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URANIUM RESOURCE ASSESSMENT THROUGH STATISTICAL ANALYSIS OF EXPLORATION GEOCHEMICAL AND OTHER DATA

George S. Koch, Jr.

Department of Geology
University of Georgia
Athens, Georgia

Richard J. Howarth

Applied Geochemisty Research Group
Imperial College of Science and Technology
London, England

John H. Schuenemeyer

Department of Mathematical Sciences
University of Delaware
Newark, Delaware

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Abstract. In the Hydrogeochemical and Stream Sediment Reconnaissance (HSSR) phase of its National Uranium Resource Evaluation (NURE) program, the U.S. Department of Energy (DOE) samples about 1400 sites for stream sediments in each two-degree quadrangle of the National Topographic Map Series (NTMS) and about 1200 sites for ground or stream water. Through a geological/statistical analysis, we find that NURE data are useful for assessing the uranium resources of the NTMS quadrangles.

Our computer-implemented System for Uranium Resource Evaluation (SURE) calculates a score for each NTMS quadrangle based on the HSSR, geologic, and radiometric data; we score the four Colorado quadrangles--Pueblo, Montrose, Durango, and Trinidad--that comprise the study area.

We interpret the scores in terms of geology and the known occurrences, which include the Hanson ore deposit with reserves of 30,000,000 lbs. U_3O_8 and the Pitch mine with reserves of 1,740,000 lbs.

SURE depends in part on distinguishing mineralized or metalliferous granitoids from barren ones through "geochemical signatures." We relate stream-sediment and whole-rock geochemical data from the study area to data from Great Britain.

Introduction

Summary of the Problem

In 1973, the United States Department of Energy (DOE) began the National Uranium Resource Evaluation (NURE) program in all of the United States except Hawaii. The program includes airborne radiometric and hydrogeochemical (stream water, ground water, and stream sediment) surveys, surface geologic investigations, and sub-surface drilling. The NURE data are published for individual two-degree National Topographic Map Series (NTMS) quadrangles. A major purpose for the program is to contribute to the assessment of uranium resources in the various quadrangles. This report gives the results of an investigation of the pertinence of NURE data for quadrangle assessment.

In particular, we have concentrated on evaluation of extensive data obtained in the Hydrogeochemical and Stream Sediment Reconnaissance (HSSR) phase of the NURE program. In this program, about 1,400 sites are sampled for stream sediments in each two-degree quadrangle and about 1,200 sites for ground or stream water. At the present time, these HSSR data have only a minor impact upon one of the terms in the formula by which the Department of Energy (or one of its subcontractors) calculates uranium endowment. In this paper, we demonstrate ways in which the HSSR data can provide independent estimates of uranium endowment, through statistical analysis. We also discuss the additional benefits of analyzing the airborne radiometric data and geological data from published maps and appraise the value of adding these sources of information.

Summary of the Results

Our statistical model for evaluation (system EVAL) provides an estimate of uranium endowment for each two-degree quadrangle. Because this model requires experience in geology, statistics, and data analysis, we have also devised a simplified model, presented in the package SURE, a System for Uranium Resource Evaluation. We have developed these models and successfully tested them for four contiguous quadrangles in southern Colorado; to establish their generality and further evaluate their validity, they need to be applied to other quadrangles.

For the study area, we compiled data bases of HSSR, radiometric, uranium-occurrence, and geologic information.

Finally, we devised a statistical analysis of the stream-sediment geochemistry to distinguish mineralized granites from unmineralized ones.

Our report to DOE (Koch and others, 1980) details our results; in this paper, we concentrate on our statistical model for evaluation (system EVAL). Additional papers, in preparation, will cover other parts of our study.

Objective and Scope

Our objective was to develop a practical system for quantitatively assessing the uranium resources of a particular area using HSSR, radiometric, uranium-occurrence, and published geologic data.

To meet this goal, we selected a study area consisting of the contiguous Pueblo, Montrose, Durango, and Trinidad two-degree NTMS quadrangles in southern Colorado (figure 1). The geology of this area is diverse; available data included geologic maps on the scale of the 1:250,000 quadrangles, multi-element HSSR data, and geologic occurrence data. In a previous project (Koch and others, 1979) we had studied the Pueblo quadrangle data and were familiar with it. Also, the area contains major uranium resources, including the Hanson ore deposit with reserves of 30,000,000 lbs. of U_3O_8 and the Pitch mine with reserves of 1,740,000 lbs. (Nelson-Moore and others, 1978, p. 149, 393).

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Data Bases

Content

The data bases are for HSSR stream-sediment and water samples, radiometric anomalies, geology in cells, and uranium occurrences.

Figure 2 shows the principal structural-geomorphic units in Colorado. The eastern one-quarter of the study area, including about half of the Pueblo quadrangle and a third of the Trinidad quadrangle, is in the High Plains part of the Great Plains geologic province. To the west are mountain ranges separated by broad valleys, including South Park and the San Luis Valley. The extreme northeastern part belongs to the Colorado Plateau.

Figure 2 also shows the Colorado Mineral Belt. According to Tweto (1968, p. 555), "Most of the metal mining districts of Colorado lie in the Colorado Mineral Belt, a generally narrow but somewhat irregular strip of ground that extends southwestward across the state from the mountain front near Boulder to the region of the San Juan Mountains."

Figure 3 summarizes the geology of the study area in relation to that of Colorado. In the High Plains, the rocks are horizontal or gently dipping sedimentary ones; those exposed at the surface range in age from Cretaceous to Recent, except for a few small areas of older Mesozoic rocks. Westward, the rocks in the Colorado Front Ranges are from Cambrian to Recent in age, and lie unconformably on the Precambrian metamorphic and igneous rocks that make up the core of the ancestral Rockies. To the west, the Paleozoic and Mesozoic rocks in the Sangre de Cristo Mountains and the Sawatch Range give way to the Cenozoic rocks of the San Luis Valley and the volcanic rocks of the San Juan Mountains. The quadrangle reports of the Los Alamos Scientific Laboratory (LASL) provide sketch maps and geological summaries for the four quadrangles together with references to detailed accounts of the geology (Shannon, 1978, 1979-a, 1979-b; Broxton and others, 1979; Dawson and Weaver, 1979; Morris and others, 1978).

