National Uranium Resource Evaluation

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

FINAL REPORT

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PREPARED FOR U.S. DEPARTMENT OF ENERGY
Assistant Secretary for Resource Applications
Grand Junction Office, Colorado

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SECTION 1. INTRODUCTION

1.1 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 hydrogrochemical (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.

In the Hydrogeochemical and Stream Sediment Reconnaissance (HSSR) phase of the program, extensive data are collected. About 1,400 sites are sampled for stream sediments in each two-degree quadrangle and about 1,200 sites for ground or stream water (These numbers are very general; the number of sample sites varies from laboratory to laboratory, from quadrangle to quadrangle, and by sample types.) At the present time, these HSSR data have only a minor impact upon one of the terms in the Department of Energy formula to calculate uranium endowment.

The primary purpose of this project was to develop a practical system for quantitatively assessing the uranium resources in individual quadrangles based upon the HSSR data and tonnage/grade data for occurrences.

1.2 CURRENT TECHNIQUES FOR RESOURCE EVALUATION AND ASSESSMENT

Resource appraisal consists of a series of steps from making abundance estimates in a geological province or other large region to obtaining location, grade, tonnage, and the probability of occurrence estimates for a deposit. The procedures used in resource estimation depend on the purpose of the study as well as on the quantity and quality of available information.

Techniques frequently used to estimate resources in areas where comparatively little exploration or deposit data are available include abundance estimation (Celenk and others, 1978), volumetric estimation (Kingston and others, 1978), and subjective probability. Abundance estimates compare the crustal abundance of minerals in known areas to those in unknown areas. Volumetric estimates compare the

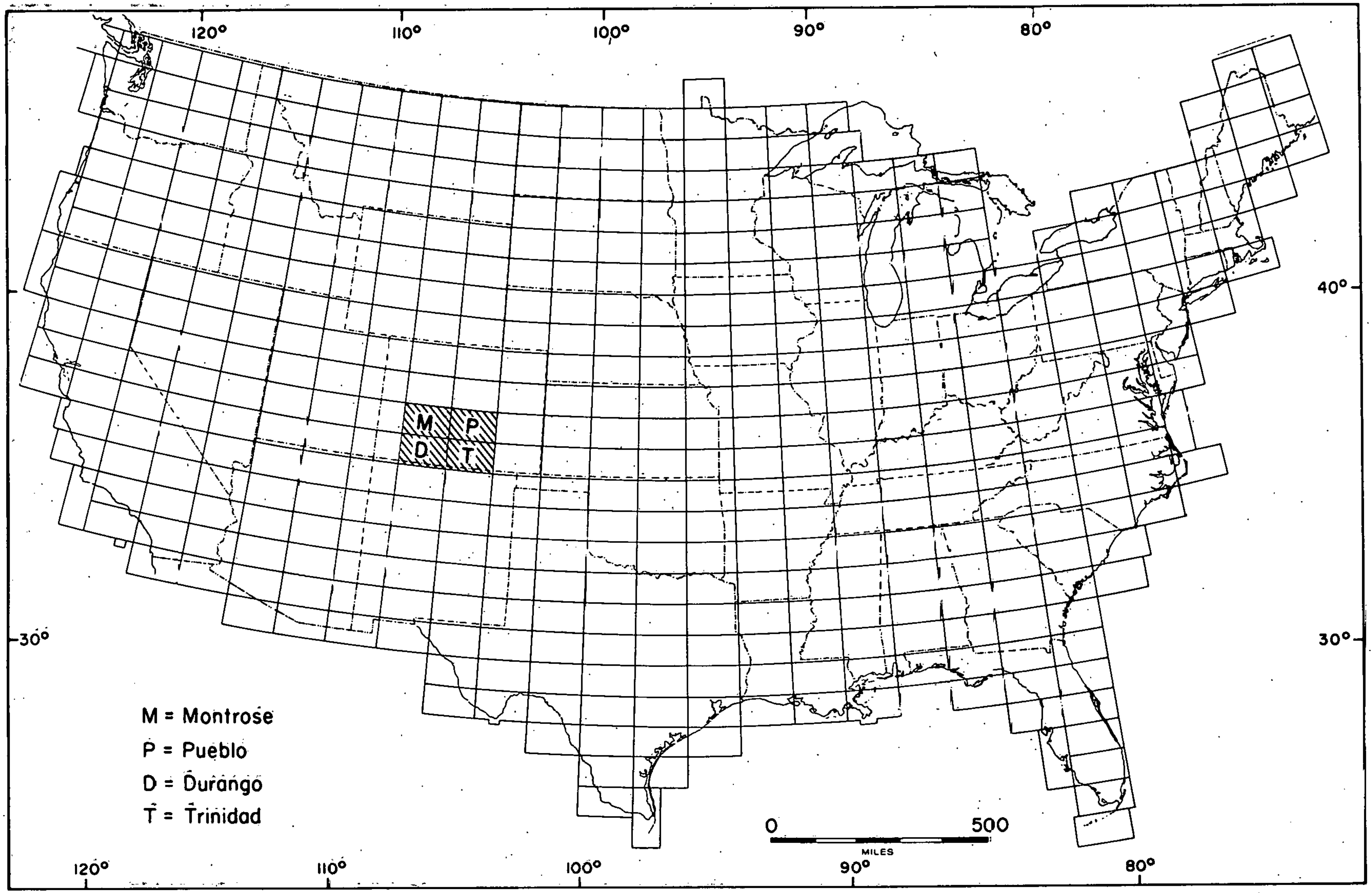


FIGURE 1.1.- Index map locating the four quadrangles studied.

richness of an unexplored part of a region to an explored part. Subjective probability estimates are based upon expert judgement.

In explored areas, deposit modeling (Sinding-Larsen and Vokes, 1978) can be used for resource estimation. Deposit modeling consists of any type of a model which uses deposit information to make resource estimates. One specific type is the discovery process model (Drew and others, 1980; Barouch and Kaufman, 1977) which estimates undiscovered petroleum resources in a partially explored region based upon characteristics of the discovery process. Many different types of multivariate models have used deposit information to estimate mineral resource potential. These include multiple linear regression, factor analysis, discriminant analysis, logistic analysis, and characteristic analysis.

The first two of these techniques are well known. In multiple linear regression, a plane (for a linear regression) or a curved surface (for a higher-order regression) is fitted to the observations in order to minimize the sum of the squared distances from the fitted surface to the reference plane, as measured perpendicular to that plane. Factor analysis ascertains whether multivariate observations occupy a number of dimensions equal to the number of measured variables or instead may be contained in a smaller number of dimensions, implying fewer variables present than those measured. Koch and Link (1971, p. 77-152) explain the application of these techniques to geological problems.

The latter three models will be reviewed briefly. Many of these models have been used to estimate the chance that a deposit will occur in a cell or other small geographic region. Some comments will be made in the summary section on the strength and weakness of these approaches.

Discriminant analysis is a multivariate statistical technique to classify an observation into one of several populations. It has been used by Harris (1965) and Beauchamp and others (1979) to identify favorable areas for uranium. For our purposes, one population could be the uranium occurrence cells while the other would be the non-occurrence cells. Another application of discriminant analysis is to classify an observation by rock unit. Lachenbruch and Goldstein (1979) present a general review of discriminant analysis.

Logistic analysis may be used to estimate the probability that a given cell contains one or more deposits.

The form of this model is

$$\theta_i = \exp(\underline{x}_i'\underline{\beta})/(1 + \exp(\underline{x}_i'\underline{\beta}))$$

where θ_i is the probability that cell i contains a deposit, $\underline{x}_i$ is the multivariate observation in cell i, and $\underline{\beta}$ is a parameter vector which is usually estimated from a training set. The training set consists of a binary response variable indicating the presence or absence of a deposit and a set of predictor variables such as the stream-sediment data. The logistic model has been applied to geological variables by Agterberg (1974) and by others. Chung (1978) has developed a computer program, and Chung and Agterberg (1979) discuss various parameter estimation techniques and present a case study.

Another classification technique used by Botbol and others (1978) is characteristic analysis. It may be regarded as a principal component analysis on a data matrix consisting of 0's and 1's. To use this procedure a model is developed by coding each of the variables in each cell as 1 or 0 to indicate the presence or absence of a variable which helps to define an anomalous cell. One coding technique is to code local maximums for each variable as 1's. Suppose this data matrix is X(n x p) where there are n cells and p variables each coded as 0 or 1. The form of the model is $R = \underline{\nu}'\underline{x}_i$ where $\underline{\nu}$ is the eigenvector (a set of weights) corresponding to the largest eigenvalue of X'X. The vector $\underline{x}_i$ is a vector of coded variables for the ith cell. A large value of R is evidence in favor of the occurrence of a deposit.

The results from all models are of course dependent upon the choice of parameters. The parameters for these models are usually estimated from a set of data called a training set. There are several potential weaknesses associated with multivariate modeling including the large number of parameters that must be estimated. For example, in a quadratic discriminant analysis model for 2 populations and 40 variables, there are 1720 parameters to be estimated including variance and covariance terms. Most models assume multivariate normality and homogeneity of variance; these assumptions rarely hold. Even though the power and logarithmic transformations normalize skewed data, not enough is known about their effect on misclassification errors. The effects of outliers and skewed distributions in discriminant analysis has been studied by Broffitt, Clarke, and Lachenbruch (1980) and Lachenbruch (1979). A major source of misclassification error is initial misclassification in the training set. For example, if certain occurrence cells are classified as non-occurrence cells, then the actual misclassification-error rate may be appreciably higher than the apparent-error rate. This problem has been studied in discriminant analysis by Lachenbruch (1974) and by Krazanowski (1977). There are few studies which provide guidelines for choosing among the various deposit models. Press and Wilson (1978) discuss the choice between logistic regression and discriminant analysis. Finally, when two models are applied to a virgin area, there is an assumption that the population parameters are the same as those in the training-set area.

1.3 ACKNOWLEDGEMENTS

We acknowledge with thanks the following contributions. Susan F. Carpenter devised the geological rock code. Roy K. Lowry participated in several phases of the study and wrote some of the computer programs. Chris Blaeser, Tommy Brazell, Verner Guthrie, and Gary Paulsen analyzed data. D. C. Hawkins advised on technical computing problems. Jane Plant and Peter Simpson worked on geochemical signatures of granitoids.

We also wish to thank the scientists and engineers of the United States Department of Energy, the Bendix Field Engineering Corporation, and the Los Alamos Scientific Laboratory with whom we had contact.

We want to stress that we accept responsibility for all errors in judgement and mistakes.

SECTION 2. DATA BASES

2.1 CONTENT OF THE DATA BASES

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

Figure 2.1 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 north-eastern part belongs to the Colorado Plateau.

Figure 2.1 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 2.2 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).

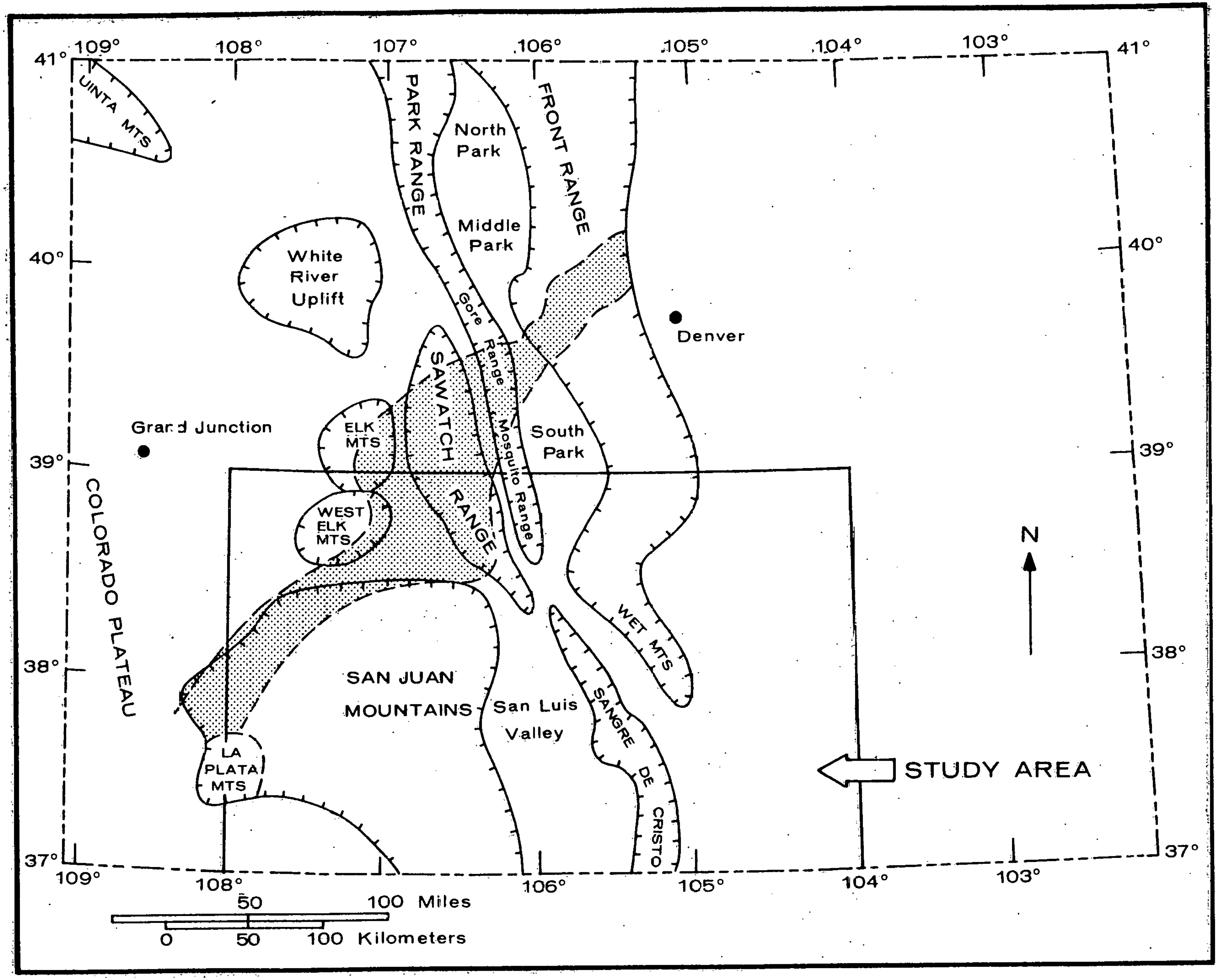


FIGURE 2.1.-Principal structural-geomorphic units in the mountain province of Colorado and outline of the Colorado Mineral Belt (stippled area) (after Tweto, 1968).

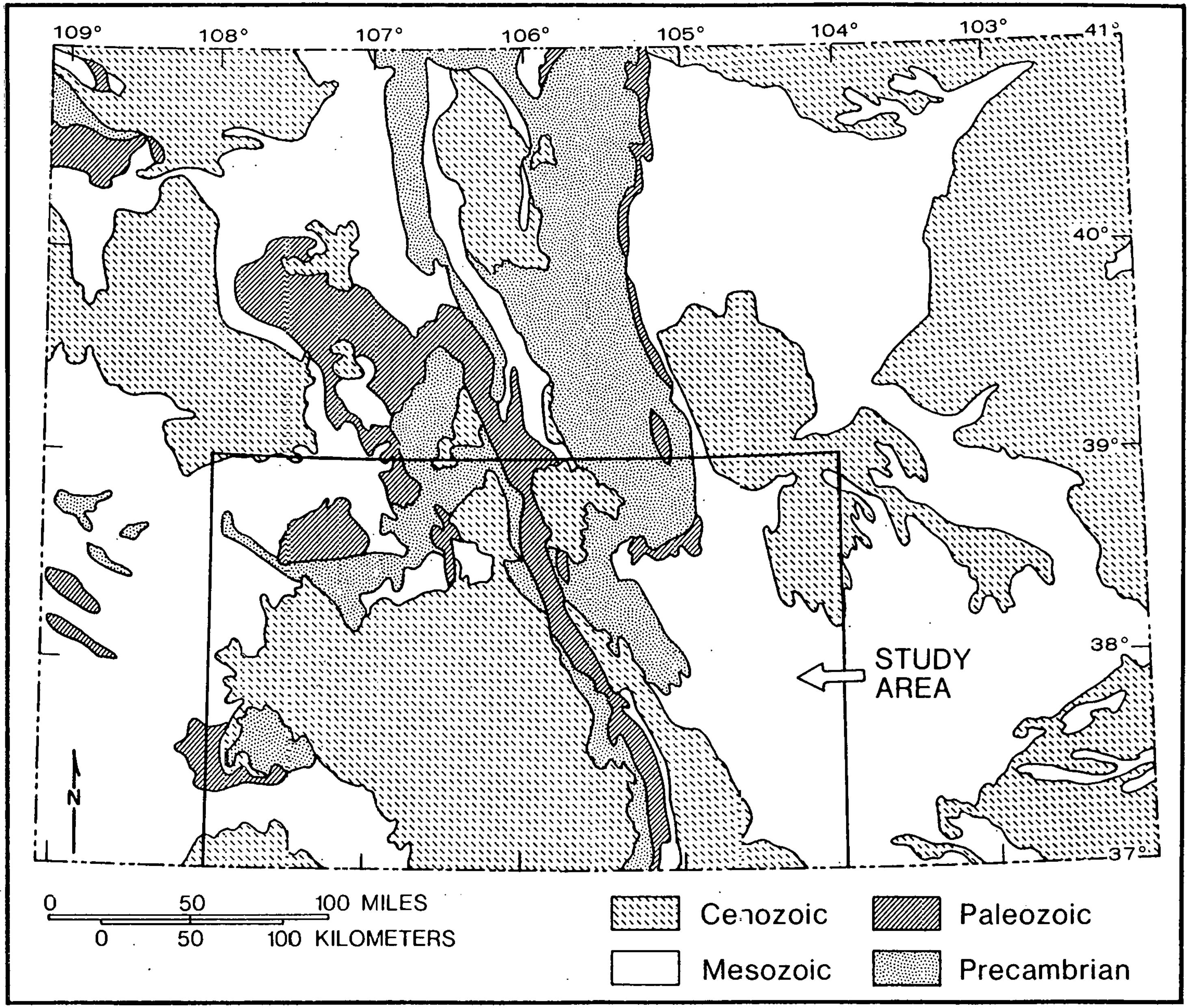


FIGURE 2.2. - Geological map of the study area (after King and Beikman, 1974).

HSSR Data Base

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.

This description of the field and analytical procedures used by LASL for the HSSR data is abstracted from a report by Broxton and others (1979, p. 238-242), for the Montrose quadrangle. Essentially the same procedures were followed for all four quadrangles.

> Water samples are collected first, directly from the source wherever possible, filtered through a 0.45-μ membrane filter . . . directly into one each, prewashed and sealed, 41-ml reactor "rabbit" and 25-ml vial (both polyethylene). Water samples in both the rabbit and vial are then acidified to a pH <1 with 8N reagent-grade HNO_3. . . Springs are sampled as near to their point of emergence as possible; stream waters are taken from the fast-flowing current away from the bank; ponds (including small lakes and reservoirs) are sampled from just below the surface, near their center; and well waters are taken near the wellhead if the well is pumping or from a holding tank if not. . . Following the collection of the water sample (if any), enough fine-grained, organic-rich, water-transported sediment to yield a composite sample of 25 g after processing (as indicated below) is taken from beneath the water level (where water exists) at three adjacent spots at each spring or stream location. . . After drying at <100°C, each sample is sieved through a 100-mesh stainless steel sieve. The minus 100-mesh fraction is put into a prewashed, 25-ml polyethylene vial which is then appropriately double-labeled . . . and sealed for shipment to the LASL . . . Delayed-Neutron Counting (DNC) Only waters with >40 ppb uranium (as determined by fluorometry at the LASL, where this is the upper limit of detection without recalibration) or those with impurities that cause interference with uranium-induced fluorescence are analyzed using DNC. . . . The concentrations of Ca, Co, Cr, Cu, Fe, Mg, Mn, Mo, Ni, Pb, Ti, and Zn in water samples are determined at the LASL by inductively coupled plasma-source emission spectrography. . . All sediment samples are analyzed for total uranium by DNC. . . A computer-controlled, energy-dispersive x-ray fluorescence system is used to determine Ag, Bi, Cd, Cu, Nb, Ni, Pb, Sn, and W in sediments.

Beryllium and lithium are determined in sediment samples by arc-source emission spectrography. Neutron activation analysis is used to determine concentrations of these 31 additional elements in sediment samples: Al, Au, Ba, Ca, Ce, Cl, Co, Cr, Cs, Dy, Eu, Fe, Hf, K, La, Lu, Mg, Mn, Na, Rb, Sb, Sc, Sm, Sr, Ta, Tb, Th, Ti, V, Yb, and Zn.

Table 2.1 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.

TABLE 2.1.-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

Tables 2.2 and 2.3 list the means, standard deviations, and the numbers of observations above the detection limits for the stream-sediment and water samples. We set values below detection limits to one-half these limits. This setting is reasonable, though arbitrary, and allows us to assume that the elemental abundance is greater than zero although indeterminate. For many chemical elements most values are below the detection limit; however, the few higher values may contain significant geological information.

Besides the numerical data on chemical elements for each sample site, we think it essential to consider the geologic age and lithology of the rock units. For the

TABLE 2.2.- Basic statistics for 5759 stream-sediment samples. Number of observations, n; mean (ppm) except as indicated as percentages, $\bar{w}$; standard deviation, s; coefficient of variation, C. "D.L." means detection limit. (For starred detection limits, values below these limits have been set to one-half this limit and included in the analyses. NAA values below a variable detection limit but exceeding these values have been similarly treated.)

Element or Variable	No. of observations, n			D.L.	Original data			Logarithms		
	Total	Missing	Below d.l.		$\bar{w}$	s	C	$\bar{w}$	s	C
Ag	5720	39	5485	5*	2.46	4.42	1.80	.3290	.1474	.45
Al	5755	4	7	.8%	6.51%	1.28	.20	.8037	.1025	.13
Au	5709	50	5562	.05*	0.04	0.21	5.25	-1.6652	.2178	.13
Ba	5755	4	114	300*	701.01	775.58	1.11	2.8125	.1583	.06
Be	5718	41	643	1*	2.14	1.40	.65	.2558	.2688	1.05
Bi	5720	39	5166	5*	2.47	1.87	.76	.3500	.1556	.44
Ca	5754	5	44	.1%	2.61%	2.58	.99	.2839	.3455	1.22
Cd	5720	39	5420	.5*	1.47	3.59	2.44	.0462	.2049	4.43
Ce	5706	53	0	10	99.23	108.15	1.09	1.9308	.2008	.10
Cl	5755	4	4969	100*	79.47	338.00	4.25	1.7754	.2121	.12
Co	5708	51	2	2*	13.20	7.01	.53	1.0768	.1870	.17
Cr	5708	51	371	10*	44.01	28.77	.65	1.5593	.2964	.19
Cs	5709	50	1125	1*	3.84	3.54	.92	.4261	.4079	.96
Cu	5720	39	145	10*	40.53	118.33	2.94	1.4462	.2684	.19
Dy	5755	4	33	2*	6.03	5.50	.91	.7179	.1996	.28
Eu	5706	53	0	.5	1.80	.77	.43	.2286	.1473	.64
Fe	5709	50	0	.2%	3.38%	2.39	.71	.4636	.2269	.49
Hf	5706	53	0	1	14.74	21.39	1.45	1.0499	.2684	.25
K	5754	5	0	.3%	1.86%	.54	.29	.2487	.1427	.57
La	5708	51	215	10*	52.58	66.78	1.27	1.6328	.2676	.16
Li	5718	41	19	1*	32.91	18.78	.57	1.4555	.2517	.17
Lu	5704	55	60	2*	.62	.69	1.11	-.2897	.2299	.79
Mg	5754	5	235	0.2%	1.49%	.79	.53	.1024	.2891	2.82
Mn	5754	5	0	10	847.15	1289.6	1.52	2.8375	.2503	.09
Na	5755	4	3	0.1%	1.34%	.53	.39	.0841	.2139	2.54
Nb	5720	39	5159	20	13.67	22.61	1.65	1.0534	.1842	.17
Ni	5720	39	4029	15	13.22	11.94	.90	1.0230	.2633	.26
Pb	5720	39	720	5	52.06	378.81	7.28	1.0940	.4860	.44
Rb	5709	50	2333	20*	41.63	31.05	.75	1.4612	.3977	.27
Sb	5706	53	5413	2*	1.42	4.87	3.43	.0375	.1819	4.85
Sc	5709	50	0	.1	10.29	3.92	.38	.9840	.1562	.16
Sm	5667	92	0	.5	7.82	10.89	1.39	.8148	.2140	.26
Sn	5720	39	5556	10	5.37	4.49	.84	.7123	.0848	.12
Sr	5721	38	4354	200*	213.50	237.85	1.11	2.1745	.3191	.15
Ta	5695	64	4960	1	.80	1.39	1.74	-.2201	.2351	1.07
Tb	5705	54	4858	1	.72	.89	1.24	-.2244	.2061	.92
Th	5705	54	0	.8	14.07	20.09	1.43	1.0604	.2271	.21
Ti	5751	8	0	200	5032.04	2292.99	.46	3.6674	.1623	.04
U	5759	0	0	20ppb	5.72	12.42	2.17	.6384	.2523	.39
U/Th	5705	54			.44	.73	1.66	-.4222	.1814	.43
V	5751	8	27	10*	104.21	66.16	.63	1.9567	.2294	.12
W	5720	39	5379	15	8.41	9.86	1.17	.8775	.1406	.16
Yb	5706	53	0	1*	4.85	5.66	1.17	.5495	.3654	.66
Zn	5657	102	0	50*	149.51	633.55	4.24	1.8910	.3864	.20
Cond	3712	2047			454.34	1858.87	4.09	2.2576	.4810	.21
pH	3708	2051			7.47	.81	.11			

TABLE 2.3.- Basic statistics for 4805 water samples. Number of observations, n; mean (ppb), $\bar{w}$; standard deviation, s; coefficient of variation, C. "D.L." means detection limit.

Element or Variable	No. of observations, n			D.L.	Original data			Logarithms		
	Total	Missing	Below d.l.		$\bar{w}$	s	C	$\bar{w}$	s	C
Ca	4772	33	0		64033.56	109025.52	1.70	4.5056	.4867	.11
Co	4772	33	2275	55	91.46	108.54	1.19	1.7752	.3748	.21
Cr	4772	33	3214	25	27.40	33.12	1.23	1.2844	.3185	.25
Cu	4772	33	2330	4	15.17	109.14	7.19	.7255	.4818	.66
Fe	4772	33	203	25	561.03	3969.50	7.08	2.2240	.5172	.23
Mg	4772	33	0	2	17816.02	41738.23	2.34	3.7661	.6208	.16
Mn	4772	33	781	3	107.20	1127.52	10.52	1.2413	.7491	.60
Mo	4772	33	3593	25	32.50	92.78	2.85	1.2703	.3600	.28
Ni	4772	33	0	25	51.66	118.64	2.30	1.4454	.4370	.30
Pb	4772	33	3793	200	274.69	740.46	2.72	2.1625	.3500	.16
Ti	4772	33	2810	4	11.95	55.17	4.62	.6718	.4976	.74
U	4805	0	69	.2	2.73	9.86	3.61	-.1830	.6836	3.73
Zn	4772	33	0	50	297.49	2754.68	9.26	2.0499	.5033	.25
Cond	4796	9			613.71	2176.46	3.55	2.3605	.5217	.22
pH	4784	21			7.45	.78	.10			
Temp	4767	38			12.99	5.34	.41	1.0692	.2239	.21

study area, Susan F. Carpenter devised a scheme to represent each U.S.G.S. formation symbol by an eight-character code (Appendix 1).

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. For additional identification, the quadrangle and county names, and the number of the deposit within county (corresponding to Bulletin 40) are listed.

Bulletin 40, the principal source of information, was compiled mainly through a literature search without opportunity for field checking nor time to reconcile some discrepancies, particularly in locations. Plotting the data on seven and one-half minute topographic quadrangles indicated various mistakes, and we could not find some deposits. For the located deposits, we calculated latitudes and longitudes. For the Pueblo quadrangle, most deposits that produced more than one ton of ore were field checked by the U.S. Geological Survey (Hills, 1980), and we adjusted locations and other data as a result of this work. Not every item in this data base is correct, but we believe that it provides a generally accurate account of uranium occurrences.

We also compiled a supplementary occurrence data base for the entire state of Colorado, based on Bulletin 40 with little additional editing by us. For each deposit, this supplementary data base contains county name, mine name, tons of ore, grade of ore, major uranium minerals, host rock or rocks, age of rocks, structures, and associated metals. Because this data base did not require accurate deposit locations, it was easier to compile. Our purpose was to relate the uranium mineralization in the study area to a larger area.

Geology by Cells

This data base lists the presence or absence of geologic formations and faults in essentially square 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. These variables were then keypunched and processed by computer to identify inconsistencies, which then were reconciled. The variables were processed by computer to convert the U.S.G.S. symbols to our eight-digit codes. For each quadrangle, we then made maps for each rock code on the line printer to indicate the cells containing each one. Through editing we removed erroneous entries.

Our reasons for the form of this data base are as follows: in digitizing geological information, we need to define the ideal product and then consider how closely we can approach it given the limitations of cost and technology. Ideally, geology would be digitized on a fine grid in three-dimensional space extending deep down into the crust. Rocks would be classified in detail according to mode of formation, lithology, faults, folds, age and other factors related to uranium mineralization. In actuality, we can only approach this ideal. We faced the decision of whether to measure quantitatively the extent of different geologic units plotted on these maps or simply to record their presence or absence. There was a trade-off between choosing cell size and making this decision, because if the chosen cell is large, it is both technologically easier and also less laborious to measure quantitative areas than if the cell sizes are small. On the other hand, if the cell sizes are small enough, then the presence/absence data become semi-quantitative for larger cells formed by aggregating the small ones. Moreover, using the small-scale 1:250,000 geologic maps, it is difficult to make quantitative measurements of the smaller formational areas, which also may be only nominal in size. We selected presence/absence data in cells smaller than those that have been used by most previous investigators.

Our cell size is one-twentieth of a degree of latitude, equal to 5.556 km on a side of a cell. This yields 40 cells from north to south across the two-degree area. At the latitude of the study area, setting the cell size approximately square, yields 62 cells in an east-west direction. Because we wished to use existing maps and because the maps and HSSR data were gridded by latitude and longitude, setting up cells in this way provided a better representation than devising a new square grid with an origin at the center of the study area. (A new grid would have been required because the square grid system for Colorado uses three grids across the study area so that no one of them would have served.) The difference in cell area from north to south is only 5 percent.

