UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

EQUIVALENT URANIUM MAP OF
CONTERMINOUS UNITED STATES

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

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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 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 uranium data are usually expressed as concentrations in units of parts per million of equivalent uranium (ppm eU). The term equivalent is used because the technique measures the gamma-ray flux from the decay of bismuth (^{214}Bi) which is a decay product of ^{238}U and because of the possibility of radioactive disequilibrium in the uranium decay series. Because radon (^{222}Rn) is also a daughter product of the ^{238}U decay series, the ^{238}U concentrations can be used to estimate the amounts of ^{222}Rn in the near surface soil gas.

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 systems used to make these surveys were calibrated, many of the earlier surveys were done without calibration and conversion 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 of adjacent areas. For these reasons the data must be corrected to obtain a consistent data base for the conterminous United States.

Because of the problems with indoor ^{222}Rn and the expected utility of maps of uranium concentrations to estimate relative amounts of ^{222}Rn, the U.S. Environmental Protection Agency (EPA) entered into an interagency agreement with the U.S. Geological Survey (USGS) to reprocess the NURE aerial gamma-ray data to produce a map showing apparent surficial uranium concentrations 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 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. The purpose of the upward-looking detectors was to measure the amount of radiation from ^{214}Bi 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, 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). Map A is an index map of the conterminous United States with the names of the 2 degree by 1 degree National Topographic Map Series (NTMS) quadrangles and the 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

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

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

where $\underline{k}$ is a constant dependent upon the properties of the gamma-ray detector, $\underline{d}$ is a constant proportional to the density of the ground, and $\underline{f(E,h)}$ is a function dependent upon the energy of the gamma ray (E) and the height of the detector (h) above the ground. The calibration procedures used in the NURE Program result in a single conversion constant

$$(2) \qquad c = \frac{k}{d}$$

which assumes that the density of all rocks and soils to be measured are approximately the same as the calibration site.

In practice, an aerial gamma-ray system is calibrated using a set of concrete pads with known concentrations of the radioactive elements (see Ward, 1978) to determine spectral correc-

tion factors (Compton stripping) and using a dynamic test strip (see Geodata International, Inc., 1977) to determine the conversion constants. The determination of the conversion constants by this technique 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 estimate of the surface concentrations of uranium. Such an error is, however, independent of the aerial gamma-ray system. Differences in the apparent surface concentrations measured by different systems could be caused by errors in the determination of the conversion constants, but increasing soil moisture increases the effective density of the soils and 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 uranium gamma-ray flux, either or both of them can be corrected by multiplying the data by an appropriate constant.

Other possible sources of differences between adjacent surveys are errors in the background corrections applied to the data. 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 may contain some unrecognized background errors.

