UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

RESEARCH ON URANIUM RESOURCE MODELS

A PROGRESS REPORT

PARTS I, II, and III

Open-File Report 80-2018

1980

Work done in cooperation with the U.S. Department of Energy

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Preface

The quantitative estimation of undiscovered mineral and energy resources is a relatively young but increasingly important activity that has developed over the past few decades. Quantitative resource estimation for uranium has received particular attention in the past ten years. In the forefront has been the development of assessment methods for uranium resources (Harris, 1977). To date, the most accepted methods are based on geologic analogy. These methods by their nature tend to be subjective and therefore questioned as to their reliability. Only recently have probabilities been attached to the estimates. The estimates of undiscovered uranium resources reported by the U.S. Department of Energy (DOE) at this writing (March 1980) are probably the best available; however, past DOE estimates have received severe criticism (Silver, 1978; Keeny, 1977).

The need for improved resource assessment methods in order to lessen subjectivity and to increase reliability (repeatability) is widely recognized. An improved method at the same time would increase the credibility (believability) of uranium-resource estimates, and, presumably would result in a more acceptable energy policy. It is this urgent need for an improved method that drives our current research.

The need for genetic models for uranium exploration and to assess undiscovered uranium resources has been expressed repeatedly over the past several years (Adams, 1975; Davis, 1977; Bailly, 1978; Cathles, 1978). In late 1976, the decision was made under the leadership of F. C. Armstrong to initiate in the U.S. Geological Survey a research project to develop geologic resource models based on genetic principles that could be used for estimating undiscovered uranium resources. Also anticipated was that such models would generate data sets of a degree of complexity that would require the described of computer-based methods similar to characteristic analysis developed by Botbol and others (1977). Finally, the fact was recognized that resource assessment is enhanced by knowledge of grade-tonnage relations among known deposits. A research plan to develop genetic-geologic models, to establish grade-tonnage relationships, and to apply geologic decision (characteristic) analysis was presented to the National Research Council's Workshop on concepts of uranium resources and producibility, September 20-21, 1977 (Finch, 1978; McCammon, 1978). Although the initial timetable for achieving the proposed research goals has proved premature, progress has been made, and the present document summarizes the progress to date.

The prime objective of our current research on uranium resource assessment methodology is to assist the Department of Energy's (DOE) National Uranium Resource Evaluation (NURE) program (U.S. Energy Research and Development Administration, 1976). There are deadlines of October 1980, to complete assessment of the most favorable parts of the country and of 1985 to complete the assessment of the entire country (Everhart, 1978). Such stringent demands have prompted DOE to provide financial and technical support to the U.S. Geological Survey for research on resource-assessment methodology. As of the annual estimate issued 1 January 1980, DOE's current methodology is based on engineering concepts derived from the estimation of reserves and is highly dependent upon the knowledge and experience of a few individuals. New and improved methodology in development for the DOE October 1980 assessment uses a subjective geologic analogy approach to estimate uranium endowment from which potential forward-cost resources are assigned on a basis akin to that for reserves. The methodology proposed by the U.S. Geological Survey provides for maximum utilization of the available geologic data and, in addition, provides for objectivity in applying current geologic concepts. Thus, the estimates derived should be more reliable and more credible than before. Because the methodology is untested, however, it is being applied using a prototype model in the San Juan Basin, the Nation's dominant uranium production area.

This progress report is divided into a number of parts. Those parts that are completed are listed below. Anticipated parts describe models of additional types of uranium deposits and the results of the testing of the San Juan Basin model. Critiques of each part are solicited and should be mailed to the authors: U.S. Geological Survey, Mail Stop 916, P.O. Box 25046, Federal Center, Denver, CO 80225.

Parts released in the initial series

Part I--Genetic-geologic models--A systematic approach to evaluate geologic favorability for undiscovered uranium resources by W. I. Finch, H. C. Granger, Robert Lupe, and R. B. McCammon.

Part II--Geologic decision analysis and its application to genetic-geologic models by R. B. McCammon.

Part III--Genetic-geologic model for tabular humate uranium deposits, San Juan Basin, New Mexico by H. C. Granger, W. I. Finch, R. E. Thaden, and A. R. Kirk.

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PART I. GENETIC-GEOLOGIC MODELS--A SYSTEMATIC APPROACH TO EVALUATE GEOLOGIC FAVORABILITY FOR UNDISCOVERED URANIUM RESOURCES

By Warren I. Finch, Harry C. Granger, Robert Lupe,

and Richard B. McCammon

Open-File Report 80-2018-A

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ABSTRACT

Current methods of assessing undiscovered uranium resources may be unduly subjective, quite possibly inconsistent, and, as a consequence, of questionable reliability. Our research is aimed at reducing subjectivity and increasing the reliability by designing a systematic method that depends largely on geologic data and their statistical frequency of occurrence. This progress report outlines a genetic approach to modeling the geologic factors associated with uranium mineralization in order to evaluate the geologic favorability for the occurrence of undiscovered uranium deposits of the type modeled.

Uranium has been concentrated by various processes into many types of deposits in different igneous, sedimentary, and metamorphic environments--all of which makes a genetic scheme of geologic modeling attractive. Most geologic models are descriptive of the three-dimensional setting of the deposits and have only limited or implied genetic qualities. The genetic-geologic model pertains to <u>all</u> the factors that describe the habitat and process of formation of a specific group of deposits thought to have a common origin. These models relate the processes of uranium concentration in a time sequence of events--the fourth dimension--that produced the characteristics we can now either observe or infer.

A matrix has been designed to facilitate model building and later computerization and application of the model to determine favorability. The rows of the matrix consist of the eight chronological process stages proposed for the formation of a uranium deposit: (1) precursor processes, (2) host-rock formation, (3) rock preparation, (4) uranium-source development, (5) uranium transport, (6) primary uranium deposition, (7) modification of primary minerals, and (8) preservation. These basic eight stages may be modified to fit a particular type of deposit. The columns of the matrix consist of the genetic processes, the geologic evidence or observations that led to identifying each process, a set of questions to apply the model, and the corresponding data requirements to answer the questions. The genetic-process and geologic-evidence columns form the basic genetic-geologic model. The set of questions in the third column is for testing the presence or absence of each genetic-geologic parameter or attribute. For the geologic-decision-analysis computer application each question is asked so as to require a positive, negative, or don't know answer. The questions are related to a particular model of uranium occurrence and their relationship can be described by a chronological logic circuit, which is used to evaluate favorability. The eight process stages make up a circuit. For a particular control area, statistically derived weights are obtained for each stage. The weights are then combined to determine a composite weight for the control area. The logic circuit can then be used to evaluate the favorability of unknown areas. The types of products from geologic-decision analysis are a favorability map of each stage and a composite map of all stages.

Extension of the models to resource assessment requires the integration of the grade-tonnage characteristics of known deposits and the prior probability of uranium occurrence. To accomplish this, we have extended the application of geologic-decision analysis beyond favorability determination.

INTRODUCTION

Conventional methods of determining favorability for undiscovered uranium resources are based on analogical comparisons of the test area with a known or control area of similar geology. The basic concept of geologic analogy is a valid one; its application has met with increasing success as our understanding of the environments of uranium ore deposits has increased. Where the factors of similarity or favorability are determined subjectively, the favorability has been calculated as the sum of judgmental numerical ratings of various geologic parameters (Hetland and Grundy, 1978). In large part, the favorability determined this way has been regarded by many as arbitrary and, hence, unreliable (that is, not consistently reproducible by two or more assessors, or perhaps even by a single assessor at different times).

In a less-structured way, and with equally unsatisfying response, an area can be judged subjectively, based on experience or "gut-feeling", to have a percentage of favorability relative to that of a control area. A testimony to the variability of purely subjective approaches is the 1,000-fold range in estimates of the undiscovered uranium in New Mexico made by more than 40 recognized "experts" (Ellis and others, 1975).

A recent method for evaluating the mineral potential of a given prospect has been developed by Stanford Research Institute International (Duda and others, 1978). This method, called Prospector, is a computer-based consultant system that permits a field geologist to subjectively compare knowledge of a given prospect with an exploration model built by a specialist for the given type of deposit. Subjective weighting of each attribute of the model is built into the system by the model builder. Although the Prospector system is intended to evaluate a specific prospect relative to the model, it could be adapted to evaluate an area for favorability, and subsequently used for resource assessment, but this conversion has not been made. Present Prospector uranium models are only for ores in sandstone.

The need for an improved method for determining favorability that lessens subjectivity and thereby increases reliability has largely motivated our research. Our immediate aim is to design a system of models that represents more accurately the occurrence of uranium deposits of specific types, grades, and tonnages. Such a system would incorporate uranium endowment, including grade-tonnage relations, and the prior probability of occurrence of one or more deposits of the model type in an area.

In the early stages of our research, we considered the classification of uranium deposits in the model design. This proved to be unsatisfactory, and classification is dismissed here as an immediate goal. Ultimately, we hope that the modeling will lead to a useable genetic classification. Such a classification should have defined boundaries in which any new type of deposit discovered would fit; in fact, new types should be predicted by such a process-oriented classification.

In general, we use the term "model" to mean any systematic and complete description of a single deposit or of a group of deposits that mostly have common characteristics. A genetic model pertains to all those processes having common origins. Such processes include not only ore-forming ones, but also those that preceded mineralization and had some direct or indirect bearing on the actual mineralization, and those that followed primary mineralization. Listing of the processes in chronological order is the basis of the genetic-model concept and provides the link with geologic-occurrence models. Genetic models involve four dimensions--the common three dimensions of space plus the all-important time dimension. A system of genetic and geologic models constructed interactively is best described as a genetic-geologic model.

An important aspect of our modeling that tends to decrease subjectivity is that the models are based more on data rather than on subjective evaluation. This is not to say that knowledge or experience is not required in model building, but a model once built can be applied chiefly with data obtained from observations and measurements. More important, the use of data allows correlation tests to determine the relative importance of the various factors, and thus to achieve a statistical weighting of factors that increases objectivity. There is an obvious disadvantage when inadequate data are available in the test area to permit rigorous application, but paucity of data will also limit use of purely subjective methods.

Each genetic-geologic model is designed to characterize a uranium-deposit type within a specific geologic province, such as a particular sedimentary basin, pluton, or metamorphic facies. Ideally, a model can be used to assess the favorability of the deposit type within any other geologic province judged to be similar. A model can be used, with some loss of effectiveness, however, to assess parts of geologic provinces or even a single outcrop or drill hole. For computer-based application, most convenient is to construct geographic cells of some fixed size and assess each cell and then to aggregate groups of cells to delineate favorable portions within larger geographic regions.

Genetic-geologic models are intended to be interactive within and among themselves, as objective as available data will allow, systematic, thorough and complete, logical and auditable, consistent but flexible, and ultimately predictive of new undiscovered environments for uranium occurrence.

There are multiple uses of genetic-geologic models. The current models are aimed specifically at assessing favorability for undiscovered uranium resources. With little if any modification, the same models can be used to guide exploration. Moreover, models of a more theoretical basis could be built that would characterize in greater detail the processes of ore formation and related geochemical reactions. Whatever models are developed, the skills and knowledge of exploration geologists as well as beginning uranium geologists should be upgraded. Finally, genetic-geologic models are applicable not only to uranium deposits but also to mineral deposits in general.

Acknowledgements

This research on uranium resource models was funded in significant part by the U.S. Department of Energy. Various colleagues, particularly J. T. Nash and R. I. Grauch, have contributed to the research with helpful discussions.

GEOLOGIC BACKGROUND FOR GENETIC MODELING

Understanding the history of uranium movement and concentration within the Earth's crust throughout geologic time is essential to the genetic-geologic model concept. Each of the many types of uranium deposits is the result of a series of different processes that had some role in the ultimate resultant deposit of uranium in a specific geologic environment. These processes taken as a whole gave rise to characteristic host rocks, alteration patterns, mineralogy, and grade-tonnage ranges.

The average uranium content of the Earth is probably similar to that of meteorites, but the uranium content of typical crustal rocks varies widely, and nearly all these rocks are considerably enriched in uranium compared to the mantle and core (Table 1). As an ubiquitous and highly mobile metallic element, uranium has been concentrated into deposits in many different igneous, sedimentary, and metamorphic environments. The resulting variety of uranium deposits occur in widely different forms, rock and metal associations, and grades. Most uranium deposits represent local concentrations much greater than that of the average crustal rocks and probably contain uranium that has been mobilized many times (table 1). Every deposit, therefore, represents the culmination of a complex series of events or processes that can be viewed as starting with the early evolution of the primordial Earth.

Although the location of individual deposits is most closely related to properties of the host rock and the immediate source of the uranium, the location of uranium-rich provinces is probably related to much larger features that involve the gross structural and geochemical evolution of the earth.

The concept of plate tectonics, as it has unfolded in the last few years, yields an insight into how crustal rocks may have become enriched in uranium and how at least some uranium-rich provinces may have developed. A detailed discussion of Earth history and its relation to the evolution of uranium deposits is not within the scope of this paper, although a brief summary may be appropriate.

Four stages in the Earth's history were particularly critical to the segregation and concentration of uranium and to the types of deposits that could be formed. These stages were (1) segregation of the sialic crust, (2) the development of life, (3) the development of an oxygen-rich atmosphere, and (4) the development of land plants.

1. Segregation of sialic crust

There seems to be no general agreement among geologists regarding the details of the origin of sialic crust. There is agreement, however, that this part of the crust is variably heterogeneous, forms the continental cratons,

Table 1.--Concentration of uranium in natural materials

[See also Klepper and Wyant, 1957, p. 91)]

Mean or range of means--ppm U_3O_8	Material	Reference
640,000-880,000	Uraninite	
6000	Ore from Schwartzwalder mine, Colo.	E. J. Young (oral commun., 1978).
4500	Jabiluka ore	
2600	Average U.S. ore, 1963	U.S. Atomic Energy Commission (1973).
1200-1600	Blind River-Elliott Lake	Finch and others (1973).
375-700	Witwatersrand ore	--Do.
375	Rossing, Namibia ore	U.S. Bureau Mines (1970).
300	Swedish alum shale	Finch and others, 1973.
120-240	Florida phosphate	--Do.
100-10,000	Sandstone ores	--Do.
100	Nigerian riebeckite-albite granite	MacKay and Beer (1952).
70-700	Marine phosphate	Finch and others (1973).
70-	Chattanooga Shale (Tenn.) black shale	--Do.
15	Conway Granite, (N.H.) biotite phase	--Do.
7	Volcanic glass	
4	Acidic igneous rock	Finch and others (1973).
3.7	Shale	Green (1959).
2.2	Carbonate rock	Adams and others, 1959.
2.0	Mean crustal abundance	Finch and others (1973).
1.4	Bituminous coal, Applachians	Z. S. Altschuler (oral commun., 1978).
1.2	Sandstone	Finch and others, 1973.
1.1	Freshwater peat, Everglades (USA)	Z. S. Altschuler (oral commun., 1978).
.9-10	Porphyry copper	Bieniewski and others (1971).
.9	Mafic igneous rocks; lignite, Northern Plains (USA)	
.2-4.0	Crustal abundance: range	
.2	Diorite	
.005	Ground water	
.0055	Iron meteorites	
.0013-.003	Seawater	Koczy (1954).
.001	River water	--Do.

and is much richer in uranium and other radioactive elements than either the oceanic crust or mantle. Presumably, this uranium enrichment was largely accomplished early in the Earth's history by a partitioning between the mafic mantle rocks and more salic crustal rocks. Most uranium deposits have probably been the result of both physical and chemical reworking of these sialic continental rocks through anatexis and differentiation, on the one hand, and through weathering, sedimentation, and leaching and redeposition processes, on the other.

Accretion of later rocks to this early continental crust has probably been accomplished by processes related to plate tectonics. Where oceanic crust was subducted under continental cratons, heat and pressure caused metamorphism, anatexis, and differentiation of both crystalline oceanic crust and marine sediments derived in large part from continental erosion. Material stripped from the continents was, therefore, reworked and reunited with the continental cratons. In so doing, it is likely that the more sialic and uranium-rich fraction probably was preferentially retained by the continents, whereas some of the more mafic and uranium-depleted material was returned to the mantle.

Radioactive decay within the uranium and thorium series and potassium provides most of the heat now being generated within the Earth. Because the continental crust is richer in these elements than are either the oceanic crust or mantle, there is much more radiogenic heat generated per unit mass of continental crustal rocks than in other rocks. When oceanic crustal rocks were subducted under the edges of continental cratons, some of them evidently became molten and rose through the crust to yield both intrusive and extrusive igneous rocks. Not surprisingly, that some of these rocks underwent a certain amount of differentiation and became further enriched in uranium. Within continental cratons, large masses of uranium-enriched rock may not have been able to dissipate radiogenic heat as fast as it was formed, and some of this rock may have melted and become further differentiated. As with the molten products of subducted rocks, the uranium-rich rock may have risen in the crust to become intrusive and extrusive masses.

Early differentiation of a low-density, uranium-enriched, sialic continental crust has probably played a most important part in the creation of all uranium deposits. This differentiation was the first of a series of preconcentration processes that have probably preceded the deposition of all economic uranium deposits.

2. Role of life

Paradoxically, primitive life forms on the Earth created two new and entirely opposite environments that have been extremely important in the redistribution of uranium. Near the middle of Proterozic X time, about 2400 million years ago, the so-called oxyatmoversion occurred when life forms had developed that liberated free oxygen, probably by photosynthesis. Shortly after this time, bacterial organisms may have developed that could have reduced sulfate and other sulfur species to H_2S. The action of these bacteria created environments of highly reducing conditions in extreme contrast to the action of the oxygen-producing organisms. Because uranium is highly mobile under oxidizing conditions and is generally immobile under reducing conditions at low temperatures, the importance of this aspect of certain living organisms is highly evident.

Living organisms also concentrated organic carbon and, when they died, their remains were incorporated in fine-grained marine sediments. Organic carbon compounds are well-known concentrators of uranium by adsorption, reduction, and chelation. As soon as oxidation liberated uranium from rocks to meteoric solutions in the Precambrian, the uranium began to migrate to the seas and to be entrapped by organic-rich marine sediments.

The relation of living organisms to the organic-rich uraniferous phosphate deposits that have formed in certain shallow, restricted marine environments is not well known. The uranium occurs in the reduced form in the apatite in these deposits. However, because oxidized uranium must have been transported into these environments by water, oxidation likely played an important part in the creation of the uraniferous phosphates, which are as old as the late Precambrian.

3. Consequences of an oxygen-rich atmosphere

As noted above, the development of an oxygen-rich atmosphere was closely linked to the development of oxygen-liberating living organisms. Once oxygen was available, meteoric surface waters became strongly oxidizing. Weathering, previously controlled largely by physical processes and pH imposed by CO_2, then became influenced by oxidation processes. Uranium, relatively insoluble under reducing weathering conditions, became readily leachable under oxidizing weathering conditions. Placer concentrations of easily oxidized uranium minerals, such as uraninite, could not form or persist except under unusually rapid transport or cold conditions. Transport of uranium in solution by meteorically derived waters created the opportunity for a host of new varieties of uranium deposits.

4. Consequences of the development of land plants

After the time of the oxyatmoversion and prior to the Devonian Period, when land plants became abundant, most of the uranium liberated by weathering conditions was carried to the sea by surface waters. Few, if any, continental sediments are known to have accumulated supergene uranium during that interval of time, probably because there was little terrestrial organic carbon either to concentrate the uranium directly or to serve as a nutrient for sulfide-reducing bacteria. Nearly all uranium deposits in continental sediments are associated in some way with organic materials and were formed after the Devonian Period. Most of the uranium deposits we see today are probably the result of a long, complex history of preconcentration processes, intermingled with dispersive processes such as weathering. Some old uranium deposits, such as the uraniferous Precambrian quartz-pebble conglomerates, probably were preceded by only a few preconcentration steps or cycles. The uranium in more recent deposits, however, could have undergone many cycles. These cycles are too numerous, complex, and tenuous to expand upon here but there are, perhaps, three prominent, although speculative, processes that should be mentioned. These cycles involve (1) metamorphic, (2) igneous, and (3) sedimentary processes.

Marine sediments are probably much more likely to become involved in metamorphic processes than are continental sedimentary rocks. Whereas large volumes of marine sediments may be either subducted or involved in collisions between crustal plates, most continental sediments are probably destroyed by erosion. For the most part, marine rocks are not highly uraniferous but there are two types of marine rocks that could be metamorphosed and contribute uranium to later rocks through metamorphic mobilization: carbonaceous shales and phosphates, because these sediments can concentrate uranium from seawater. Under metamorphic conditions, uranium may be difficult to separate from phosphatic rocks, because apatite is fairly refractory, but probably it is easily separated from organic substances. Hydrothermal solution emanating from metamorphosing carbonaceous marine shales, therefore, may have been a significant contributor to certain uranium deposits in metamorphic terranes.

According to simple, conventional plate-tectonic theory, metamorphic zones of such sedimentary rocks should be localized near convergent plate boundaries. Subduction related to convergence between an oceanic and a continental plate would be the most likely mechanism to convey organic shales into a metamorphic environment. Some uranium, however, could be liberated where uraniferous continental rocks were thrust into metamorphic regions by collisons between continental plates.

Cycling of uranium through igneous processes could occur along subduction zones of oceanic crust or near the sutures between colliding continental blocks. Here, rocks already somewhat enriched in uranium might be drawn to great depths, heated, partly melted, and thrust back to the surface as molten, further enriched magmas. Such magmas might be emplaced as plutons, hypabyssal bodies, or extrusive rocks; or, they might undergo further differentiation and give rise to uranium-rich hydrothermal solutions.

Farther within the continental craton, rocks melted locally at depth in the roots of the craton might undergo evolution similar to that noted above, giving rise to similar suites of rock but that could, because of their sialic derivation, be even more sialic and highly differentiated.

The continental sedimentary cycles may be the most complex uranium redistributing cycles of all. Presumably, most of the uranium in continental sedimentary rocks was derived orginally from metamorphic or continental crystalline and extrusive rocks. Erosion and leaching of these rocks yielded uranium to meteoric solutions which then provided transport to sites in continental sediments where the uranium was redeposited by geochemical processes. Subsequent cycles might then have only continental sediments as both the immediate source and host rocks but, ultimately, some deposits must be destroyed and the uranium delivered to the sea. Here, the entire process involving organic shales, subduction, and so forth, can start all over again. Some deposits, particularly those in island arcs, such as in Japan, could have undergone several complete cycles of this type before coming to temporary rest where we see them today.