Radiometric Data

We incorporated limited information on airborne radiometric 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), and 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.

2.2 DATA BASE MANIPULATION

Introduction

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.

Encoding of Geology

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 words of computer storage. The programs are specific to the 60-bit words of the Control Data Corporation (CDC) Cyber computer system, but the principle is general.

By using fairly broad categories, we were able to code the 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. One could either use more words to encompass all formations in all quadrangles simultaneously, or overlay similar formation presence/absence information in the same two words in storage by treating each quadrangle separately. In the latter case, which we have adopted, a specific subroutine encodes the information for each quadrangle, and it is therefore necessary to specify (from the sample coordinates or in some other way) in which quadrangle a sample lies. Table 2.4 details the bits set for the various geologic categories. Assigning a particular sample geologic code to one or more of these presence/absence categories is done using the legend of the relevant 1:250,000 geological map.

Retrieval based on bit-encoded geologic information

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

TABLE 2.4.- Bit assignments for encoding presence/absence geologic information in a single 60-bit word.

AGE - Bits 1-15 and 45-49:	
01	Quaternary
02	Tertiary
03	Cretaceous
04	Jurassic
05	Triassic
06	Permian
07	Pennsylvanian
08	Mississippian
09	Devonian
10	Silurian
11	Ordovician
12	Cambrian
13	Precambrian
14	Precambrian X
15	Precambrian Y
45	Pliocene
46	Miocene
47	Oligocene
48	Eocene
49	Paleocene

LITHOLOGY - Bits 16-44 and 50-60:	
16	Drift
17	Sedimentary
18	Igneous
19	Metamorphic
20	Acid
21	Intermediate
22	Basic
23	Ultramafic
24	Pyroclastic
25	Extrusive
26	Intrusive
27	Conglomerate
28	Sandstone
29	Shale
30	Limestone
31	Granite
32	Gneiss
33	Diorite
34	Quartz diorite
35	Granodiorite
36	Quartz monzonite
37	Syenite
38	Alluvium
39	Colluvium
40	Travertine
41	Aeolian sand
42	Glacial deposits
43	Landslide deposits
44	Gabbro
50	Metasediment and metavolcanics
51	Sand and gravel
52	Siliceous
53	Andesitic
54	Rhyolitic
55	Granitic
56	Volcanic
57	Biotite
58	Latite
59	Dioritic
60	Quartzite

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 encoding is carried out automatically using the 8-character rock codes. Table 2.5 details the possible lithologies represented by characters 3 and 4 of the code. The extraction program (EXTRACT) is able to retrieve information of both age (A), specific lithology (L), and broad lithologic descriptors (D), or entire 8-character codes if the retrieval of information for specific formations is desired. The key words used for retrieval are listed in table 2.6. Thus, by using combinations of age and/or lithologic key words, flexible retrieval of the sample geochemical data for subsequent analysis is easy.

TABLE 2.5.- 8-character code lithology mnemonics (characters 3 and 4).

(1) Descriptor format: "-X" or "X-" where X is one of the following:

Z Alluvium
W Colluvium
T Travertine
J Glacial deposits
S Sandstone
C Conglomerate
X Landslide deposits
F Lava flow
G Granite
V Volcanics (flows and/or pyroclastics)
A Andesite
K Sediment
H Shale
L Limestone
Y Syenite
U Ultramafics
B Gabbro
N Gneiss
P Metasediments and metavolcanics
Q Quartzite
I Intrusive
D Diorite
R Rhyolite

(2) Lithologic descriptor "XX" where XX can be one of the following:

ES Aeolian sand
RA Rhyolites and andesites
GD Granodiorite
UM Ultramafics
QM Quartz monzonite
QD Quartz diorite
ST Siliceous tuff
SC Sand and gravel
IT Intermediate tuffs
RT Rhyolitic tuffs
MT Mafic (basic) tuffs
LT Latite tuffs
LH Limestones and shales
LS Limestones and sandstones
SH Sandstones and shales

(3) A descriptor followed by one of the codes in (1) above:

S Siliceous
A Andesitic
R Rhyolitic
G Granitic
I Intermediate
M Mafic (basic)
V Volcanic
U Ultrabasic
O Biotite
L Latite
D Dioritic

(4) A descriptor of the form "XY", where both X and Y are as (1) above. If X occurs in both (1) and (3), then (3) is assumed to take precedence.

NOTE- This coding applies to the Pueblo, Trinidad, Durango, and Montrose quadrangles; care must be taken when applying this technique to new areas.

TABLE 2.6.- Key words for geologic retrieval.

AGE:	
AQUAT	Quaternary
ATERT	Tertiary
APLIO	Pliocene
AMIOC	Miocene
AOLIG	Oligocene
AEOCE	Eocene
APALA	Paleocene
ACRET	Cretaceous
AJURA	Jurassic
ATRIA	Triassic
APERM	Permian
APENN	Pennsylvanian
AMISS	Mississippian
ADEVO	Devonian
ASILU	Silurian
AORDO	Ordovician
ACAMB	Cambrian
APREC	Precambrian
APREY	Precambrian Y
APREX	Precambrian X

GENERAL LITHOLOGY:	
LDRIF	Drift (all recent sediments, Quaternary)
LSEDI	Sedimentary
LIGNE	Igneous
LMETA	Metamorphics
LPYRO	Pyroclastics
LEXTR	Lavas
LINTR	Hypabyssal and plutonic intrusive rocks

SPECIFIC LITHOLOGY:	
LALLU	Alluvium
LCOLL	Colluvium
LAEOL	Aeolian sand and loess
LGLAC	Glacial deposits
LLAND	Landslide deposits
LTRAV	Travertine
LCONG	Conglomerate
LSAND	Sandstone
LGRAV	Sand and gravel
LSHAL	Shale
LLIME	Limestone
LQUAR	Quartzite
LGRAN	Granite
LSYEN	Syenite
LQTZM	Quartz monzonite (adamellite)
LGDIO	Granodiorite
LQTZD	Quartz diorite
LDIOR	Diorite
LGABB	Gabbro
LMSED	Metasediments and metavolcanics
LGNEI	Gneiss

LITHOLOGIC DESCRIPTOR: (Should be followed by lithologic key word, above)	
DACID	Acid
DINTE	Intermediate
DBASI	Basic
DULTR	Ultrabasic
DSILI	Siliceous
DANDE	Andesitic
DRHYO	Rhyolitic
DGRAN	Granitic
DBIOT	Biotitic
DLATI	Latite
DDIOR	Dioritic

SECTION 3. STATISTICAL MODELS

In this section, we describe the two statistical models developed through our research. While all of the principal investigators have worked on both models, George Koch and Richard Howarth are primarily responsible for the first model, which is point-oriented. SURE, a package for a System for Uranium Resource Evaluation for the quadrangle evaluators (explained in Section 4) was developed from this model. John Schuenemeyer devised the second model, which is cell-oriented. In the rest of this section, we describe these two models.

3.1 THE POINT-ORIENTED STATISTICAL MODEL

Introduction to the Point-Oriented Statistical Model

Our point-oriented statistical model analyses HSSR, aerial radiometric, and geologic data to calculate a total score for an entire quadrangle. This score is made up of contributions from the presence of stream-sediment anomalies, water anomalies, favorable host rocks, favorable source rocks, and radiometric anomalies. We weighted these contributions 20, 20, 30, 20, and 10 percent, respectively (although different weights could be used if desired). These contributions are based on occurrences in individual map cells. To compare the total scores among quadrangles, we arbitrarily equated that for Pueblo to 100 percent and compared the total scores for other quadrangles to it.

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, using a procedure which reduces the effect of uranium in resistate minerals by regressing the rare earths on uranium and selecting the residuals. For the Pueblo quadrangle, total points for stream-sediment anomalies were 20 percentage points.

In the second part of the model, we add water-data anomalies obtained by regressing uranium on calcium and magnesium concentrations and conductivity. Handling the water data in this way does not seem unreasonable. 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.

Third, we allow input of identifiers for geologic formations that are potential host- or source-rocks for uranium. The number of sites identified divided by the total number of sample points yielded a percentage of points for a given formation; we assume that sample locations are evenly distributed across the quadrangle. (For the study area, this assumption is reasonable; for other quadrangles a modification might be needed.) For the Pueblo quadrangle, total points so obtained were equated to 30.

We followed a similar procedure for the source rocks. An essential part of the assignment of points to favorable or unfavorable source rocks was the model developed by Simpson and others (1979) in Great Britain. This model is discussed in section 6. Simpson and his co-workers have found that through analysis of the REE and 'incompatible' elements they can distinguish favorable granitic rocks from unfavorable ones. While their work was on whole-rock geochemistry and our work was on stream-sediment samples, meaningful relationships can be developed. For the Pueblo quadrangle, the total points obtained for the presence of source rocks was equated to 20.

Finally, we used the presence or absence of radiometric anomalies to develop the last 10 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. These have to be run as separate phases on the Imperial College CDC 6500 computer system because of limited core storage (60,000 octal) available for interactive processing; this limitation does not apply to the University of Georgia or other larger CDC installations. 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 3.1. 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 up to five lithologic groups: igneous, metamorphic, pre-Quaternary sediments, and 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 keywords (sub-section 2.2). 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.

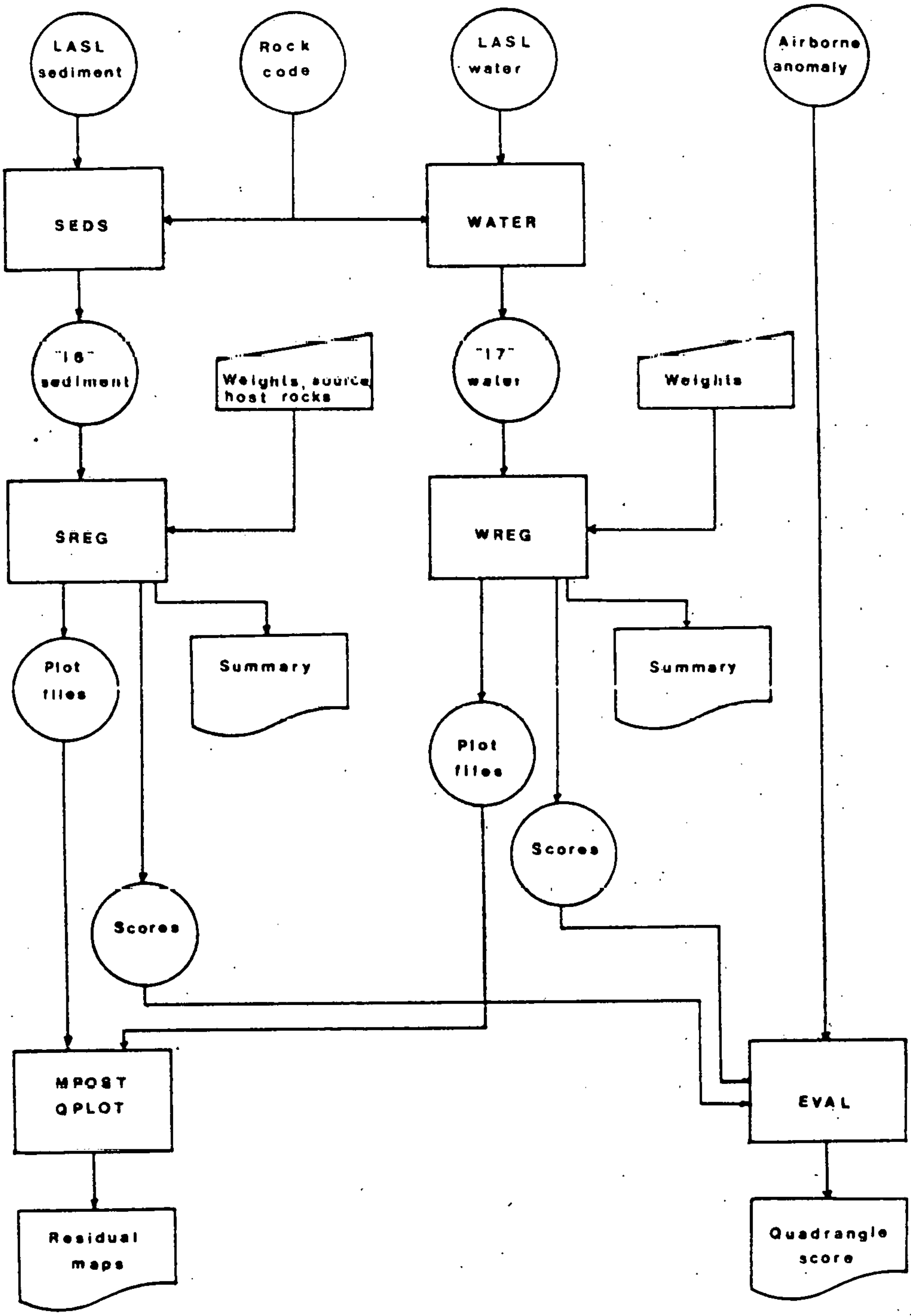


FIGURE 3.1.- Flowchart to show file and program interaction in the EVAL system.

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 (at Imperial College) which plots the anomalous values in several colors, but vector plotting commands in the Fortran program could be easily adapted for other output media.

Basis of the Model

Regression

R. H. Carpenter has shown in work on HSSR data from the south-eastern 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. However, such an approach requires detailed knowledge of the contents of uranium and other elements in these minerals from a given region. Carpenter was able to derive a mineralogical formula to correct uranium values by estimating the tetravalent uranium in monazite, xenotime, and zircon from the thorium, cerium, hafnium and dysprosium values of the stream-sediments (Koch and others, 1979, p. 44-54). His technique worked well in the southeast, but does not generalize to other regions without detailed geochemical information on the typical concentration ranges of uranium and other elements in the resistate minerals; therefore, a method which can be applied semi-automatically would be preferable.

For all the major lithologic groups in the Pueblo quadrangle, preliminary investigations of the rare-earth element (REE) abundances showed that the stream sediments exhibit REE patterns which closely resemble those for solid rocks (Wildeman and Haskin, 1973; Shaw, Dostal, and Keays, 1979; Nance and Taylor, 1976, 1977; Hanson, 1980). The abundances were ratioed to the composition of chondritic meteorites (Haskin and Frey, 1966). The REEs are lanthanum, cerium, samarium, europium, terbium, dysprosium, ytterbium, and lutetium. The <u>residual uranium</u> (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. These were found to be no longer significantly correlated with, for example, hafnium and thorium. (Zirconium, not determined in the LASL data set, would be expected to follow closely the behavior of hafnium). 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 stream-sediment types selected, as a weighted sum. However, it is desirable to treat these uniformly to allow for different behavior between the various stream-sediment types selected 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). R-squared lies between 0.0 and 1.0, the latter value corresponding to perfect correlation or 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 (figure 3.2). Therefore, we have included the option to post-multiply all the uranium residual values by the corresponding R-squared value prior to calculating the favorability scores. 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.

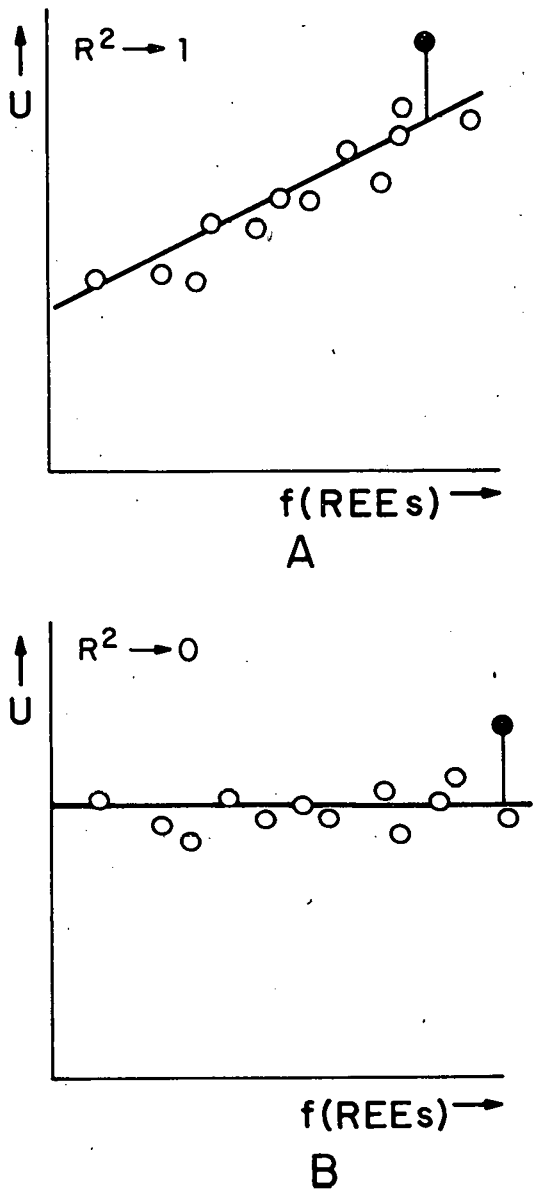


FIGURE 3.2.- Concept of residual uranium anomaly significance in relation to regression on REE's with high (A) or low (B) R-squared value.

Calculation of Scores

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

For any cell, we define the average uranium anomaly, $\underline{A}$, as the sum of the positive regression residuals (either raw or post-multiplied by $\underline{R}$-squared) divided by the total number of samples in that cell. Then, for any subset of either the water or stream-sediment types (for example, stream waters, or sediments derived from igneous rocks) the contribution to the cell score for that subgroup, $\underline{S}$, is assigned a value of zero if there is no positive average anomaly, 0.01 if $\underline{A}$ is between zero and 1, 0.1 if A, is between 1 and 10, and 1.0 if $\underline{A}$ exceeds 10. We multiply this value by the relative weight, $\underline{w}$, assigned to the sample type (for example, stream waters, 0.50; spring waters, 0.30; pond waters, 0.15; and well waters, 0.05; or igneous = metamorphic = sedimentary rock = Quaternary derived stream sediments, all weighted 0.25). Hence, if several subgroups occur in a given cell, the maximum ranked score for that cell is equal to the sum of the weights over all categories present, $\Sigma \underline{w}$. The total cell score is then $(\Sigma \underline{S}/\Sigma \underline{w})$, expressed as a percentage, the summations applying over all categories. The final mean quadrangle score is then the sum of these total scores from cells with at least one sample type present (clearly different subsets can occur in different cells), divided by the total number of such cells. We modify scoring in the SURE package (section 4) to use the actual or post-multiplied residual values, rather than these classed values.

<u>Treatment of the Stream-Sediment Data</u>

Uranium is regressed on the REEs present in the LASL data file (La, Ce, Sm, Eu, Tb, Dy, Yb, and Lu) for four sub-groups. These are selected from the data by scanning the binary bit-patterns corresponding to the 8-character rock codes (section 2.2), to include all samples in the groups: all igneous rocks; all metamorphic rocks; all pre-Quaternary sediments; all Quaternary sediments. Except for the Pueblo quadrangle, for which regressions were carried out on additional subgroups using the EXTRACT program (section 2) together with the MINITAB package (Ryan and others, 1976), we obtained all results using the standard sub-groups in EVAL.

While selecting sub-groups on the basis of catchment or sample-site geology is obviously advantageous, coding of the numerous formations present in many quadrangles takes time even using the above broad categories. An alternative strategy would be to classify the stream-sediments into categories based solely on their geochemical signature. Preliminary studies for the Pueblo quadrangle suggest that while certain groups (such as the Pikes Peak granitoids) would be clearly identifiable, classification of the different sedimentary lithologies may prove to have unacceptably high error rates. For the present, we assume that sub-groups will be defined in both the EVAL and SURE packages with 8-character geologic codes. We also provide for the user to interactively assign weights to the subgroups for scoring.

Both EVAL and SURE allocate scores to the proportion of cells that contain potential uranium source or host rocks. By source rock we mean a unit which could provide uranium to the surrounding environment. The Pikes Peak granite in the Pueblo quadrangle is an example (section 6).

We use the term host rock for formations known to be closely associated with the occurrence of uranium deposits of significant size (for example the Tallahassee Creek Conglomerate, Morrison Formation, Dakota Sandstone). The presence of these formations could be supplied to the model using the data base which records all the rock types present in a given cell, but this detailed information takes time to compile. Consequently, the model uses the occurrence of 8-character geologic codes associated with the sample sites. The investigator enters the information into the EVAL model by supplying the model with key-word mnemonics, on an interactive basis. SURE uses 8-character rock codes. The cell score is then calculated for the proportion of samples in the cell with source or host rock codes. These cell sources are then averaged to give the quadrangle source or host rock score. If the sample-point spacing is relatively even, this averaging provides a reasonable estimate.

Treatment of the Water Data

The water-sample codes allow splitting these data into the categories: stream water, pond water, and spring- and well-waters. For the EVAL model, we group spring- and well-waters together as a general "groundwater" category. Regression for the uranium is done on the basis of calcium, magnesium and conductivity. Of the other available parameters in the LASL data (Section 2), we investigated including pH and/or temperature in the multiple regressions for the Pueblo quadrangle data. Neither made a significant improvement to the results as measured by the R-squared value. We calculated the cell scores on the same basis as that discussed for the stream-sediment data. As before, the user can interactively assign weights to each sub-group prior to scoring.

Treatment of the Airborne Radiometric Data

The presence of airborne gamma-ray anomalies is entered into EVAL as the row and column coordinates of all cells containing one or more of the anomalies recorded on the "uranium anomaly interpretation map" of the quadrangle contractor reports (geoMetrics, 1979a, 1979b; Western Geophysical, 1979; Texas Instruments, 1980), after omitting false anomalies attributed to highways, yellowcake plants, etc. Clearly, more sophisticated geophysical input could be included, and SURE provides for cells to be ranked on a 1 to 10 scale, following assessment of the airborne data by a geophysicist. The proportion of "anomalous" cells contributes to the overall quadrangle score, and again this component can be weighted high or low as desired.

Calculation of the Final Quadrangle Scores

EVAL determines the final quadrangle score as a weighted combination of the stream-sediments, waters, source and host rocks, and airborne anomalies. The default weights are set within the program to 20, 20, 20, 30, and 10 percent, respectively. SURE allows the user to interactively change the weights.

Assigning subjective weights in the model will influence the final quadrangle score, but an informal poll of geologists' preferred weights (at a seminar in Grand Junction, Colorado, in March 1980) indicated generally similar choices. Figure 3.3 shows the change in possible score for the Pueblo quadrangle for all (144) combinations of suggested weights. We have devised a method to assign an approximate confidence interval to the quadrangle score and incorporated it into the SURE model.

Typical CDC 6500 timings (central-processor seconds under the NOS 1.1 operating system) to do an EVAL analysis for the Pueblo quadrangle data (which includes performing regressions, printing maps of the number of points per cell, total and average cell scores, and the generation of files for off-line map plotting for each sub-group) are as follows:

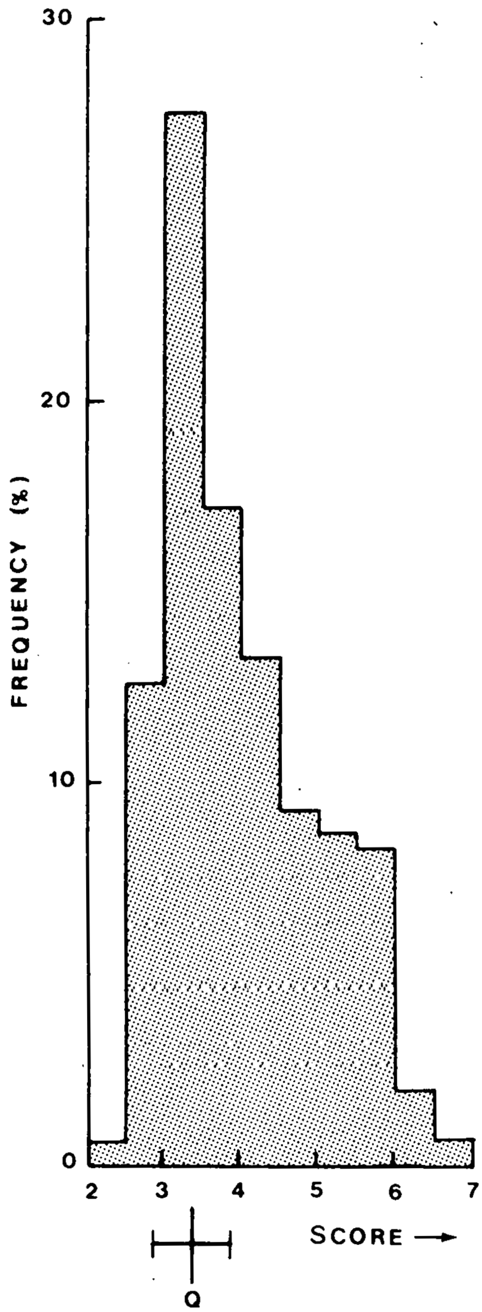


FIGURE 3.3.- Frequency distribution of EVAL quadrangle scores for Pueblo on the basis of all possible (144) combinations of subjective weights chosen by geologists for the categories: stream sediments, water, source and host rocks, and radiometric data. Also shown is the mean quadrangle score using default weights (Q), with its approximate 95 percent confidence interval.

Water analysis
(3 regression passes; 861 samples) .....8.31 sec.

Sediment analysis
(5 regression passes; 1060 samples) ...26.31 sec.

Aerial radiometric analysis and summary
(620 cells)............................0.47 sec.

Regional Anomaly Patterns

This discussion is based on the EVAL point-source-regression residual maps which contain the most detailed information; the patterns are essentially the same as the SURE cell-based maps. All the patterns are based on the uranium residuals (in ppm for stream-sediment data and ppb for water data) post-multiplied by the R-squared values. Table 3.1 lists the R-squared values and sample sizes. The terms low, moderate, and high refer to post-multiplied positive residuals in the ranges 0.1-0.9, 1.0-4.9, and 5.0 and greater, respectively.

TABLE 3.1.- R-squared values (percent) for stream-sediment and water regression analyses for each quadrangle. Sample sizes in parentheses.

Type	Quadrangle							
	Pueblo		Montrose		Durango		Trinidad	
				Stream sediments				
Igneous	69	(282)	41	(742)	57	(520)	94	(113)
Metamorphic	33	(115)	64	(157)	92	(61)	94	(14)
Sediments	57	(331)	33	(524)	71	(706)	95	(744)
Quaternary	55	(324)	62	(413)	59	(287)	59	(297)
				Water				
Streams	65	(356)	9	(1073)	57	(1168)	43	(342)
Springs & wells	22	(427)	94	(275)	6	(303)	23	(658)
Ponds	23	(72)	-	(0)	52	(41)	27	(49)

Pueblo

High residual values in the stream sediments generally occur over the Pikes Peak batholith, Cripple Creek-Phantom Canyon gneiss, Eleven Mill Canyon quartz monzonite, Castle Rock Gulch granodiorite, and the granodiorite of Boulder

Creek age east of the Cotopaxi Fault at Fernleaf Gulch. Scattered low to moderate values occur over the Cripple Creek granitoids and on the Precambrian granitoids at Gribbles Run in the headwaters of Badger Creek, northeast of Salida. Elsewhere in the Precambrian, a line of low to moderate values follows the Ilse fault zone, especially where it crosses the San Isabel batholith, although no anomalies appear to be related to the area of Cambrian alkalic intrusives (McClure Mountain, Gem Park and Democrat Creek) and associated Th-bearing carbonatite dykes in the central Wet Mountains (Armbrustmacher, 1979). Scattered low to moderate values occur over the Paleozoics of the Sangre de Cristo range (for example the Crestone Conglomerate), the Cretaceous Niobrara Formation (east of the southern Rocky Mountains), the Late Eocene Echo Park Alluvium, and the Oligocene Tallahassee Creek Conglomerate. Drainage in the southern Rocky Mountains was conditioned by a shallow southeasterly-dipping paleoslope from late Eocene time onwards, following the Laramide uplift of the Precambrian crystalline rocks. This influence continued through to the late Oligocene (Epis and others, 1976) and controlled the deposition of the Echo Park Alluvium, Tallahassee Creek Conglomerate and later units. Following Neogene block-faulting, sediments were carried directly from highlands into adjacent basins (Epis and others, 1976) resulting in low to moderate residual values in the San Luis and Wet Mountain valleys and over the High Plains east of Pikes Peak.

The highest water anomalies occur in wells and streams in small areas over the Pikes Peak Granite, the Fernleaf Gulch granodiorite of Boulder Creek age, the Tallahassee Creek Conglomerate at Tallahassee Creek, and in wells and springs 5 to 10 miles east of Salida. Low to moderate values occur in streams over the Pikes Peak Granite and the Precambrian rocks northwest of Canon City; streams over the Quaternary in the Wet Mountains and San Luis valleys, and wells in the High Plains, east of Colorado Springs and Pueblo.

Montrose

The main stream-sediment regression residuals are the high values over the Precambrian granitoids of the Sawatch Range, and the Tertiary Mount Princeton batholith complex (particularly the Mount Antero Granite). Moderate values are related to the Laramide Twin Lakes stock and drainage from the Precambrian of the Mosquito Range, and from the areas of Precambrian metamorphics in the Sawatch Range (south and west of Gunnison, and in the Powderhorn district). Moderate values are associated with the Dry

Union Formation of Pliocene to Miocene age and with later Quaternary sediments of the Arkansas Valley derived from the surrounding crystalline rocks. Low to moderate values are associated with the Oligocene rhyolitic ash-flows from the San Juan Mountains to the south, and with three upper Cretaceous units: Mancos Shale, Dakota Sandstone, and Burro Canyon Formation.

Because the regression for stream waters is low (9 percent R-squared) in this quadrangle, the post-multiplied residuals are small. Mostly low to moderate values occur over the Precambrian, and over some acid tuffs in the San Juan area. Moderate values occur in an area of radioactive springs (Nelson-Moore and others, 1978) in the Mancos Shale north of the Gunnison River. The few high values in the quadrangle are in streams draining the Marshall Pass area.

Durango

The few high residual values are related to drainage from the Precambrian Eolus and Florida River Granites, or the rims of the Tertiary Uncompahgre and Lake City calderas. Other scattered moderate to high values occur over the Tertiary rhyolitic lavas and pyroclastic flows in the region between the Needle and La Garita Mountains. Samples with low values are irregularly scattered over most of the quadrangle.

Despite the fairly high regression for most of the water samples (streams and ponds, table 3.1), all of the values are low for this quadrangle except for a few moderate ones in streams over the Eocene San Jose Formation and the upper Cretaceous sediments in the San Juan basin. Low post-multiplied residuals also occur in a few wells in the Rio Grande valley.

