UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

POTASSIUM AND THORIUM MAPS OF THE CONTERMINOUS UNITED STATES

by

Joseph S. Duval, William J. Jones,
Frederick R. Riggle, and James A. Pitkin
U.S. Geological Survey
927 National Center
Reston, VA 22092

OPEN-FILE REPORT 90-338

1990

POTASSIUM AND THORIUM MAPS OF THE CONTERMINOUS UNITED STATES

by
Joseph S. Duval, William J. Jones,
Frederick R. Riggle, and James A. Pitkin
U.S. Geological Survey
927 National Center
Reston, VA 22092

INTRODUCTION

Aerial gamma-ray surveys measure the gamma-ray flux produced by the radioactive decay of the naturally occurring elements potassium (^{40}K), uranium (^{238}U), and thorium (^{232}Th) in the top few inches of rock or soil (Duval, Cook, and Adams, 1971). If the gamma-ray measuring system is properly calibrated (e.g. see Grasty and Darnley, 1971), the data can be expressed in terms of the estimated concentrations of the radioactive elements. The potassium concentration data are usually expressed in units of percent potassium (percent K) and the thorium concentration data are expressed as parts per million equivalent thorium (ppm eTh). The term equivalent is used because the technique actually measures the gamma-ray flux from the decay of thallium (^{208}Tl) which is a decay product of ^{232}Th. Radioactive disequilibrium in the thorium decay series may make the equivalent thorium measured differ from the actual thorium present in the surface rocks and soils.

During the period 1975-1983, the U.S. Department of Energy carried out the National Uranium Resource Evaluation (NURE) Program which included aerial gamma-ray surveys of most of the conterminous United States. Although many of the airborne gamma-ray measuring systems used to make these surveys were calibrated, many of the earlier surveys were done without calibration and were not converted to the concentrations of the radioactive elements. Detailed examinations of the digital data available on magnetic tape also showed that many of the "calibrated" surveys do not match the data from other "calibrated" surveys at the boundaries of adjacent areas. For these reasons the data must be corrected in order to obtain a consistent data base for the conterminous United States.

Because thorium and potassium concentration data are useful in geologic studies and because the NURE data are the only nationwide data base on the natural radiation environment, the U.S. Geological Survey reprocessed the aerial gamma-ray data to produce maps showing surface concentrations of potassium and thorium for the conterminous United States.

NURE AERIAL GAMMA-RAY DATA

The NURE aerial gamma-ray data were collected by several private contractors using high-sensitivity gamma-ray measuring systems. These systems used sodium iodide detector crystals with detector volumes of 2000-3300 in^3 (33-54 L). All of the systems included electronic navigation equipment, radar altimeters, magnetometers, and "upward-looking" gamma-ray detectors. The upward-looking detectors were partially shielded from radiation coming from the ground by placing them on top of the other detectors or by using lead shielding. The purpose of the upward-looking detectors was to measure the amount of radiation from ^{214}Bi (a radon decay product) in the atmosphere and to use that information to correct the estimated ground concentrations of ^{238}U. The data were corrected by the contractors for background radiation due to aircraft contamination and cosmic rays, and for Compton scattering effects, altitude variations, and airborne ^{214}Bi.

The gamma-ray surveys were flown at a nominal altitude of 400 feet (122 m) above the ground. The gamma-ray systems were calibrated using the calibration pads at Grand Junction, Colorado (Ward, 1978), and the dynamic test strip at Lake Mead, Arizona (Geodata International, Inc., 1977). Figure 1 is an index map of the conterminous United States showing the 2 degree by 1 degree National Topographic Map Series (NTMS) quadrangles with an indication of the nominal spacings between the flight lines of the NURE aerial gamma-ray surveys. Most of these surveys also included tie lines flown approximately perpendicular to the flight lines at intervals of 25 to 29 km.

DATA PROCESSING AND COMPILATION

Duval, Cook, and Adams (1971) present an equation for calculating the gamma-ray flux from the ground that can be written:

(1) $$F = \frac{k}{d} f(E,h) U,$$

where k is a constant dependent upon the properties of the gamma-ray detector, d is a constant proportional to the density of the ground, $f(E,h)$ is a function dependent upon the energy of the gamma ray (E) and the height of the detector (h) above the ground, and U is the concentration of the radioisotope in the ground. This equation shows that measured gamma-ray flux can be converted to concentration values by multiplying the flux measurement by a constant if the measurement has been corrected for background radiation and altitude variations. This can be written as the equation

(2) $$U = c \frac{1}{f(E,h)} (M - B), \quad c = \frac{d}{k}$$

where M is the measured gamma-ray flux after spectral corrections have been made and B is the correction for background radiation.

The calibration procedures used in the NURE Program determined spectral correction factors (Compton stripping) by measuring the gamma-ray flux at ground level on concrete pads for which the