Level differences among 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 corrected to match the data within the quadrangle. Figure 1 shows the data for the Havre quadrangle in Montana before and after corrections were applied to specific flight lines in the data set. After flight-line specific corrections 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 longitude by 8 degrees of latitude. Figure 2 shows the data for a block of quadrangles centered in Colorado before and after corrections. 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
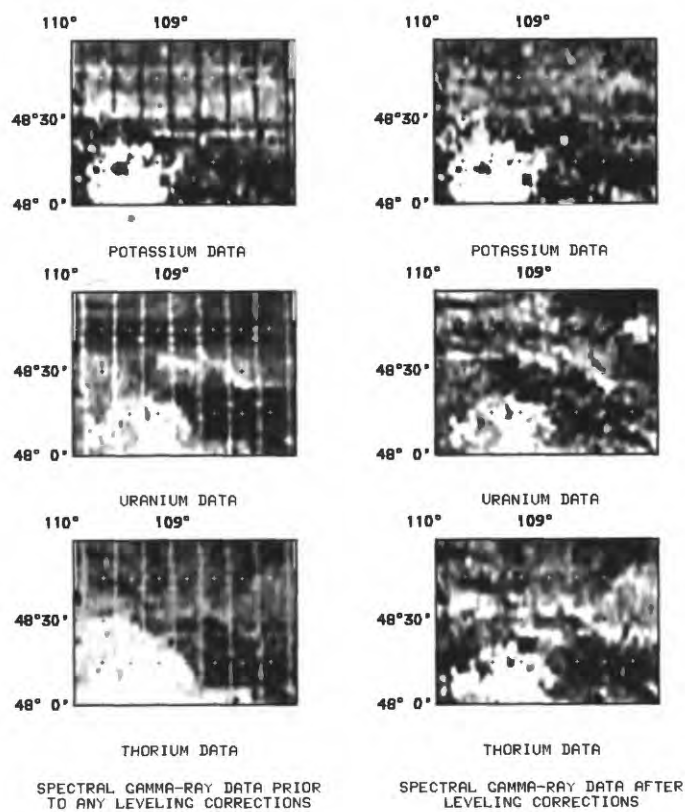
Figure 1. Data for Havre, Montana
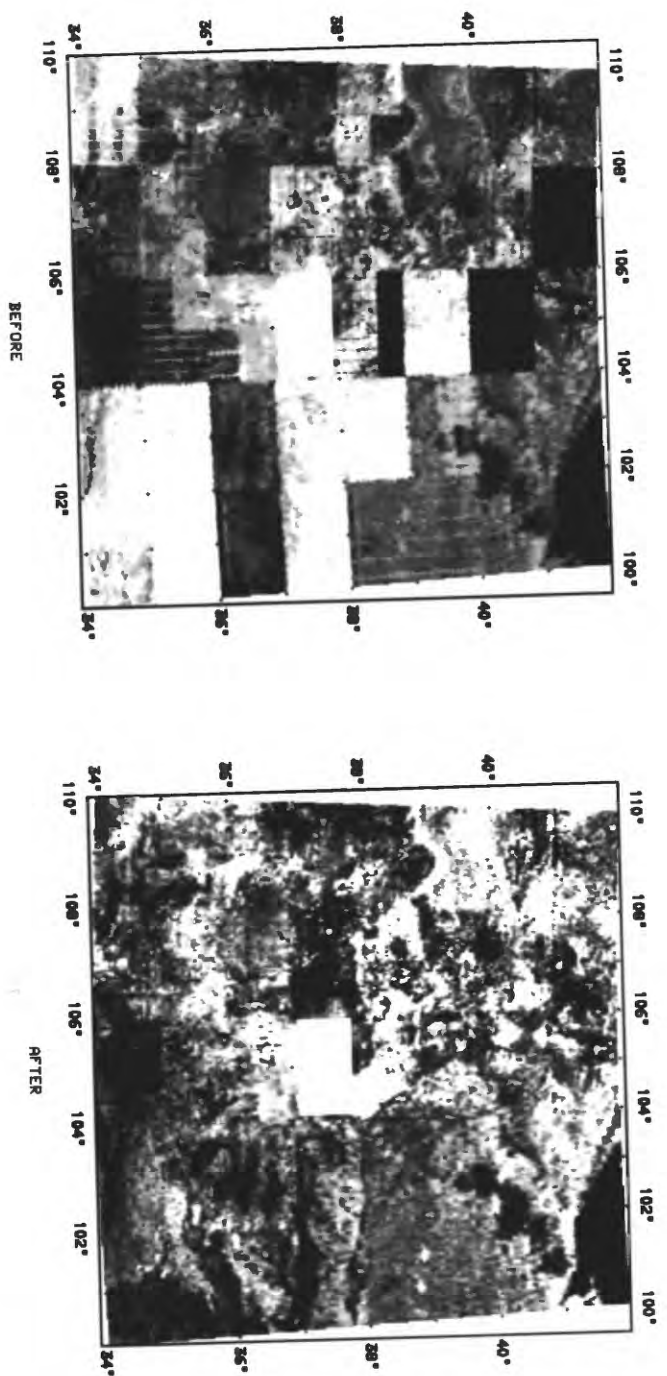quadrangle before and after
corrections.

Figure 2. Data for a block of quadrangles centered in Colorado before and after corrections.

between adjacent blocks of data should generally be less than 5 percent. In a few parts of the uranium map (Map C) rectangular patterns (e.g. in eastern Arizona) suggest that some of the errors are greater than 5 percent.

Map B is an index map of the NTMS quadrangles with the corrections applied to the data in each quadrangle. The data consist of the apparent surface concentrations of percent potassium (K), parts per million (ppm) equivalent uranium (eU), and ppm equivalent thorium (eTh), or count rates in the potassium (CK), uranium (CU), and thorium (CTH) data channels. In the index map the concentration data are denoted as K, U, and TH and the count rate data as CK, CU, and CTH. If a correction was applied to all of the data for the quadrangle, the letter q was appended to the data type and if individual flight lines were corrected, the letter l was appended. In all cases the count rate data required a correction factor for the entire quadrangle and for that reason the q was not used.

EQUIVALENT URANIUM MAP

Map C presents the equivalent uranium at a scale of 1:2,500,000. The data have been grouped into intervals of 0.5 ppm eU. Blank areas on the map correspond to areas of no data. 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) also 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 the digital data are missing from the archive 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 and because mining in such areas would not be permitted).

