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3. An Investigation of the Estimation Process of Predictive Metallogeny

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Rudonosnost' i geologicheskie formatsii structur zemnoi kori (Ore content and geological formations of the Earth's crust structures), Nedra, Leningrad, 1981, 421 p.

3. An Investigation of the Estimation Process of Predictive Metallogeny

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Introduction

The substance of this paper is relevant to the subject of predictive metallogeny only to the extent that a quantitative prediction of some resultant of metallogenesis is a primary objective. Identification of prediction as a primary goal imposes on the geologist or team of geologists involved in prediction the necessity of integrating available geodata, data which are often sparse and of poor quality, with respect to those concepts of metallogenesis that can be related to some quantity, e.g., number of deposits or quantity of metal.

For the remainder of this paper, I shall refer to predictive metallogeny as the estimation of mineral endowment, meaning the number of deposits or the tonnage of metal that occurs in the region, given some minimum size of accumulation (deposit), minimum concentration (grade) and maximum depth of occurrence. Because of the often great uncertainty about mineral endowment, the estimate of interest is taken to be a probability distribution for the endowment of the region.

Methods of predictive metallogeny understandably vary with 1) the amount and the quality of geodata, 2) the data available on mineral discoveries and resources of the region, and 3) the time and human resources provided for analysis. Consider prediction for a region for which the geodata that are available on the entire region are at the reconnaissance level. These data may include geologic maps, aeromagnetic maps, gravity maps, geochemical surveys and maps of mineral occurrence. Exploration may have identified prospects and ore bodies. There may be a few producing mines. Even so, the region is not considered to be well explored, and resource data are either too meagre or are too restricted geographically to support the estimation by multivariate statistical methods of a quantitative relationship between geodata and a quantity of mineral occurrence. This circumstance is one which is frequently encountered in regions which generally are considered to have high potential for mineral occurrence. Regions in Canada and Mexico, for example, would be accommodated by this description.

Given these circumstances, a quantitative estimate of mineral endowment may be pursued by two basically different approaches:

1. The selection of other, well explored areas (control areas) which are geologically similar to the region of interest, and the identification on these control areas of multivariate statistical relationships which can be used to infer mineral endowment.
2. The identification of one or more geological experts who, by virtue of rich experience in exploration on other areas, specific knowledge of the geology of the area of interest and an understanding of concepts and principles of metallogeny are capable of providing subjective estimates in probability terms of the mineral endowment of the area of interest.

Each of these approaches has its advantages and disadvantages; the basis for selecting one of them over the other will not be considered here. The assumption, rather, is made that the latter of these approaches has been selected. Given that assumption, the central issue of this paper is the methodology to support the use of observed geodata by the geologist to describe a probability distribution for a region's mineral endowment. The emphasis of the paper is on the *process* or *methodology* of subjective estimation of an uncertain quantity, *mineral endowment*.

While it is commonly understood and acknowledged that estimation of mineral endowment is difficult, it is my perception that the difficulty is greater than is commonly perceived. This difficulty arises from three major sources: limitations of geoscience, insufficient geodata and inadequate methodology for probability estimation of mineral endowment.

The use of geodata to infer the presence of a mineral deposit when there is no direct evidence of the presence of the deposit requires a model of the relationship between either the geodata and mineral occurrence or of the processes implied by the geodata and mineral occurrence. Such a model can be basically empirical, reflecting mainly observed associations, or it may be based upon genetic relations.

Every geologist is aware of the limitations of his science to explain unequivocably all mineral occurrences. Often there is more than one theory for the genesis of a particular deposit. Furthermore, experienced geologists have witnessed the revision of theories as more data become available and as our knowledge of the earth increases.

The limitations of geoscience referred to above include this lack of an unequivocal explanation. But, with respect to the estimation of mineral endowment, these limitations take on a considerably greater dimension. This greater dimension reflects the lack of geoscience, as it is generally understood and practiced, of a scale (magnitude) dimension with regard to mineral occurrence. It is one thing to recognize the necessity for the sequential operation of a sequence of earth processes to form a mineral deposit of a specified kind, but it is quite another to be able to relate the spatial dimensions and intensities of these processes to the *number* of deposits – to the *total quantity of metal* – within the region. It is the latter of these acts that poses great difficulty to the geologist.

The next section discusses generally major methodologies for the subjective estimation of mineral endowment when the estimate is a product of geological analysis and is a probability distribution. Following this general description, a case study is described which allowed for the comparison of two different methodologies for the probabilistic estimation of the uranium endowment of the San Juan Basin of New Mexico. Finally, some thoughts are presented of an improved methodology for the estimation of mineral endowment of frontier regions.

Conventional Methods of Subjective Geological Analysis and Probability Estimation

Subjective probability methods for the estimation of mineral or energy endowment have been classified as implicit or explicit (Harris, 1977, 1982). These terms refer to the way in which probability and endowment are related by the methodology to geology. The conventional approach to geologic analysis and subjective probability estimation is of the implicit type.

In the implicit methodology the geologist examines all relevant geodata and resources data, if such are available, and after due integration of these data and reflection upon the geoscience of this particular mode of occurrence, he selects either percentiles or statistics from which the parameters of the endowment distribution may be estimated (Fig. 1). As is evident, the process of estimation by the implicit methodology is relatively unstructured and relies heavily upon intuitive processes.

In its simplest form, this methodology produces a probability for mineral endowment or one of the components of endowment, e.g., number of deposits (see Harris and Carrigan, 1981; Singer and Ovenshine, 1979). A more complex form of implicit estimation was employed by the U.S. Department of Energy (1980) to make the NURE estimates of the uranium endowment of the United States. The NURE methodology decomposes uranium endowment (E) to five components (A, F, T, G, and P_0):

A = size of favourable area

F = fraction of favourable area underlain by mineralization

T = tonnage of mineralized material per square mile of favourable area

G = average grade of mineralized material

P_0 = probability for at least one deposit having at least 10 tons of U_3O_8 given a cutoff grade of .01% uranium

Although the original design of the appraisal methodology, as shown in Figure 1, treated A as a random variable, as the methodology was applied, only the most likely estimate of A was employed. Subsequent to their geological investigations, geologists provide most likely plus 5th and 95th percentile estimates for each of A, F, T and G. They also provide a single point estimate of P_0. Distributions are fitted to A, F, T and G and these distributions and P_0 are combined appropriately to yield a probability distribution for uranium endowment (see Fig. 2).

Some Deficiencies of Implicit Estimation
Implicit appraisals of mineral endowment rely upon the geologist's qualitative geologic analysis to infer from geologic evidence to potential mineral occurrence. Uncertainties about the evidence and about inference are the bases for subjective probabilities about mineral endowment, or about its components. This is a highly intuitive and judgemental process. The geoscience relations employed by geologists and the relative weights given by them to various kinds of geologic evidence by this procedure are not identified or documented. Similarly, the roles played by perceived geoscience-endowment relations and observed geodata in the uncertainties which are reflected in the subjective probabilities are not identified. Both the geologic and probability analyses can be decribed as implicitly made. Difficulties in mentally performing simultaneous geologic and probability analyses create needs for 1) using geosecience in a way that diminishes the biases due to heuristics of subjective assessment, 2) preventing purposeful hedging, 3) documenting the estimation procedure and 4) promoting thorough data integration.

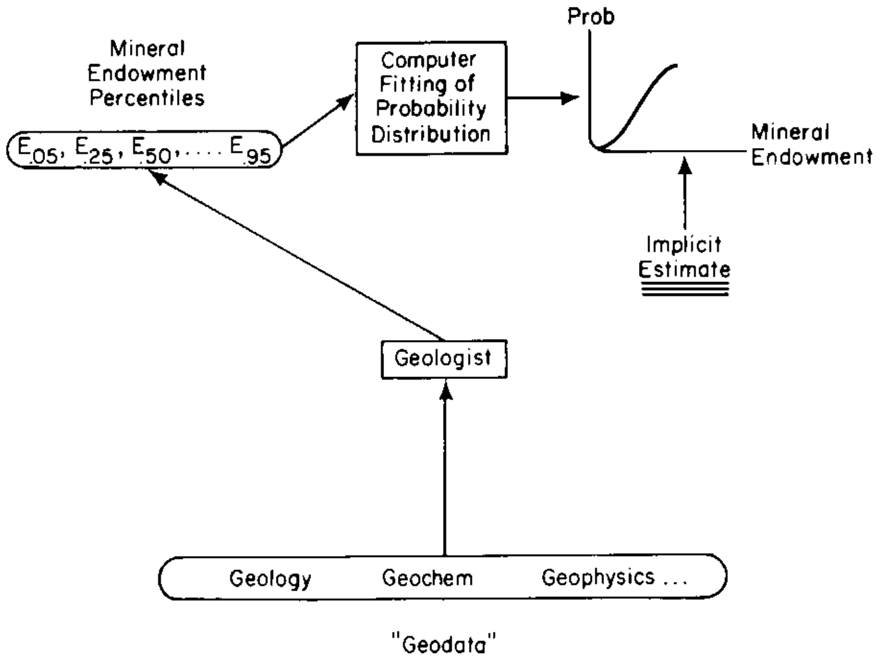


Figure 1 *Conventional subjective probability estimation (implicit geological analysis).*

Heuristics and Bias. Given the complexity of the real world, our limited understanding and our insufficient data, the inclination to employ a loose, intuitive estimation of the probability for a stated level of endowment is understandable; however, some observations and laboratory experiments suggest that intuitive estimation may produce descriptions that have some undesirable characteristics, at least when estimation is routinely made. Overall, these studies (Tversky and Kahneman, 1972, 1974; Alpert and Raiffa, 1969; Pickhardt and Wallace, 1974) suggest that geologists believe they have more knowledge about the event than they actually possess. Generally, the subjective probability distribution is only about one-half as broad as it should be.