Trinidad

The post-multiplied residuals are higher in this quadrangle than in the others, partly because the stream-sediment regressions are high (table 3.1). Moderate to high anomalies are associated with the Precambrian alaskite granites and gneisses of the Culebra Range, and with the Paleozoic rocks of the Sangre de Cristo Mountains. High values also occur over the Cenozoic Raton Formation, Poison Canyon Formation, and Farisita Conglomerate, all of which contain derived Precambrian material (Tweto, 1975). Scott and Taylor (1975) think that the Farisita Conglomerate is equivalent to the Echo Park Alluvium to the north.

Moderate to high values are associated with the Dakota Sandstone to Niobrara Shale interval of the Cretaceous. Low to moderate values occur in the Quaternary sediments of the southern Wet Mountains Valley and in the southeastern part of the San Luis Valley (mainly in Costilla County).

High water-residual values occur in springs and wells in the Tertiary Huerfano Formation, which is mainly derived from the Pennsylvanian and Permian rocks of the Sangre de Cristo Range (Scott, 1975), and the Farisita Conglomerate. Moderate to high residuals are also associated with wells in the Cretaceous interval from the Carlile Shale to the Pierre Shale. Generally low to moderate values are associated with wells in the Quaternary of the San Luis Valley and wells and streams in the Precambrian rocks of the southern Culebra Range.

3.2 THE URANIUM OCCURRENCE CELL-CLASSIFICATION MODEL USING STREAM-SEDIMENT DATA

Introduction

We have developed the cell-classification model for stream-sediment data in the Pueblo quadrangle. Of the 620 cells in the quadrangle, 75 contain at least one reported uranium deposit and 23 produced uranium. In the Pueblo quadrangle there are 1056 stream-sediment samples. Most known deposits (figure 3.4) and most samples (figure 3.5) occur in the western half of the quadrangle.

The purpose of this phase of the investigation was to develop a model to predict the probability that one or more uranium deposits occurs in a cell. The logistic model was chosen because it has been used in deposit modeling by Chung and Agterberg (1979) and others. The form of the model is

$$\theta_i = P(Y_i = 1) = \exp(\underline{x}_i'\underline{\beta})/(1 + \exp(\underline{x}_i'\underline{\beta}))$$

where θ_i is the probability of finding one or more deposits in the given cell, $\underline{x}_i' = (1, x_{i1}, \ldots, x_{ip})$ is the observed vector of p variables, and $\underline{\beta}$ is the vector of parameters to be estimated from a training set.

For the purposes of partitioning the cells into a training and a validation set three categories of cells were considered: (1) the occurrence cells with production, (2) the occurrence cells without production, and (3) the

NUM OBS/CELL

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
1	4	2	1	2	1	2	3	0	1	3	0	3	0	3	1	2	2	3	2	1	1	1	2	1	2	2	0	2	1	1	4
2	0	1	1	0	2	3	1	1	1	3	3	5	5	2	2	1	2	2	3	1	2	1	0	2	0	0	1	1	1	1	3
3	3	0	3	2	2	3	2	4	4	4	0	2	2	4	1	1	2	3	2	0	1	1	1	1	0	1	2	0	2	0	1
4	6	1	3	4	3	3	0	1	1	1	2	3	4	2	1	2	3	2	1	1	1	2	2	0	1	1	0	1	1	2	2
5	2	2	2	0	1	2	7	0	5	2	2	2	3	2	1	1	2	0	3	1	1	2	1	2	0	1	0	0	1	0	2
6	1	3	3	0	0	1	3	5	0	2	0	1	1	0	4	3	2	0	1	1	1	0	0	0	1	1	3	1	3	0	2
7	0	2	5	2	3	5	1	2	0	1	3	3	2	2	1	0	1	1	3	0	0	2	0	3	2	0	1	1	0	1	0
8	6	2	4	1	2	1	5	1	4	3	0	2	3	1	0	1	3	0	2	0	3	2	1	0	0	0	1	0	1	2	1
9	3	1	1	1	2	1	2	3	1	1	0	1	2	0	2	2	2	3	0	0	2	2	2	1	2	1	1	1	2	1	2
10	5	0	3	1	6	1	2	3	1	2	0	1	3	2	0	2	0	3	1	2	2	1	2	0	0	0	1	0	1	0	1
11	3	2	2	1	0	2	6	1	1	4	1	1	1	2	1	2	2	0	3	1	0	0	0	0	0	3	0	0	2	1	2
12	0	4	6	2	3	5	3	2	2	1	3	3	3	0	2	0	0	1	1	3	0	3	1	0	0	3	1	0	1	1	1
13	1	0	1	2	5	2	1	0	2	1	1	1	5	7	5	3	1	0	0	1	4	5	0	0	0	0	0	0	1	1	1
14	4	0	3	3	3	0	4	0	3	2	3	2	4	6	3	2	1	3	2	2	3	3	0	0	0	0	4	0	0	0	1
15	3	3	0	1	0	1	4	0	4	1	3	1	2	2	2	1	0	1	2	3	6	0	2	0	1	1	0	4	1	1	0
16	2	3	2	0	0	2	1	0	1	3	1	7	0	2	7	2	0	2	1	3	3	0	1	0	2	0	0	1	2	2	0
17	0	2	3	2	2	0	1	3	1	4	0	2	5	2	1	3	3	1	4	1	2	2	2	1	2	2	4	1	0	2	0
18	2	4	0	4	1	0	4	4	2	3	4	3	1	3	5	2	2	2	3	2	2	2	0	2	1	5	0	0	2	2	0
19	0	1	1	2	2	0	1	7	3	4	3	0	0	5	4	2	2	1	3	2	3	1	4	3	0	1	3	2	1	1	1
20	2	2	4	1	2	1	0	3	5	2	3	2	1	1	5	3	2	3	1	2	0	3	1	2	1	0	0	1	2	1	2

FIGURE 3.4.- Stream-sediment samples per cell in the Pueblo quadrangle.

LOCATION OF U OCCURRENCES (1ST LINE)
TRAINING SET=1, VALIDATION SET=2 (2ND LINE)

1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0
	1	1	2	2	2	2	2	2	2	2	2	1	1	2	1	1	1	1	1	2	2	2	1	1	1	1	2	2	1	1	2
2	1	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	1	2	2	1	1	1	2	1	1	2	2	2	1	1	2	2	1	2	1	1	2	1	1	1	2	1	1	1	2	2	1
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2	1	1	1	2	2	1	1	2	2	1	2	1	1	1	2	1	1	1	1	2	2	2	1	2	1	1	2	2	1	1
4	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	1	1	1	2	2	2	2	1	2	2	1	1	1	2	2	1	1	2	1	2	2	1	1	2	2	2	1	1	2	1	1
5	2	0	0	0	0	2	0	0	0	0	0	0	1	1	0	0	3	3	0	0	0	0	0	0	0	0	1	0	0	0	0
	1	2	1	1	1	2	1	1	1	2	1	2	2	1	2	1	2	2	2	2	1	1	1	1	2	1	1	2	1	2	2
6	0	0	0	0	0	0	2	0	0	0	0	5	1	1	0	0	2	1	0	0	0	0	0	0	0	1	0	0	0	0	0
	2	1	1	2	1	2	2	2	1	1	2	1	1	1	1	2	2	2	2	2	1	2	2	2	2	1	2	1	1	1	2
7	2	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0
	1	2	1	1	1	2	2	2	2	2	1	1	2	2	2	2	2	2	1	1	1	1	2	2	2	1	1	2	2	2	1
8	4	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	1	2	1	1	1	2	1	2	2	1	1	2	1	2	2	1	2	1	1	1	1	2	1	2	2	2	2	1	2	2	2
9	0	0	0	0	0	0	1	6	0	0	0	2	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
	2	1	2	2	2	1	2	2	1	2	2	1	2	1	2	2	2	1	2	2	2	2	1	2	1	2	1	1	1	2	2
10	0	0	0	0	0	1	2	7	2	0	0	3	1	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
	1	1	2	1	2	2	1	2	2	2	2	2	2	1	2	2	2	2	1	2	2	2	2	1	1	1	1	2	2	2	2
11	0	1	1	0	0	0	2	2	0	1	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
	2	2	1	2	1	1	2	1	2	2	1	1	1	2	2	1	1	1	2	1	2	1	2	1	1	2	2	2	2	2	1
12	0	0	0	0	0	0	1	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2	2	1	1	2	1	1	2	1	1	1	1	2	1	1	2	2	1	1	2	1	2	1	2	2	1	1	2	1	2	2
13	0	0	0	0	1	1	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	1	2	2	2	2	2	2	2	1	2	2	1	1	1	2	2	1	1	1	2	1	1	1	1	1	1	1	2	2	2	1
14	0	0	0	0	3	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	1	1	1	1	1	2	1	2	2	2	2	1	1	1	1	1	2	2	2	1	1	1	2	2	1	2	1	1	2	2	1
15	0	0	1	0	0	0	0	0	0	1	3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	1	1	1	2	1	1	1	1	2	2	2	2	2	2	2	2	2	2	1	2	1	1	2	2	1	1	2	2	2	2	2
16	0	0	0	0	0	0	0	0	0	2	1	2	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2	2	2	2	2	1	2	1	1	2	2	1	1	2	1	2	1	2	1	2	2	2	2	1	1	2	2	1	1	1	1
17	1	0	0	0	0	0	0	0	1	0	6	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2	1	1	2	1	1	1	2	2	2	1	1	2	1	2	2	1	1	2	1	1	2	1	1	1	1	1	1	2	2	2
18	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	1	2	2	2	2	2	1	2	1	2	1	2	1	2	2	1	1	2	1	1	1	2	1	1	1	1	1	1	2	1	1
10	0	0	0	1	2	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	1	1	2	1	2	1	2	2	1	2	1	1	1	1	1	2	2	2	1	2	1	1	1	1	1	2	1	2	1	1	2
20	0	0	0	0	1	0	1	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2	1	1	1	2	1	2	2	1	1	1	2	2	1	2	1	2	2	2	2	2	1	1	2	1	2	2	1	1	1	2

FIGURE 3.5.- Locations of uranium occurrence cells and identification of the training set in the Pueblo quadrangle.

non-occurrence cells. Cells within each of these three groups were randomly assigned so that one-half were assigned to the training set and one-half to the validation set. The production cells were randomly assigned in descending order of production. Each cell contained from 0 to 7 stream-sediment samples with the greatest sample density occurring in the Tallahassee Creek region.

Descriptive Comparison of the Stream-Sediment Elements for Occurrence versus Non-Occurrence Cells

We plotted side-by-side box plots for each of the chemical elements using the Pueblo training set data. The left box (figure 3.6) represents the distribution in the uranium-occurrence cells (o) while the right one is for the non-occurrence cells (n). Following the usual practice in analysis of trace-element data, all box plots are in logarithms. The ability of the chemical element to identify occurrence cells is a function of the displacement in the positions of the two distributions. For Ca, Ce, Co, Cr, Fe, La, Mg, Mn, Na, Sc, Sm, Th, and Ti, the distribution in the uranium-occurrence cells is shifted upwards from the non-occurrence cells. Nowhere does the lower quartile in the occurrence cells exceed the upper quartile in the non-occurrence cells; (a) of figure 3.6 is typical of these distributions. For the other chemical elements, no difference in the relative positions of the two distributions was observed; (b) and (c) of figure 3.6 are typical. However, none of the individual elements appear to be good discriminators of occurrence cells.

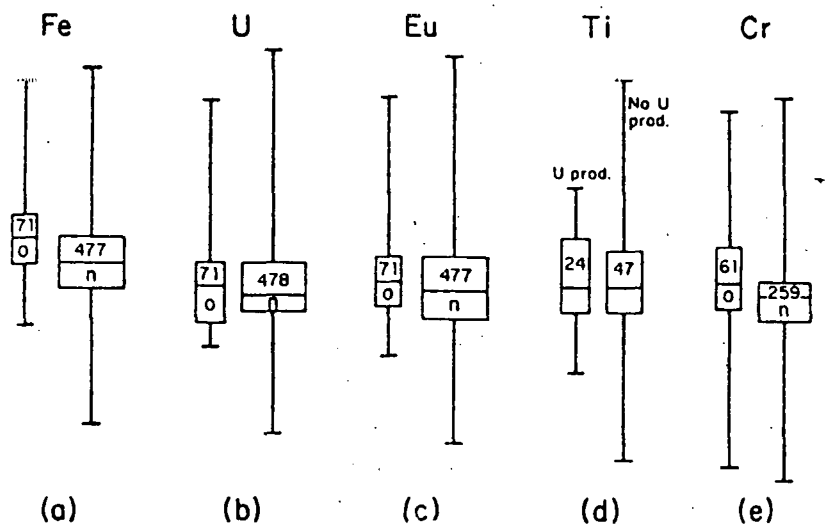


FIGURE 3.6.- Side by side box plots comparing two populations by various chemical elements.

One concern was that within the cells classified as containing one or more uranium deposits there might be a difference between the cells with zero and non-zero production. We generated side-by-side box plots for stream-sediment data to examine this conjecture. No displacement was observed in the distributions. The box plots shown in (d) of figure 3.6 are typical of these.

In addition, the area in the Pueblo quadrangle between 105.032 and 106 degrees longitude was examined separately. This area (20 rows and the 15 leftmost columns) is primarily the Tallahassee Creek region and contains most of the known deposits. Although side-by-side box plots which appear to be weak discriminators of occurrence cells (Co, Cr, Dy, Li, Mg, Mn, Sc, V) were somewhat different from those for the entire Pueblo quadrangle, no element was a good discriminator. The box plot shown in (e) of figure 3.6 appears to be typical of the elements which may be weak discriminators.

The Logistic-Regression Model

We used subsets of the 44 variables in the Pueblo training set to estimate the model parameters. The variables chosen were those that best discriminated between occurrence and non-occurrence cells on the basis of a distribution shift. Unfortunately no model was found which effectively discriminated between occurrence and non-occurrence cells. Some reasons for this will be discussed.

We fitted a logistic-regression model (Chung, 1978) to a 14 variable subset of the stream-sediment variables in the Pueblo quadrangle. The variables Ca, Ce, Co, Cr, Fe, La, Mg, Mn, Na, Sc, Sm, Th, Ti, and U, were selected as the best univariate discriminators between the occurrence and non-occurrence cells by visual inspection of the box plots. A natural log transformation was performed on all variables. When multiple samples occurred in a given cell, each sample was entered separately in the model. When two or more samples occur in a cell, the largest probability is shown. A cell is arbitrarily designated as a misclassification if $P(Y_i = 1) < .5$ given that the cell contains a uranium deposit or $P(Y_i = 1) > .5$ given that the cell does not contain a uranium deposit. The probabilities of classifying a cell in the Pueblo quadrangle as an occurrence cell are given in figure 3.7. Table 3.2 is the misclassification table for both the training and validation sets and table 3.3 is the frequency distribution of probabilities of occurrences of the samples in both sets. Almost all samples are classified as being non-uranium (NU) deposit cells.

```
PROB CELL MAP -    1ST LINE = PROB IN PERCENT
              2ND LINE =  -- EMPTY CELL, T TRAINING SET, M MISCLASSIFIED

     1 2 3 4 5 6 7 8 910111213141516171819202122232425262728293031

 1  39171211111414 01019 018 01924 726 1 1 1 011 2 2 1 4 014 5 2 4
    T T           --    --T --  T T T T T TM    T T T  M--  T T
 2   01212 029 92015 73030163023 7 514 8 0 7 7 0 018 0 0 5 2 6 6 3
    --TM  -- M M  T T       T T     T   T T   T --  ----T T T
 3  20 01714 92016161510 013 623122627 612 0 3 7 5 1 0 2 5 0 4 0 4
    T --T T T     T T   --T   T T T   T T --T       --  T --  --T
 4  331714132312 0 9181518202719 5362212 3 1 4 9 7 0 1 6 0 5 3 3 5
     MT T T     --  T     T T T     T T   T     T --    --T T   T
 5  191713 010 662 03828133524 910 345 027 5 3 2 4 3 0 1 0 0 5 0 9
     MT   --T TMTM--T T   T  MTM    TM--T     T T T --  ----  --
 6   63630 0 0171530 038 011 8 0234621 018 7 5 0 0 0 1 2 3 4 4 0 3
        T ----T TM  --T -- M M--  T TM--      ------   M    T --T
 7   047283413161231 0152921252716 0241212 0 0 7 0 7 1 0 2 4 0 3 0
    --    T T T     --     MT     --  TM  ----T --    --T T --  --
 8  29141714121618324413 0122519 03133 0 8 011 4 2 0 0 0 2 0 3 3 6
     MT   T T T TM      --T   T --  T --T --T T   ------  --T
 9  16131523171315212433 02319 024251516 0 013 714 3 2 0 1 3 2 8 4
        T       TM MT T --TM  --T  M  TM----      T   T   T T T
10  19 02324231314172931 0 31318 021 0 8 4 412 4 6 0 0 0 1 0 3 0 3
      --T   T   TM MTM  -- MTMT --  --  TM        ------T --  --
11  75182726 048412819381410 1 622 6 7 0 4 6 0 0 0 0 0 3 0 0 6 4 4
     M MTM    T TM M  T T T   T TMT     T   ----------  ----  T
12   0282221165847293420472821 0 4 0 0 7 1 5 021 8 0 0 6 3 0 5 3 6
    --T T   T  M MT  M   MTMT --  ----T   T --T   ----T   --    T
13  19 01815607832 0174348 814 611 814 0 0 8 416 0 0 0 0 0 0 7 2 5
      --T   T T   --T   TMT T T     T ----  T T ------------    T
14  31 0221947 038 030264626141312 7 013 41111 9 0 0 0 0 7 0 0 0 4
    T --T T TM--T --TM    T T T T T       T T T --------T ------T
15  4318 0 7 01522 043513949 82324 1 01515 6 6 024 015 6 0 712 7 0
    T  M--  --T T --  T TMTM        --  T   T --  --T T --      --
16  101717 0 01814 035443443 01830 7 012 2 711 0 9 015 0 0 51911 0
          ----T   --T TM M M--   M  --  T     --  --T ----T T T --
17   0 914 813 027224050 02343183010 9 6161110 4 8 8 9112113 016 0
    --T T   T --T   TM  -- M MT     T T   T T   T T T T T T --  --
18  1916 01717 01819162731331946311510 811 5 9 6 0101319 0 0 8 9 0
    T   --    --T   T    M  T     T T   T T T   --T T T ----  T --
19   0 4 63021 0 820173830 0 031242410 710 312 4 9 9 01013 8 8 8 6
    --T    MTM--    T    M----T T       T   T T T T --  T   T T
20  101415111627 025202724251025281710 9 3 2 0 4 8 7 9 0 0 9 712 9
      T T T TMT --  T T T      M  T         --T T T   ----T T T
```

FIGURE 3.7.- Probabilities of classifying cells in the Pueblo quadrangle.

TABLE 3.2.- Numbers of misclassified cells for the training and validation sets, Pueblo quadrangle. Classifications are based on the maximum probabilities for cells with multiple samples.

Type of cell	Totals	Training set		Validation set	
		NU	U	NU	U
Non-uranium deposit (NU)	418	208	1	207	2
Uranium deposit (U)	62	29	3	30	0
Empty cells	140				

TABLE 3.3.- Distributions of estimated probabilities of occurrences of samples.

Percent	Training set		Validation set	
	NU	U	NU	U
0 - 10	232	11	202	18
10 - 20	167	27	140	28
20 - 30	57	13	47	22
30 - 40	16	8	22	11
40 - 50	3	9	9	6
50 - 60	0	1	2	0
60 - 70	1	1	0	0
70 - 80	0	1	1	0
80 - 90	0	0	0	0
90 - 100	0	0	0	0
Total	476	71	423	85

We also considered separately the area between 105.032 and 106.000 degrees longitude. A different logistic model was estimated; however, classification was no better than that using the model for the entire quadrangle.

Discussion

There are three major reasons for the poor performance of the logistic model:

(1) The cells are not homogeneous,
(2) A sample indicating the presence of a deposit may be in a different cell from the deposit; and
(3) Misclassification errors may exist in the training set.

Cells frequently contain multiple rock types, and some of these are not indicators of uranium occurrences. Thus, the distribution of stream-sediment samples associated with occurrence cells is mixed or contaminated. Later analysis will show that certain stream-sediment variables are good discriminators of rock types. One possible solution to this heteroscedasticity problem is to reduce the cell size; however, this results in more empty cells. Also for smaller cells, it is less likely that the sample derived from a deposit will occur in the same cell as the deposit. Filtering techniques might be applied to select the appropriate sample. The success of any classification technique depends in part on the initial classification of the cells into the correct populations. Initial misclassification may result in biased estimates for the model parameters and incorrect apparent-classification errors. This misclassification would exist if some of the nonoccurrence cells contained a deposit. Therefore, the combination of events just described could account for the poor performance of the logistic model.

SECTION 4. SURE, A SYSTEM FOR URANIUM RESOURCE EVALUATION

4.1 INTRODUCTION

SURE is a System for Uranium Resource Evaluation based on the EVAL model. SURE is adapted for input and output by means of a single computer package. Man/machine communication is completely interactive, using a remote terminal. No external plotting facilities are required, because all maps are produced at the terminal.

A simplified flowchart of the SURE system is given in Appendix 3, with emphasis on the stages at which the user interacts with the flow of the program. Unlike EVAL, the program contains options to enable the user to carry out a quadrangle analysis in the absence of complete information. For example, if coded geology is not available, the user may lump the stream-sediment data together. Alternatively, the user can attempt to split the data into a number of sub-groups based on sample-site geochemistry. The data files used are the same as those for the EVAL system: the stream-sediment, water and radiometric data bases.

For the user, program operation is simple because the package issues prompts or requests for alternative action as appropriate. Appendix 4 is an example of detailed interaction for the Pueblo quadrangle.

Percentage weights used in the scoring operations were set arbitrarily as follows:

(1) Data types: host rocks, 26; source rocks, 14; water, 20; stream-seidments, 24; and radiometrics, 16.
(2) Water sub-populations (A) streams, 60; springs and wells, 30; and ponds, 10; or (B) streams 50; springs, 30; ponds, 15; and wells, 5.
(3) Stream-sediment sub-populations: igneous, 25; metamorphic, 25; sediments, 25; drift, 25; unknown, 0.

The user enters the quadrangle name, the program then checks whether the appropriate water-data file is available and whether it contains data on the nature of the sample types. If the latter are not available, the program asks whether the user wishes to treat the data lumped together or ignore it in the subsequent scoring (the latter action will be reflected in the confidence interval on the final quadrangle score). The program then checks to see whether geologic codes are present for the stream-sediment data (although we use our 8-character codes, SURE allows the use of the formation codes of the United States Geological Survey). If such codes are absent the user has the option of single population regression or data set rejection, with the potential option of dividing the data into sub-populations on the basis of geochemistry. (New discriminatory logic may be necessary to extend the latter option to other parts of the United States.) The user is now given the option to change the default scoring weights (above) for the different types of data.

Multiple regression for the water or stream-sediment data proceeds much as in the EVAL package, except that here there is more flexibility in assigning the nature of the sub-groups for regression analysis; sub-population default weights may be changed; output of the anomalies is optional, and listing of values below a user-defined threshold can be suppressed; the full output of correlation matrices, regression equations, univariate statistics and maps of sample occurrence and anomaly distribution for each sub-group may be suppressed. The geologically-based default categories (igneous, metamorphic, sediment, and glacial drift or other surficial deposits) are retained in SURE for the stream sediments. (Applying the model to new quadrangles would require some form of encoded geology to allow this retention, unless cruder analysis on pooled data or geochemically defined sub-groups is done.)

The water analysis includes an option to differentiate between spring and well waters if desired. This should be helpful, as many of the wells may penetrate deep aquifer systems. If such subdivision is requested, the program re-assigns the default water sub-population weights.

Host and source rock occurrence in a quadrangle may be based on the count of appropriate geological formation codes present on a per cell basis if the relevant information is available. If not, provision exists to enter an overall proportion. A similar capability to enter an overall score exists for the airborne radiometric data file. As before, guessed overall scores will result in a larger confidence interval on the final quadrangle score. Maps of cell-score distributions for these data types can be obtained if required.

4.2 SCORING FOR PACKAGE SURE

Scoring is similar in general to that used in EVAL; however, positive residual values for a cell are now summed directly (rather than being ranked with a possible maximum of one) 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, rather than the full 620 cells used in EVAL. This allows for possible differences in airborne coverage from one quadrangle to another. The final quadrangle score is the weighted sum of the component scores.

If we consider the estimate of the overall quadrangle score $\hat{S}$ to be a linear composite of approximately randomly distributed normal variables, then the scores for the i individual data types a_i, each weighted by an amount w_i may be shown (JHS) to have a workable conservative approximation to a 95 percent confidence bound on $\hat{S}$ which is given by

$$\sqrt{\left(\sum_{l=1}^{n} (w_i^2/n_i)\right)}$$

where n_i is the number of data points (cells) in the ith category. This has been implemented in SURE.

4.3 SURE RESULTS

The full interaction possible for a quadrangle analysis is typified by the man/machine dialogue for the Pueblo quadrangle in figure 4.2, which is essentially self-explanatory. As described above, options are present throughout the program to enable the user to suppress full details of the regression analysis and/or score maps if he wishes. Results for the Pueblo, Durango, Montrose, and Trinidad quadrangles are essentially compatible with those previously obtained with the EVAL suite of programs, with the exception of the scoring methodology described above. Final score values are larger as a result of the use of full, rather than ranked, regression residual values (cf. figure 3.3).

Table 4.1 compares the scores for each category for all four quadrangles. If we take the Pueblo quadrangle as a standard, we may compare the other quadrangle scores for each category by multiplying them by the specified weight percent for that category divided by the corresponding raw score for Pueblo. The recalculated Pueblo scores then match the weights which each category contributes to the final quadrangle score, and those for the other quadrangles are in the same proportion.

For Pueblo the total score is 100, the Durango total score is two-thirds that of Pueblo, the Montrose score is 45 percent larger, and the Trinidad score is 30 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 131.5 percent that of Pueblo.

TABLE 4.1. SURE quadrangle scores per category compared to Pueblo scores (percent)

Scored item	Weight, %	Quadrangle			
		Pueblo	Durango	Montrose	Trinidad
Water (4 groups)	20	20.0	2.7	3.1	10.5
Stream sediments (4 groups)	24	24.0	12.2	36.7	52.6
Airborne radiometrics	16	16.0	14.3	15.0	9.5
Source rocks	14	14.0	0.6	28.8	10.0
Host rocks	26	26.0	37.1	60.2	48.9
TOTAL	100	100.0	66.9	143.8	131.5

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, all four quadrangles in the study area have been explored, although not equally.

A further increase in efficiency over EVAL is obtained by using binary input/output for the internal scratch files.

SURE requires 45k (decimal) of central memory on a typical CDC 6500 installation, which allows data sets containing up to 2000 samples to be processed. However, this requirement is easily adjusted and the program can be run in as little as 25k if the data sets contain only 450 samples. Consequently, the program could be run interactively at most CDC sites. Overlay structure and bit-manipulation operations (section 2.2) would need modification for other computers.

Ideally, SURE considers data from each of three files containing: "I6" format stream-sediment data, "I7" format water data, and free-format radiometric data (cell coordinates and a user-assigned anomaly score). The absence of one or more of these files will not prohibit an evaluation.

In order to make SURE easier to use than EVAL, none of the data-base files are reused as scratch files; therefore permanent file copies (or magnetic tapes) can be safely used in direct access mode. Seventeen local files are required for the procedure, source code, absolute and relocatable binary, data, input/output, and scratch files.

SURE contains internal error checks. As discussed above, the options presented to the user are governed by the standard of the available data. In addition, the program checks the following: that the sample sites lie within the bounds of the quadrangle; that data are present for all the predictors used in the multiple regression; that no cell is assigned more than one radiometric score; and that all input values lie within expected limits. If any error is detected, the least disruptive course of corrective action is taken. Additional error checks in the regression software prevents regression on data sets containing less than 10 samples, or issues a warning if the data set contains from 10 to 25 samples.

A typical timing for the complete SURE quadrangle analysis is 23.3 CDC 6500 central-processor seconds under the NOS 1.1 operating system for the Pueblo quadrangle, including regression calculations and output of all maps (Appendix 3).

SURE can be easily adapted to process quadrangles other than those in the study area. For each quadrangle requiring new geologic codes, programs would need to be rewritten to interpret these codes; the present programs would serve as models, so the rewriting would be routine.

Table 4.2 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.

TABLE 4.2.- Production and reserves of uranium for the four quadrangles in the study area. Production data from Nelson-Moore and others (1978), reserve data from DOE files (1980).

Quadrangle	Production lbs. U_3O_8	Production & published reserves lbs. U_3O_8	Production & published reserves Tons U_3O_8
Montrose	2,630,272	8,410,272	4,205
Pueblo	468,748	40,158,748	20,079
Trinidad	1,417	1,417	0.7
Durango	956	956	0.5

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.

4.4 COMPUTING DETAILS

The SURE package consists of a single FTN compatible Fortran program which is heavily overlaid, as table 4.3 shows, in order to optimize the use of computing resources.

TABLE 4.3.- SURE overlay structure.

Level (0,0), program INTRO:
User introductions;
Input file testing;
Primary overlay loading;
BITSET (bit-manipulation) and EDIT (change input parameters) options.

Level (2,0), program REGPRI:
Load secondary overlays for regression and anomaly scoring operations;
Multiple regression and correlation subroutines.

Level (2,1), program WREG:
Water regressions on streams, springs plus wells, and ponds.

Level (2,2), program SCORIT:
Water and stream sediment anomaly scoring operations.

Level (2,3), program SREG:
Stream sediment regression on basis of assigned geologic groups.

Level (2,4), program WREG4:
Water regressions on streams, springs, wells, and ponds.

Level (2,5), program GREG:
Stream sediment regression on basis of sample geochemistry.
(This is currently a dummy subroutine requiring discriminant logic).

Level (3,0), program RMETRIC:
Airborne radiometric (cell) anomaly input and scoring.

Level (4,0), program GCODE:
Perform source and host rock scoring on basis of geologic codes.

Level (5,0), program GCODE2:
Perform source rock scoring on basis of geochemistry.
(This is currently a dummy subroutine requiring discriminant logic).

Level (6,0), program TERM:
Combine results and compute overall cell and total quadrangle scores.

SECTION 5. 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. For instance, analysis of coal resources in western Pennsylvania, of petroleum in the Denver-Julesburg Basin of Colorado, or of zinc mineralization in the Tri-State district of Missouri, Oklahoma, and Kansas would be straightforward because the geology is simple and exploration is relatively complete. In short, the uranium-occurrence data in the study area are what one would expect: not ideal, but nonetheless the basis for meaningful analysis. We will summarize the occurrence data and then discuss them.