HSSR Data Bases: The HSSR data base consists of stream-sediment and water data obtained from LASL on magnetic tape. The data are listed in the quadrangle reports.

Table 1 lists the number of samples of various types from the four quadrangles. Because we omitted a few samples for which analytical or rock-type data were unavailable, there are fewer samples than in the published reports.

Besides the numerical data on chemical elements for each sample site, we consider it essential to include the geologic age and lithology of the rock units. Susan F. Carpenter devised a scheme to represent each U.S.G.S. formation symbol by an eight-character code.

Uranium Occurrences: The uranium-occurrence data base contains edited data from Bulletin 40 of the Colorado Geological Survey (Nelson-Moore and others, 1978) with additional information from other sources; it lists the name of the occurrence, latitude and longitude, tons of ore, grade of ore, pounds of contained uranium, and host rock or rocks according to the eight-character codes.

Geology by Cells: This data base lists the presence or absence of geologic formations and faults in cells that are about 5.5 km on a side. In the study area, there are 2,480 of these cells. The geological data were obtained from the 1:250,000 geologic maps of the U.S. Geological Survey (Johnson, 1969; Scott and others, 1978; Steven and others, 1974; Tweto and others, 1976). Two workers recorded for each cell the presence and absence of faults and geologic formations, according to the U.S.G.S. symbols. Each cell contains from one to 20 formations. The variables were processed by computer to convert the U.S.G.S. symbols to our eight-digit codes.

Radiometric Anomalies: We incorporated limited information on airborne anomalies into the model, by classifying each cell as either "anomalous" or not. "Anomalous" cells were taken to be those containing at least one airborne radiometric anomaly as summarized in the uranium-anomaly interpretation maps from the contractor reports for the Pueblo, Montrose, Trinidad, and Durango quadrangles (geoMetrics, 1979-a, 1979-b; Western Geophysical, 1979; Texas Instruments, 1980) after anomalies attributed to highways, uranium-processing plants, etc. were omitted. While the EVAL model accepts presence or absence data only, the SURE model allows individual cells to be rated on a scale of zero to ten. Clearly, such a scheme could also take into account the presence of thorium and potassium anomalies if so desired, but we believe that any interpretation of this type would best be made by a geophysicist prior to entering the cell ratings into the model.

Data-Base Manipulation

We organized the data by the geology of the sample sites. This allowed us to study the characteristics of the geochemical variation in formations or groups of formations, as well as that of the total (pooled) data sets, and thus to understand better the patterns of geochemical behavior.

We devised a method to encode the characteristics of the sample-site geology to facilitate rapid and flexible retrieval of a variety of geologic characteristics. The basis of the method is to transfer the geological information inherent in the eight-character rock code to presence/absence records by setting a binary bit to 1 (present) or 0 (absent) in up to four 60 - bit words of computer storage. By using fairly broad categories, we were able to code the geology information into one word, which includes both age and lithologic information. Two additional words are required for the recording of individual geologic formations, one bit being set 'on' (logical 1) for each formation.

The power of the method becomes clear when we need to retrieve samples in particular categories. To retrieve all samples from one, or more, formations we set the appropriate bit(s) in the words corresponding to individual formations to 1; one can also apply more powerful logic to retrieve, for example, requests like "all granites or granodiorites"; "all Tertiary pyroclastics"; "all Jurassic or Cretaceous shales and sandstones"; etc. This forms a useful tool for rapid exploratory analyses of data, particularly in conjunction with interactive statistical-analysis packages such as MINITAB (Ryan and others, 1976).

The Statistical Model for Evaluation (System EVAL)

Introduction

Our statistical model analyzes HSSR, radiometric, and geologic data to calculate a score for each quadrangle. The model is not a genetic one as such; instead of seeking environments favorable for formation of uranium deposits or source beds or for redeposition, it summarizes a variety of favorable factors.

We normalized the score to an arbitrary 100 percent for the Pueble quadrangle and then calculated comparative scores for the other three quadrangles. The model contains both geological and statistical elements. Of the total score of 100, we assign 24 to stream-sediment anomalies, 20 to water anomalies, 26 to favorable host rocks, 14 to favorable source rocks, and 16 to radiometric anomalies.

The geological intuition of a group of geologists determined the scores assigned to each of these variables. Both statistical theory (Tukey, 1948) and experience (Koch and Link, 1974) indicate that if the weights assigned to scores are reasonable, no serious differences will result in comparing two quadrangles with one or another set of weights.

In the first part of the model, we introduce data for stream sediments, reducing the effect of uranium in resistate minerals by regressing the rare earths on uranium and selecting the residuals.

In the second part, we add water-data anomalies that we obtain by regressing uranium on calcium and magnesium concentrations and conductivity. Handling the water data in this way seems reasonable. Langmuir (1978, p. 558) has written that:

> ". . . there are seven or more factors, including source rock U content, which can influence the uranium dissolved in water. These are:
> (1) the uranium content in source rocks, sediments or soils and its leachability;
> (2) the proximity of the water to uranium-bearing rocks or minerals;
> (3) the degree of hydraulic isolation of the water from dilution by fresher surface or subsurface waters;
> (4) climatic effects and their seasonal variability, particularly the influence of evapotranspiration;
> (5) the pH and oxidation state of the water;
> (6) concentrations of carbonate, phosphate, vanadate, fluoride, sulfate, silicate, calcium, potassium and other species which can form uranium complexes or insoluble uranium minerals; and
> (7) the presence of highly sorptive materials such as organic matter, ferric, manganese, and titanium oxyhydroxides and clays."

Detailed analysis was not justified because several important elements were not analyzed and the samples were relatively widely spaced.

