Prepared in cooperation with the Vermont Geological Survey

Surface Gamma-Ray Survey of the Barre West Quadrangle, Washington and Orange Counties, Vermont

Scientific Investigations Report 2005–5276

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

Cover: Geofyzika GS–512 portable gamma-ray spectrometer.

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Conversion Factors

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Volume	
cubic meter (m^3)	0.0008107	acre-foot (acre-ft)

Surface Gamma-Ray Survey of the Barre West Quadrangle, Washington and Orange Counties, Vermont

By Gregory J. Walsh and Aaron M. Satkoski[1]

INTRODUCTION

This study was designed to determine the levels of naturally occurring radioactivity in bedrock from surface measurements at outcrops during the course of 1:24,000-scale geologic mapping and to determine which rock types were potential sources of radionuclides.

Elevated levels of total alpha particle radiation (gross alpha) occur in a public water system in Montpelier, Vermont. Measured gross alpha levels in the Murray Hill water system (Vermont Dept. of Environmental Conservation, unpub. data, 2005) have exceeded the maximum contaminant level of 15 picocuries per liter (pCi/l) set by the Environmental Protection Agency (EPA) (EPA, 2000). The Murray Hill system began treatment for radium in 1999. Although this treatment was successful, annual monitoring for gross alpha, radium, and uranium continues as required (Jon Kim, written communication, 2005). The water system utilizes a drilled bedrock well located in the Silurian-Devonian Waits River Formation. Kim (2002) summarized radioactivity data for Vermont, and aside from a statewide assessment of radon in public water systems (Manning and Ladue, 1986) and a single flight line from the National Uranium Resource Evaluation (NURE) (Texas Instruments, 1976) (fig. 1), no data are available to identify the potential sources of naturally occurring radioactivity in the local bedrock.

Airborne gamma-ray surveys are typically used for large areas (Duval, 2001, 2002), and ground-based surveys are more commonly used for local site assessments. For example, ground-based surveys have been used for fault mapping (Iwata and others, 2001), soil mapping (Roberts and others, 2003), environmental assessments (Stromswold and Arthur, 1996), and mineral exploration (Jubeli and others, 1998). Duval (1980) summarized the methods and applications of gamma-ray spectrometry.

In this study, we present the results from a ground-based gamma-ray survey of bedrock outcrops in the 7.5-minute Barre West quadrangle, Vermont. Other related and ongoing studies in the area are addressing potential mineral sources of radionuclides (Satkoski and Walsh, 2004; Satkoski and others, 2005), radionuclides in ground water (Kim and others, 2005), and bedrock geology.

METHODS

Data were collected with a Geofyzika 512-channel portable gamma-ray spectrometer (GS-512) with a sodium iodide, thallium-activated scintillation probe.

The primary natural sources of gamma radiation come from radioactive decay of the radioisotopes ^{40}K, ^{232}Th, ^{235}U, and ^{238}U (Adams and Gasparini, 1970). The GS-512 measures total counts for eight regions of interest (ROIs), compares the ROIs to stored calibration constants, and calculates values for potassium in percent (K%) and equivalent uranium (eU) and equivalent thorium (eTh) values in parts per million (ppm). In April 2003, the GS-512 was calibrated for ^{238}U, ^{232}Th, and ^{40}K at the Eastern Mineral Resources calibration facility of the USGS in Reston, Virginia, with assistance from Joseph S. Duval.

During the summer of 2003, 493 data points were collected at outcrops throughout the Barre West quadrangle. Two detailed transects were conducted at two roadcuts along Interstate 89 at Exits 7 and 8 to identify outcrop-scale differences in gamma radiation emissions.

In the initial phase of this investigation, the scintillation probe was mounted on a tripod with the probe's base 0.5 m above the outcrop surface in an effort to characterize gamma-ray emissions from a large-diameter area, especially in outcrops that had more than one rock type. Initial findings and detailed transects at two large roadcuts allowed identification of the rocks that were elevated in gamma-ray emissions, and subsequent measurements were made with the probe directly on the outcrop surface (see cover photo). Placing the probe directly on the outcrop surface may reduce the potential masking effects of soil cover (Adams and Gasparini, 1970), because the higher the probe is off the ground the greater likelihood

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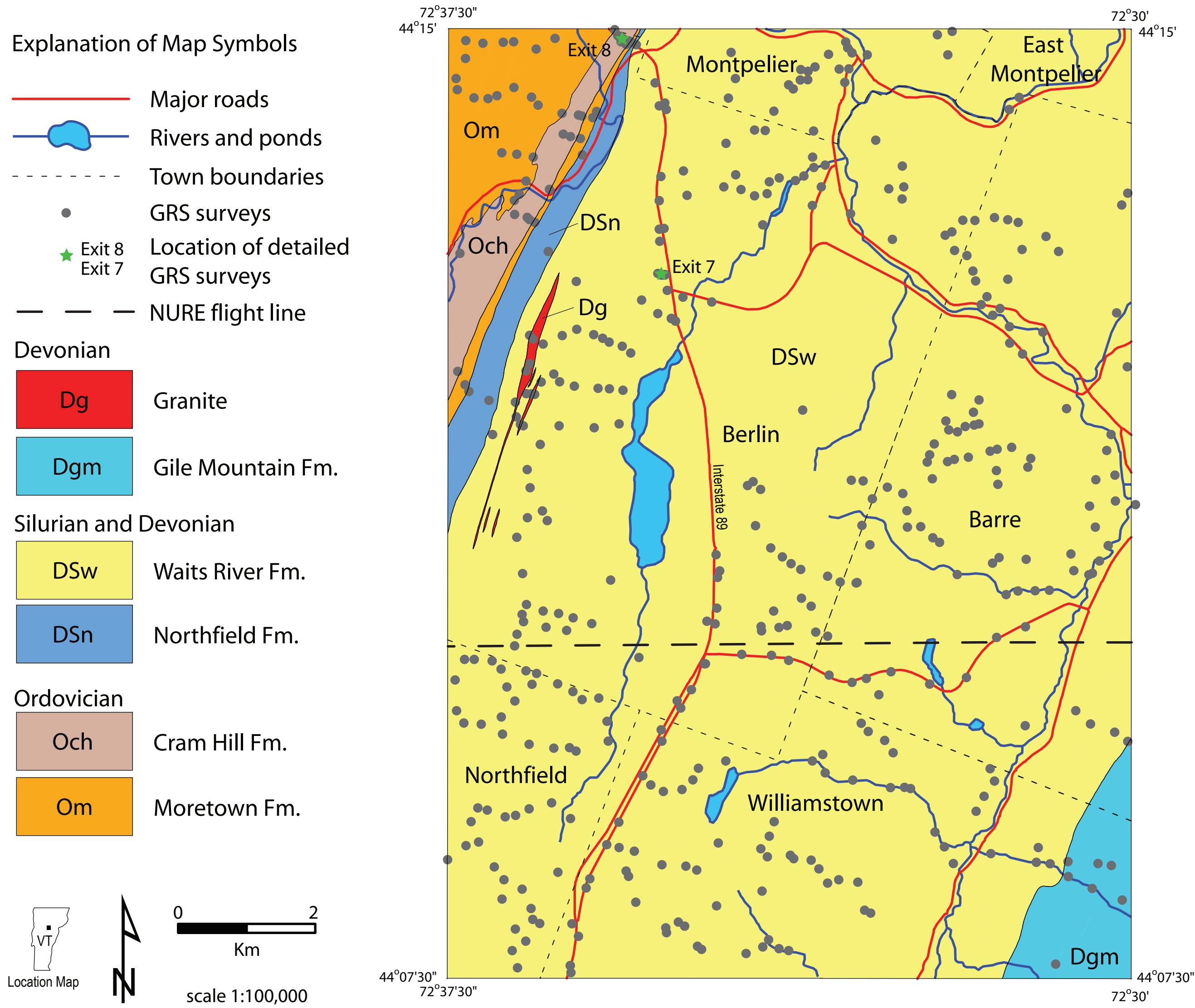


Figure 1. Simplified geologic map of the 7.5-minute Barre West quadrangle (at 1:100,000 scale) showing the locations of gamma-ray survey (GRS) stations and detailed GRS surveys at Exits 7 and 8 on Interstate 89. Geology modified after Doll and others (1961). STATE-PLANE projection, zone 5526. 1983 North American Datum. Roads and surface water from digital line graph (DLG) data obtained from the Vermont Center for Geographic Information (www.vcgi.org).

that measurements may extend beyond the immediate area of clean, exposed bedrock. Rock type at each measurement location is included in the database.

GEOLOGIC SETTING

The Barre West quadrangle is largely underlain by Silurian to Devonian metasedimentary rocks of the Connecticut Valley synclinorium, including the Northfield, Waits River, and Gile Mountain Formations (fig. 1). The northwest part of the quadrangle is underlain by Ordovician metasedimentary and metavolcanic rocks of the Cram Hill and Moretown Formations (fig. 1). Devonian granite intrudes the rocks of the Connecticut Valley synclinorium (fig. 1). Glacial overburden covers most of the bedrock in the area. Till covers the bedrock in the upland areas and glacial lacustrine and modern alluvial deposits fill the valleys (Wright, 1999). Exposed bedrock in the upland areas occupies approximately 5 percent of the total area of the quadrangle.