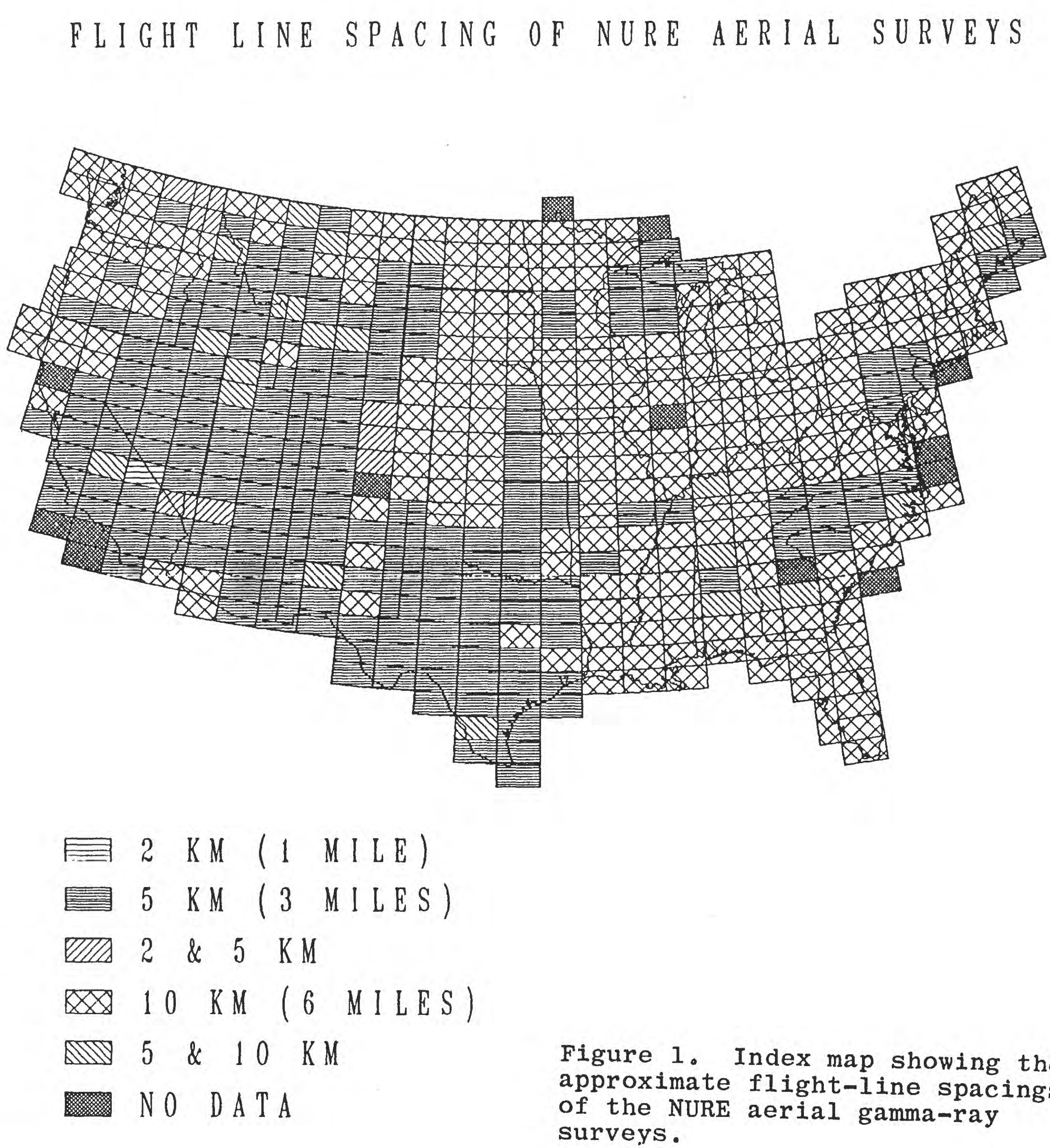

Figure 1. Index map showing the approximate flight-line spacings of the NURE aerial gamma-ray surveys.

concentrations of the radioactive elements were known from laboratory measurements (see Ward, 1978). Darnley (1970) and Grasty and Darnley (1971) describe the methods used to calculate the spectral correction factors. The calibration constants for conversion of the gamma-ray flux after corrections for spectral effects, altitude variations, and background radiation were determined by flying over a dynamic test strip (see Geodata International, Inc., 1977).

The spectral correction factors are dependent upon the characteristics of the gamma-ray measuring system and upon the altitude of the system above the ground (Grasty, 1975). Because the spectral correction factors change on the order of 10 percent for an altitude change of 100 feet (30.5 m), this effect was not included in the data reduction procedures of the contractors. For the purposes of this work, the spectral correction factors were assumed to be a constant property of the gamma-ray measuring systems.

The altitude variations were corrected by the contractors using equations based upon measurements of the gamma-ray flux at different altitudes above the ground. This equation does depend upon the density of air but the effects of changes in air density are small and no data on this effect have been published. Duval, Cook, and Adams (1971) present calculations that indicate that a 20 percent change in the air density causes a change of about 10 percent in the gamma-ray flux. Increasing air density reduces the gamma-ray flux.

The background radiation consists of a constant source of radiation from the aircraft and associated equipment and varying radiation from cosmic rays and airborne bismuth. The radiation from cosmic rays and airborne bismuth were continuously monitored by the contractors. The radiation from the aircraft and associated equipment was determined by making measurements over water or at high altitudes such that no radiation from ground sources was included in the measurements.

The NURE calibration procedure also assumes that the dynamic calibration site has soil density, soil moisture, and radon emanation characteristics that are typical of the areas to be measured. To the extent that these conditions are not met, the estimated concentrations will be incorrect. Equation 1 shows that the gamma-ray flux is inversely proportional to the density. The determination of the calibration constants assumes that the rocks and soil to be measured will have densities similar to the dynamic test strip. If the densities are not the same then there will be some error in the estimation of surface concentrations. Such an error is, however, independent of the aerial gamma-ray measuring system. The observed differences in the apparent surface concentrations measured by different systems could be caused by errors in the determination of the calibration constants. However, because moisture increases the effective density of the soils, differences in soil moisture will result in a similar, indistinguishable effect. Because both of these effects can be written as a constant times the corrected count rate for the gamma-ray flux, either or both of them can be corrected by multiplying the data by an appropriate constant. Differences in the radon emanation characteristics tend to modify the apparent source of gamma rays by removing sources from the soil and this effect cannot be directly estimated.