Subjective distributions that are too narrow may result when the event being estimated is a compound event, because of the difficulty encountered by intuitive processes in perceiving the many combinations of the components of the event that can result in extreme values. A seemingly reasonable proposition is that forcing the geologist to decompose the estimation process, although more difficult to do, should result in a more complete capturing of the possible outcomes. Of course, employing such a procedure is contingent upon the ability to decompose and reconstitute the compound event in the proper manner. In practice, this can be very difficult when due consideration is given to both the physical and probabilistic dimensions. The construction and use of a geologic decision model is an attempt to decompose the estimation activity and to formalize geoscience of mineral endowment. Formalizing geoscience into a geological decision model forces the geologist to critically evaluate geoscience as it relates to mineral endowment. Such an experience identifies weaknesses or problems that can be supressed by implicit estimation. Furthermore, the experience of formally estimating the probabilities for the earth processes forces the geologist to interpret and integrate geologic data. Without using a formalized decision model, some of this interpretation and integration may be bypassed.

Hedging. Another issue which bears upon the selection of an appraisal methodology is the desire for and ability to produce estimates that are not knowingly and purposefully biased. When geologists consider geology implicitly, it is very difficult for them to erase from their minds previously made estimates and the opinions of others.

The fact that deposits have not yet been found in a unit may downgrade the "gut feelings" for the potential of the region more than is indicated by the geology of the region. The converse may be the case for a rich region. Or, geologists may feel that they are doing society a favour by providing conservative estimates on the grounds that it is always better to be pleasantly surprised than occasionally disappointed. When this desire for conservatism is very strong it can lead to absurd results. For example, Harris and Carrigan (1981) observed that the cumulative effect over all areas of a conservative bias by a geologist was a probability distribution for the aggregate of areas for which the 5th percentile endowment was less than known reserves plus cumulative production. Not only is this result impossible in view of known information, it also contradicts the geologist's general impression of endowment, as informally stated in conversation. For whatever motivations, a geologist appraising endowment implicitly is afforded abundant opportunity to hedge the estimate. An appraisal system which requires the geologist to use a formalized geologic decision model can reduce considerably the opportunity to hedge an estimate.

Credibility and Track Record. Subjectively made resource appraisals often suffer lack of credibility because they may not be reproducible and they do not provide the data and computational algorithm employed in making the appraisal. The use of an appraisal system does not mitigate fully this problem, for it too is subjective in nature. However, a geologic decision model does provide a description of the logic sequence and the computational procedure. This may ease these criticisms. Of course, the design of the model itself may invite other, more specific, criticisms. Consequently, this issue and capability should not be oversold.

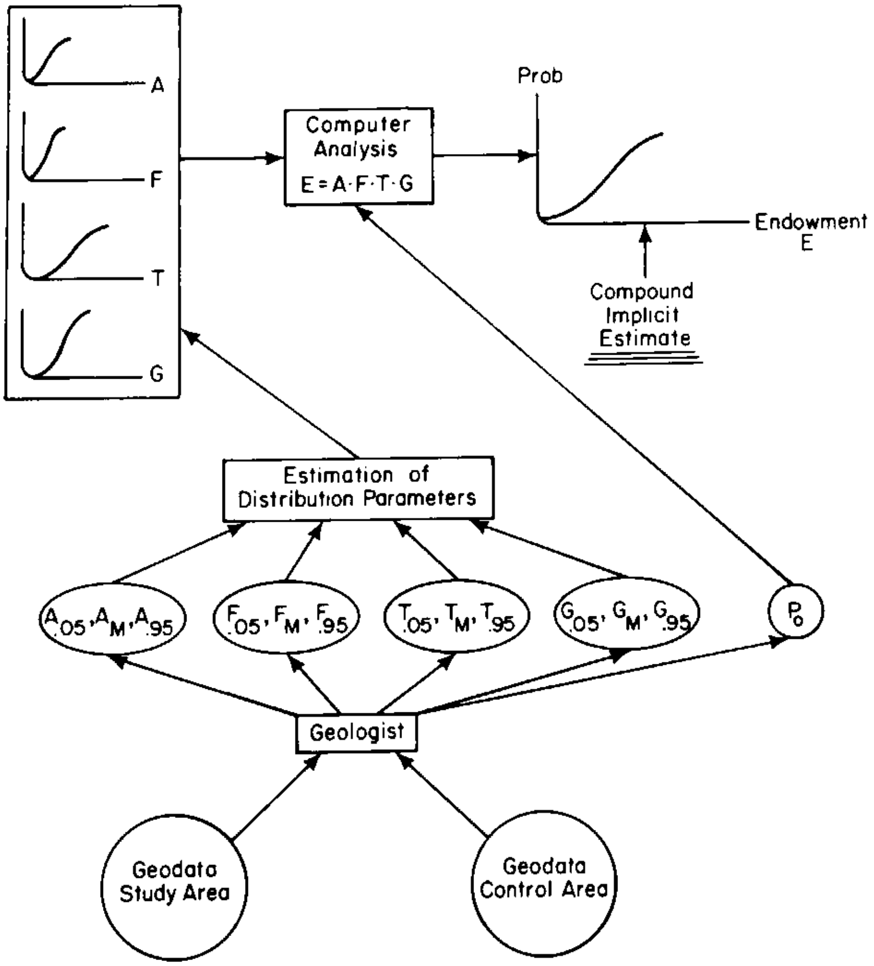


Figure 2 *Implicit methodology of U.S. Department of Energy - NURE.*

Rigor of Analysis. Finally, a motivation for abandoning implicit estimation for the formalizing of geoscience into a geologic decision model is the learning benefit of modelling. Formalizing geoscience forces the geologist to critically examine our science as it relates to the estimation of endowment. Such an experience identifies "fuzzy" concepts and thinking, and problem areas which could otherwise be suppressed or "glossed over". Furthermore, subsequent use of the decision model requires the geologist to more rigorously interpret and integrate geodata. Some of this critical thinking and data interpretation and integration would probably be bypassed if implicit analysis were employed.

Explicit Estimation: Formalized Geologic Inference and Probability Estimation

Explicit estimation of the probability distribution for mineral endowment requires computing the probabilities for endowment from the probabilities for states of those earth processes or geologic conditions which, according to geoscience, dictate the magnitude of endowment. Consequently, explicit estimation requires 1) a specification of geoscience as a decision structure, 2) either observations on geology or probabilities for states of earth processes or geologic conditions of the decision structure and 3) an algorithm for the computation of probabilities for endowment, given the geological observations or geological probabilities.

There are two recently developed approaches which strive to implement geoscience by first identifying the relevant interrelations of processes and geologic conditions and then formally stating these relations as a decision structure. For the moment, these two approaches are referred to simply as A and B (Fig. 3). While A and B are similar in that they both employ geoscience and a formal decision structure, they differ greatly in many other respects. Only one of these is identified here: mode of data use and integration. Figure 3 is a schematic representation of these two approaches, highlighting differences in use and integration of geodata. The schematic diagrams are overly simplified in that they do not show the differences that exist in the design, structure and function of decision analysis. This is purposefully done so as to expose a basic difference, which is both philosophical and methodological, between approaches A and B.

While both approaches formalize geoscience, the philosophy of approach B is that analyses of geodata should be quantitative, i.e., subjective geologic analysis of data is purposefully avoided. In this approach the various forms of geodata are each quantified to binary or ternary form, and these data are submitted directly to decision analysis. Approach B requires that these various kinds of quantified geodata be integrated through quantitative relations (equations) involving the binary or ternary variables, and that this be done within the decision module. Once the decision module has been constructed and is ready for use, the geologists who use it to make estimates function passively in that they do not perform geologic analyses or integrate geodata.

The philosophy represented by approach A runs counter to that of B; namely, the quantifying to a binary or ternary scheme of geodata fails to capture much of the information present in the geodata, and the subsequent integration of such quantified geodata by strictly quantitative relations falls far short of the information captured, integrated and employed by the mental processes of the geologist. This approach requires the geologist to play the active role of analyzing and integrating—through the practice of conventional geoscience—the information present in the various kinds of geodata when considered collectively. Only after analysis and integration of these data does the geologist use the decision model. This is done by answering questions about the states of processes or geologic conditions of the decision model; all answers, which are subjective probabilities, are made only after completion of the analysis and integration of the basic geodata.

Those who favour approach B would defend their choice by the fact that it is an objective geologic analysis. They may argue further that only by excluding the subjective analysis of geologists can one avoid the variations in estimates among geologists and the biases due to the the psychometric issues. Those favouring approach A would argue that simplistic coding (binary or ternary) of geodata and simplistic integration of data by quantitative relations may combine data but cannot, at least at present, achieve the same levels of information relevant to geoscience as is achieved by the integration which takes place in the mind of an expert and experienced geologist.