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, may 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 5.1 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-six mines,

TABLE 5.1.- Location, production, and geologic data for the 51 mines in the study area that have produced 1 ton or more uranium ore. Quad. - quadrangle; Page, page in Nelson-Moore and others, 1978.

Rank	Name	Quad.	Page	Lat.	Long.	Tonnage	Grade, %	Lbs. U_3O_8	Geologic unit(s)
1	Los Ochos	MO	391	38.369	106.747	448,685	.14	1,253,513	-X-G---- -J-S--ME
2	Pitch	MO	393	38.405	106.298	104,520	.58	1,206,112	PN-K--MB
3	T-2	MO	394	38.369	106.730	37,565	.13	97,618	-J-S--ME
4	Last Chance	PU	149	38.530	105.591	18,575	.31	114,765	TOVCTMTC
5	Gunnison School	PU	148	38.529	105.511	14,308	.24	68,116	TOVCTMTC
6	Picnic Tree	PU	151	38.538	105.530	13,525	.20	52,776	TOVCTMTC
7	Avery Ranch	PU	376	38.510	104.825	10,553	.15	32,213	KJ-S--DB
8	Joan 2	PU	149	38.569	105.515	10,286	.23	47,801	TECZ--EP
9	Dickson-Snooper	PU	147	38.540	105.530	9,664	.22	43,149	TOVCTMTC
10	Little Indian	MO	175	38.426	106.303	8,152	.44	71,762	OCLS----
11	Smaller Lease	PU	152	38.570	105.521	4,871	.30	29,322	TECZ--EP
12	Section 36	PU	151	38.540	105.509	3,379	.28	18,834	TOVCTMTC
13	Knob Hill	PU	149	38.548	105.544	2,901	.20	11,681	TOVCTMTC
14	Thome	PU	153	38.535	105.517	2,593	.27	13,771	TOVCTMTC
15	Mary L.	PU	150	38.570	105.511	2,402	.24	11,610	TECZ--EP
16	Little Abner	PU	150	38.569	105.515	1,647	.36	11,651	TECZ--EP
17	Colexco 1-43	PU	145	38.572	105.250	1,407	.08	2,326	KJ-S--DB
18	Sunshine	PU	152	38.536	105.491	1,145	.27	6,235	TOVCTMTC
19	Good Hope	DU	205	37.353	107.988	650	.07	956	-J-S--ME
20	First Chance	PU	147	38.532	105.483	606	.19	2,303	TOVCTMTC
21	Badito Cone	TR	182	37.774	105.022	510	.13	1,326	KJ-S--DB
22	Brown Derby	MO	173	38.540	106.626	400	.03	238	-X-G----
23	Section 36	PU	454	38.707	105.172	305	.16	965	TOVCTMTC
24	Bonita	MO	389	38.398	106.160	163	.14	472	?
25	Big Red 22	MO	173	38.516	106.387	127	.22	557	OCLS----
26	Mike Doyle	PU	141	38.682	104.861	108	.13	277	KJ-S--DB
27	Lightning 2	PU	149	38.340	105.720	102	.09	193	-Y-GPPPP
28	Bob Cat	PU	389	38.033	105.725	46	.14	131	-X-G----
29	High Park	PU	453	38.708	105.268	46	.13	115	TOVCTMTC
30	Amrine	MO	365	38.976	106.063	45	.12	108	OCLS----(?)
31	City Slicker	TR	182	37.555	105.152	40	.07	56	TOAF----
32	McVey	PU	454	38.723	105.282	37	.10	73	TOVCTMTC
33	Cap Rock	PU	145	38.342	105.472	30	.11	68	TOVCTMTC
34	Ram Lode	PU	393	38.092	105.747	29	.10	73	-X-P----
35	Dilley	PU	147	38.542	105.233	19	.10	38	-J-S--ME
36	Beth	MO	179	38.050	107.450	18	.20	68	TOAD----
37	Hass	PU	367	38.761	105.621	16	.10	32	TOVCTMTC
38	Folbre	PU	141	38.369	105.738	12	.09	21	-J-S--ME
39	Lady Stith	PU	453	38.749	105.158	12	.24	58	TOAF----
40	Abril	PU	453	38.723	105.263	8	.18	29	TOVCTMTC
41	Watters	PU	120	38.176	105.222	8	.11	17	TOAD---- -X-N----
42	La Rue	MO	390	38.306	106.770	7	.20	28	-J-S--ME KJ-S--DB

TABLE 5.1. (Continued)

Rank	Name	Quad.	Page	Lat.	Long.	Tonnage	Grade, %	Lbs. U_3O_8	Geologic unit(s)
43	James-Taylor	PU	148	38.597	105.520	6	.10	12	TOVK----
44	Mocking Bird	PU	392	38.267	105.854	6	.20	24	-X-N----
45	Anal No. 1	TR	182	37.874	105.244	6	.28	33	-K-H--MS
46	Genevieve	PU	453	38.816	105.151	5	.44	44	TOVCTMTC
47	Misery	PU	150	38.472	105.544	3	.17	10	TOVCTMTC
48	Sand Creek	PU	151	38.692	105.279	1	.20	4	TOVCTMTC
49	Good Hope	PU	147	38.459	105.604	1	.20	4	-X-N----
50	Beck Mountain	TR	119	37.940	105.486	1	.10	2	PN-K--MB
51	School Section	PU	151	38.395	105.334	1	.36	7	-XGDBC--

about three fourths of the 51, are in the Pueblo quadrangle; 10, or less than a fourth, 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 5.1 also shows that the two 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.

Table 5.2 compares these occurrence data to those for all deposits. For all deposits, the largest number, 98, are in Precambrian rocks, with the second largest number, 89, in Tertiary rocks, followed by 43 in Mesozoic rocks and 35 in Paleozoic rocks. Notably, for rock types, there is no reliable correlation between the occurrences with and those without production. Much of the disparity reflects the fact that many pegmatites and other deposits in Precambrian rocks are occurrences that never yielded production.

TABLE 5.2.- Host rocks for uranium occurrences in the study area.

Geologic unit	Rock code	Number of occurrences	
		Production <1 T	Production ≥ 1 T
Miocene intermediate flows	TMIF----	10	0
Antero Fm	TOITTMBA	1	0
Tallahassee Creek Conglomerate	TOVCTMTC	24	17
Farisita Conglomerate	TOCS--FA	4	
Oligocene flows	TOAF----	17	2
Oligogene volcanics and sediments	TOVK----	2	1
Wall Mountain Tuff	TORT--WM	1	
Echo Park Conglomerate	TECZ--EP	6	3
Tertiary veins in Precambrian rocks	TCGI----	24	1
Fox Hills Sandstone	-K-S--LF	2	0
Mesaverde Formation	-KSH--MV	1	0
Mancos Shale	-K-H--MS	1	1
Pierre Shale	-KLH--PG	3	0
Dakota Sandstone, etc.	KJ-S--DB	15	4
Morrison Formation, etc.	-J-S--ME	21	5
Cutler Formation	-P-K--CL	1	0
Sangre de Cristo Formation	PPCS--SC	15	0
Belden Formation, etc.	PN-K--MB	7	1
Leadville Limestone, etc.	PA-K--LI	2	0
Fremont Formation	DO-L----	1	0
Harding Quartzite, etc.	OCLS----	10	2
Uncompahgre Formation	PC-P--UN	2	0
Pikes Peak Granite	-Y-GPPPP	10	1
Mount Rosa Granite	-Y-GPPMR	1	0
Precambrian Y	-Y-G----	2	0
Silver Plume Granite	-YQMSP--	1	0
Eolus Granite	-Y-G--EO	1	0
Precambrian X, gneiss	-XGN----	13	0
Precambrian X, granodiorite	-XGDBC--	4	1
Precambrian X, granitic rocks	-X-G----	28	2
Precambrian X, metasedimentary rocks	-X-P----	2	1
Precambrian X, metasedimentary and metavolcanic gneisses	-X-N----	34	2

Table 5.3 is a frequency distribution of grades for the 51 mines in the study area that have produced one ton or more ore. Most grades are less than 0.30 percent U_3O_8; the highest grade (0.58 percent) was that of the Pitch mine, which produced the second largest tonnage of ore and also the second largest amount of U_3O_8.

TABLE 5.3.- Grade distribution for the 51 mines in the study area that have produced 1 ton or more uranium ore.

Grade, % U_3O_8	Frequency	Cumulative frequency	Relative cumulative frequency, %
.00 - .05	1	1	2
.05 - .10	11	12	24
.10 - .15	11	23	45
.15 - .20	11	34	67
.20 - .25	6	40	78
.25 - .30	5	45	88
.30 - .35	3	48	94
.35 - .40	0	48	94
.40 - .45	2	50	98
.45 - .50	0	50	98
.50 - .55	0	50	98
.55 - .60	1	51	100

For our study, the occurrence data serve two purposes. The first is to introduce bedrock geology into the model by identifying the rock units that are favorable host or source rocks for uranium. The second (discussed in section 7) is to calibrate the results of the model by relating the scores to the known uranium endowment. Most mines that produced uranium are in the Tallahassee Creek Conglomerate, associated Tertiary units, the Dakota Sandstone, and the Morrison Formation. The tables show that some rock units have neither producing mines nor known uranium occurrences.

6. GEOCHEMICAL RECOGNITION OF METALLIFEROUS GRANITOIDS: IDENTIFICATION OF PIKES-PEAK-TYPE BATHOLITHS FROM HSSR DATA

6.1 INTRODUCTION

Recent studies of granitoids ranging in age from 750 to 250 m.y. in the Caledonian and Hercynian provinces 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; Plant and others, in press). Fission tract 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 break down later 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. Most of the literature on granites has concentrated on major element geochemistry or on petrographic and mineralogic aspects. The recent surveys by Nishimori and others (1977), Castor and others (1977), and Murphy and others (1978) confirm the general lack of reliable whole-rock geochemical data in relation to uranium geochemistry in granitoids and allied rocks.

Simpson and others (1979), Plant and others (in press), and Brown and others (in press) have shown that, in the British Isles, metalliferous (and therefore potentially mineralized) 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; (3) high Rb/Sr and U/Th ratios; (4) and enriched REE with chondrite-normalized REE distribution patterns having pronounced negative Eu anomalies; (5) in many negative gravity and magnetic anomalies (perhaps related to emplacement in deeply buried Archaean basement). The expected spatial association between the occurrence of 'tin-granites' and uranium mineralization may be obscured when uranium is moved away from the granites by hydrothermal processes or weathering.

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; they have low pressure thermal metamorphic aureoles, and probably crystallized near to the surface under conditions of low water partial pressure.

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 a 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. Fehn and others (1978) have shown theoretically that high concentrations of U, Th, and K could have produced hot rock regions capable of maintaining temperatures of from 100 to more than 200 degrees Centigrade for a long period of time over batholiths of the Conway, New Hampshire, type, particularly during periods of higher than average heat flow, such as the Tertiary. Faults in the granite would favor the formation of a system of channels to heat and circulate the water.

In the mineralized granitoids of the British Isles, petrographic criteria indicating high-temperature water-rock interaction (Simpson and others, 1979; Plant and others, in press) 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 recognise metalliferous granitoids of potential importance as uranium source rocks on the basis of the HSSR data. Geochemical and petrographic evidence from the literature on the Pikes Peak batholith supplies confirmatory evidence.

6.2 PIKES PEAK PLUTON: WHOLE-ROCK GEOCHEMISTRY

The Pueblo quadrangle contains the southern half of the Pikes Peak batholith, including the associated small sodic and potassic plutons of Lake George and Mount Rosa. The batholith was intruded under conditions similar to those for metalliferous granitoids of the British Isles. Barker and others (1975) estimate that crystallization was completed at about 700 degrees C. and 1.5 Kbar, corresponding to 5 km depth. Hawley and Wobus (1977) suggest from the metamorphic assemblage associated with the pluton that maximum P-T conditions were about 6 Kbar and 700 degrees C., that water was available to reactions, and that the system was locally open to carbon dioxide. Criteria supporting extensive hydrothermal alteration include: the presence of biotite and muscovite; alteration of feldspars and ferro-magnesian minerals; greisenization; and the occurrence of accessory fluorite, topaz, and beryl. The mineralogy, petrography, and geochemistry of the batholith have been described by Gross and Heinrich (1965, 1966), Barker and others (1975, 1976), Wobus (1976), Bryant and Hedge (1978), and Carpenter and others (1979).

The petrographic, mineralogic, and geophysical features associated with the metalliferous granitoids of the British Isles and the Pikes Peak batholith (table 6.1) are similar. Recent aeromagnetic data (geoMetrics, 1979a) for the Pueblo quadrangle show strong negative magnetic patterns associated with the batholith. Barker and others (1975) report I. Zeitz (United States Geological Survey) as stating that the pronounced magnetic low associated with the batholith is due to a permanently reversed remanent magnetization; that it may be underlain at depth by a layered gabbro-anorthosite complex, formed when the earth's magnetic field was reversed. From a broad-scale regional gravity survey, Qureshy (1958, 1962) has reported a positive Airy-Heiskanen anomaly of 35 mgal over the batholith, assuming a 30 km crustal thickness at sea-level and a density of 3.27 g/cc, implying a regional crustal thickness of the order of 40 km with a local upwarping of 2 to 3 km. Qureshy (1962) gives a Bouguer anomaly map for Colorado which is not terrain corrected; it is therefore uncertain what the Bouguer residuals are over the batholith. However,

TABLE 6.1.-Comparison of geological and geophysical characteristics of metalliferous granitoids of the British Isles with Pikes Peak batholith.

	Metalliferous (a-c)	Pikes Peak (d-g)
PETROGRAPHIC CHANGES		
Two-mica granite; muscovite replacing biotite	Yes	Yes
Feldspars to sericite/ kaolinite	Yes	Yes
Ferromagnesians to chlorite/ epidote, etc.	Yes	Yes
Hematization of ferromagnesians	Yes	Yes
Tourmalinization	Yes	Yes
Greisenization	Yes	Yes
ACCESSORY MINERALS		
Fluorite	Yes	Yes
Topaz	Yes	Yes
Beryl	Yes	Yes
Cassiterite	Yes	Yes
Columbite-tantalite	Yes	Yes
Uraninite, uranothorite, etc.	Yes	Yes
Thorite	Yes	Yes
Xenotime	Yes	Yes
Monazite	Yes	Yes
Apatite	Yes	Yes
GEOPHYSICAL		
Strong negative Bouguer anomaly	Yes	?
Negative magnetic anomaly	Yes	Yes (h)
Zone of high heat flow	Yes	Probably (i)
SETTING		
Intruded into 'wet' country rock	Yes	Probably

(a) Plant and others (in press); personal communications, 1979/80
(b) Brown and others (in press)
(c) Tischendorf (1977)
(d) Gross and Heinrich (1965,1966)
(e) Barker and others (1975)
(f) Carpenter and others (1979)
(g) Hutchinson (1976)
(h) geoMetrics (1979a)
(i) Blackwell (1978), Lachenbruch (1978)

over granite batholiths strong positive gravity anomalies are evidently rare. Only two of 28 Scottish granitoids have them (Plant and others, in press); in both bodies the Bouguer anomaly is less than 13 mgal and is unaccompanied by a negative magnetic anomaly. Furthermore, the southwest England granites show negative gravity anomalies of about -20 mgal (Bott and others, 1958). Therefore, the interpretation of Qureshy's regional gravity data is uncertain. Barker and others (1975) suggest that a positive gravity anomaly would be consistent with reaction-melting and the accumulation of olivine and pyroxene in the lower crust, or that much of the mafic cumulate may have sunk into the mantle and is no longer present in the lower crust.

Table 6.2 compares the available whole-rock chemical data for the batholith with that of barren and metalliferous granitoids of the British Isles. Pikes Peak is similar in its whole-rock geochemistry to the metalliferous suite.

TABLE 6.2.- Comparison of whole-rock geochemistry of granitoids of British Isles with Pikes Peak batholith (ppm except for K and F percent.

	Normal (a,b)	Metalliferous (a,b)	Pikes Peak (c-e)
Ba	700-4000	10-800	300-1000
Be	0-3	1-19	3-9
F	0.1 (f)	0.1-0.4 (f)	0.3-0.6
K	1-10	3-7	4-6
Li	5-40	20-600	16-140
Nb	?	20-30	40-150
Rb	50-200	200-1000	320-800
Sr	150-2000	40-150	70-150
Sn	0-5	5-25 (g)	4-18
Th	1-10	10-60	57
U	1-5	5-60	5-7
Y	2-40	2-100	70-200
Eu anomaly	No	Yes	Yes
Enhanced HREEs	No	Yes	Yes

(a) Plant and others (in press); personal communications 1979/80
(b) Brown and others (in press)
(c) Carpenter and others (1979)
(d) Hawley and Wobus (1977)
(e) Barker and others (1976)
(f) Tischendorf (1977)
(g) Wilson (1972)

Figure 6.1 shows a whole-rock Sr versus K plot for the British granitoids in which the field of 'barren' granitoids is distinguished from that of the metalliferous suite represented by (1) the field for the Cairngorm granite, Scotland, (Sn-Nb-Pb-Zn-Li-F), together with batholiths of southwest England (Sn-W-Cu-As-Zn-Pb-U-Mo), and (2) the field of the Etive granite, Scotland, (Mo-Cu-Th). The Helmsdale granite, Scotland, (U-Pb-Ba-F) is

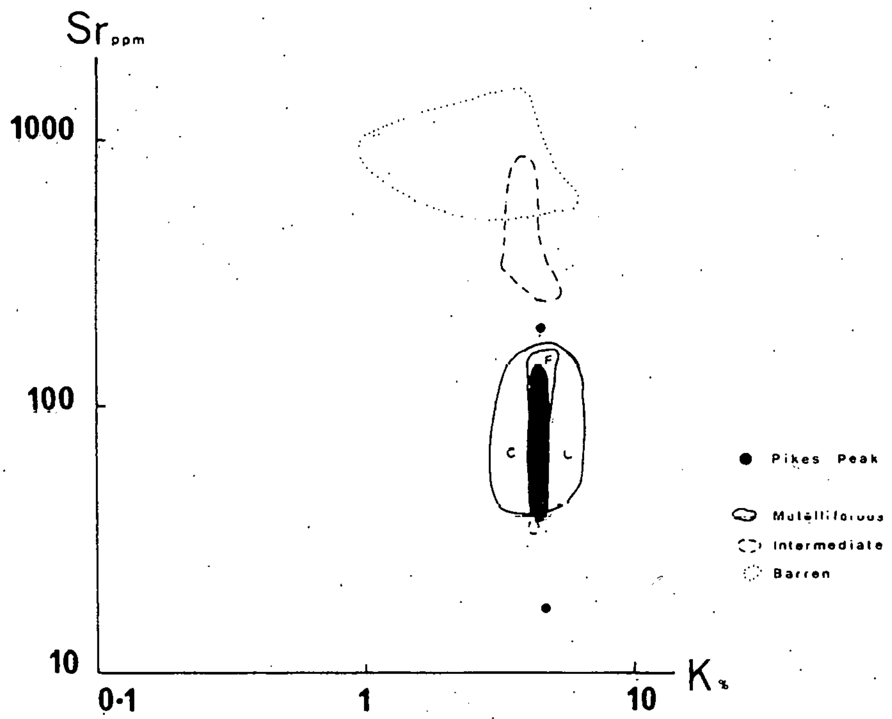


FIGURE 6.1.- Comparison of whole rock Sr and K for Pikes Peak batholith with granitoids of British Isles. C--Cairngorm granite; E--Etive granite.

designated "intermediate" in figures 6.1 and 6.2 because the uranium was evidently introduced by post-magmatic fault-controlled mineralization (Simpson and others, 1979; Tweedie, 1979; Plant and others, in press). For Pikes Peak (Hawley and Wobus, 1977), the Sr versus K (figure 6.1) and Y (figure 6.2) plots are similar to those for Britain, despite differences in the analytical methods.

6.3. PIKES PEAK PLUTON: STREAM-SEDIMENT GEOCHEMISTRY

Stream-sediment samples from the Pikes Peak pluton reflect characteristics of the whole-rock geochemistry, although element concentrations change in the stream-sediment regime. Table 6.3 compares the concentrations 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. Collaborative work with Jane Plant (Institute of Geological Sciences, London) has shown

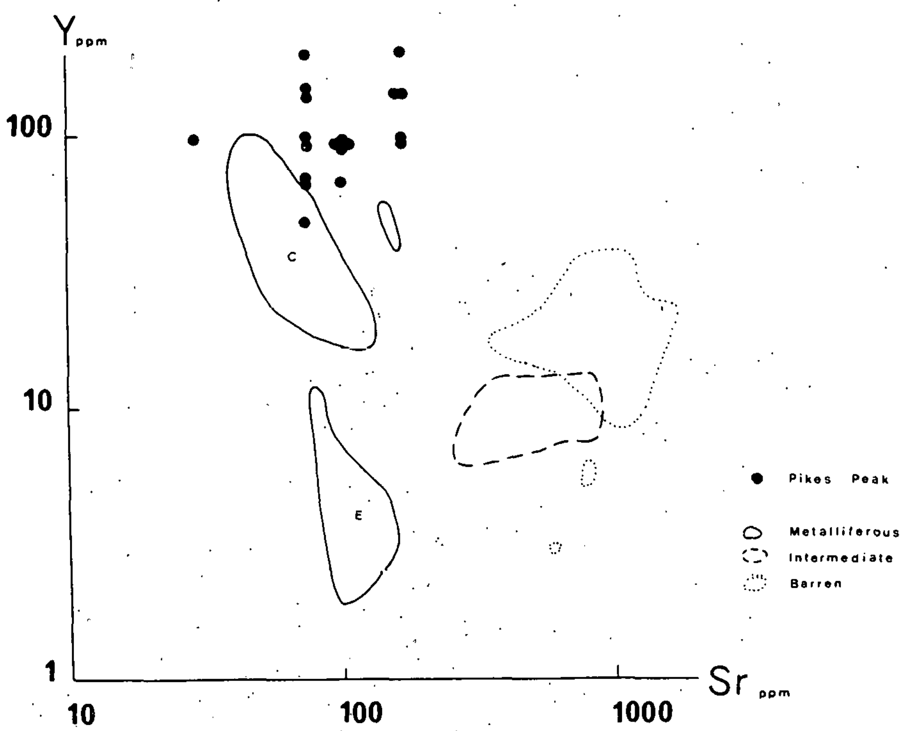


FIGURE 6.2.- Comparison of whole rock Y and Sr for Pikes Peak batholith with granitoids of British Isles.

TABLE 6.3 Concentration levels for selected elements in stream sediments over granites.

	Pueblo				Durango		Trinidad		Montrose	
	Pikes Peak (60)		San Isabel (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	

$\bar{w}$ = Mean
s = Standard deviation

that many of the whole-rock trends identifying metalliferous granitoids in the British Isles are also present in the Pikes Peak stream-sediment samples. In comparison, the San Isabel pluton appears to be a typical barren granite. Unfortunately, the relatively high detection limit for Sr in the LASL stream-sediment data prevents using it as a sensitive indicator, as can be done with the whole-rock data (Plant and others, in press), but other elements are useful. Similar Pikes Peak and British metalliferous granite trends are shown by plots for whole-rock Ba versus K, Sr versus K, Sr versus Rb, Zr versus Rb, and K versus Rb.

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 6.3), reflecting the whole-rock geochemistry of the fayalite, riebeckite, and potassic granites which constitute the pluton (Barker and others, 1976). In addition, the whole-rock patterns have REE enhancement, which is also shown by the chondrite-normalized Lu/Eu ratio in the stream sediments (figure 6.4A). A few stream sediments from the Montrose and Durango quadrangles have high REE concentrations (figure 6.4A), but not so pronounced as those in the Pikes Peak area. While most of the granite-derived sediments in the study area do not show Eu-anomalies, some from the

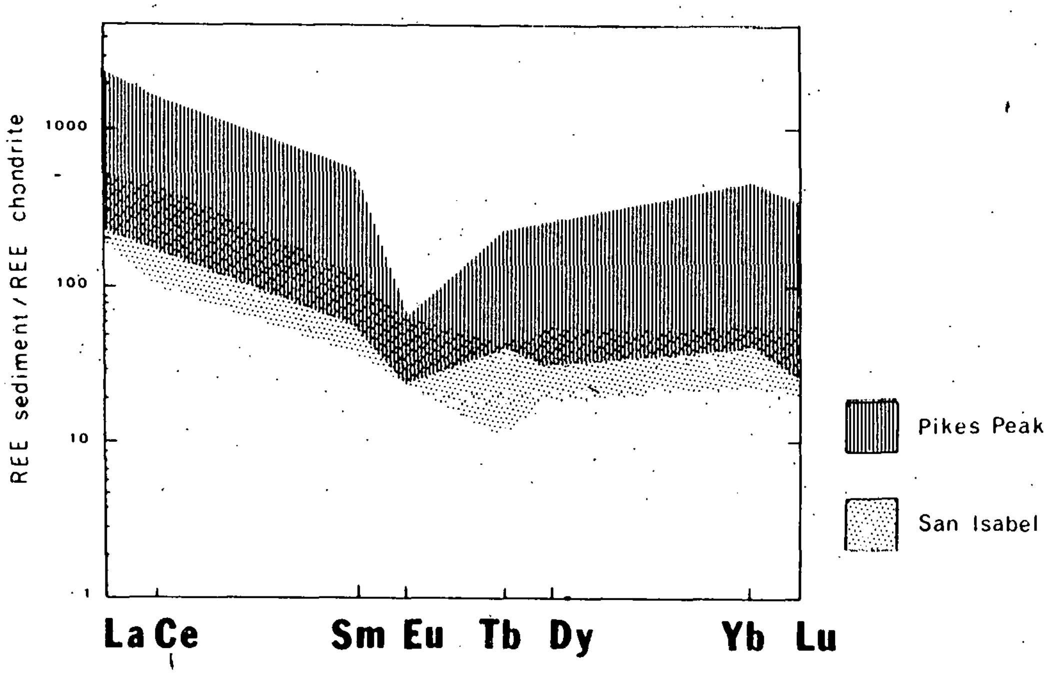


FIGURE 6.3.- Chondrite-normalized REE distribution pattern ranges for stream sediments from San Isabel (14) and Pikes Peak (60) granites.

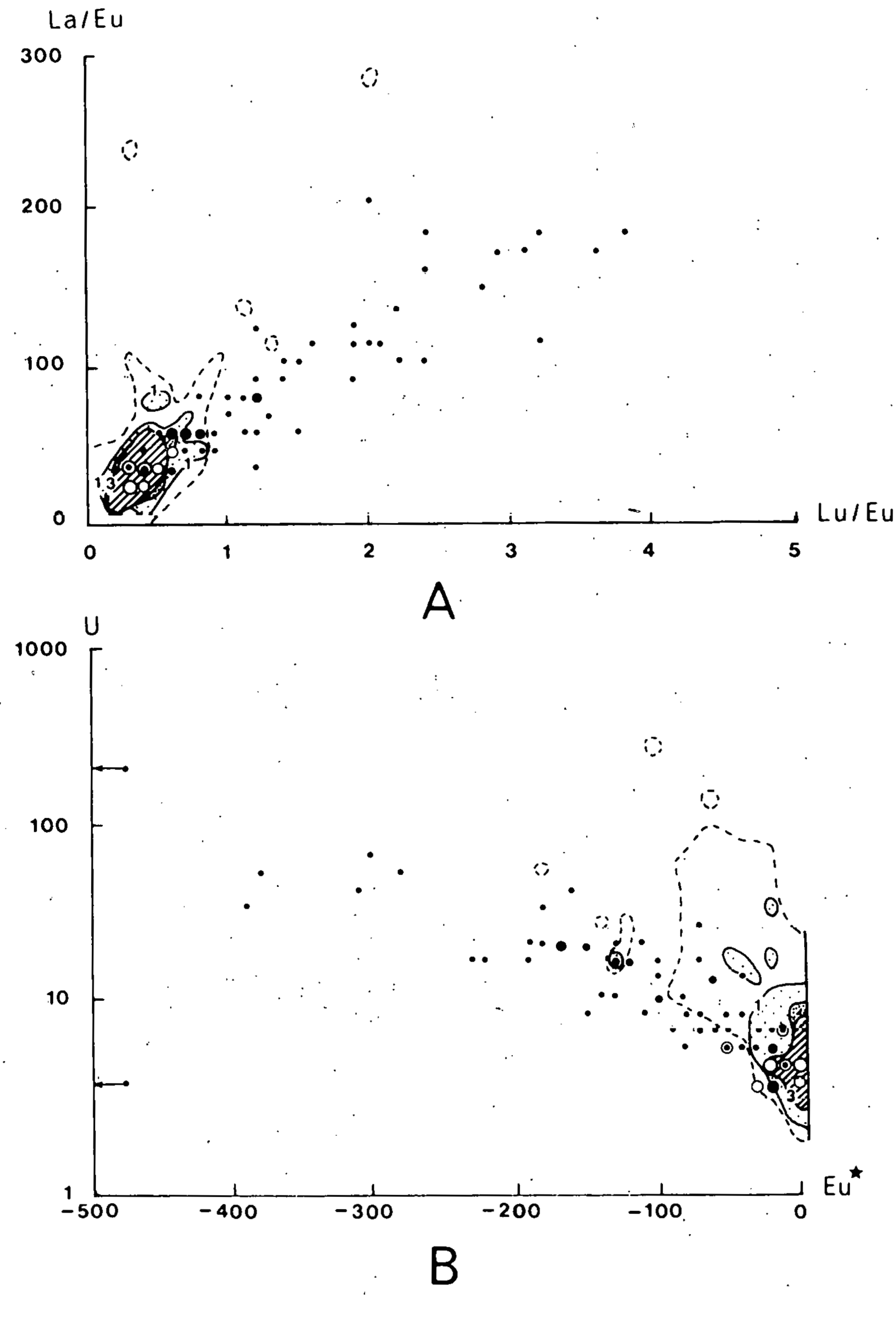


FIGURE 6.4.- Comparison of 60 Pikes Peak (solid dot) and 14 San Isabel (open circle) stream sediments with all 227 granite-derived sediments excluding Pikes Peak, contoured at 1, 2, and 3 percent frequency. Dot size proportional to 1, 2, 3, and 5+ coincident samples.