The significance of this discussion to genetic modeling for uranium-resource assessment is to stress the importance of preconcentration and precursor conditions to most deposits, particularly to those that contain uranium of economic grade. We commonly cannot reconstruct all these conditions in any detail, but their importance to the genesis of deposits should not be underestimated. By reconstructing the basic geologic history of a region, we may be able to determine its basic favorability for undiscovered uranium deposits.

In the geochemical cycles of uranium in the Earth's development, a first genetic distinction can be made as to whether a deposit is either syngenetic or epigenetic. Syngenetic deposits were formed contemporaneously with the host rock. These uranium deposits commonly are the same shape as the host-rock body. The uranium is fairly uniformly disseminated and generally is closely related to the allogenic mineral phases of the host rock. Syngenetic deposits are commonly low grade, such as uraniferous granite and marine black shale, but a few are high grade, such as uraniferous parts of pegmatites. Genetic models of syngenetic deposits are generally more simple than those of epigenetic deposits, as mineralization itself is but a single stage, and hence the determination of favorability for uranium resources is also more simple.

Epigenetic deposits, on the other hand, are more complex for they were concentrated after the host-rock formation, commonly distinctly afterwards. Furthermore, they have many shapes, occur in many geologic environments, have complex mineralogy, and have wide ranges in grade, both among and within deposits. Two and commonly more stages of uranium concentration are evident in epigenetic deposits. Thus, the prediction of occurrence of unfound epigenetic deposits and the projection of mineralized rock into unexplored ground are far more difficult and subject to chance than for syngenetic uranium. More controversy surrounds the genesis of epigenetic deposits than syngenetic ones, and it is fair to state that the genesis of no single epigenetic deposit can be absolutely proven. Thus, the design of genetic models for epigenetic deposits must be flexible to accomodate variable genetic concepts. It is the epigenetic deposit at which genetic modelling is aimed, and these models will prove most useful in evaluating favorability for undiscovered uranium resources.

THE CONCEPT OF A GENETIC-GEOLOGIC MODEL

Uranium has been concentrated by various processes into deposits in many different igneous, sedimentary, and metamorphic environments. For a given deposit, or group of like deposits, these processes can be presented in a chronologic sequence of genetic concepts. Each process has left behind evidence in the form of observable features in the host rock and its general environs. These geologic features can be woven into a basic geologic story that forms the geologic occurrence base. The genetic concepts and their corresponding geologic bases are dependent upon one another, and the two can be molded into an interactive chronological matrix that we call the "genetic-geologic" model. It is this genetic-geologic model that we use as a framework for using geologic and related data to evaluate favorability of an area for undiscovered uranium deposits.

Genetic Scheme of Process Stages

General processes

A sequential scheme of chronological process stages is formulated here to include the entire genetic history of an uranium province and its contained uranium deposits. This scheme expands beyond that used for resource modeling by Ruzicka (1977). The eight general process stages are as follows:

I. Precursor processes
II. Host-rock formation
III. Host-rock preparation
IV. Uranium-source development
V. Transport of uranium
VI. Primary uranium deposition
VII. Post-deposition modification
VIII. Preservation

These various stages in the model are intended to be an all-encompassing general framework in which to list every event, condition, and process that influenced mineralization. A few comments on each stage will clarify the kinds of concepts that are intended under each heading. Furthermore, these comments will indicate the kinds of geologic evidence that were used to develop the genetic concepts.

Precursor processes

The precursor process generally produced regional features that describe the geologic history prior to host-rock deposition. These processes may extend back to the Earth's formation when certain parts of the crust became more rich in uranium than other parts--in other words, the creation of a uranium-rich province. Such a uranium province may have been modified later by various geologic processes during which some uranium deposits could have been formed. Furthermore a given uranium province may have been separated into smaller geologic provinces or domains, and some of these were separated by tectonic plate movements and are now on different continents. For many types of deposits, parts of Precambrian shield areas and orogenic belts are provinces; for others, forelands are more likely than geosynclines; and continental basement rocks are more likely to be uraniferous than are oceanic rocks, except for carbonaceous shale and phosphate. The precursor processes may be represented by smaller scale features and may be more closely related in time to the host rock formation, such as the development of intermontane basins, caldera centers, and plutons.

Some precursor products may have become subsequently a source for uranium. For example, deep-seated igneous activity may have produced a labile uranium source rock that was later to become a provenance for sediments, or to be exposed to weathering. Ancient uraniferous marine shales have in some places acted as protore for later metamorphic uranium deposits. Sandstone-type uranium ores of early Precambrian age have even been postulated as sources for later ores in faulted and metamorphic environments at Gabon (Diouly-O and Chauvet, 1977).

The usefulness of precursor events, particularly those of regional nature, may be limited in favorability assessment in some areas, for example, the extension of a known uranium belt into deeper parts of the same basin.

Host-rock formation

The history of the host-rock formation bears closely on the uranium concentrating process. The initial host-rock components--both reactive and inert chemicals--initial porosity and permeability, and relative stratigraphic position and geologic age are important attributes to consider. For certain rock types, because their genetic history is tied closely to that of a particular kind of uranium deposit, the rock name becomes part of that uranium deposit type, such as uraniferous marine black shale.

For certain types of sedimentary host rocks, for example sandstone, this stage might best be divided into three substages: (1) source of sediments, (2) transport of sediments, and (3) deposition of sediments. For igneous and volcanic host rocks, one or more magmatic substages and possibly an accompanying sedimentary substage may be required to model the uranium deposits.

Host-rock preparation

Preparation of the host rock may be the most important step in the mineralization process. In some host rocks, preparation begins during rock deposition or soon thereafter; in others it is much later, and there may be several stages. Diagenesis may play an important role in the preparation of sedimentary and volcanic host rocks. Tectonism is important not only in some sedimentary rocks, but is vitally important in brittle igneous and metamorphic rocks that are host for breccia and fissure-vein deposits. The absence of tectonism can be critical, such as for uranium deposits in sandstone. Weathering, thermal activity and metamorphism are important in soluble rocks to create void space for sites of mineralization, such as replacement of limestone or dolomite by chert to form solution breccia. Alteration that precedes introduction of uranium-bearing solution is also part of rock preparation. Clearly, the preparation of host rock consists of both chemical and physical changes.

Uranium-source development

As noted above, the potential source of uranium may develop before host-rock deposition, as in uranium-rich granite plutons and pelitic rocks--the first for later weathering of uranium and the second for later release of uranium during metamorphism. Other sources, such as contemporaneous volcanism, may develop during sedimentation of the host rock. In still others, an even later development (commonly volcanism) may provide a viable source for uranium.

Transport of uranium

For most deposits, a plumbing system was necessary to transport uranium and accompanying metals and other components from their source or sources to where they accumulated. But evidence for the system and transporting fluids is most commonly faint if detectable at all. An interface between two fluids of differing composition is commonly called upon to account for shapes of tabular ore bodies and their boundaries with barren rock. Most important to uranium movement are hydrologic systems; unfortunately, far too little is known about the paleohydrology of the environment of uranium deposition. Nevertheless, knowledge of present ground-water conditions, recharge points in both present and postulated past systems, a possible hydraulic-gradient condition (such as dip), potential conduits (location of aquavoids, faults, joints), and discharge points for the system are important pieces of evidence to list. Timing is also important; there must have been communication at the proper time between the proposed source and the present site of the uranium deposits.

Primary uranium deposition

Uranium minerals are deposited by many processes, including adsorption and absorption; reduction by organic matter, gases, or sulfides; evaporation; or temperature and pressure changes in hydrothermal igneous and metamorphic systems. The primary uranium minerals may be either low valent, such as uraninite, pitchblende, brannerite, uranothorite, and coffinite formed in reducing environments, or high valent, such as carnotite, soddyite, and schroeckingerite formed in near-surface evaporative and calcrete deposits. In organic- and phosphate-rich host rocks no crystalline mineral in which uranium is an essential constituent may be present. Evidence of alteration synchronous with uranium mineralization is commonly more pervasive and widespread than the ore body, such as in a roll-front; this is an attribute of great importance.

Some primary uranium ores are closely related to the source and deposition of other metals, such as iron, vanadium, gold, molybdenum, selenium, chromium, nickel, and thorium, and other substances, such as organic materials (humate). Thus, the depositional history of these materials may be important to include in the model, particularly if their presence as geochemical halos extends far beyond the known uranium deposits.

The presence of uranium minerals, either observed or indicated indirectly by radioactivity, is thought of by many to be the most diagnostic evidence for the process of uranium mineralization. From a viewpoint of evaluating favorability of a rock or geologic setting to contain economic deposits of uranium, however, the mere presence of uranium minerals must be used with caution, if at all. Minor occurrences of uranium are far too widespread to place great confidence on their use in favorability evaluation. This problem is discussed further under a section dealing with favorability versus probability of occurrence.

Recognition of the mineralization processes may not be as useful for determining favorability as premineralization processes because mineralization processes were commonly too localized at the site of uranium deposition. From the viewpoint of understanding the geochemistry of ore deposits themselves, however, genetic modeling of mineralization will be important. For our purposes of resource assessment, the primary uranium deposition stage will be used chiefly for model selection.

Post-deposition modification

Modification after primary deposition can either increase or decrease the uranium grade. Some deposits have been completely destroyed, and the uranium either transported to the ocean or redeposited elsewhere, commonly as a different type of deposit. For example, some humate-related tabular deposits in the Westwater Canyon Member of the Morrison Formation in the San Juan Basin were partly to completely destroyed by oxidation since mid-Tertiary time. Some of the uranium from these deposits was redistributed as roll-type deposits (stacked or post-fault ores) whose classical C-shapes were modified by permeability variations related to fractures and sedimentary structures and textures. Further modification related to the present-day conditions is a part of the preservation stage.

Preservation

Preservation of the deposits is essential. It is dependent upon protection by stable overburden conditions, favorable climatic conditions, the erosional cycle, ground-water conditions, and time. Some otherwise favorable ground may be unfavorable because of failure of preservation. If there is evidence of destruction of deposits, one should look for new loci of concentration, such as downdip, along tectonic structures, and in other host rocks.

Chronology of Process Stages

The process stages listed above may be neither distinctly separate, for they commonly overlap in time, nor always in the identical chronological order for all types of deposits. This is especially true for the stage of uranium-source development, which may occur in surges that precede, accompany, or follow host-rock formation. There may be other complications in timing and because of these complications modeling of each type of uranium deposit will require suitable arrangement of stages to fit the best interpretation of the geologic history of that deposit. The genetic scheme proposed here is designed to be flexible in order to accommodate such variations. We will illustrate this flexibility in dealing with variations by giving a few examples of syngenetic, modified-syngenetic, and epigenetic deposits.

Typically, syngenetic deposits are characterized by few distinct stages, as shown by the example of uraniferous marine black shale on figure 1. In these deposits, uranium was concentrated out of sea water that derived its uranium from subaerial weathering of adjacent highlands, or possibly from contemporaneous volcanism. Moreover, the uranium was precipitated along with host rock so that host-rock formation, rock preparation, uranium transport, and primary uranium deposition stages merge into a single time span. The nature of the uranium bond to the organic matter in the shale and the near impermeability of the rock have allowed little if any modification since uranium deposition, and preservation has been almost guaranteed under normal weathering conditions. Thus, in terms of time the genetic model for uraniferous black shale is essentially a single-stage model that has only minor pre- and post-depositional stages.

Syngenetic deposits in quartz-pebble conglomerate can be explained by a simple model as shown on figure 2. Note that modification of the original deposits by low-grade metamorphism is a distinct stage. This modification has been interpreted by some workers in the past as the primary mineralization stage, but this view does not fit the dominant character of the deposits. The moderate permeability of these ores had led to some destruction of ore minerals in the zone of weathering during the latter part of the preservation stage.

PROCESS STAGES	TIME----->
Precursor processes	---------------
Uranium-source development	-- -- -------------
Host-rock formation	----------
Preparation of host rock	----------
Transport of uranium	----------
Primary uranium deposition	---------- --
Modification	Absent
Preservation	-- -- -- -- ------------------

Figure 1.--Probable timing of process stages for uraniferous marine black shale.

```
PROCESS STAGES                 TIME----->
------------------------------------------------------------------------
Precursor                      -----------

Uranium-source development        -- -------------

Host-rock formation                    -----------

Preparation of host rock               -- -- -- --

Transport of uranium                   -----------

Primary uranium deposition             -----------

Modification                                -- -- -----------

Preservation                           -- -- -- -- -- -- -- -- --------
------------------------------------------------------------------------
```

Figure 2.--Probable timing of process stages for quartz-pebble conglomerate uranium deposits.

Deposits of low-grade uraniferous phosphate are generally syngenetic as exemplified by the Idaho Permian phosphate deposits on figure 3A. However, other phosphate deposits are richer in uranium because two episodes of uranium concentration occurred. The first was syngenetic similar to the Permian phosphate; the second was a distinctly later stage related to preservation, as in the model of the so-called "land-pebble" phosphate deposits in Florida shown on figure 3B. These deposits with two stages of uranium concentration might be considered epigenetic because the second stage was much later than the first and was the actual "ore-forming" process. They can at least be called modified-syngenetic.

Epigenetic deposits have had more complex histories than most syngenetic deposits. In terms of time, epigenetic deposits commonly display seven or more distinct stages plus the overprint of prolonged or multiple surges in the development of the uranium source. To illustrate their history, clear separation of host-rock history from that of uranium may even be desirable; and in some deposits, uranium deposition may require more than one stage. Figure 4 illustrates generalized timing of processes that led to the formation of most epigenetic deposits in sandstone. Figure 5 more specifically describes the formation of a particular type of sandstone deposit--the tabular humate uranium deposit. For this type of deposit, we separated the history of the host rock from that of the uranium deposit, because they complexly overlap in time. Furthermore, by separating these histories as we have, we can more readily handle two possible uranium sources and alternative ideas about the timing of the alteration of host rock, including a separate stage or substage that was contemporaneous in part with primary uranium mineral deposition. The actual time scales for the host rock and uranium deposit were probably different; neither was the timing of the first stage of primary uranium

```
PROCESS STAGES             TIME----->
--------------------------------------------------------------------------
                (A) Idaho Permian phosphate
--------------------------------------------------------------------------
Precursor                  -----
Uranium-source development   - - -----
Host-rock formation              -----
Preparation of host rock         -----
Transport of uranium             -----
Primary uranium deposition       -----
Modification                          - - -
Preservaton                           - - - ------
--------------------------------------------------------------------------
                (B) Florida land-pebble phosphate
--------------------------------------------------------------------------
Precursor                  -----
Uranium-source development   - - -----      -----
Host-rock formation              -----
Preparation of host rock         -----
Transport of uranium             -----
Primary uranium deposition       ----- - - - -----
Modification                                -----
Preservation                                -----
--------------------------------------------------------------------------
```

Figure 3.--Probable timing of process stages for (A) Idaho Permian uraniferous phosphate, and (B) Florida land-pebble uraniferous phosphate.

```
PROCESS STAGES               TIME----->
______________________________________________________________________________

Precursor processes          -------

Host-rock formation                 -------

Preparation of host rock                -- --------

Uranium-source development    -----------------------------

Transport of uranium                            -- ------ --

Primary uranium deposition                               ------

Post-deposition modification                                    -------

Preservation                                             - -- -- ---- --------
______________________________________________________________________________
```

Figure 4.--Generalized timing of process stages for epigenetic uranium deposits in sandstone.

PROCESS STAGES	TIME----->
Precursor conditions and events	------
Host-rock	
Source of host-rock constituents	- ------ --
Transport of host-rock constituents	-- ------ ----
Deposition of host rock	-- -------
Alteration and preparation of host rock	--- ------ --
Uranium deposit	
Source of uranium	------- -- ? -- -- ?-------- --
Transport of uranium	-- ------- -- -- --
Primary uranium deposition	-------- ---
Modification of primary ores	----- - ---
Modification of primary and redistributed deposits	-------- --
Preservation	-- -- -- -- -- -- -- ------

Figure 5.--Possible timing of process stages for tabular humate uranium deposits.

deposition necessarily just after the last stage of the host rock. Note that there appear to be at least 10 separate stages in the humate uranium model.

We close our discussion of the ability of the genetic scheme to accommodate variations in time by illustrating one of the most complicated types of deposits of all--the so-called "unconformity-vein type" (figure 6). This preliminary attempt to identify the possible processes that formed these poorly understood deposits identifies several episodes of host-rock and uranium-deposit formation, some of which overlap. More specific examples of this type of deposit would illustrate more precise stages, but this crude attempt suffices to illustrate again the complex nature of the chronology of uranium-deposit processes.

We end this discussion with the following caution concerning the use of the genetic scheme. If one plans to build a large number of models to use as a means of identifying a prospect with a specific model, the ordering and labeling of stages must be standardized to allow computerized search for common and dissimilar characteristics to facilitate the use of a bank of genetic models.

The Geologic Base and its Interaction with Genetic Concepts

The genetic concepts are generated from interpretations based on observations of the geologic setting (including mineralogy and geochemistry) of a given type or group of uranium deposits with similar characteristics. The development of a genetic model most logically goes from field evidence and related laboratory analyses to the conceptual ideas about the genesis, but because of our basic knowledge of the science of uranium geology, some genetic processes can be inferred without any field evidence. The evidence may not yet have been observed. In some processes, the evidence may have been destroyed, or be far removed from the site of uranium occurrence, but

PROCESS STAGES	TIME----->
Precursor	------
Protore host-rock formation	------
Prograde metamorphic host-rock preparation	------
Retrograde metamorphic host-rock preparation	------
Uranium-source development	------------------
Uranium transport	---------
Primary uranium deposition	---------
Modification at unconformity	-- ------
Modification after burial	-- ------
Preservation	-- -----

Figure 6.--Possible timing of process stages for unconformity-vein type uranium deposits.

nevertheless the process must have taken place. Fundamentally, the geologic-occurrence base is described first and the genetic model follows, but during the development of the genetic model an interactive feedback loop is established between the two, as diagrammed on figure 7. This feedback points out a strength of our system of modeling in that it forces the field geologist to think about the entire process of mineralization.

The geologic-occurrence base consists largely of the three-dimensional empirical relationships of the known deposits to their surroundings. The fourth dimension, time, is introduced by listing the geologic-occurrence data in the chronological order of the genetic model. Some geologic data do, however, have a bearing on time relationships; both field evidence for timing of geologic events and laboratory evidence of mineral age are important to developing a more accurate genetic model.

MODEL BUILDING

The ultimate goal in our resource modeling is to build genetic-geologic models that represent distinct classes of deposits that have had similar genetic histories. Because of significant regional variations and the uncertainty of genesis of most classes of deposits, construction of regional representatives of a class is more useful at this time. When we have constructed enough models for representative areas we may be able to integrate them into acceptable general models for each distinct class of deposits.

The building of genetic-geologic models can be broken into the following steps: (1) decide on the type of deposit to model and set the geologic and geographic boundaries; (2) prepare a general scenario to identify the key events of the genetic history of the deposits; (3) compile the geologic evidence and related processes into the genetic scheme proposed above; and (4) finally, prepare an epilogue stating the unsolved problems and inadequate

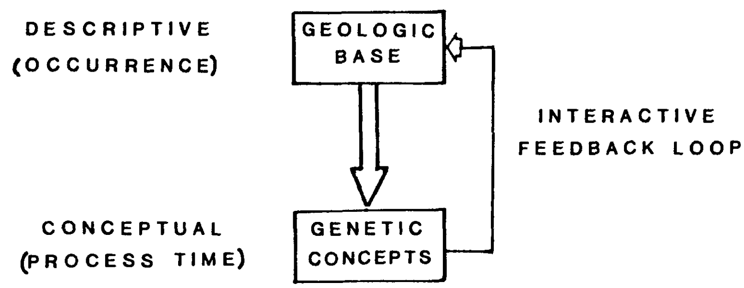

Figure 7.-Relation of geologic base to genetic concepts.

observations encountered. More than one iteration of the initial model may be required to arrive at an acceptable provisional model. The number of elements to this model may total more than 100, many of which are not diagnostic for the determination of favorability. Either by subjective selection or, as we propose, through statistical weighting, the key elements need to be identified to arrive at a shorter working model.

After a group of deposits has been selected to model, a general narrative statement should be prepared to describe briefly in a chronological order the salient points of the geologic occurrence and genetic concepts of these deposits. Variations in genetic concepts should be discussed, and, if necessary, the reasons for choosing one over others should be given. The general narrative of the model serves as an introduction to the more detailed model itself.

Genetic-geologic uranium-deposit models are built of pertinent geologic data tied together by conceptual interpretations of how those data can be related in time to processes before, during, and after uranium deposition. The available data concerning the geologic setting of the specific deposit or deposits are assembled in the eight-step chronologic order outlined above; this part of the model is designated the geologic-occurrence base, which becomes the second column of the matrix format shown in table 2. From the geologic-occurrence base, more generalized process-oriented genetic conceptual statements are presented in the first column of the matrix. The genetic concepts are placed to the left of the geologic base even though a reverse order seems more logical. Two practical reasons for doing this are related to the mechanics of listing entries under each heading. First, for many genetic concepts more than one bit of evidence supports the concept, and thus the flow of the outline from left to right and top to bottom is smoother and more

Table 2.--General genetic-geologic model and application matrix format

	The genetic-geologic model		Application	
Stages	Genetic concept	Geologic occurrence base	Questions	Required data
I. Precursor	x	x	x	x
II. Host-rock formation	x	x	x	x
III. Preparation of host rock	x	x	x	x
IV. Uranium-source development	x	x	x	x
V. Transportation of uranium	x	x	x	x
IV. Primary uranium deposition	x	x	x	x
VII. Post-deposition modification	x	x	x	x
VIII. Preservation	x	x	x	x

consistent toward increasing detail. Second, the question set to be later listed in the third column is more closely tied to the geologic evidence and needs to be adjacent to it.

In the actual preparation of the model, the ordinary outline form is used to enter the material related to each stage. Once a heading is established it should be carried to the right with appropriate corresponding statements in the next column. The statements within the outline should be brief full sentences that describe the essence of the ideas and evidence. A definite grammatical style is required for each of the two parts of the matrix to insure uniform construction. The geologic base is to be described in the present tense because it concerns observations that can be made today. The genetic concepts, on the other hand, are to be stated in the past tense for they describe events that have taken place in the past. Within each stage the statements should be placed in a chronological order, if possible, from the oldest to youngest event or process. An example is shown in table 3.