In a broad sense, then, approach B formalizes geoscience and strives for a strictly quantitative use of geodata by this formalized geoscience, while approach A formalizes geoscience as part of a system in which the geologist plays an active role in the analysis and integration of geodata as a prerequisite to the use of decision analysis. As implied in earlier comments, differences in these two approaches are far greater than this basic difference in use and integration may suggest. While Figure 3 shows A and B to be similar in that each has a decision model, these models differ greatly in design and function. These differences have been ignored in this discussion on perspective so as to examine the "big picture" of the use in a system of the geologist, geoscience and geodata.

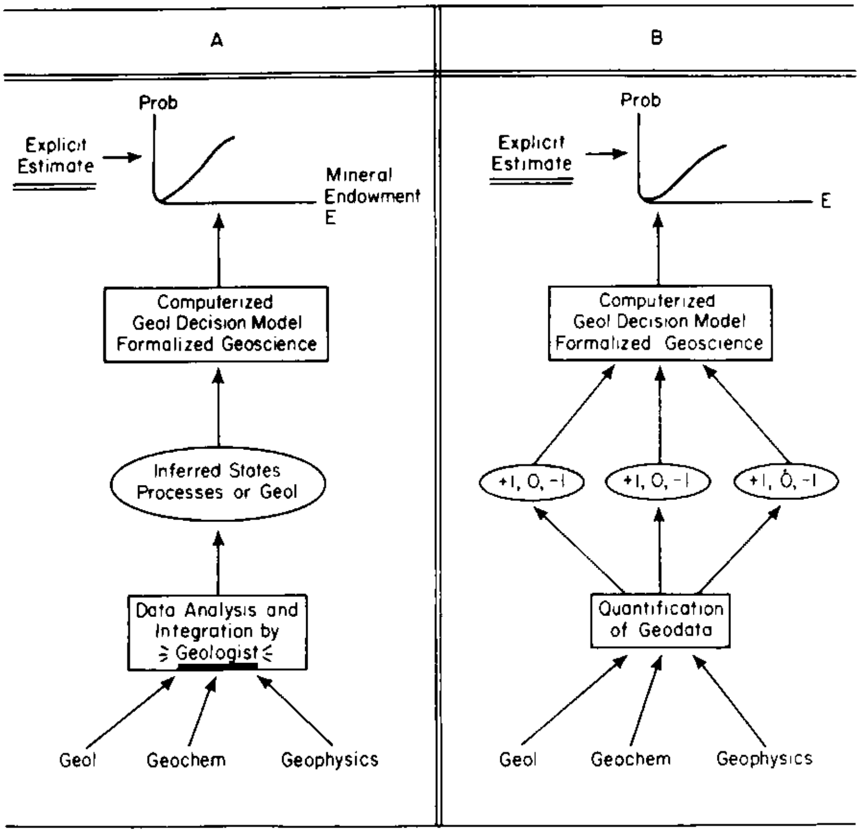


Figure 3 *Two approaches to formalizing geoscience for endowment estimation.*

Methodology of the U.S. Geological Survey: Approach B. Approach B has been pioneered by the U.S. Geological Survey. This methodology brings together three separate efforts, some of which have been in development for several years: characteristic analysis (Botbol, 1971; Botbol *et al.*, 1978), genetic modelling of uranium environments (Finch *et al.*, 1980) and decision analysis (McCammon, 1980).

Characteristic analysis was demonstrated (Botbol, 1971) as a means for quantitatively describing how typical each of a number of characteristics (stratigraphic, mineralogic, geochemical, structural, etc.) is of a set of mining districts. As initially demonstrated, a tableau (matrix) was constructed which showed for each district the presence, denoted by the integer 1 or the absence (0), of each characteristic in each of the districts. Figure 4, which is a specific schematic diagram of the U.S.G.S. methodology, shows the ternary quantification of information on three maps (mudstone/sandstone, alteration and geochemical); for a given cell (map subdivision) each attribute is represented by +1 if present, -1 if absent and 0 if nonobservable. The idea of the attribute matrix derives from characteristic analysis; however, instead of analyzing this matrix for characteristics, the matrix is analyzed by logic circuits which combine attributes in ways that are indicated by genetic models. The design of the logical framework is a result of the construction of genetic models and the identification of those geologic data that are reflective of genetic processes. The result of analyzing the attributes matrix by logic circuits is a new matrix of ternary data in which the data represent genetic factors for each cell. The genetic factors are weighted and combined in a linear equation to yield a measure of favourability for a cell. The final step, which is not indicated on Figure 4, is to convert the measures of favourability to a probability for the occurrence of a deposit within the cell. McCammon (1980) describes how this conversion could be made by strictly objective statistical analysis, given that sufficient data on control areas are available, or by subjective means. However, this part of the methodology has not yet been demonstrated.

Geoscience, including concepts of metallogeny, plays major roles at two levels. First, it is the basis for the construction of the genetic model. Then, given the genetic model, geoscience is used to identify those geologic circumstances and geodata that give evidence of the processes of the genetic model. The logic circuits simply serve as a directory for the combination of the ternary data to reflect genetic factors. Once the model is constructed, the geologist is not an active component in the estimation of endowment for a region.

The Arizona Appraisal System: Approach A. Approach A has been developed and demonstrated in two independent research programs. One of these took place at the University of Arizona (Harris and Carrigan, 1981), where a probabilistic endowment appraisal system, which is based upon the formalization of geologic decisions, was developed and demonstrated on the San Juan Basin of New Mexico. The other research program was conducted at the Stanford Research Institute, where a decision model and extensive supportive software, referred to as *Prospector*, have been developed (Duda *et al.*, 1976; Duda *et al.*, 1977; Hart *et al.*, 1978a, 1978b). Both of these systems employ an inference net as a device to structure formally the

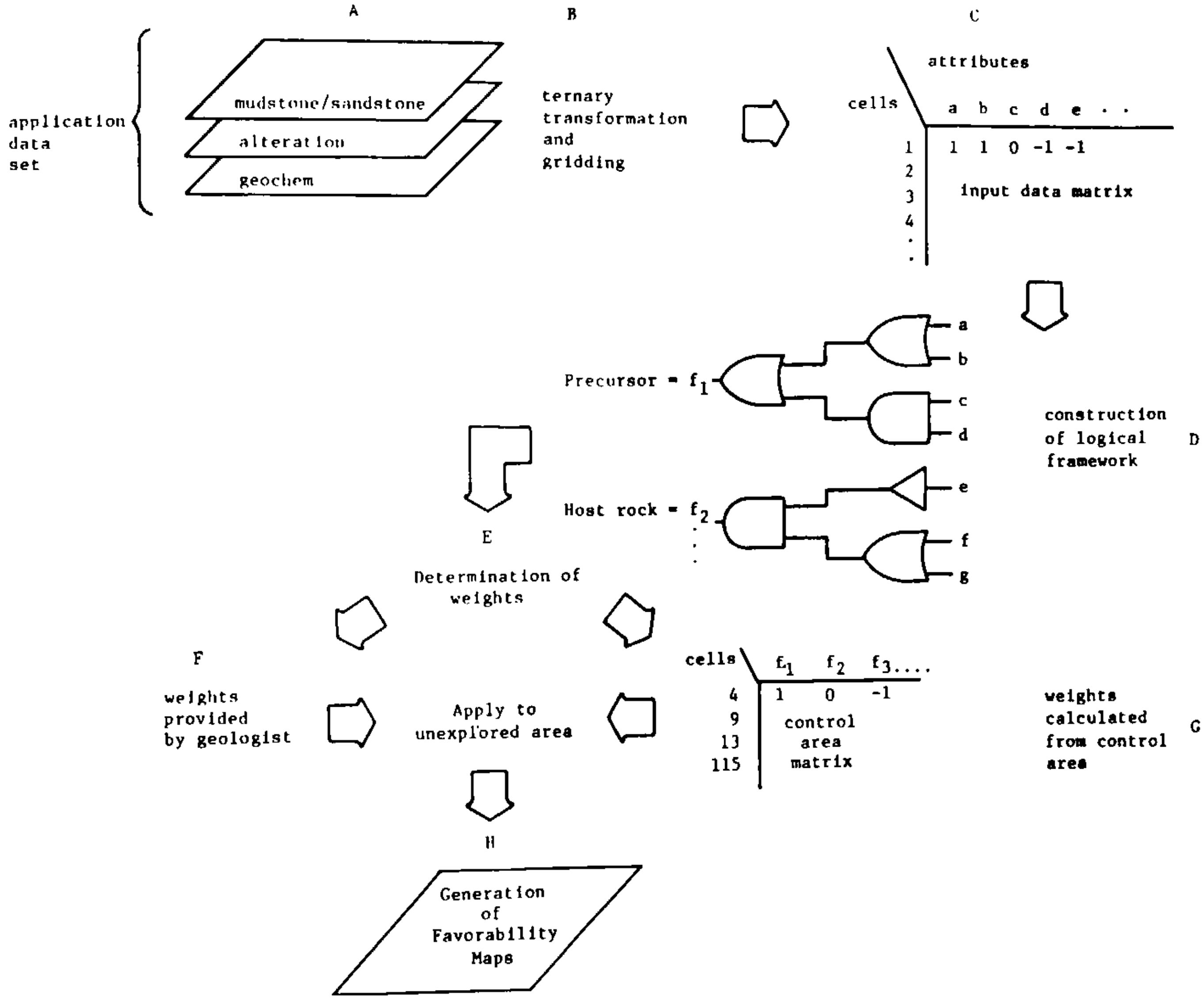


Figure 4 *Flowchart showing steps for generating favourability maps (McCammon, 1980, p. 22).*

geoscience and decision structure of the geologist. Of these two systems, only the Arizona system has actually been employed to estimate mineral endowment of a large region. In a subsequent section of this paper use of the Arizona system to estimate uranium endowment of the San Juan Basin of New Mexico is described.