RESULTS

Outcrop-Scale Surveys

Two outcrop-scale surveys were completed at roadcuts located at Exits 7 and 8 of Interstate 89 (fig. 1).

Exit 7

The Exit 7 roadcut is located in the Waits River Formation and consists of subvertical, north-northeast striking, interbedded dark-gray carbonaceous sulfidic quartz-muscovite phyllite and impure siliceous limestone, with bed thickness ranging from 0.15 to 8 m. Forty-three measurements in the center of each alternating phyllite and metalimestone bed over a 58-m-thick section show consistently higher radioactivity in the phyllite beds (fig. 2). The phyllite beds (n=22) average 2.9% ^{40}K, 3.1 ppm eU, 11.3 ppm eTh. The metalimestone beds (n=21) average 1.3% ^{40}K, 1.5 ppm eU, 5.2 ppm eTh. The data also indicate that measured concentrations are locally dependent on bed thickness because the probe's 30-cm-diameter zone of detection exceeds the thickness of some beds. Thus, measurements of beds thicker than 30 cm represent the concentrations of the radionuclides in each rock type, while thinner (<30 cm) phyllite beds yield lower values due to the detection of adjacent, less radioactive limestone beds.

Exit 8

The Exit 8 roadcut is located in the Cram Hill Formation and consists of subvertical, north-northeast striking, interlayered rusty weathering silver-gray to dark-gray locally carbonaceous and sulfidic quartz-muscovite phyllite and micaceous feldspathic quartzite. Quartzite lenses locally measure up to 3m thick but are generally less than 0.3m thick. The Cram Hill Formation is highly sheared at this roadcut, and bedding is typically transposed. Thirteen measurements over an approximately 200-m-thick section show consistently higher radioactivity in the phyllite beds (fig. 3).

Quadrangle-Scale Results

Quadrangle-scale data include results by rock type, comparison of natural versus manmade outcrops, and concentration maps.

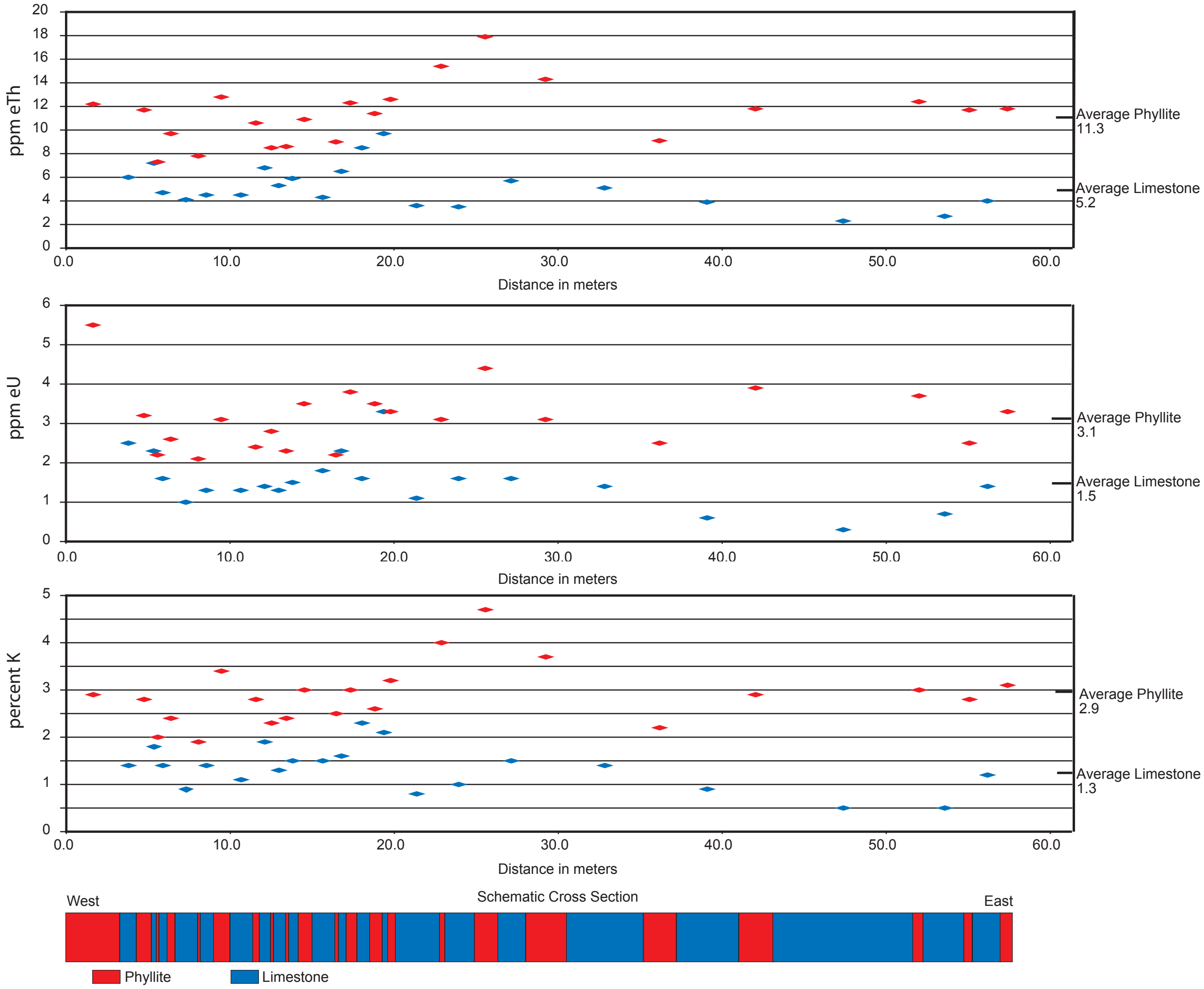
Results by Rock Type

Results by rock type are summarized in figure 4. Rocks with the highest values of K, eU, and eTh include the phyllites of the Waits River, Cram Hill, Northfield, and Gile Mountain Formations. All of the phyllites are carbonaceous and locally sulfidic. The phyllites of the Cram Hill Formation generally do not contain as much graphite as the other phyllites, and carbonaceous matter in the Cram Hill phyllite is not as uniformly distributed as it is in other phyllites. The likely protolith for all of the phyllites was black shale deposited in anoxic conditions. Minerals that may be potential sources of uranium and thorium include monazite as the primary source and apatite and pyrite as secondary sources (Satkoski and others, 2005). Other potential sources of uranium and thorium may include sphene, zircon, allanite, pyrochlore, thorite, uraninite, and xenotime (Duval, 2001). Potential sources of potassium include muscovite and biotite (Duval, 2001). The phyllites have been regionally identified as having moderate to high radon potential (Gundersen and Schumann, 1993), although Manning and Ladue (1986) found no positive correlation between phyllites and radon concentrations in public water supplies in the Connecticut Valley synclinorium, perhaps in part because their database was not rock type or formation specific. Rocks with the lowest measured values of K, eU, and eTh include quartz veins, greenstone, Waits River Formation quartzite, and Moretown Formation granofels (fig. 4).

Natural versus Roadcut Outcrops

An evalution of the quadrangle-scale data indicates that the highest values of K, eU, and eTh come from outcrops in phyllite of the Waits River and Cram Hill Formations. Twenty-two of the highest 25 values of eU come from Waits River Formation phyllite. Of the highest 25 K values, 17 (68%) are from manmade outcrops, such as roadcuts, and 8 are from natural outcrops. Twenty-one (84%) of the highest 25 eU values are from roadcuts, and 20 (80%) of the highest 25 eTh values are also from roadcuts. The high number of roadcuts in this part of the database is not representative of the data as a whole because only 167 (34%) of the 493 gamma-ray stations were located on roadcuts. These data suggest that fresh, less-weathered outcrops emit higher levels of gamma radiation than natural, weathered outcrops, although there is considerable overlap in the data distributions (fig. 5). Statistics on all measurements from phyllite in the Wait River Formation (n=352) as a function of natural (n=259) versus roadcut (n=93) outcrops confirm these findings (fig. 5).