With today's state of knowledge, even the best models that can be devised will have some processes that are controversial or speculative. If there is more than one genetic concept for certain data, each concept may be placed in the model as alternatives to be tested. Some important aspects may be omitted because they have not been recognized; others may be misinterpreted for various reasons. In the best models that can be devised, therefore, there may be both omissions and imperfections. In addition, extraneous geologic observations may be included that can be neither related to nor disassociated from the genesis of deposits. They should remain as parts of the model, however, because to omit them from later testing without adequate justification would be presumptuous.

Table 3.--The precursor process stage of the tabular humate-related uranium deposit model, San Juan Basin, N. Mex. (modified from Granger and others, 1980)

Genetic concept	Geologic base
A. Precursor processes	
1. A uranium-rich province developed in and south of the San Juan Basin prior to host-rock deposition.	1a. Precambrian crystalline basement rocks contain anomalously uraniferous zircon.
	1b. Regional basement rocks are abnormally uraniferous.
	1c. Uranium deposits occur in older (Paleozoic, Triassic, earlier Jurassic) and younger (Cretaceous and Tertiary) rocks in the region.
	1d. Lead-isotope studies show that regional basement rocks have lost in U in the past.
2. An extended period of marine and later dominantly continental deposition of red beds took place on a broad stable platform.	2a. The underlying strata constitute a sequence of dominantly marine Paleozoic rocks overlain by dominantly continental lower Mesozoic rocks.
	2b. The host rock is part of a thick, dominantly red-bed sequence of sedimentary rocks.
	2c. The regional dip of the underlying rocks as well as of the host rock is generally low, less than 5°.
3. Host rock deposition was preceded by uplift along the margins of the platform, perhaps coinciding with shallow downwarp of the depositional basin.	3a. Distribution and thickness of the Jurassic Westwater Canyon Member of the Morrison Formation roughly coincides with the present form of the southern San Juan Basin, indicating downwarp prior to and during sedimentation.
	3b. Sediment-transport directions indicate a positive area to the south of the Cordilleran foreland margin.

Some parts of a process stage--either in the genetic concept or geologic base--may require justification or explanation that would clutter the presentation of the model. Thus, these explanatory statements should be listed in an appendix to the model and identified by the corresponding outline letter-number code such as IA2. This will also facilitate recall of explanatory notes if the model is computerized.

In assembling a model from the geologic base, incompleteness of the genetic history will commonly become evident. This, in turn, suggests that additional geologic data are required or that existing data have not been adequately interpreted. In this manner, the dynamic feedback loop is maintained between the two parts of the model, which can result in constant improvement of the model as new data and improved interpretations become available. The kinds of new data and research needed should be listed and discussed in the form of an epilogue at the conclusion of the model report. For deposits poorly understood, this epilogue may be the most important aspect of model building.

The initial provisional model will likely contain tens of parts to possibly a hundred or more parts, but only some of these will prove to be ultimately useful in its application. In other words, the model will require "fine-tuning" in order to be predictive. The next section addresses this aspect of our research on modeling for determining favorability, eventually leading to the end-use of estimating undiscovered uranium resources by extending available grade-tonnage data in control areas to unknown but similar areas quantitatively characterized as favorable.

FAVORABILITY EVALUATION

Application of the Model

Once constructed, a genetic-geologic model can be used in various ways to evaluate favorability. In the simplest case, the model can be used to evaluate a region in a purely subjective manner by arbitrarily deciding how well the region fits the model. One could go a step farther and subjectively assign relative weights to each part of the model and thereby derive a "perfect" score for a control area. Based on this score, an unexplored area could be similarly scored and evaluated. A formal system called "Prospector" (Duda and others, 1978) uses such a weighting scheme, and the genetic-geologic model could be "prospectorized". As part of our research, we have designed a different method called geologic-decision analysis that is based on a logical framework of questions that relate the factors that comprise each genetic-geologic model.

Questionnaire and the Logic Circuit

A particular genetic-geologic model is a tool for assessing the favorability of an area to contain uranium deposits of a certain grade and size--in essence, an estimate of the undiscovered uranium resources. To do this, we have devised a system of questions that correspond to the geologic base and genetic concepts of the model (the third column in the matrix shown in table 2). Answers to these questions provide a means of comparing test areas with a given control area. The questions are asked in a uniform manner so that they may be answered in the positive (+1), in the negative (-1), or as don't know (0). This ternary logic system is discussed in detail in Part II (McCammon, 1980). Questions that need to be answered by specifying some numerical quantity must be phrased to conform with the above scheme.

Examples of some questions asked that relate to the model part described above are shown in column 2 of table 4.

The geologic attributes and their corresponding questions from a model, such as exemplified in table 4, can be classified as (1) strictly necessary, (2) sufficient, or (3) indeterminate. Those questions for attributes necessary for the presence of a stage are multiplicative (in a logic sense) and are expressed in the generalized circuit by an "AND" relation (fig. 8). Those questions for attributes sufficient for the presence of a stage are additive (in a logic sense, not arithmetic) are expressed by an "OR" relation. The "NOT" relation is used to include relations for which absence is favorable and expressed either as a necessary or sufficient attribute. As an alternative, but perhaps awkward, a question can be asked in the negative, thus avoiding the use of the "NOT" relation. Attributes that are indeterminate as to whether they are either necessary or sufficient are treated separately outside of the circuit.

Applying this logic, we can construct a circuit as shown on figure 9 for the questions given in table 4. In determining favorable precursor conditions for this example, the questions are answered from the available data. In the "uranium province", "pre-host rock setting", and "basin development" parts, which are "OR" relations, only one positive (+1) answer is required to establish their favorability. In the "stable platform" part, which is an "AND" relation, a negative answer (-1) indicates an unfavorable platform condition. More complicated combinations of +1, -1, and 0 in a logic circuit are described in Part II of this open-file series (McCammon, 1980).

In order for precursor conditions to be favorable in the example shown on figure 9, the uranium province result must be affirmative as well as the three parts of the sedimentation framework. In a similar fashion, each of the other genetic process stages are assessed as to their favorability.

Table 4.--Application questions and required data for the precursor stage of the tabular humate-related uranium deposit model (after Granger and others, 1980) described in table 3

1a. Do regional basement rocks contain abnormally uraniferous zircon?	1a. Uranium analyses of zircons from basement rocks.
1b. Are crystalline basement rocks abnormally uraniferous.	1b. Uranium analyses of basement rocks.
1c. Do associated strata contain uranium deposits?	1c. Knowledge or location of uranium deposits in associated strata.
1d. Do lead-isotope analyses of the nearby basement rocks show loss of U?	1d. Lead-isotope analyses of nearby basement rocks.
2a. Are both marine and continental strata represented in the sequence beneath the host rock?	2a. Presence or absence of marine and continental sequence below host.
2b1. Is the host rock part of a red-bed sequence of rocks?	2b1. Presence/absence of red-bed sequence in host unit.
2b2. Is there evidence of a primary (early-diagenetic) red bed facies of the host unit?	2b2. Knowledge of primary red-bed facies in host unit.
2c1. Is the regional dip of the host rock $<5^{o}$?	2c1. Regional dip of host rock.
2c2. Is the regional dip of the underlying rocks $<5^{o}$?	2c2. Regional dip of underlying rocks.
3a1. Is there evidence of basin subsidence during Morrison sedimentation?	3a1. Evidence for subsidence during host-rock sedimentation.
3a2. Is the host rock within X kilometers of the southwestern erosional edge of the basin? (What is the shortest distance in kilometers of this deposit from the Dakota truncation of the Morrison?)	3a2. Distance from eroded edge of host rock.
3b1. Is there evidence of uplift of areas marginal to the Morrison depositional basin?	3b1. Evidence of uplift of nearest margin of basin.
3b2. Are average current directions in the host sandstone as shown by cross-beds, channel trends, lineations, or other features toward the north or east?	3b2. Direction of resultant current directions of host unit (cross-beds, lineation trends, channel trends, etc.).

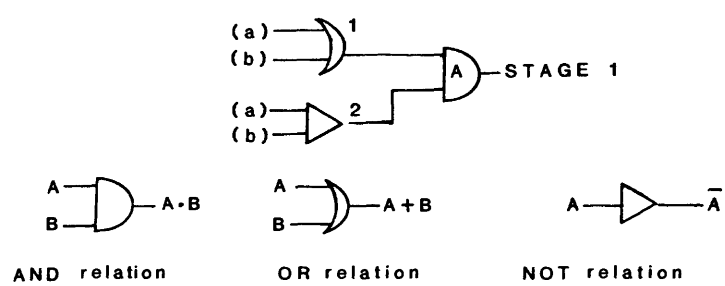

Figure 8.-General logic circuit elements and an
example of a general circuit.

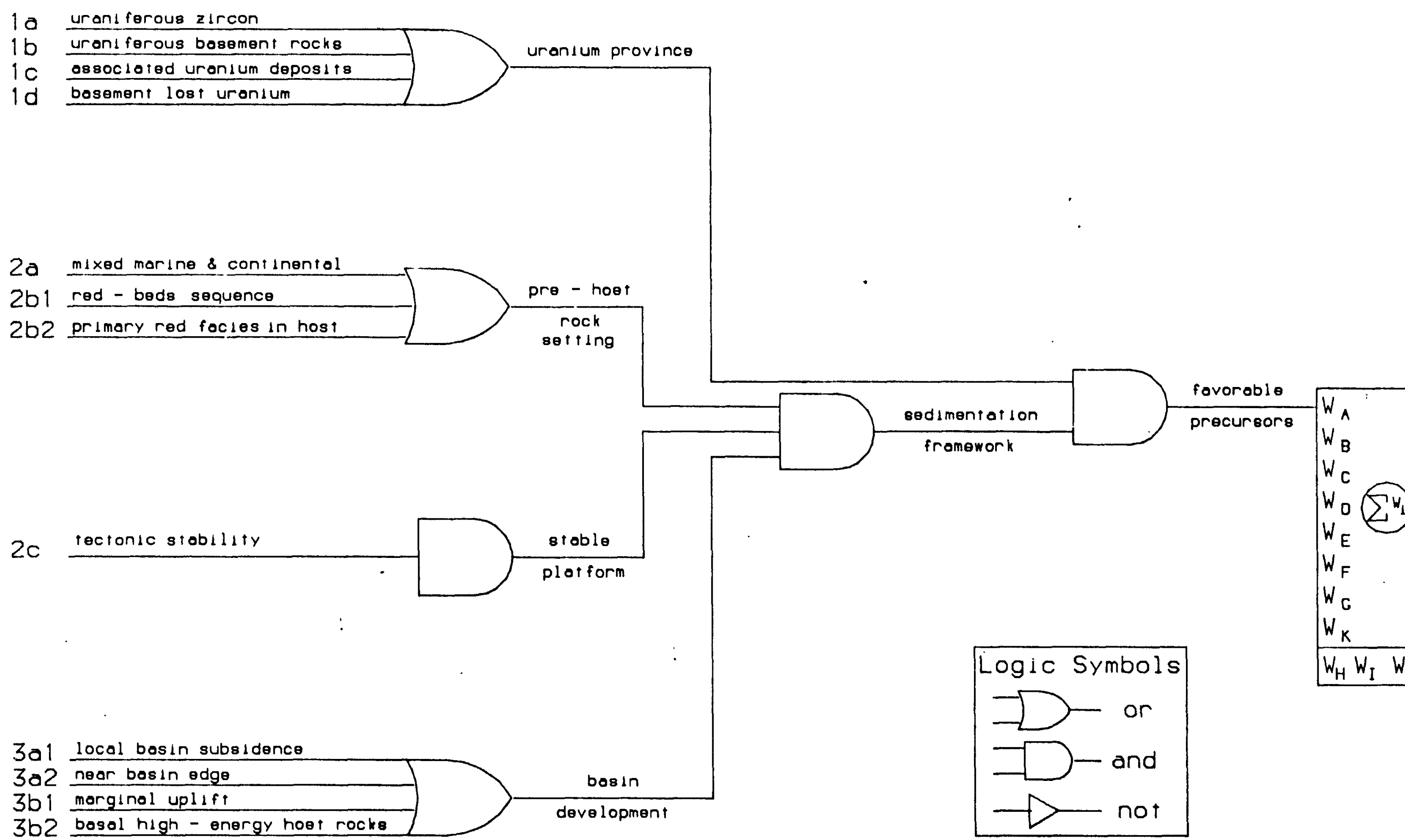

Figure 9

An example of a provisional logic circuit for precursor - process questions given in table 4

Geoscience Data Requirements

The data needed to answer each question posed for the model components can be identified opposite each question as indicated by column 4 in table 2 and as illustrated in table 4 for a part of a model. These data may be available from published reports and files of the user. Most data are referenced geographically, commonly by latitude and longitude and sometimes by altitude. Both surface and subsurface data are required, and their distribution and density will be uneven. Subsurface data by their very nature will be incomplete and mostly the application of a model will be restricted partly by the kinds and amount of subsurface data available. In order to extend the data base, the data may be contoured and thus interpolated between data points and extrapolated beyond by utilizing trends and other geologic principles. In many instances, use of the computer will facilitate this step. The limits to which data can be extrapolated should be reviewed by a knowledgeable geologist, and the areas beyond this limit should be excluded.

The types of data need to be grouped into like categories or sets to facilitate field and laboratory collection and computer use. Data sets fit broadly into the geological, geochemical, and geophysical groupings, but some overlap is apparent. Data sets are required for both a control or training area in which known uranium deposits occur and the test evaluation area.

Compilation of the data available will undoubtedly point to those areas where more data are needed. Moreover, for certain questions to be answered an extensive research program may be indicated, for example, isotopic age determinations.

Grade-tonnage Data Requirements

Essential to both determination of favorability, and eventually the estimates of undiscovered uranium resources, is a knowledge of the grade-tonnage relations among the deposits of the type being modeled. Such relations are poorly known because much of the data required to attain these relations is in the hands of private companies and in the confidential files of the U.S. Department of Energy. Some data were not collected or measured at the time of exploration and mining, such as for lower grade material, especially that below 0.05 percent U_3O_8. Furthermore, most of the available data are strongly influenced by economic factors and are for mining properties rather than for geologically outlined deposits. Nevertheless, there are some public data in a form which can be defined in general terms the grade-tonnage distributions of United States uranium deposits. These data are the basis for relating questions and process stages to uranium endowment.

Statistical Calibration of Questions and Circuits in Control Area

Many questions, especially those addressing a range in numerical data, will require the setting of the range of threshold values that correlate with favorable ground and its contained uranium deposits in the control area. This calibration is best done using statistics and a computer program. Examples of questions of this nature in the tabular humate-related uranium-deposit model include thickness of host rock units, and mudstone-sandstone ratios and the number of mudstone-sandstone alternations. Furthermore, the logical relations among attributes for particular process stages may have to be modified. Such modifications of attributes and their relations is anticipated and should result in more workable models.

The next step involves the determination of the weights given to the various stages of the model based on the known presence or absence of uranium, in the designated control area. Where deposits of different sizes and grades are geographically grouped, some parts of the model may prove to be more closely correlative with the larger and higher grade deposits. The method of calculating weights using geologic decision analysis is described in Part II (McCammon, 1980).

To provide a basis for estimating the uranium resources in the San Juan Basin, which has been divided into square cells 4 km on a side (figure 10), the Grants mineral belt has been selected as the control area and it has been divided into square cells 2 km on a side. The smaller size of cells in the control area is desirable because of the greater amount of exploration data available for the Grants mineral belt.

Application of Model to Test Area

The ultimate use of a model is to apply it to an unknown area. An unknown area can be adjacent to a known producing area or it may be located in a similar geologic setting far removed from a producing area. In testing for likely extensions of known producing area, only parts of the model generally will be used, whereas in frontier areas the complete model, will be required. This is particularly true for the precursor stage of a model, which is regional in nature and thus is of little use in extending known producing areas.

For our present stage of research, we plan to apply the tabular humate-related uranium-deposit model based on the Grants mineral belt as the control area to the unexplored parts of the San Juan Basin. Using weights derived for the control area based on the data collected mainly from subsurface samples,

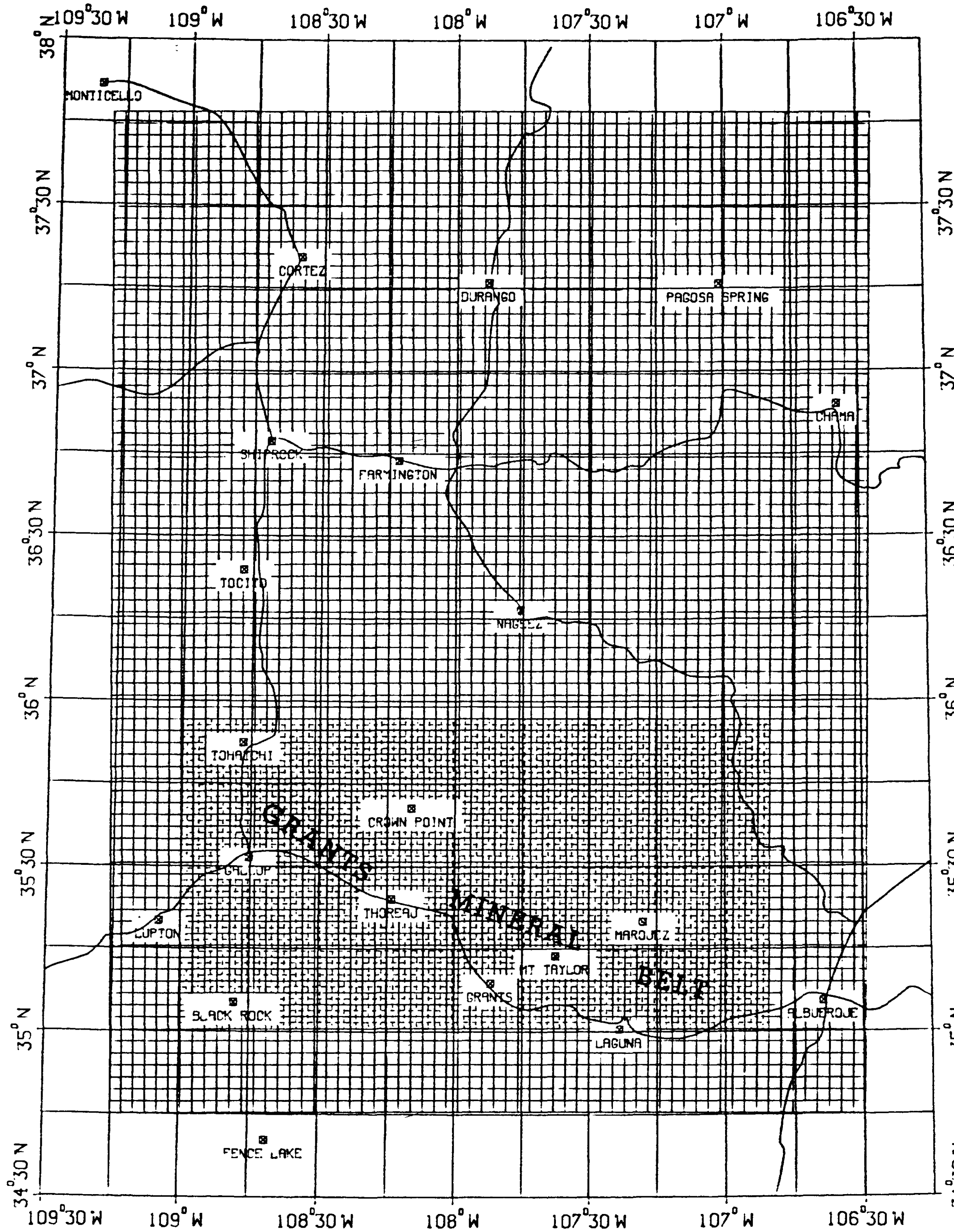

Figure 10.--The grid systems for the san Juan Basin study area. Large cells are 4-kilometers on a side; small cells in the Grants Mineral Belt area are 2-kilometers on a side.

the appropriate questions and the relations between then will be evaluated for each of the unexplored cells. Using geologic-decision analysis, favorability maps will be generated for each stage of the model. These maps will be combined into a composite map that will provide for the overall favorability of the unexplored part of the basin.

GEOLOGIC FAVORABILITY VERSUS PROBABILITY OF URANIUM OCCURRENCE

The presence of anomalous uranium is commonly used as an important favorability factor. Although the presence of uranium can be interpreted as demonstrating that the process of uranium concentration or mineralization has taken place, its mere presence, using such a philosophy, may negate more numerous and perhaps more important geologic indicators. For this reason, and because the high mobility of uranium may cause it to be distributed in anomalous concentrations far more widespread than in uranium mining districts, we have omitted the use of uranium and related direct evidence from the determination of geologic favorability.

Instead, the presence of uranium and related direct evidence of uranium are to be used to aid in the determination of probability of uranium deposits occurring in the area. If a given area is favorable but contains no known abnormal concentrations of uranium, the prior probability for finding uranium in any economic quantity in the area is low. However, if a large uranium anomaly is detected later by a airborne gamma-ray survey, the probability of uranium concentration is increased significantly but the geologic favorability remains unchanged. Some factors that may be useful in arriving at estimates of the probability of uranium occurrence are as follows:

Actual presences of uranium

A. Analytical test on rock samples

1. >0.001 percent U_3O_8

2. >0.01 percent U_3O_8

3. >0.1 percent U_3O_8

4. >1.0 percent U_3O_8

B. Mode of occurrence

1. Increased likelihood

a. Uranium mineral present

b. Prospect with no production

c. Mine with production

(1) <10 tons U_3O_8

(2) >10 tons U_3O_8

(3) >100 tons U_3O_8

(4) >1000 tons U_3O_8

(5) >10,000 tons U_3O_8

2. Decreased likelihood

a. Uranium only in scattered carbonaceous trash fragments, none disseminated in rock

b. Uranium as a substitute element only in non-uranium mineral, such as resistate minerals and uraniferous silicified bones

C. Number and extent of occurrences

D. Distance of area (cell) from known uranium deposits

1. Along extension of ore trend

2. Between known deposits

Indications of presence of uranium

A. Gamma-ray anomalies

1. Airborne radiometric

2. Ground

3. Drill hole

B. Radon anomaly

1. Soil gas

2. Ground water

C. Radium

1. Springs

2. Soil gas

3. Oil-field brine

D. Helium

1. Soil gas

2. Productive fields

3. Ground water

E. Uranium in water and soil

F. Presence of elements closely associated with uranium deposit

1. Thorium (can be either positive or negative)

2. Vanadium

3. Copper

4. Others (molybdenum, selenium, etc)

Adequate volume for significant tonnage

A. As a function of host-unit thickness

B. As related to structure

1. Sedimentary

2. Tectonic

Preservation (Should this process stage be left in favorability model?)

