are excluded.

3 The mean value for pH is calculated from the mean value of hydrogen ion.

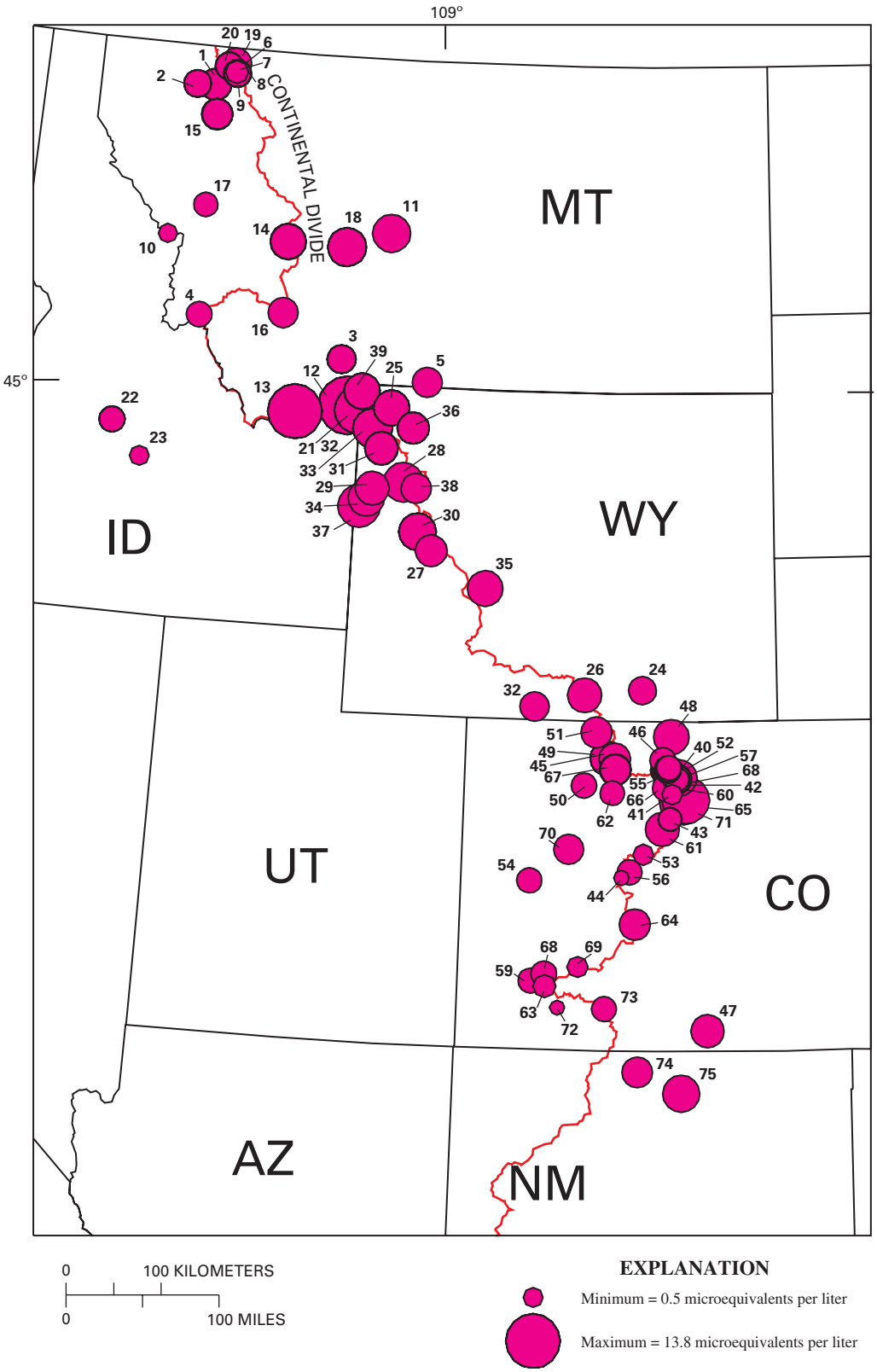

Figure 3. Relative ammonium ion concentrations in snowpacks, 2002.