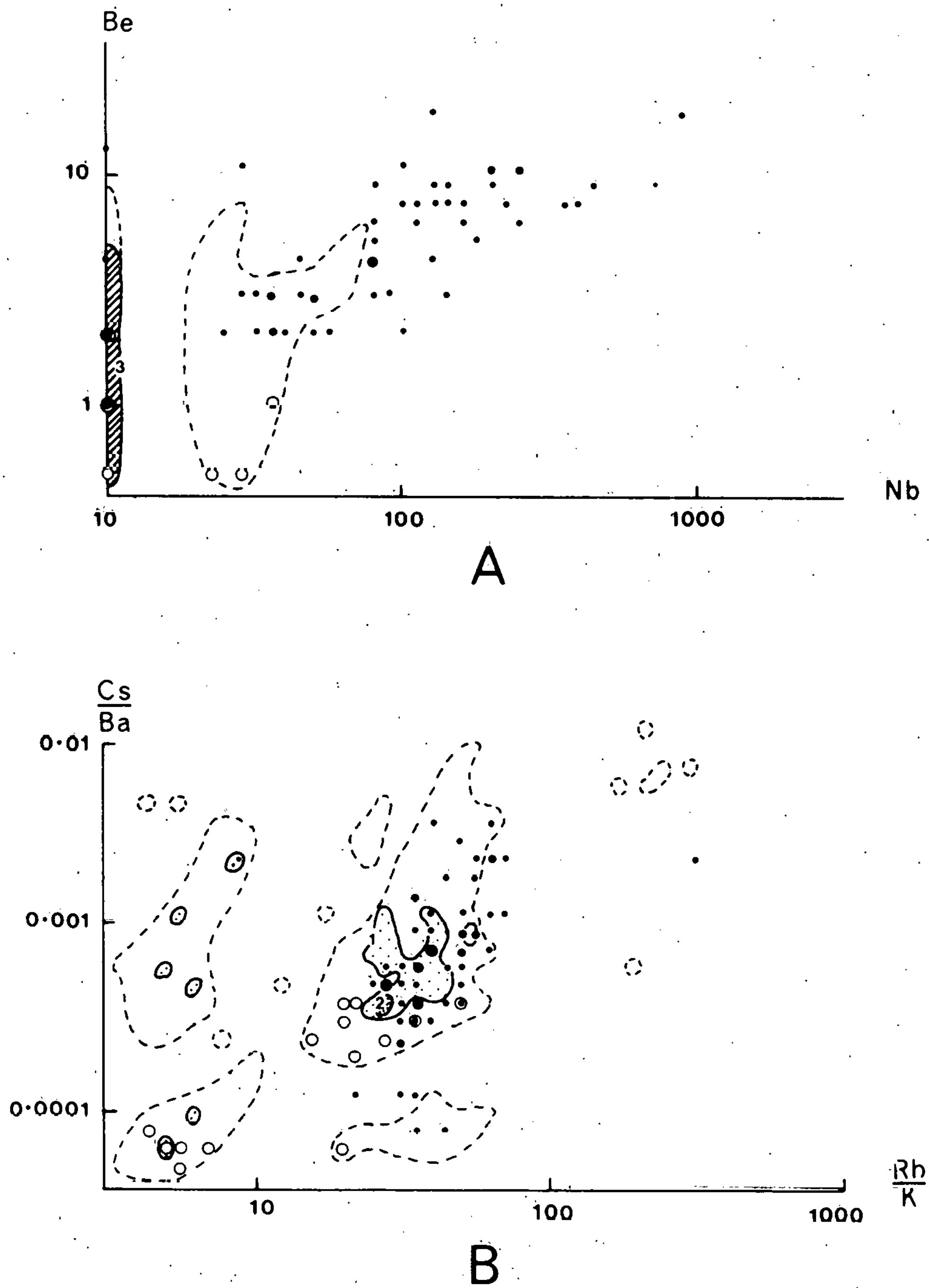


FIGURE 6.5.- Comparison of 60 Pikes Peak and 14 San Isabel stream sediments with all 227 granite-derived stream sediments excluding Pikes Peak. Symbols etc. as Fig. 6.4.

Montrose and Durango quadrangles show a similar but less pronounced trend to that of the Pikes Peak samples (figure 6.4B), accompanied everywhere by increased U contents.

Be and Nb are enhanced in the samples from Pikes Peak compared with those from the San Isabel granite (figure 6.5A), and, except for a few Montrose samples, Nb is essentially at background levels in the other stream-sediment samples from granites. The Pikes Peak pluton is also distinguished by enhanced Cs/Ba and Rb/K ratios compared with San Isabel (figure 6.5B), although there is some overlap. Similar high ratios to Pikes Peak occur in a few samples from the Durango and Montrose quadrangles.

We hypothesized that some uranium in the stream sediments is contained in the heavy resistate minerals (monazite, allanite, xenotime, zircon, etc.), particularly because of the good correlation between U and Hf (r=0.812) for the Pikes Peak samples (figure 6.6). If this hypothesis is correct, regressing U on the REEs would account for uranium in these minerals, and residual uranium could then be used as a guide to regions of enhanced uranium mineralization for incorporation in the EVAL and SURE models. Table 6.4 shows the correlation coefficients

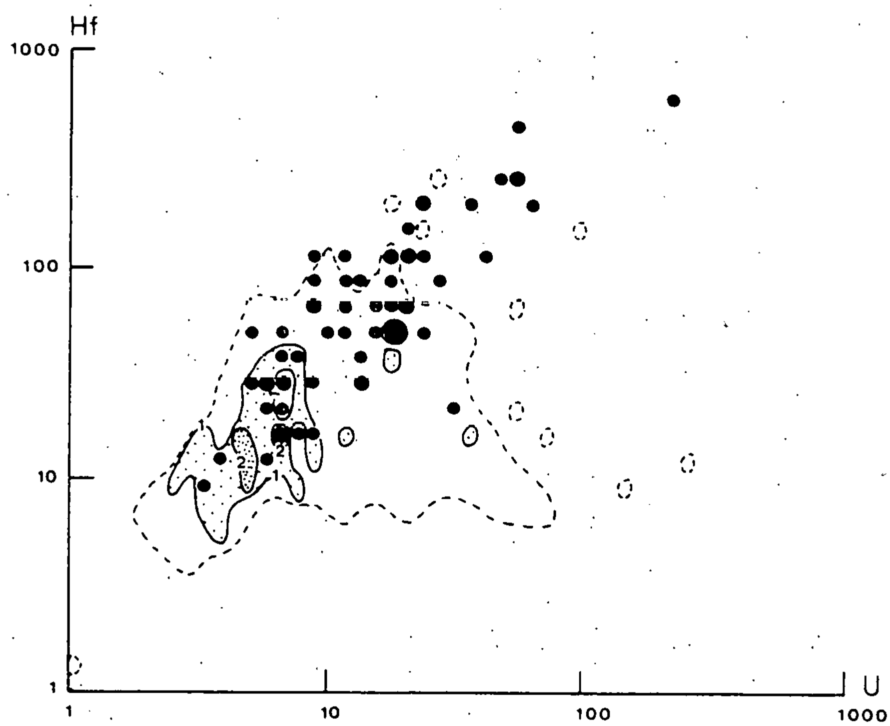


FIGURE 6.6.- Comparison of 60 Pikes Peak stream sediments with all 227 other granite-derived stream sediments. Symbols etc. as Fig. 6.4.

TABLE 6.4.- Correlation of uranium and residual uranium from regression on REEs with other selected elements for 74 samples of Pikes Peak and San Isabel granites.

	Uranium	Residual uranium
Ba	-.669	-.163
Be	.715	.023
Cs	.126	.109
Eu	.430	-.030
Hf	.812	-.103
K	.009	-.290
La	.898	.005
Li	.064	.406
Lu	.932	-.011
Mg	-.422	.035
Nb	.821	-.060
Rb	.497	-.086
Sr	-.165	-.045
Th	.936	.092
U	1.000	.283

for uranium and residual uranium with selected elements for the stream sediments derived from the San Isabel and Pikes Peak granites. The REE-based regression (R-squared = 0.917) completely removes the correlation of residual uranium with all other elements, including Hf (considered an adequate guide to Zr which was not determined), except for a moderate residual correlation with Li. Since all the corresponding high-Li samples are near the Mount Rosa intrusion, the spatial pattern of anomalies is not unreasonable.

The Th content is high relative to U in the Pikes Peak samples, compared with other granite-derived samples (figure 6.7). This result, in accord with the whole-rock data from the granites of the Granite Mountains district, Wyoming (Stuckless, 1979), suggests that, owing to the greater mobility of U compared to Th in the weathering environment, U is lost from uraniferous granite batholiths, which may now only be recognizable by enhanced Th levels. This high Th/U ratio also supports the uraniferous granite as a potential source rock for uranium deposits formed in surrounding sedimentary basins after the emplacement of a metalliferous batholith.

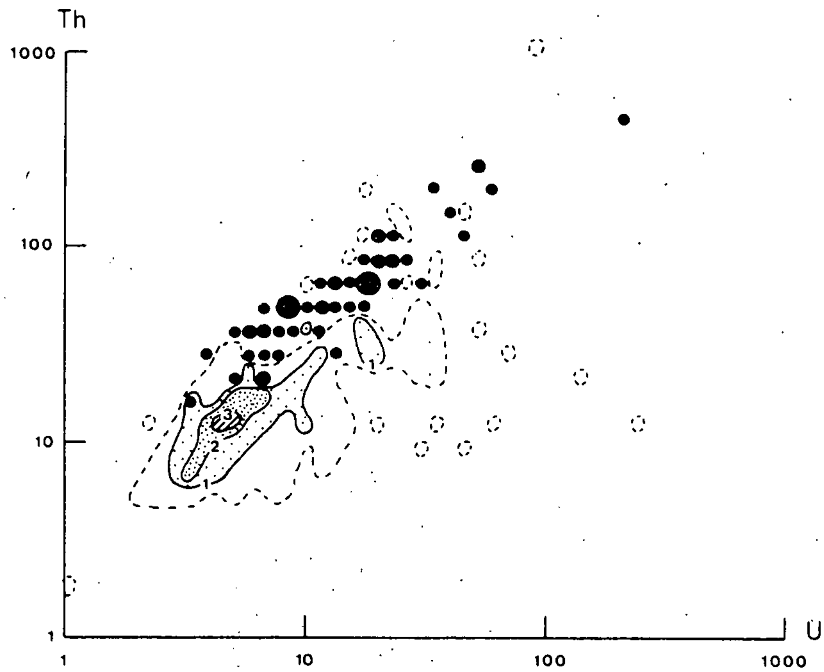


FIGURE 6.7.- Comparison of 60 Pikes Peak stream sediments with all 227 other granite-derived stream sediments. Symbols etc. as Fig. 6.4.

6.4. IMPLICATIONS FOR RECOGNITION OF PIKES PEAK TYPE BATHOLITHS FROM HSSR DATA

Examination of 277 stream-sediment samples from other granites in the four quadrangles (table 6.3; figures 6.4-6.7) suggests that similar granites to Pikes Peak exist in the region, but whole-rock data to confirm this hypothesis are lacking. The whole-rock geochemistry of the granitoids of the Spanish Peaks complex (Jahn and others, 1979) and the Tertiary stocks of the Colorado mineral belt (Simmons and Hedge, 1978) have been studied recently with emphasis on REE distribution patterns. Only three specimens strongly resembled the metalliferous granitoid trends; an aplite from the Empire stock, a leucocratic monzonite from the Audubon-Albion stock, and a bostonite dike near the Apex stock. Although no uranium values were reported by Simmons and Hedge (1978), high uranium concentrations are associated with bostonite dikes elsewhere in the Front Range (Carpenter and others, 1979). On the other hand, 90 stream sediments from the granodiorite, quartz monzonite, and quartz diorite suite of the Pueblo quadrangle show broadly similar trends to those described earlier for Pikes Peak. But no similarity in trend are shown by 428 stream sediments derived from intermediate extrusive rocks of the four quadrangles, the 12 rhyolite-derived stream sediments from the Durango quadrangle, or the 351 stream sediments derived from metamorphic rocks in the region.

6.5 TEST OF METHOD

We established an empirical "Pikes Peak Index" (PPI), based on observed differences between stream sediments draining the Pikes Peak and San Isabel batholiths. Each criterion met (table 6.5) 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 San Isabel samples had a significant score. Discrimination between the data used to establish the index was therefore good.

TABLE 6.5.- 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 Yb.

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

The PPI is strongly correlated with logU and logTh for granite-derived sediments in the four quadrangles (r=0.603 and 0.771 respectively, n=337), and also for sediments from other acid and intermediate intrusive rocks, which consist mainly of syenites, quartz monzonites, and granodiorites (r=0.543 and 0.823, n=123). The overall trends are identical, and these data have been combined in figure 6.8. Correlation with untransformed U and Th is less pronounced in both sets of data (0.325 and 0.335, n=337; 0.308 and 0.723, n=123). The spatial distribution of PPI values greater than 50 in the study area identified several intrusive bodies, which are described in more detail below. Screening the entire data set for each quadrangle showed that the number of "false alarms" from samples draining non-granitoid rocks is small. Such samples usually have PPIs below 60, and rarely form multi-sample spatial clusters. Several sediment samples from the periphery of a granitoid body but formed largely from other formations gave a high PPI value, reflecting granitoid detritus. The best examples are the sediments to the east of the Pikes Peak batholith in the Pueblo quadrangle, particularly the Paleocene Dawson Formation, the Quaternary Nussbaum Alluvium, and eolian sands. Elsewhere, such samples further indicated the extent of a Pikes Peak-type intrusion, particularly when coverage of the granitoid itself was relatively sparse: for example, near the granites centered on Forest Hill and Emerald Peak, in the Sawatch Range northwest of Gunnison in the Montrose quadrangle.

Pueblo

Most samples with a PPI of 70 or more were taken over the Boulder-Creek age (1700 to 1690 m.y.; Hutchinson, 1976) Cripple Creek-Phantom Canyon granite gneiss and migmatite immediately south of Pikes Peak, in Teller, El Paso and Fremont counties; minor uranium was produced from the Mike Doyle Carnotite Deposit in the adjacent Dakota Sandstone (Nelson-Moore and others, 1978). Other PPIs greater than 70 are associated with the granodiorite of Boulder Creek age (southeast of Salida, Fremont County), which extends from South Burno Mountain in the north to Fernleaf Gulch in the east. Minor uranium was produced from a small open cut near Cotopaxi, and uraninite and fluorite have been identified in Precambrian metasediments nearby (Nelson-Moore and others, 1978). The Castle Rock Gulch granodiorite north of Salida in Chaffee County has PPIs of 50 to 70 and contains monazite and the Nb-Ta-Ti-U-Th oxide euxenite in associated pegmatites (Nelson-Moore and others, 1978). The Silver Plume age (1460 m.y.; Hutchinson, 1976) Eleven Mile Canyon and adjacent quartz monzonites (Park County) have PPIs of 50-60, and, although not associated with known uranium mineralization, show strong REE-regressed uranium anomalies just north of Saddle Mountain.

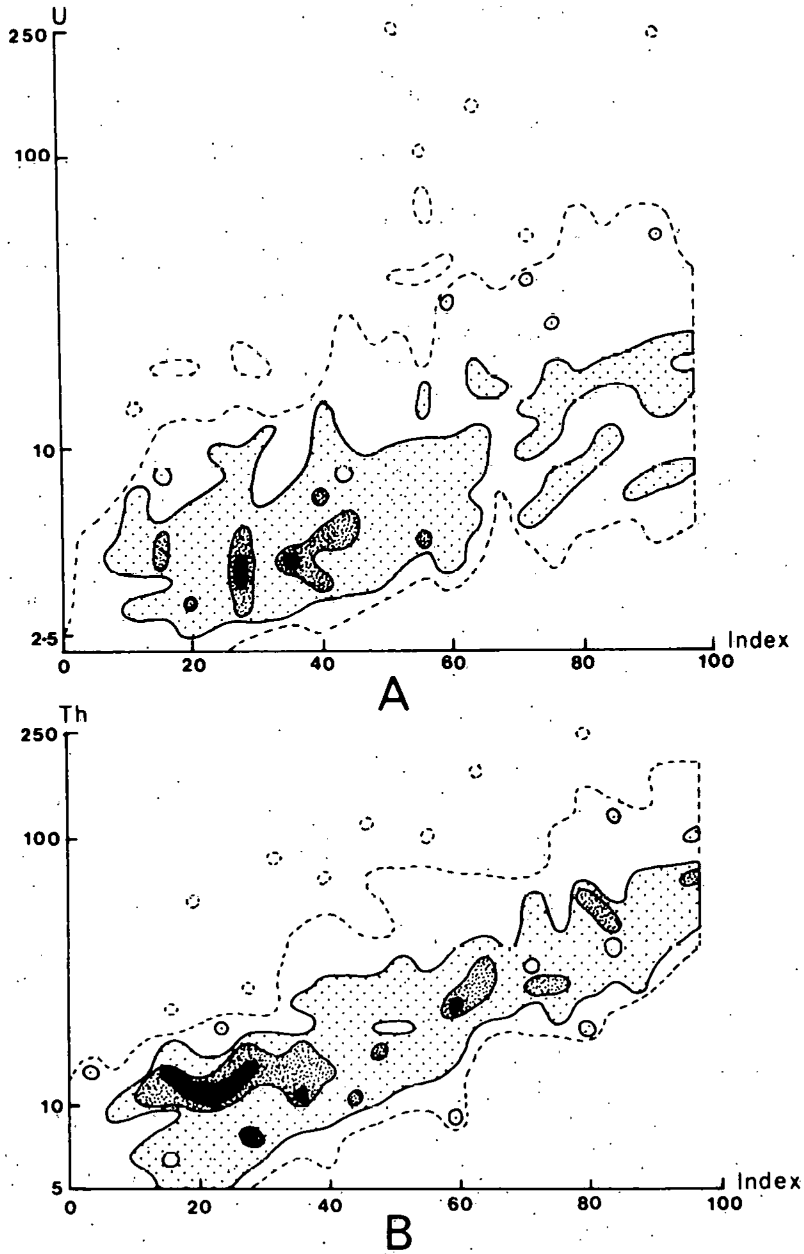


FIGURE 6.8.- Correlation of Pikes Peak Index with uranium (A) and thorium (B) in all 460 stream-sediments draining acid and intermediate intrusives. Contoured at 0.5, 1, and 2 percent.

Most other Precambrian intrusives northwest of Canon City (near Tallahassee Creek) and in the Wet Mountains have PPIs below 50. No high PPIs are associated with the area of Cambrian alkalic igneous rocks (McClure Mountain, Gem Park and Democrat Creek complexes) and their associated Th-rich carbonatite dikes in the central Wet Mountains (Singewald and Brock, 1956; Parker and Sharp, 1970; Armbrustmacher, 1979). These PPIs are not associated with high whole-rock uranium values, and the stream-sediment data are not enhanced in uranium or thorium. No high PPIs occur over the Cretaceous Whitehorn Granodiorite (Wrucke, 1974), which does not have similar whole-rock geochemistry to that of the Pikes Peak batholith.

Montrose

In the Mosquito Range east of the Arkansas River in Chaffee and Park Counties, moderate to high PPIs are associated with the Precambrian granitoids which contain monazite, euxenite, and other REE-bearing minerals in pegmatite veins (Nelson-Moore and others, 1978) and have PPIs from 60 to 90 between Browns Canyon and Buffalo Peaks. In the Sawatch Range between Gunnison and Buena Vista in Gunnison County, PPIs greater than 70 are also associated with the granites, which are associated with minor uranium occurrences in the Paleozoic inliers in the Monarch Pass body. These granites have fluorite, tourmaline, and beryl as accessory minerals (Nelson-Moore and others, 1978; Brady, 1975). The granites at Cochetopa Canyon, related to the Los Ochos mine, and at Stubbs Gulch (Saguache County) have PPIs of 60 to 70, although the uranium deposits in the adjacent sediments postdate the Tertiary faulting (Nelson-Moore and others, 1978).

At Iron Hills in the Powderhorn District of Gunnison County, the carbonatite complex (a thorite and REE-rich 570 m.y. pyroxenite-nepheline syenite) and the associated Powderhorn Granite of Boulder Creek age do not have high PPIs. The whole-rock Th content of the carbonatite ranges from 6 to 150 ppm (average 32) and has a low uranium content (Armbrustmacher, 1980). Surprisingly, associated stream sediments do not have particularly high uranium or thorium values (4 to 9 ppm and 14 to 30 ppm, respectively) although some samples have high Ba, Sr and Nb.

The few small Laramide stocks (probably ranging from 70 to 65 m.y.; Tweto, 1975), do not have high PPIs, although the Twin Lakes stock has a few moderate PPIs. Many granodiorite and quartz monzonite rocks of Middle Tertiary age (36 to 30 m.y.; Tweto, 1975) occur in the West Elk Mountains and Sawatch Range. Unfortunately, stream-sediment coverage in the West Elk mountains is sparse; no high PPIs occur in the samples taken.

In contrast, there is an area of high PPIs to the east of the Sawatch Range where the large Mount Princeton batholith, its associated Mount Pomeroy quartz monzonite, and the Mount Antero Granite are intruded at the edge of pre-existing 1650 m.y. (Wetherill and Bickford, 1965) Precambrian granitoids. The Mount Princeton batholith, dated at 36 m.y. (Olson and Dellachaie, 1976), abuts the small, possibly slightly older, Mount Pomeroy quartz monzonite (Dings and Robinson, 1957). The area of the granodiorite and associated quartz monzonite has PPIs in drainage channels from 60 to 70. Dikes of more granitic composition extend from the Mount Princeton batholith, and accessory tourmaline is present, but pegmatites are rare. Dings and Robinson (1957) suggest that the batholith may be genetically related to the W-Mo mineralization present in the area. The few published whole-rock analyses of the Mount Princeton batholith (Simmons and Hedge, 1978) do not strongly resemble the Scottish metalliferous granitoids (although few trace-element data are available).

The smaller Mount Antero Granite (31 m.y.; Olson and Dellachaie, 1976) which intrudes the Mount Princeton batholith is particularly interesting because it has PPIs greater than 90 (with high REE-residual uranium values) in associated drainage sediments. The beryl-bearing granite has extensive hydrothermal alteration and the mineral brannerite (containing U, Th, Ti, Si) associated with molybdenite, huebnerite, wolframite, topaz, fluorite, and tourmaline in pegmatites (Dings and Robinson, 1957). Related hydrothermal activity is evident in an alteration zone of zeolite, chlorite, illite, epidote, calcite, and fluorite covering at least 64 sq. km. of the Mount Princeton batholith near the Chalk Creek and Cottonwood hot springs; the latter may have formed within a temperature range of 145° to $220^{\circ}C$ and depths of 150 to 200 m (Sharp, 1970). Olson and Dellachaie (1976) suggest that the alteration may be related to a zone of high heat-flow in the Rio Grande rift system. The hot springs probably come from deep circulation of meteoritic waters along fractures at the northern end of the Rio Grande rift system of late Cenozoic age.

The area of the Mount Princeton batholith is a deep gravity low. This low coincides with a regional Bouguer anomaly of -310 mgal and a regional residual anomaly of -10 mgal, and is also associated with the -30 to -50 mgal northwest-trending residual anomaly over the Colorado mineral belt. This second anomaly is attributed to a complex of large Laramide and middle Tertiary batholiths underlying central Colorado (Tweto and Case, 1972; Steven, 1975). The rhyolitic Wall Mountain Tuff (36-35 m.y.), covers about 10,400 sq km of the post-Laramide, late-Eocene erosion surface to the east of the Arkansas River valley. This tuff, which separates the Echo Park Alluvium and Tallahassee Creek Conglomerate in the Thirty-nine Mile Volcanic Field and northern Wet Mountains Valley, may have originated from a caldera (Epis and Chapin, 1975; Epis and others, 1976).

Durango

The highest PPIs in the Durango quadrangle are associated with streams draining eastward from the Trimble Granite of Silver Plume age (1350 m.y.; Bickford and others, 1969), the Florida River Granite, and the Eolus Granite (1454 m.y.; Hutchinson, 1976) south of the Needle Mountains in La Plata County. The Trimble and Florida River biotite-muscovite granites show signs of extensive hydrothermal alteration (Barker, 1969; Bickford and others, 1969). Nelson-Moore and others (1978) state that an area of at least 10 sq. mi. of the Eolus Granite contains uranium anomalies, where uraninite and gummite mineralization is associated with fluorite in hydrothermally altered granite. At Columbine Pass, Schmitt and Raymond (1977) describe local Cu-Pb-Zn-Mo-F mineralization associated with the Tertiary (10 m.y.) Chicago Basin stock of granite and rhyolite porphyry, which has undergone extensive hydrothermal alteration. A second area of Eolus Granite, which occurs in the Pine River batholith to the east of Emerald Lake (Hinsdale County), only has low PPIs. PPIs from 50 to 90 are associated with the Cataract Gulch Granite of Silver Plume age and the edges of the 28 m.y. Lake City and Uncompahgre calderas abutting it (Durango and Montrose quadrangles). Minor uranium mineralization is associated with veins in the rim of the Uncompahgre caldera (Nelson-Moore and others, 1978) where it is cut by the younger Lake City caldera. Both show extensive hydrothermal alteration associated with Au-Ag-Pb-Zn-Cu mineralization (Steven and others, 1974).

The post-tectonic Bakers Bridge Granite (La Plata County) of late Boulder Creek age (1612 m.y.) and the 1724 m.y. Ten Mile Granite (San Juan County) do not have high PPIs although both have some hydrothermal alteration, and fluorite occurs in the granites of the Bakers Bridge area (Bickford and others, 1969). Scattered PPIs of 50 to 60 in the sediments of the Hermosa Creek and Lime Creek areas in La Plata County may be associated with Tertiary acid intrusives or the Precambrian Twilight Granite (Bickford and others, 1969).

Trinidad

The only sediments with PPIs exceeding 50 are in a few streams draining west from the crest of the southern Culebra Range, between Whiskey Pass and Devils Park in Costilla County. Other areas mapped as alaskite granite do not have PPIs greater than 50. (The PPIs are different in the areas mapped as "granite" and "metamorphic" at the junction of the Pueblo and Trinidad sheets, suggesting that the areas mapped as alaskite granite in the latter may in fact be gneiss). Since the northward extension of these alaskite granites into the Pueblo quadrangle forms the San Isabel Granite, which is a typical barren granite, this lack of similarity is to be expected.

SECTION 7. URANIUM ENDOWMENT

The term uranium endowment was defined by Harris (1978, p. 52) who relates it to earlier terminology in figure 7.1. Harris writes that:

> First, I propose two new terms: 'uranium endowment' and 'potential uranium supply,' or more generally, 'mineral endowment' and 'potential mineral supply.' 'Mineral endowment' {figure 7.1} is distinguished from the resource base, which consists of the totality of material, in that it includes only those accumulations of uranium in deposits of some minimum grade (q), a minimum tonnage (t), a maximum depth (h), and perhaps, even some specified mode of occurrence. Economics does not figure in the definition of 'mineral endowment'.

DOE has adopted somewhat different terminology. In its assessment report on uranium in the United States (U.S. Department of Energy, 1980, p. 21.22), DOE defines "resources" equivalent to Harris's "endowment" and divides resources into two broad categories, inventory and endowment.

In DOE's usage, inventory "is a compilation of all uranium-bearing material for individual mining properties, derived mainly from company drilling data, which exceeds both specified minimum mining thicknesses and grades of 0.01 percent U_3O_8; economic availability is not a consideration." Reserves, which are a part of inventory, "are the estimated quantities of uranium in known deposits of such tonnage, grade, configuration, thickness, and depth that the uranium can be recovered at, or less than, a specified cost with state-of-art mining and processing technologies."

Uranium endowment "is an estimate of all uranium-bearing material having a grade of at least 0.01 percent U_3O_8, postulated to occur in geologic settings favorable for undiscovered uranium deposits." Potential resources, which are a part of endowment, "are those estimated to occur in unexplored extensions of known deposits, in undiscovered or undelineated deposits within or adjacent to known uranium areas, or in other geologically favorable settings." Subgroups of potential resources, that we need not define for this report, are probable potential resources, possible potential resources, and speculative potential resources.

SURE scores do not provide endowment estimates but we can establish relationships with other estimates. Table 7.1 lists endowments estimated by geologists familiar with the

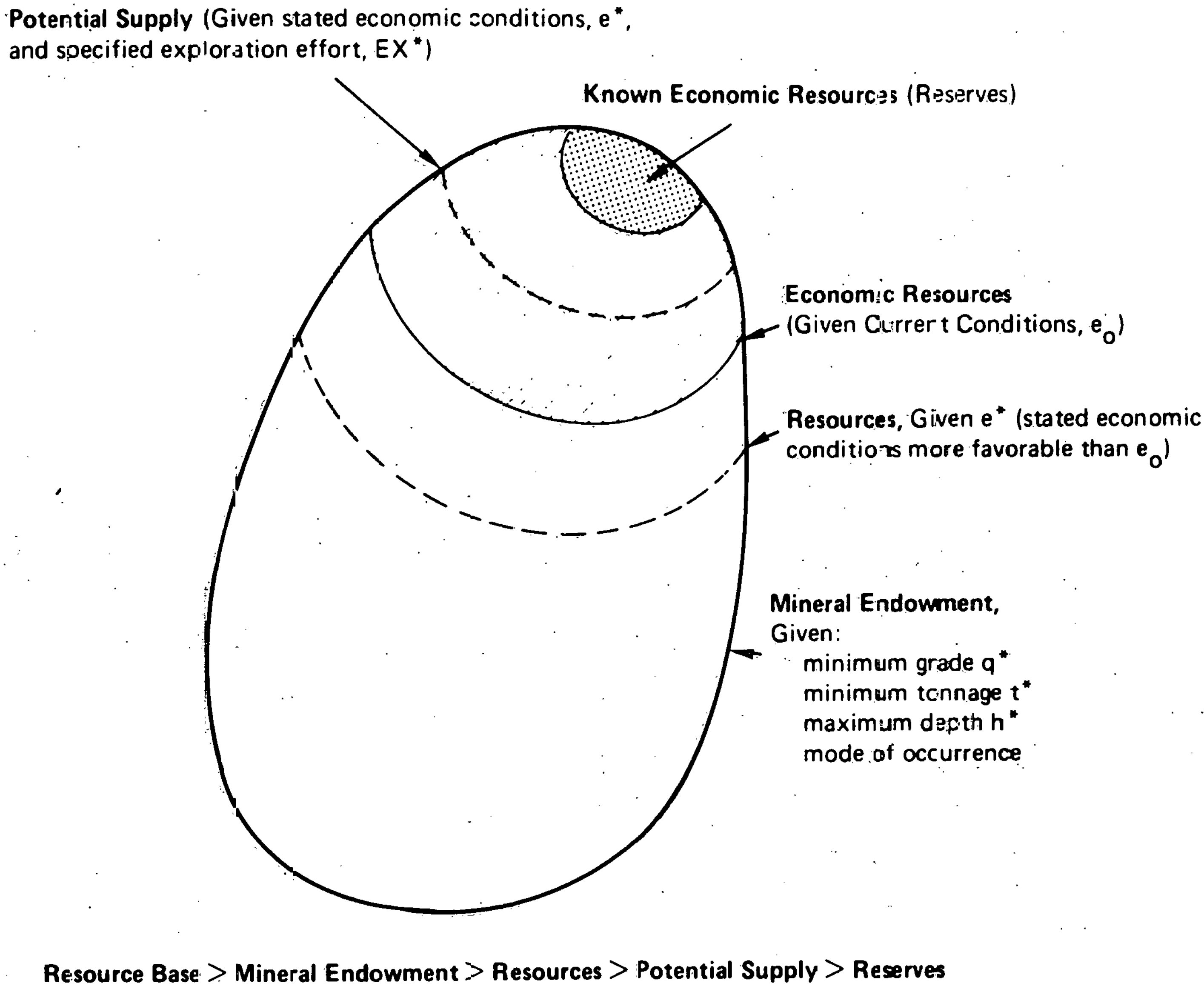


FIGURE 7.1.-Resource terminology and relations (from Harris, 1978, p. 53).