Because the data were corrected by the DOE contractors to remove background radiation from aircraft contamination and cosmic rays and to correct for altitude variations and airborne ^{214}Bi, all differences between different gamma-ray systems were assumed to be the result of errors in the calibration or of differences in soil moisture. The correction procedures used for this work further assume that all of the data for a particular survey or a particular flight line can be multiplied by a single constant to make the data consistent with surrounding data. Because soil density, soil moisture, and radon emanation characteristics can vary within the area of a survey, the estimates of the surface concentrations are likely to contain some unknown errors.

Other possible sources of differences between adjacent surveys are errors in the background corrections applied to the data by the contractors. Corrections for such errors would require the addition or subtraction of a constant. The possibility that some of the observed differences could be caused by errors in background corrections was tested and the results indicated that adjacent data sets could not be matched by adding a constant to the data nor could they be matched by addition followed by multiplication. Because this is a subjective observation, the data as corrected by us may contain some unrecognized background errors.

Differences between the various surveys were common and differences within the individual NTMS quadrangles were also common. These latter differences were related to specific flight lines and required that the data for those flight lines be separately adjusted to match the data within the quadrangle. Figure 2 shows the data for the Havre quadrangle in Montana before and after corrections were applied to specific flight lines in the data set. The approach used to make these corrections was as follows:

1. Lines representing the flight paths were plotted and labeled.
2. The data were converted into a rectangular grid using a minimum curvature algorithm (Briggs, 1974; Webring, 1981).
3. This grid was examined as a grey-scale image to identify flight lines judged to be inconsistent with the surrounding data. This judgement was based upon the presence of a linear feature along the flight path of values either significantly higher or lower than adjacent values.
4. The data for the identified flight lines were multiplied by an appropriate constant such that the linear feature could not be seen in the grey-scale image. Experience with this method showed that differences on the order of 5 percent of the data values could be seen in the image.

After flight-line-specific adjustments were made to the data for a single survey, the resulting data were compared to data in adjacent areas and corrections were applied to entire data sets as required.

Because of the large amount of data and limited computer resources, the data were processed in blocks of 10 degrees of

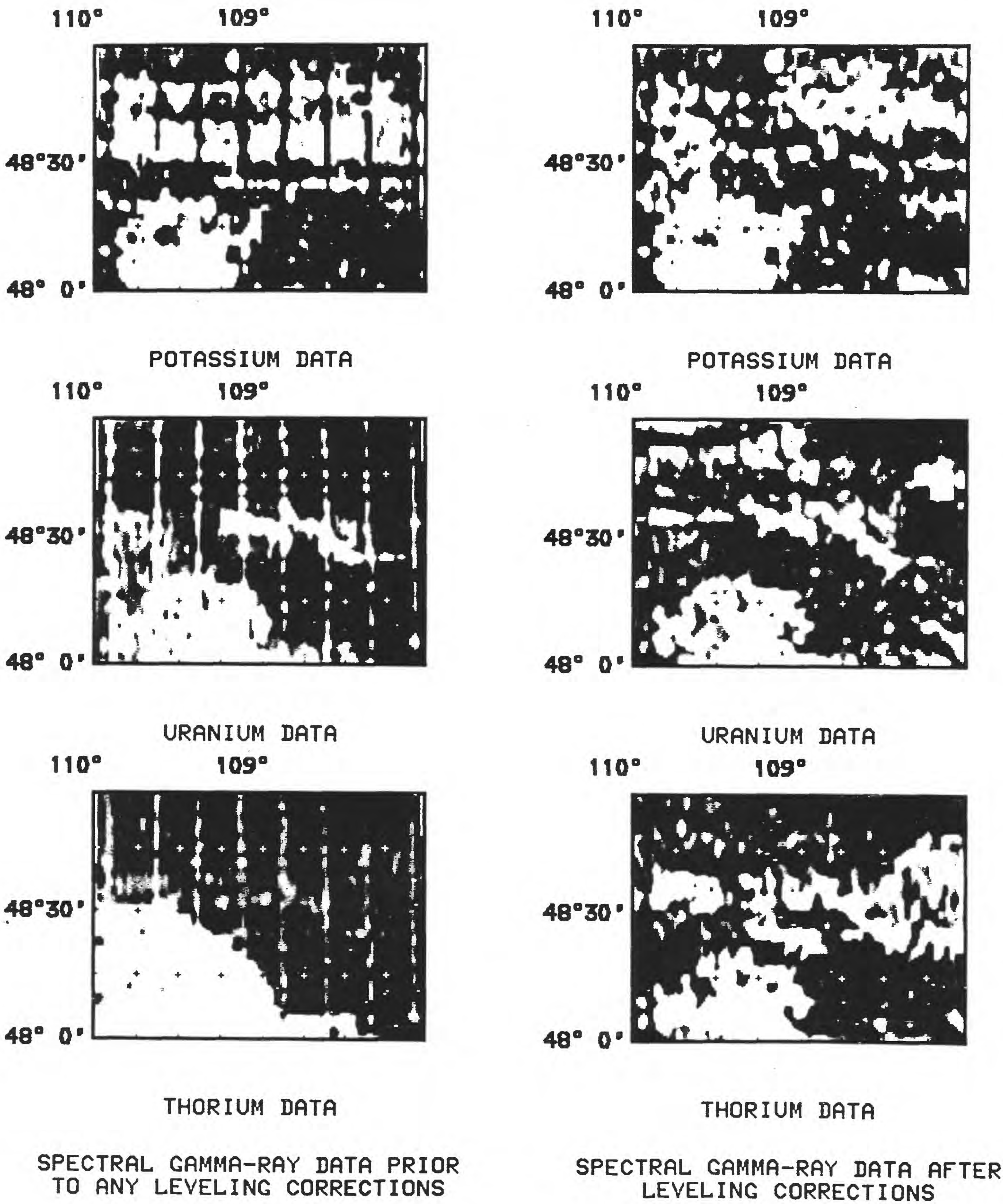

Figure 2. Data for the Havre, Montana quadrangle before and after corrections.