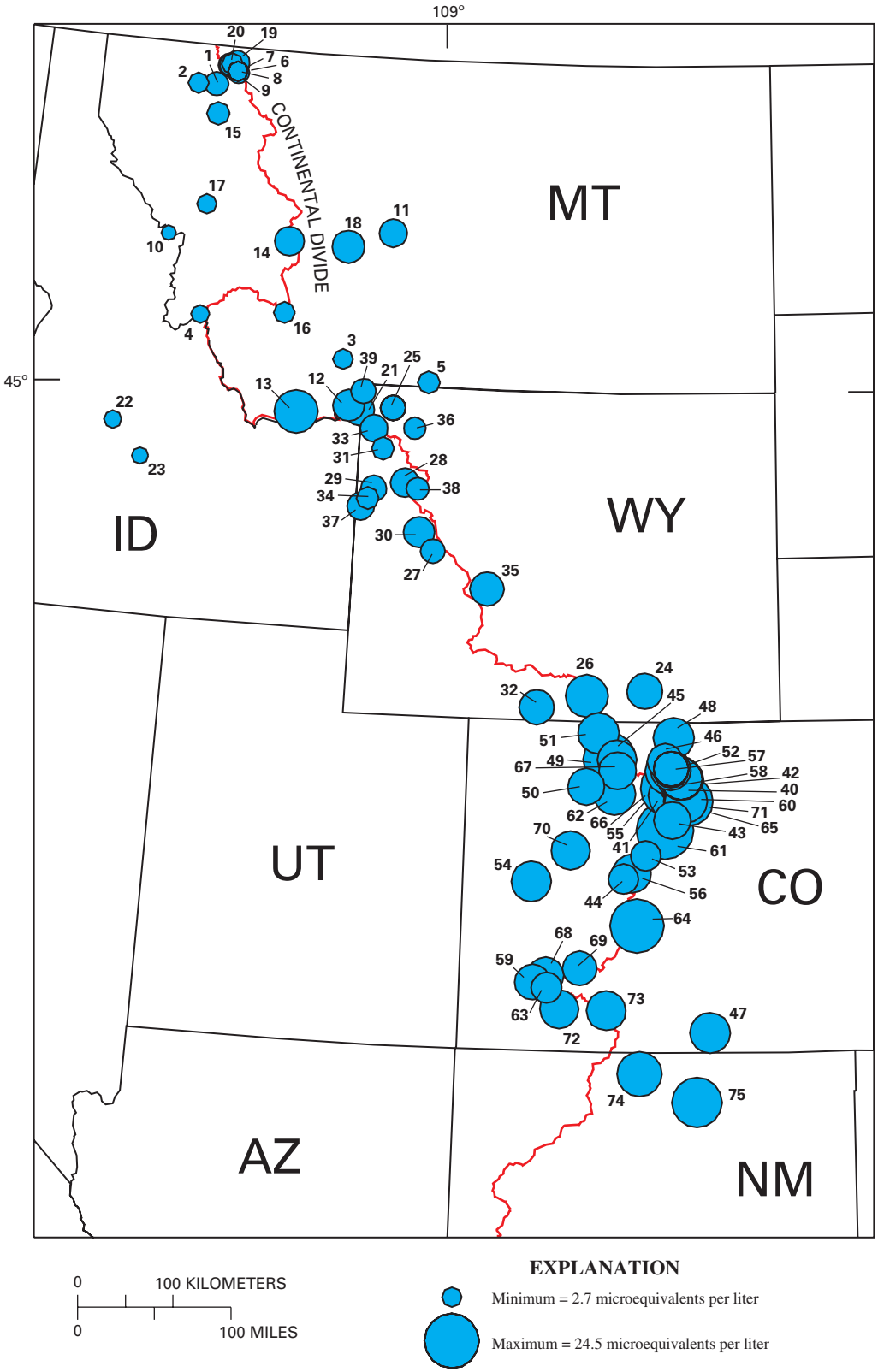

Figure 4. Relative nitrate ion concentrations in snowpacks, 2002.

