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STREAM SEDIMENT GEOCHEMICAL SURVEYS FOR URANIUM

by

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91

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ABSTRACT

One of the major objectives of the National Uranium Resource Evaluation (NURE) program (sponsored by the U. S. Department of Energy) is to identify areas favorable for commercial recovery of uranium. One phase of this program is Hydrogeochemical and Stream Sediment Reconnaissance (HSSR) of the contiguous forty-eight states and Alaska. Stream sediment is more universally available than ground and surface waters and comprises the bulk of NURE samples.

Orientation studies conducted by the Savannah River Laboratory indicate that several mesh sizes can offer nearly equivalent information. Sediment is normally sieved in the field to pass a 420-micrometer screen (U. S. Std. 40 mesh) and that portion of the dried sediment passing a 149-micrometer screen (U.S. Std. 100 mesh) is recovered for analysis.

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Sampling densities usually vary with survey objectives and types of deposits anticipated. Principal geologic features that can be portrayed at a scale of 1:250,000, such as major tectonic units, plutons, and pegmatite districts, are readily defined using a sampling density of 1 site per 5 square miles (13 km²). More detailed studies designed to define individual deposits require greater sampling density.

Analyses for elements known to be associated with uranium in a particular mineral host may be used to estimate the relative proportion of uranium in several forms. For example, uranium may be associated with thorium and cerium in monazite, and with zirconium and hafnium in zircon. Readily leachable uranium may be adsorbed or trapped in oxide coatings on mineral particles. Soluble or mobile uranium may indicate an ore source, whereas uranium in monazite or zircon is not likely to be economically attractive.

Various schemes may be used to estimate the form of uranium in a sample. Simple elemental ratios are a useful first approach. Multiple ratios and subtractive formulas empirically designed to account for the presence of particular minerals are more useful. Residuals calculated from computer-derived regression equations or factor scores appear to have the greatest potential for locating uranium anomalies.

INTRODUCTION

The National Uranium Resource Evaluation (NURE) program was begun in the spring of 1973 to improve the assessment of domestic uranium resources in the continental United States and to identify areas favorable for commercial exploration in response to the rapidly increasing national demand for uranium. The Savannah River Laboratory (SRL) has accepted responsibility for Hydrogeochemical and Stream Sediment Reconnaissance (HSSR) of 1,500,000 square miles in 30 eastern and 7 western states. Oak Ridge Gaseous Diffusion Plant (ORGDP) and Los Alamos Scientific Laboratory (LASL) accepted responsibility for similar reconnaissance in the rest of the continental United States, including Alaska.

The principal NURE-HSSR objective is to define regional geochemical features at a scale of 1:250,000 which may be related to the presence or absence of uranium resources. Stream sediment is one of several media being sampled in the NURE geochemical reconnaissance. Although media such as ground water, surface water, lake sediments, soil, and botanical samples may offer unique capabilities or advantages and have been or are being sampled by SRL and other NURE labs, this paper is oriented primarily to the discussion of stream sediments.

SAMPLING

Density

SRL orientation studies indicate that principal geologic features that can be portrayed at a scale of 1:250,000, such as major tectonic units, plutons, and pegmatite districts, are readily defined using a sampling density of one site per five square miles. This sampling density is commonly accepted in other reconnaissance studies. Garrett (1977) has published data indicating that information returned from reconnaissance geochemical sampling for uranium at densities as low as one site per ten square miles (26 km²) was equivalent to that at five square miles in most geologic terranes. The notable exception was for an area where uranium occurred primarily in pegmatites, in which case, even the maximum density of one site per five square miles was marginal.