A. Primary deposits

B. Secondary deposits

How these various factors will be used in estimating the (prior, posterior, etc) probability of uranium occurrence is currently being investigated. Obviously the topic needs much thought and research. For the present study, a number of different approaches will be attempted. Perhaps questions can be posed to answer the presence or absence of each factor in a unit cell. A ratio between the test and control areas could be calculated. These ratios might be integrated statistically to give a range of probability for a favorable area.

EXTENSION OF FAVORABILITY TO ESTIMATING UNDISCOVERED URANIUM RESOURCES

From the overall favorability based on a particular genetic-geologic model, estimates of the undiscovered uranium resources in the area under study will be generated utilizing probabilities determined according to one or more schemes and a variety of grade-tonnage distributions. Thus, we expect that a range of resource estimates will be generated based on different assumptions. No single estimate should be regarded as the best estimate but rather, the range of estimates provided by the method is expected to span the true estimate.

CONCLUDING REMARKS

We have attempted to show that the genetic aspect of the genetic-geologic model is inseparable from the geologic evidence that supports it. Different models can likewise be related in the sense that the process stages of formation of a deposit in one environment may in part be similar to those of a deposit in a different environment. Study of these types of relationships between different models may result in the definition of environments not yet examined for uranium occurrences. Eventually, we hope that genetic-geologic modeling will lead to an acceptable genetic classification of uranium deposits.

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United States Department of the Interior

Geological Survey

RESEARCH ON URANIUM RESOURCE MODELS

A PROGRESS REPORT

PART II. GEOLOGIC DECISION ANALYSIS AND ITS APPLICATION TO GENETIC-GEOLOGIC MODELS

By

Richard B. McCammon

Open-File Report 80-2018-B

Work done in cooperation with the U.S. Department of Energy

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FIGURES

PREFACE

This report is Part II of a U.S. Geological Survey Open-File Report on the progress of research on methodology for assessing undiscovered uranium resources; this research is an effort to devise an alternate methodology for the U.S. Department of Energy. For more background on this research, the reader is referred to the Preface of Part I (Finch and others, 1980). Part I deals with the philosophy and guidelines for building an interactive matrix for relating the geologic characteristics of uranium deposits to the various processes that formed them. The matrix is called a genetic-geologic model. Each model is designed within a chronologic framework of events. It is used to evaluate the favorability of occurrence of a particular type of uranium deposit for a given set of data within a logical framework of a series of questions. The overriding goal of this approach is to reduce subjectivity in resource assessment. In order to integrate the favorability of occurrence based on genetic-geologic models with grade-tonnage data on known deposits and also to consider the prior probability of occurrence of one or more deposits in an area, a computer-based method has been devised--namely, geologic decision analysis, which is the topic of Part II, this report. As the initial test of the method, a prototype genetic-geologic model has been formulated for the tabular humate uranium deposits in the San Juan Basin, New Mexico. A description of the model is the topic of Part III (Granger and others, 1980) of this Open-File Report. Other models are being built.

Critiques of each part of the three open-file reports (see below) are solicited and should be mailed to the authors: U.S. Geological Survey, Mail Stop 916, P.O. Box 25046 Federal Center, Denver, CO 80225.

Part I--Genetic-genetic models--a systematic approach to evaluate geologic favorability for undiscovered uranium resources, by W. I. Finch, H. C. Granger, Robert Lupe, and R. B. McCammon.

Part II--Geologic decision analysis and its application to genetic-geologic models, by R. D. McCammon.

Part III--Genetic-geologic model for tabular humate-rated uranium deposits, San Juan Basin, New Mexico, by H. C. Granger, W. I. Finch, R. E. Thaden, and A. R. Kirk.

RESEARCH ON URANIUM RESOURCE MODELS

A PROGRESS REPORT

PART II GEOLOGIC DECISION ANALYSIS AND ITS APPLICATION TO GENETIC-GEOLOGIC MODELS

By Richard B. McCammon

ABSTRACT

Because economic uranium deposits occupy a volumetrically insignificant part of the rocks in which they are found, those who estimate potential uranium resources are primarily concerned with the factors that control their distribution. Geologic decision analysis has been devised as a method for integrating those factors defined for a particular genetic-geologic model for the purpose of determining the favorability of occurrence of undiscovered uranium deposits in untested or partially tested areas. Favorability is determined on the basis of the combined presence-absence of the attributes that compose a particular genetic-geologic model. By combining this favorability with grade-tonnage data for deposits in known uranium areas and using estimates of the prior probability of occurrence, one can estimate the undiscovered uranium resources in partially tested or unknown areas. With this approach, geologic reasoning is explicitly incorporated within the resource estimate. However, each step in the process can be modified independently; thus, multiple estimates can be made and the limits of uncertainty can be established for any particular genetic-geologic model.

INTRODUCTION

Perspective on uranium deposit occurrence

One of the few statements that can be made with confidence about uranium deposits is that they compose a volumetrically insignificant part of the rocks in which they are found. Granger and Warren (1978) stated, for instance, that in roll-type deposits, the width of ore-grade uranium (>0.1 percent U_3O_8) in a typical roll-front deposit is commonly less than 10 m. The oxidized tongue of the roll extends 10 km or more parallel to the direction of ground-water flow. Whereas a roll-front deposit can commonly be traced for several kilometers, the tongues of oxidized rock can have an areal extent of tens of square kilometers. Such oxidized tongues make up but a small fraction of the sedimentary basins in which they are found, and these basins commonly exceed several thousand square kilometers in area. All in all, a uranium deposit makes a difficult target.

Not surprisingly, considerable attention has been given to searching for indicators that effectively increase the size of targets offered by uranium deposits. Geologic factors that control the occurrence of uranium deposits ultimately should prove most valuable for assessing the undiscovered uranium resources in a region.

The basic situation is shown in figure 1. An ore body, (A/1000), occupies an insignificant fraction of an area, A, being evaluated. Surrounding the ore body is a larger area, (A/100), which could reflect a geochemical halo associated with the ore body. For a roll-type deposit, such an area is represented by the zone of pyrite redeposition. Recognizing this fact increases the size of the target and, therefore, increases the chances of discovery in exploration or increases the reliability of a resource estimate based on geologic evidence. Surrounding the area of mineraliztion is a larger area,

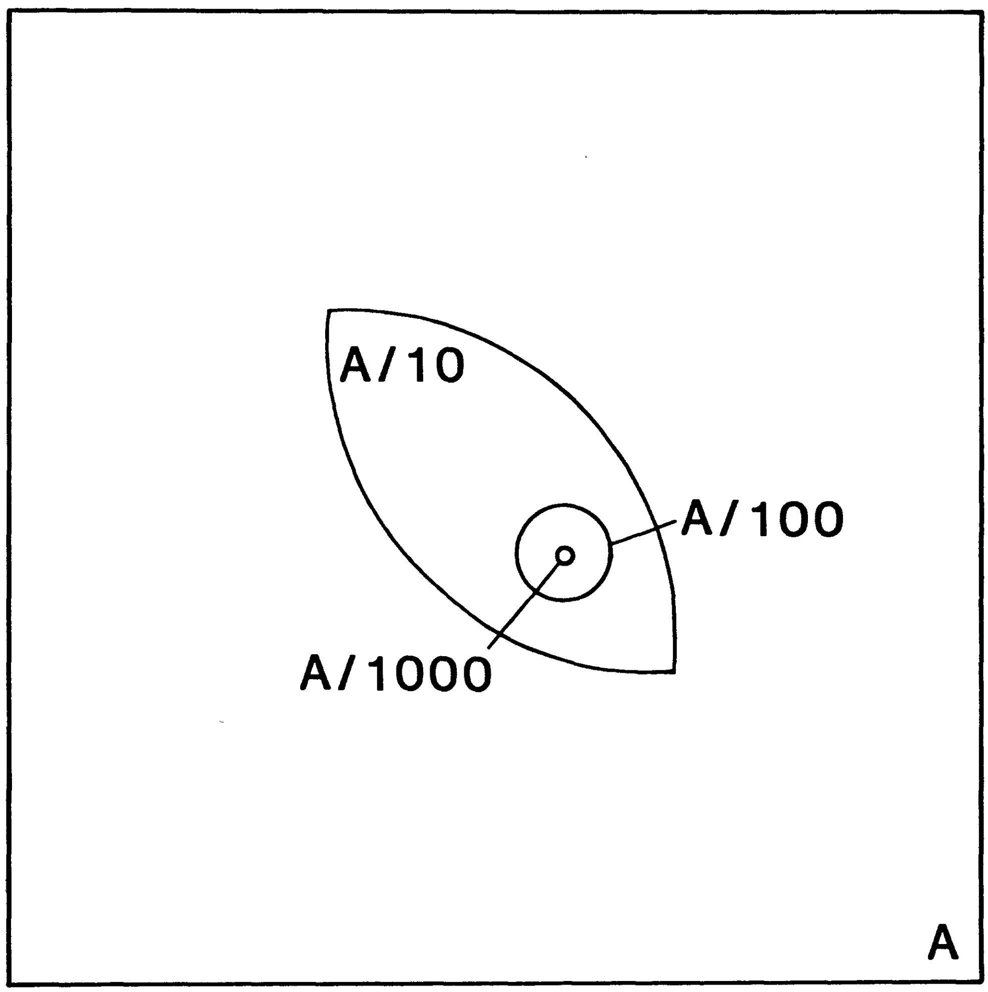


Figure 1.--Diagram which shows the partitioning of an area, A, which contains favorable area, (A/10), which contains favorable "target", (A/100), which contains concealed uranium ore body, (A/1000).

(A/10), which represents the favorable ground in which the deposit occurs. For a rolltype deposit this could include the area underlain by a porous, permeable, fluvial sandstone unit.

This type of reasoning justifies broad regional-scale, geologic mapping to identify, classify and delineate areas favorable for the occurrence of uranium deposits and justifies detailed geologic and geochemical investigations in and around uranium ore bodies to identify characteristics that reflect the proximity of these deposits. Because of the diverse types of data collected in such studies, a quantitative method must be devised to identify areas favorable for the occurrence of deposits and to estimate the undiscovered uranium resources, if any, in these areas.

Nature of the data

Mounting evidence suggests that much of the information collected in studies related to the occurrence of uranium deposits is important only in a qualitative sense. With respect to porosity, for example, one needs to determine only whether the rock can be characterized by a certain porosity or whether it lacks that porosity. With respect to rock alteration, one must determine ony whether the rock has been altered. These are two of many examples that could be given to illustrate that presence or absence is all that must be known about most geologic factors considered relevant for establishing the favorability of occurrence of a uranium deposit. Thus, recognition criteria for evaluating favorability can be established by reducing all data to a ternary form, that is, presence, absence, or unevaluated. The last category is important for borderline situations in which presence or absence is difficult to determine and for situations in which some parts of the data are missing. A ternary classification scheme does not imply that measurements of rock properties are irrelevant. On the contrary, the available data are critical in determing whether a particular attribute is judged as present or absent. For example, the concentration of a trace element in a rock sample could be considered as being indicative of the nearby presence of a deposit if the concentration exceeds some specified threshold value. Threshold values should not be considered as fixed quantities however. As more data are collected in an area, such threshold values are likely to be changed.

Once it is decided how the data are to be reduced to a ternary form, presence can be assigned the value, +1, absence, the value, -1, and unevaluated, the value, 0. This form of encoding the data is readily adapted to subsequent computer processing and is especially useful for handling large numbers of attributes.

Need for a model as predictor

In the ideal situation, the existence of a uranium deposit at depth at a location would be established on the basis of the combined presence-absence of a finite set of measured attributes. In addition, in the absence of their combined presence-absence, the presence of a deposit would be precluded. Such a set would be considered necessary and sufficient and would constitute perfect discrimination; that is, a deposit would not occur without the combined presence-absence of the set of attributes and correspondingly, it would always occur with the combined presence-absence. The closest to an ideal example of an attribute whose presence-absence is necessary and sufficient is the humate in the Grants Mineral Belt, New Mexico; the humate is authigenic carbonaceous matter contained in a sandstone host rock.

It is more realistic to assume, however, that the combined presence-absence of a set of attributes at a location is more likely only to favor the presence of a uranium deposit rather than to locate a deposit. Thus, if an altered, porous, permeable, low-dipping sandstone body is identified at the outcrop, this would be interpreted as being highly favorable for the presence of a roll-type uranium deposit downdip. There is no certainty of the presence of a uranium deposit attached to the observation; for instance, the presumed downdip roll-front, even if it exists, may be barren of uranium. Conversely, an unaltered, nonporous, impermeable, steeply dipping sandstone body would be interpreted as being unfavorable for the presence of a roll-type uranium deposit downdip. However, the pesence of the sandstone does not preclude the possibility that downdip, due to faulting, facies change, or some other condition, an uranium deposit of some other type may be indeed present.

At present, we do not know of any single attribute or set of attributes whose combined presence-absence is necessary and sufficient for establishing the presence of a uranium deposit. Therefore a logical framework is needed for inferring, from the combined presence-absence of a critical number of attributes, the likelihood of occurrence of a particular uranium deposit-type. Such a framework has been embodied in the concepts of the genetic-geologic model, which was described in Part I (Finch and others, 1980) of this Open-File Report.

Definition of a logical framework

Because our knowledge of uranium deposits is incomplete, an uncertainty is necessarily inherent in any form of logical relationships we may propose with respect to a particular genetic-geologic model. Even in areas where uranium deposits occur and large amounts of information have been collected, we are not yet able to construct a logical framework that is consistent with all the data. Two-hundred-foot offsets in the process of drilling are still common in the Grants Mineral Belt in the search for deposits within favorable ground. Thus, the interactions among the geologic factors that control the occurrence of deposits are unknown in any quantitative sense, and this lack of knowledge precludes any meaningful parametric approach.

Despite these limitations, the probable qualitative interactions among geologic factors that govern the distribution of uranium deposits can be stated. In particular, these interactions can be expressed as logical functions. A set of logical functions translates a particular genetic-geologic model into a form that can be evaluated for a given set of data. A given logical function can take on the values true (presence), false (absence), or neither true nor false (unevaluated).

A defined set of logical functions can be used to evaluate a particular genetic-geologic model. The combined presence-absence of the selected attributes of the model are the arguments of the set of functions. To evaluate the model, one must first establish the relative importance or the weights to be assigned to the relationships defined by a given logical framework. The relative importance of the relations considered critical for the occurrence of uranium deposits is based on the statistical correlation of the logical functions observed in areas where the deposits occur -- the control areas. The weights are derived from these correlations.

The favorability for a particular genetic-geologic model is expressed in the form of a weighted linear function that takes on continuous values ranging from +1, which, for a given set of data, indicates a perfect match with the model, to -1, which indicates a perfect mismatch with the model. Intermediate values between +1 and -1 indicate the degree of match or mismatch. A value of zero is interpreted as meaning that the information provided indicates neither a match nor a mismatch.

THE LOGIC OF FAVORABILITY

Nature of inference from attributes

An expression of favorability for uranium can be interpreted as a function of a set of attributes whose combined presence-absence is associated with the known occurrences of the type deposit being modeled. Each attribute can be considered as a variable which, in its simplest form, is considered to be present or absent at a given location (in addition, it can be neither present nor absent and this possibility is considered below). Critical attributes of a genetic-geologic model are selected (or rejected) on the basis of their observed presence-absence relationships to deposits in control areas. To understand the basis for selection, it is easiest to consider the selection of a single attribute and its relationship to the deposits in an area.

Within a control region, R, the set of locations in which discovered and undiscovered uranium deposits of a particular type occur can be represented as a target, T, as shown in figure 2. T/R represents the probability that a deposit will be discovered by chance. This occurrence (O) probability P is given by Pr(O) = T/R = P.

We are interested in increasing our knowledge of the occurrence probability on the basis of the observed presence-absence of selected attributes. Ideally, we wish to identify an attribute that is always associated only with uranium deposits of the type sought (fig. 3). In this situation, the attribute A is present if and only if a deposit is present. Its presence, therefore, is a necessary and sufficient condition. Consequently, information about the presence or absence of such an attribute, A, results in information on the presence or absence (occurrence or non-occurrence) of a uranium deposit. We express this as a statement of conditional probability in the form

$$Pr(O/A) = 1$$

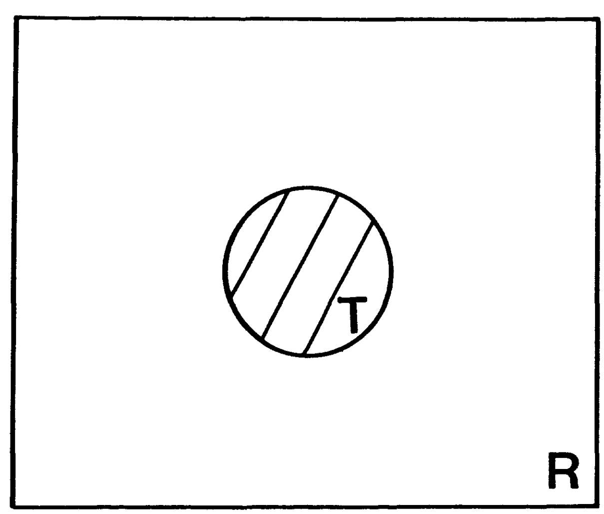


Figure 2.--Diagram which shows a set of locations T within region R which contains uranium deposits.

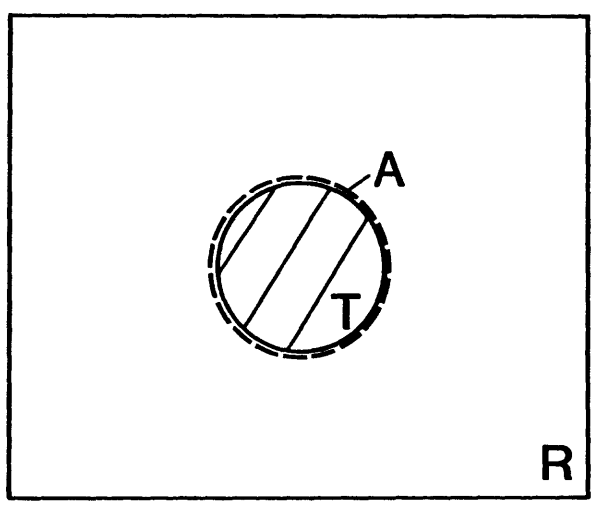


Figure 3.--Diagram which shows a set of locations within R in which the presence of attribute A and uranium deposits T coincide.

Such an attribute is a perfect discriminator and constitutes a perfect guide to uranium deposits. Although we seek attributes that are perfect discriminators, we realize that because of the complexity of the geologic processes and their uncertain relative influences on the actual location of each individual deposit, such attributes are as rare as the deposit itself. Thus, in figure 3, we see that

$$Pr(A/O) = Pr(O/A).$$

In the Grants Mineral Belt, a candidate for the ideal discriminator of primary uranium deposits in the Morrison Formation is the presence of the carbonaceous matter, humate. Unfortunately, humate cannot be detected by indirect methods; hence, its presence is of limited value for exploration.

Next is the situation in which a deposit occurs if the attribute is present, as shown in figure 4. Thus, the presence of the attribute is a sufficient but not a necessary condition. An example of such an attribute would be a particular trace element such as molybdenum whose presence was restricted within a zoned part of an ore body. Such an attribute would not produce a false-positive in terms of occurrence of an deposit. It could happen, however, that a deposit occurs without such an attribute being present so that

$$Pr(A/O) < Pr(O/A) = 1$$

Next, a deposit may occur only if a particular attribute is present, for example, the presence of a favorable host rock (fig. 5). Clearly, not all rock bodies having favorable host characteristics contain economic deposits, but without a host, a deposit cannot occur. Such an attribute is, therefore, a necessary but not a sufficient condition. In this situation,

$$Pr(O/A) < Pr(A/O) = 1.$$

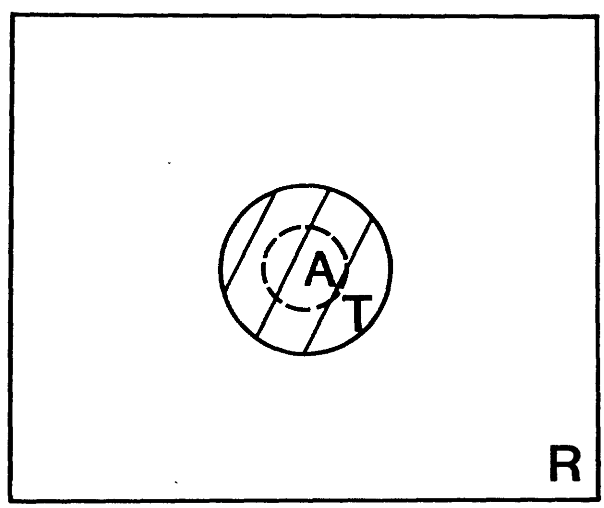


Figure 4.--Diagram which shows a set of locations T within R in which uranium deposits occur if attribute A is present.

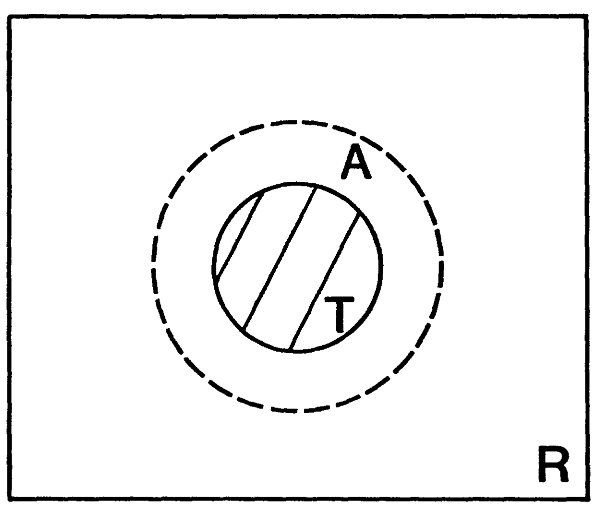


Figure 5.--Diagram which shows a set of locations T within R in which uranium deposits occur only if attribute A is present.