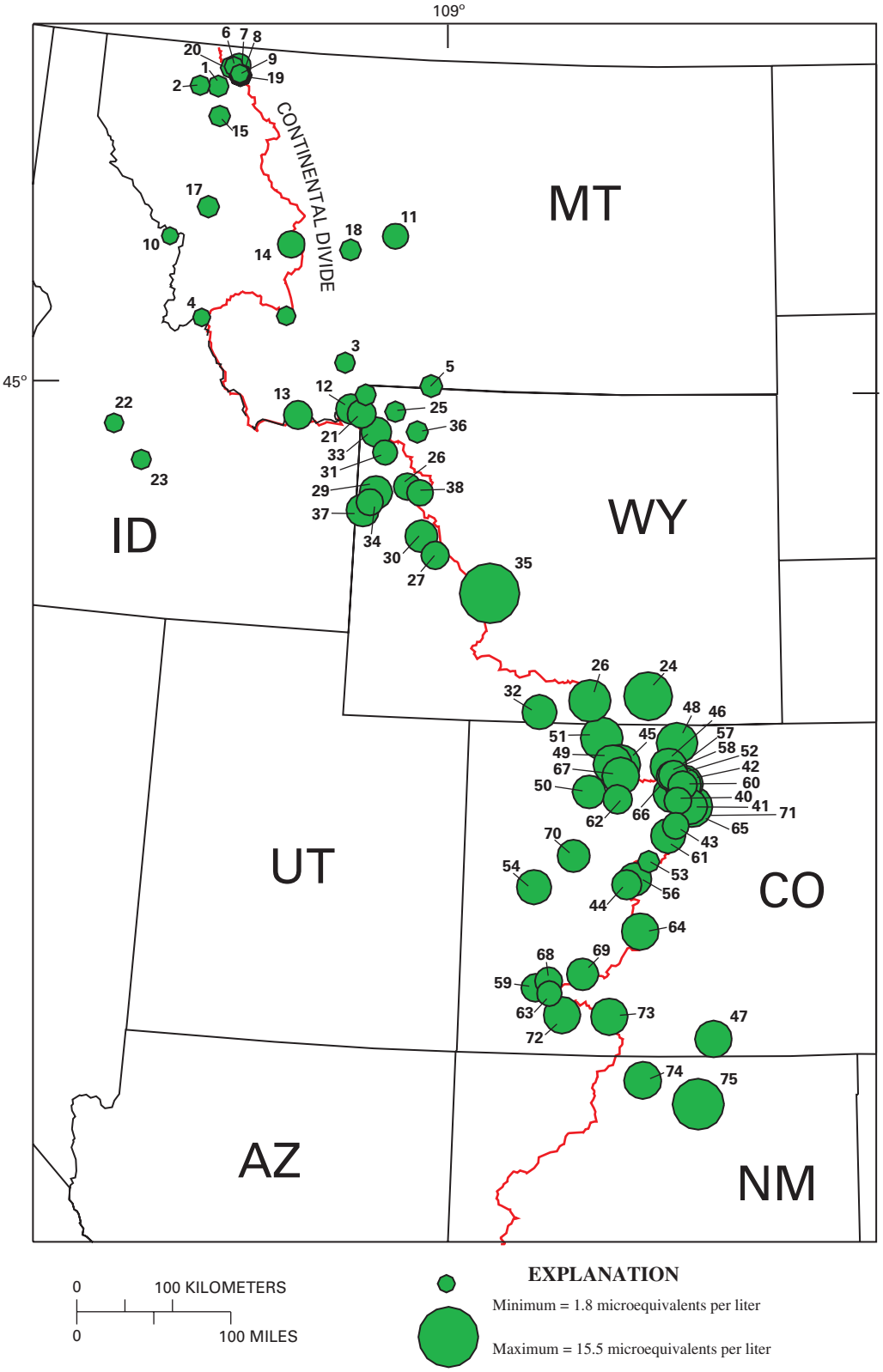

Figure 5. Relative sulfate ion concentrations in snowpacks, 2002.