Collecting Representative Samples

The total variability of sediment samples from a particular site or locality (S_1^2) can be broken down into an analytical variance (S_a^2), plus a sampling variance (S_s^2), reflecting differences between samples within the length (~15 to 30m) and width of stream termed the site:

$$S_1^2 = S_a^2 + S_s^2$$

The sampling variance can be further subdivided into effects of different samplers, sampling method, sampling location in the stream, etc. A study of sampling variability in the southeastern United States (SRL, 1975) indicated the variance of samples

collected from different spots at a site was considerably larger than variance due to sampling method and samplers. In this study, the standard deviation (S_1) for within-site variability was equal to $0.28 \log_{10}$ of the uranium concentration (i.e., at a mean of 10 ppm 68% of values at a site fall within a factor of about 1.9 of the mean). The sampling variability limits the resolution for detecting anomalies.

To reduce S_1 , and thereby improve resolution of anomalies, sampling techniques may be improved (for example, by training samplers in consistent techniques; Price and Jones, 1979) and multiple samples may be taken in each stream. The samples can then be combined (compositioned) or the analytical results averaged. In view of the dominant effect of within-site variations over personnel and methods, as noted above, the combination of samples is a very effective method. If n samples are taken at a site, then the sampling variance becomes S_s^2/n . Combination of two samples reduces S_s by 30%, but the improvement from the fifth to the sixth sample is only about 10%. Therefore, five ^{was} ~~ways~~ selected by SRL-NURE personnel as the minimum number of spaced (~5 m apart) samples to be composited and sieved together at each stream site. ✓ was

The optimum mesh size for sediment analysis should be determined by an orientation sampling program within the study area before any reconnaissance program is undertaken (Levinson, 1974, p. 255). Orientation studies conducted by SRL sampling teams indicate that several mesh sizes can offer nearly equivalent information. Factors in the choice of optimum size for analysis include the type of uranium deposit being sought and the presence of contaminants which are size-fractionated, for example, windblown material. Wenrich-Verbeek, et al.

(1976, p. 273) strongly recommend that "only grain-size fractions of less than 90 μm (170 mesh) should be analyzed" to enhance the signal from adsorbed uranium relative to the dilution effects of economically uninteresting minerals. Ferguson and Price (1976) and Price (1979) discuss some results from NURE orientation studies in the eastern United States and conclude that -100 and -200 mesh material should offer nearly equivalent information. Because many routinely collected samples do not have sufficient -200 mesh material for analysis, -100 mesh ($<149 \mu\text{m}$) is the size chosen by SRL.

SAMPLE INTERPRETATION

Once a suite of representative sediment samples has been collected, the often difficult task of extracting from them the information they contain about economic deposits begins.

Analytical data should be reliable enough that interpretation can be based mainly on geological and geochemical considerations. Analytical chemistry has progressed to the point where this is possible; it is up to the geologist to insist that adequate methods are used and to understand and check the analytical methods sufficiently to verify their reliability.

A sufficient number of reference standards and duplicate samples should be analyzed to evaluate accuracy, precision, and sensitivity. Precision and sensitivity are more important to geological interpretation of exploration geochemical data than absolute accuracy. Good precision means that samples will maintain their relative order upon reanalysis. Good sensitivity implies the element being sought will be detected in most samples.

Poor sensitivity artificailly forces many samples into a single class below the analytical detection limit, thereby obscuring any statistical distribution that may exist for those samples. Only if these requirements of good precision and sensitivity are met can standard interpretive techniques, such as cumulative frequency plotting, be applied (Sinclair, 1974, p. 146).

Details of analytical methodology for uranium are the topic of another paper in this issue (Ward and Price, 1980). If precision and accuracy are adequate, then the choice of method is primarily governed by the available facilities and by whether an analysis for total uranium or partial (such as readily leachable) uranium is desired.

Sediment samples may be analyzed by a variety of methods. SRL has relied primarily on neutron activation analysis (NAA) of untreated samples. NAA analyzes sediment samples for total uranium together with thorium, cerium, hafnium, and several other elements. NAA for sediment samples was chosen at SRL for four reasons: (1) NAA is a readily automated technique suitable for large numbers of samples, (2) uranium and related elements could be determined simultaneously, (3) NAA for uranium is subject to few interferences, and (4) an operating reactor was readily available.