The most typical situation for a given geologic attribute is that not only is it present for some deposits and absent from others, but also it is present when in fact no deposit occurs. An example of such an attribute for sandstone-type uranium deposits is the sandstone-mudstone ratio within a selected range of ratio values for the host sandstone. Such an attribute is considered to be a favorable indicator of a uranium deposit if it is associated more often with the occurrence of a deposit than with a non-occurrence as shown in figure 6. In this situation,

$$Pr(O/A) > Pr(\bar{O}/A)$$

where $\bar{O}$ represents the non-occurrence of a deposit.

Clearly, we wish to identify those attributes for which $Pr(O/A)$ is large relative to $Pr(\bar{O}/A)$. The latter is the error committed in inferring from the presence of the attribute, A, that a deposit exists. Similarly, in the absence of attribute, A, we wish to make $Pr(\bar{O}/\bar{A})$ large relative to $Pr(O/\bar{A})$. The latter is the error committed in inferring from the absence of the attribute, A, that a deposit does not exist. Clearly we would like to select the attribute, A, such that both errors are as small as possible.

A ternary logic

Our present knowledge of the geology of uranium deposits indicates that the presence or absence of a single attribute at a location is inadequate for establishing the presence or absence of a uranium deposit. Some combination of presence and absence for several attributes, however, should provide a measure of the likely presence or absence of a deposit. We need to establish which combinations of attributes are positively or negatively associated with the occurrences of deposits. In addition, we need to allow for the

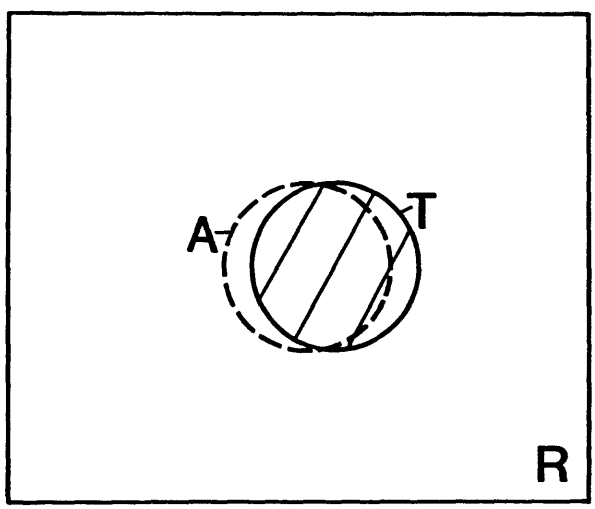


Figure 6.--Diagram which shows a set of locations T within R in which uranium deposits are more closely associated with the presence of attribute A than with its absence.

situation in which presence or absence cannot be determined; hence, we need to define a "don't know" condition. For the above reasons, we need to establish rules for ascertaining the state of specified combinations of attributes. Such rules are based on a ternary logic.

We begin with the assumption that each attribute at a location can be assigned a state of presence, absence, or unevaluated. We associate the values +1, -1 or 0, respectively, with these three states. If we then combine a set of attributes according to a specified logical relation for a given genetic-geologic model, we can define the state of the combined set of attributes as presence, absence, or unevaluated and can associate with the combined attribute set, the values +1, -1, or 0.

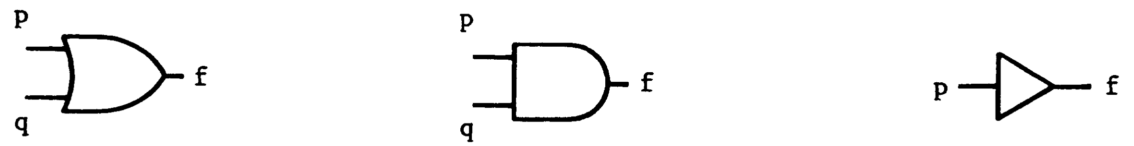
The states of possible logical combinations of attributes can be expressed as a table. In a ternary logic system, we can describe the state of any logical combination of attributes P and q by use of the following table:

p	q	p or q	p and q	not p
1	1	1	1	-1
1	0	1	0	-1
1	-1	1	-1	-1
0	1	1	0	0
0	0	0	0	0
0	-1	0	-1	0
-1	1	1	-1	1
-1	0	0	-1	1
-1	-1	-1	-1	1

The functional values of p, q, p or q, p and q, and not p are shown under the appropriate headings for all possible states of p and q. The logical connectives "or", "and", and "not", constitute the three basic logical operations. Once these relationships are defined, the functional value of any compound logical expression involving more than two attributes, a, b, c, for instance, can be evaluated, as for example, (a or b) and (not c).

Logic circuit

The interactions among the different geologic attributes associated with either the occurrence on non-occurrence of uranium deposits are of most interest. Such interactions can be expressed as the combined presence-absence of a chosen set of attributes for a given genetic-geologic model. In terms of combining attributes, we can specify the following as the basic elements of any logic circuit:



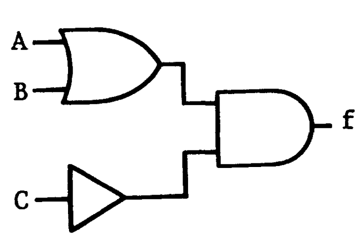
<u>or</u>	<u>and</u>	<u>not</u>
$f = p + q$	$f = p \cdot q$	$f = \bar{p}$

The above equations provide a shorthand expression for each of these relationships. The "+" sign refers to the logical "or" relation, the "·" sign refers to the logical "and" relation, and the "–" sign refers to the logical "not" relation. It must be remembered that "+" and "·" are logical operators rather than arithmetic operators.

When we combine groups of attributes, we must specify the logical operators. For example, we can consider the relation f among three attributes A, B, and C defined by the following expression:

$$f = (A + B)\,\bar{C}$$

such a relationship is represented by the following logic circuit:



Thus, for different presence-absence values of A, B and C (that is, their observed states of +1, -1, or 0), we obtain a different result for f. For instance, if attributes A and B represent two related textural properties of a sandstone body, the presence of either of which is considered favorable for the occurrence of a uranium deposit, and if attribute C represents a third textural property independent of A and B, the presence of which is considered unfavorable, f can be considered a host rock textural factor that takes on the value 1 if and only if A or B or both are present and C is absent.

In general, attributes A, B, C, D, E, and so forth will compose the ith stage of a particular genetic-geologic model factor defined by:

$$f_i = g(A, B, C, D, E, \dots)$$

where g represents a function such that the process stage represented by factor f_i takes on the value of +1 if all the conditions implied by the factor are met.

Favorability function

A favorability function (f) is defined as a weighted linear combination of factors, f_i, each of which contributes information about the presence or absence of a uranium deposit of a given genetic-geologic model. For a model involving n factors, we can write

$$f = a_1 f_1 + a_2 f_2 + \dots + a_n f_n .$$

Each factor, f_i, represents a stage of the model. A factor can be represented either by a single attribute or by a combination of attributes. In either case, each factor, f_i, takes on the values, +1, -1, or 0, depending on the combined presence-absence-don't know states of the chosen set of attributes.

For a given set of f_i's defined by a particular genetic-geologic model, which can be evaluated for a set of geographically defined cells within a selected control area, one can determine the weights, a_i's, that characterize the model best in a statistical sense. The weights are calculated in such a way that the measured f for each cell matches as nearly as possible the corresponding f_i's for that cell.

If we consider f and the f_i's as vectors where the components of the vectors are the individual values of f and f_i's observed in each geographic cell of a selected control area, a measure of the similarity between f and any given f_i can be expressed as the scalar product $f'f_i$ where f' is the transpose of f (the transpose means that each column vector becomes a row vector). In order that the scalar product $f'f_i$ be bounded, we divide the product by $f'f$ and obtain

$$f'f_i/f'f$$

as a scaled product. The greater the similarity between f and f_i, the more closely the value of the scaled product approaches 1. For n factors, the overall measure of similarity is given by

$$\sum_{i=1}^{n} f'f_i/f'f.$$

We wish to calculate the set of weights, a_i, $i=1, \ldots, n$, such that the above expression is a maximum. This calculation is made by solving the linear systems of equations given by

$$F'F\,A = \lambda A$$

where F is the matrix composed of the vectors f_i; A is the eigenvector associated with the largest eigenvalue, λ, of the matrix $F'F$.

Thus, for a given control area, the weights, a_i's, reflect the relative importance of the f_i's with respect to the interactions among the f_i's. The higher the value of a_i, the greater is the relative importance of the corresponding f_i.

In order that f be bounded above by the value, +1, and below by the value, -1, each a_i is divided by the sum of the absolute values of the a_i's so that the final form of the equation is given by

$$f = a_1'f_1 + a_2'f_2 + \ldots . \; a_n'f_n \qquad -1 \leq f \leq 1$$

where

$$a_i' = a_i / \sum_{i=1}^{n} |a_i| .$$

The value of f can be considered as the measure of the favorability of a region cell with respect to matching a particular genetic-geologic model. A favorability of one is interpreted to indicate as meaning that the observed attributes for the region cell possess all the favorable qualities of the model. Values less than one are interpreted to indicate that the cell possesses some but not all the favorable qualities of the model and hence, that the cell has a less chance of containing a deposit of the type described by the model. The equation can be used for a set of similar size geographic cells in an unknown area to generate a spatially continuous measure of favorability, that is, a map of the relative chance of occurrence of one or more deposits in each of the cells considered.

RESOURCE ASSESSMENT

Construction of favorability function

A favorability function unfortunately cannot be constructed directly. Many steps involved, for instance, are dependent on the present state of knowledge among geologists, and such a state is not always universally acknowledged. In constructing a logic circuit, the geologist may often have several changes of mind about the arrangement of the logic elements. The construction of logic circuits is a trial and error process, and, consequently, intermediate steps in the process must be evaluated.

The process of formulating a favorability function follows more or less the steps outlined in figure 7. The data are prepared in the form of a series of maps, in which each map depicts the spatial distribution of a particular attribute shown in Step A. In many maps, the attribute will represent the response (presence, absence, don't know) to a question included as part of a particular genetic-geologic model question set. Thus, for areas in which humate related type uranium deposits may occur, the attributes will contain information on such factors as precursor conditions, host-rock formation, source of uranium, or preservation. Such information may be represented by a particular mudstone/sandstone ratio, alteration, trace-element concentration, and so forth. In the event that an observed attribute has not been transformed into ternary form by prior assignment, such a transformation and subsequently, the gridding of the data is performed in step B. For most attributes, the data are gridded so that each region cell in the grid contains at least one control point, that is, a location at which data have been collected.

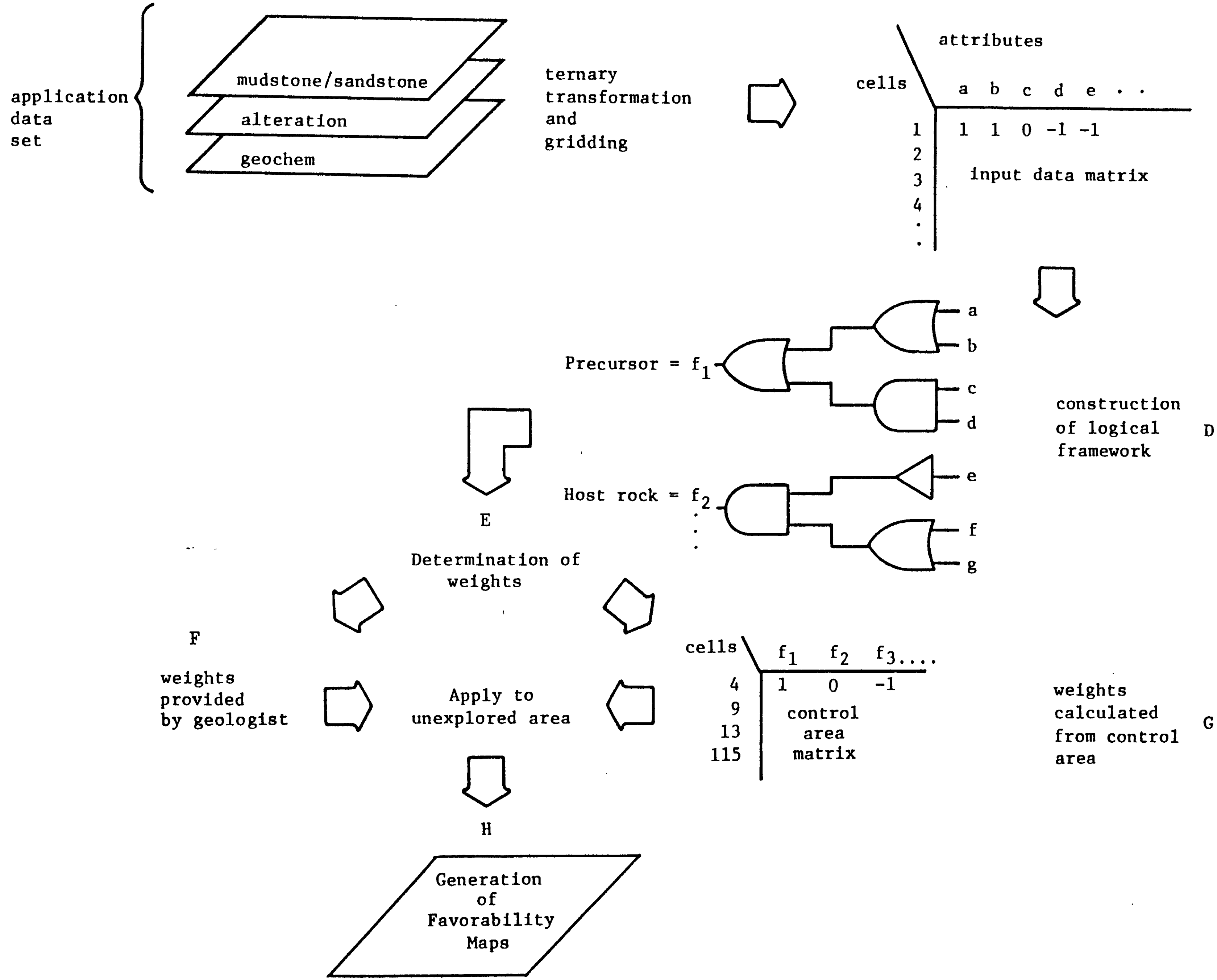


Figure 7.--Flowchart showing steps for generating favorability maps

The transformed data are arranged in the form of a matrix in which the rows refer to region cells and the columns refer to attributes (step C). In an area in which the potential uranium resource is to be evaluated, the matrix may consist of a thousand or more rows (cells) and a hundred or more columns (attributes). The matrix serves as the input to a computer program that facilitates the evaluation of the favorability function.

As discussed previously, the geologist usually has formulated prior judgements concerning the attributes that combine to form factors that are part of any genetic-geologic model. Moreover, the geologist may even have determined how the different attributes should be combined into process stages. In such cases, the logical combinations of attributes that form the different factors in a genetic-geologic model can be specified directly (step D). In the event that the geologist may wish to explore the relationships among the various attributes in a control area, computer-generated maps can be prepared to depict the spatial distribution of factors that are logical combinations of selected attributes. If a control area contains known uranium deposits that can be characterized by a particular genetic-geologic model, the presence (or absence) of such factors can be related to the presence (or absence) of these deposits. Such relationships assist in the identification and selection of factors that compose a model.

Once the factors in a genetic-geologic model have been specified, the next step E is to determine the relative contribution or weight of each factor in the model. The weights can be determined in two ways. One way is for the geologist to specify the weights directly (step F). For instance, the geologist can specify that the source-of-uranium factor contributes 20 percent to the overall favorability of occurrence of a roll-front type uranium deposit. The other weights could be specified in a similar manner. The second way (step G), and the way which is preferred, is when the geologist identifies areas in which statistical comparisons can be made between the occurrence or non-occurrence of deposits and the presence or absence of geologic factors of the particular model. Such areas are treated as control areas, and region cells within these areas are called model cells. Once a control area is selected, the weights associated with each factor of the model are calculated according to the method outlined in the previous section. The weights obtained for each model are used in evaluating the favorability of region cells outside the control area.

Conversion of favorability to probability of occurrence

The favorability with respect to a particular genetic-geologic model for a particular unexplored area does not equal the probability of occurrence of a deposit. The reason is that the proposed models are not perfect discriminators of the factors that control the occurrence of deposits. Even if a region cell possesses all the attributes of a model the probability of occurrence of a deposit is not necessarily one. Similarly, if a region cell possesses none of the attributes of a model, the probability of occurrence of a deposit is not necessarily zero. Consequently, the favorability does not equal the probability.

In an ideal situation, the conversion of favorability to probability could be accomplished by analogy by relating the occurrence or non-occurrence of deposits in areas that have been essentially drilled out to the measures of favorability determined by the method described in this report. Thus, if such an area were to be divided into region cells and if the favorability were to be determined for each cell, one could count the number of cells in which one or more deposits occurred for which the favorability fell within a given range. On this basis, favorability could be converted to probability by counting the number of cells having nonoverlapping ranges and dividing by the total number of cells.

Such detailed data from control areas are not always available, and consequently, an alternate approach is proposed. The geologists' best estimates for the probabilities of occurrence of one or more deposits, given that a region cell possesses all the attributes of a particular model or none of the attributes, can be compared with a subjective estimate of the probability of occurrence of one or more uranium deposits.

The relationship between favorability and the probability of occurrence of a particular type of deposit can be expressed as

$$F = \begin{cases} \dfrac{P - Po}{P_1 - P_o} & P_o \leq P < P_1 \\[2ex] \dfrac{P - P_o}{P_o - P_{\bar{1}}} & P_{\bar{1}} < P < P_o \end{cases}$$

where F is the favorability and P-, P_o, and P_1 are probabilities. P_1 is the probability of occurrence when F = 1 and all the attributes of a model are present. $P_{\bar{1}}$ is the probability of occurrence when F = -1, and none of the attributes of a model are present. P_o represents the probability of occurrence when F = 0, and information about the attributes of a model is missing or else the combined presence-absence of the attributes yields ambivalent results; if the combined presence-absence of attributes yields ambivalent results, the probability is based on nonmodel evidence for the presence of uranium.

The relationship between favorability and probability is shown in figure 8. Even if all the attributes of a model are observed, the probability of occurrence is estimated at being less than one. Similarly, even if none of the

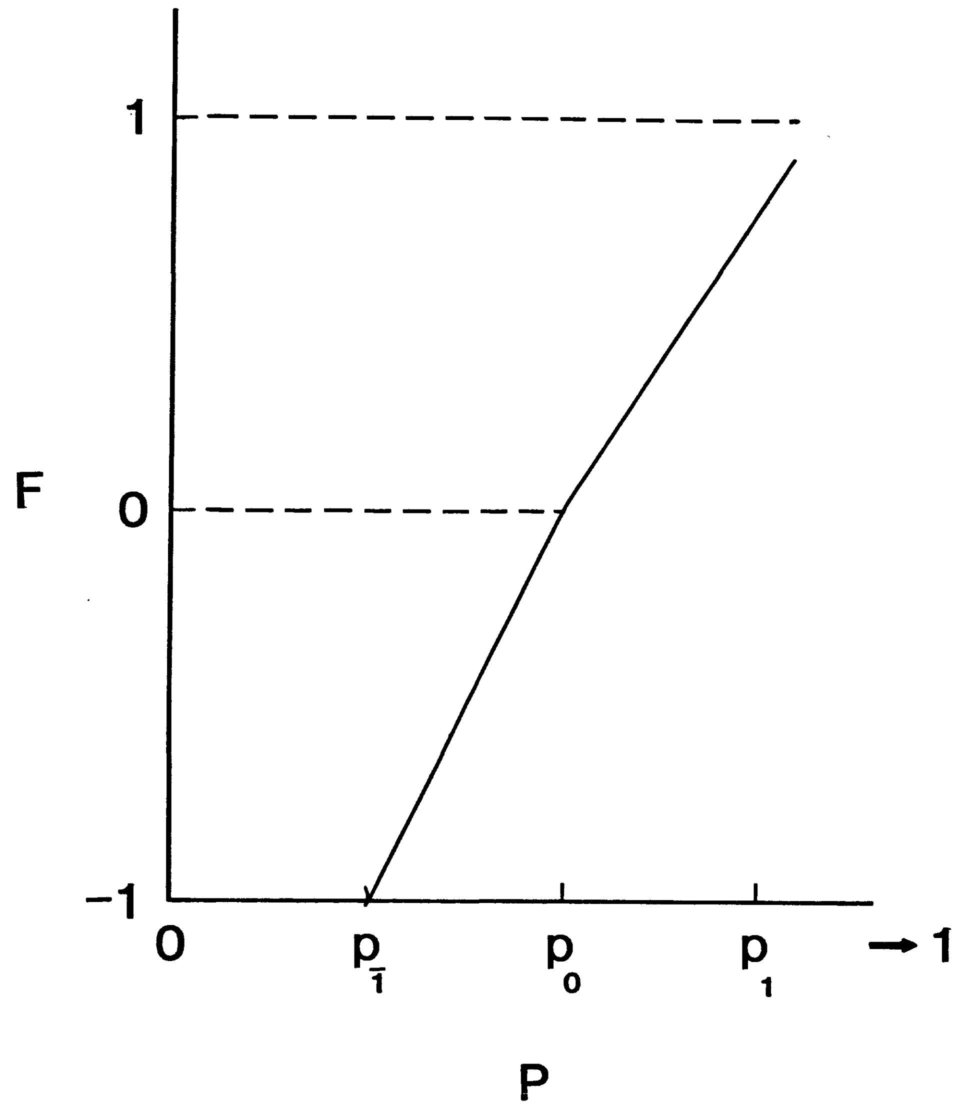


Figure 8.--Graph which shows relationship between favorability (F) and probability of occurrence (P).

attributes are observed, the probability of occurrence can be estimated as being greater than zero. Should information on the attributes of a model be either lacking or contradictory, that is, F = 0, the probability of occurrence could be non-zero and would be estimated from the available evidence for the presence of uranium.

Given estimates for P_1, P_T, and P_o and given that the favorability, F, has been determined within a region cell, the probability of occurrence of one or more deposits within the cell is given by

$$P = \begin{cases} P_o + F(P_1 - P_o) & F \geq 0 \\ P_o + F(P_o - P_T) & F < 0 \end{cases}$$

As more geologic information becomes available, the estimates for P_1, P_T, and P_o will change, and therefore the probability of occurrence within any given region cell should not be regarded as some fixed value.