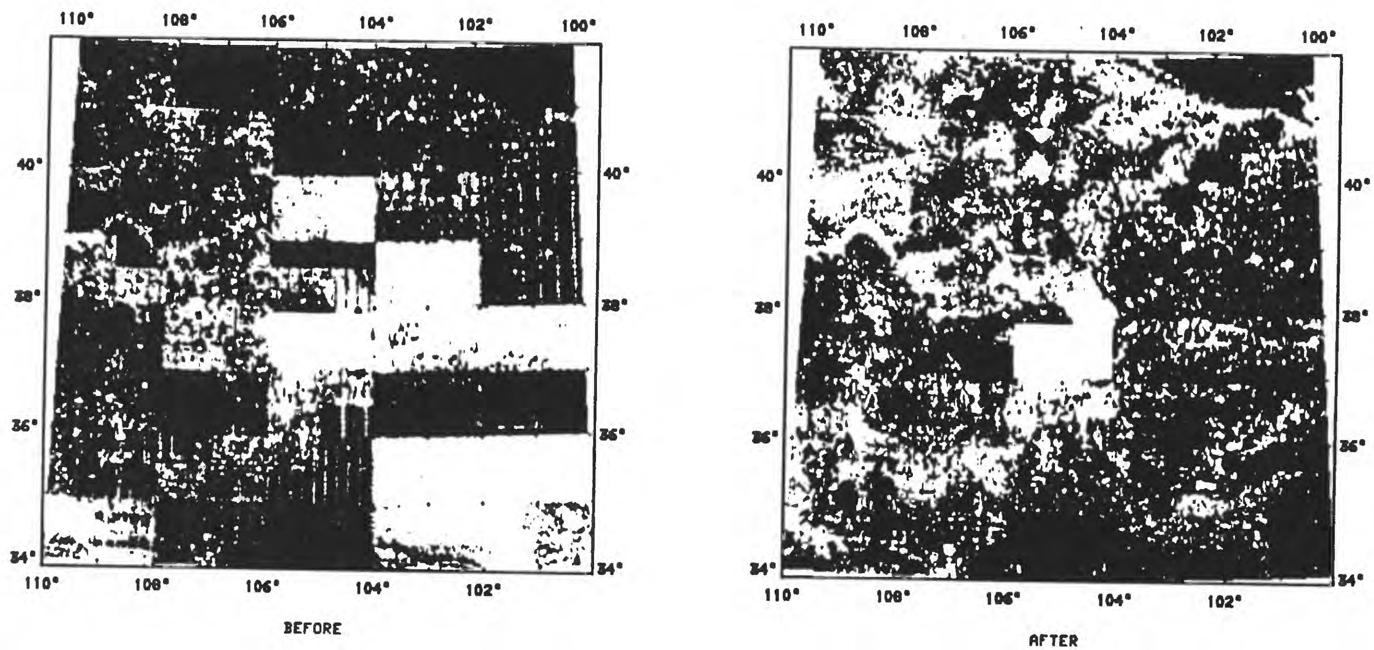

Figure 3. NURE data for a block of quadrangles centered in Colorado before and after corrections.