Third, we allow input of identifiers for geologic formations that are potential host rocks or source rocks of uranium. For the study area, the favorable host rocks are some Precambrian ones (which contain Tertiary veins too small to yield geochemical signatures), the Morrison Formation, the Dakota Sandstone, and the Tallahassee Creek Conglomerate and similar Tertiary sedimentary or volcanic beds. The number of sites identified divided by the total number of points yielded a percentage of points for a given formation; we assume that sample locations are evenly distributed across the quadrangle. As discussed below, we followed a similar procedure for the source rocks.

Finally, we used the presence or absence of radiometric anomalies defined by DOE's reconnaissance survey subcontractors to develop the last 16 points of the 100 point total score.

The point-oriented model provides data aggregated for entire quadrangles. The computer program also keeps track of scores for individual cells; these data will be valuable for a projected study analyzing frequency distributions for the cell scores. Forms of distributions may be as important as single-valued estimates for the quadrangles. For instance, if two quadrangles had the same overall score, presumably the more valuable one would be that with the larger variability of map-cell scores.

Preliminary investigations for the Pueblo quadrangle have shown that although potential source rocks could be identified from the geochemistry of the stream-sediment samples alone, distinction between host rocks and other sedimentary rocks may not be possible. Compiling the geologic cell data base was expensive and time consuming; effort and expense would be saved if further investigations could provide reliable results without using the geological maps.

Outline of the EVAL Scheme

For convenience in computer processing, the analysis is performed by a series of computer programs linked through a set of common files. Man/machine communication is via a remote terminal.

The overall scheme linking the Fortran modules SEDS, WATER, SREG, WREG, MPOST, QPLOT and EVAL is shown in figure 4. The modules SEDS and WATER reformat the original LASL data tapes into suitably structured data files, and at the same time the eight-character geologic codes are added to each sediment record.

SREG allows definition of five groups: igneous, metamorphic, pre-Quaternary sediments, Quaternary sediments and "unknown" (an error trap for rock codes which cannot be assigned to one of the previous groups). We also provide for scoring on the inferred presence of uranium source and host rocks which are defined using up to 45 different key-words. Output includes: (1) printed summary information, (2) site coordinates and regression residual values (for each geologic group to be used for later off-line map plotting) and (3) map-cell scores.

WREG carries out an analysis similar to SREG for the water data; these are automatically categorized as stream, pond, or spring-plus-well waters.

EVAL combines the individual map-cell scores (based on the presence of stream-sediment anomalies (SREG), water anomalies (WREG), source and host rocks (SREG), and cells containing airborne anomalies) into a final overall quadrangle score. A lineprinter map of the distributions is made.

MPOST and QPLOT reformat the sample-point regression residual files for the various sample categories used in SREG and WREG into a form suitable for plotting. They plot the positive residual values from the Universal Transverse Mercator projected 1:250,000 quadrangle sheets (Cheadle, 1977) together with the map-cell grid. The output was designed for a Kongsberg Kingmatic flat-bed plotter; the anomalous values are printed in several colors.

Basis of the Model

Regression: R. H. Carpenter has shown in work on HSSR data from the southeastern United States (Koch and others, 1979) that correcting the observed stream-sediment uranium content for the presence of uranium in resistate minerals (including monazite, xenotime, allanite, zircon, etc.) can enhance local uranium anomalies. His technique worked well in the Southeast, but does not generalize to other regions without detailed geochemical information.

Preliminary investigations of the chondrite-normalized rare-earth element (REE) abundances for all the major lithologic groups in the Pueblo quadrangle showed that the stream sediments exhibit normalized REE patterns (of lanthanum, cerium, samarium, europium, terbium, dysprosium, ytterbium, and lutetium), which closely resemble lithogeochemical ones in the literature. Also, multiple linear regression for uranium from normalized REE values generally gave statistically significant results. The residual uranium (observed minus regression-predicted uranium) values represent the part of the uranium variation that cannot be explained in terms of the independent variables used in the linear regression model. In 74 stream sediments from the Pikes Peak and San Isabel granites, the regression reduced the U-Th correlations from 0.936 to 0.092, and the U-Hf ones from 0.812 to -0.013. This reduction suggests that the effect of the resistate minerals on observed stream-sediment uranium values has been successfully removed, in general accord with Carpenter's results. Residual stream-sediment uranium values based on REE regression have therefore been used in our model as an index of favorability.

The model combines the uranium residuals, based on the different populations selected, as a weighted sum. However, it is desirable to treat these uniformly to allow for different behavior between the various stream-sediment types in the model. The square of the multiple correlation coefficient (R-squared) expresses the proportion of the total variability explained by the multiple regression. R-squared is defined as: (Sum of squares due to regression)/(Total sum of squares of the uranium values about their mean). It lies between 0.0 and 1.0, the latter value corresponding to a perfect linear regression. It seems intuitively reasonable that a residual of, say, +20 ppm from a regression with R-squared close to 1.0 will be of greater interest than one of the same size from a regression with an erratic relationship (fig. 5). Therefore, we have included the option to post-multiply the uranium residual values by the corresponding R-squared values prior to calculating the favorability scores. Empirical trials using the MINITAB statistical package (Ryan and others, 1976) give good correlation between the post-multiplied residuals and MINITAB Studentized residuals. Results from the Pueblo quadrangle show that this procedure eliminates a number of low-amplitude anomalies associated with the Quaternary of the Denver plateau, etc. We treated the water data similarly.

Calculation of Scores: We have used the concept of a score value as a favorability index for the individual cells and for each quadrangle. The score of the water and stream-sediment data in the EVAL package is derived as follows:

Let the average regression residual (raw or post-multiplied by R-squared) for uranium in a cell be $\underline{A}$, the sum of the positive anomalies divided by the total number of sample points in the cell. Then for the $\underline{i}$-th of $\underline{n}$ sub-groups, each of which has a weight $\underline{w}$ assigned to the score, the corresponding EVAL score $\underline{S}$ is zero if $\underline{A}$ is zero; 0.01 times the weight $\underline{w}$ if $\underline{A}$ is between zero and one; 0.1w if $\underline{A}$ is between one and ten; and 1.0$\underline{w}$ if $\underline{A}$ exceeds ten. The maximum possible score is then $\underline{W}$, the sum of the weights, and the total cell score is $(\underline{S}/\underline{W})$x100 percent.