Undiscovered resource estimates

Once favorability and probability have been determined, the potential uranium resources within an area can be estimated. Information on grade and tonnage of known deposits in control areas is used to estimate undiscovered resources in partially tested and untested areas. Because the probability of occurrence is determined at a region-cell level, grade and tonnage of deposits likewise need to be aggregated at the region-cell level. Thus, for an appropriately selected set of region cells within a control area, an average grade and tonnage can be estimated along with the distributions of the values for grade and tonnage. The averages for grade and tonnage represent the endowment of the particular genetic-geologic model identified for the control area, and the distributions of the values of grade and tonnage represent the range of values likely to be encountered outside the control area in areas judged to be similar.

Once the grade and tonnage of each genetic-geologic model have been established at the region-cell level, the potential uranium resources of a given region cell in which the probability of occurrence of one or more deposits has been evaluated for an appropriate genetic-geologic model can be estimated by multiplying the probability of occurrence by the product of the average grade and average tonnage of the model. The potential resources of a larger area can be determined as the sum of the potential resources of region cells contained within the larger area.

To provide a measure of the uncertainty in the estimates, the probability of occurrence can be combined with the distributions of the grade and tonnage of a genetic-geologic model by use of methods described recently by Ford and McLaren (1980). These methods produce a range of potential resource estimates having varying likelihoods of being correct.

SUMMARY

Geologic decision analysis has been described in this report as a proposed method for estimating the potential uranium resources in areas where observed geologic characteristics can be compared with those in areas where the uranium resources are known. Although it is still being researched, the method integrates geologic data within a logical framework of genetic-geologic models. The general steps involved in the application of geologic decision analysis consist of constructing a favorability function, converting favorability to probability of occurrence of a deposit, and combining probability of occurrence with the expected grade and tonnage of a deposit. Each of the steps represents an identifiable component of the resource estimation process and, though each step is an integral part, each can be audited independently. This independence of each step gives a greater sense of credibility to the final resource estimate. Should geologic decision analysis prove successful for the test areas currently being evaluated, it will provide a non-subjective, quantitative approach to resource estimation for the future.

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UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Research on Uranium Resource Models

A Progress Report

PART III - GENETIC-GEOLOGIC MODEL FOR TABULAR HUMATE URANIUM DEPOSITS, GRANTS MINERAL BELT, SAN JUAN BASIN, NEW MEXICO

By

Harry C. Granger, Warren I. Finch, Allan R. Kirk,

and Robert E. Thaden

Open-File Report

80-2018-C

Work done in cooperation with the U.S. Department of Energy.

Contents

Illustrations

Tables

PREFACE

This report is part III of a series of reports on the progress of research on methodology for assessing undiscovered uranium resources, an effort funded for the most part by the U.S. Department of Energy to develop alternative assessment methods. The overriding goal of this research is to reduce subjectivity in the procedure for resource assessment. For more background on this research the reader is referred to the Preface of Part I (Finch and others, 1980). Part I deals with the philosophy and guidelines for building an interactive matrix of genetic processes related to uranium deposition and their corresponding geologic evidences. This matrix is called a genetic-geologic model. These models are formatted in a chronological fashion that facilitates a logical framework circuit to utilize data to evaluate favorability for uranium deposits of the type modeled. The first genetic-geologic model to be built as a prototype along the guidelines set forth in Part I is the subject of the present report--Part III. The tabular humate-related uranium deposits of the San Juan Basin, New Mexico are the best known of our domestic deposits so that they are ideal to develop and test the model-building principles.

In order to use the models and accompanying logic circuits to determine favorability and to integrate this favorability with grade-tonnage data on the deposits and with prior probability of occurrence of one or more deposits, a single basic computer-oriented system was developed--namely, geologic-decision analysis, which is the topic of Part II (McCammon, 1980). The geologic-decision analysis method will be used on the tabular humate-related uranium deposit model for further work on uranium-resource models for resource assessment.

Critiques of each part of the three open-file reports (see below) are solicited and should be mailed to the authors: U.S. Geological Survey, Mail Stop 916, P.O. Box 25046 Federal Center, Denver, CO 80225.

Part I--Genetic-genetic models--a systematic approach to evaluate geologic favorability for undiscovered uranium resources, by W. I. Finch, H. C. Granger, Robert Lupe, and R. B. McCammon.

Part II--Geologic decision analysis and its application to genetic-geologic models, by R. D. McCammon.

Part III--Genetic-geologic model for tabular humate-rated uranium deposits, San Juan Basin, New Mexico, by H. C. Granger, W. I. Finch, R. E. Thaden, and A. R. Kirk.

Genetic-geologic Model for Tabular Humate Uranium Deposits, Grants Mineral Belt, San Juan Basin, New Mexico

INTRODUCTION

The tabular humate uranium deposits occur only in the Westwater Canyon Member and the Poison Canyon and Jackpile sandstones, two economic units, of the Brushy Basin Member of the Morrison Formation of Late Jurassic age in the Grants mineral belt in the southern part of the San Juan Basin (fig. 1). These deposits represent one of the most important subtypes of the so-called sandstone-type uranium deposits. Within the San Juan Basin, uranium deposits are also found in the sandstones in other members of the Morrison and in the Todilto Limestone also of Late Jurassic age. The tabular humate uranium-deposit model, however, applies specifically to the primary deposits in sandstones of the Westwater Canyon and Brushy Basin (including the Jackpile sandstone) Members of the Morrison Formation and only in part to roll-type deposits or other varieties of uranium deposits in these rocks and in older and younger formations.

This exercise was initiated on the premise that the greater the information available about the genesis and geologic setting of a given deposit or group of deposits, the better should be our ability to estimate their resource endowment. We have adhered to this fundamental premise throughout our study. Data that may seem unrelated to ore deposition have been included in the belief that excluding them at this stage would violate the premise. The model, therefore, contains data and questions that may appear to be immature and superfluous to the task of resource assessment. We hope that subsequent statistical treatment will help to cull out those data that are, indeed, unnecessary without relying on the subjective judgment of a

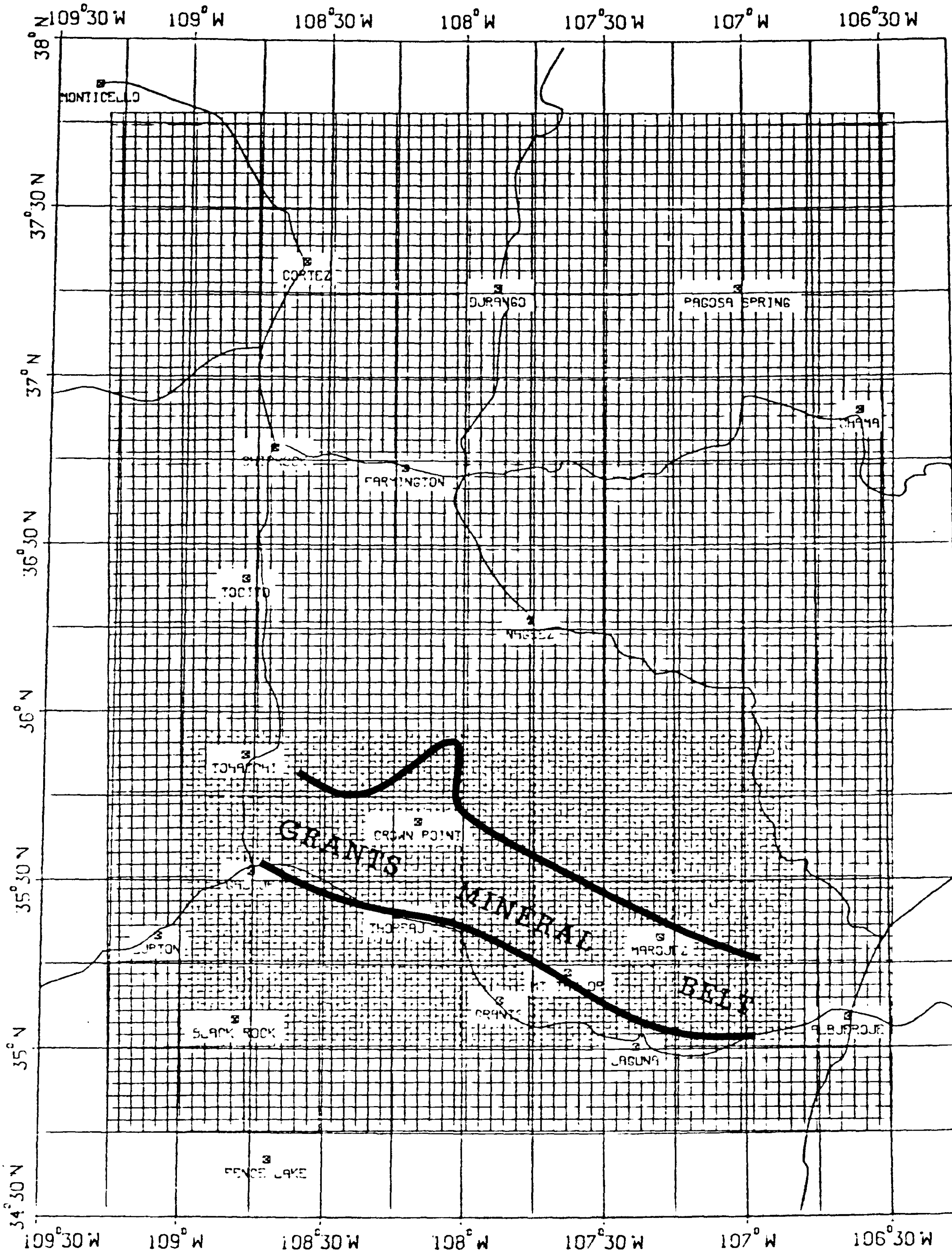


Figure 1.--Index map of the Grants Mineral Belt, San Juan Basin area.

geologist. It is expectable, however, that both the computer program and the geologist would tend to eliminate similar data from consideration when assessing endowment.

ACKNOWLEDGMENTS

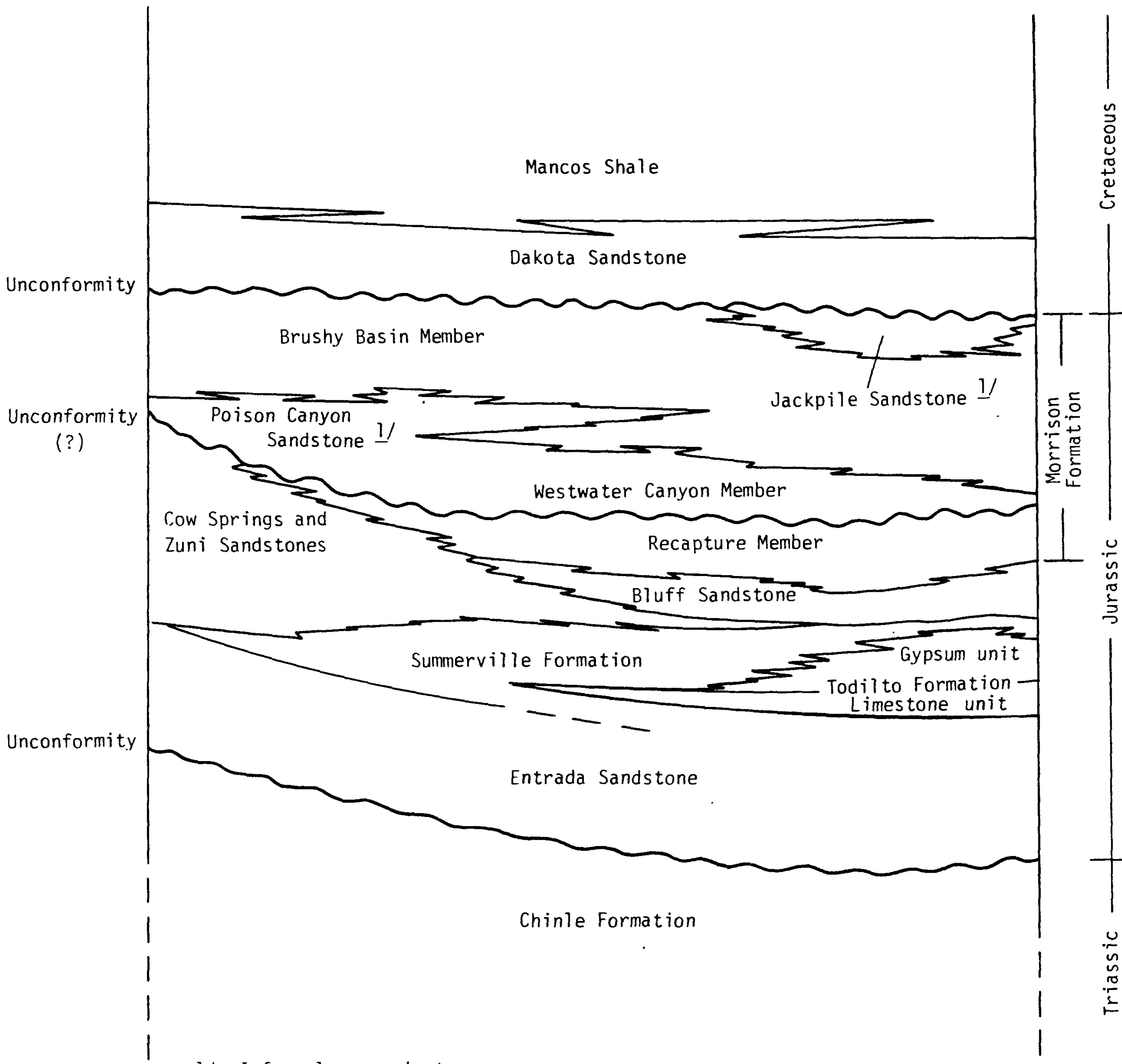
The model described in this report is based on the work of literally hundreds of people over the past 25 years. We have documented the text and tabulated material sparingly and only where necessary. In order to prepare for the model building, several group discussions were held within the U.S. Geological Survey to review all aspects of the uranium geology of the basin. We also discussed these things with other individuals. Among those who contributed were V. P. Byers, R. A. Cadigan, K. A. Dickinson, L. C. Craig, C. A. Huffman, Jr., M. W. Green, Robert Lupe, Fred Peterson, R. B. O'Sullivan, C. T. Pierson, J. L. Ridgley, J. F. Robertson, E. S. Santos, C. E. Turner-Peterson, and R. S. Zech, all of the U.S. Geological Survey. The second Grants Uranium Region Symposium sponsored by the New Mexico Bureau of Mines and Mineral Resources and the American Association of Petroleum Geologists held in May 1979, was particularly helpful to add new data and thinking on genesis of the uranium deposits. We thank William A. Scott and Robert M. Turner, U.S. Geological Survey, Reston, for writing the program to print the logic circuits shown in Plate I.

GENERAL STATEMENT OF THE MODEL

The type of deposits on which this model is based has not been recognized as of 1980 elsewhere in the world, yet it has supplied a greater domestic production and represents more reserves of uranium than any other type of uranium ore in the United States. The deposits are distinguished from other uranium deposits principally in that the uranium is concentrated with an authigenic organic material--an interstitial humate cement, which forms elongate undulatory layers within the host sandstone units (Granger and others, 1961). (Humate, as used here, is a variety of kerogen believed to have formed originally by the precipitation and aging of a water-soluble humic substance.) The geochemistry and geologic history of the humate is intimately related to the localization of the uranium.

All these deposits occur within fluvial sandstone units of the Morrison Formation (table 1). However, they are distributed through a considerable stratigraphic interval that includes rocks of both the Westwater Canyon and the Brushy Basin Members. Most of the deposits have been found in a belt about 30 km wide and 120 km long roughly parallel to the southern margin of the San Juan Basin (Kelley, 1963). Recent discoveries, deeper in the basin, contradict the early concept of a single relatively narrow mineral belt.

The Morrison Formation was deposited in Late Jurassic time as a series of coalescent fans on a large alluvial plain that constituted the Cordilleran foreland (Osterwald and Dean, 1961; Finch, 1964). Pre-Morrison history of the Cordilleran foreland included a period of mixed marine and continental deposition in the late Paleozoic and early Mesozoic followed by continental deposition during the middle Mesozoic. By Morrison time structural uplifts evidently had created a highland along the southern and western borders of the foreland.



1/ Informal economic terms

Table 1.--Schematic sequence of stratigraphic units of Late Jurassic age in the southern part of the San Juan Basin.

Granitic basement rocks in many places throughout the cordilleran foreland have been found to contain zircons that have an unusually high uranium content (Silver, 1976). This, coupled with both minor uranium occurrences and ore deposits of uranium in numerous sedimentary units older than the Morrison, suggests that the Morrison was deposited in an abnormally uraniferous region from source rocks that were also abnormally high in uranium content.

In the Colorado Plateau region, which includes the San Juan Basin, the Morrison Formation has been separated into four members. The basal Salt Wash and Recapture Members were essentially synchronous and were succeeded by the Westwater Canyon and the Brushy Basin Members, although only the Brushy Basin was deposited throughout the entire region (Craig and others, 1955).

The Salt Wash Member (not shown on table 1) is a fan-shaped wedge of fluvial sediments deposited in the northern and western parts of a shallow depression that we will call the ancestral San Juan Basin. The epiclastic detritus was largely quartzose sand derived from older sedimentary rocks to the west and southwest. Various proportions of intercalated mudstones within the Salt Wash have been interpreted as overbank and floodplain deposits. These deposits were at least partly derived from argillized volcanic ash.

The Recapture Member was deposited in a shallow depression as it was forming between the Salt Wash fan and the south edge of the ancestral San Juan Basin (Craig and others, 1955). It is made up mostly of a sequence of fine sandstones, siltstones, and mudstones, probably deposited in a fluvial and eolian-dune-sabkha environment.

In the southern part of the San Juan Basin, M. W. Green (1975; in press) has described a widespread disconformity separating two dominantly aeolian-sabkha-evaporitic sequences that include the Recapture Member and the Cow

Springs, Summerville, Todilto, and Entrada Formations from an overlying sequence of dominantly fluvial and lacustrine deposits that include the Westwater Canyon and Brushy Basin Members. This disconformity separates the traditional Recapture from the Westwater Canyon for the most part but, in places, it occurs well down in the traditional Recapture where Recapture beds are stratigraphically equivalent to Westwater Canyon beds. All the tabular humate uranium deposits occur above this disconformity and, for the purposes of the model, we have arbitrarily assigned all presently known uraniferous humate deposits to the Westwater Canyon and Brushy Basin Members (including the Jackpile sandstone) of the Morrison.

The Westwater Canyon Member was deposited principally by braided streams as a wedge-shaped fan (or multiple fan) controlled by approximately the same boundaries as the Recapture. Isopachs of the Westwater Canyon (Craig and others, 1955) suggest that its source area was to the southeast of the Salt Wash source rocks, possibly in the region of the Mazatzal and Pinal Mountains of Central Arizona. A granitic provenance is suggested by the epiclastic arkosic components. The Westwater Canyon also contains many mudstone or claystone splits and lenses compositionally similar to the overlying Brushy Basin Member. In the Ambrosia Lake uranium mining district near the outcrop, a tongue of Westwater Canyon-type sandstone, called the Poison Canyon sandstone (Santos, 1970), projects into the mudstone facies a few meters above the base of the Brushy Basin.

Sediment transport directions in the Westwater Canyon Canyon Member, which are inferred to be northerly (from descriptions by Craig and others (1955) in the northwest part of the fan), tend to change to east-southeast directions in the central and eastern parts of the unit (Saucier, 1979). Near the top of the Westwater Canyon in the Ambrosia Lake district and in the overlying Poison Canyon sandstone, however, transport data suggest that the stream directions were turning more to the northeast (Granger and others, 1961). Reconstruction of depositional conditions suggests that the northward extent of the Westwater Canyon was limited by prior deposition of the Salt Wash Member, which forced streams to flow more easterly in mid-Westwater Canyon time but ultimately to resume their northeastward trend as the Salt Wash sediments were inundated.

Recently acquired data that indicate consistent northeast depositional directions in the lower part of the Westwater Canyon, and consistent southeast depositional directions in the upper part of the Westwater Canyon, (Christine Turner-Peterson, oral commun., 1979) may require a revised interpretation of Westwater Canyon history and provenance.

The Brushy Basin Member overlies either the Westwater Canyon Canyon or the Salt Wash Member throughout the region of the ancestral San Juan Basin, and merges with undifferentiated Morrison farther to the north and northeast (Craig and others, 1955). The Brushy Basin consists dominantly of montmorillonitic or zeolitic mudstone and claystone, but also encloses many lenticular sandstone bodies, most of which are compositionally similar to the Westwater Canyon. The largest of these is called the Jackpile sandstone (Moench and Schlee, 1967). It is a northerly trending channel sandstone system that was deposited contemporaneously with upper Brushy Basin and whose provenance area may have been even farther southeast than that of the Westwater Canyon.

Rb-Sr dating of "barren-ground" montmorillonite in the Westwater Canyon suggests deposition at least 139 ± 12 m.y. ago (Lee and Brookins, 1980).

The facies relationship between the Brushy Basin and the underlying Westwater Canyon is not considered clear by all workers but may be attributed simply to lacustrine or distal facies deposition by the broad fan systems or possibly to choking of the depositing streams by greatly increased contributions of tuffaceous material. The source of the montmorillonitic or zeolitic components originally deposited as tuffs is conjectural, but prevailing Late Jurassic wind directions (Poole, 1962) and known Jurassic volcanism suggest sources to the west and northwest.

Fossil wood in the form of logs, limbs, and smaller debris is a common, though generally not abundant, constituent of the Westwater Canyon Canyon and Brushy Basin sandstones. Much of it was preserved by coalification soon after burial. Sandstone in broad zones where coalified wood is present were diagenetically bleached even well away from the fossil wood, and pyrite was deposited sparsely throughout by the action of sulfate-reducing bacteria. This leaching may also have been augmented by contemporaneous or later organic-acid-bearing solutions of either intrinsic or extrinsic origin. Where coalified wood is absent, the Westwater Canyon commonly became a hematitic red through diagenetic oxidation.

The greenish-gray color of the Brushy Basin and of mudstone lenses in the Westwater Canyon in the Southern San Juan Basin suggests a reduced state for any iron that is not contained structurally within the clays. There is little evidence for included organic matter in most of the mudstones, but molds and imprints of leaves and rushes have been found locally. Along the southern margin of the basin, nearly all the mudstone is montmorillonitic, but zeolitic facies have been found along the east margin (Santos, 1975).