CORRECTIONS APPLIED TO POTASSIUM DATA

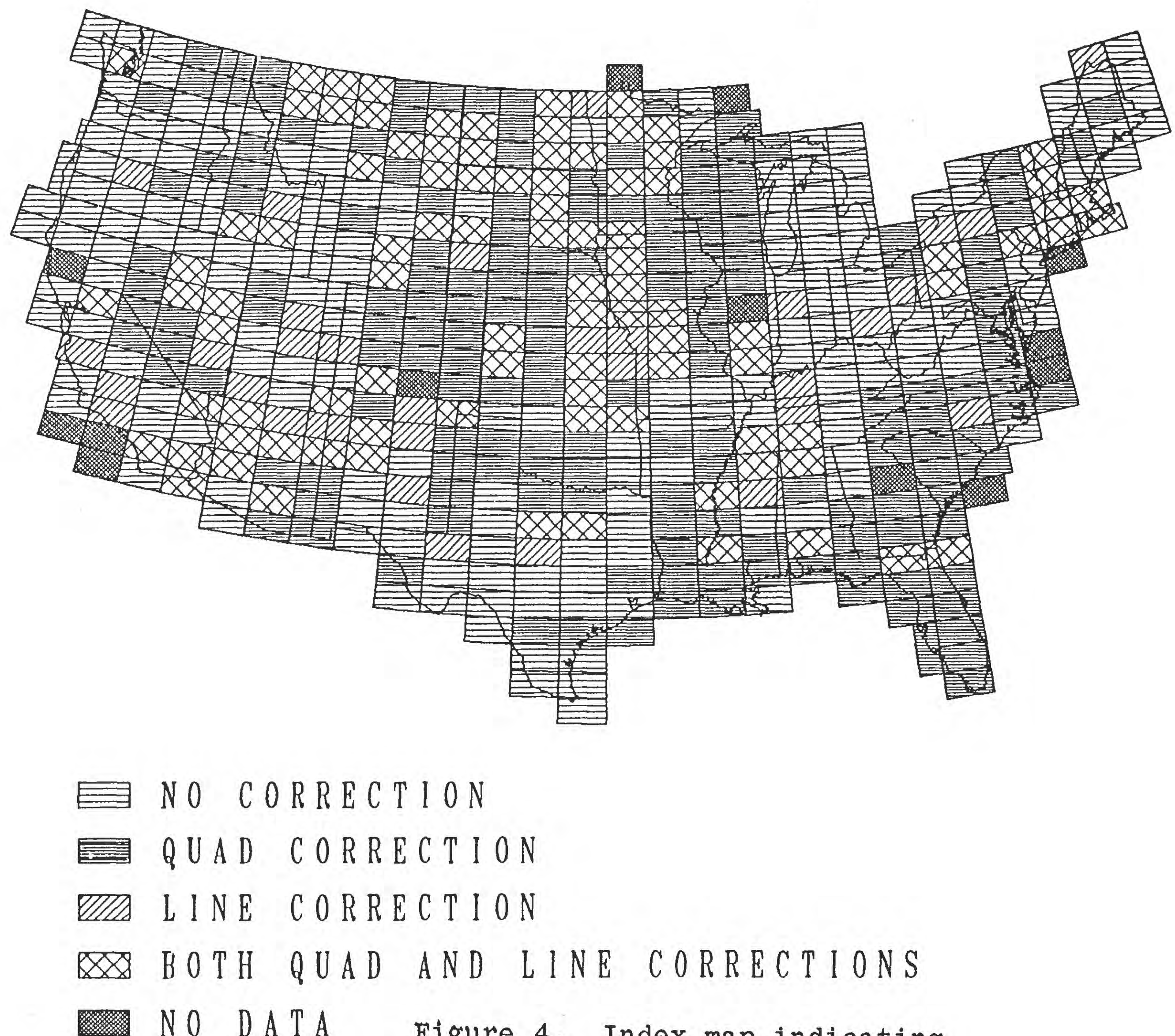

Figure 4. Index map indicating the type of corrections applied to the NURE potassium data.

CORRECTIONS APPLIED TO THORIUM DATA

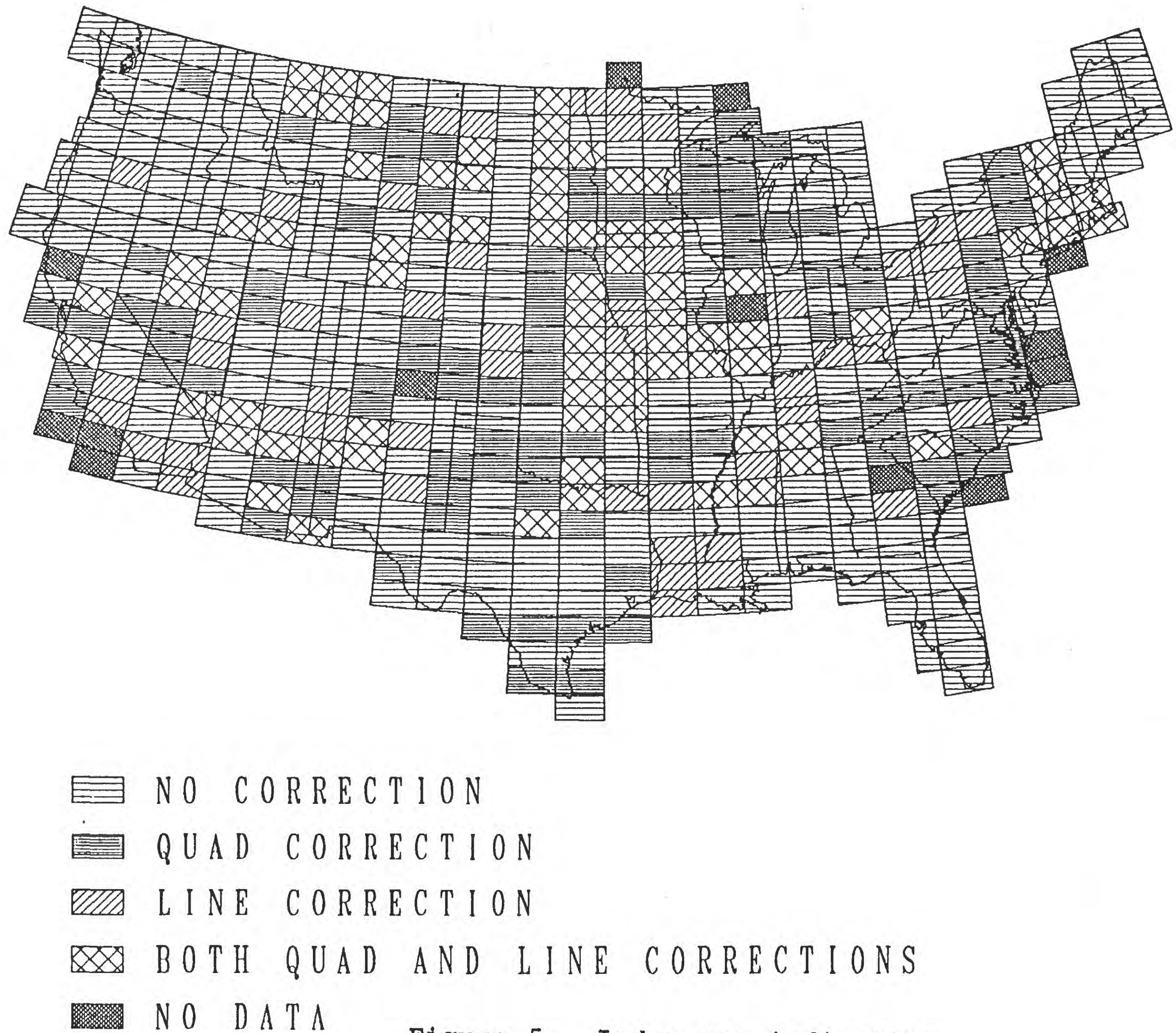

Figure 5. Index map indicating the type of corrections applied to the NURE thorium data.

longitude by 8 degrees of latitude. Figure 3 shows the data for a block of quadrangles centered in Colorado before and after corrections. The approach used to make corrections to quadrangles was as follows:

1. The data were converted to a rectangular grid using the minimum curvature algorithm.
2. The grid was examined as a grey-scale image to identify quadrangles judged to be inconsistent with the adjacent quadrangles. This judgement was based upon the data values at the boundaries between quadrangles being significantly higher or lower than the values in the adjacent quadrangles. This judgement also used the criterion that the fewest possible number of quadrangles should be identified as being inconsistent. An examination of the data before correction in figure 3 shows that many of the quadrangles required flight-line adjustments as well as quadrangle adjustments. The quadrangles seen in figure 3 as mostly white are data that were not converted by the contractors to concentration values.
3. After all flight-line adjustments were made, the data for the identified quadrangles were multiplied by a constant such that the differences at the quadrangle boundaries could not be seen in the grey-scale image.