The weathering of the pyrite in the sulfidic phyllites is a likely contributor to the acidic and oxidizing conditions of fresh bedrock. Schumann and others (1995, p. 112) report, "sulfide-bearing shales can produce acidity, sufficient to release significant amounts of uranium to throughflowing surface and ground water." Leaching of uranium is therefore likely in sulfidic rocks and has been reported elsewhere (Schumann and others, 1995; Hills, 1979). According to Adams and Gasparini (1970), both U and Th occur in the tetravalent state and remain stable in reducing conditions. Under oxidizing conditions, however, Th remains in the tetravalent state, but U is oxidized to the hexavalent state and is more soluble in an aqueous environment. Focazio and others (2001) state that ^{238}U is relatively more soluble than Th. According to Focazio and others (2001, p. 5), Zapecza and Szabo



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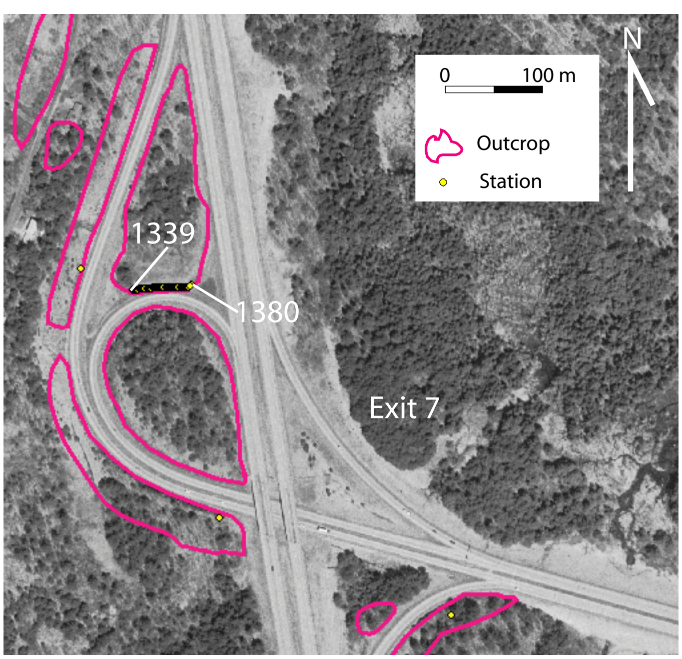

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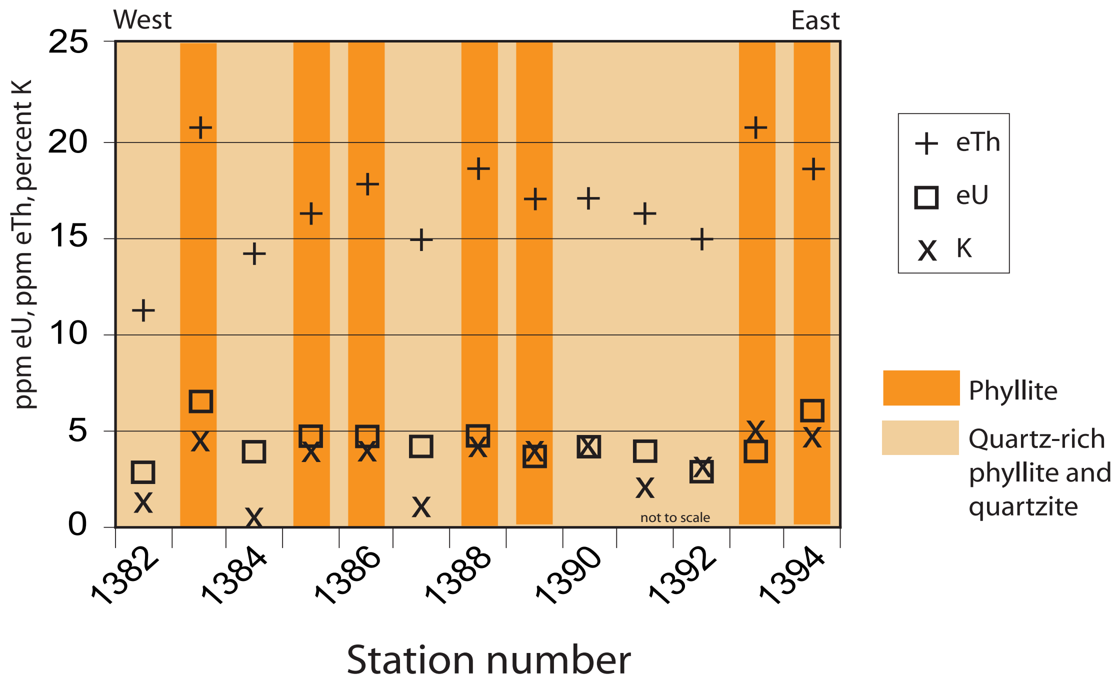
Figure 2. *A*, Graphs of potassium in percent (percent K), equivalent uranium in parts per million (ppm eU), and equivalent thorium in parts per million (ppm eTh) from a detailed gamma-ray survey across interbedded phyllite and limestone of the Waits River Formation at Exit 7 on Interstate 89. The survey was conducted generally from west to east across a 58-m-thick, subvertical section. *B*, Orthophotograph showing the location of the survey stations, including the start and end points and outcrops; photograph from www.vcgi.org.



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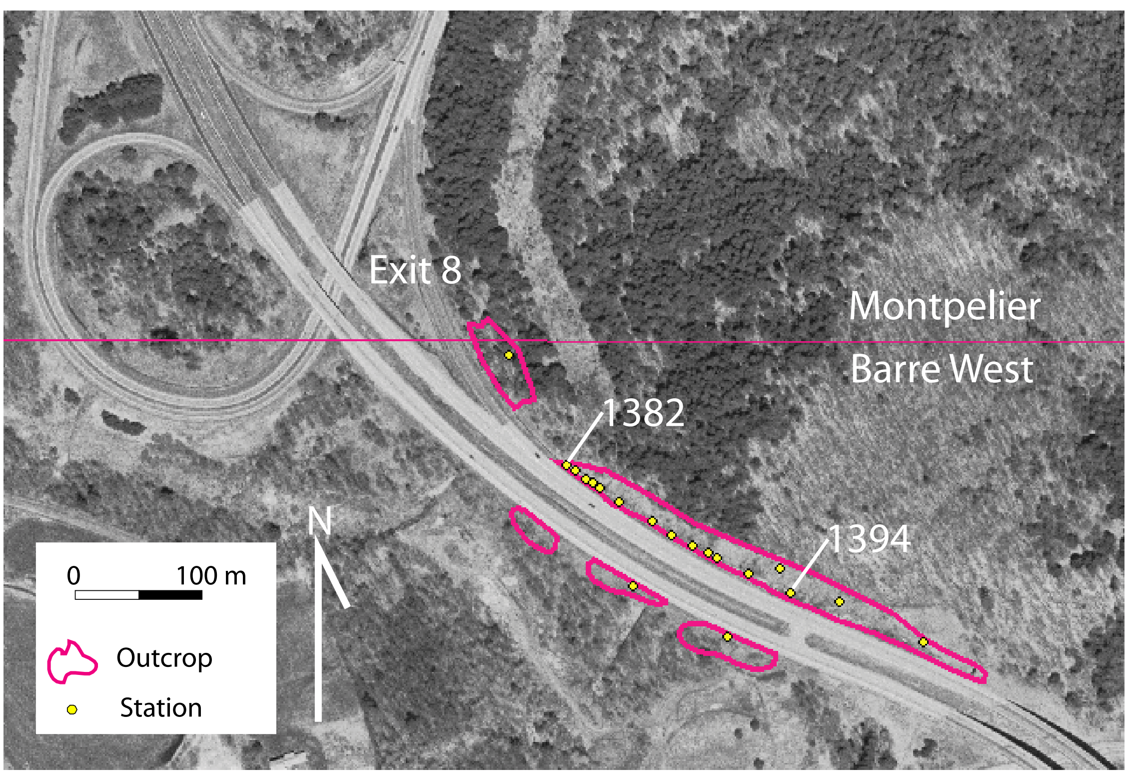
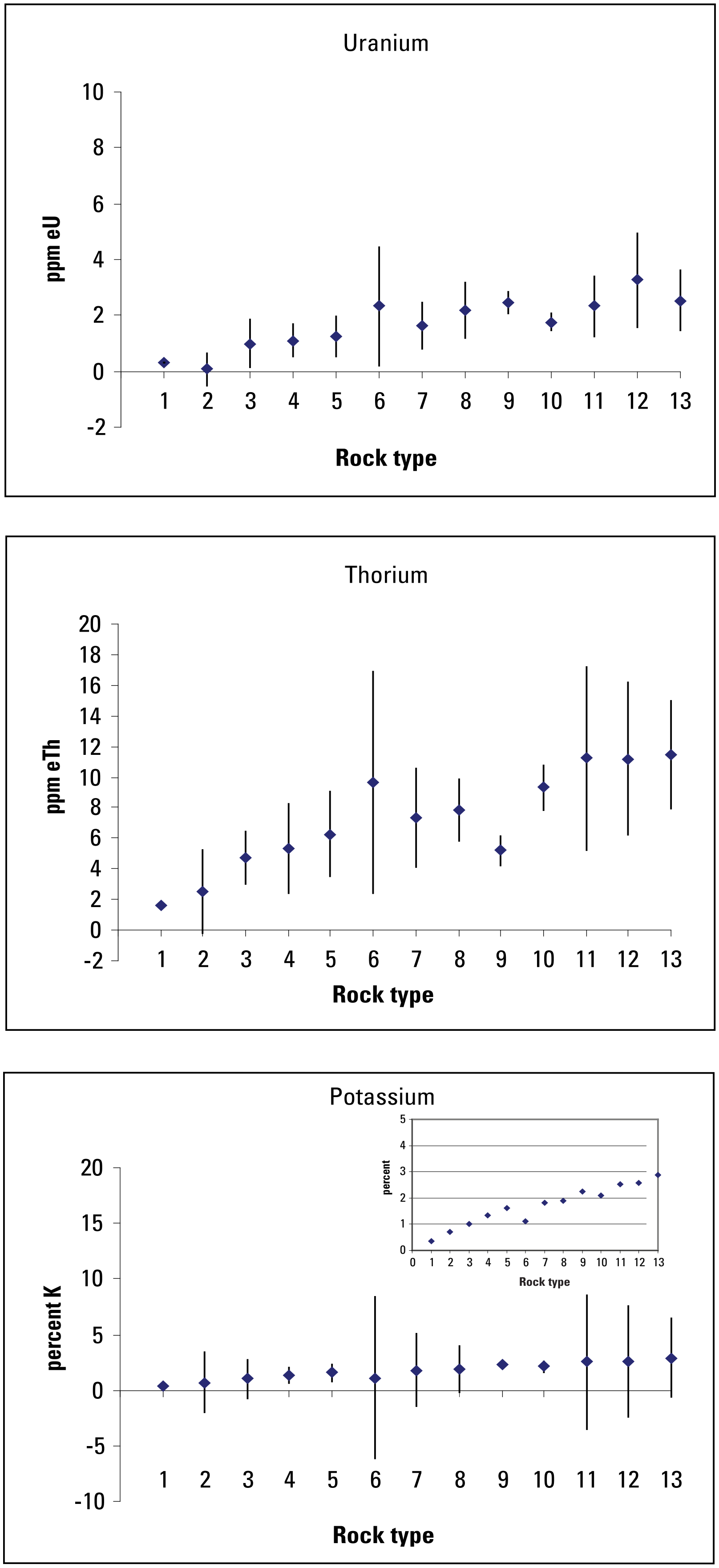