The timing of geologic events in the southern San Juan Basin from the end of the Upper Jurassic Morrison deposition until Cretaceous Dakota deposition is poorly documented. Subsequent to deposition of the Morrison, the alluvial plain in the Zuni Mountains region was uplifted and the Morrison and underlying rocks were truncated at low angles. Humid, swampy conditions prevailed, and the exposed Morrison and older units were kaolinized and bleached by downward-percolating humic acid-rich meteoric waters (Granger, 1962, 1968). Nearly all the Westwater Canyon along the southern margin of the basin was bleached, but not necessarily kaolinized, probably through the combined reducing effects of the included coalifying plant material and the downward-percolating humic acids. Either later than or contemporaneous with these swampy conditions, the Dakota Sandstone was deposited along the migrating strandline of a Cretaceous sea that encroached from the north and east (Landis, and others, 1973). Rb-Sr dates of authigenic montmorillonite in the Dakota yield ages of 92 ± 6 m.y. (Brookins, 1979).

At about this time, or earlier, a humic authigenic cement was deposited as extensive undulatory layers in the Westwater Canyon, at least along the southern margin of the Basin. This humic material, or humate, may have been derived from the swampy terrane that was a forerunner of, or the base of, the Dakota Sandstone (Granger and others, 1961). Alternatively, it could have had an intrinsic source related to ground-water underflow of the rivers that deposited the Westwater Canyon, to the coalifying and petrifying fossil wood debris incorporated in the Westwater Canyon, or to organic-rich lacustrine deposits associated with distal parts of the alluvial plain.

In general, the layers are subparallel to stratification and are elongate parallel to sedimentary trends in the sandstone units that enclose them.

The shapes of these humate layers suggest that they may have been deposited at the interfaces between chemically different solutions. Humic acids are soluble in neutral to alkaline solutions but are easily precipitated by acid conditions or by the addition of divalent and trivalent cations.

Granger (1968) proposed that the humic precipitate had been localized at the interface between a supergene fresh-water solution containing dissolved humic acids and a more stagnant brine-like ground water solution. The mineral belt was believed to be defined by the intersection of this nearly horizontal solution interface with the upper and lower surfaces of the gently dipping Westwater Canyon and Jackpile units.

Squyres (1969) proposed that the humic matter was derived from plant matter deposited within the host rocks. After flocculation by dissolved cations, masses of gel-like humate were molded by the moving ground water into streamlined forms elongate in the directions of greatest permeability.

Peterson and Turner-Peterson (1979) are authors of the "lacustrine humate model" in which they proposed that the humate was derived from finely comminuted organic matter deposited with the mudstone unit, which they attributed to lacustrine environments. They proposed that the dissolved humic acids were expelled from the mudstones by compaction, and were precipitated in layers, by waters of contrasting composition that permeated the host sandstones.

None of the suggestions regarding source and localization of the humate bodies seems to have met with universal acceptance by geologists working in the mineral belt, and disposition of this problem awaits further study.

The primary uranium deposits seem to be controlled by the positions of the humate bodies (Granger, 1968). Existing evidence indicates that the primary uranium deposits are completely coextensive with the humate. There are no reliable data as yet, however, to indicate if uranium was introduced concurrently with the humate, or later. Submicroscopic coffinite disseminated in the humate indicates that the uranium was deposited partly by reduction, although reported urano-organic associations suggest that such processes as adsorption and chelation may have been equally important. Coalified fossil wood enclosed by the humate is highly enriched in uranium, but similar wood outside the humate layers commonly is almost barren. Chemically reduced mineral forms of Mo, Se, and V in anomalously large amounts in the ores, suggest that they were introduced with the uranium.

The ages of the primary ores, based on Rb-Sr dates on associated chlorite-rich clay minerals, is 139 ± 13 m.y. for Westwater Canyon ores (Lee and Brookins, 1980). Ore in the Jackpile sandstone is reported to have been redistributed about 113 ± 7 m.y. ago (Lee and Brookins, 1980). Pb-U ages of the ores are discordant and inconsistent, but the seemingly most reliable of these suggest ages of about 94 ± 3 m.y. (Berglof, 1970) for the Jackpile ores and 112 m.y. (K. Ludwig, written commun., 1977) or older for the Westwater Canyon ores.

During Late Cretaceous time the region accumulated several thousand feet of marine and continental sediments. The uranium deposits presumably were little affected by this burial during which groundwater probably was nearly stagnant and temperatures probably did not much exceed $100^{\circ}C$; however, actual temperatures are unknown.

After post-Cretaceous (Laramide) deformation of the foreland region, during which the Colorado Plateau was epeirogenically uplifted and faulted and the present San Juan Basin was formed, the host rocks once again were exposed along the southern edge of the Basin, this time by Tertiary erosion. Exposure of the host rocks in some places permitted oxygen-rich ground waters to percolate down-dip, guided locally by faults, and to attack the primary ores below the static water table. In a manner similar to creation of roll-type uranium deposits, this process resulted in what are variously called post-fault, redistributed, or stacked ores, which are localized near the edges of tongue-shaped lobes of oxidized sandstone in the host rocks. These oxidized rocks have been extensively exposed by erosion along the outcrop of the Westwater Canyon in many places (Granger and others, 1961). Although both are typically red, the oxidized tongues associated with the post-primary-ore can be distinguished from a pre-ore diagenetic oxidized facies (Squyres, 1969). Diagenetic red sandstone contains partly hematitized ilmenite-magnetite grains but no evidence of an intermediate pyritic alteration; hematite in the post-primary-ore oxidized tongues commonly displays textures indicating the former presence of pyrite (Reynolds and Goldhaber, 1978).

An alternative chronology for the red oxidized tongues recently has been proposed (R. J. Peterson, 1979; Smith and Peterson, 1979). By this hypothesis the humate layers were deposited at about the same time as the host rocks. Following Late Jurassic or Early Cretaceous truncation of the edge of the Westwater Canyon, oxygenated ground waters entered the rocks and produced an altered tongue that redistributed many of the humate layers in its path. Primary uranium deposition in the humate is believed to have taken place about 139 ± 13 million years ago (Lee and Brookins, 1980) but not clear is whether this ore mineralization preceded or followed the inferred humate redistribution process. Although the altered tongue originally contained iron oxyhydroxides, an aging process under the conditions of Late Cretaceous and early Tertiary burial helped to convert them to hematite. After the rocks were once again exposed by upper Tertiary erosion, oxidation of ore minerals and pyrite was resumed along the edges of the tongues to create a border zone of limonitic rock (Saucier, 1979[1]), which extends beyond the original oxidized tongue, and during which time uranium was redistributed into so-called "stacked" ore bodies. Although the general picture of early humate-rich ore being redistributed by one or more surges of oxygen-rich ground water seems to be firmly established, the elucidation of timing and details of these events is still being considered.

The orebodies are preserved today principally by their positions beneath a protective cover of overlying rocks and below the ground-water table. Much partly weathered ore, however, persists relatively near the outcrop and above the water table because of the resistance of the humate-rich ore to oxidation. Recently weathered favorable rock is buff and commonly contains goethite pseudomorphs after pyrite.

THE MODEL

The tabular humate uranium-deposit model is presented in the format of a matrix that follows an outline form and, in essence, is comprised of a tabulation of genetic concepts and their supporting geologic evidences, the geologic base (table 2). The combination of the two columns is the genetic-geologic model. The philosophy and guidelines for building a genetic-geologic model are given in Part I of Reseach on Uranium Resource Models (Finch and others, 1980).

In order to apply the model to a given area, a set of questions is presented that corresponds to the various elements in the model; these

[1]Note that although Saucier (1979) proposes two states of oxidation, he believed they were both of Tertiary age.

questions are in the third column, Application questions, table 2. The questions are asked such as they may be answered yes (+1), no (-1), or don't know (0). Each question can be worded differently to suit specific purposes of application. In order to check out the model in the control area--Grants mineral belt--and to calibrate and statistically weigh each question, the questions need to be asked specifically as in the third column in table 2. This checking, calibration, and weighing is, in essence, the next step in the evolution of the model-building process, and it may result in the rewording of some questions. The resulting question set will be used to evaluate the favorability of the unexplored part of the San Juan Basin.

Some questions involve measurements, such as degree of dip, thickness, lithologic ratios, and rock properties, and these questions in table 2 contain variables of unknown quantity or range such as X or X and Y. In order to determine the critical values of the variables, a subquestion follows in parenthesis these types of questions. A subroutine will be carried out in the control area to statistically determine the critical values, which will then be substituted for the unknowns.

The questions can be worded in general terms so that the model can be applied to another basin, such as the Raton Basin in eastern New Mexico where Morrison rocks are known, or to a basin that contains rocks of similar or even dissimilar age elsewhere. A preliminary general set of questions corresponding to specific ones in table 2 is given in table 3. Further research may change some of these questions, but for the most part we believe that this list of general questions will be useful. We must emphasize that the model presented here is preliminary and experimental, and that any model is subject to change with new data and new concepts. Genetic-geologic models are dynamic.

Data are required to answer the questions posed in table 2. To aid in answering the questions, a list of the data required for each question is presented in table 4. This list could be consolidated by grouping the same and similar data into categories. This would aid in compiling and using the data in applying the model in both the control and unexplored areas.

In order to apply the question set using geologic-decision analysis as presented in Part II of Research on uranium resource models (McCammon, 1980), a preliminary logic circuit is presented in Plate I. This computer-generated circuit is tentative as, like the question set, it will be checked out further in the control area--Grants mineral belt. In fact, the circuit will be the routine that will aid in calibrating and weighing the questions as to presence or absence of uranium ore. This routine is in essence a discriminatory function as explained further in Part II. An improved and more complete logic circuit will be developed from the preliminary one presented here.

EPILOGUE

Although the uranium deposits in the Morrison and associated formation in the San Juan Basin have probably received more study than any other deposits, they are still not perfectly understood. As a witness to this, the U.S. Geological Survey in 1979 began a major geologic-geochemical-geophysical study of the San Juan Basin framework, which will involve more than 30 scientists. Much of this work will generate data to answer some of the questions in table 2 for which there are now insufficient data. Other work will center around gaining a better understanding of the structural evolution of the basin, the sedimentation history of the host rocks, the sources of uranium, the timing of various ore-forming processes, the geochemistry of primary, redistributed, and weathered ores, and finally a total synthesis of the complete geology of the basinal area and its surroundings.

The building of this model has pointed to some aspects that need particular attention. They included the following: Establish sources of both uranium and humate, establish the relative times of uranium and humate deposition, establish permissive geochemical processes for uranium and humate deposition; and determine if sediment geometry or composition was more important in localization of uranium than basin hydrology and kinetics. If the ratio of uranium to carbon is nearly constant, determination of favorability for organic carbon (humate) may aid greatly in uranium favorability, and eventually in estimation of uranium endowment.

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Table 2.--Tabular humate-related uranium-deposit model, Grants mineral belt, New Mexico.

[The application questions are asked specifically to test, calibrate, and further develop the model in the San Juan Basin. Explanatory notes to accompany this table are given in table 2A. A set of questions for general application in areas outside the San Juan Basin is given in table 3]

Genetic concepts	Geologic base	Application questions
A. Prehost rock conditions and events.		
1. A uranium-rich province developed in and south of the San Juan Basin prior to host rock deposition.	1a. Precambrian crystalline basement rocks contain anomalously uraniferous zircon (Silver, 1976).	1a. Do regional basement rocks contain abnormally uraniferous zircon?
	1b. Regional basement rocks are abnormally uraniferous.	1b. Are crystalline basement rocks abnormally uraniferous?
	1c. Uranium deposits occur in older (Paleozoic, Triassic, earlier Jurassic) and younger (Cretaceous and Tertiary) rocks in the region.	1c. Do associated strata contain uranium deposits?
	1d. Pb-isotope studies show that regional basement rocks have lost U in the past.	1d. Do Pb-isotope analyses of the nearby basement rocks show loss of U?
2. An extended period of marine and later dominantly continental deposition of red beds took place on a broad stable platform (see Table 2A).	2a. The underlying strata constitute a sequence of dominantly marine Paleozoic rocks overlain by dominantly continental lower Mesozoic rocks.	2a. Are both marine and continental strata represented in the sequence beneath the host rock?
	2b. The host rock is part of a thick dominantly red-bed sequence of sedimentary rocks.	2b1. Is the host rock part of a red-bed sequence of rocks?
		2b2. Is there evidence of a primary (early-diagenetic) red facies of the host unit?
	2c. The regional angular discordance between the host rock and underlying rocks is generally low, less than 2^{o}.	2c. Is the regional angular discordance between the host rock and the immediately underlying sequence less than 2^{o}?

Table 2.--Tabular humate-related uranium-deposit model, Grants mineral belt, New Mexico--continued

Genetic concepts	Geologic base	Application questions
A. Prehost rock conditions and events—continued		
3. Host-rock deposition was preceded by uplift along the margins of the platform, perhaps coinciding with shallow downwarp of the depositional basin, and resulting in fluvial sedimentation of epiclastic detritus.	3a. Distribution and thickness of the Westwater Canyon Member roughly coincides with the present form of the southern San Juan Basin indicating downwarp within the continental craton prior to and during(?) sedimentation.	3a1. Is there evidence of basin subsidence during Morrison sedimentation? 3a2. Is the host rock within X* kilometers of the southwestern edge of the basin?
	3b. Sediment-transport directions indicate a positive area to the south of the Cordilleran foreland margin.	3b1. Is there evidence of uplift of areas south of the margin of the Morrison depositional basin immediately prior to or during Morrison time? 3b2. Are moderate- to high-energy fluvial sedimentary units in the basal host rocks?
B. Source of host rock constituents.		
1. Epiclastic constituents were derived largely from terranes along the uplifted margin of the alluvial plain.	1. Stream directions and isopachs of the host rock suggest source areas to the southwest (see Table 2A).	1a. Do isopachs of the host rock unit suggest a source in extensively uplifted basin margins? 1b. Do paleostream directions suggest a source in extensively uplifted basin margins?
2. Favorable host rocks are typically composed of granitic epiclastic debris.	2. The Mazatzal Mountains, Bradshaw Mountains, and other granitic terranes lie within the Mogollon highland in the generally indicated source direction.	2. Do granitic terranes lie in the general directions indicated by 1a and 1b?
3. Sand-size components of the host rock were derived principally from a granitic crystalline terrane (see Table 2A).	3. Epiclastic sand-size components of host rock are principally quartz, intermediate to alkalic plagioclase, K-feldspars, and altered magnetite and amphibole(?)	3a. Is the host sandstone feldspathic or arkosic? 3b. Are altered amphiboles and (or) magnetite-ilmenite present in host rock?

*A fixed number for X variable has not yet been selected.

Table 2.--Tabular humate-related uranium-deposit model, Grants mineral belt, New Mexico--continued

Genetic concepts	Geologic base	Application questions
B. Source of host rock constituents--continued		
4. Rarity of granitic pebbles suggests that granitic source area was fairly distant.	4. Granitic pebbles are rare in host unit.	4. Are granitic pebbles present but rare in the host unit?
5. Chert grains and pebbles were probably derived from a source in older marine sedimentary rocks.	5. Chert grains and pebbles are sparse in host unit.	5. Are chert grains and pebbles present but sparse?
6. Volcanic clasts were derived from volcanics in source terrane.	6. Volcanic clasts are sparse in host unit.	6. Are volcanic clasts present?
7. Mudstones intercalated with host sandstone were probably derived from volcanic ash that had altered to smectite.	7. Intercalated mudstone layers that occur within the host sandstones are largely montmorillonitic (smectite clay)	7. Are intercalated mudstones in host sandstones largely smectite clay?
8. The undercutting of muddy stream banks resulted in deposition of mudstone galls in channel-sandstone units. (See Table 2A.)	8. Mudstone galls (clasts, fragments) are common just above scour surfaces in channel-sandstone deposits.	8. Are mudstone galls present in the channel-sandstone units?
9. Wind-borne pyroclastic constituents were derived from a contemporaneous volcanic terrane that was not necessarily coincident with the source of epiclastic constituents of the host rocks.	9. Known Jurassic wind directions were from the west and northwest, areas of contemporaneous acidic to intermediate volcanism.	9a. Was there contemporaneous volcanism in adjacent regions to the west and northwest?
		9b. Were contemporaneous wind directions from the west and northwest?
		9c. Are pyroclastic components of the host rock compositionally similar to the contemporaneous volcanic rocks in adjacent regions?
		9d. Are pyroclastic components of the host rock of intermediate to acid composition?

Table 2.--Tabular humate-related uranium-deposit model, Grants mineral belt, New Mexico--continued

Genetic concepts	Geologic base	Application questions
B. Source of host rock constituents--continued		
10. Contemporaneous pyroclastic volcanic activity resulted in deposition of relatively pure ash beds that later altered to smectitic clay.	10. Fairly pure structureless smectite (montmorillonite together with included or associated relict shards and biotite) beds occur in the Brushy Basin Member.	10. Can nearly pure smectite beds (bentonite) be recognized, particularly in the Brushy Basin?
11. Climatic conditions seem to have restricted the growth of large woody plants to the fairly distant headwater areas of the depositing streams. Most large plant fragments were extensively transported prior to deposition.	11. The Morrison Formation contains fossil logs stripped of their roots and limbs, and fragmental woody fossils in the sandstone facies.	11. Are larger fossil plant fragments present and largely devoid of roots and branches?
12. Low-growing nonwoody plants grew on the banks of the depositing streams in the area of deposition.	12. Sparse molds and imprints of rushes and other nonwoody plants and even rarer leaves are found locally in muddy facies of the Morrison.	12. Are sparse nonwoody fossil plant molds and imprints, and rare leaves, present in the mudstone facies?
C. Transport of host-rock constituents		
1. The major constituents of the host sandstones were transported as bedload by braided streams.	1. The Westwater Canyon Member dominantly contains trough and low-angle planar cross-bedded channel-fill sandstone units with extensive cut-and-fill structures. Pebble size epiclastic conglomerate units are sparse to rare.	1. No question (see Table 2A).
2. Mudstone components were carried principally as suspended load in waters above and lateral to channel thalwegs.	2. Mudstone layers are common in the sandstone. Mudstone layers probably represent low-energy overbank and lacustrine deposits.	2. No question (see Table 2A).
3. Mudstone galls were deposited as erosional lag in channel sands that had undercut muddy banks.	3. Mudstone galls commonly are found in high-energy channel deposits just above scour surfaces.	3. No question (see Table 2A).

Table 2.--Tabular humate-related uranium-deposit model, Grants mineral belt, New Mexico--continued

Genetic concepts	Geologic base	Application questions
C. Transport of host-rock constituents--continued		
4. Uneven adjustments to tectonic deformation within the basin controlled courses of certain host rock streams (Huffman and Lupe, 1977; R. S. Zech, oral commun., 1978).	4. Small-scale folding of pre-Morrison and earliest Morrison rocks in the San Juan Basin coincide with thicker uranium-bearing sandstone-rich sequences of Westwater Canyon rocks.	4. Is there (geologic, seismic) evidence that (Morrison) host rocks are thicker and sandier along the trend of fold directions?
5. A short break in sedimentation brought about new transport systems of higher energy and from slightly different directions developed by renewed uplift in the granitic provenance region.	5. A regional disconformity exists at the base of the Westwater Canyon or near the bottom of the Westwater Canyon-Brushy Basin interval marking a change in higher energy deposition above and a change in source of sediment (Green, 1975).	5a. Is there a regional or at least prominent disconformity at the base of the Westwater Canyon? 5b. Are sediments above the disconformity of higher energy regime than those below?
6. At least some of the pyroclastic components were transported by wind (and deposited from the air). This may have been particularly true of units that immediately overlie the host rocks.	6. Smectite (montmorillonite and bentonite) beds are present in the mudstones of the overlying Brushy Basin Shale Member. Textures and composition suggest air-fall volcanic ash.	6. No questions (see Plate 1).
D. Deposition of host rock--Late Jurassic time (~150 m.y.)		
1. Host-rock deposition was from a fluvial system debouching across a broad alluvial plain in Late Jurassic time. (See Table 2A)	1a. Isopachs and grain-size measurements on the Westwater Canyon indicate thinning and fining, respectively, to the NW., N., and E.	1a1. Does host rock show thinning in a NW., N. or E. direction? 1a2. Does the host rock fine in a NW., N. or E. direction?
	1b. Paleocurrent measurements suggest a fluvial-stream system originating to the SW. and fanning in a NE. direction?	1b. Do paleocurrents in the host rock trend northerly or easterly?

Table 2.--Tabular humate-related uranium-deposit model, Grants mineral belt, New Mexico--continued

Genetic concepts	Geologic base	Application questions
D. Deposition of host rock--continued		
2. The host rock was dominantly deposited as channel sands in a braided fluvial complex within the mid-fan facies.	2. Mineralized host rocks have characteristics of braided-stream deposits.	2a. Does the host rock contain trough and low- to high-angle cross-bedded channel sandstone and horizontally laminated beds?
		2b. Do the sandstone beds show a lack of graded bedding and fining-upward sequences?
3. Fluvial channelways persisted over a long period of time and produced trunk channels.	3. Thickest sandstone bodies in the Westwater Canyon, Poison Canyon, and Jackpile (Economic terms) form trunk channel systems that contain the largest orebodies.	3. Do host-rock sandstone bodies greater than 10 m thick lie within a trunk system?
4. Highest energy deposits are from traction-transported bed-load or from lag derived from partly indurated undercut mud banks.	4. Coarsest material, such as epiclastic chert conglomerate layers (sparse) or mudstone gall conglomerates with coarse-grained sandstone matrix and trough crossbedding, is typically underlain directly by intraformational scour surfaces.	4a. Are epiclastic conglomerates present but sparse?
		4b. Are mudstone galls and mudstone gall conglomerates common?
		4c. Is there one or more scour surfaces at or near the base of the host unit?
5. The bulk of the host rock was deposited under moderate energy conditions from traction bedload in braided stream channels.	5. Most of the Westwater Canyon, Poison Canyon, and Jackpile is composed of coarse-grained to very fine grained sand deposited in trough cross-bedded, low- to high-angle planar cross-bedded, and horizontal laminated units.	5a. Is the average grain size of the host sandstone medium grained or coarser?
		5b. Does host rock display trough and planar cross-bedding as well as horizontal laminations?
6. Low-energy deposits consist of suspended-load flood-stage overbank deposits and perhaps some lacustrine deposits.	6. Mudstone layers are common, intercalated in the host sandstones.	6a. Are intercalated mudstone layers common in the host sandstones but generally subordinate to the sandstones?
		6b. Is the sandstone-mudstone ratio of the host unit within the range of X* to Y percent? (What is the sandstone-mudstone ratio for the host of each uranium deposit?)