Single Element Analyses

Extensive literature exists on the interpretation of single-element analytical data. Typically, the values are ranked and the anomaly threshold is chosen either arbitrarily or by consideration of the distribution of the data (Sinclair, 1976). Anomalous samples,

when plotted on maps, are supposed to show where to explore in more detail.

For the location of epigenetic uranium deposits, an analysis for extractable uranium is preferable to a total uranium analysis. Rose et al. (1976) demonstrated that an acetic acid-hydrogen peroxide leach could yield data with good anomaly-to-background contrast where total uranium analyses did not clearly define an area containing uranium prospects (Figure 5 from Rose et al., 1976).

Because uranium produces a series of daughter products from radioactive decay, the detection of one of these daughters in sediments may be as valuable as the detection of uranium. Hansen et al. (1979) discuss the analysis of polonium-210 in stream sediments. Polonium-210 is near the end of the uranium-238 decay chain and follows several relatively mobile isotopes including radium-226 and radon-222. The polonium content of stream sediment and soil samples is high near concealed mineralization. The authors do not compare polonium-210 results to more conventional techniques.

Single element analyses may be augmented by physical measurements on the samples such as loss on ignition (LOI) or surface area. Brundin and Nairis (1972) illustrate the correction of stream sediment uranium concentrations for the organic content of the samples as estimated by LOI. In soil surveys, Hansen et al.

(1979) demonstrate that false anomalies for certain adsorbed elements (e.g., polonium) may be suppressed by correcting for the surface area of the sample.

Multi-Element Analyses and Ratio Interpretation

The goal of geochemical exploration is to relate chemical variations in natural samples to the presence or absence of ore deposits. Significant anomalies appear in those samples whose analyses are influenced by nearby ore. Failure to investigate controls of elemental concentrations in samples will lead to the fruitless followup of many nonsignificant or false anomalies.

Uranium or other metals of interest may occur in several forms within a sediment sample (Rose, 1977, p. 315 and p. 330; Tewhey, 1977). Some of these forms represent a background contributed by the normal uranium content of common minerals. For example, uranium contents varying between 2 and 8 ppm ($\mu\text{g/g}$) could, in an extreme case, be ascribed wholly to the relative variation of quartz and biotite, each containing their respective average uranium concentration (Rogers and Adams, 1970).

Analysis of samples for many diverse chemical elements allows the geochemist to correct for some of the vagaries of nature and to extract certain information from the data that can be demonstrated (intuitively or empirically) to be related to the likelihood of an ore occurrence.

Puchlik (1979), in a study of 1300 stream sediment samples from the Winnemucca, Nevada, $1^\circ \times 2^\circ$ NTMS quadrangle, demonstrated

that almost all known uranium occurrences in the quadrangle could be detected by considering only the U/Th ratio of the samples.

Thorium and uranium, because of similar radius ($\sim 1\text{\AA}$) and valence (+4), exhibit very similar geochemical behavior under primary geologic (magmatic) conditions. Magmatic differentiation, while producing some concentrations as at Ilimaussaq, Bokan Mountain, and Rossing, is seldom sufficient to produce uranium ore. In fact, most uranium ore deposits depend for their formation upon a mechanism to remove uranium from its primary, thorium-associated, occurrence in magmatic minerals. Removal is accomplished by oxidation of uranium to the relatively mobile 6+ valence, and re-deposition occurs where reduction can be effected. Observation of uranium concentrations significantly above the Clarke value (2 to 4 ppm) in the absence of similarly enhanced thorium levels is an intuitively obvious signal that an environment favorable for the occurrence of uranium deposits has been encountered.