TABLE 7.1.- Estimates of uranium endowment compiled from resource assessment reports (U.S. Department of Energy, 1980, p. 149). Units are metric tons of U_3O_8. Explanation in text.

Quadrangle	Endowment					
	Mean	95%	75%	50%	25%	5%
Pueblo	119,995	22,987	51,948	92,630	159,387	319,208
Durango	39,572	5,864	10,189	19,503	36,528	76,337
Montrose	57,662	17,747	31,878	48,947	74,009	128,120
Trinidad	7,485	1,043	1,570	2,788	10,540	28,972

four quadrangles and checked by other specialists, using DOE methodology (U.S. Department of Energy, 1980, p. 23-29). The percentages express the probabilities that U_3O_8 tonnages of at least those listed occur in a quadrangle. DOE has also adjusted the tabled estimates to express the geologists's judgments that one or more deposits actually are present within the areas favorable for uranium mineralization.

From highest to lowest endowment, DOE's ranking of the four quadrangles is Pueblo, Montrose, Durango, and Trinidad. In contrast, our ranking based on SURE scores is Montrose, Trinidad, Pueblo, and Durango (table 7.2). If we calibrate the scores by equating that for Pueblo to DOE's estimated endowment, we then find (table 7.2) a reasonable correspondence between our assessment of three of the four quadrangles (particularly at the 5-percent level) with a total lack of agreement for Trinidad. For Trinidad, the stream-sediment

TABLE 7.2.-Scores, predicted endowments, and DOE estimates of endowment from table 7.1. Units are metric tons of U_3O_8. Terminology as in table 7.1.

Quadrangle	Score	Predicted endowments	DOE endowments			
			Mean	95%	50%	5%
Pueblo	100.0	119,995	119,995	22,987	92,630	319,208
Durango	66.9	80,276	39,572	5,864	19,503	76,337
Montrose	143.8	172,553	57,662	17,747	48,947	128,120
Trinidad	131.5	157,793	7,485	1,043	2,788	28,972

anomalies and host rocks score higher than in any of the other four quadrangles (table 4.1). The discrepancy signals a need to examine in detail the endowment estimates for this quadrangle. We know that DOE's estimates are conservative, because its review process (U.S. Department of Energy, 1980, p. 25) reduces initial estimates but does not reappraise areas initially rated as without potential.

When we can calibrate SURE scores against DOE estimates from several additional quadrangles, we will be able to examine residuals from a fitted straight line and modify the scoring weights to make a closer match (this procedure is similar to fitting a line in a least squares procedure).

In addition to the value of the total scores, individual components of the scores (table 4.1) can give information to guide the evaluators in their estimation of endowments. One of the principal tasks of the estimation is to identify source rocks for uranium deposits. It is well known that some uranium deposits are related to particular granites (figure 7.2); using the Pikes Peak index (table 6.5), the evaluator can identify these granites. Then, using SURE, he or she can score the quadrangles; those with the higher scores may be better endowed.

Our approach to endowment estimation starts from data. SURE and EVAL provide objective models that summarize a large body of HSSR data, geologic data, and aerial radiometric data, once the evaluator has made the subjective decisions discussed in sections 3 and 4. DOE's approach is also data oriented; the evaluator is required to work with a large collection of data.

Another approach to endowment estimation starts with a theoretical model. Brinck, a Dutch geologist, uses this method. He believes that endowment can be estimated from the distributional form of deposit sizes and grades, using occurrence and geochemical abundance data. Of the two leading models for the distribution of mineral endowment (figure 7.3), Brinck (1967, 1974) selects the log-normal distribution. He uses better known information about occurrences (represented by the right end of the curve) to infer the occurrences in the shaded area.

To examine Brinck's model, we will apply it to the Pueblo quadrangle. First, we consider data required for his model. From table 5.1, we abstract table 7.3, a distribution of ore-body sizes for the Pueblo quadrangle. As a check, table 7.4 gives a distribution for the entire United States; the two distributions are similar.

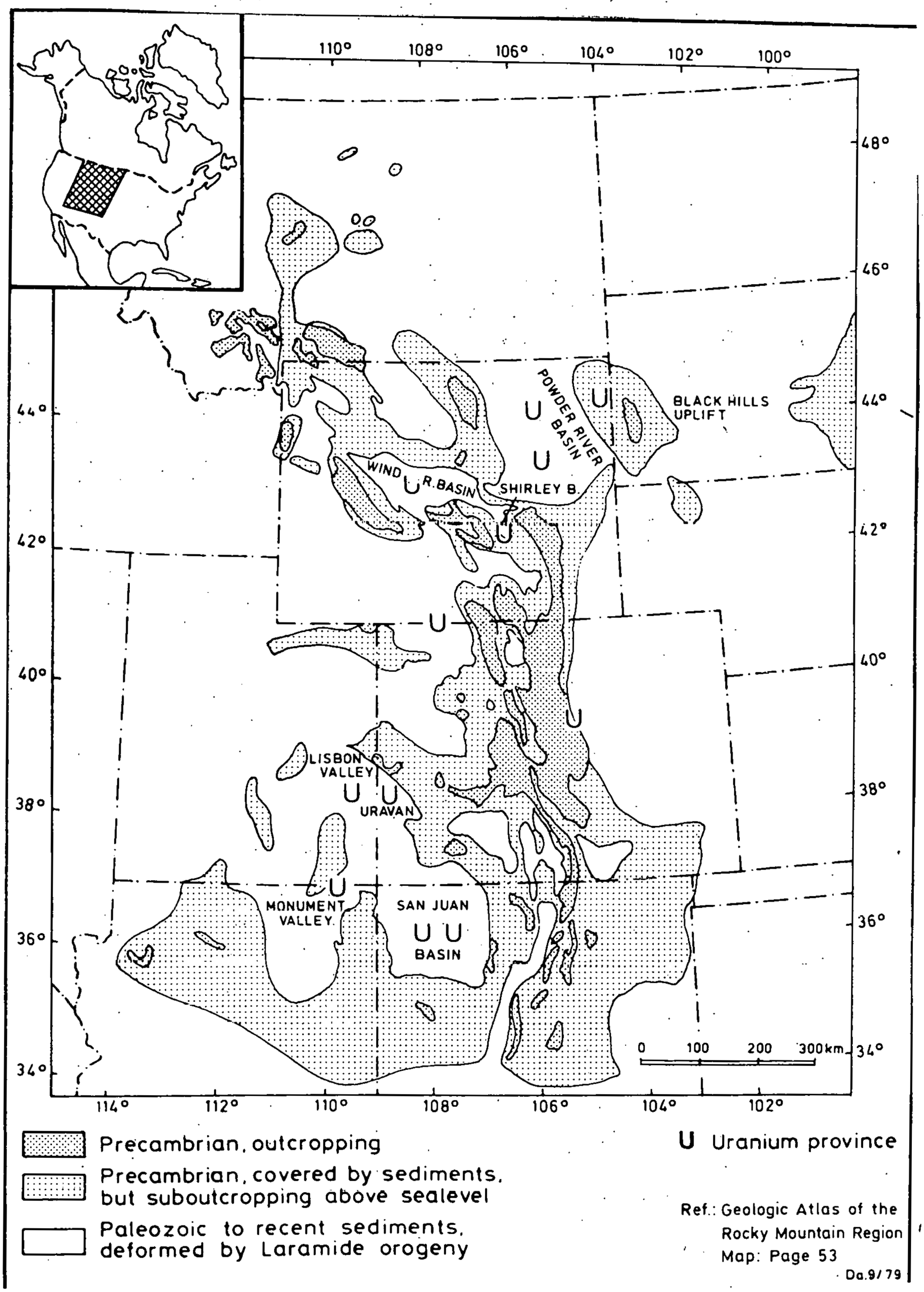


FIGURE 7.2.-Relationship of uranium deposits to Precambrian crystalline terrain in western U.S.A. (Dahlkamp, 1980, p. 525).

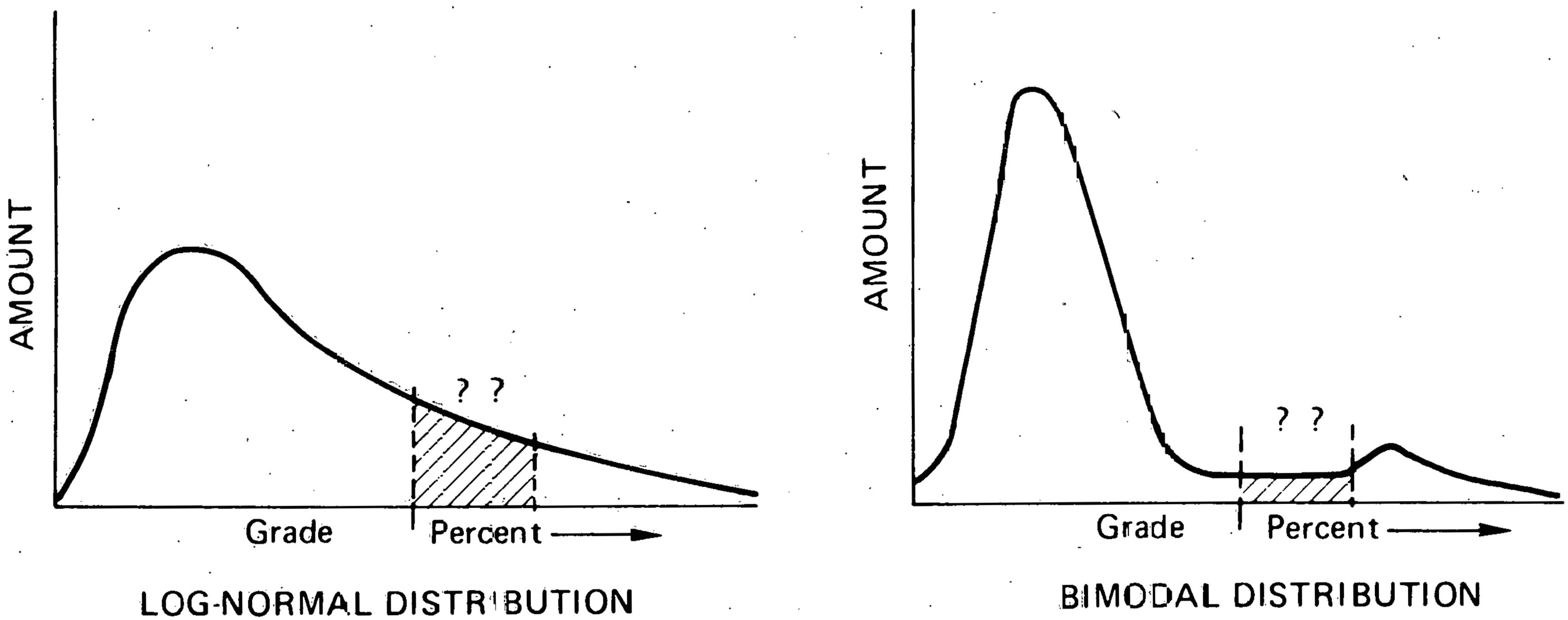
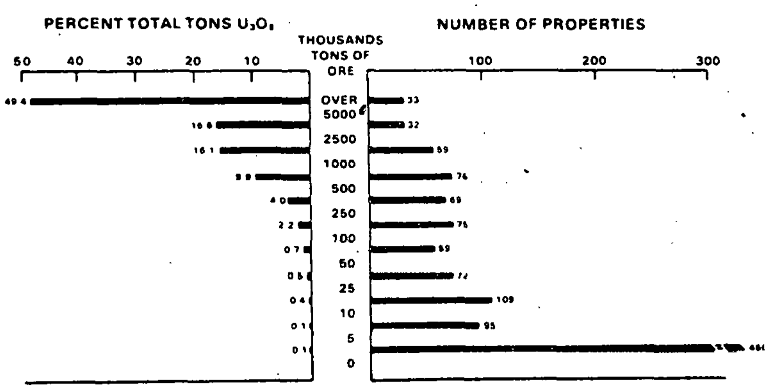


FIGURE 7.3.-Possible distribution of mineral materials in the earth's crust (from Harris, 1978, p. 60).

TABLE 7.3.-Distribution of ore body sizes for the Pueblo quadrangle.

U_3O_8, tons		Frequency	Cumulative Frequency	Relative Cumulative Frequency, %
0	5	24	24	66.7
5	10	5	29	80.6
10	15	1	30	83.3
15	20	1	31	86.1
20	25	2	33	91.7
25	30	1	34	94.4
30	35	1	35	97.2
35	40	0		
40	45	0		
45	50	0		
50	55	0		
55	60	1	36	100.0

TABLE 7.4.- Distribution of $30 reserves by size of property on January 1, 1980 (from U.S. Department of Energy, 1980a, p. 39).



Tons Range	Tons Ore	% U_3O_8	Tons U_3O_8	% Total Tons U_3O_8	No. Properties
<1.000	100.000	0 13	100		211
1.000- 5.000	600.000	0 12	800	1	255
5.000- 10.000	700.000	0 13	900		95
10.000- 25.000	1.800.000	0 14	2.400		109
25.000- 50.000	2.700.000	0.12	3.200	1	72
50.000- 100.000	4.400.000	0.11	4.700		59
100.000- 250.000	13.100.000	0 11	14.100	2	75
250.000- 500.000	25.200.000	0 10	25.700	4	69
500.000-1.000.000	58.000.000	0 11	63.700	10	76
1.000.000-2.500.000	96.400.000	0 11	103.700	16	59
2.500.000-5.000.000	120.200.000	0.09	106.900	17	32
5.000.000 or more	334.800.000	0 10	318.800	49	33
Total	658.000.000	0 10	645.000	100	1.145

For data on geochemical abundances, crustal abundance values were available from the literature; we also used the HSSR data to estimate a value specific for the Pueblo quadrangle. Taking literature values, we have two sets of estimates in tables 7.5 and 7.6. In table 7.5, one

TABLE 7.5.–Distribution of uranium in the crust of the earth (from Turekian, 1977, p. 629).

Rock type	U g/T
Ultramafic rocks	0.001
Basaltic rocks	0.9
High-calcium granitic rocks	2.3
Low-calcium granitic rocks	4.7
Syenites	3.0
Shales	3.7
Sandstones	1.7
Carbonates	2.2
Crustal abundance (Model A: .25% ultramafic rocks, 18% basaltic rocks, 39% high-calcium granitic rocks, 39% low-calcium granitic rocks, 3.75% syenites)	2.9
Crustal abundance (Model B: 50% basaltic rocks and 50% high-calcium granitic rocks)	1.6

TABLE 7.6.–Distribution of uranium in selected rocks (from Adams and Rogers, 1967). The page numbers are from the reference cited.

Rock	No. of Samples	U, g/T	Page
Precambrian granites of Front Range, Colorado	38	5.0	92-E-2
Laramide stocks west of Front Range, Colorado	25	2.2	92-E-2
Plateau basalts	26	0.5	92-E-4
Mesaverde orthoquartzite	8	1.7	92-K-1
Graywackes		2.1	92-K-1
Mancos shale	102	3.7	92-K-1
Black shales		8	92-K-1
Limestone, N. American average	25	2.2	92-K-2
Biotite schist, biotite hornblende schist, and amphibolite, Front Range, Colorado	13	4.7	92-M-2

specialist (Turekian, 1977, p. 629) offers two values for crustal abundance: 2.9 grams per metric ton (g/T) or 1.6 g/T, depending on the model selected. In table 7.6, Rogers and Adams (1967) give a second set of estimates. These agree reasonably well.

If we estimate crustal abundance by simple averaging of the HSSR data, we get a value of 7.07 g/T (table 7.7). We can check this value against estimated uranium abundances in the various rock units, if we assume that for each of the 640 cells the rock units that are present occupy equal areas. Table 7.8 lists data for the formations covering most of the quadrangle's area. The weighted average grade of uranium is 2.89 g/T. Considering that the surficial Quaternary formations comprise 44.8 percent of the area, which is about one-half of the 94 percent of the area represented by these formations, we double our estimate of 2.89 g/T to 6 g/T (rounding). We reduce this estimate of 6 g/T to 5 g/T (because the Quaternary is less widely distributed over those formations containing uranium than over the others) to reach a final estimate, by this method, of 5 g/T.

Following standard practice, when we apply Brinck's model to the Pueblo quadrangle, we may work forward from an assumed geochemical abundance (table 7.7) or backwards from the assumed endowment to check our work. We will explain the forward calculations first.

TABLE 7.7.-Data, real and assumed, used to calculate endowments for the Pueblo quadrangle. Stream-sediment data from Koch and others, 1979, p. 121.

Item	Value
Area, sq. km	18856
Depth, km	2.5
Crustal abundance of uranium, g/T	2.9, 1.6
Specific gravity of the crust	2.7
Tons of rock	1.27×10^{14}
Production, lbs. U_3O_8	468,748
Reserves, lbs. U_3O_8	39,690,000
Number of stream-sediment samples	1058
Mean uranium content, $\bar{w}$, of stream-sediment samples, g/T	7.07
Standard deviation, s, of stream-sediment samples	9.56
Estimated variance of logarithms	0.175
Tons of uranium in the quadrangle block ($1.27 \times 10^{14} \times 7.07$ g/T)	0.42

TABLE 7.8 .–Rock codes, percentage areas, and estimated abundances of uranium for the 36 formations exposed over about 94 percent of the area of the Pueblo quadrangle.

Rock Code	Area, percent	U, g/T
-QES-----	12.45744	0.0
-Q-J-----	11.10355	0.0
-Q-Z-----	9.21703	0.0
-QJZ-----	8.30086	0.0
-K-H--PS	4.86215	3.7
-K-L--NI	4.48217	2.2
-X-N-----	4.46854	2.0
-XGDBC--	4.04838	4.7
-KLU[illegible] OO	2.94[illegible]	3.0
TO-ATMTM	2.13622	2.3
-Q-W-----	1.88722	0.0
TORT--WM	1.85711	4.7
KJ-S--DB	1.84650	1.7
-Y GPPPP	1.84262	4.7
-Q-X-----	1.81162	0.0
PN-K--MB	1.80538	1.7
TACS--SF	1.62263	1.7
PA-K--LI	1.42302	1.7
TKAK--DF	1.29967	1.7
-YQMSP--	1.23280	4.7
-J-S--ME	1.14507	1.7
-K-S--LF	1.08730	1.7
PPCS--SC	1.07898	1.7
OCLS-----	1.02013	2.2
TCRAWD--	.97044	3.0
TOITTMBA	.89716	2.3
TORTTMGE	.82567	4.7
PPCS--FN	.81564	1.7
-Y-GSPSI	.78987	4.7
TOVCTMTC	.76238	3.0
-YQMSPCC	.72889	4.7
-Y-GPPWP	.66667	4.7
-XON-----	.63825	2.0
-TAFTM--	.57849	2.3
TASC--DI	.55108	1.7
TECZ--EP	.54296	1.7

Table 7.9 relates the volume (V) of the crust in the quadrangle down to a depth of 2.5 km to that of a sample volume V_s. In the table, area is equal to length multiplied by width. For convenience, we assume a length-to-width ratio of 2 to 1 and a ratio of quadrangle area to sample area of 1058 (the number of samples) to 1. We calculate the linear equivalent using the formula

$$D = 1 + w + 0.7h \qquad (7.1)$$

from Harris (1977, p. 8-62). The variance σ^2 of geochemical samples relative to the sampling volume V_s is equal to

$$\sigma_s^2 = 3\ \alpha \log (D/d_s) \qquad (7.2)$$

TABLE 7.9.-Notation and numerical values for calculations in the forward direction. Linear measurements in kilometers.

Item	Entire quadrangle		Sample volume	
	Notation	value	Notation	value
Volume	V	47045	V_s	45
Length	l	194	l'	6
Width	w	97	w'	3
Depth	h	2.5	h	2.5
Area	A	18818	a	18
Linear equivalent	D	293.5	d_s	10.75

which is derived by Harris (1977, p. 8-61) as his formula (8-108). Substituting numerical values from tables 7.7 and 7.9 and solving for α, we get

$$\sigma_s^2 = 3\ \alpha\ \log\ (293.5/10.75) \qquad (7.3)$$

$$\alpha = 0.0176.$$

Setting the linear equivalent of the typical deposit, d_d equal to 1.0 km, we can use the previous formula to solve for the logarithmic variance σ_d^2 of the typical deposit through the formula

$$\sigma_d^2 = (3)\ (0.176)\ \log\ (293.5/1) \qquad (7.4)$$

$$\sigma_d^2 = 0.30$$

and taking the square root provides us with the logarithmic standard deviation

$$\sigma_d = 0.5477.$$

Now, we are able to calculate the area under the log-normal distribution curve (figure 7.3) for deposits currently mined. We have the formula

$$P(X > 500 \text{ g/T given } \mu = \ln 7 \text{ and } \sigma = 0.5477) \qquad (7.5)$$

$$= P\ (z > 7.79) = 3.29 \times 10^{-15}$$

where P is the required probability, X is the deposit grade, 500 g/T (0.05 percent) is the assumed minimum grade for a mineable deposit, 7 is the distribution mean (table 7.7), and z is the standardized normal deviate. Then the total tons of uranium ore is equal to this probability P multiplied by the total tons of rock T (table 7.7) which is 1.27×10^{14}. This value of 0.42 tons of ore is clearly too low; there are problems with the model.

Perhaps most important is the location of the region of interest far out in the right tail of the normal distribution of logarithms; a small change in the estimate σ_d of the logarithmic standard deviation will change the probability estimate by orders of magnitude. In our calculation (formula 7.5) the estimate of σ_d was 0.5477. If we use estimates of 0.5 and 0.6 for this parameter, we get these probabilities:

$$P(X > 500 \text{ g/T given } \mu = \ln 7 \text{ and } \sigma_d = 0.5) = 6.95 \times 10^{-18}$$

$$P(X > 500 \text{ g/T given } \mu = \ln 7 \text{ and } \sigma_d = 0.6) = 5.65 \times 10^{-13}$$

and tonnages of 0.0009 or 71.76, respectively.

Therefore, even if the estimate of σ_d were efficient and unbiased (which it is not), the model lacks stability, because small changes in the parameter cause large changes in the resulting probability. This does not mean that the model is unsuitable, but one must be cautious in using it.

The potential sources of bias in estimating σ_d come from several sources: first, the geochemical or deposit distributions may not be lognormal; second, we do not know the exact geometric relation between the environment (Pueblo quadrangle block of ground) and the sample block; third, we do not know the geometric relation between the environment and a "typical" deposit.

When we use the backward approach we calculate the total number of tons of uranium in the Pueblo quadrangle block of ground starting with the estimated endowment of 120,000 tons of uranium (table 7.1). If we assume (table 5.3) that a "typical" grade is 0.15 percent, the endowment is equivalent to 85.33×10^6 tons of uranium ore. The ratio of the tons of uranium ore to the total tons of rock in the Pueblo block (table 7.7) is

$$P = 85.33 \times 10^6 / 1.27 \times 10^{14}$$

$$\underline{P = 6.72 \times 10^{-7}}$$

where the probability P is that expressed in formula 7.5. If we write this probability in the terms of formula 7.5

$P(X > 500 \text{ g/T given } \mu = \ln 7, \sigma_d \text{ unknown}) = 6.72 \times 10^{-7}$

using the numerical values as before, we can solve for σ_d. We have, then

$$P\ (z > (\ln 500 - \ln 7)/\sigma_d) = 6.72 \times 10^{-7}$$

$$\frac{\ln 500 - \ln 7}{\sigma_d} = 4.8334$$

$$\sigma_d = 0.883166$$

$$\sigma_d^2 = 0.78.$$

We can now substitute in our formula 7.4, using the same numerical values as before, except that we are solving for α rather than for σ_d^2. We have

$$0.78 = 3\ \alpha \log\ (293.5/1)$$

$$\alpha = 0.0458.$$

We can then return to formula 7.2, and, assuming that σ_d^2 is equal to 0.175 (table 7.7) we can solve for the term D/d_s,

$$\sigma_s^2 = 3\ \alpha \log\ (D/d_s)$$

$$0.175 = 3\ (0.0458) \log\ (D/d_s)$$

$$D/d_s = 3.574.$$

This ratio 3.574 is appropriate, if we assume that the variance of samples σ_s^2 is 0.175. However, if the value of σ_s^2 is a not unreasonable 0.49, for example, the ratio D/d_2 is 35.38, which is a large increase.

Our greatest problem, then, may be to choose an appropriate value for the logarithmic standard deviation σ_d of a typical deposit. Table 7.10 gives tons of uranium obtained for various values of this parameter and for mean values of uranium between 5 and 50 ppm. The table shows how sensitive are the results to the assumptions.

TABLE 7.10.—Thousands of tons of uranium in the Pueblo quadrangle for deposits above a mean grade of 0.05 percent for various geochemical μ and deposit logarithmic standard deviations σ_d. Depth is assumed to be 2.5 km, average grade of deposits is assumed to be 0.15 percent.

σ_d	μ (ppm)			
	5	7	10	50
0.5	0	0	0	39300
0.6	0	0	7	1.18×10^6
0.7	0	10	219	9.56×10^6
0.8	82	908	9617	3.81×10^7
0.9	2964	20082	131740	1.00×10^8
1.0	39300	187410	872140	2.03×10^8

SECTION 8. SUMMARY AND CONCLUSIONS

We have developed a procedure that can help quadrangle evaluators to systematically summarize and use HSSR and occurrence data. Although we have not provided an independent estimate of uranium endowment, we have devised a methodology that will provide this independent estimate when additional calibration is done by enlarging the study area.

Our statistical model for evaluation (system EVAL) ranks uranium endowment for each quadrangle. Because using 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 and tested these models for the four quadrangles in southern Colorado that comprise the study area; to investigate their generality, the models should be applied to other quadrangles. Once they are calibrated with accepted uranium endowments for several well-known quadrangles, the models can be used to give independent estimates for less-known quadrangles.

The point-oriented models structure the objective comparison of the quadrangles on the bases of:

(1) Anomalies
  (a) Derived from stream sediments
  (b) Derived from waters (stream, well, pond, etc.)
(2) Geology
  (a) Source rocks, as defined by the evaluator
  (b) Host rocks, as defined by the evaluator
(3) Aerial radiometric anomalies

The evaluator makes subjective decisions about weighting these different bases and subjective choices in defining the source and host rocks. He or she also accepts (or modifies) the methodology that identifies anomalies for that part of the uranium calculated to be associated with uranium mineralization (residual uranium).

Once these decisions are made, the model ranks quadrangles objectively. The evaluators can easily combine these rankings with the data about occurrences, production, and subjective geology. We would prefer to train potential model users; feedback at all stages would help us to evaluate and further refine the model.

The application to other quadrangles should take two directions. The first would extend the study area to adjacent quadrangles in order to make a regional analysis of uranium endowment in the Southern Rocky Mountains and related geologic provinces. The second would be to test the generality of the model in areas with different geology.

We also recommend additional development of the models using the data from the present study area. A sensitivity analysis would evaluate the effect of changing weights on the final scores. Ranked, rather than the present absolute residuals should be tried and the results evaluated. At present, we estimate the proportions of rock units from the number of sample sites for each code. The alternative of estimating the proportions from the presence/absence data should be tried. Although so far we can predict geology from geochemical signatures for only a few distinctive rocks, this promising approach merits more study. Organizing the water data by major drainage basins might significantly improve results. Ridge regression should be tried as an alternative to multiple linear regression.

An essential element of SURE and EVAL is identification of source rocks by the evaluator. Geological theory developed over many years suggests that many ore deposits in general (Lindgren, 1933, p. 103-120) and uranium ore deposits in particular (Simpson and others, 1979) are associated with particular granitoids. Geological experience likewise suggests a spatial relationship between certain granitoids and uranium deposits in adjacent sedimentary (including pyroclastic) rocks, as illustrated by figure 7.2.

Our study shows that source-rock granitoids can be identified by statistical analysis of the stream-sediment data using the Pikes Peak index (table 6.5), rather than from the whole-rock data. For quadrangle assessment, we think it essential that the evaluators distinguish source-rock granitoids from other granitoids.

We recommend extending the identification of source-rock granitoids to other areas in North America. As figure 7.2 shows, Precambrian crystalline rocks in the western United States are related to uranium ore deposits; the focus of a further study would be to classify these rocks as to source-rock or not.

Occurrence data provide one way for the evaluators to define and rank host and source rocks, a definition and ranking that are essential to using the EVAL and SURE models. These data need to be used with caution; uranium deposits may not be confined to the rocks in which they have been found thus far. The study area is not well enough explored to rule out certain rock bodies as host or source rocks.

At the present stage of its development, our cell-oriented model does not provide an effective analysis, although our current methodology warrants further development. Required is a larger study area in order to relate occurrences and stream sediments in a meaningful way.

Using Brinck's model to estimate uranium endowment seems promising. Its application to the study area would require better occurrence distributions than those presently available and better information on mean uranium abundances in various rock types. We did find a general agreement between abundances estimated in the literature and those obtained from stream-sediment data combined in various ways.

Finally, we want to emphasize our belief in the great value of the HSSR data for resource assessment; organized in a model, the high information content of these data becomes clear. When larger geographical areas are evaluated in the future, the importance of these data will be even more apparent.