Figure 5 provides a schematic overview of the components of the Arizona appraisal system. The items in the heavily outlined boxes are the active components of the system. The items in the circles are either outputs or inputs. The active components perform computations, decisions or analyses. These components include the geologist involved in the appraisal of the mineral endowment of a region; a computerized geologic decision model (this component consists of the formalized geoscience of uranium cast as an interactive computer program); and a synthesis computer program (this combines output from the decision model with other information and computes the probability distribution for U_3O_8).

The use by a geologist of an appraisal system that has already been constructed, calibrated and readied consists of providing subjective probabilities for the states of the geologic conditions and processes that make up the geologic decision model of the system. Thus, as depicted in Figure 5, the geologist processs geologic evidence to probabilistic statements about the states of processes or conditions that comprise the decision model. Table I is an example of the input prepared by a geologist for a region of the San Juan Basin of New Mexico. This table shows probability index numbers, which are probabilities multiplied by 1000. The appraisal system processes these statements to yield the probability distribution for quantity of U_3O_8.

The foregoing description provided an overview of the nature of the appraisal system and of how it is used. As indicated, a geologic decision model is an essential component of the system. Because of the importance of the geologic decision model and because of its interest to the geologist, a description of the structure of the model and the nature of its functions are provided here. By necessity, this description is very general and abridged. For a more detailed and technical description, the reader is referred to the research reports submitted to the U.S. Department of Energy (Harris and Carrigan, 1980).

The structure of the geologic decision model is illustrated in Figure 6. At the bottom of this figure there are three branch-type diagrams (inference nets), one for

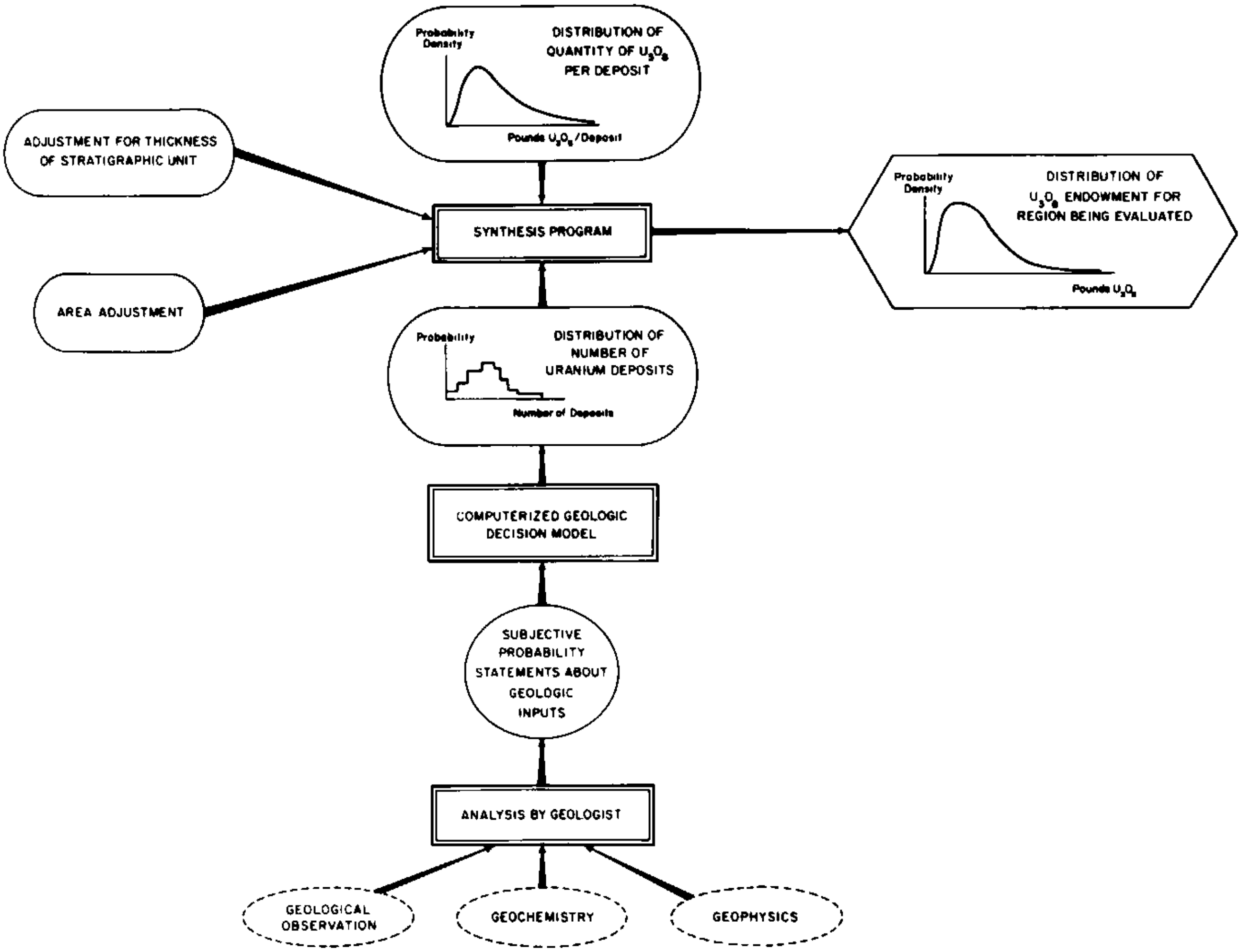


Figure 5 *Schematic representation of the endowment appraisal system (Harris and Carrigan, 1980).*

Table I *Subjective Probability Index Numbers*

Geologist: Curly
Horizon: Westwater Canyon/Brushy Basin Members
(excludes Jackpile) Typical Geologic Section

Processes and States	Probability Index Numbers
Leach Source-Transportation Factors	
Extra Basinal Factors	
Extra Basinal Source Rock	
Weathering	
adequate	990
inadequate	10
Size of Source Area	
adequate	990
inadequate	10
Ppm Soluble U_3O_8	
<2	50
2 → 4	450
>4	500
Source Rock Lithology	
crystalline — mafic	100
crystalline — felsic	400
sedimentary — feldspathic	200
tuffaceous	100
sedimentary — other	200
Transportation Characteristics	
Distance Transported	
great	600
short	400
Volume of Transporting Fluids	
large	950
moderate	49
small	1
Intra Basinal Factors	
Intra Basinal Source Rock	
Leaching	
adequate	900
inadequate	100
Volume of Source Rock	
large	950
moderate	49
small	1
Ppm Soluble U_3O_8	
<2	5
2 → 4	195
>4	800
Source Rock Type	
tuffaceous	400
quartzose	99
carbonate	1
feldspathic	500
Transportation Characteristics	
Distance Transported	
great	100
short	900
Volume of Transporting Fluids	
large	950
moderate	49
small	1
Leach Source-Transportation Factors (Cont'd.)	
Intra Basinal Factors (Cont'd.)	
Deposition-Mineralization Factors	
Mineralization Characteristics	
Uranium Anomalies	
Abundance	
abundant	800
moderate	150
sparse	50
Intensity	
high grade	900
medium grade	90
low grade	10
Reducing Agent Characteristics	
Reducing Agent Type	
humate	800
vegetal	199
H_2S	1
Amount of Reducing Agents	
abundant	800
moderate	150
sparse	50
Geochemical Cell Characteristics	
Solution Access	
excellent	700
intermediate	200
poor	100
Reprecipitation Conditions	
excellent	700
intermediate	200
poor	100
Primary Mineralization	
Meteoric Waters	
high u	800
medium u	150
low u	50
Compaction Fluids	
high u	800
medium u	150
low u	50
Depositional site Characteristics	
Climate	
favorable	800
unfavorable	200
Depositional Environment	
fluvial	997
lacustrine	1
marine	1
eolian	1
Living Organisms	
abundant	800
moderate	150
sparse	50
Duration Characteristics	
Duration	
adequate	900
inadequate	100
Rate of Deposition	
rapid	850
moderate	100
slow	50
Host Rock Characteristics	
Facies Changes	
favorable	800
unfavorable	200

Leach Source-Transportation Factors (Cont'd.)
Intra Basinal Factors (Cont'd.)

Premeability-Porosity	
Degree of Fracturing	
abundant	100
moderate	200
sparse	700
Cementation	
tight	100
moderate	200
loose	700
Sandstone Shale Ratios	
favorable	800
unfavorable	200
Post Depositional Factors	
Secondary Enrichment	
Access of Oxidizing Solutions	
adequate	800
inadequate	200
Reprecipitation Conditions	
adequate	800
inadequate	200
Degree of Preservation	
Effects of Oxidizing Solutions	
major destruction	100
moderate destruction	200
negligible destruction	700
Amount of Reductant	
adequate	800
inadequate	200

Source: Harris and Carrigan, 1980.