B

Figure 3. *A*, Graph of potassium in percent (percent K), equivalent uranium in parts per million (ppm eU), and equivalent thorium in parts per million (ppm eTh) from a gamma-ray survey across interlayered phyllite and quartz-rich phyllite and quartzite of the Cram Hill Formation at Exit 8 on Interstate 89. The survey was conducted generally from west-northwest to east-southeast across an approximately 200-m-thick subvertical section. *B*, Orthophotograph showing the location of the survey stations including start and end points, outcrops, and the boundary between Barre West and Montpelier quadrangles; photograph from www.vcgi.org.



1 - Quartz vein (2)
2 - Moretown Fm. greenstone (7)
3 - Waits River Fm. quartzite (2)
4 - Waits River Fm. limestone (24)
5 - Moretown Fm. granofels (25)
6 - Cram Hill Fm. quartzite (3)
7 - Waits River Fm. phyllite and limestone (55)
8 - Diabase dike (3)
9 - Granite (4)
10 - Gile Mountain Fm. phyllite (6)
11 - Northfield Fm. phyllite (3)
12 - Cram Hill Fm. phyllite (7)
13 - Waits River Fm. phyllite (297)

Figure 4. Mean percent potassium (K), equivalent uranium in parts per million (ppm eU), and equivalent thorium in parts per million (ppm eTh) by rock type. Numbers in parentheses for each of 13 rock categories indicate the number of measurement points in each category. Inset graph on mean potassium plot shows detailed means without error bars. Rock type category 7 includes phyllite and limestone where they are interlayered within the detection limit of the probe when it was placed directly on the ground (30 cm). Vertical error bars are ± 1 sigma; negative values on the error bars are calculated.

Potassium (K)

Outcrop	N	Mean	SD	Max	Min
Roadcut	93	3.08	1.05	5.9	0.7
Natural	259	2.58	0.84	5.4	0.4

Separate variance:

Difference in means	=	0.501
95.00% CI	=	0.262 to 0.740
t	=	4.150
df	=	136.8
p-value	=	0.000
Bonferroni adj p-value	=	0.000

Pooled variance:

Difference in means	=	0.501
95.00% CI	=	0.287 to 0.716
t	=	4.602
df	=	350
p-value	=	0.000

Uranium (eU)

Outcrop	N	Mean	SD	Max	Min
Roadcut	93	3.03	1.39	7.1	0.0
Natural	259	2.15	0.85	5.6	0.2

Separate variance:

Difference in means	=	0.875
95.00% CI	=	0.570 to 1.180
t	=	5.682
df	=	117.5
p-value	=	0.000
Bonferroni adj p-value	=	0.000

Pooled variance:

Difference in means	=	0.875
95.00% CI	=	0.632 to 1.118
t	=	7.080
df	=	350
p-value	=	0.000

Thorium (eTh)

Outcrop	N	Mean	SD	Max	Min
Roadcut	93	12.48	4.55	23.8	3.1
Natural	259	10.23	3.26	19.0	1.5

Separate variance:

Difference in means	=	2.239
95.00% CI	=	1.224 to 3.255
t	=	4.364
df	=	127.7
p-value	=	0.000
Bonferroni adj p-value	=	0.000

Pooled variance:

Difference in means	=	2.239
95.00% CI	=	1.373 to 3.106
t	=	5.082
df	=	350
p-value	=	0.000

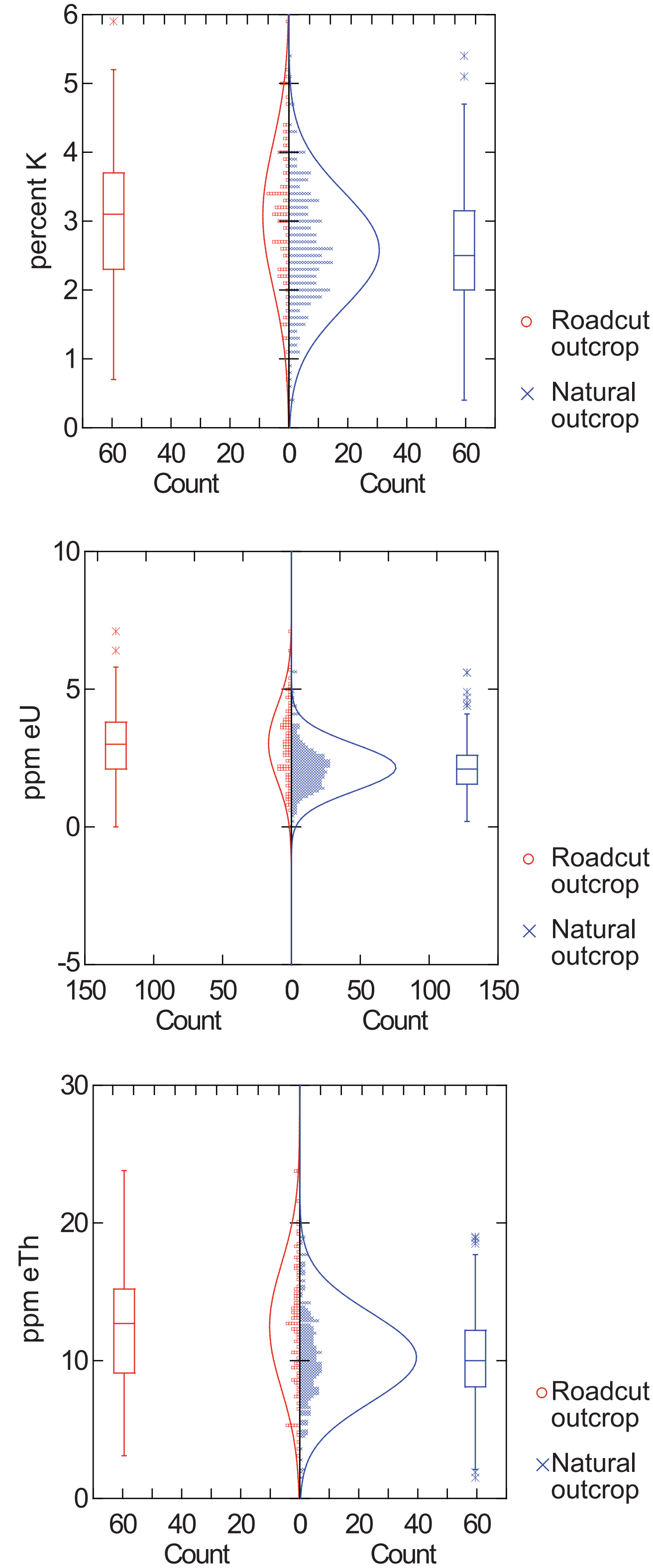


Figure 5. Summary statistics, box plots, histograms, and model normal distributions for roadcut and natural outcrops in phyllite of the Waits River Formation. N, count or number of points in the dataset; SD, standard deviation; CI, confidence interval; t, t statistic; and df, degrees of freedom. In all cases, p-value = 0, so the sample sets are statistically different.

(1987) and Milvy and Cothern (1990) found that "uranium forms soluble complexes particularly with carbonates under oxygen-rich conditions, and precipitates from ground water under oxygen-poor conditions." Hydrolysis of K-bearing micas (Boul and others, 1980), such as muscovite and biotite in the phyllite, may be responsible for the relative reduction of potassium from the fresh roadcuts. Satkoski and others (2005) note a strong correlation between U and Th and phosphate from the phyllite, suggesting that apatite and monazite may be host phases for these elements. While apatite and monazite are generally considered insoluble at surface conditions (Wood, 2003), U and Th may be more mobile in organic-rich soil horizons (Gray, 1998). Alternatively, Adams and Lowder (1964) noted that increased water content in soils can explain why field measurements of U, Th, and K are lower in comparison to laboratory measurements of the same samples. It is possible, therefore, that natural outcrop measurements may be influenced by nearby soil cover to a greater degree than roadcut measurements, which are generally free of soil horizons.

Concentration Maps

Concentration maps of eU, eTh, K, and composite eU-eTh-K were created by calculating grids from the 493 measurements at individual stations (figs. 6, 7, 8). Grids were calculated in ArcMap Spatial Analyst using inverse distance weighting with an optimized power value of 1, search radius of 12 points, and an output cell size of 40 and 500 meters.