Sure, A System for Uranium Resource Evaluation

Introduction

SURE is a System for Uranium Resource Evaluation derived from the EVAL model. Man/machine communication is completely interactive, using a remote terminal. No external plotting facilities are required as all maps are produced at the terminal.

Scoring for SURE

Scoring is similar to that used in EVAL; however, positive residual values for a cell are summed directly before dividing by the number of samples in a cell to give the average anomaly value; this value is multiplied by the appropriate sub-population (or total population) weight. The final score for the water or stream-sediment regressions is equal to the sum of the cell anomalies over all groups, divided by the number of cells occupied by one (or more) sub-group(s). Host and source rock scores come from the weighted proportion of occupied cells. The radiometric score is computed from the total weighted cell scores divided by the number of scored cells.

SURE Results

Table 2 compares the scores for all four quadrangles normalized to the total score for Pueblo as a standard. For Pueblo, the total score of 100 is also equal to the sum of the weights for each of the five items scored. The

Durango total score is about a third that for Pueblo; the Montrose total is about two thirds; the Trinidad score of 111.46 is about 10 percent larger. Therefore, if Pueblo were fully explored we could equate its score of 100 to the total value of uranium as measured by one or another attribute of the occurrence data; and, if Trinidad were unexplored, we could predict its value to be 111.46 percent that of Pueblo.

Our suppositions in the previous paragraph are to illustrate a method that would be applicable to the evaluation of quadrangles in a little-explored region, as in parts of Alaska. In reality, the quadrangles in the study area have been explored, although not equally. Table 3 shows that Montrose and Pueblo productions have been far higher than those from the other two. Adding ore reserves published for the Hanson ore body in Pueblo and the Pitch mine in Montrose (Nelson-Moore and others, 1978, p. 148, 393) reverses the position of these quadrangles but they still lead. Considering the high score from Trinidad together with its low production, we can predict an excellent exploration potential for this quadrangle.

Trinidad scores higher than Pueblo chiefly because the contribution from stream-sediment anomalies is about double that in Pueblo. Of course, different weightings for the scored items or changes in model details would yield different rankings for the four quadrangles.

We did not score the source rocks for Durango and Montrose because information was lacking when the analyses were made; however, even if we rated these source rocks as high as Pueblo, the total scores would still be well below those for Pueblo.

Analysis of Uranium Occurrences

The uranium-occurrence data reflect these facts about the study area: (1) uranium deposits were formed through a variety of geological processes taking place at different times in diverse stratigraphic and structural geologic units, (2) geological exploration is incomplete and varies in intensity from place to place, and (3) questions about how to define an occurrence arise. Therefore, our analysis contains many subjective elements and is less straightforward than one for other geological situations.

We needed to appraise the occurrences. Certainly, those with production have uranium mineralization in commercial or near-commercial amounts; but others are more difficult, using Colorado Bulletin 40 (Nelson-Moore and others, 1978). Some are clearly ore deposits with substantial reserves; some are clearly uranium deposits, having been examined and sampled by qualified individuals; others, however, represent wishful thinking, may have no identifiable mineralization, and may not have been revisited since their original location under the mining laws. They represent a mixed bag, difficult to analyze; we used an arbitrary cutoff to distinguish deposits that have produced at least one ton of uranium ore from the others.

Table 4 lists data for the 51 mines in the study area that have produced at least one ton of ore, arranged in order of decreasing tonnage. The table shows a familiar pattern. A few deposits are relatively large but most are small; tonnage and grade are not clearly related; the deposits are distributed non-uniformly throughout the study area; and although certain geologic units are favorable for ore occurrences, the largest tonnages have come from geologic units that have not been particularly productive otherwise. Thirty-one mines, more than half of the 51, are in the Pueblo quadrangle; 16, or about a third, are in the Montrose quadrangle; four are in the Trinidad quadrangle; and only one is in the Durango quadrangle. The first two quadrangles have produced the most uranium, with the largest mine in another quadrangle being nineteenth in rank. The three most productive mines, accounting for 84 percent of the total tonnage, are in the Montrose quadrangle.

Nearly half of the mines are in Tertiary rocks. The Tallahassee Creek Conglomerate contains 17, or about one-third of the 51 mines, and other Tertiary units account for another seven. Nine of the rest are in either the Dakota Sandstone of Cretaceous age or the Morrison Formation of Jurassic age.

Table 4 also shows that the largest mines have produced similar amounts of U_3O_8, about 1,200,000 lbs. each, although the Los Ochos tonnage is about four times that of Pitch. This production of U_3O_8 is ten times that of the third and fourth ranked T-2 and Last Chance mines.

For our study, the occurrence data serve two purposes. The first is to introduce bedrock geology into the model by identifying rock units that are favorable host or source rocks for uranium. The second is to calibrate the results of the model by relating the scores to the known uranium endowment.

For the first purpose, the data are adequate, though not ideal. Most mines that produced uranium are in the Tallahassee Creek Conglomerate, associated Tertiary units, the Dakota Sandstone, and the Morrison Formation. Certain granites are favorable source rocks for uranium. In a negative sense, the table shows that some rock units have neither producing mines nor known uranium occurrences. This information is quantifiable through our scoring system. Of course, a difficulty with this or any other scoring system is that it reflects only present knowledge; lithologies known to be favorable receive weight. On the other hand, formations with no known uranium production are discounted, since we have not, as yet, taken into account non-producing rock units with lithologies similar to favorable formations. Thus, if the model is correct, using it improves appraisal; if incorrect, the model may mislead.