The corrections were made using the subjective judgement of the data processing personnel based upon a visual examination of the data displayed as gray-scale and color maps on color television monitors. Experience showed that the data could be matched to within about 5 percent with this technique. It is possible and perhaps even likely that this process results in errors that propagate across the various data sets. In order to minimize the propagation of such errors, the various data blocks were frequently compared, and overlap between blocks was used to ensure that no visible differences would occur at block boundaries. Because differences on the order of 5 percent are visible in the gray-scale images, the overall relative errors between adjacent blocks of data should generally be less than 5 percent.

Figure 4 is an index map of the NTMS quadrangles showing the type of corrections applied to the potassium data in each quadrangle. Figure 5 is an index map of the NTMS quadrangles showing the type of corrections applied to the thorium data in each quadrangle. The potassium and thorium data consist of the surface concentrations of percent potassium (K) and ppm equivalent thorium (eTh), or count rates in the potassium and thorium data channels. In all cases the count rate data required a correction factor for the entire quadrangle.

POTASSIUM AND THORIUM MAPS

The corrected potassium distribution maps are shown in Plates 1A and 1B. The data have been grouped into intervals of 0.3 percent K. The corrected thorium distribution maps are shown in Plates 2A and 2B. The data have been grouped into intervals of 2 ppm eTh. Blank areas on the map correspond to areas for which no data was available. In some cases, the areas were included in the aerial surveys but the data were excluded from the data set because they were determined to be invalid. Invalid data can be the result of measurements over water (e.g. the Great Salt Lake in Utah) where the corrected count rates are frequently negative because of statistical variations in the data. Survey altitudes greater than 180 m (600 ft) were also found to produce statistically invalid data because of the attenuation of the gamma-ray flux by the atmosphere. Some of the largest blank areas correspond to entire quadrangles (e.g. in California, Colorado, and Illinois) which were surveyed but for which the digital data are missing from the archival data tapes. Other areas were not surveyed for a variety of reasons (large urban areas, military training areas, and some national parks were not flown for safety reasons or because mining in such areas would not be permitted).

DISCUSSION

Examples of transport and redistribution can be readily seen in the potassium and thorium maps (refer to Figure 6 for the locations of the various geographic features mentioned below). In the Pacific Northwest the Columbia Plateau basalts cover a large area and the radiometric signature of the outcrop area is divided into two distinct patterns. North of a curved line that runs south of and approximately parallel to the Columbia River, the gamma-ray data show significantly higher concentrations of potassium and thorium than in the area south of the line. This curved line coincides approximately with a regional drainage divide and the data pattern suggests that the surface materials north of the line are derived from the more radioactive rocks along the Canadian border. One hypothesis is that these are materials brought in by glacial fluvial waters and redistributed by winds and fluvial processes whereas the surface materials south of the line are more locally derived from the basalts.

The holocene deposits along the Mississippi River and some of its tributaries similarly have a distinctive gamma-ray signature characterized by locally higher concentrations of potassium and thorium. The more radioactive rocks along the northern part of the river system and to the west of the river are the probable source of these materials. These deposits have only moderate levels of potassium (1-2 percent K) and thorium (6-10 ppm eTh) and the fact that they are a marked feature of the maps emphasizes the very low concentrations of potassium (less than 0.9 percent K) and thorium (less than 6 ppm eTh) in the sediments through which the river is flowing. Other rivers along the coast of Texas and the mid-Atlantic coast show a similar contrast with the surrounding sediments in the potassium maps (Maps 1A and 1B) but not in the thorium maps.

Another example of transport can be seen in the Sandhills of north-central Nebraska. These sands cover a very large area and are characterized by lower radioactivity with values less than 1.5 percent K and less than 6 ppm eTh.

States with large areas of low values (less than 0.9 percent K and less than 8 ppm eTh) are Oregon, western Washington, Northern California, northwestern Nebraska, northern Maine, Michigan, Wisconsin, Minnesota, Florida, and the outer coastal plains of New