Grids were calculated at greatly different cell sizes to test whether the cell size would influence the concentration maps, because the distribution of survey points is not uniform across the map. Generally, the two different cell sizes created overall similar patterns in the resulting concentration maps. Maps created with the 40-meter grid locally show model results that may not be represented by survey points ("bulls eyes"), suggesting that the larger 500-meter grid may represent more accurate model results. Statistics on the distance between survey points indicate that the average minimum distance between points is 492 meters, justifying further the 500-meter grid spacing. Color ramps were divided into 20 classes and based on airborne gamma-ray survey maps by Duval (2002). Concentration maps of eU, eTh, and K show variations in the amounts of U-, Th-, and K-bearing minerals (Duval, 2002). The composite eU-eTh-K map (fig. 9) shows relative differences in the amounts of U, Th, and K in bedrock. Composite maps show amounts of U, Th, and K relative to each element in the survey data but not absolute abundances (Duval, 2002). The composite map was created by first producing grayscale maps for U, Th, and K and then combining the three maps as red, blue, and green bands, respectively. According to Duval (2002), red areas on composite maps show relatively higher concentrations of U, blue areas show relatively higher Th, and green areas show relatively higher K. A comparison between concentration maps for the complete dataset and the dataset without the roadcuts showed virtually the same distribution, so only the maps for the complete dataset are included in this report.

On the concentration maps, it is apparent that rocks of the Waits River Formation show both the highest concentrations and the greatest variability. Geologic contacts superimposed on the composite map (fig. 9) show the Waits River Formation distinctly. Relatively lower concentrations occur in the rocks of the Moretown and Gile Mountain Formations to the northwest and southeast, respectively. Uranium is relatively abundant in the Northfield Formation.

The composite map also shows internal variation in the Waits River Formation that is parallel to the regional strike of the layering and the dominant foliation (approximately N.20°E.) and is irregularly distributed across the strike of the belt. Dashed lines on figure 9 show along-strike variation that is parallel to the compositional layering within the Waits River Formation. During the course of geologic mapping, it was noted that rocks in the western part of the Waits River Formation consist of interbedded phyllite and impure limestone with bed thicknesses that generally range from 0.2 to 3.0 m thick. In the eastern part of the Waits River Formation, generally east of the dashed line that extends the length of the quadrangle, the formation consists of interbedded phyllite and impure limestone with bed thicknesses that generally range from 1.0 to 5.0 m thick and locally up to 9.0 m thick. The eastern part of the formation has relatively uniform abundances of U, Th, and K (white areas) with local relatively higher amounts of K (green areas). The western part of the formation has relatively higher amounts of U (red areas) than the eastern part. The composite map (fig. 9) also shows intriguing cross-strike patterns, particularly in the northeast part of the quadrangle from Barre to Montpelier, subparallel to the river valley along a northwest trend. This trend is similar to a regional fracture trend in the area, but the data here are limited and it is unclear at this time if the trend is related to a regionally trend in the bedrock.

CONCLUSIONS

A ground-based gamma-ray survey of bedrock outcrops at 493 locations in the 7.5-minute Barre West quadrangle, Vermont, indicates the following:

- Rocks with the highest values of K, eU, and eTh include the carbonaceous and sulfidic phyllites of the Waits River, Cram Hill, Northfield and Gile Mountain Formations.

- Rocks with the lowest measured values of K, eU, and eTh include quartz veins, greenstone, Waits River Formation quartzite and limestone, and Moretown Formation granofels.

- The minerals that may be potential sources of uranium and thorium include monazite as the primary source and apatite and pyrite as secondary sources. Muscovite and biotite are the probable sources for potassium.

- A comparison of natural versus roadcut outcrops in the Waits River Formation suggests either that the fresh, less-weathered roadcuts emit higher levels of gamma radiation than the natural, weathered outcrops, or that the natural, weathered outcrop measurements may be influenced by increased water content in nearby soil cover.
- A composite eU-eTh-K map shows quadrangle-scale variations due to the structural trend of the formations and internal variations within the Waits River Formation that is both parallel to the regional strike of the layering and the dominant foliation (approximately N.20°E.) and is irregularly distributed across the strike of the belt.

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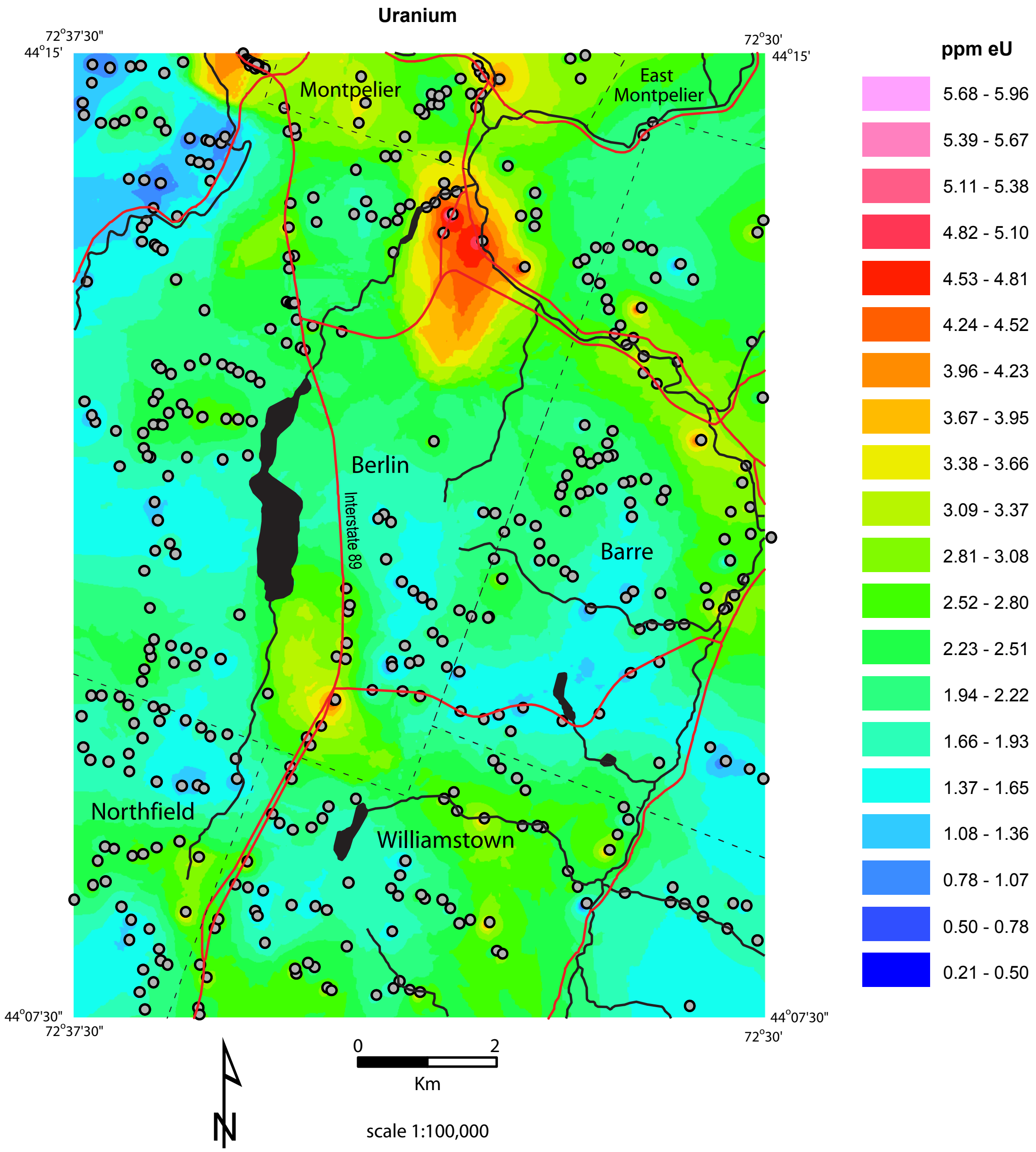

Figure 6*A*. Map of equivalent uranium concentrations (ppm eU) using a 40-meter grid. Survey points shown as circles. STATEPLANE projection, zone 5562. 1983 North American Datum.