For the second purpose, the data are inadequate. To understand this point, consider the state of knowledge in the Tri-State district (Koch and Schuenemeyer, 1980) where mineral endowment is well-known. Zinc (and smaller amounts of other metals) were mined for many years in an area of relatively simple geology that had been exhaustively explored through more than 100,000 drill holes and many miles of underground workings; distributions of tonnages, grade, and amounts of contained metals in orebodies are recorded.

In contrast, the geology of the study area is complex; many targets are smaller, and exploration is incomplete; therefore, the analyses that are appropriate for a well-explored region seem inappropriate to us. For example, Poisson distributions of occurrences would be of those that are known, rather than of those that actually exist; and similarly, analysis of distributions of tonnages, grades, or amounts of contained uranium would be of little value because the information is incomplete. The differences in apparent endowment of uranium in the four quadrangles may indicate artificial factors; the larger apparent endowment in the Pueblo quadrangle may reflect proximity to large centers of population in Colorado, to areas with previous mineral production, to favorable outcrops, to available public land, or to other factors.

Therefore, we do not believe that attempts to relate our scores to endowments in a rigorous way are likely to be helpful.

Geochemical Recognition of Metalliferous Granitoids

Introduction

Recent studies of granitoids of the British Isles suggest that uranium mineralization results from the redistribution of uranium in granitoids which start with a high mean content of uranium in the whole rock and not from further introduction of uranium (Watson and Plant, 1979; Simpson and others, 1979). Fission track studies indicate that the high 'background' uranium content of granites away from mineralization is due to the occurrence of uranium in resistate primary minerals such as zircon. These minerals later break down to release uranium.

We can distinguish two types of granitoids. Metalliferous granitoids contain high primary concentrations of uranium and other metals, predominantly in the silicate minerals. In mineralized granitoids the metals are in discrete ore minerals.

Simpson and others (1979) have shown that, in the British Isles, metalliferous intrusive complexes with a high mean content of uranium have these characteristics:

(1) Increased whole-rock levels of Th, Rb, K, Sn, Nb, Y, Cs, Ta, Li, Be, and F

(2) Low Ba, Sr, and Zr; high Rb/Sr and U/Th ratios

(3) Enriched REE with chondrite-normalized REE distribution patterns having pronounced negative Eu anomalies (Eu*).

(4) In many, negative gravity and magnetic anomalies (perhaps related to emplacement in deeply buried Archaean basement).

The metalliferous intrusions evidently rose rapidly along deep post-tectonic fractures; the magmas supplied heat, metals, and elements such as fluorine for complexing. Mineralization is associated with these intrusions only where rising magma interacted with epizonal water during or after emplacement. The intrusions were probably emplaced at a high structural level following regional cooling of the crust.

The initial concentration of uranium (and related elements) and the low K/Rb ratio in the magma are attributed to scavenging during ascent of fluorine-rich volatiles following breakdown of phlogopite at depth. The low K/Rb ratio is consistent with a sub-crustal origin.

Simpson and others (1979) suggest that mineralization involves leaching of hot granite magma, enriched in metals and fluorine, by meteoric or formational water containing dissolved carbonate. They attribute the breakdown of primary minerals to a brief phase of high temperature interaction of granite magma with epizonal waters, and believe that uranium mineralization occurred at that time.

The subsequent hydrothermal stage follows granite emplacement. It requires the flow of epizonal waters through channels to produce sericitization, greisenization, tourmalinization or similar rock alteration. Later (at lower temperatures) kaolinization results as metals are removed from the cooling body and precipitated in mineral veins. Faults in the granite would favor the formation of a system of channels to heat and circulate the water.

In the British mineralized granitoids, petrographic criteria indicating high-temperature water-rock interaction include: the presence of two micas, with muscovite replacing biotite; greisenization; alteration of feldspar to sericite and/or kaolinite; alteration of ferromagnesian minerals to chlorite; hematization or martitization of ferromagnesian minerals and magnetite; and the presence of 'accessory' minerals such as fluorite, topaz, beryl, columbite-tantalite, uraninite, thorite, monazite, xenotime, and apatite.

We believe that it is possible to recognize metalliferous granitoids of potential importance as uranium source rocks on the basis of the HSSR data. Elsewhere (Koch and others, 1980), we discuss in detail the whole-rock and stream-sediment geochemistry of the Pikes Peak pluton, with implications for recognition of Pikes Peak-type batholiths from HSSR data, together with a list of batholiths of this type in the study area.

Pikes Peak Pluton: Stream-Sediment Geochemistry

Stream-sediment samples derived from the Pikes Peak pluton will reflect characteristics of the whole-rock geochemistry, although element concentrations will change in the stream-sediment regime. Table 5 compares the concentration levels of selected elements in stream sediments from the Pikes Peak and San Isabel batholiths of the Pueblo quadrangle with those for all granites from the Durango, Trinidad, and Montrose quadrangles. Many of the whole-rock trends identifying metalliferous granitoids in the British Isles are also present in the Pikes Peak stream-sediment samples; the San Isabel pluton appears to be typical of the 'barren' type of granite.

One of the striking characteristics of the Pikes Peak stream-sediment samples is the pronounced negative Eu anomaly in the chondrite-normalized REE distribution pattern (figure 6), reflecting the whole-rock geochemistry of the fayalite, riebeckite, and potassic granites which constitute the pluton (Barker and others, 1979).

We established an empirical "Pikes Peak Index" (PPI) based on observed differences between stream sediments from the Pikes Peak and San Isabel batholiths. Each criterion met (table 6) merits a score; these are summed, and the total is multiplied by four to yield a maximum PPI of 100. Using a lower PPI cut-off of 50, an initial screening of all 337 sediment samples from granites detected 58 samples (of a possible 60) from the Pikes Peak batholith; of these, 93 percent scored between 72 and 96 (mean 86, standard deviation 10). Only one of the 14 San Isabel samples had a significant score.