LOCATING URANIUM DEPOSITS BY ELEMENTAL RATIO INTERPRETATION

Physico-Chemical Basis

Price and Ferguson (1977) discuss using elemental ratios of uranium to thorium, hafnium, and dysprosium as corrections for uranium anomalies due to the presence of the minerals monazite $[(\text{Ce}, \text{La}, \text{Nd}, \text{Th})\text{PO}_4]$, zircon $[(\text{Zr}, \text{Hf})\text{SiO}_4]$, and xenotime $[(\text{Y}, \text{Dy})\text{PO}_4]$, respectively, in stream sediments. Stream sediment analyses for uranium in the Kings Mountain, North Carolina,

area outlined a sub-area which has been known for nearly a century to contain monazite. Therefore, this information is of little utility for designating new areas which appear likely to contain commercial uranium deposits.

In addition to monazite, several other minerals known to occur in this general area may contain significant amounts of uranium. Perhaps the most common one is zircon, but others such as xenotime or samarskite may contain very large amounts of uranium and have been reported either from the study area or nearby regions (Conley, 1958). The uranium content of these minerals is given in Table 1 along with the element which can be determined by NAA to indicate the presence of the mineral. These key elements will be referred to in discussions below.

Figure 1 is a logarithmic plot of uranium versus thorium concentrations for -100 to +200 mesh stream sediments in the Kings Mountain area. An increase in uranium plus thorium (e.g., Site 69) could be simply due to an unusually high concentration of minerals such as zircon or monazite in a particular sample. Conversely, low uranium and/or thorium concentrations may indicate only an abundance of common silicate minerals such as quartz or feldspar in a particular sample. Variations in the uranium-thorium ratio could represent variations in the ratios between uranium- and thorium-bearing minerals, such as monazite and zircon. Interpretation of data for thorium, hafnium, and cerium can allow distinction of these alternatives.

Figure 2 shows reported uranium and thorium concentrations in monazite from the Piedmont of the Carolinas (Overstreet et al., 1968). Note that uranium-thorium ratios in most monazites are less than about 0.15. However, a typical uranium-thorium ratio for zircons might be 2:1, with the lowest expected about 0.15, as shown in Figure 3 (Hurley and Fairbairn, 1957).

Line A-A' on Figure 1 represents a uranium-thorium ratio of 0.15. It may be presumed that samples having a higher ratio (about 65% of the samples) have uranium from a mineral other than monazite. This mineral could be zircon. Assuming line B-B' to be a threshold anomaly level of uranium-thorium ratios in the samples, eight samples (Numbers 6, 8, 44, 53, 58, 69, 72, 80) have anomalously high uranium-thorium ratios.

When the hafnium-cerium values are plotted (Figure 4), the eight samples with high uranium-thorium ratios do not remain grouped. Samples 72 and 80 have a high hafnium-cerium ratio and may be presumed to contain zircon as a significant uranium-rich mineral. Samples 6 and 8 have relatively low hafnium-cerium ratios, indicating that zircon is not an important mineral constituent. Because the high uranium-thorium ratios of Samples 6 and 8 eliminate monazite as their important uranium mineral, it may be concluded that either an unknown uranium-rich phase is present or that the monazite or zircon present in these samples is unusually rich in uranium.

Analytical data for thorium, hafnium, and cerium provide an indication of samples which are anomalously high in uranium after a correction is made for: (1) the presence of typical monazite, (2) the presence of zircons, and (3) the total abundance of heavy or resistate minerals. Two sites (6 and 8) persist as anomalous.

In Figure 5, the sum of the logarithms for dysprosium (representing xenotime), thorium (representing monazite), and hafnium (representing zircon) concentrations are plotted against uranium concentrations. Seven samples (6, 7, 8, 14, 44, 57, and 70) were chosen as being anomalous. The map distribution of the ratio $\ln U / (\ln Th + \ln Hf + \ln Dy)$ is shown in Figure 6. Only Sample 44 comes from the known monazite area; all others come from an area yielding high concentrations of dissolved uranium in ground water and stream water samples. It is logical to assume that these seven anomalous samples contain either common minerals unusually enriched in uranium or some peculiar or uncommon uranium-rich phase.