Table II *Probabilities for States of the Major Processes*

State of Process	Process Identification		
	ST[1]	DM[1]	PD[1]
Excellent	0.89136586	0.32869540	0.35840000
Intermediate	0.10786639	0.42641618	0.21760000
Poor	0.00076775	0.24488841	0.42400000

Geologist: Curly
Horizon: #9/8 Westwater Canyon/Brushy Basin Members
(excludes Jackpile)
Typical geologic section

[1] ST is the Source-Transportation major process.
DM is the Deposition-Mineralization major process.
PD is the Post Depositional major process.

Source: Harris and Carrigan, 1980.

each of three major processes: source-transportation (ST), depositional-mineralization (DM) and post depositional (PD). These nets are a partial formalization of the geoscience of the geologist, for they show cause and effect relations of the important processes. Figure 7 shows an actual net constructed by one of the participants in the study. Each net consists of three separate nets, one for each of the major processes. While an inference net shows the identity and interrelations of processes, it says nothing about the effect of intensity or level of a process on the state of a higher level process. Therefore, to complete the formalization of the geoscience of uranium endowment, the geologist provides a scheme that relates intensities (states) of minor processes to higher level processes. This scheme (directory) is shown as a double-ringed component of Figure 6, between the inference nets and computational algorithm A. Probabilities for the states of the major processes are the output of the computational algorithm. Table II shows this output, given the sue states for each of the three major processes.

The component in Figure 5 referred to as the synthesis program takes as inputs the thickness of the stratigraphic unit being evaluated, the area underlain by the stratigraphic unit, the probability distribution for number of deposits (which was computed by the geologic decision model) for an area of standardized dimensions (reference area), the probability distribution for tonnage of uranium per deposit and adjustment relations for thickness and area. Given these inputs, the synthesis program computes a probability distribution for the quantity of uranium contained by that stratigraphic unit within the region under evaluation.

Selected Comments. It is useful here to recall the perspective initially established of two general approaches to the formalizing of geoscience and their use in the appraisal of mineral endowment. The methodology developed by Harris and Carrigan is representative of one of these: the geologist performs analysis and integration of various kinds of geodata on relatively large areas and then makes probability statements about the states of the processes of the inference net (formalized geoscience); these probabilities are processed to yield a probability distribution for number of deposits for each area. This approach relies heavily upon geologic expertise in two ways, other than identifying the genetic concepts: 1) the linkage of geoscience to endowment and 2) the integration of geodata and the assessment of subjective probabilities about the geologic conditions and processes of the decision model. In this approach, the geologist plays an active part in evaluation by performing the data analysis and integration. In other words, this methodology must rely heavily upon subjective judgements of geologists even apart from the formalizing geoscience. To some this is seen as a liability because of its subjectivity, while to others it is seen as an asset because of its flexibility in integrating various kinds of information.

One appealing feature of the methodology developed by the U.S. Geological survey – Approach B – is that apart from identifying the genetic concepts (geoscience) and the data to support its use, the methodology is basically one of quantitative procedures and quantified geodata. Use of an existing model does not require subjective analysis of the geodata. Application of the model to evaluate the degree of association of an unknown region to the control cells is objective and produces a quantitative measure of this association. Everything else being equal, objectivity is preferred to subjectivity. To some degree, everything else may not be equal, even for use, as distinct from construction, of a model. This statement has particular relevance if the geologist's judgement is used to convert the degree of association – computed by the USGS model – to probability. Constructing a probability dimension for the estimates in this fashion must raise the question of, why? If probability ultimately is to be a judgement call, then asking the geologist to make that judgement about a synthetic measure like f, the measure of degree of association with control cells, seems like questionable procedure. Why not allow the geologist to estimate probability of occurrence as a result of reviewing the familiar (real) geodata? Furthermore, even if the geologist can provide these probabilities, the possibility of heuristic bias may cast some doubt upon the credibility of the estimates, particularly if the probabilities were to be for number of deposits instead of for the presence of at least one deposit. The number of deposits is a complex function terms of the various geologic factors which influence it and which would be considered by the geologist in providing estimates of it. Therefore, asking the geologist to provide probability estimates about this quantity, given only f, provides little support to the

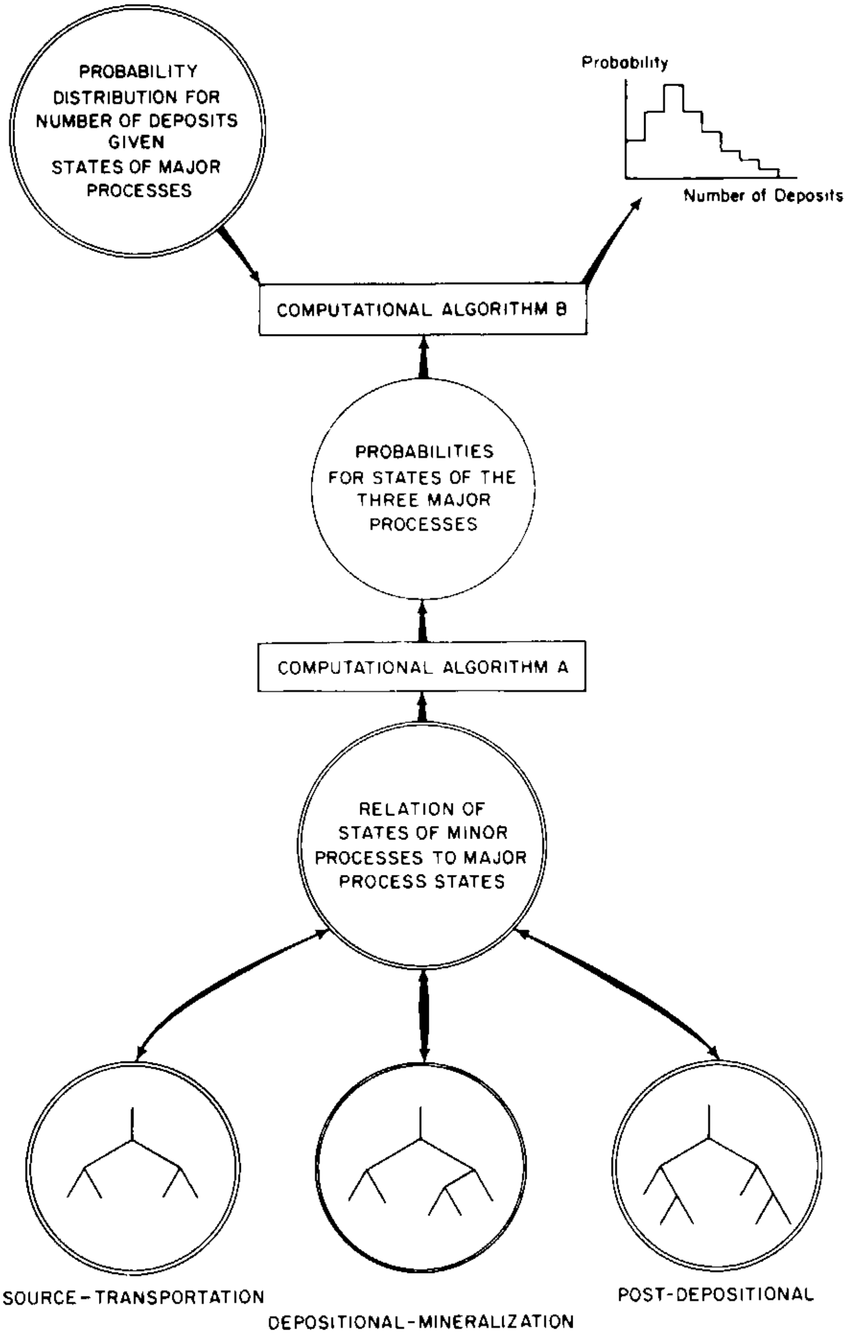


Figure 6 *Structure of the geologic decision model (Harris and Carrigan, 1980).*

Table III *Stratigraphic Units and Partitions Selected for Endowment Appraisal*

Unit	Number of Partitions
San Jose Formation	3
Nacimiento/Animas Formation	2
Ojo Alamo Formation	2
Fruitland Formation	2
Menefee Formation	2
Dakota Sandstone	6
Burro Canyon Formation	3
Jackpile Bed	3
Westwater Canyon/Brushy Basin	8
Recapture Member	4
Saltwash Member	3
Todilto Limestone	5
Chinle Formation	2
Cutler/Abo Formation	3
Madera Limestone	2

Source: Harris and Carrigan, 1980.