States with large areas of low values (less than 1.5 ppm eU) are Oregon, western Washington, Northern California, northwestern Nebraska, northern Maine, Michigan, Wisconsin, Minnesota, Florida, and the outer coastal plains of New 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.

In central Ohio most of the rocks have elevated uranium concentrations (greater than 3.0 ppm eU). Most of the elevated values occur in areas underlain by Devonian and upper Silurian limestones and shales. In central Ohio the uranium is widely dispersed as a result of glacial processes, but in southern Ohio below the glacial boundary (Bownocker, 1965) the elevated uranium values are more localized and occur in areas underlain by the Devonian black shales. Some of these areas have concentrations greater than 5.0 ppm eU. Similar high values

occur at intervals along the outcrop of the Devonian shales and adjacent Silurian rocks in Kentucky.

Many of the rocks in the Inner Piedmont areas in Georgia, South Carolina, and North Carolina have concentrations greater than 3.0 ppm eU and some areas have concentrations greater than 5.0 ppm eU. Most of these areas are underlain by granites, granitic gneisses, and metamorphic rocks. The zone of highest eU concentrations is bounded on the north by the Brevard zone of cataclasis within which most of the faults have a NE trend. 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).

The upper Cretaceous rocks in eastern Mississippi and central Alabama have uranium concentrations generally greater than 2.0 ppm eU and several large areas of these rocks have levels greater than 3.0 ppm eU. The highest concentrations (greater than 4.5 ppm eU) in these rocks occur in eastern Alabama. The rocks at the base of the Prairie Bluff Chalk, which is part of this group of rocks, are described as containing phosphatic nodules (Eargle, 1950; Bicker, 1969) which generally contain concentrations of uranium greater than 5.0 ppm eU (Osmond, 1964). However, the extent of the Prairie Bluff Chalk cannot explain the broad regional pattern seen in the uranium data. These data suggest that most of the upper Cretaceous rocks in Alabama contain uranium concentrations greater than 3.0 ppm eU and the same stratigraphic units in eastern Mississippi also have locally high uranium concentrations although the general levels are lower than in Alabama.

Many of the rocks in eastern Pennsylvania have uranium concentrations greater than 3.0 ppm eU. Some of the highest values (greater than 5.0 ppm eU) occur in east central Pennsylvania in areas underlain by middle to upper Devonian rocks. Many of these higher values occur near the ends of various folds. Most of the higher values in northeastern Pennsylvania occur in areas underlain by rocks of the Catskill Formation (refer to Pennsylvania Geological Survey, 1980) and many of the known uranium occurrences in Pennsylvania are in these rocks (McCauley, 1961; Rose, 1970).

Uranium concentrations greater than 2.5 ppm eU occur over large areas in east central New Hampshire and southwestern Maine. About 30 percent of these areas have concentrations exceeding 5.0 ppm eU. In New Hampshire the highest concentrations generally occur in areas underlain by Conway Granite which is known to have uranium concentrations greater then 5 ppm eU (Richardson, 1964). In Maine the areas of highest uranium 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 elevated uranium concentrations (greater than 2.5 ppm eU) and presumably the surface soils (which are being measured by the gamma-ray data) contain materials derived from the granitic rocks. Other locally higher uranium concentrations in Maine occur along the Atlantic coast and in north-central Maine which are also related to two-mica granites. A southwestward trending zone of uranium concentra-

tions greater than 2.5 ppm eU extends from southwestern Maine through New Hampshire and across Massachusetts. This area is underlain by Paleozoic granites and eugeosynclinal deposits of Devonian and Silurian ages.

In southwestern New Mexico, a large area of Tertiary volcanic rocks, and sediments derived from them, have uranium concentrations greater than 3.0 ppm eU and about 50 percent of the area has values greater than 4.5 ppm eU. In northern New Mexico much of the area underlain by upper Cretaceous rocks has uranium concentrations greater than 2.5 ppm eU with localized areas greater than 5.0 ppm eU. Numerous uranium occurrences within the area defined by lat 34°45' N to lat 36° N and long 103° W to long 105° W are described by Finch (1972). Northwestern New Mexico also has numerous occurrences of uranium mineralization which are discussed in Granger and Finch (1988). These uranium occurrences and mines lie within the area denoted as the Colorado Plateau Uranium Province and many other areas of uranium mineralization are found in Colorado, Arizona, Utah, and Wyoming (Granger and Finch, 1988).