The only criterion for the validity of the stream-sediment anomaly available for this study was correspondence to an area of high dissolved uranium. Subsequent field investigations including a detailed gamma spectrometer survey and limited soil sampling have confirmed the location of the anomaly area. Soil samples from the area contain up to several hundred ppm leachable uranium.

In the Kings Mountain study, the U/Th ratio alone identified an approximately equal number of valid and false anomalies. A

significant number of high uranium analyses was due to the presence of zircon (as indicated by Hf) in the samples.

Ratio Interpretation

The total uranium content (U) of a sample may be considered partitioned into a series of components:

U_a - anomalous uranium related to a hydromorphic anomaly
or to above-normal uranium content in major or minor
rock-forming minerals.

U_m - average content in common rock-forming minerals of sample.

U_{tc} - uranium in light rare-earth minerals such as monazite.

U_y - uranium in heavy rare-earth minerals such as xenotime.

U_z - uranium in zircon.

U_{pa} - uranium dependent on physical attribute such as organic
content, surface area, etc.

such that: $U = U_a + U_m + U_{tc} + U_y + U_z + U_{pa} \dots$. The objective
of any multi-element data treatment is to enhance U_a relative to
total U.

In many samples with high total uranium, U_{tc} will be the
largest component of U. For these samples:

$$U \approx U_a + U_{tc} \quad (1)$$

and the ratio, $R = (U)/(Th)$, [() used for analytical values],

reduces to:

$$R = \frac{U_a + f(Th)}{(Th)} \approx \frac{U_a}{Th} + C \quad (2)$$

Graphically, a profile along a (geographic) line of samples would be similar to that shown in Figure 7.

In the Kings Mountain, North Carolina, study discussed above, definition of U_a was improved by a ratio of the form:

$$R = \frac{U_a + (U_{tc} + U_y + U_z)}{[(Th) + (Dy) + (Hf)]} = \frac{U_a + f(Th, Dy, Hf)}{[(Th) + (Dy) + (Hf)]} \approx \frac{U_a}{[...] } + C \quad (3)$$

The need to include as many elements as practical in the calculation of R is consistent with the correlation of uranium with such elements as cerium, dysprosium, hafnium, and others in mineral analyses. It seems intuitively that weak anomalies ($U_a \ll U$, denominator terms) may be suppressed, but the examination of Figure 5 above suggests that this may not always be the case.

Calculation of Residual Uranium

Koch et al. (1979) have attempted to correct (U) in SRL stream sediment data for mineral contributions by a subtractive technique. Literature values for typical ratios of uranium to other elements in detrital minerals were used to derive the proposed empirical relation:

$$U_{\text{residual}} = (U) - Ce/45 - Hf/60 - (Dy - 0.02 Ce)/7 - 0.3 (Th - Dy/9 - Ce/5.75 - Hf/60) \quad (4)$$

An intuitive advantage of this technique is that the residual uranium value is not divided by values for other elements. Unfortunately, published averages for U/Hf ratios in zircon and U/Ce ratios in monazite are not adequate to precisely define the mineral

subtraction model. Uncertainties in mineral analyses remain as uncertainties in U_{residual} or U_a .

A promising approach is to use all available analytical data for a set of samples in order to calculate a multiple linear regression equation against uranium. Thereby, any or all elements which show positive or negative correlation with uranium will be given proper consideration. The resultant regression equation can then predict a uranium value for a sample. The excess or deficiency of the observed value from the predicted value may be taken as a measure of the "promise" of that sample. Rose et al. (1970) use a similar multiple regression technique to reduce background noise and to enhance weak anomalies in a 3000-sample base-metal survey covering 7500 square miles of southeastern Pennsylvania.