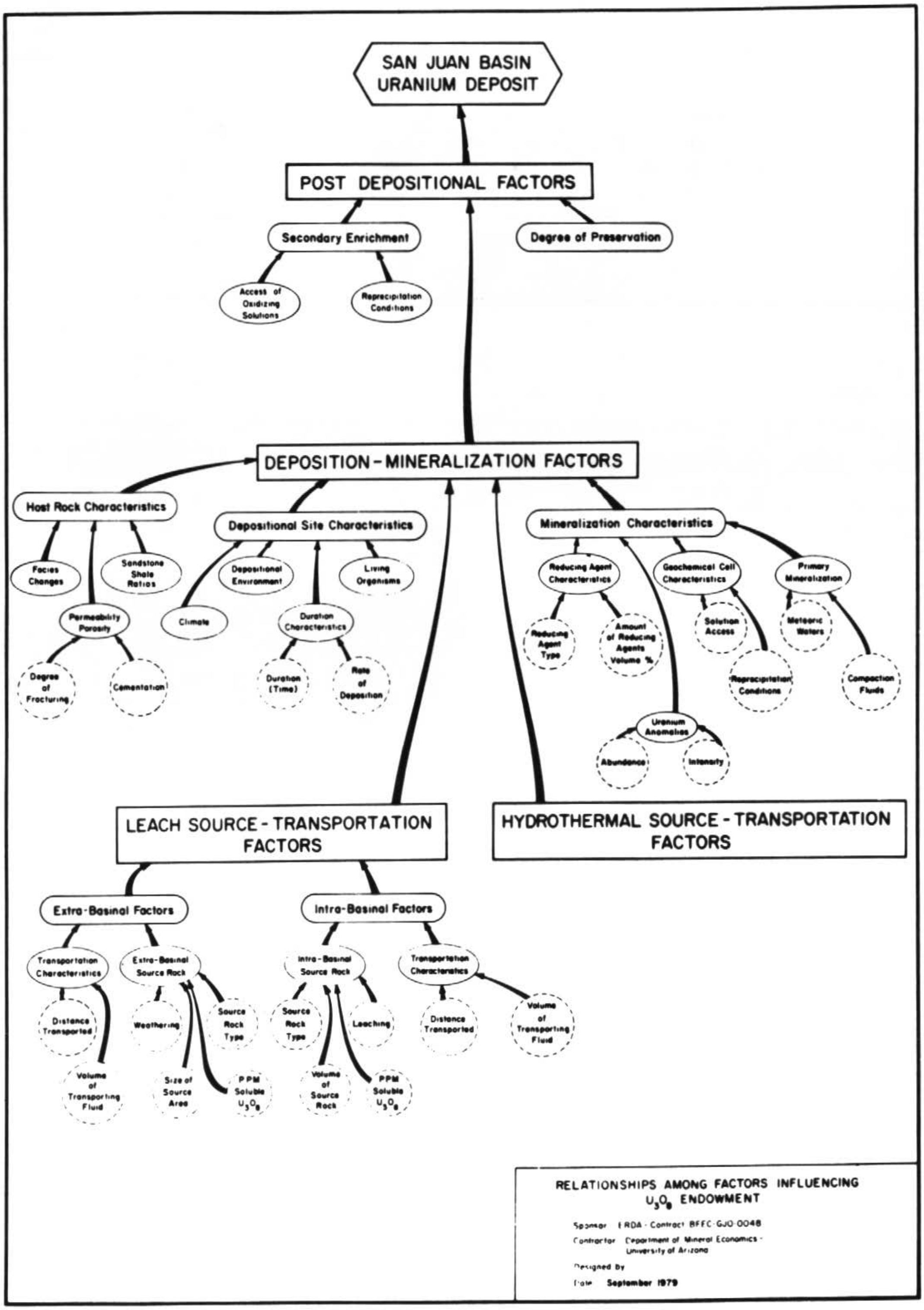


Figure 7 *Completed inference net of participant Curly (Harris and Carrigan, 1980).*

reasoning processes. Given such a circumstance, he or she may be forced to rely heavily upon heuristics, which have been found to lead to bias in the probability distribution.

In order for the methodology developed by the U.S. Geological Survey to be extended so that it estimates endowment—instead of describing only degree of association - it is applied to small cells; otherwise, geology is not effectively represented or used in determining mineral density. But, some factors that influence the level of endowment of a region can best be perceived and described for large regions. Furthermore, for some data, e.g., geophysics, pattern of anomaly and its location *vis-a-vis* other factors may be far more important than a simple description of presence or absence. The point to be made here is that the use of small cells may carry two costs, one being simply the increased time required to assess a large number of cells; the other one is the cost of information lost by using cell sizes so small that the unit of observation is not easily associated with the large-scale geologic factors that have affected endowment. But, employing large cells may make a ternary data scheme inadequate because it does not carry dimensional information. One must wonder about the cost of information lost due to use of a binary or ternary data scheme. Of course, this must be weighed against the benefits of simultaneous consideration of great amounts of data permitted by this approach.

Finally, what about the state of indeterminacy that is represented by zero in the ternary scheme? Geologists commonly are unable to determine presence or absence from direct observation, but are also influenced by the indirect evidence offered from other observations and from Geoscience in general? What is lost when indeterminacy is declared for this circumstance?

A question to be pondered by those studying methodology is, how do the gains of objectivity promoted by the methodology of the U.S. Geological Survey balance against these informational issues? In a larger sense, we need to investigate the benefits of objective data analysis and integration as compared to employing the geologist to analyze and integrate basic geodata. To the extent that the various kinds of geodata provide information which is scale dependent or which interrelates in complex fashions, and to the extent that an experienced geologist understands these complexities, the use of the geologist as an active participant in an appraisal system seems desirable. However, if the ability of the geologist in these regards is quite limited, the undesirable features of subjectivity may outweigh the small benefits that derive from his or her analysis and integration of geodata. At present, we are just recognizing relevant questions. Improved appraisals and appraisal methodologies will require many iterations on theory, methodology and data.

The next section provides a demonstration of approach A (a system within which the geologist is an active component) on the estimation of uranium endowment of the San Juan Basin, and an experiment on the effect of methodology (implicit compared with explicit) on estimates of uranium endowment.

An Experiment and Case Study of Implicit versus Explicit Endowment Estimation

Perspectives of Experiment. This study can be viewed as an experiment on the effect of methodology on subjective estimates of endowment; more specifically, it examines estimates of uranium endowment of the San Juan Basin of New Mexico made by four geologists, each using two methods of estimation: 1) implicit and 2) an appraisal system which employs the geologist's formalized geoscience. The latter method was referred to in a previous section as the Arizona system. This system requires the geologist to integrate and analyze all geodata as a means of providing probability statements to the computerized decision model about the states of the processes and geological conditions that are identified as decision variables within the system.

Each of four expert geologists was asked to examine the stratigraphic column for the San Juan Basin and to identify those lithologic or formational units that they would group together for the purpose of uranium endowment appraisal. (Initially, five geologists participated in the study, but one of these did not satisfactorily complete the calibration of his model; consequently, the estimates of only four geologists were analyzed.) Table III shows the groupings, referred to as stratigraphic units, made by one of the geologists (code-name, Curly) who participated in the demonstration.

Subsequent to identifying such stratigraphic units, the geologists were asked to partition the geographic distribution of each stratigraphic unit into geographic subdivision (partitions) which are relatively homogeneous with respect to the earth processes and geologic conditions that influence uranium endowment. The second column of Table III shows the number of partitions delineated by one of the geologists for his stratigraphic units. Thus, this geologist made 50 (total number of partitions) appraisals of U_3O_8 endowment by each methodology. Figure 8 shows the geographic locations of partitions for the Westwater Canyon member of the Morrison Formation.

Subsequent to the identification of stratigraphic units and their partitions, each of the four geologists estimated the uranium endowment of each of the partitions by two main methods: implicit and appraisal system. As explained previously, implicit estimation of uranium endowment for a partition consisted of providing selected percentiles of endowment, given the partition's geology. The lognormal distribution which best fit these percentiles is referred to as an Implicit 1 estimate for the partition. Subsequently, the geologist was shown the statistics of the fitted lognormal distribution and allowed to modify the initial percentiles. A lognormal distribution fitted to the revised percentiles is known as an Implicit 2 estimate. Subsequent to estimation of endowment of all partitions by implicit analysis, the geologist was required to estimate uranium endowment using the appraisal system which he had previously constructed and calibrated and which had been computerized. Estimation of the uranium endowment using this system consisted of answering questions posed by the computer about states of the earth processes and geologic conditions in the partition of interest. Table I shows responses of the geologist who was codenamed Curly to his decision model for a typical Westwater Canyon-Brushy Basin section. The appraisal system accepted these index numbers as input and pro-

Table III *Summary of typical resource assessment Open File reports published by Geological Survey of Canada*

1. Geological compilation map of assessed area (base map).
2. Mineral deposit/occurrence distribution map (coal, oil/gas in some cases).
3. Description, classification and listing of known mineral deposits/occurrences (computer printout format).
4. Capsule geological descriptions and interpretations of assessed area(s).
5. Extensive bibliography.
6. Mineral potential ratings derived by experienced economic geologists.
7. Text discussions of rationales and method(s) used in deriving assessment ratings.

duced a probability distribution of U_3O_8 as output. This probability distribution is referred to as a System estimate. Thus, for a given geologist, this study produced three estimates of U_3O_8 endowment for each of his partitions. Mathematical techniques were used to compute from partition distributions a probability distribution for the uranium endowment of the entire San Juan Basin averaged across geologists.

Results of Experiment. Figure 9 shows the average composite distribution for the Basin by Implicit 1, Implicit 2, and System methods, plus a fourth one, the NURE 1980 estimate made by the U.S. Department of Energy (1980). In terms of decomposition and control on hedging, these four methodologies are ranked from least to greatest as follows: Implicit 2, Implicit 1, NURE (1980) and System. This figure suggests that the greater the opportunity for hedging and the use of heuristics, the smaller is the estimate of expected (mean or average) U_3O_8 endowment and the narrower is the 90 percent confidence range.