Conclusions

The HSSR stream-sediment and water data can contribute significantly to quadrangle assessment by evaluators, using statistical analysis implemented by computers. Package SURE processes these data to provide a score for each quadrangle. Alternatively the EVAL system of programs can be used, if the evaluators provide sufficient statistical, computational, and geological experience. The value of the stream-sediment data is demonstrated clearly by the variance in the scores for the four quadrangles making up the study area (table 2); the difference in the scores shows that the data are meaningful. Moreover, they are consistent with the known geology, particularly in terms of host and source rocks, and with the occurrence data. Similarly, the scores for water data vary (table 2) and agree in part with the occurrence and geologic data.

Our attempts to unequivocally recognize host rock and alternative lithologies at the sample points using 'geochemical signatures' was unsuccessful.

The airborne radiometric data do not aid assessment with our model in its present form, which analyzes just the presence or absence of anomalies by cells. Table 2 shows small differences in scores for the four quadrangles and small contributions to the total scores.

The statistical methodology, particularly the multiple regression approach in SURE and EVAL, has worked effectively, as have the routines for handling data. By using SURE or EVAL, the quadrangle evaluator can remove subjectivity from the evaluation; the scoring system allows him or her to exercise geological judgement, which the program applies consistently.

As background information, the occurrence data are useful, but because of the complexity of the geology and the differing degrees of exploration they cannot be quantified with rigorous statistical methodology.

Mineralized and metalliferous granitoids can be distinguished by their "geochemical signatures." This sorting allows us to estimate the amount of granitoids in a quadrangle that may be potential source rock, and this distinction is crucial for evaluation.

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TABLE 1.- Sources of data

Sample type	Entire study area	Quadrangle			
		Pueblo	Montrose	Durango	Trinidad
Stream-sediment	5759	1058	1857	1604	1240
All waters	4804	861	1365	1518	1060
Streams	2960	359	1086	1171	344
Wells	963	271	15	179	498
Springs	719	159	264	127	169
Artificial ponds	100	55	-	19	26
Natural ponds	62	17	-	22	23

TABLE 2.- SURE quadrangle scores per category relative to Pueblo total score (percent).

Scored item	Weight, %	Quadrangle			
		Pueblo	Durango	Montrose	Trinidad
Host rocks	26	6.53	9.33	15.12	12.26
Source rocks*	14	4.68	0	0	3.34
Water (4 groups)	20	56.88	7.65	8.96	29.81
Stream-sediments (4 groups)	24	29.68	15.06	45.36	64.72
Airborne radiometrics	16	2.23	2.00	2.08	1.33
TOTAL	100	100.00	34.04	71.52	111.46

* where known

TABLE 3.- Production of uranium from the four quadrangles in the study area

Quadrangle	Production lbs. U_3O_8	Production & published reserves lbs. U_3O_8
Montrose	2,630,272	4,370,272
Pueblo	468,748	30,468,748
Trinidad	1,417	1,417
Durango	956	956

TABLE 4.- Tonnage, grade, and production for the 51 mines in the study area that have produced 1 ton or more uranium ore. Quad. - quadrangle, DU - Durango, MO - Montrose, PU - Pueblo, TR - Trinidad

Rank	Name	Quad.	Tonnage	Grade, %	Lbs. U_3O_8
1	Los Ochos	MO	448,685	.14	1,253,513
2	Pitch	MO	104,520	.58	1,206,112
3	T-2	MO	37,565	.13	97,618
4	Last Chance	PU	18,575	.31	114,765
5	Gunnison School	PU	14,308	.24	68,116
6	Picnic Tree	PU	13,525	.20	52,776
7	Avery Ranch	PU	10,553	.15	32,213
8	Joan 2	PU	10,286	.23	47,801
9	Dickson-Snooper	PU	9,664	.22	43,149
10	Little Indian	MO	8,152	.44	71,762
11	Smaller Lease	PU	4,871	.30	29,322
12	Section 36	PU	3,379	.28	18,834
13	Knob Hill	PU	2,901	.20	11,681
14	Thome	PU	2,593	.27	13,771
15	Mary L.	PU	2,402	.24	11,610
16	Little Abner	PU	1,647	.36	11,651
17	Colexco 1-43	PU	1,407	.08	2,326
18	Sunshine	PU	1,145	.27	6,235
19	Good Hope	DU	650	.07	956
20	First Chance	PU	606	.19	2,303
21	Badito Cone	TR	510	.13	1,326
22	Brown Derby	MO	400	.03	238
23	Section 36	PU	305	.16	965
24	Bonita	MO	163	.14	472
25	Big Red 22	MO	127	.22	557
26	Mike Doyle	PU	108	.13	277
27	Lightning 2	PU	102	.09	193
28	Bob Cat	PU	46	.14	131
29	High Park	PU	46	.13	115
30	Amrine	MO	45	.12	108
31	City Slicker	TR	40	.07	56
32	McVey	PU	37	.10	73
33	Cap Rock	PU	30	.11	68
34	Raw Lode	PU	29	.10	73
35	Dilley	PU	19	.10	38
36	Beth	MO	18	.20	68
37	Hass	PU	16	.10	32
38	Folbre	PU	12	.09	21
39	Lady Stith	PU	12	.24	58
40	Abril	PU	8	.18	29
41	Watters	PU	8	.11	17
42	La Rue	MO	7	.20	28
43	James-Taylor	PU	6	.10	12
44	Mocking Bird	PU	6	.20	24
45	Anal No. 1	TR	6	.28	33
46	Genevieve	PU	5	.44	44
47	Misery	PU	3	.17	10
48	Sand Creek	PU	1	.20	4
49	Good Hope	PU	1	.20	4
50	Beck Mountain	TR	1	.10	2
51	School Section	PU	1	.36	7

TABLE 5.- Concentration levels for selected elements in stream sediments over granites. Numbers of samples in parentheses. Mean, $\bar{w}$; standard deviation, s. Values in ppm, except for K and Mg.