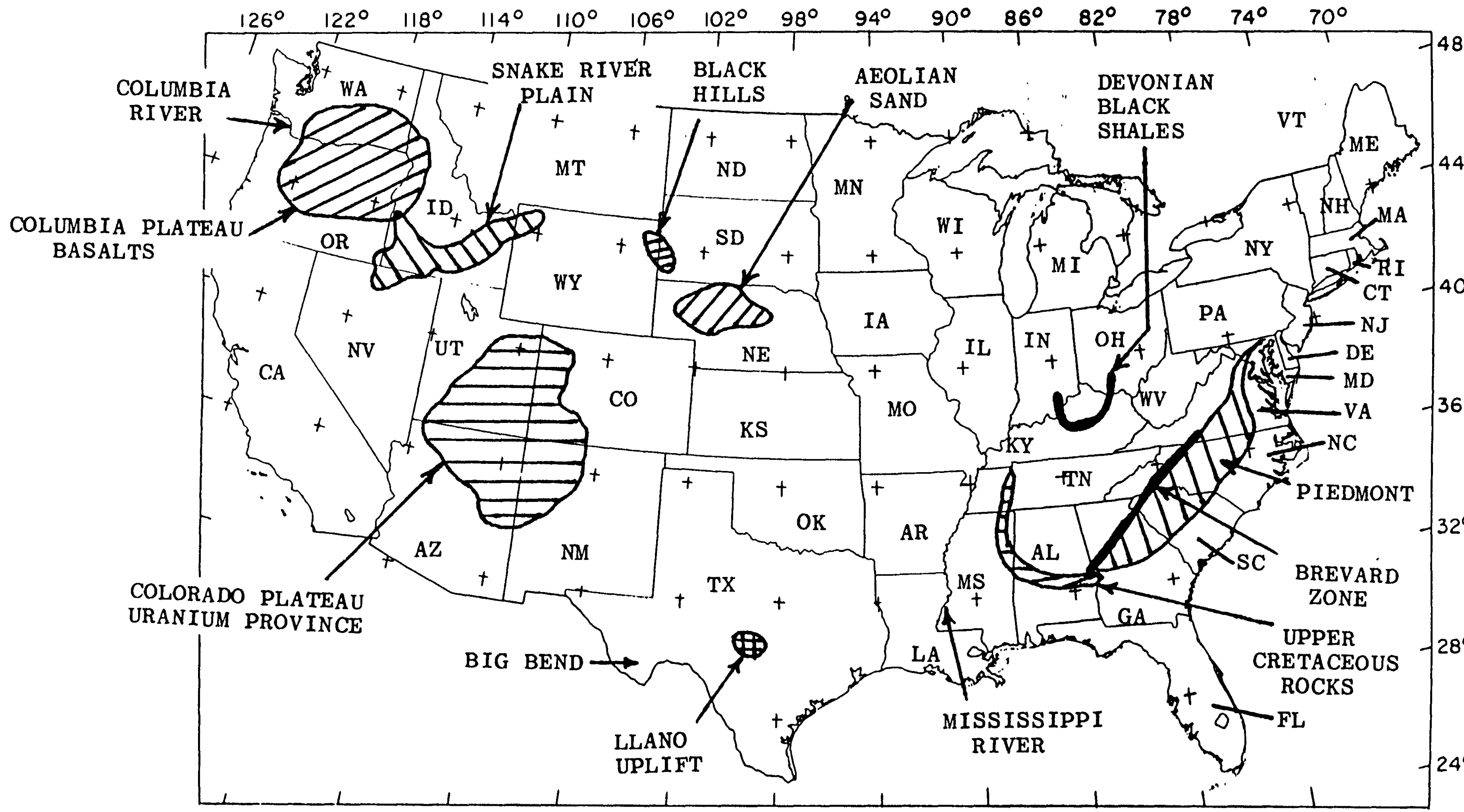

Figure 6. Shematic showing the various geographic features mentioned in the text.

Jersey, Delaware, Maryland, North Carolina, South Carolina, and Georgia. Some of the highest concentrations occur in areas with distinctive patterns and some of these are described below.

Many of the rocks in the Piedmont areas in Georgia, South Carolina, and North Carolina have concentrations greater then 1.8 percent K and greater than 8 ppm eTh. Most of these areas are underlain by granites, granitic gneisses, and metamorphic rocks. The zone of highest eTh concentrations is bounded on the north by the Brevard zone of cataclasis. Various other fault systems seem to provide a southern boundary, for example the Towaliga and Goat Rock faults in Georgia (see Georgia Geological Survey, 1976 for fault locations).

Concentration values greater than 1.5 percent K and greater than 8 ppm eTh occur over large areas in east central New Hampshire and southwestern Maine. About 30 percent of these areas have concentrations exceeding 12.0 ppm eTh. In New Hampshire the highest thorium concentrations generally occur in areas underlain by Conway granite which is known to have thorium concentrations greater then 30 ppm eTh (Richardson, 1964). In Maine the areas of highest thorium concentrations are underlain by rocks described as two-mica granites (Moench, 1984). The areas to the south and east of the granitic intrusions also have regionally elevated concentrations (greater than 1.5 percent K and greater than 8 ppm eTh) and presumably the surface soils (which is what are being measured by the gamma-ray data) contain materials derived from the granitic rocks. Other locally higher potassium and thorium concentrations in Maine occur along the Atlantic coast and in north central Maine and these areas are also underlain by two-mica granites.

In central Nevada and west-central Utah, the Tertiary volcanic rocks and sediments derived from them have concentrations generally greater than 1.5 percent K and greater than 12 ppm eTh. Within Nevada, most of the higher potassium and thorium concentrations occur where 17-34 Myr old sedimentary and igneous rocks are common (Stewart and Carlson, 1976). Within Utah, the two largest areas of higher radioactivity are associated with volcanic centers. The northern area (centered near 39° 45' north latitude and 113° west longitude) covers the Keg Caldera and parts of the Dugway Valley and Dugway and Thomas Ranges. The southern area (centered near 38° 30' north latitude and 112° 30' west longitude) covers much of the Marysvale volcanic field.

Volcanic rocks in the Big Bend area in west Texas are particularly evident in the potassium map with a large area of values greater than 3.3 percent K. Some of the volcanic rocks in the Big Bend area are known to have thorium concentrations of 3-67 ppm Th (Nelson and Nelson, 1986); however, the area of thorium-rich rocks is much less than that of the potassium-rich rocks.

Because it is surrounded by low potassium sediments, the Llano Uplift in central Texas is also readily recognized in the potassium map with values greater than 1.5 percent K but its thorium signatures is less evident. The Llano uplift area has a core of Precambrian igneous and metamorphic rocks surrounded by Paleozoic and Cretaceous sedimentary rocks (Texas Bureau of Economic Geology, 1981). Most of the surrounding sedimentary rocks are limestones and dolomites and one would expect low radioactivity for these rocks. The most abundant igneous rock type is the Town Mountain granite which has been reported to have values of about 3.6 percent K and 24 ppm eTh (Duval and others, 1972). The most abundant metamorphic rock type is the Valley Spring gneiss with reported values of about 2.1 percent K and 5 ppm eTh (Duval and others, 1972). The outcrops of the Valley Spring gneiss are generally larger than the outcrops of the Town Mountain granite and the 5 km survey flight-line spacing may have resulted in the Valley Spring gneiss being the dominant contributor to the gamma-ray signatures.