Earlier in this paper the use of heuristics for the subjective estimation of the state of an uncertain event, particularly a compound event, was introduced. Furthermore, the general observation of psychometricians is that the use of these heuristics results in biases (Tversky and Kahneman, 1972, 1974; Slovic, 1972) and a considerable understatement of the variance of the event – subjective distributions have been observed to exclude 40% to 50% of the states described by the true distribution. In this study we do not have a statement of "ground truth", i.e., the true amount of U_3O_8 endowment for the San Juan Basin; therefore, we cannot make unequivocal judgements as to which methodology produces the most accurate probability distribution. The strongest judgement that can be made is that the 90% confidence ranges for Implicit 1, Implicit 2 and System estimates compare to each other as experimental results and theory of subjective assessments suggest they should. That is, estimation of the compound event by estimating the states of its components and subsequently recomposing endowment from its components produces a much broader distribution than the one obtained by unconstrained subjective processes.

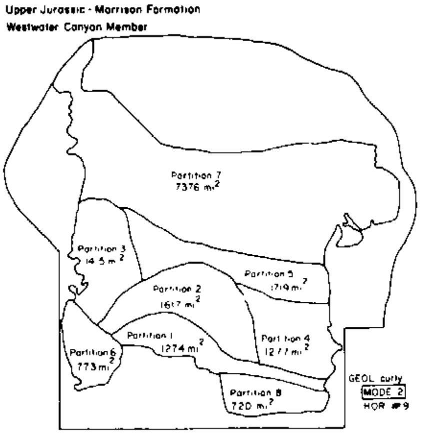


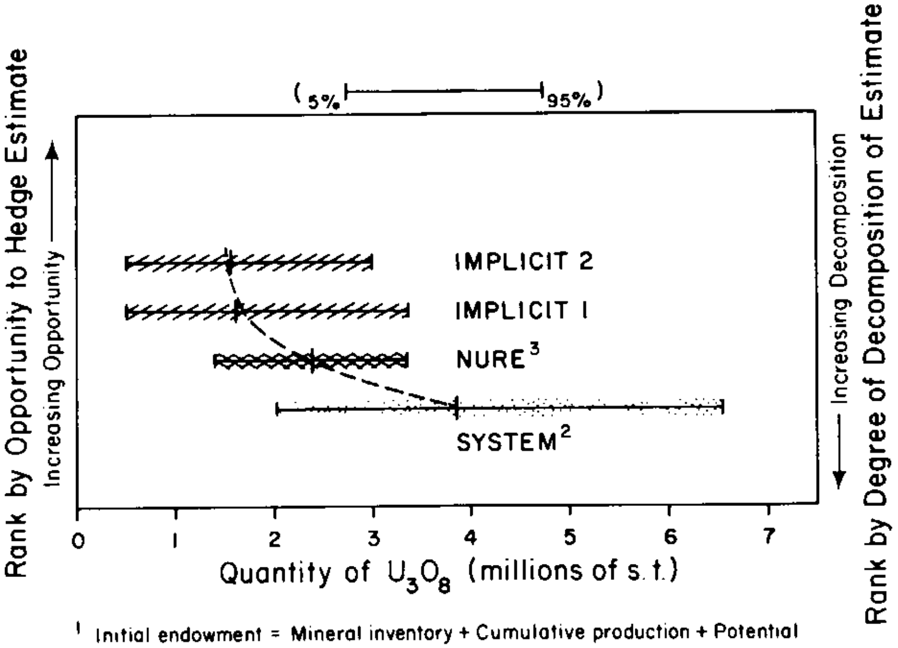
Figure 8 *Partitions made by geologist* Curly *of the Westwater Canyon Member of the Morrison Formation (Harris and Carrigan, 1980).*

An *a priori* ranking of methods by the degree to which they decompose the estimation process, and hence mitigate narrowness of distribution and discourage hedging is also the correct ranking by size of expected endowment produced by these methods. With exception to the NURE estimates, this a priori ranking is also the correct one for breadth of the 90% confidence range. The system-estimated distributions generally have both the largest expected value and the largest 90% confidence range. Since this methodology employs great decomposition and many decision aids, these results agree well with *a priori* expectations based upon findings and theories of psychometricians regarding the subjective assessment of an uncertain event.

Basically, this study found that use by the geologist of explicitly stated geoscience to evaluate the geology of the San Juan Basin indicates a greater endowment of U_3O_8 than has previously been estimated. However, this study also found that there exists much greater uncertainty about the magnitude of the U_3O_8 endowment of this region than has previously been expressed.

An Improved Estimation by Approach A

In this section, I wish to limit the subject of predictive metallogeny to the circumstances identified in the introduction to this paper, namely to a region for which geodata are available but which has been only lightly explored and within which there are at most a few known orebodies, although there may be a number of recognized mineral occurrences. Estimation of mineral endowment for such a region is at best a difficult task because of the lack of sufficient development of mineral resources to allow the formal investigation of relationships of geological features to magnitude of mineral occurrence. The "scale" dimension of prediction is very difficult to deal with for such regions. Of course, there are no easy and satisfying solutions to the problem of prediction for this circumstance, and there are only two basic avenues to prediction:



[1] Initial endowment = Mineral inventory + Cumulative production + Potential

[2] Average of estimates by four geologists, each using his own appraisal system

[3] For the calculation of Initial Endowment, the assumption was made that the mineral inventory for the Colorado Plateau region is the mineral inventory of the San Juan Basin

Figure 9 *Graphic comparison of estimates of initial U_3O_8 endowment of the San Juan Basin— expected values and 90% confidence ranges (Harris and Carrigan, 1980).*

1. the use of one or more basic relations of element concentration and geologic processes
2. the use of an empirical relationship, such as the relationship of quantity of endowment to geology, observed from previous experience on other regions.

Crustal abundance and geochemical cycles represent attempts to take the first of these avenues; however, these have not included geologic conditions or processes. Since geology varies considerably, at least across small regions, a basic relationship which accommodates such variation clearly would be ideal. My experience with geologists has been that they have great difficulty in approaching prediction in this way. The geologist's geoscience does not prepare him or her for this task. At least at the present, some empirical relationship or model seems to be needed. Perhaps some of the principles of predictive metallogeny cited in this conference by Dr. Rundquist, e.g., Curie-Shafranovsky symmetry and spatial and time similarities, may be useful in this regard.

In the remainder of this section, I wish to explore the second of these avenues, the use of an empirical relationship of geology to endowment observed on other regions. Taking this avenue requires that the empirical relationship be general enough that differences in observed geology of the region being evaluated and of the control regions do not challenge the credibility of the prediction, or that the relationship be dynamic in that it contains as explanatory (decision) variables those geologic conditions which account for regional variations in geology and endowment.

The approach that is described in the remainder of this section employs geologic decision analysis combined with statistical analysis. Simply stated, this approach would preserve the richness and flexibility – and other benefits, mentioned in previous sections – that result from formalizing geoscience, using earth processes as much as possible. But, the geologist would not be asked to link process states or geologic conditions to magnitudes of mineral endowment, as was done in the Arizona system and the experiment on the San Juan Basin of New Mexico. Instead, this linkage would be made by a statistical relationship between known endowment and the probabilities for major process states computed by the geologic decision model for control areas. As is explained below, this linkage requires additional information, information on exploration intensity or thoroughness of search for each control area. In fact, this information is as important to this approach as are geodata.

Before explaining the approach to linking the geologic model to endowment, a comment on motivation is in order. The previous sections identified advantages of formalizing geoscience, linking the resulting decision model to endowment in an appraisal system and using this system for the estimation of endowment. These benefits included reduction of heuristic biases, control on hedging, a documented procedure and educational benefits of modelling.

The experiment on the San Juan Basin suggested that uncertainty about uranium endowment is much greater than is indicated by implicit estimates. This experiment revealed that the singularly most difficult and uncertain dimension of modelling is the linkage of the major processes or geological conditions of the decision model to magnitude of endowment. Undoubtedly, this uncertainty is a major contributor to the greater variance in the system distributions. To the extent that the objective of an appraisal is to express the true uncertainty in the minds of the appraisers, forcing the geologist to deal with this uncertainty is best procedure. Avoiding it, as is done in the implicit methodology, does not remove the uncertainty; it only ignores and suppresses it.

There is, however, another perspective to be considered: the variability of endowment in nature versus uncertainty in the mind of the geologist. Suppose that geologists had perfect knowledge of the relations between earth process states and magnitude of endowment. But, suppose that for a given region they had no knowledge of the states of some of the processes. If they were able to examine a universe of regions which had the same circumstances of known and unknown processes, they would observe a distribution of endowments. Consequently, even given their perfect knowledge of the abbreviated relations, the effect of some processes being unknown is a probability distribution for the unknown endowment for any region under consideration. It is this distribution – a distribution of endowment in nature – which is desired when estimating mineral endowment. Geology and the geologist are a means of reaching this objective; furthermore, formalizing geoscience into a decision model is a rational approach. However, to the extent that geologists are very uncertain of the relationship of earth processes to magnitude of mineral endowment, their subjective distribution, if accurately measured, will reflect much greater variation in the magnitude of endowment for a region than is present in nature. If this uncertainty were great, the subjective distribution would approach a rectangular distribution with a wide range of possible states of mineral endowment, even when endowment in nature is normal or lognormally distributed. Thus, if our objective is to have a good estimate of the distribution of uranium endowment in nature, we may not be satisfied with a rectangular distribution when that distribution shape is believed to express a high level of ignorance. On the other hand, the subjective distribution may be preferred in an exploration model, because the uncertainty of the geologist is a real component of exploration performance and cost.