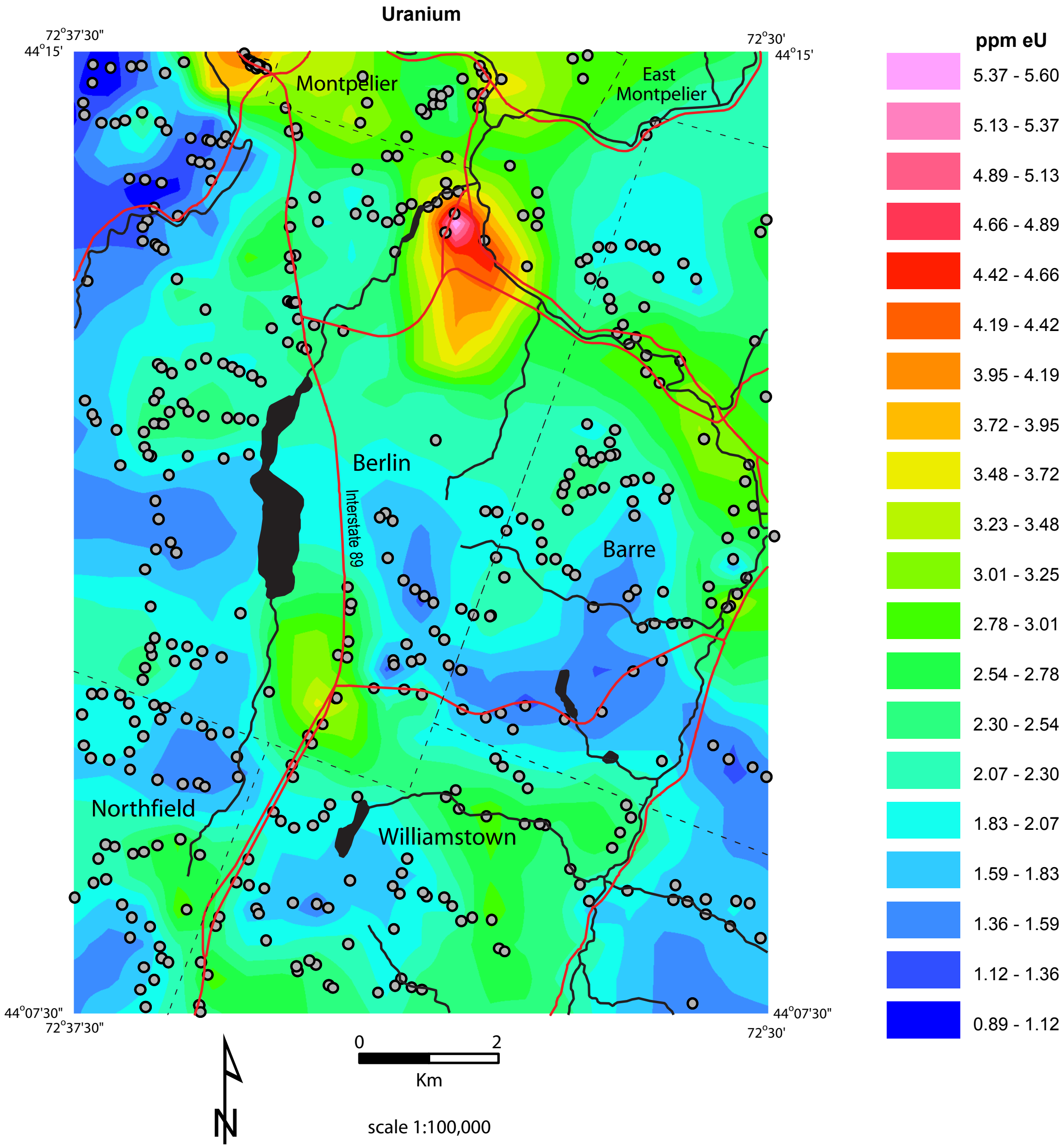

Figure 6*B*. Map of equivalent uranium concentrations (ppm eU) using a 500-meter grid. Survey points shown as circles. STATEPLANE projection, zone 5562. 1983 North American Datum.

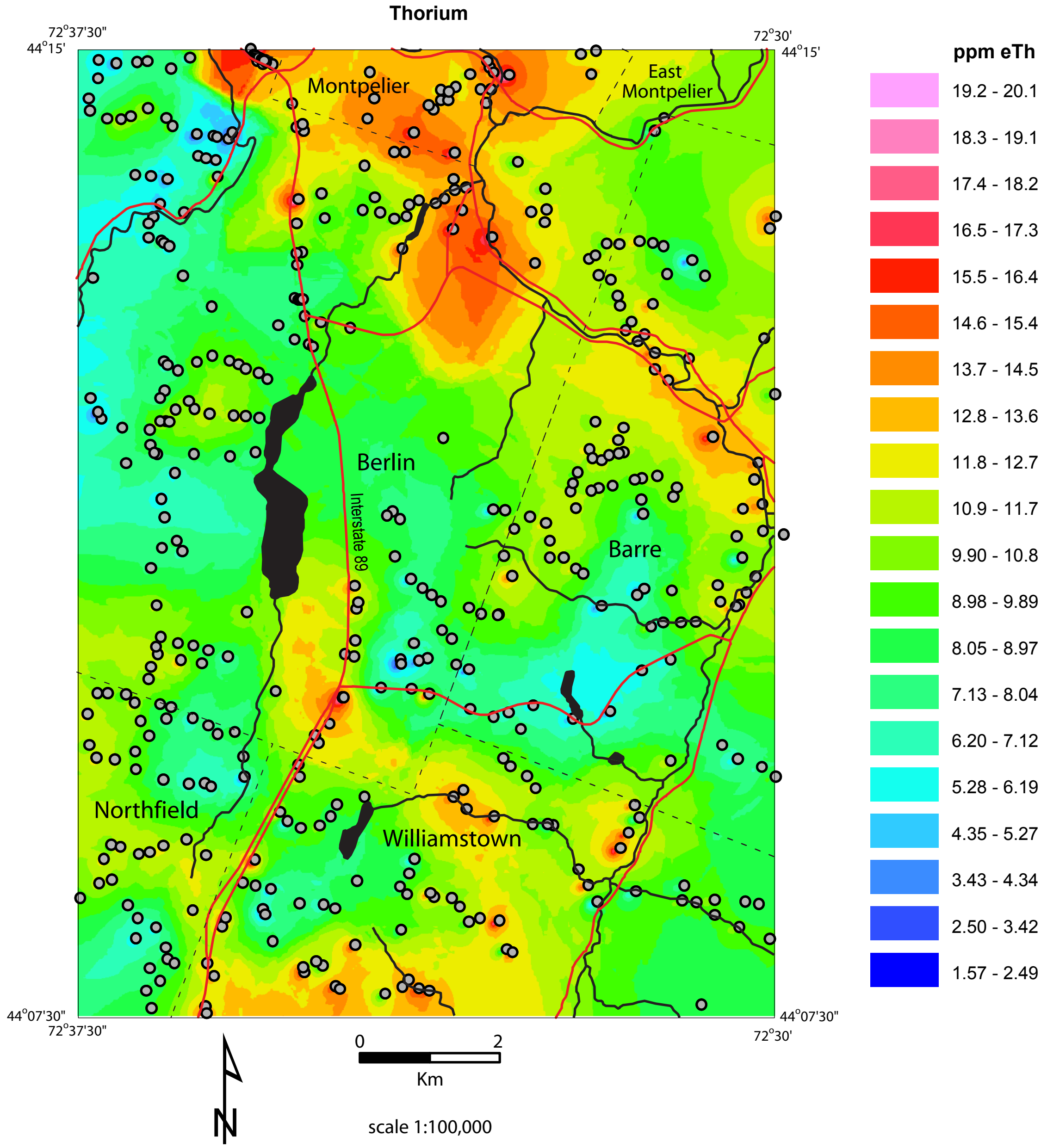

Figure 7*A*. Map of equivalent thorium concentrations (ppm eTh) using a 40-meter grid. Survey points shown as circles. STATEPLANE projection, zone 5526. 1983 North American Datum.