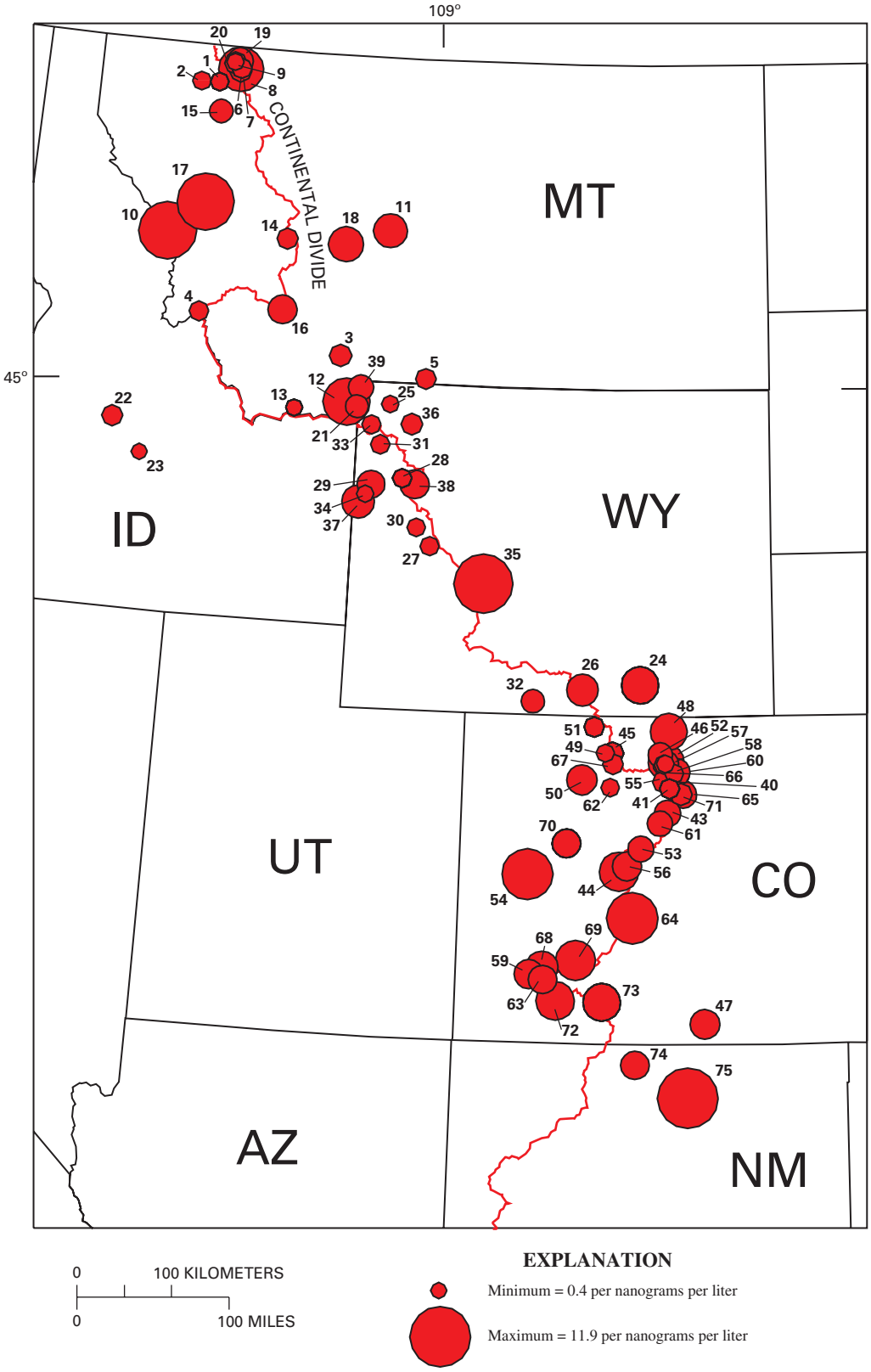

Figure 6. Relative total mercury concentrations in snowpacks, 2002.