Let us assume here that the objective of predictive metallogeny is to describe variation in nature. Then the difficulty experienced by the geologists in the San Juan Basin demonstration in linking mineral endowment to the geologic decision model raises a question about the impact of ignorance and motivates the desire for an alternative approach, one which would make this linkage by statistically analyzing known states of nature and the states (or probabilities for the states) of the earth processes and geologic conditions of the geologic decision model on well known (control) areas. If achievable, such a linkage may provide a better estimate of variability in nature. It is with this motivation that the follwing approach is described.

While linking the decision model to endowment by the quantitative analysis of data is immediately appealing in concept, implementation of such a linkage would require 1) endowment data, such as either the number of deposits or the fraction of the partition that is mineralized and 2) data on the states of the earth processes. We have neither of these kinds of data. For one thing, resource data reflect only what has been discovered, not what is there. Even so, we may be able to use such data to achieve our objective. Consider this proposition: the fraction of an area (or number of deposits per unit of area) that is presently known to be mineralized is a function of geologic favourability of the area and the intensity to which this area has been explored. Let us formalize this by representing the fraction by *f*, geologic favourability by the 27 probabilities, $P_1, \ldots, P_{27}$, one for each combination of major process states, and exploration by v:

$$f = (\alpha_1 P_1 + \alpha_2 P_2 + \ldots + \alpha_{27} P_{27})\,(1 - e^{\alpha_0 v}) \qquad (1)$$

Thus, if the coefficients, $\alpha_0, \alpha_1, \ldots, \alpha_{27}$, were known, given the 27 probabilities and the amount of exploration, the equation would yield an estimate of the fraction of the area known to be mineralized. Of course, our objective is not the fraction known at present but the actual fraction. Even so, if the coefficients were known, by setting *v* to infinity, we could obtain an estimate of the actual fraction. The advantage of this approach is that it does not require data on the actual *f*, only on the presently measurable fraction. Of course, to estimate this equation, we must also have data on the 27 probabilities and on the amount of exploration, *v*. The remainder of this section "walks through" how this approach might be implemented.

Suppose that the geologic decision model were complete, meaning that it would have been calibrated satisfactorily: the probabilities computed by the system for states of the three major processes, given the probabilities for the states of the minor processes, for each reference condition would be satisfactory to the team designing the system. Suppose further that states of the major processes were not yet linked to endowment.

Suppose also that other, independent efforts had recorded for each partition *v*, the amount of exploration per square mile conducted in that partition, or some other description of exploration maturity, such as drilling density or conditional probability for existence of a target. Suppose that for every partition, the presently known fraction, *f*, were recorded. Finally, suppose that the geologists had described the geology of each partition probabilistically, just as was done in the study by Harris and Carrigan (1980). The input data to the geologic decision model – probabilities for the states of the minor processes or geologic conditions – could be processed by the geologic decision model. The output of the decision model for each partition would be probabilities for each of the three states of each of the three major processes. Accounting for all combinations of major process states, there would be 27 probabilities for each partition, one probability for each combination.

Let us summarize what has been postulated. Consider Figure 10, which is a hypothetical map of partitions of some stratigraphic unit. Only those partitions which have received significant exploration are of interest at the moment. For each of these partitions, there are three kinds of information:

v_i = exploration effort in the ith partition.

f_i = fraction of the ith partition known at this time to be underlain by uranium mineralization (alternatively, this measure, f, could be number of known deposits per unit of area).

$P_{1i}, \ldots, P_{27i}$ = probabilities for each of the 27 combinations of processes states for the ith partition.

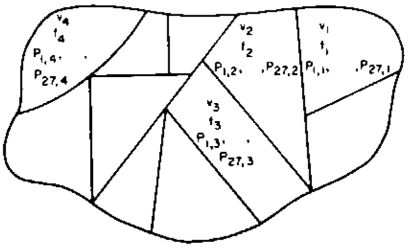


Figure 9 *Graphic comparison of estimates of initial U_3O_8 endowment of the San Juan Basin—expected values and 90% confidence ranges (Harris and Carrigan, 1980).*

V_i and f_i are measured data, but $P_{1i}, \ldots, P_{27i}$ are computed by the decision model. Suppose that this procedure were repeated for each of the geologists's stratigraphic units and that a table of these data over all units were prepared, such as Table IV. The data of Table IV could be analyzed by statistical and computer methods, e.g., iterative or non-linear regression analysis, to give estimates of $\alpha_0, \alpha_1, \ldots, \alpha_m$, where $m < 27$:

$$\hat{f} = (\hat{\alpha}_1 P_1 + \ldots + \hat{\alpha}_m P_m)(1 - e^{-\hat{\alpha}_0 v}) \qquad (2)$$

This equation provides an estimate of the fraction of the area that is presently known to be mineralized (contains endowment).

Since the sum of 27 probabilities is 1.0, only 26 probabilities are needed to convey the probability information. Furthermore, while conceptually only 26 probabilities are required to convey full information, an analysis may find that with respect to the data analyzed on endowment and exploration, less than 26 probabilities convey statistically meaningful information. This is a likely result, since very little, if any, endowment may be present when the states of all major processes are poor. Consequently, P_m, the last probability in the equation, may be the sum of several of the probabilities for the least favourable combinations of process states:

$$P_m = \sum_{j=m}^{26} P_j \qquad (3)$$

Thus, the equation which results from the analysis of data may require fewer coefficients than indicated conceptually:

$$\hat{f} = (\hat{\alpha}_1 P_1 + \ldots + \hat{\alpha}_{m-1} P_{m-1} + \hat{\alpha}_m \sum_{j=m}^{26} P_j)(1 - e^{-\hat{\alpha}_0 v}) \qquad (4)$$

For example, it is conceivable that statistical analysis could indicate that as few as 10 probabilities are required (m = 10), meaning that probabilities P_{10} through P_{26} are summed and treated as one probability.

To see how Equation 2 would be used, imagine that by implementing the decision model we have a set of 27 probabilities for each of the partitions, those explored and unexplored. Suppose that for each partition the intensity of exploration were specified to be infinity. Since $1-e^{-\hat{\alpha}_0 v}$ evaluates to 1.0 when $v = \infty$, the above relationship is reduced to $\hat{f} = \hat{\alpha}_1 P_1 + \ldots + \hat{\alpha}_m \sum_{j=m}^{26} P_j$. Thus, evaluation of this equation at $v = \infty$ and with the probabilities computed by the decision model for a partition would provide an estimate of the expected actual fraction of the partition that contains endowment.

Regression analysis also provides *S*, the standard error of the estimate, $\hat{f}$. Thus, by employing the assumptions of the regression model and the statistics $\hat{f}$ and S, we would be able to describe a probability distribution for *f* for each partition, given $P_1, \ldots, P_m$ and $v = \infty$. In this way, it may be possible to avoid the subjective linkage of the decision model to endowment. Of course, implementation requires the measurements of currently known *f* and of *v* for each partition that has received any significant amount of exploration. Furthermore, implementation of this approach for appraisal would require the description of a histogram or a probability density for the amount of U_3O_8 in a mineralized cell (subdivision of a partition). This would be an input to the synthesis program. While such data have not routinely been gathered, they could be, given a concerted effort by knowledgeable persons to measure or estimate them.

In summary, by using only the geologic decision model component of the appraisal system, data on the states of the major earth processes in each partition can be generated. If for each explored partition these data are augmented with measurements on exploration and the fraction of the

Table IV *Data Tableau*

Case	Exploration (v)	Fraction (f)	Process Probabilities ($P_1 P_2, \ldots, P_{27}$)
1	V_1	f_1	$P_{1,1}\ P_{2,1}, \ldots, P_{27,1}$
2	V_2	f_2	$P_{1,2}\ P_{2,2}, \ldots, P_{27,2}$
		⋮	
n	V_n	f_n	$P_{,n}\ P_{2,n}, \ldots, P_{27,n}$

Source: Harris and Carrigan, 1980.

partition currently known to be mineralized, the earth process of the geologic decision model could be linked to endowment by a statistical relationship determined by the quantitative analysis of these data. This relationship could replace the subjective conditional probability distributions for *f* or number of deposits that the system currently employs.

There is another benefit of this linkage approach when the objective is to average the system estimates made by two or more geologists: it would provide a means for weighting the estimates by the geologists. In the demonstration of the system on the San Juan Basin, a simple (unweighted) average was computed because there was no objective way of weighting the responses of the geologists. But, if the statistical analysis described in this section were made separately for each geologist, using the probabilities computed by his or her system but using the same data on exploration and *f*, a measure of the fraction of variance in the known *f* that is explained by decision model probabilities and exploration effort could be computed for each geologist. This fraction of explained variance could be employed as a weight for the computation of a weighted average endowment distribution. Simply stated, such a weighting scheme would weight preferentially the estimates of those geologists whose model's estimates were most compatible with known endowment.

In summary, I offer the suggestion that for frontier (lightly explored) regions, a useful initial contribution to estimation is an estimate that is based upon formalized geoscience and a linkage of this geoscience to endowment by statistical analysis of known endowment and probabilities for the major processes states computed from the decision model. Application of this approach requires a geologic model that is sufficiently general and dynamic that it accommodates a wide variety of geologic environments. Predicating the geologic model upon earth processes instead of upon recognition criteria may facilitate the required generality and dynamics. A methodology like this would preserve the flexibility and richness of geoscience, maintain the geologist as an integrator and analyzer of geodata and retain statistical credibility of estimates.

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