Areas of known uranium occurrences in Arizona are presented by the Arizona Department of Mineral Resources (1958). In northeastern Arizona a large area underlain by upper Cretaceous rocks (centered near lat 36°25' N and long 110°20' W) has uranium concentrations generally greater than 2.5 ppm eU and, although known uranium occurrences are not found within this area, they are found in the adjacent Jurassic rocks. Uranium mineralization has also been found in the area of outcropping Triassic rocks (along a line from lat 36°10' N and long 111°30' W to lat 34°35' N and long 109°30' W), within which, localized areas have concentrations greater than 4.5 ppm eU. Additionally, the entire southwestern portion of Arizona has concentrations greater than 2.0 ppm eU with large areas greater than 4 ppm eU. Many of the more radioactive rocks in this area are either Precambrian granites or Tertiary volcanic rocks. This zone of higher eU concentrations extends into southeastern California and the southern tip of Nevada. Many of the known uranium occurrences in Arizona are distributed throughout this area (Arizona Department of Mineral Resources, 1958).

In central Nevada and west-central Utah, the Tertiary volcanic rocks and sediments derived from them have concentrations generally greater than 2.5 ppm eU. Within this area most of the higher uranium 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 uranium concentrations are associated with volcanic centers. The northern area (centered near lat 39°45' N and long 113° W) covers the Keg Caldera and parts of the Dugway Valley and Dugway and Thomas Ranges. The southern area (centered near lat 38°30' N and long 112°30' W) covers much of the Marysvale volcanic field

Another zone of elevated uranium values (greater than 2.5 ppm eU) follows a sinuous pattern in east-central Utah and west-central Colorado in the area bounded by lat 38° N to lat 40° N and long 107° W to long 111°30' W. This zone of higher values coincides mostly with areas underlain by the upper Cretaceous

Mancos shale. The Tertiary age shales of the Green River Formation in northeastern Utah (centered near lat 39°45' N and long 109°30' W) also have uranium concentrations generally greater than 2.5 ppm eU.

RADON POTENTIAL

Because an aerial gamma-ray system is measuring the gamma-ray flux from the decay of ^{214}Bi in the ground (corrections have been made for ^{214}Bi in the air) and because ^{214}Bi is produced by the decay of ^{222}Rn, the aerial gamma-ray data should be useful for estimating the concentrations of ^{222}Rn in the soil gas. Gunderson and others (1988) made simultaneous measurements in Montgomery County, Maryland, of the apparent surface concentrations of uranium in the soils and of radon in the soil gas, and the results indicate that the surface gamma-ray data can be used to estimate the radon in the soil gas. Duval (1989) compared the average indoor radon in counties in New Jersey to the average apparent surface concentrations of radium (radium = 0.333 eU) and the results indicate that the average radium concentrations can be used to estimate the average indoor radon levels in New Jersey.

In another study, Duval and Otton (1989) compared average indoor radon levels in townships in Washington, Oregon, and Idaho to apparent surface concentrations of radium. These results also suggest a predictive relationship; however, townships underlain by highly permeable soils (greater than 6 in/hr as measured by water percolation tests) constitute a distinct subset compared to townships with less permeable soils. In this study the effects of highly permeable soils apparently increased the average indoor radon for a given concentration of radium by about a factor of 6. Another important factor in the determination of the indoor radon level is the type of housing construction and Haig Kasabach (New Jersey Geological Survey, personal communication) has data which indicates that, for soils with similar radium concentrations, the difference in the average indoor radon levels for homes with basements is about twice the average indoor radon levels for homes without basements.

All of the above results indicate that the map of the apparent surface concentrations of uranium can be used to estimate average indoor radon levels in a relative sense. In other words, an area in a particular region of the country with 4 ppm eU should result in higher average indoor radon levels than another area in the same region with 2 ppm eU; however, because of differences in soil weathering, 4 ppm eU in New Jersey would not be expected to result in the same average indoor radon levels as 4 ppm eU in Colorado. Areas with inherently permeable soils should tend to have higher average indoor radon levels than areas with less permeable soils if the areas have similar radium concentrations.

CONCLUSIONS

The compilation of the NURE aerial gamma-ray data to produce a map of the apparent surface concentrations of uranium for the conterminous United States has resulted in a reasonably accurate representation of the distribution of uranium in the surface rocks and soils. This statement is supported by the general agreement between mapped geology and the patterns seen in the uranium distribution. Because of the relationship between uranium and radon, this map is also useful as a tool for estimating indoor radon levels; however, this map cannot be used to directly estimate the radon levels because of the effects of permeability, housing construction, and differences in soil weathering profiles.

ACKNOWLEDGEMENTS

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