yet very useful. The USGS and cooperators in this study have been analyzing total mercury in snow samples only since 2001 (during the period 1993–2000 samples were mostly analyzed for dissolved mercury). Continued monitoring and evaluation of results are needed to better understand patterns in total mercury concentrations in Rocky Mountain snowpacks.

Although the spatial variability of mercury levels found in 2002 is complex, the results are in fair agreement with other determinations of mercury including snowpack- and other precipitation-mercury concentrations in 2001 or recent years. Mercury concentrations detected in the 2001 snowpack in the study area were within a similar range (0.3 to 13.1 ng/L) compared to the 2002 concentrations (0.4 to 11.9 ng/L). Snowpack-mercury concentrations generally may be compared to weekly precipitation-mercury concentrations at sites in the National Atmospheric Deposition Program (NADP) Mercury Deposition Network (MDN) (National Atmospheric Deposition Program (NRSP-3)/Mercury Deposition Network, 2002). Precipitation samples were collected weekly during winter and early spring at four MDN sites within about 600 kilometers of snow-sampling sites in the study area as part of the Mercury Depositon Network. The MDN site nearest to snowpack sampling sites is located in the Rocky Mountain region at Buffalo Pass, Colorado (45); the three other sites are located in western Washington State, southeastern Alberta, and southern New Mexico. At the Buffalo Pass MDN site, concentrations from October through April during years 1998–2002 typically ranged from 1 to 19 nanograms per liter. Although MDN samples were collected using an automated collector with different methods than those used for snowpack sampling, mercury concentrations were similar to concentrations detected in snowpacks in the study area during 2001 and 2002. This suggests that composite snowpack samples may be reasonable alternatives to weekly sampling from MDN collectors. A fifth MDN site about 30 kilometers south of the Canyon, Wyoming, snow-sampling site (25) was created and began reporting a similar range of mercury concentrations (6.1 to 17.0 ng/L) in February 2002 near Yellowstone Lake in northwestern Wyoming. Mercury concentrations detected at the MDN site in southern New Mexico during the snowfall seasons of 2001 and 2002 were several times greater than many concentrations detected in snow samples in the Rocky Mountain region. However, the highest mercury concentration detected in 2002 snowpacks was at Taos Ski Valley in northern New Mexico.

Stable sulfur isotope ($\delta^{34}S$) ratios were determined at a subset of 20 sites in the region (fig. 7, table 1). $\delta^{34}S$ ratios ranged from 4.3 to 8.0 per mil and exhibited a regional pattern with the lightest $\delta^{34}S$ ratios clustered in southern Colorado and the heaviest values in northern Colorado and Wyoming. The light $\delta^{34}S$ ratios of 4.3 to 5.3 at sites in southern Colorado and northern New Mexico indicate sulfate in atmospheric deposition at the southern end of study area may have been derived from different sources than the rest of the study area. Results for $\delta^{34}S$ ratios from this study are consistent with previous work (Ingersoll, 1995; Mast and others, 2001).

Quality Assurance

Laboratory blanks, field blanks, and field- or laboratory replicates comprised about 10 to 21 percent of sample processing depending upon constituent. Additional laboratory aliquots of barium sulfate precipitate were analyzed for determination of replicate $\delta^{34}S$ ratios. Ionic-charge balances were computed as a measure of the quality of the chemical analyses for major ions (table 1).