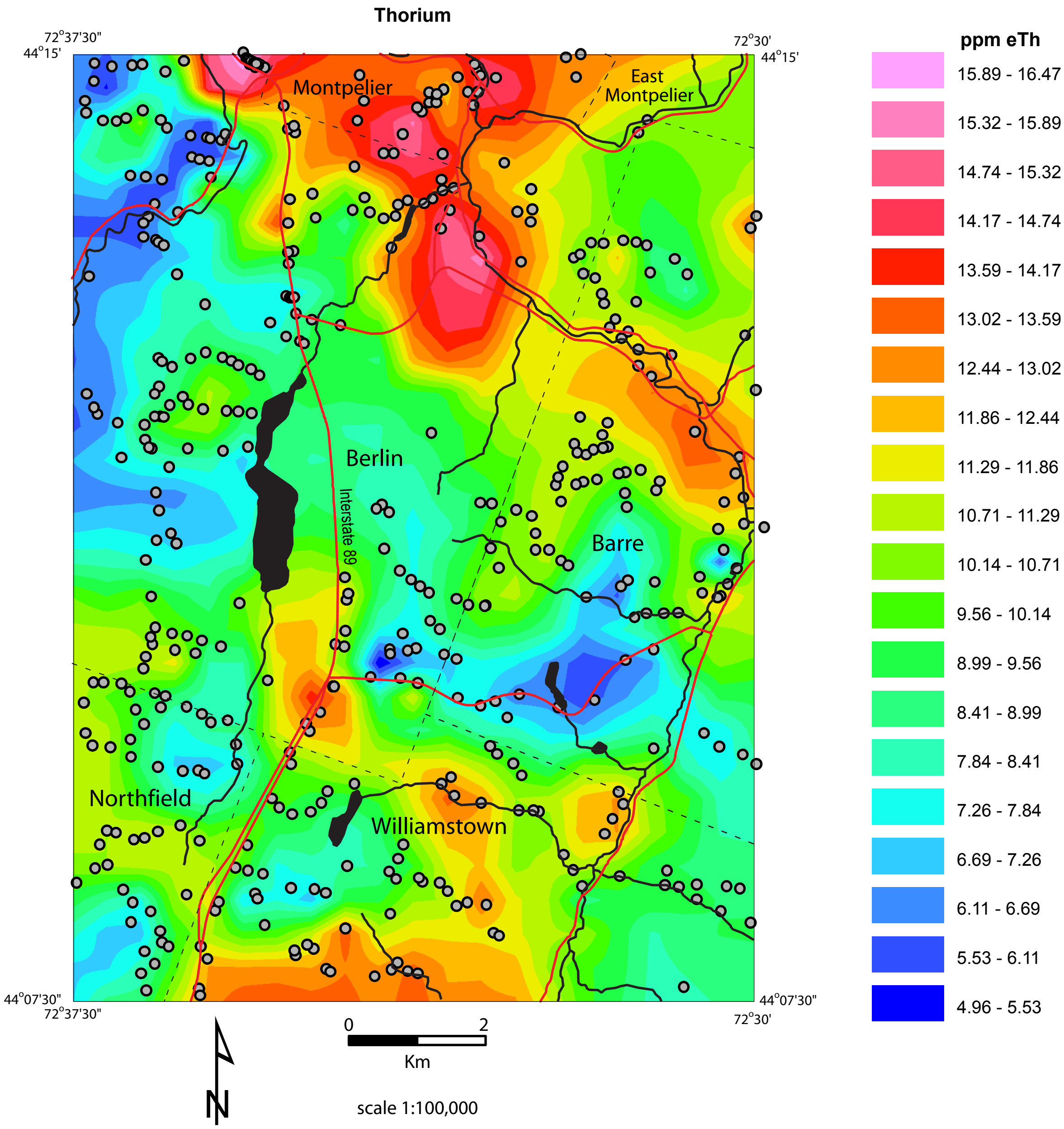

Figure 7*B*. Map of equivalent thorium concentrations (ppm eTh) using a 500-meter grid. Survey points shown as circles. STATEPLANE projection, zone 5526. 1983 North American Datum.

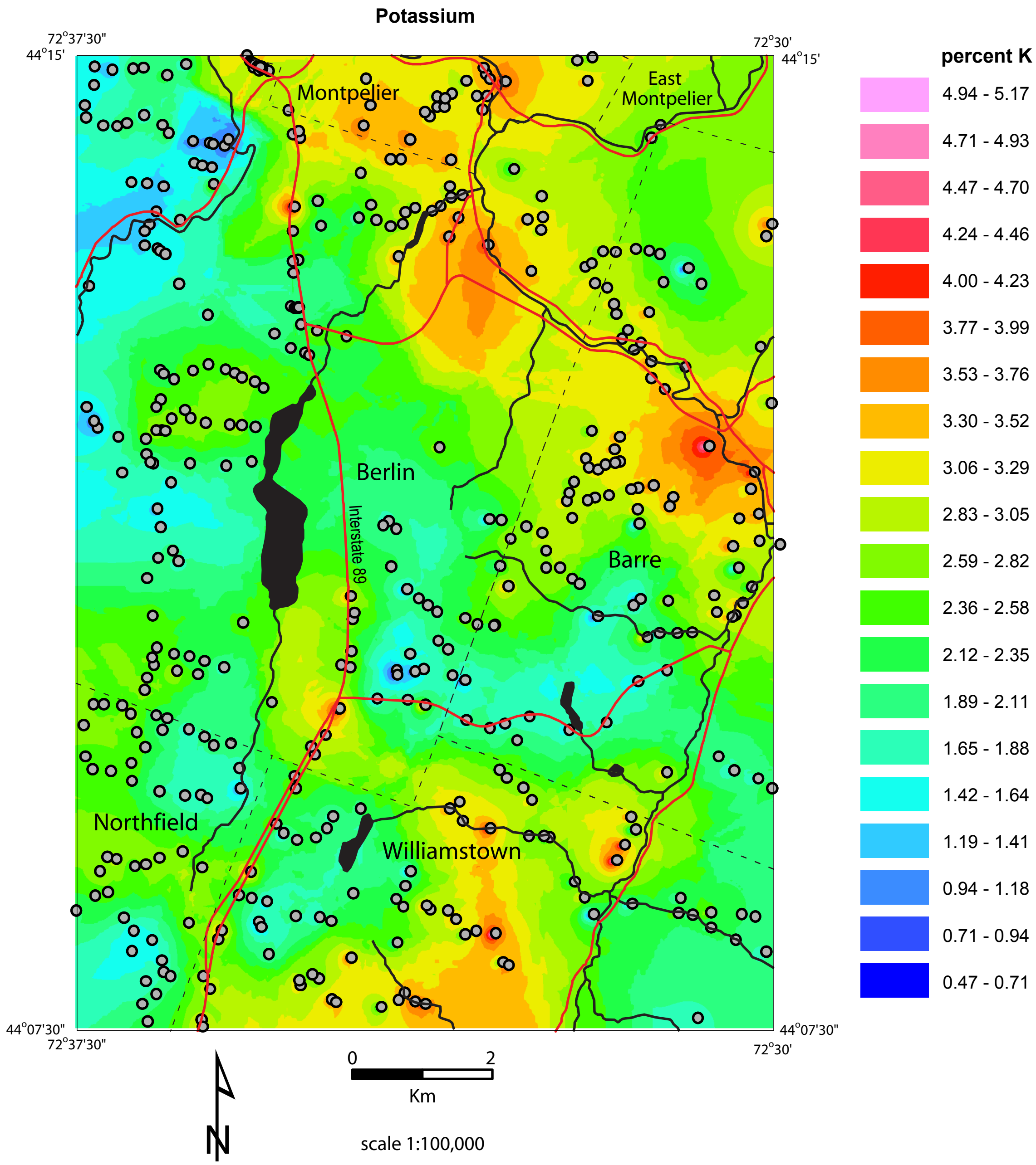

Figure 8*A*. Map of potassium concentrations (percent K) using a 40-meter grid. Survey points shown as circles. STATEPLANE projection, zone 5526. 1983 North American Datum.

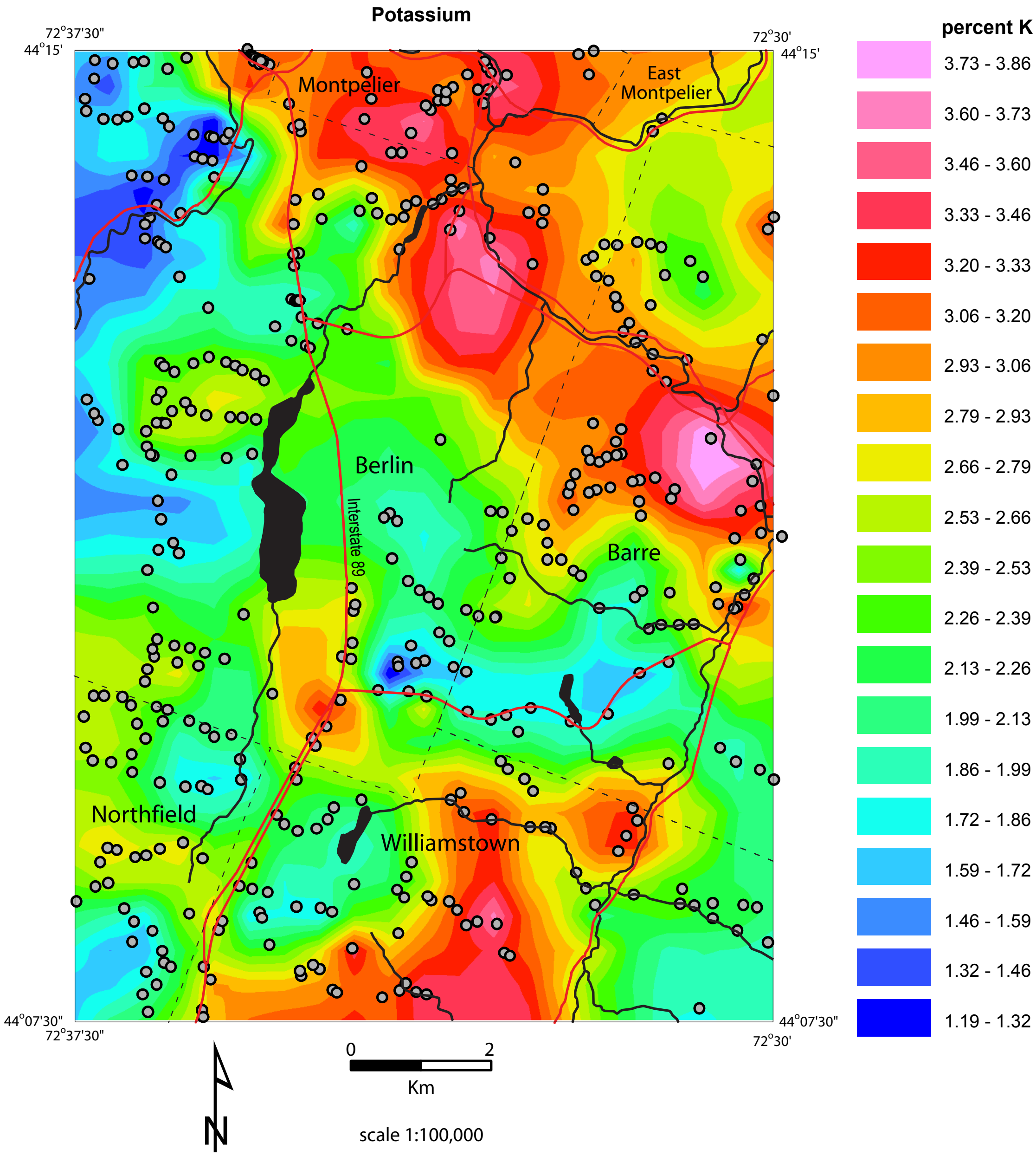

Figure 8*B*. Map of potassium concentrations (percent K) using a 500-meter grid. Survey points shown as circles. STATEPLANE projection, zone 5526. 1983 North American Datum.