The Black Hills area in South Dakota and eastern Wyoming has a distinctive pattern of alternating lows and highs in both the potassium and thorium maps but the pattern is most evident in the potassium map (Map 1A). The Black Hills area has a core of Precambrian granites and metamorphosed sedimentary rocks surrounded by a sequence of Mississippian and Devonian limestones, Permian and Pennsylvanian sandstones and limestones, and Cretaceous sandstones (DeWitt and others, 1989) and all of these sedimentary rocks are less radioactive than the Precambrian rocks. In the northwestern part of the Black Hills area, the Jurassic age Sundance and Gypsum Spring Formations also have a distinctive pattern of locally higher potassium values but are not evident in the thorium map (Map 2A).

The Snake River Plain in Idaho, Wyoming, and Nevada has a characteristic but subtle radiometric signature. Most of the area has 2-3 percent K and 6-10 ppm eTh. The Snake River Plain shown in Figure 6 is a physiographic province and does not everywhere coincide with the Snake River Plain volcanic province. In eastern Idaho the physiographic province coincides with the volcanic province and thus the gamma-ray maps show the higher radioactivity associated with the rhyolitic volcanic rocks of the Yellowstone volcanic province. In southwestern Idaho the physiographic province diverges to the northwest from the axis of the volcanic province (for more details see Bonnichsen and others, 1989). Some of the rhyolitic volcanic centers are seen along the edges of the physiographic province as areas of higher radioactivity in the thorium map (Map 2A).

CONCLUSIONS

The compilation of the NURE aerial gamma-ray data to produce maps of the apparent surface concentrations of potassium and thorium for the conterminous United States has resulted in a reasonably accurate representation of the distribution of these elements in the surface rocks and soils. This statement is supported by the general agreement between mapped geology and the patterns seen in the data.

REFERENCES

Bonnichsen, Bill, Christiansen, R.L., Morgan, L.A., Moye, F.J., Hackett, W.R., Leeman, W.P., Honjo, Norio, Jenks, M.D., and Godchaux, M.M., 1989, Silicic volcanic rocks in the Snake River Plain - Yellowstone Plateau province in Chapin, C.E. and Zidek, Jiri, eds., Field Excursions to Volcanic Terranes in the Western United States, Volume II: Cascades and Intermountain West: New Mexico Bureau of Mines and Mineral Resources Memoir 47, p. 135-182.

Bownocker, J.A., 1965, Geologic Map of Ohio: Ohio Geological Survey, scale 1:500,000.

Darnley, A.G., 1970, Airborne gamma-ray spectrometry: Canadian Mining and Metallurgical Bulletin, v. 73, p. 20-29.

DeWitt, Ed, Redden, J.A., Buscher, David, and Wilson, A.B, 1989, Geologic map of the Black Hills area, South Dakota and Wyoming: U.S. Geological Survey Miscellaneous Investigations Series Map I-1910, scale 1:250,000.

Duval, J.S., Cook, Beverly, and Adams, J.A.S., 1971, A study of the circle of investigation of an airborne gamma-ray spectrometer: Journal of Geophysical Research, v. 76,no. 35, p. 8466-8470.

Duval, J.S., Schwarzer, T.F., Cook, B.G., Worden, J.W., and Adams, J.A.S., 1972, Experimental comparison of NaI(Tl) and solid organic scintillation detectors for use in remote sensing of terrestrial gamma rays: Geophysics, v. 37, no. 5, p. 879-888.

Geodata International, Inc., 1977, Lake Mead dynamic test range for calibration of airborne gamma radiation measuring systems: U.S. Department of Energy Open-File Report GJBX-46(77), 83 p.

Georgia Geological Survey, 1976, Geologic map of Georgia: Georgia Geological Survey, scale 1:500,000.

Grasty, R.L., 1975, Uranium measurement by airborne gamma-ray spectrometry: Geophysics, v. 40, no. 3, p. 503-519.

Grasty, R.L. and Darnley, A.G., 1971, The calibration of gamma-ray spectrometers for ground and airborne use: Geological Survey of Canada, Paper 71-17, 27 p.

Moench, R.H., ed., 1984, Geologic map of the Sherbrooke-Lewiston area, Maine, New Hampshire, and Vermont: U.S. Geological Survey Open-File Report 84-0650, scale 1:250,000.

Nelson, D.O. and Nelson, K.L., 1986, Evolution of igneous rocks in the Trans-Pecos magmatic province in Pause, P.H. and Spears, R.G., eds., Geology of the Big Bend Area and Solitario Dome, Texas: West Texas Geological Society Publication 86-82, p. 143-149.

Richardson, K.A., 1964, Thorium, uranium, and potassium in the

Conway granite, New Hampshire, U.S.A. in Adams, J.A.S. and Lowder, W.M., eds., The natural radiation environment: The University of Chicago Press, p. 39-50.

Stewart, J.H. and Carlson, J.E., 1976, Distribution and lithologic character of 34- to 17-million-year-old sedimentary and igneous rocks of Nevada, showing centers of volcanism: Nevada Bureau of Mines and Geology Map 52, sheet 2, scale 1:1,000,000.

Ward, D.L., 1978, Construction of calibration pads facility, Walker Field, Grand Junction, Colorado: U.S. Department of Energy Open-File Report GJBX-37(78), 57 p.