Element	Quadrangle									
	Pueblo				Durango		Trinidad		Montrose	
	Pikes Peak		San Isabel							
	(60)		(14)		(68)		(42)		(153)	
	$\bar{w}$	s	$\bar{w}$	s	$\bar{w}$	s	$\bar{w}$	s	$\bar{w}$	s
Ba	594	266	898	103	482	189	743	152	630	219
Be	5.7	4.1	1.0	0.5	2.9	1.2	3.1	0.6	2.3	1.1
Cs	3.7	1.7	1.7	1.2	11	7	2.2	1.8	4.1	2.7
Eu	2.9	1.2	3.0	0.8	2.1	0.5	2.9	1.0	2.1	1.4
Hf	89	102	26	11	18	17	20	14	28	33
K %	2.3	0.9	1.9	0.2	1.8	0.8	2.1	0.4	1.8	0.5
La	265	211	94	31	51	26	80	93	114	263
Li	39	25	21	6	53	31	41	16	41	20
Lu	4.3	3.6	1.1	0.4	0.7	0.5	0.8	0.4	1.0	0.6
Mg %	0.4	0.5	1.4	0.6	1.8	1.1	1.7	0.4	1.7	0.9
Nb	116	139	14	8	10	0	11	3	13	10
Rb	96	32	34	21	64	53	33	35	52	31
Sr	100	0	197	195	137	119	127	84	127	114
Th	74	66	13	3	17	16	11	3	35	83
U	21	30	5	1	9	11	12	36	14	17
Eu anom	Strong		None		Weak		None		Moderate	

TABLE 6.- Pikes Peak Index (PPI) for stream-sediment data. Values in ppm except for K and Mg. Eu anomaly and Y are estimated from averaged chondrite normalized Dy and Nb.

Criterion	Score
Ba < 912	1
Be > 1.7	2
Cs > 2.5	1
Cs/Ba > 0.0036	2
Eu anomaly < -30	3
K > 2.3%	1
La/Eu > 34	3
Li > 30	1
Lu/Eu > 0.48	3
Mg < 1%	1
Nb > 25	2
Rb > 68	1
Rb/K > 28.2	2
Sr < 500	1
Y (est.) > 63	1

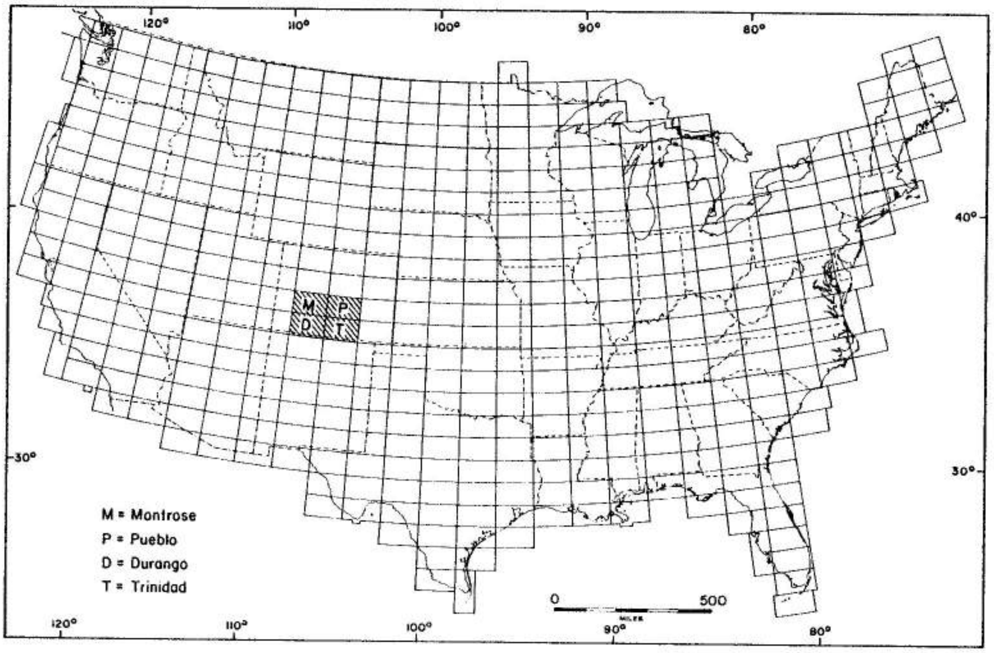

Fig. 1 - Index map locating the four quadrangles studied.

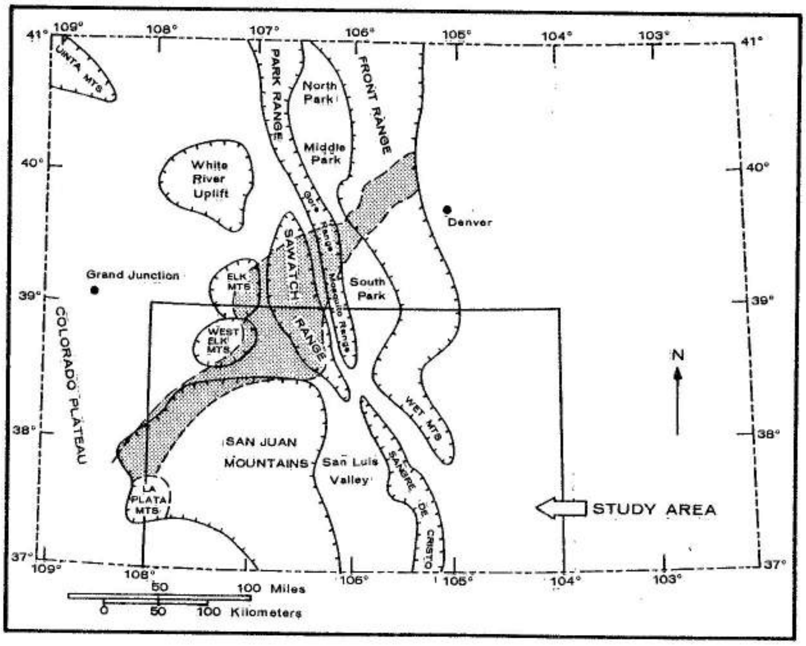

Fig. 2 - Principal structural-geomorphic units in the mountain province of Colorado and outline of the Colorado Mineral Belt (after Tweto, 1968).