Five laboratory blanks were analyzed testing the quality of the sample-processing equipment and DI water used during analyses. Field blanks were collected at seven snow-sampling sites by rinsing sampling tools with DI into Teflon bags after collecting snow samples. Concentrations of all blanks were less than or equal to detection limits of major ions (< 1 μeq/L) and dissolved organic carbon (0.2 mg/L), and the mean total mercury concentration in blanks (0.4 ng/L) was higher than the detection limit (0.1 ng/L).

Seven replicate snow samples were collected at snow-sampling sites for evaluation of sampling precision. Six were collected from the same snowpit face as the original samples at six sites around the network. The seventh replicate, at Rabbit Ears Pass, Colorado, was collected from a second snowpit 10 m away from the original snowpit. Correlations of analytical results for major ions, pH, alkalinity, and dissolved organic carbon between original and replicate snow samples averaged 0.98. Five snow-sample replicates were analyzed for total mercury, and each compared favorably to original results (R2 = 0.98). Differences between two pairs of original- and laboratory-replicate samples for determination of $\delta^{34}S$ values were less than 4 percent.

Ionic charge balance of each major-ion analysis was calculated by dividing the sum of cations (hydrogen ion, calcium, magnesium, sodium, potassium, and ammonium) minus the sum of anions (alkalinity, chloride, nitrate, and sulfate) by the total cations and anions in solution. Ion balances calculated for the 2002 snow chemistry were mostly positive with a mean value of +10.8 percent, indicating an excess of measured cations over anions in solution. Other ionic balances calculated for precipitation chemistry of comparable ionic strength in a separate network yielded similar deviations (National Atmospheric Deposition Program, 1993). One possible explanation for the positive bias of the ionic balances (table 1) is that organic acids were not included in the calculation. Organic acids such as acetate and formate have been detected in snow in the region in earlier work, with mean concentrations of 1.2 microequivalents per liter and 0.6 microequivalent per liter (Turk and others, 2001).

Summary and Conclusions

The 2002 snowfall season was much drier than usual in most of the study area with snow depths below the 1993–2000 average; snow-water equivalent in annual snowpacks sampled