Analysis of Field Data from Six NTMS Quadrangles

NAA data from six $1^\circ \times 2^\circ$ NTMS quadrangles in the southeastern United States were combined into a single data set upon which several of the interpretive techniques discussed above were tried. The quadrangles were: Knoxville (Baucom and Ferguson, 1979), Charlotte (Heffner and Ferguson, 1978a), Greenville (Ferguson, 1978a), Spartanburg (Heffner and Ferguson, 1978b), Augusta (Jones, 1979), and Athens (Ferguson, 1978b).

Figure 8 is an outline geologic map of the area 33° to 36° N latitude by 80° to 84° W longitude comprising the six NTMS $1^\circ \times 2^\circ$

quadrangles. This figure was prepared by Jack S. Whisnant of Carolina Geoscience, Columbia, South Carolina, from information published in the six SRL quadrangle reports listed above. The original sources and compilers of geologic information, referenced in these reports, should be consulted to identify the map units shown in Figure 8.

Figure 9 is a plot of the cerium content of stream sediments in the six-quadrangle area. Since monazite contains about 25% cerium, the 2000-ppm Ce contour indicates samples containing about 1% monazite. The southeastern monazite belts of Mertie (1953) are better defined in this figure than by the original limited USGS monazite sampling. On this and following figures, no statistical analysis was done to pick contour levels. The contours are essentially arbitrary.

Figure 10 is a map of U/Th ratios over the area of Figure 8. The ratio of the Clarke values of these elements is about 0.3, and the figure is contoured at U/Th ratios of 0.4, 0.5, 0.6, 0.8, and >1.0. Comparison with Figure 9 reveals that U/Th ratios are generally high where cerium values are low, such as in the western flank of the Inner Piedmont and in the Charlotte belt. Broad areas yield stream sediments with U/Th ratios greater than twice the Clarke value. Despite these high U/Th ratios, gross geologic features of much of the area are unfavorable for the occurrence of uranium ore. Thus, the U/Th ratio alone yields many false anomalies.

Figure 11 is a map of the ratio $\{\log U/(\log Th + \log Hf + \log Dy)\}$ as discussed above. Note that some areas of high U/Th ratios (Figure 10) persist as highs on this figure, whereas some do not, and some new highs appear. The new anomalies appearing in Quadrants AG, CG, and DE and the blank Quadrants FB and HB will be followed through further discussions. (In designating quadrants, rank precedes file.)

The small anomaly at the intersection of Quadrants BI and CI includes the radioactive Hegler prospect described by Sundelius and Bell (1964), who noted the occurrence of molybdenite and allanite, but did not detect uranium or thorium in emission spectrographic analyses of samples. Radioactivity measurements by SRL using a 4-channel gamma spectrometer indicate estimated uranium (eU) values of up to 250 ppm and low (15 ppm) estimated thorium (eTh) values on the dump. This anomaly does not appear on other figures.

Figure 12 was prepared using the subtractive formula of Koch et al. (1979). Anomalies in Quadrants AG and DE are very similar to those in Figure 11. Note that the anomaly in Quadrant CG is missing in this figure, and that a large anomaly appears in Quadrant HB. Quadrant FB remains blank.

Figure 13 represents residual uranium calculated by the following equation:

X = residual uranium

$$X = \log(U) - [0.071 + 0.603 \log(\text{Th}) + 0.297 \log(\text{Hf}) + \\ 0.101 \log(\text{Ce}) + 0.210 \log(\text{Al}) - 0.012 \log(\text{Sc}) \\ - 0.185 \log(\text{Fe})] \quad (5)$$

The equation was obtained as best-fit by multiple linear regression of uranium vs. other NAA data for the study area. The anomalies in Quadrants AG, CG, and DE persist. There is no anomaly in Quadrant HB. A new anomaly area has appeared in Quadrant FB.

Figure 14 represents residual uranium values calculated from a regression equation in which raw analytical data are replaced by factor scores. Results are very similar to those shown on Figure 13. A notable exception is that the anomaly area in Quadrant ~~BH~~ does not appear on these figures.