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APPENDIX 1.-Listing of the rock codes

Rock Code	Geologic Unit
-Q-J----	Quaternary; glacial deposits;--; ;--; 04, 05, 07, 08.
-Q-T----	Quaternary; travertine deposits;--; ;--; 05.
-Q-W----	Quaternary; colluvium ;--; ;--; 05.
-Q-X----	Quaternary; landslide deposits ;--; ;--; 04, 05, 07, 08.
-Q-Z----	Quaternary; alluvium ;--; ;--; 04, 05, 07, 08.
-QES----	Quaternary; eolian sand and loess;--; ;--; 04, 05, 07, 08.
-QJZ----	Quaternary; interglacial alluvium;--; ;--; 05.
QT-B----	Quaternary and Tertiary; basic plug;--;--; 08.
QT-Z----	Quaternary and Tertiary; alluvium (high-level) ;--; ;--; 04.
QTMF----	Quaternary and Tertiary; mafic flows;--; ;--;
TPMF--SV	Tertiary Pliocene (3.6-4.5 my); mafic flows;--; Servilleta Fm; 07.
TACS--SF	Tertiary Pliocene and Miocene; conglomerate and sand;--; Santa Fe Fm; 04, 05.
TAMF--HI	Tertiary Pliocene and Miocene; mafic flows (olivine basalt and basaltic andesite);--; Hinsdale Fm; 07.
TARF--HI	Tertiary Pliocene and Miocene; rhyolite flows;--; Hinsdale Fm; 07.
TASC--DI	Tertiary Pliocene and Miocene; sand and gravel ;--; Gravel at Divide; 05.

APPENDIX 1.-(Continued)

Rock Code	Geologic Unit
TMIF----	Tertiary Miocene; intermediate flows ;--; ;--;
-TAFTM--	Tertiary Miocene; andesite flows; Thirtynine Mile Area; Big Baldy and Waugh Mtn and others; 05.
-TRATM--	Tertiary Miocene; rhyolite to andesite dikes and sills; Thirtynine Mile Area;--; 05.
-TRVTMWA	Tertiary Miocene; rhyolitic volcanics; Thirty-nine Mile Area; Waugh Mtn; 05.
-TSTTM--	Tertiary Miocene; siliceous tuff; Thirtynine Mile Area;--; 05.
TMMI----	Tertiary Miocene; mafic intrusives and flows ;--; ;--; 04.
TMRF--CR	Tertiary Miocene; rhyolite flows (quartz latite and rhyolite flows);--; Volcanics of South Mountain and Cropsy Ridge; 07.
TMRF-FLC	Tertiary Miocene; rhyolite flows; Lake City Caldera; silicic rocks associated with the Lake City Caldera; 07.
TMRT----	Tertiary Miocene; rhyolitic tuffs and intrusives ;--; ;--; 04.
TMRT-FSN	Tertiary Miocene (22.5 my); rhyolitic ash-flow tuff; Lake City Caldera; Sunshine Peak Tuff; 07.
TMSCTMWG	Tertiary Miocene; sand and gravel; Thirtynine Mile Area; Wagontongue Fm; 05.
-T-GWMSG	Tertiary Miocene; granite; Wet Mtn Area; Soda Granite; 05.
-T-P----	Tertiary; metamorphic and igneous complex ;--; ;--; 04.

APPENDIX 1.-(Continued)

Rock Code	Geologic Unit
TCGI----	Tertiary Miocene and Oligocene; granitic intrusives;--; ;--; 04.
TCRAWD--	Tertiary Miocene and Oligocene; rhyolitic to andesitic rock; Wet Mtn and Rosita-Deer Park; Devils Hole Fm, Deer Peak Volcanics,
-TIICD--	Tertiary Miocene and Oligocene; intermediate intrusives (phonolite, syenite, latite phonolite); Cripple Creek-Divide Area;--; 05.
TORTTMGE	Tertiary Oligocene; rhyolite ash-flow tuff; Thirtynine Mile Area; Gribbles Park Tuff, Thorn Ranch Tuff, East Gulch Tuff; 05.
-TAVTMBP	Tertiary Oligocene; andesite volcanics; Thirty-nine Mile Area; Buffalo Peaks Andesite; 05.
TOITTMBA	Tertiary Oligocene; intermediate ash-flow tuff; Thirtynine Mile Area; Badger Creek Tuff, Antero Fm; 05.
TO-ATMTM	Tertiary Oligocene; andesite (flows and laharic breccia); Thirtynine Mile Area, Thirtynine Mile Andesite; 05.
TOVCTMTC	Tertiary Oligocene; volcanic conglomerate; Thirtynine Mile Area; Tallahassee Creek Conglomerate; 05.
TOVF----	Tertiary Oligocene; volcanic flows (rhyolitic to latitic flows);--; ;--; 07.
TORATMGU	Tertiary Oligocene; rhyolite to andesite ash-flow tuffs; Thirtynine Mile Area; near Guffey; 05.
TOLF----	Tertiary Oligocene; latitic flows;--; ;--; 04.
TOLF-CFI	Tertiary Oligocene (26.4 my); latite flows; Creede Caldera; latite; 07.

APPENDIX 1.-(Continued)

Rock Code	Geologic Unit
-T-GWMRA	Tertiary Oligocene; granite rhyolite and tonalite; Wet Mtn Area; Rio Alto Stock; 05.
TORT--WM	Tertiary Oligocene; rhyolite ash-flow tuff;--; Wall Mtn Tuff; 04, 05.
TOCS--FA	Tertiary Oligocene; conglomerate and sandstone ;--; Farisita Conglomerate; 08.
TOIF----	Tertiary Oligocene; intermediate flows;--; ;--; 04.
TO-F--EN	Tertiary Oligocene; porphyritic andesite to rhyodacite flows;--; near source facies of early intermediate lavas and breccias; 07.
TO-F--HU	Tertiary Oligocene; flows (andesite to rhyodacite);--; Huerto Fm; 07.
TO-F--SH	Tertiary Oligocene; flows (andesite to rhyodacite);--; Sheep Mountain Fm. 07.
TO-I----	Tertiary Oligocenc (&) intrusives;--; ;--; 07, 04.
TO-T--HB	Tertiary Oligocene; tuffs;--; Henson and Burns Fm; 07.
TOAF----	Tertiary Oligocene; andesitic flows;--; ;--; 04.
TOAF--BH	Tertiary Oligocene; andesitic flows;--; Andesite of Bristol Head; 07.
TOAFIJSU	Tertiary Oligocene; andesitic flows; Platoro and Summitville Calderas; Andesite of Summitville; 07.
TOAVCDFL	Tertiary Oligocene; andesitic volcanic rocks; Cripple Creek-Divide Area; Florissant Lake Beds; 05.

APPENDIX 1.-(Continued)

Rock Code	Geologic Unit
-TMFTM--	Tertiary Oligocene; mafic flows (basalt, hornblende andesite, biotite andesite); Thirtynine Mile Area;--; 05.
TORT----	Tertiary Oligocene; rhyolitic to quartz latite ash-flow tuffs;--; ;--; 04.
TOLT--RK	Tertiary Oligocene; quartz latite ash-flow tuff ;--; Tuff of Rock Creek; 07.
TOLT-CSM	Tertiary Oligocene; quartz latite ash-flow tuff; Creede Caldera; Snowshoe Mtn Tuff; 07.
TOTK-CCD	Tertiary Oligocene; travertine and sediments; within Creede Caldera, Creede Formation; 07.
TOLT-GPH	Tertiary Oligocene; quartz latite ash-flow tuff; La Garita Caldera; Phoenix Park Member of La Garita Tuff; 07.
TOLTKOSD	Tertiary Oligocene; latite ash-flow tuff; San Juan and Uncompahgre Caldera; Sapinero Mesa Tuff, Eureka Tuff, Dillon Mesa Tuff; 07.
TOVK----	Tertiary Oligocene; volcanics and sediments ;--; ;--; 04.
TOVK--EV	Tertiary Oligocene; volcaniclastic sediments ;--; volcaniclastic facies of early intermediate lavas and breccias; 07.
TORT--WS	Tertiary Oligocene; rhyolite ash-flow tuff;--; Wason Park Tuff; 07.
TORT-ABC	Tertiary Oligocene; rhyolite ash-flow tuff; Bachelor Caldera; Bachelor Mountain Tuff, Carpenter Ridge Tuff; 07.
TORT-EBM	Tertiary Oligocene; rhyolite ash-flow tuff; Lost Lake Caldera; Blue Mesa Tuff; 07.

APPENDIX 1.-(Continued)

Rock Code	Geologic Unit
TORT-LCK	Tertiary Oligocene; rhyolite ash-flow tuff; Silverton Caldera; Tuff of Crystal Lake; 07.
TORT-MRC	Tertiary Oligocene; rhyolite and latite ash-flow tuffs; San Luis Caldera; Rat Creek Tuff; 07.
TORT-UUR	Tertiary Oligocene; rhyolite ash-flow tuff; Ute Creek Caldera; Tuff of Ute Ridge; 07.
TOLT--MM	Tertiary Oligocene (26.7 my); latite ash-flow tuff;--; Mammoth Mountain Tuff; 07.
TOLT-GFG	Tertiary Oligocene (27.8 my); quartz latite ash-flow tuff; La Garita Caldera; Fish Canyon Tuff, Outlet Tunnel Member of La Garita Tuff; 07.
TOLT-HMP	Tertiary Oligocene (28.2 my); quartz latite ash-flow tuff; Mount Hope Caldera; Tuff of Masonic Park; 07.
TOLTIJTU	Tertiary Oligocene (29.8 my); quartz latite ash-flow tuff; Platoro and Summitville Caldera; Treasure Mountain Tuff; 07.
TB-C--VL	Tertiary Eocene to Oligocene; conglomerate;--; Vallejo Fm of Upson (1941); 08.
TBII----	Tertiary Eocene to Oligocene; intermediate intrusives;--; ;--;
TBIF----	Tertiary Eocene to Oligocene; intermediate to basic flows;--; ;--;
TBSI----	Tertiary Eocene to Oligocene; silicic intrusives ;--; ;--;
TBRF----	Tertiary Eocene to Oligocene; silicic lava flows;--; ;--;
TBUI----	Tertiary Eocene and Oligocene; ultrabasic dikes;--;--; 08.

APPENDIX 1.-(Continued)

Rock Code	Geologic Unit
TBRA----	Tertiary Eocene to Oligocene; basic to silicic lava flows;--; ;--;
TBMI----	Tertiary Eocene to Oligocene; mafic intrusives ;--; ;--;
TDCS--TO	Tertiary Eocene; conglomerate and sandstone;--; Telluride Conglomerate, Cimmaron Ridge Fm Wasatch Fm, Ohio Creek Fm; 04.
TE-S--HC	Tertiary Eocene; sandstone;--; Huerfano Fm, Cuchara Fm; 08.
TECS--ST	Tertiary Eocene; conglomerate and arkosic sandstone;--; San Jose Fm, Blanco Basin Fm, Telluride Conglomerate; 07.
TECZ--EP	Tertiary Eocene; conglomerate (alluvium);--; Echo Park Alluvium; 05.
TLAKTMSP	Tertiary Paleocene; andesitic sediments (andesitic conglomerate, sandstone, siltstone); Thirtynine Mile Area; South Park Fm; 05.
TLCS--PC	Tertiary Paleocene; conglomerate and sandstone ;--; Poison Canyon Fm; 08.
TK-P----	Tertiary Cretaceous; sediments (quartzite, slate, and slightly altered sandstone;--;--; 08.
TK-S--RP	Tertiary and Cretaceous; sandstone;--; Raton and Poison Canyon Fm (undivided on Pueblo Quad); 05.
TK-S--RT	Tertiary and Cretaceous; sandstone;--; Raton Fm; 08.
TKAK--DF	Tertiary and Cretaceous; andesitic sediments (arkosic and andesitic sandstone, siltstone, conglomerate);--; Dawson Fm; 05.

APPENDIX 1.-(Continued)

Rock Code	Geologic Unit
TKVS--SA	Tertiary and Cretaceous; volcanics and sediments (shale, sandstone, conglomerate, volcanic detritus);--; Nacimiento Fm, San Jose Fm, Nelson Mtn Tuff, Animas Fm, Blanco Basin Fm; 07.
-K-S--TV	Cretaceous; sandstone;--; Vermejo Fm, Trinidad Sandstone; 05, 08.
-K-S--LF	Cretaceous; sandstone;--; Laramie Fm, Fox Hills Sandstone; 05.
-KGDTMWH	Cretaceous; granodiorite; Thirtynine Mile Area; Whitehorn Granodiorite; 05.
-KSH--CP	Cretaceous; sandstone and shale;--; Cliff House Sandstone, Menefee Fm, Point Lookout Sandstone; 07.
-KSH--MV	Cretaceous; sandstone and shale;--; Mesaverde Fm, Lewis Formation; 07, 04.
-K-P----	Cretaceous; sediments (slate and plyllite);--; --; 08.
-K-K--KP	Cretaceous; sandstone and shale;--; Kirtland Fm, Fruitland Fm and Pictured Cliff Fm; 07.
-K-H--Kl	Cretaceous; mostly shale with sandy shale and sandstone;--; Kirtland Shale; 07.
-K-H--LW	Cretaceous; shale with thin sandstone beds;--; Lewis Shale; 07.
-K-H--PS	Cretaceous; shale;--; Pierre Shale; 05, 08.
-K-H--MS	Cretaceous; shale with calcareous shale and limestone;--; Mancos Shale; 04, 07.
-KLH--PG	Cretaceous; shale and limestone;--; Pierre Shale, Niobrara Fm, Carlile Shale, Greenhorn Limestone, Graneros Shale Undifferentiated; 08.

APPENDIX 1.-(Continued)

Rock Code	Geologic Unit
-KLH--CG	Cretaceous; shale and limestone;--; Carlile Shale, Greenhorn Limestone, Graneros Shale, Dakota Sandstone, Purgatoire Fm; 05, 08.
-K-L--NI	Cretaceous; limestone;--; Niobrara Fm, Carlile Shale, Greenhorn Limestone, Graneros Shale; 05.
KJ-S--DB	Cretaceous and Jurassic; sandstone;--; Dakota Sandstone, Purgatoire Fm, Morrison Fm, Burro Canyon Fm, Ralston Creek Fm, Wanakah Fm, Entrada Fm, Junction Creek Fm; 04, 05, 07, 08.
-J-S--ME	Jurassic to Permian; mainly sandstone;--; Morrison Fm, Entrada Sandstone, Wanakah Fm; Ralston Creek Fm, Lyons Sandstone, Fountain Fm, Lykins Fm; 07, 08.
RP-S--DC	Triassic and Permian; sandstone;--; Dolores Fm, Cutler Fm; 04.
JR-K--MD	Jurassic and Triassic; sediments (mostly non-marine red shale, siltstone sandstone, and limestone pebble conglomerate);--; Dolores Fm, Morrison Fm, Wanakah Fm, Entrada Fm; 07.
-R-K--JG	Triassic; sediments (limestone conglomerate, limestone, sandstone, siltstone, shale;--; Johnson Gap Fm; 08.
-P-K--CL	Permian; nonmarine sediments (shale, siltstone, mudstone, arkosic grit, and conglomerate);--; Cutler Fm; 07.
PPCS--SC	Permian and Pennsylvanian; conglomerate and sandstone;--; Sangre de Cristo Fm; 05, 08.
PP-K--RM	Permian and Pennsylvanian; sediments (shale, siltstone, arkosic sandstone and conglomerate);--; Rico Fm, Hermosa Fm, Molas Fm; 05.

APPENDIX 1.-(Continued)

Rock Code	Geologic Unit
PPCS--FN	Permian and Pennsylvanian; conglomerate and sandstone;--; Fountain Fm; 05.
PN-K--MB	Pennsylvanian and Permian; sediments (shale, siltstone, sandstone and conglomerate);--; Minturn Fm, Belden Fm, Maroon Fm; 04, 05, 08.
PN-K--HE	Pennsylvanian; sediments (arkosic sandstone, conglomerate, shale and limestone);--; Hermosa Fm; 04.
PNLH--KB	Pennsylvanian; limestone and shale);--; Kerber Fm; 08.
PA-K--LI	Paleozoic (Mississippian to Cambrian); sediments (limestone, shale, siltstone, sandstone, conglomerate);--; Leadville Limestone, Ouray Limestone, Elbert Fm, Rico Fm, Hermosa Fm, Molas Fm, Ignacio Quartzite, Chaffee Group, Fremont Dolomite, Harding Sandstone, Manitou Limestone, Williams Canyon Limestone, Peerless Dolomite, Sawatch Sandstone; 04, 05, 07.
DO-L----	Devonian to Ordovician; limestone;--; Chaffee Fm, Fremont Dolomite, Harding Quartzite; 08.
OCLS----	Ordovician and Cambrian; limestone and sandstone ;--; Fremont Limestone, Harding Sandstone, Manitou Limestone, Sawatch Sandstone; 05.
-C-Y----	Cambrian; syenite;--; Gem Park Complex, McClure Mtn Complex, Syenite Complex at Democrat Ck; 05.
-CUMWMIM	Cambrian; mafic-ultramafic; Wet Mtn Area; Iron Mtn Complex; 05.
-C-I----	Cambrian; alkalic and mafic intrusive rocks;--; ;--; 04.

APPENDIX 1.-(Continued)

Rock Code	Geologic Unit
-C-SCSSW	Cambrian; sandstone; Colorado Sp; Sawatch Sandstone; 05.
PC-B----	Precambrian; gabbro;--;--; 08.
PC-G----	Precambrian X and Y; granite and alaskitic granite;--; ;--; 04, 08.
PC-N----	Precambrian; gneiss and amphibolite;--; ;--; 08.
PC-P----	Precambrian; metasediments;--; ;--; 08.
PC-P--UN	Precambrian; metasediments (slate, quartzite, quartz pebble conglomerate);--; Uncompahgre Fm; 04, 07.
PC-Q----	Precambrian; metaquartzite ;--; ;--; 08.
PCDN----	Precambrian; diorite gneiss ;--; ;--; 08.
PCGD----	Precambrian; granodiorite gneiss ;--; ;--; 08.
PCGD--CB	Precambrian; gneissic granodiorite;--; Culebra Peak; 08.
PCGN----	Precambrian; granite gneiss;--; ;--; 08.
PCQD----	Precambrian; quartz diorite gneiss ;--; ;--; 08.
-Y-Y--UT	Precambrian Y; melasyenite;--; Melasyenite of Ute Creek; 07.
-Y-YPPSC	Precambrian Y; syenite; Pikes Peak (1.0 by); Spring Creek Pluton Center; 05.
-YYGPPLG	Precambrian Y; syenite and granite; Pikes Peak (1.0 by); Lake George Center; 05.

APPENDIX 1.-(Continued)

Rock Code	Geologic Unit
-Y-GPPWP	Precambrian Y; granite; Pikes Peak (1.0 by); Windy Point Granite; 05.
-Y-GPPPP	Precambrian Y; granite; Pikes Peak (1.0 by); Pikes Peak Granite; 05.
-Y-GPPMR	Precambrian Y; granite; Pikes Peak (1.0 by); Mount Rosa Center; 05.
-Y-I----	Precambrian Y (app. 1.4 by); alkalic and mafic rocks;--; ;--; 04.
-Y-G--CA	Precambrian Y; granite;--; Granite of Cataract Gulch; 07.
-Y-G--TR	Precambrian Y; granite;--; Trimble Granite; 07.
-Y-G----	Precambrian Y (app. 1,400 my); granitic rocks; --; ;--; 04.
-YQMSPCC	Precambrian Y; quartz monzonite; Silver Plume (1.45 by); Cripple Creek Quartz Monzonite; 05.
-YQM--KR	Precambrian Y; quartz monzonite;--; Porphyry at the Keeton Ranch; 05.
-YQMSP--	Precambrian Y; quartz monzonite; Silver Plume (1.45 by);--; 05.
-YQD--PR	Precambrian Y; quartz diorite;--; Quartz Diorite of Pine River; 07.
-Y-GSPSI	Precambrian Y; granite; Silver Plume (1.45 by); San Isabel Granite; 05.
-YQMSPEM	Precambrian Y; quartz monzonite; Silver Plume (1.45 by); Elevenmile Canyon; 05.
-Y-G--EO	Precambrian Y (1,460 my); granite;--; Eolus Granite; 07.

APPENDIX 1.-(Continued)

Rock Code	Geologic Unit
-Y-B--El	Precambrian Y (1,460 my); gabbro;--; Electra Lake Gabbro; 07.
-XQMBC--	Precambrian X; quartz monzonite; Boulder Creek (1.7 by);--; 05.
-XMI----	Precambrian X; mafic intrusive rocks ;--; ;--; 04.
-XGN----	Precambrian X; gneiss ;--; ;--; 04.
-XGDBC--	Precambrian X; granodiorite; Boulder Creek (1.7 by);--; 05.
-XQDBC--	Precambrian X; quartz diorite; Boulder Creek (1.7 by);--; 05.
-XGDBCMM	Precambrian X; granodiorite; Boulder Creek (1.7 by); Methodist Mtn; 05.
-X-G----	Precambrian X (App. 1,700 my) granitic rocks ;--; ;--;
-XBU----	Precambrian X; metagabbro and metamorphosed ultramafic rocks ;--; ;--; 05.
-X-G--BB	Precambrian X (1,700 my); granite;--; Baker Bridge Granite; 07.
-X-G--TN	Precambrian X (1,720 my); granite (granodiorite and quartz monzonite) ;--; Tenmile Granite; 07.
-X-P--IR	Precambrian X; metavolcanic and metasedimentary rocks;--; Irving Fm; 07.
-X-P--VA	Precambrian X; metaconglomerate and quartzite; --; Vallecito Conglomerate; 07.
-X-P----	Precambrian X; metavolcanic and metasedimentary rocks;--; ;--; 05.

APPENDIX 1.-(Continued)

Rock Code	Geologic Unit
-X-Q----	Precambrian X; arkosic quartzite ;--; ;--; 04.
-XON----	Precambrian X; biotite gneiss ;--; ;--; 04, 05.
-X-N----	Precambrian X; gneiss formed from sedimentary and volcanic rocks;--; ;--; 05.
-X-N--TW	Precambrian X (1,800 my); gneiss probably formed from dacite and basalt, Twilight Gneiss; 07.

APPENDIX 2. LIST OF FILES ON MAGNETIC TAPE

Data Files

PUEBI6, MONTI6, DURAI6, TRINI6 - Reformatted HSSR stream-sediment data, including 8-character geologic codes.

PUEBI7W, MONTI7W, DURAI7W, TRINI7W - Reformatted HSSR water data.

PURAD, MORAD, DURAD, TRRAD - Map-cell radiometric anomaly data.

SURE Package

SURE - System for Uranium Resource Evaluation.

EVAL Package

SREG, WREG, EVAL, MPOST, QPLOT - Program modules described in text.

Data Manipulation Program

EXTRACT - Example of geologic based data retrieval using 60-bit string binary encoded geologic data.

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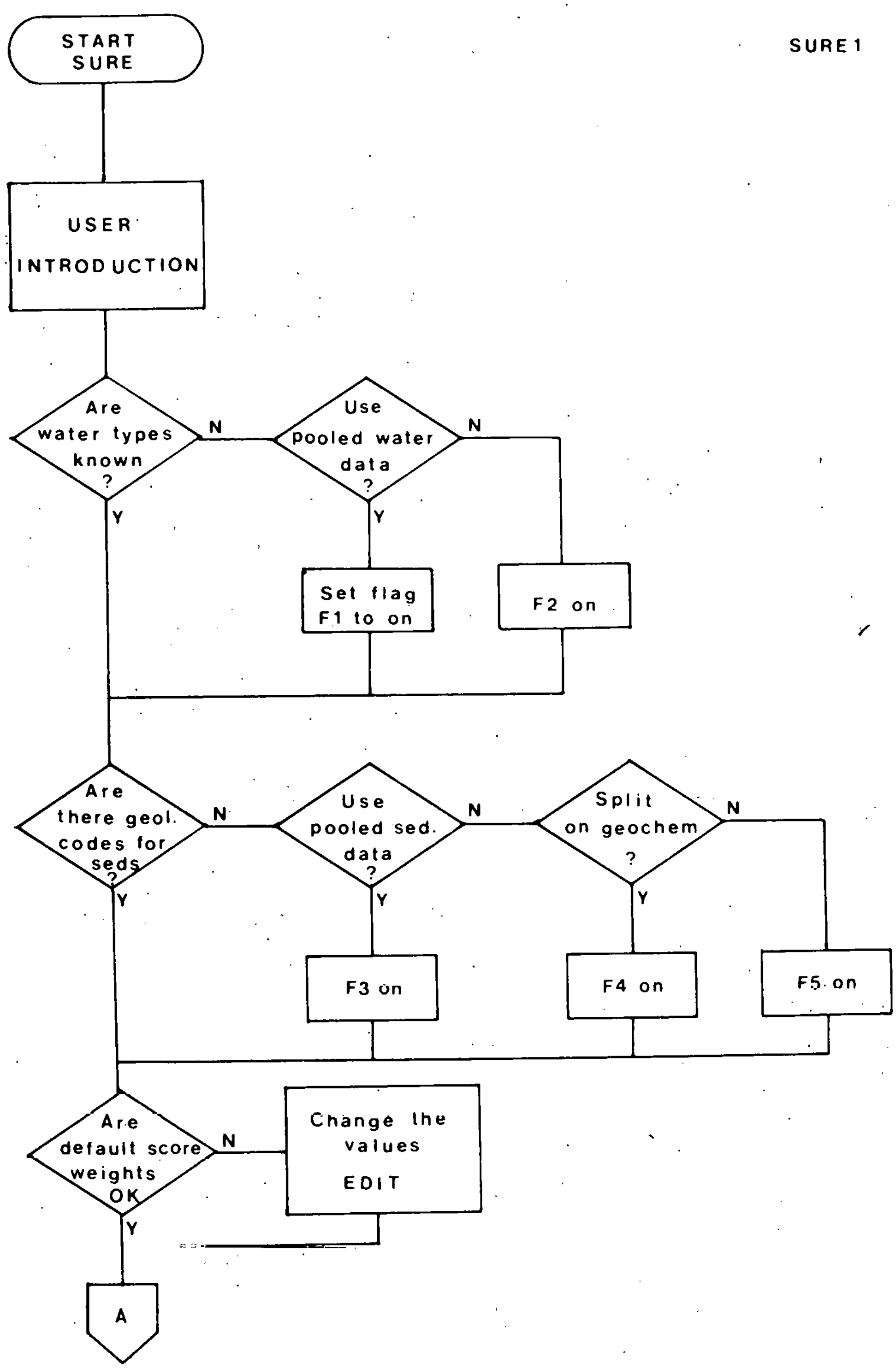
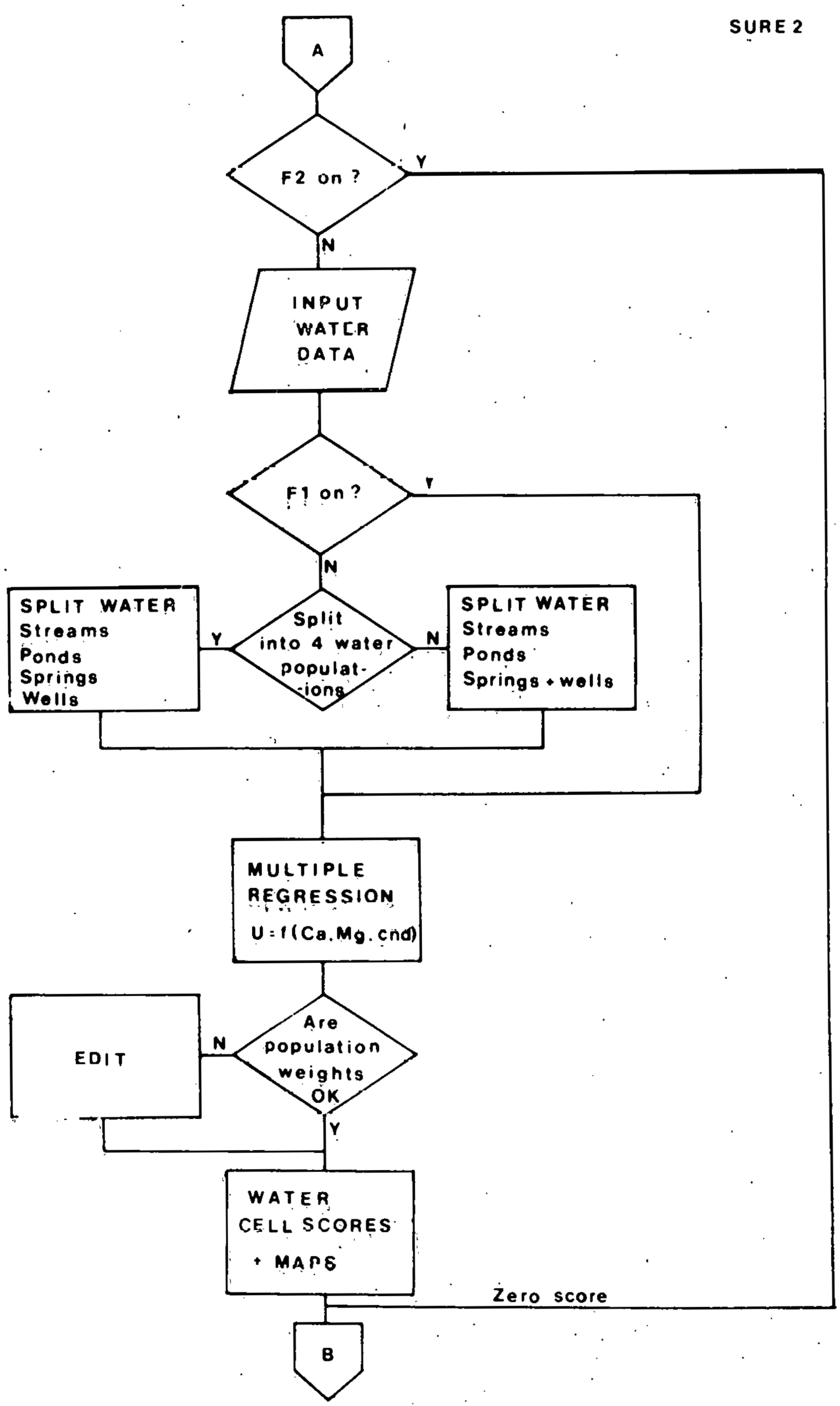
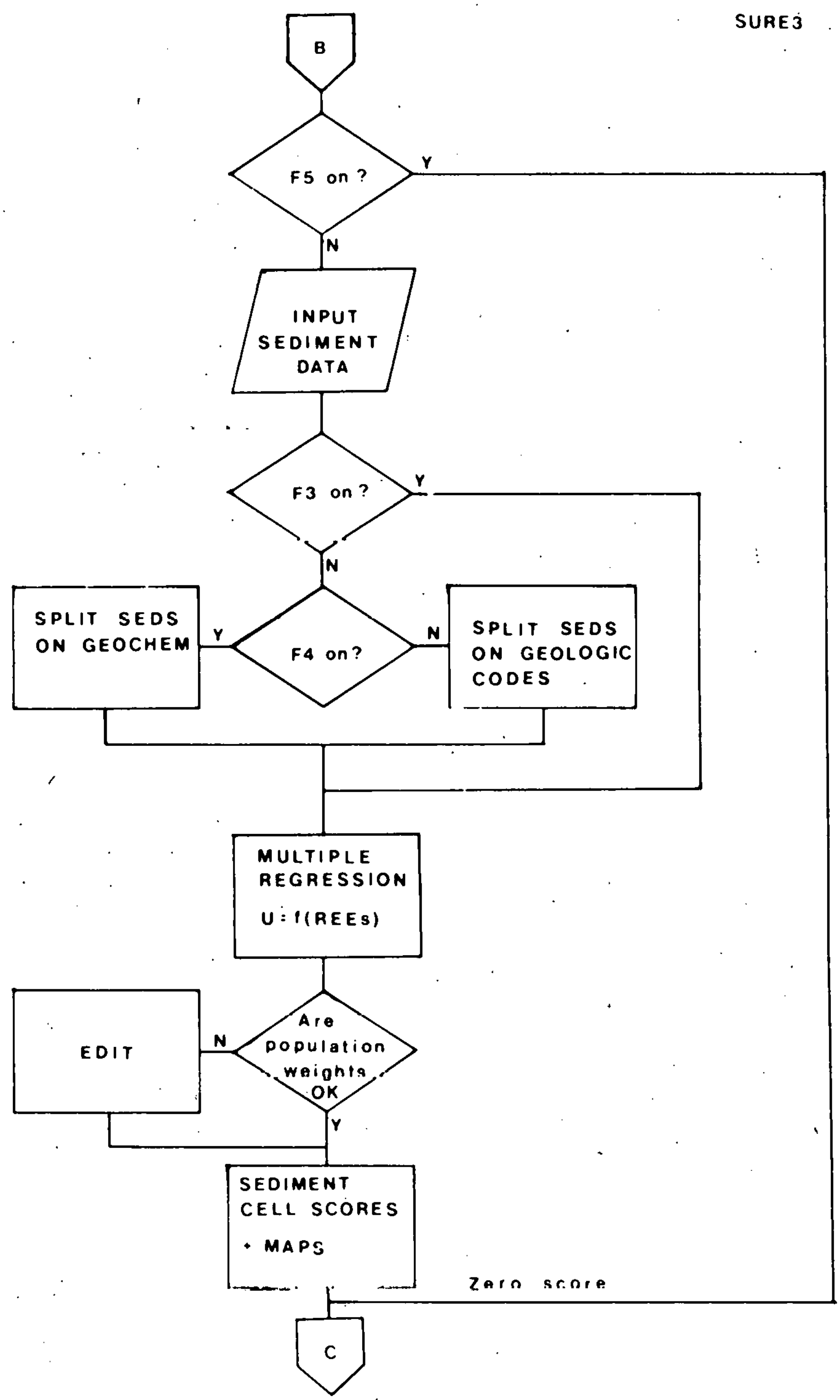