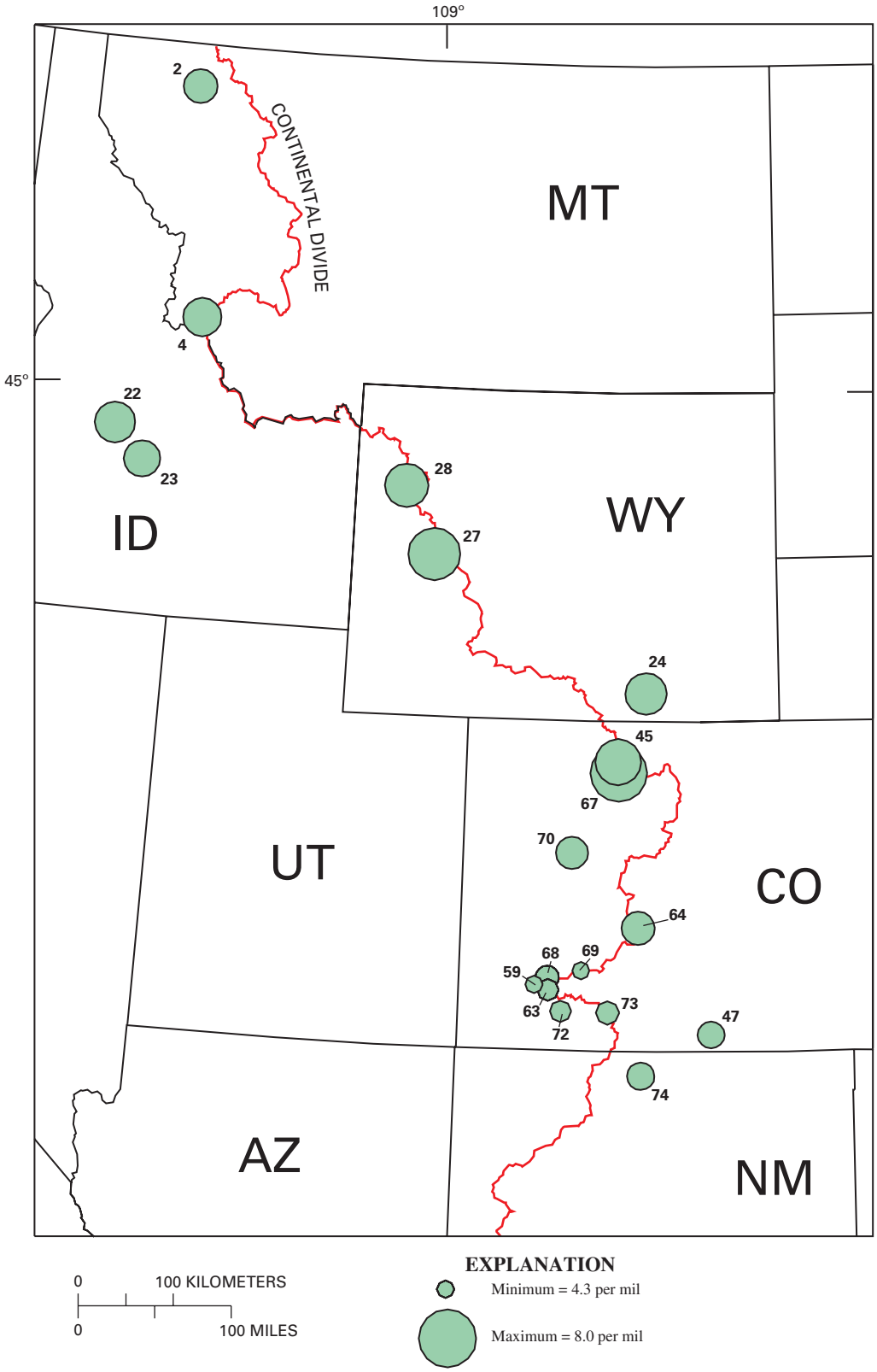

Figure 7. Relative stable sulfur isotope ratios in snowpacks, 2002.

generally was below average to much below average in most of the region. Compared to the 2001 snowpacks, which also were products of a drier-than-usual year, the 2002 snowpacks yielded noteworthy regional patterns in the concentrations of ammonium, nitrate, sulfate, mercury, and the ratio of stable sulfur isotopes. Ammonium concentrations increased in 2002 at 66 percent of snow-sampling sites in Montana compared to concentrations in the 2001 snowpack but decreased at 74 percent of sites sampled in Wyoming, Colorado, and New Mexico. Nitrate decreased at all sites in Montana and at all but one site in Wyoming and increased at all but two Colorado sites and increased at all New Mexico sites. Sulfate concentrations were lower across the region at 77 percent of the sites. The range of mercury concentrations for the region was similar to that of 2001 but showed more complex spatial variability than ammonium, nitrate, and sulfate concentrations. Snowpack total mercury also compared reasonably well to total mercury in precipitation samples in the Mercury Deposition Network. Concentrations of stable sulfur isotope ratios exhibited a distinct regional pattern with the range of values increasing northward from southern Colorado to northern Colorado and Wyoming. This finding is consistent with previous work suggesting isotopically distinct sulfur sources exist in the region and are likely related to sulfate concentrations in snowpacks.

Data presented in this report suggest reductions in concentrations of ammonium and nitrate occurred in large areas of the region, yet increases in concentrations of these constituents in opposite areas of the region happened during 2002. The clearest regionwide decrease appears to be in sulfate concentrations. If reductions in emissions of sulfur dioxide from developed areas and power-production facilities continue to occur nationally, downward trends in regional concentrations of sulfate concentrations should be reflected in annual snowpack chemistry. Such results would be particularly meaningful in areas where costly emissions-reductions programs are enacted, such as at coal-fired powerplants or large urban centers. Continued monitoring of nitrogen and the mercury concentrations in Rocky Mountain ecosystems also will be important as the region becomes increasingly developed.

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