✓ HB

Validity of Data Treatment

The ideal proof of a geochemical anomaly would be an operating mine. No uranium mines exist in the area of this study. However, the anomaly in Quadrant CG has been confirmed to contain several hundred ppm extractable uranium in soils.

Cursory examination of aerial radioactivity surveys conducted by DOE indicates general agreement between geochemical anomalies and radioactive anomalies in the study area.

As noted above, most commercially interesting uranium minerals are relatively soluble so that one test of anomalies in stream sediment surveys might be the presence of coincident anomalies in dissolved uranium.

Each of the data treatment techniques discussed above has some intuitive advantages to recommend it, but none has been verified by the actual discovery of uranium ore. Relative evaluation of the techniques cannot be done at this time.

A few uranium mineral localities are noted in the HSSR reports for the six-quadrangle area. Even though several of these localities lie within the anomaly areas indicated on Figures 10 through 14, they do not provide a very satisfying test of the validity of the anomalies.

SUMMARY

Stream sediments provide a very powerful sampling medium for uranium exploration. Because uranium occurs in several forms in a sample and many anomalies in reconnaissance surveys are weak, either sample treatment or data treatment must be used to enhance the signal from uranium associated with potentially economic sources. Simple elemental ratios and graphical analysis offer a useful approach to multi-element data treatment, but may yield false anomalies or fail to disclose some valid anomalies which exist within the data set. Calculation of residuals from multiple linear regression of scaled data is recommended as the most promising approach to data interpretation.

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TABLE 1

Some Minerals of Stream Sediments

NAA Key	Mineral	Formula	U Content, ppm
-	Common Silicates	-	1 to 10
Hf	Zircon	(Zr, Hf)SiO ₄	100 to 10,000
Ce, Th	Monazite	(Ce, La, Nd, Th)PO ₄	500 to 20,000
Dy	Xenotime	(Y, Dy)PO ₄	500 to 35,000
Ta	Samarskite	(RE, Nb, Ta) ₂ O ₆	> 120,000

Fig. 1. Uranium and thorium concentrations in stream sediment samples from the Kings Mountain area. Lines A and B discussed in text. Numbers refer to sample identities.

Fig. 2. Uranium and thorium concentrations in monazite from the Carolinas Piedmont.

Fig. 3. Uranium and thorium concentrations in zircon.

Fig. 4. Hf/Ce in -100 +200 mesh sediment samples.
Numbers refer to sample identities.

Fig. 5. Uranium concentration versus sum of concentrations of dysprosium, thorium, and hafnium in stream sediment samples. Numbers refer to sample identities.

Fig. 6. Anomaly Map of $\ln U / (\ln Th + \ln Hf + \ln Dy)$ for the Kings Mountain, North Carolina, Area. Monazite abundant in NW 1/3 of area; for explanation of map patterns see Price and Ferguson (1977).

Fig. 7. Typical profile of uranium/element ratios. Left box shows total uranium broken into uranium in monazite or other minerals where $U = f(\text{Th})$ and anomalous hydromorphic uranium. Right box shows U/Th ratio broken into components according to source of uranium.

Fig. 8. Composite geologic map for the Athens, Augusta, Charlotte, Greenville, Knoxville, and Spartanburg NTMS quadrangles. Granitic rocks are indicated by checks and gabbroic rocks by a stippled pattern.

Fig. 9. Cerium concentrations in stream sediment samples from the area of Figure 8.

Fig. 10. Uranium/thorium ratio in stream sediment samples from the area of Figure 8.

Fig. 11. The ratio: $\log(U)/\log(\text{Th}) + \log(\text{Hf}) + \log(\text{Dy})$ in stream sediment samples from the area of Figure 8.

Fig. 12. Residual uranium anomaly areas (subtractive mineral formula of Koch, et al., 1979).

Fig. 13. Residual uranium anomaly areas from Equation 5.

Fig. 14. Residual uranium anomaly areas (four-factor scoring method for each sample to replace analytical data for regression calculations).