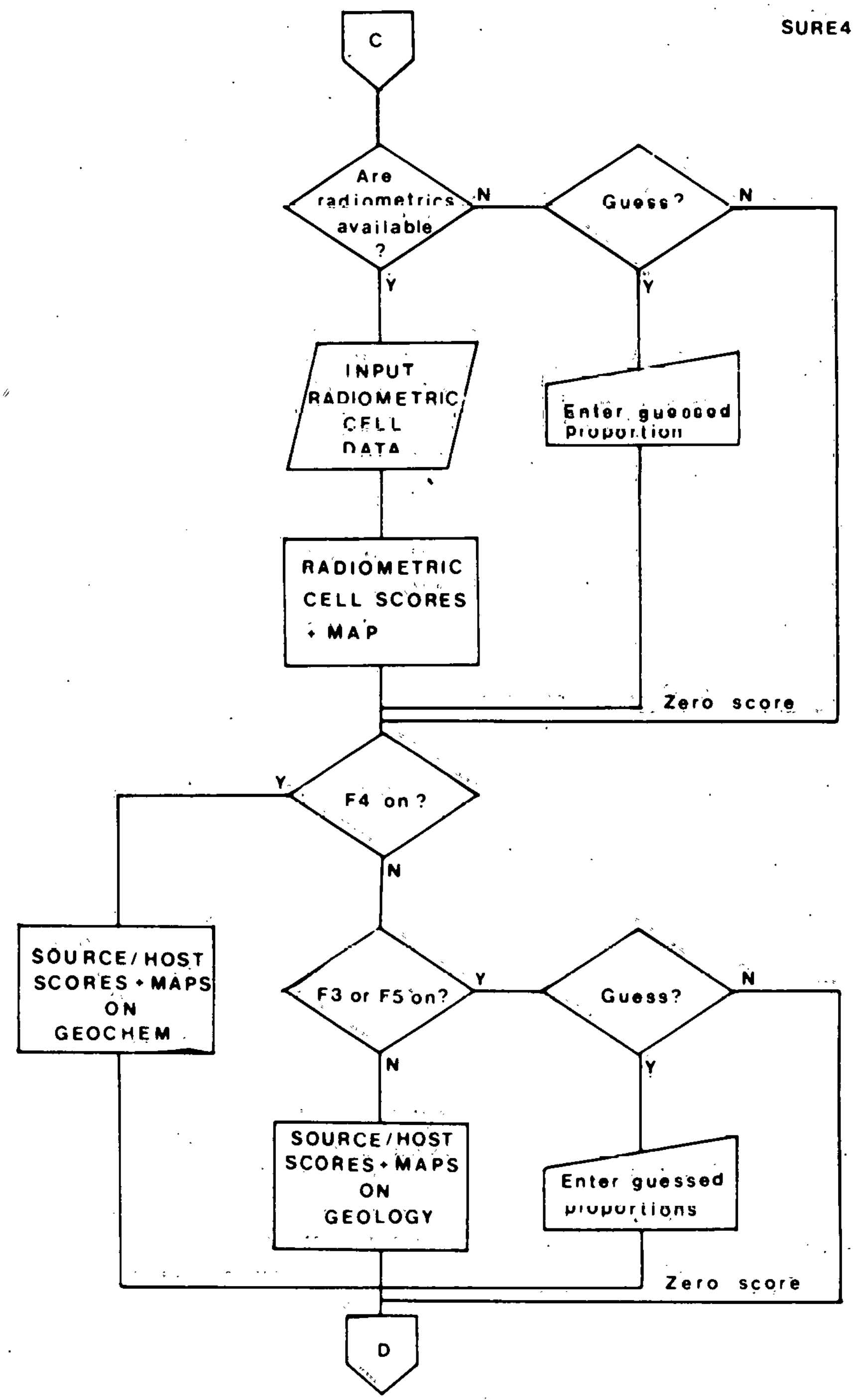
APPENDIX 3.- SIMPLIFIED FLOW CHART OF THE SURE SYSTEM.



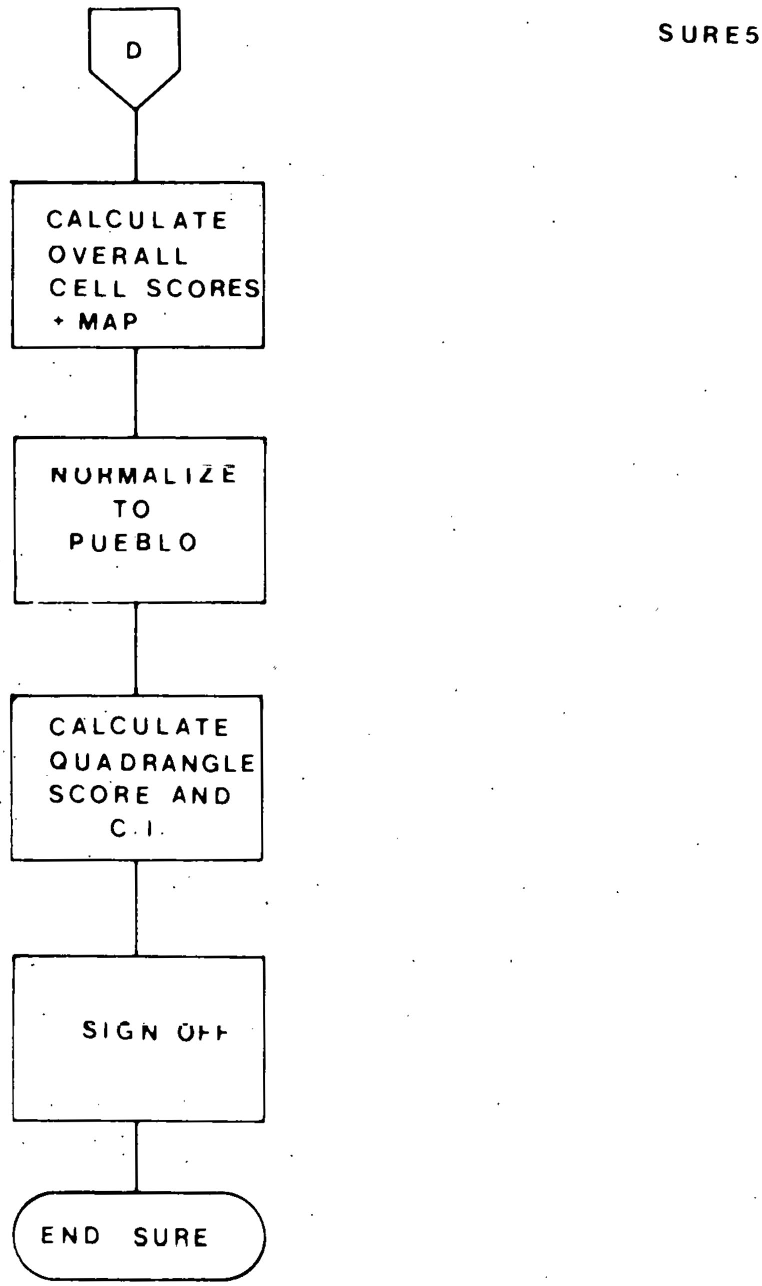
APPENDIX 3. (Continued)



APPENDIX 3. (Continued)



APPENDIX 3. (Continued)



APPENDIX 3. (Continued)

```
PLEASE ENTER YOUR NAME (UP TO 10 CHARACTERS)

? ROY


ENTER NAME OF QUADRANGLE TO BE EVALUATED

? PUEBLO


S.E. CORNER - LATITUDE =  38.00 LONGITUDE = 104.00

DEFAULT SCORING WEIGHTS


HOST ROCK                        26.00000000000
SOURCE ROCK                      14.00000000000
WATER ANOMALIES                  20.00000000000
SEDIMENT ANOMALIES               24.00000000000
RADIOMETRIC ANOMALIES            16.00000000000


ARE THESE VALUES SATISFACTORY - Y/N
? Y
DO YOU REQUIRE DETAILS OF THE WATER REGRESSION - Y/N
? Y
DO YOU REQUIRE SEPARATION OF SPRINGS AND WELLS
? Y


WATER DATA INPUT COMPLETE


 855 SAMPLES ACCEPTED


   6 SAMPLES REJECTED


STREAMS         356  REGRESSION PASS  1
SPRINGS         158  REGRESSION PASS  2
PONDS            72  REGRESSION PASS  3
WELLS           269  REGRESSION PASS  4
```

APPENDIX 4.- Example of SURE interaction for the Pueblo quadrangle.
Part 1: Introductory dialogue for the quadrangle and for the water data.

REGRESSION ON FOUR SUB-POPULATIONS

REGRESSION PASS 1

CORRELATION MATRIX

	U	CA	COND
CA	.53		
COND	.55	.60	
MG	.79	.78	.67

DETAILS OF REGRESSION
REGRESSION EQUATION
U = -.47E+00 + -.47E-04 CA + .21E-03 COND + .35E-03 MG

VARIABLE NUMBER		MULTIPLE REGRESSION		UNIVARIATE STATISTICS	
		SLOPE	STD.ERROR	MEAN	STD.DEVIATION
DEPENDENT		...	...	4.9273	16.6997
INDEPENDENT	1	-.0000	.0000	66941.8961	85700.5583
	2	.0002	.0002	1011.9888	4797.2181
	3	.0004	.0000	23526.2331	44354.7639

INTERCEPT= -.4662 MULT. R-SQUARED= .6507

STD.ERROR OF EST.= 9.9117 F= 218.5833

APPENDIX 4.- (continued)
Part 2: Typical regression output for stream-water data.

```
COMBINATION OF ALL DATA SUBSETS
NB - SCORES HAVE NOW BEEN MULTIPLIED BY THIER SCORING
WEIGHT

****************************************************************
*4 1 1 1 1 3 2   1 1   3   3 1 1 2 1 2 4 3 2 2 2 1 1 1 3 2 2 2 *
*    2   2 2       3 4 7 5 2 2 2 2 1     2 2 3 1 3 3 2 1   2 4 *
*3     2 2 3 2 4 4 2   2 2 4 1 1 1   1 1 2 2 2 4 3 3 5   3 2   *
*4 1 2 3 4 3   1 2   2 3 5 2 1 2 2 2 1   1 3 3 1     2 3 2 1 1 *
*2 2     1 2 5   6 2 3 2 3 2 1 1 2   2 3 1 1 1 1 2     4 1 1 1 *
*2 1 1     1 2 2   1     1   4 3 5       1     1 1 2 2   1 1 1 *
*  3 3 2 3 2 1     1 1 3 2 2 1   1 2   1 4 1     3 2 3 3 3 2 3 *
*1 1 3 1 1   3 2 2 3     3 1   1 2 5     1   1   1 2 1 2 5 3 3 *
*2 1 1 1 1 1 2 4   1   1 1   2 3   1     2 2 1           2 3 1 *
*2   3 2 4 1 2 2 1       1 2 1 1   1     3 1 2           5 1   *
*3 1 2     1       2   1   1 2       2     2       1     3 2 4 *
*  3 4   2 3 1     1 2 1 2   3 2 1 1         1     1     1 1 3 *
*1   1   2   1 1 1 1 1     2 1 4         1                 2 2 *
*3   3 3 3   2   2 2 2 2 1 1   1 1   1 1     1       1     2 3 *
*2 3   1   1 5       1 1 2   2       1           1   1 1 1 3   *
*1 2 2     3 1 1   1 2 2     3 1     2 2         1 4 1 2 1 1 2 *
*  2 3 2 2   1 3 1 1 1 1 5 2 2     1         1 1     2 2 2 2 5 *
*  1   3 1   4 4 1 3 3 3 1 3 4 2 2   1     1 2   2 1 2   1 3 4 *
*2 1 2 2 2   1 6 4 1       5 4 3 1 1 3   2 1 1 1 2 1 1 3 1   2 *
*2 2 4 1 2 2   3 4 5 2   1 1 5 4 1 1 2   2   1 3       1 1     *
****************************************************************
SAMPLE DISTRIBUTION
(* - MORE THAN 10, BLANK - 0)


****************************************************************
*B . . + . B .   . +   B   0 0 + + + B + + + - , , , , , , , . *
*    -   . .       B B B B 0 B B + .     . . , . + , , .   . , *
*0     . . B 0 B . , . + . B B 0 B   . . , B + , . . ,   , .   *
*B . , . . +   . .   + B 0 0 + + + + .   . , - -     , + , . . *
*. .     + . .   - . 0 0 0 B + + +   . . . . . , ,     . , . . *
*. . B     . . .   B     .   + 0 B       -     . . . .   . . . *
*  . B , . B .     0 B 0 + + +   . .   . . .     . . . , . . . *
*. . . . +   . . B B     B .   0 + .     .   .   , , . . . . + *
*. . . + . . B B   B   B B   + 0   +     . . ,           , , . *
*B   . , . . . B +       B 0 . +   B     + - .           - -   *
*B . 0     B       B   .   . B       .     +       .     + - - *
*  + .   0 B .     . B B B   B + . .         .     .     . . + *
*+   .   .   B . . . .     , B B         .                 - - *
*B   . . B   B   + . . B . .   . .   . 0     0       .     - + *
*+ 0   .   . +       . . .   .       .           .   , B . B   *
*- + B     + + B   . , .     , .     . B         . - , + . + + *
*  , . . ,   . . , . . . + . +     .         B .     B B . . + *
*  .   . +   , + 0 . . + . + - + .   .     . .   B B ,   , - - *
*. . , + +   + 0 0 .       + , + , 0 +   . . . . . . . . .   , *
*. . + . B B   0 0 , +   , + + . . . .   .   . .       . .     *
****************************************************************
WEIGHTED AVERAGE ANOMALIES

AVERAGE SCORE =       914.36
```

```
  MISSING
. 0 - 10
, 10 - 50
- 50 - 100
+ 100 - 500
0 500 - 1000
B 1000 +
```

APPENDIX 4.- (continued)
Part 3: Anomaly map for combined water types.

```
COMBINATION OF ALL DATA SUBSETS
NB - SCORES HAVE NOW BEEN MULTIPLIED BY THIER SCORING
WEIGHT

****************************************************************
*4 2 1 2 1 3 3   1 3   3   3 1 2 2 3 2 1 1 1 2 1 2 2   2 1 1 4 *
*  1 1   2 3 1 1 1 3 3 5 5 2 2 1 2 2 3 1 2 1   2       1 1 1 3 *
*3   3 2 2 3 2 4 4 4   2 2 4 1 1 2 3 2   1 1 1 1   1 2   2   1 *
*6 1 3 4 3 3   1 1 1 2 3 4 2 1 2 3 2 1 1 1 2 2   1 1   1 1 2 2 *
*2 2 2   1 2 7   5 2 2 2 3 2 1 1 2   3 1 1 2 1 2   1     1   2 *
*1 3 3     1 3 5   2   1 1   4 3 2   1 1 1       1 1 3 1 3   2 *
*  2 5 2 3 5 1 2   1 3 3 2 2 1   1 1 3     2   3 2   1 1   1   *
*6 2 4 1 2 1 5 1 4 3   2 3 1   1 3   2   3 2 1       1   1 2   *
*3 1 1 1 2 1 2 3 1 1   1 2   2 2 2 2     2 2 2 1 2 1 1 1 2 1 2 *
*5   3 1 6 1 2 3 1 2   1 3 2   2   3 1 2 2 1 2       1   1   1 *
*3 2 2 1   2 6 1 1 4 1 1 1 2 1 2 2   3 1           3     2 1 2 *
*  4 6 2 3 5 3 2 2 1 3 3 3   2     1 1 3   3       3 1   1 1 1 *
*1   1 2 5 2 1   2 1 1 1 5 7 5 3 1     1 4 5             1 1 1 *
*4   3 3 3   4   3 2 3 2 4 6 3 2 1 3 2 2 3 3         4       1 *
*3 3   1   1 4   4 1 3 1 2 2 2 1   1 2 3 6   2   1 1   4 1 1   *
*2 3 2     2 1   1 3 1 7   2 7 2   2 1 3 3   1   2     1 2 2   *
*  2 3 2 2   1 3 1 4   2 5 2 1 3 3 1 4 1 2 2 2 1 2 2 4 1   2   *
*2 4   4 1   4 4 2 3 4 3 1 3 5 2 2 2 3 2 2 2   2 1 5     2 2   *
*  1 1 2 2   1 7 3 4 3     5 4 2 2 1 3 2 3 1 4 3   1 3 2 1 1 1 *
*2 2 4 1 2 1   3 5 2 3 2 1 1 5 3 2 3 1 2   2 1 2 1     1 2 1 2 *
****************************************************************
SAMPLE DISTRIBUTION
(* - MORE THAN 10, BLANK - 0)

****************************************************************
*+ + , 0 . + .   . .   +   . . . 0 . , . . . . + . .   + . B - *
*  0 .   + . + . . B . + B 0 . . . . . . 0 .   -       . . . B *
*+   B 0 . . . . B B   . . . . . . + ,   . . . .   . B   .   + *
*B . 0 + . +   . . . + . . . . B . 0 . . . . .   . 0   + . . + *
*0 B .   . + +   + + . . 0 0 , . .   B . . . . -   .     ,   0 *
*. . +     . 0 -   .   . B   B B B   B - .       . . . . .   . *
*  . B 0 . 0 + +   0 + B B 0 .   . . 0     .   + .   . .   .   *      MISSING
*0 0 B + B . 0 . + B   . B 0   B B   B   0 . .       .   . .   *    .  0 - 10
*B 0 . 0 . . . 0 . .   0 +   B 0 , .     + + 0 . . . . . . . . *    ,  10 - 50
*+   , 0 0 . + + 0 0   . B B   +   - + 0 - . .       .   +   . *    -  50 - 100
*, , . .   B , . . . . . B + . - .   , .           .     . + + *    +  100 - 500
*  . . 0 , B , B . + . - B   B     . . ,   +       . .   . . . *    0  500 - 1000
*B   . . + B +   0 + . . , . - B .     . 0 +             . + B *    B  1000 +
*B   + . 0   .   0 . . . + , . 0 + + 0 + 0 -         ,       . *
*+ +   .   . B   - . + - B , . B   . 0 0 0   +   + .   + 0 .   *
*+ , B     . .   . . . ,   . + .   . 0 .   .   0     B B .   *
*  . . . 0   . . . ,   , - + . , , . . . , B 0 . + . 0 .   0   *
*. -   B 0   + + . , + - . + + . . . . . . ,   . B +     . .   *
*  B B . 0   . 0 . + +     - - . . . + + . . . ,   . . . . . + *
*. B . . B 0   0 + . - . . + - 0 . - B +   . . - .     . B . . *
****************************************************************
WEIGHTED AVERAGE ANOMALIES

AVERAGE SCORE =       476.67
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APPENDIX 4.- (continued)
Part 4: Map of combined stream-sediment scores.

RADIOMETRIC ANOMALY SCORING

NOTE THAT SCORES HAVE NOT BEEN MULTIPLIED BY ANY WEIGHT

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****************************************************************
*+ . . . . . . . . . . . . . . . . + . . . . . . . . . . . . . *
*0 + + + + + 0 + . . . . . . . . . . . . . . . . . . . . . . . *
*. . + . . . . + . . . . . . . . + + . . . . . . . . . . . . . *
*. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . *
*. . . . . . . . . . . . + + . . . . . . . . . . . . . . . . . *
*. . . . . . . . . . . + . + . . + + . . . . . . . . . . . . . *
*. . . . . . . . . . + + . . . . . + + . . . . . . . . . . . . *
*+ . . . . . . + 0 . . . . . . . . . + + . . . . . . . . . . . *
*+ . . . + + + 0 + + . + . . + . . . + + . . . . . . . . . . . *
*+ 0 0 . + . . + + . . + . + + + . . + + . . . . . . . . . . . *
*. + + + + + + . . . . + 0 + + . . . . + + . . . . . . . . . . *
*. . . . . . + + . . + + + + + + . . . . + . . . . . . . . . . *
*. . . . . + + + . . . + . . + + . . . . + . . . . . . . . . . *
*+ . + + + + . . . . . . . . . . . + + . + . . . . . . . . . . *
*. . . . . . . . . + + . . . . + . . . . . . . . . . . . . . . *
*. . + . . . . . . . . . . . . + . . . . . . . . . . . . . . . *
*. + . . . . . . . . . . . . . . + . . . . . . . . . . . . . . *
*. . . . . . . . . . . . . . . . . . . . . . . . . . . . . + . *
*. . . . . . . . . . . . . . + . . . . . . . . . . . . . . . . *
*. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . *
****************************************************************
```

	MISSING
.	0 - 0.1
,	0.1 - 0.5
-	0.5 - 1
+	1 - 5
0	5 - 10
B	10 +

RADIOMETRIC ANOMALY SCORES

MEAN RADIOMETRIC ANOMALY WEIGHTED SCORE = 35.79

ENTER NUMBER OF GEOLOGIC CODES YOU WISH TO USE TO
REPRESENT HOST ROCKS - MAXIMUM = 5
? 4

ENTER GEOLOGIC CODES IN RESPONSE TO SEPARATE PROMPTS
BLANK BEFORE CODE NOT ALLOWED
? TOVCTMTC
? TECZ--EP
? -J-S--ME
? KJ-S--DB

ENTER NUMBER OF GEOLOGIC CODES YOU WISH TO USE TO
REPRESENT SOURCE ROCKS - MAXIMUM = 5
? 3

ENTER GEOLOGIC CODES IN RESPONSE TO SEPARATE PROMPTS
BLANK BEFORE CODE NOT ALLOWED

? -Y-GPPPP
? -Y-GPPMP
? -Y-GPPWP

APPENDIX 4.- (continued)
Part 5: Map of radiometric anomalies. Dialogue for the selection of host and source rocks.

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ARE MAPS OF THE HOST AND SOURCE ROCK SCORES REQUIRED -Y/N
? Y

****************************************************************
*. . . . . . .   . .   .   . . . . . . . . . . . . .   . . . . *
*  . .   . . . . . . . . . . . . . . . . . .   .       . . . . *
*.   . . . . . . . .   . . . . . . . .   . . . .   . .   .   . *
*0 . . . . .   . . . . . . . . . . . . . . . . . . .   . . . . *
*. . .   . . .   . . . B . . . . .   . . . . . .   .     .   . *
*. . .     . . .   .   . .   . . .   . . .       . . . . .   . *
*  . . . . . . .   . . . . . .   . . .     .   . .   . .   .   *      MISSING
*. . . . . . B . . 0   . . .   . .   .   . . .       .   . .   *  .  0 - 10
*. . . . . . . . . .   . .   . . B B     . . . . . . . . . . . *  ,  10 - 50
*.   . . . . . B . .   . 0 .   B   B B . . . .       .   .   . *  -  50 - 100
*. . . .   . . . . B . . . . B B B   0 .           .     . . . *  +  100 - 500
*  . . . . . . B . . B . .   .     . B .   .       . .   . . . *  0  500 - 1000
*.   . . . . .   . . . . . . . . .     . . .             . . . *  B  1000 +
*.   . . .   .   . . . . . . . . . . . . . .         .       . *
*. .   .   . .   . . . . . . . .   . . . .   .   . .   . . .   *
*. . .     . .   . . . .   . 0 .   . . . .   .   .     . . .   *
*  . . . .   . . . .   . . . B 0 B B 0 . . . . . . . . .   .   *
*. .   . .   . . . . . . . . B . B . . . . .   . . .     . .   *
*  . . . .   . . . . .     . . . B . 0 . . . . .   . . . . . . *
*. . . . . .   . . . . . . . . . . 0 . .   . . B .     . . . . *
****************************************************************
HOST ROCK SCORES

****************************************************************
*. . . . . . .   . 0   B   0 B B B . . . . . . . . .   . . . . *
*  . .   . . . . . . B 0 0 0 B B B B . . . .   .       . . . . *
*.   . . . . . . . .   0 B B B B B . .   . . . .   . .   .   . *
*. . . . . .   . . . . . B B . B B 0 . . . . .   . .   . . . . *
*. . .   . . .   . . . . B . . . B   . . . . . .   .     .   . *
*. . .     . . .   .   . .   . B B   . . .       . . . . .   . *
*  . . . . . . .   . . . . . .   . . .     .   . .   . .   .   *      MISSING
*. . . . . . . . . .   . . .   . .   .   . . .       .   . .   *  .  0 - 10
*. . . . . . . . . .   . .   . . . .     . . . . . . . . . . . *  ,  10 - 50
*.   . . . . . . . .   . . .   .   . . . . . .       .   .   . *  -  50 - 100
*. . . .   . . . . . . . . . . . .   . .           .     . . . *  +  100 - 500
*  . . . . . . . . . . . .   .     . . .   .       . .   . . . *  0  500 - 1000
*.   . . . . .   . . . . . . . . .     . . .             . . . *  B  1000 +
*.   . . .   .   . . . . . . . . . . . . . .         .       . *
*. .   .   . .   . . . . . . . .   . . . .   .   .     . . .   *
*. . .     . .   . . . .   . . .   . . . .   .   .     . . .   *
*  . . . .   . . . .   . . . . . . . . . . . . . . . . .   .   *
*. .   . .   . . . . . . . . . . . . . . .     . . .     . .   *
*  . . . .   . . . . .     . . . . . . . . . . .   . . . . . . *
*. . . . . .   . . . . . . . . . . . . .   . . . .     . . . . *
****************************************************************
SOURCE ROCK SCORES

AVERAGE HOST ROCK SCORE =       104.94
AVERAGE SOURCE ROCK SCORE =     75.09
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APPENDIX 4.- (continued)
Part 6: Map of host and source rock scores.

SUMMARY OF QUADRANGLE AVERAGE SCORES

PUEBLO NORMALISED SCORE IS THE CALCULATED SCORE EXPRESSED AS A PERCENTAGE OF THE SCORE DETERMINED FOR THE PUEBLO QUADRANGLE

THE PUEBLO SCORES WERE CALCULATED USING DEFAULT WEIGHTS THROUGHOUT. RESIDUALS WERE MULTIPLIED BY R2. DISTINCTION WAS MADE BETWEEN SPRINGS AND WELLS. CELL BY CELL RADIOMETRIC DATA WERE AVAILABLE. GEOLOGICAL CODES WERE USED TO SUBDIVIDE THE STREAM SEDIMENT SAMPLES AND TO RECOGNISE SOURCE AND HOST ROCKS.

DO YOU THINK THAT SUCH NORMALISING VALUES ARE APPLICABLE TO YOUR CURRENT EVALUATION RUN - Y/N
? Y

SCORE TYPE	DEFAULT WEIGHT	ACTUAL WEIGHT	ABSOLUTE SCORE	PUEBLO NORMALISED SCORE
HOST	26.0	26.0	.105E+03	100.00
SOURCE	14.0	14.0	.751E+02	100.00
WATER	20.0	20.0	.914E+03	100.00
SEDIMENT	24.0	24.0	.477E+03	100.00
RADIOMET	16.0	16.0	.358E+02	100.00

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********************************************
**                                        **
**  QUADRANGLE SCORE =  100.00 +/-    2.6 **
**                                        **
********************************************
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EVALUATION SUCCESSFULLY COMPLETED

GOODBYE ROY

HAVE A GOOD DAY

APPENDIX 4.- (continued)
Part 7: Summary of final quadrangle average scores.