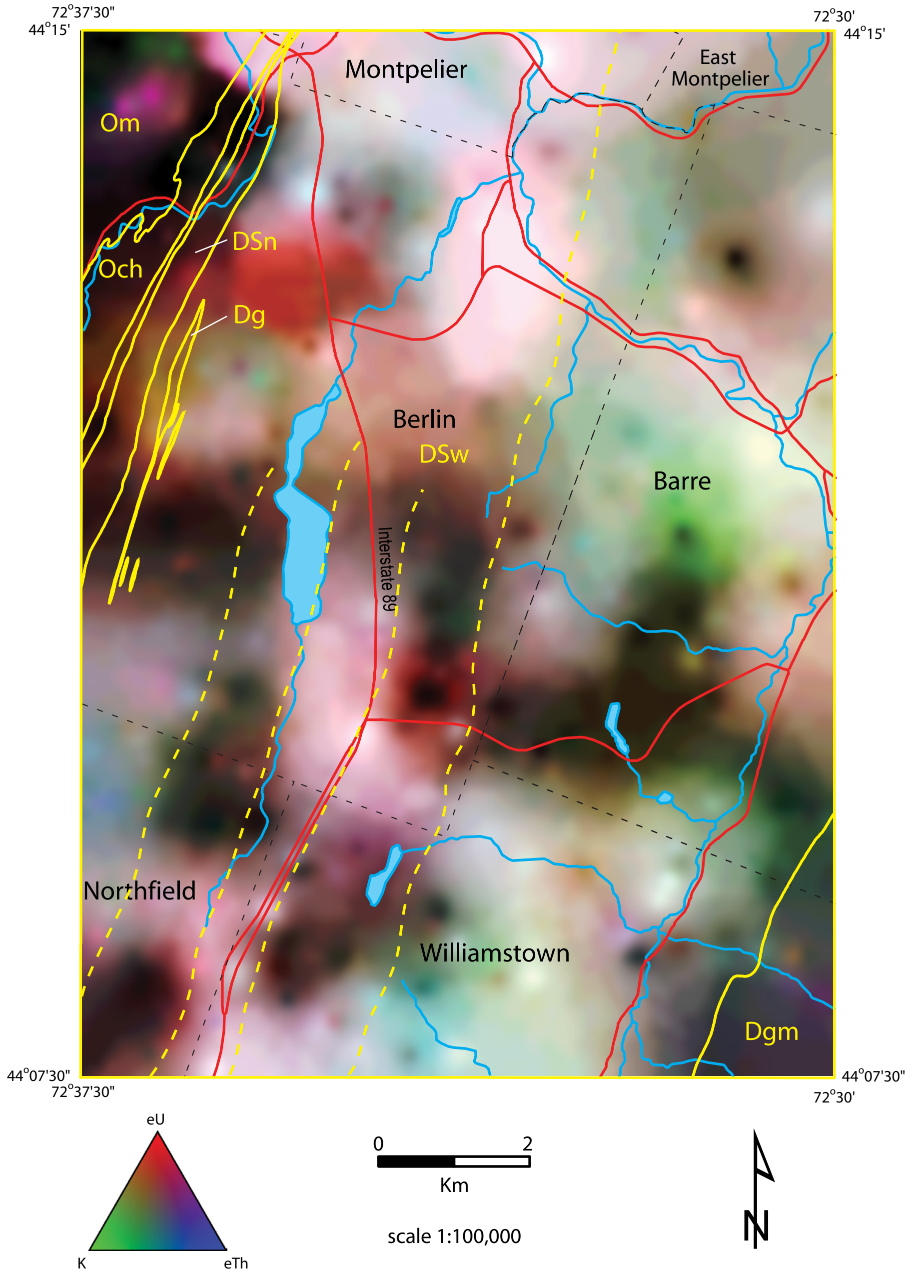

Figure 9*A*. Composite eU-eTh-K concentration map (40-meter grid) showing relative abundances of U, Th, and K. Red areas indicate relatively higher U, blue areas indicate relatively higher Th, green areas indicate relatively higher K, white areas indicate relatively high concentrations of all three elements, and dark areas indicate relatively low concentrations of the three elements. Solid yellow lines are geologic contacts from figure 1. Dashed yellow lines are interpretive boundaries between similar belts of rock; these boundaries are parallel to the layering and dominant foliation in the Waits River Formation. STATEPLANE projection, zone 5526. 1983 North American Datum.

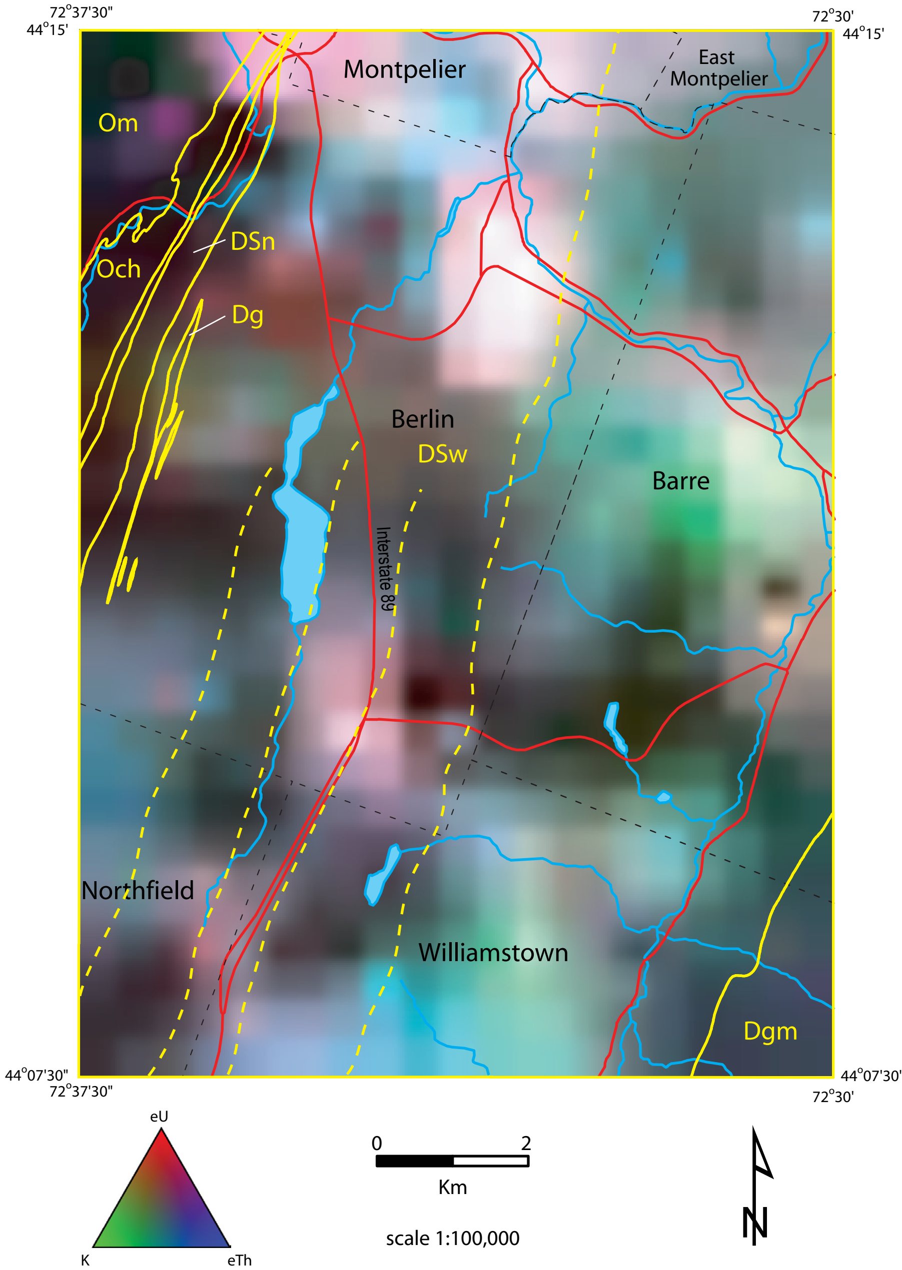

Figure 9*B*. Composite eU-eTh-K concentration map (500-meter grid) showing relative abundances of U, Th, and K. Red areas indicate relatively higher U, blue areas indicate relatively higher Th, green areas indicate relatively higher K, white areas indicate relatively high concentrations of all three elements, and dark areas indicate relatively low concentrations of the three elements. Solid yellow lines are geologic contacts from figure 1. Dashed yellow lines are interpretive boundaries between similar belts of rock; these boundaries are parallel to the layering and dominant foliation in the Waits River Formation. STATEPLANE projection, zone 5526. 1983 North American Datum.

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