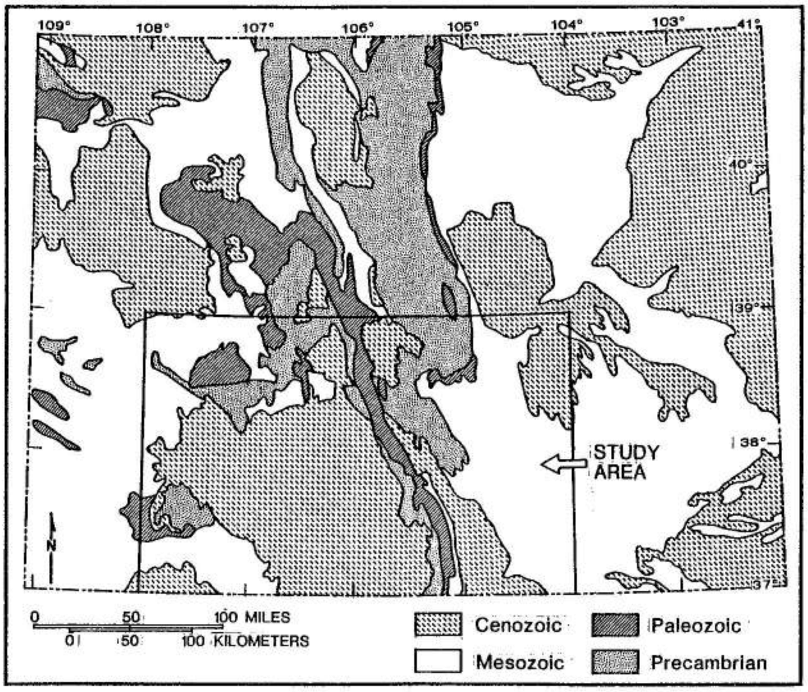

Fig. 3 - Geological map of the study area (after King and Beikman, 1974).

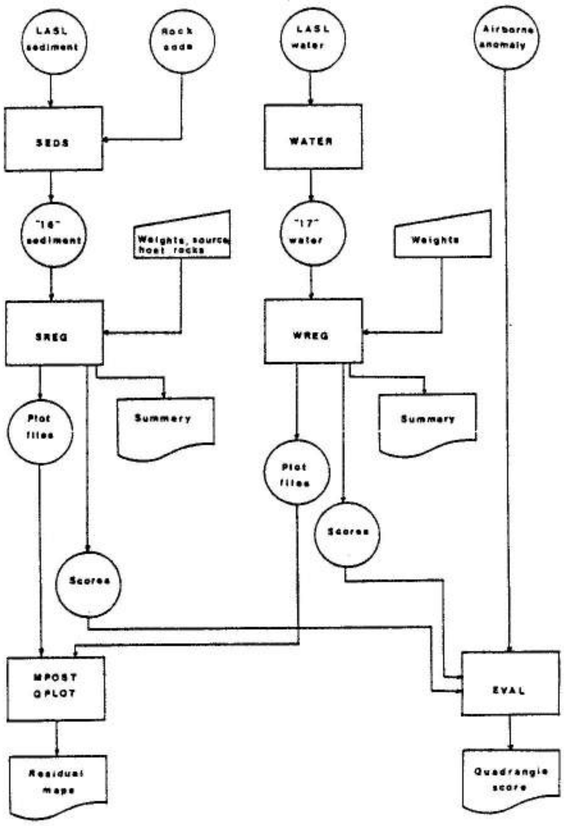

Fig. 4 - Flowchart to show file and program interaction in the EVAL system.

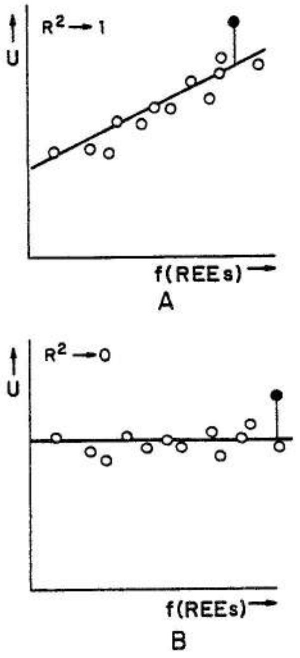

Fig. 5 - Concept of residual uranium anomaly significance in relation to regression on REE's with high (A) or low (B) R-squared value.

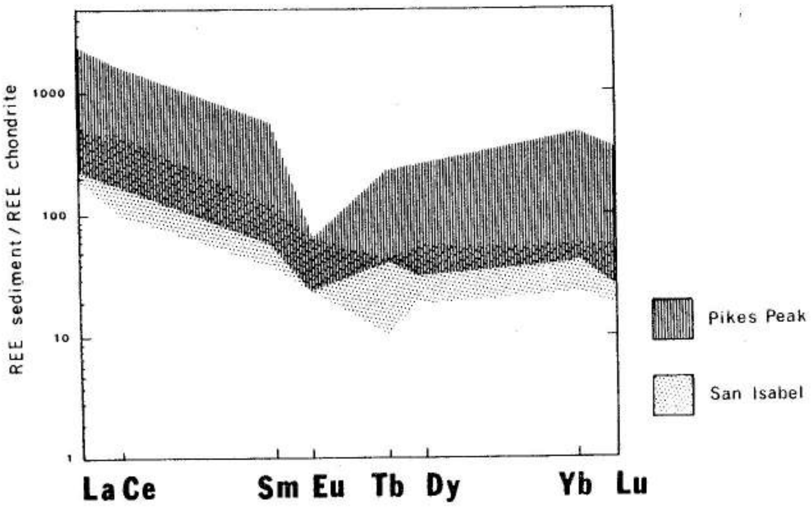

Fig. 6 - Chondrite-normalized REE distribution pattern ranges for stream sediments from San Isabel (14) and Pikes Peak (16) granites.