Table 2.--Tabular humate-related uranium-deposit model, Grants mineral belt, New Mexico--continued

Genetic concepts	Geologic base	Application questions
D. Deposition of host rock--continued		
6. continued—		6c. Are the number of alternations between sandstone and mudstone between X* and Y per 100 ft of thickness? (What is the mean number of sandstone-mudstone alternations for host of each deposit?)
7. Lowest energy deposits were from airborne volcanic ash falling either on interfluvial areas or into shallow flood plain lakes.	7. The Brushy Basin contains almost pure smectite layers presumably derived from airborne volcanic ash.	7a. Are nearly pure smectite layers found in Brushy Basin mudstones and other low-energy sediments?
		7b. Are either volcanic lithic fragments or relict glass shards present in the host sandstone?
8. Fossilized logs and large woody fragments were waterlogged, deposited, and buried below the water level, principally in the thalwegs of fluvial channels. (See Table 2A)	8. Logs and large woody fragments (now converted to coal or, perhaps, partly silicified) are found in sandstone-channel deposits.	8. Are large woody fossils at least partly converted to coal (carbonized)?
9. Fine plant material was deposited largely from suspended load together with overbank clays and silts, and was commonly subjected to subaerial degradation.	9. Finer fossil plant fragments are typically found in silty or muddy depositional units.	9. Are fine grains of detrital fossil plant material present but sparse in the host rock?
10. As the energy of the streams diminished, mudstone facies onlapped the host sandstone bodies either by intertonguing with them or by burying the already deposited sand-filled channels.	10. The host sandstones (Westwater Canyon, Jackpile, and Poison Canyon) intertongue with the mudstones (Brushy Basin).	10. Is the host sandstone interdigitated with lateral (distal) and overlying mudstone facies?

*A fixed number for X variable has not yet been selected.

Table 2.--Tabular humate-related uranium-deposit model, Grants mineral belt, New Mexico--continued

Genetic concepts	Geologic base	Application questions
D. Deposition of host rock--continued		
11. Rapid deposition of the host sands in channels of braided streams resulted in poor packing and winnowing of silt and clay minerals, which were then deposited as distal facies or overbank flood-stage sediments.	11. The host sandstones are poorly to moderately well packed, and generally permeable except where cemented by authigenic minerals. Clay minerals are present but generally do not choke the pores.	11a. Are the host sandstones permeable now, or is there evidence that they were permeable early in their history? (see Table 2A) 11b. Are host sandstone beds presently good aquifers? 11c. Is the host sandstone poorly to moderately consolidated? 11d. Are there aquitards present in the host unit?
E. Alteration and preparation of host rock.		
1. Unfavorable zones within the host unit were subjected to early oxidation due to absence of plant fragments or to presence of already decayed or silicified wood. Without the protection of reducing agents, ferrous iron minerals such as magnetite were at least partly converted to authigenic hematite that imparts a red color.	1. Early diagentic oxidized red (hematitized) sandstones are unfavorable; they may contain both unaltered and hematitized ilmenite-magnetite grains and other mafic minerals. Organic matter, pyrite, and pseudomorphs after pyrite are missing. (See Table 2A)	1a. Is at least a part of the host sandstone characterized by diagenetic red (hematitized) oxidation? 1b. Are associated mudstones similarly red? 1c. Are ilmenite-magnetite and other mafic minerals altered to hematite? 1d. Is carbonized plant matter absent? 1e. Are pyrite and pseudomorphs after pyrite absent?

Table 2.--Tabular humate-related uranium-deposit model, Grants mineral belt, New Mexico--continued

Genetic concepts		
E. Alteration and preparation of host rock--continued		
2. Favorable zones within the host unit were bleached to light non-red tints by coalifying plant matter, sulfate-reducing bacteria that released H_2S, and organic acids that attack magnetite and other iron-bearing minerals and aid in their alteration to authigenic pyrite, leucoxene, and anatase.	2. Early diagenetic reduced light-gray or bleached-appearing rocks are favorable; they typically contain both disseminated pyrite grains and aggregates, and pyritized magnetites and other relict mafic minerals; titanium-bearing minerals are altered to leucoxene and anatase. Coalified detrital woody plant matter is common. (See Table 2A)	2a. Is sandstone light colored or bleached appearing? 2b. Are associated mudstones green-gray? 2c. Is coalified fossil wood present? 2d. Is pyrite or marcasite present? (Goethite near surface.) 2e. Are leucoxene and (or) anatase present? 2f. Are magnetite and mafic minerals largely destroyed and leached? 2g. Is fresh-looking or pyritized biotite present?
3. Pyroclastic material in the host rock was altered and redistributed as authigenic montmorillonite.	3. Sand grains commonly have a thin coat of authigenic montmorillonitic clay. (See Table 2A.)	3a. Is interstitial montmorillonite present? 3b. Have relict glass shards been observed in the host rock?
4. The host rock at the basin margin was, at least locally, gently uplifted and truncated across a broad featureless surface.	4. The Morrison, including Westwater Canyon, and older rocks are truncated by Dakota Sandstone along the south edge of the San Juan Basin. (See Table 2A.)	4. Was the Morrison slightly tilted, beveled, and covered by Dakota and succeeding sedimentary rocks at the basin margin?
5. Bogs and swamps resting on the truncated surface furnished organic acids that filtered downward into the underlying rocks, removing iron and converting aluminum silicate minerals to kaolinite.	5. Rocks below the Dakota erosion surface--especially feldspar-rich rocks such as the Westwater Canyon--are bleached and kaolinized. They are devoid of pyrite and contain leached and mostly destroyed mafic minerals.	5a. Are rocks immediately below the beveled surface bleached and rich in authigenic kaolinite? 5b. Are rocks immediately below the beveled surface devoid of pyrite and almost devoid of mafic minerals?

Table 2.--Tabular humate-related uranium-deposit model, Grants mineral belt, New Mexico--continued

Genetic concepts	Geologic base	Application questions
E. Alteration and preparation of host rock--continued		
6. Volcanic ash, chert grains and, perhaps, altered feldspars furnished silica that was redeposited on quartz grains at various times in the rock's history.	6. Quartz overgrowths are common in the host sandstone. (See Table 2A.)	6. Are quartz overgrowths present?
7. Calcite was mobile under various conditions and at various times but may have little relation to ore except as an omnipresent carbonate buffer.	7. Calcite cement is common in the host sandstone and also within humate-rich ore. (See Table 2A.) It is ordinarily post-humate in age.	7a. Is calcite cement common? 7b. Is calcite cement authigenic? 7c. Is calcite largely of late diagenetic or of epigenetic age?
8. Kaolinite "nests" throughout the host rock may be a mobile phase of the kaolinite zone just beneath an overlying erosion surface.	8. Kaolinite "nests" are common in the host sandstone but are small and sparse in the humate-rich ore. (See Table 2A)	8. Are kaolinite "nests" present?
9. Layers of humate were deposited in the host rock at interfaces between solutions that carried the (dissolved) humic matter and solutions in which the humate was insoluble. Several possible sources of humate exist: (see Table 2A) (1) organic acids in contemporaneous streams and underflow related to streams that deposited the Westwater Canyon; (2) organic acids extracted from contemporaneous coalifying plant fragments incorporated in the host rock; (3) organic acids extracted from lacustrine mudstone facies interbedded with, distal to, or overlying the host rock; (4) organic acids in bogs and swamps of pre-Dakota or basal Dakota age that rested on the slightly uplifted and erosionally beveled edges of the host rocks.	9a. An authigenic organic material (humate) fills or partly fills interstices and forms extensive peneconcordant layers within the host sandstones. This humate is now insoluble. (See Table 2A.) 9b. Coalified and silicified fossil plant matter is present in the host sandstone, which suggests that decaying plant matter during sedimentation and diagenetic degradation could have yielded an adequate supply of organic acids for humate. 9c. Carbonaceous lacustrine mudstone beds are associated with the host sandstone near uranium deposits. 9d. Coal beds are present at or near the base of the Dakota.	9a. Do insoluble humates fill interstices in bodies of the host rocks? 9b. Are either coalified or silicified plant fossils abundant in the host rock? 9c. Are carbonaceous lacustrine mudstone facies found intercalated with or overlying the host sandstone? 9d. Are coal beds present in the overlying Dakota?

Table 2.--Tabular humate-related uranium-deposit model, Grants mineral belt, New Mexico—continued

Genetic concepts	Geologic base	Application questions
F. Source of uranium. (See Table 2A)		
1. Labile uranium was leached from uranium-rich granitic rocks (that supplied some of host rock detritus) and carried to the host rocks by streams that deposited the host rock.	1. Several granites in the proposed general direction of provenance of the Westwater Canyon were originally uranium-rich and show signs of uranium depletion by leaching. (See Table 2A.)	1a. Is there isotopic evidence (Th-U-Pb) that granite in the Morrison provenance area was uranium rich? 1b. Do uranium contents of zircon from granitic rocks in the Morrison provenance area indicate uranium leaching?
2. Minerals that normally carry much of the labile uranium in granitic rocks yielded this uranium to ore-bearing solutions upon diagenetic alteration of clasts in the host rocks. (See Table 2A.)	2. Minerals that might have contained labile uranium in the Westwater Canyon sandstones are largely altered or destroyed. These include principally biotite and epidote.	2. Are biotite and epidote in the host rock highly altered or destroyed?
3. Labile uranium was released upon devitrification of volcanic ash, which might have been carried by the same streams that deposited the clays derived from altered ash and that was deposited with rocks immediately overlying the host rocks. (See Table 2A.)	3a. Clay minerals in the mudstone layers enclosed in the Westwater Canyon consist of bentonite that was probably formed from volcanic ash, which fell elsewhere and was devitrified prior to deposition in the mudstones.	3a. Do clays in mudstone beds in and overlying the host sandstone consist of bentonite (smectite)?
	3b. Certain nearly pure bentonite (smectite) beds in the Brushy Basin are interpreted as air-fall volcanic ash that devitrified in place.	3b. Are there nearly pure bentonite (smectite) beds in the overlying Brushy Basin?
	3c. Clays derived from volcanic ash and leached of a part of their original uranium should have anomalously large (>5.0) Th-U ratios, but data not yet available. (See Table 2A)	3c. Do clays or mudstones in and above the host sandstone have abnormally large (>5.0) Th-U ratios?
	3d. Se and Mo are consistently associated with the ores. A volcanic source is suggested. (See Table 2A)	3d. Do nearby ores and geochemical samples contain anomalous amounts of Se or Mo?

Table 2.--Tabular humate-related uranium-deposit model, Grants mineral belt, New Mexico--continued

Genetic concepts	Geologic base	Application questions
G. Transport of uranium and humate.		
1. Uranium was transported by ground water that moved through permeable sandstone beds.	1. The Westwater Canyon Member, Poison Canyon, and Jackpile sandstones are now permeable. Permeability is presumably greatest parallel to sediment depositional directions and somewhat less so in transverse directions. It is severely restricted vertically between sandstone layers by mudstone layers and clay-rich seams.	1a. Do the host sandstones presently have a permeability of more than 500 millidsrcies on the average? 1b. Is there evidence that the flow of mineralizing solutions through the sandstone was channeled by confining mudstone layers?
2. As with many other sandstones, permeability soon after deposition was probably 1 to 3 orders of magnitude greater than it is today.	2. Partial to complete clogging of many pore spaces in the Westwater Canyon sandstones by humate, calcite, clays and other authigenic minerals suggests that the sands were originally even more permeable than now.	2. Is there evidence that the original permeability has been reduced by alteration and deposition of authigenic minersls?
3. Ground-water movement was roughly downdip basinward by gravity and from surface recharge.	3. The natural movement of ground water is downdip through surface recharge near the edge of the basin.	3a. Is there evidence that ground-water recharge shortly after host-rock deposition was updip through surface exposures? 3b. Is the host rock within X* kilometers of the southwestern erosional edge of the basin? (X = the longest distance from the Dakots truncation of the Morrison to most basinward known uranium deposit.)
4. Humates were introduced by solutions percolating subparallel to stratificstion.	4. Elongate tabular layers of uraniferous humate with low permeability suggest that ore-bearing solutions moved parallel to the stratification.	4. Are humate layers peneconcordant with the stratifications?
5. Porous volcanic ash beds permitted percolation of water both across and parallel to stratification prior to devitrification.	5. Both Westwater Canyon and Brushy Basin mudstones are now highly impermeable, but evidence that these rocks were partly derived from volcanic ash suggests that they may have been considerably more permeable when deposited.	5. Do the Brushy Basin and Westwater Canyon mudstone facies contain volcanic ash, or is there evidence that they were derived from volcanic ash devitrifying in place?

*A fixed number for X variable has not yet been selected.

Table 2.--Tabular humate-related uranium-deposit model, Grants mineral belt, New Mexico--continued

Genetic concepts	Geologic base	Application questions
G. Transport of uranium and humate—continued		
6. Vertical collapse structures, such as sandstone pipes, were not principal conduits for ore-forming solutions.	6. Vertical permeability has locally been enhanced by vertical collapse structures. Evidence that these provided vertical conduits for the ore-bearing solutions is rather tenuous, except for one pipe that is uranium bearing.	6a. Is a uranium-bearing pipe present nearby? 6b. If present, is there any evidence that sandstone pipes were conduits for the ore-forming solutions?
7. Ore solutions originating in underlying rocks had local access to the host rock through sandstone pipes (collapse structures).	7. Possible hydraulic connection between the Westwater Canyon and underlying rocks is provided by sandstone pipes that probably bottom at the Todilto Limestone. (See Table 2A.)	7. Do sandstone pipes cut the Morrison and extend to the Todilto?
8. Pre-ore faults provided conduits for ore solutions from enclosing rocks.	8. Possible hydraulic connection between Westwater Canyon and both underlying and overlying beds is provided by faults but all known faults are post-ore.	8. Are pre-ore faults present in the host rock?
9. Although permeability is enhanced by faults and fractures, they were principally formed after uranium deposition.	9. Primary uranium and humate are earlier than any faulting. (See Table 2A)	9a. Is there evidence for control of primary humate by faults? 9b. Is there evidence for control of primary uranium by faults?
H. Primary (trend) uranium and associated mineral deposition.		
1. Localization of ore deposits was partly controlled by factors related to uplift and erosional truncation at basin margin.	1. Individual elongate tabular uranium deposits as well as belts of deposits are dominantly subparallel to the strike of the Morrison Formation and to the edge of the formation truncated by the Dakota Sandstone.	1a. Are known uranium deposits elongate and groups of deposits subparallel to the strike of the host unit? 1b. Are known uranium deposits and groups of deposits subparallel to the Dakota truncated edge of the Morrison Formation? 1c. Is the host rock test area near (within X* kilometers) of the truncated edge of the host rock unit? (What is the greatest distance (= X) between known uranium ore and Dakota truncation?)

Table 2.--Tabular humate-related uranium-deposit model, Grants mineral belt, New Mexico--continued

Genetic concepts	Geologic base	Application questions
H. Primary (trend) uranium and associated mineral deposition--continued		
2. Primary uranium was deposited before the host rocks were buried by more than a shallow cover of overlying rocks--probably before the next formation was deposited.	2a. Isotope age determinations on primary uranium minerals yield pre-Dakota dates. (See Table 2A)	2a. Do isotopic ages indicate that uranium was deposited before Dakota time?
	2b. Clasts of primary ore are present in basal beds of the Dakota Sandstone (Nash and Kerr, 1966.)	2b. Do clasts of primary Morrison ore occur in the Dakota or other Cretaceous rocks?
	2c. Primary ore layers are displaced by faults.	2c. Do essentially all faults displace primary ore?
3. Uranium and humate were deposited coextensively; uranium deposition was geochemically dependent on humate. Perhaps, uranium was initially scavenged from ore-forming solution by the humate, forming a urano-organic compound and was later reduced.	3a. Primary uranium ore and primary authigenic humate are coextensive.	3a. Is primary humate in the host rock uraniferous?
	3b. X-ray tests of primary humate-rich phases show chiefly coffinite.	3b. Is coffinite the chief primary uranium mineral?
	3c. Metallurgical tests and X-ray patterns indicate that uranium is held in more than one form, perhaps partly as urano-organic complexes (Kittel, 1963, p. 170).	3c. Is there evidence for a urano-organic compound?
	3d. The weight ratio of organic C to U in primary ore averages about 1 but individual samples commonly range from about 0.1 to 2.0. (See Table 2A.)	3d. Is the average weight ratio C:U in unaltered authigenic humate about 1?
4. V, Mo, and Se probably accompanied U in the ore-forming solutions and were concentrated in and near humate under similar geochemical conditions.	4. V, Mo, and Se are anomalously concentrated either in or near uraniferous humate.	4. Do samples of either uraniferous humate or barren host rock contain anomalous amounts of V, Mo, and (or) Se?
5. Molybdenum sulfide was concentrated locally adjacent to uraniferous humate but seemingly under different specific geochemical conditions than for the uranium.	5. Jordisite (amorphous MoS_2) forms rounded and feathering black-stained zones, principally marginal to uraniferous humate.	5. Do the host rocks adjacent to ore contain jordisite or anomalous Mo?

Table 2.--Tabular humate-related uranium-deposit model, Grants mineral belt, New Mexico—continued

Genetic concepts	Geologic base	Application questions
H. Primary (trend) uranium and associated mineral deposition--continued		
6. Concentration and reduction of uranium was probably much more closely related to humate than to H_2S.	6. Uranium generally does not correlate well with either sulfide sulfur or sulfide mineral concentrations.	6a. Are either pyrite or marcasite present but unevenly distributed in ore? 6b. Are U-sulfide S ratios erratic?
7. Mg-rich chlorite was formed at the expense of montmorillonite in the humate-rich ore. (See Table 2A.)	7. Both Mg and chlorite tend to increase in the uraniferous humate layer concomitant with relative decrease of montmorillonite.	7. Do Mg and chlorite abundances correlate inversely with montmorillonite in ore?
8. Authigenic kaolinite is probably later than uraniferous humate.	8. Kaolinite nests are generally small and sparse in the uraniferous humate layers in contrast to their greater size and abundance in more porous sandstones that lack primary mineralization.	8a. Are kaolinite nests present in barren rock? 8b. Do kaolinite nests seem to be later than ore minerals?
I. Modification of primary uranium ores.		
1. Primary humate-rich ore layers, which had been formed prior to succeeding formations, were locally ripped up at the basin's edge and deposited as conglomerate clasts in overlying beds.	1. Clasts of primary humate-rich ore reportedly (Nash and Kerr, 1966) occur in a conglomerate layer at the base of the Dakota Sandstone in the Jackpile mine, Laguna district.	1. Are there clasts of primary ore found in the basal conglomerate beds of the Dakota Sandstone?
2. Primary ores were partly oxidized and removed by encroachment of a tongue of iron-rich oxidizing ground water.	2. Primary (trend, pre-fault) ores are partly destroyed by oxidation associated with a large tongues of red, hematitic, oxidized rock that extend downdip from the outcrop in the area between Ambrosia Lake and Gallup (Saucier, 1979).	2. Are there remanents of trend orebodies enclosed by oxidized rock?
3. Uranium and some humate were redeposited into roll-type bodies locslly controlled by faults and fractures near the margins of the hematitic, oxidized tongue. (See Table 2A)	3a. Redistributed uranium, some humate-rich, occurs near the edges of the large red, hematitic oxidized tongues.	3a1. Is there a red hematitic oxidized zone in either Westwater Canyon or Brushy Basin sandstone? 3a2. Do uranium orebodies occur adjacent to margins of a hematitic oxidized tongue?

Table 2.--Tabular humate-related uranium-deposit model, Grants mineral belt, New Mexico--continued

Genetic concepts	Geologic base	Application questions
I. Modification of primary uranium ores--continued		
3. continued	3b. Redistributed ores marginal to the red hematitic tongue form stacked roll-type bodies locally controlled by pre-existing faults and fractures.	3b1. Do the redistributed ores have roll-front form? 3b2. Are the roll-type bodies stacked along faults and fractures?
	3c. Post-fault redistributed (stacked, roll-type) ores contain both coffinite and uraninite and are typically depleted in organic C and Mo relative to primary ore but may be enriched in FeS_2, V, and Se. The Se is typically richest in a narrow zone enclosing the oxidation interface.	3c1. Are the weight ratios of organic C-U far less than 1 and the Mo content low in the deposits? 3c2. Do the deposits contain both coffinite and uraninite? 3c3. Are FeS_2, V, and Se enriched in the deposits? 3c4. Is selenium distribution in narrow bands at the edge of the deposits similar to that of typical roll-type deposits?
J. Recent modifications of primary and redistributed deposits.		
1. Recent weathering caused oxidation of pyrite, both uranium leaching and deposition of uranyl minerals, and partial destruction of humate.	1. Weathered deposits are generally in pale-buff, commonly speckled, sandstones colored by hydrous iron oxides after pyrite; they may contain autunite, carnotite, and gypsum and generally show depleted uranium and humate contents.	1a. Are either surface exposures or shallow drill samples of host rock pale-buff sandstone that contain hydrous iron oxides or gypsum? 1b. Are there secondary uranyl minerals in the zone of weathering? 1c. Do either surface exposures or shallow drill hole samples of host rock contain relict humate accumulations either with or without anomalous uranium? 1d. Is the average uranium grade of oxidized ore lower than normal oxidized ore (>0.1 percent)?

Table 2.--Tabular humate-related uranium-deposit model, Grants mineral belt, New Mexico--continued

Genetic concepts	Geologic base	Application questions
J. Recent modifications of primary and redistributed deposits--continued		
2. Radioactive elements were dispersed during exposure and weathering but not removed completely.	2. Anomalous radioactivity is commonly detectsble at surface exposures of weathered deposits.	2. Do surface exposures of host rock display abnormal radioactivity?
3. Recent uranium mobilization resulted in uranium anomalies in both ground and surface waters.	3. Most deposits, weathered or unweathered and both above and below the water table, show relatively recent uranium depletion relative to ^{231}Pa (Granger, 1963).	3. Do ground waters or surface waters downslope from the outcrop contain uranium anomalies?
4. Under some conditions Ra was more mobile than U.	4. Most deposits tend to show recent loss of ^{226}Ra relative to ^{238}U and ^{231}Pa (Granger, 1963).	4. Do surface or ground waters contain ^{226}Ra anomalies?
5. Ra halos were produced around some orebodies.	5. Rocks, barite, and Mn oxides near ore commonly show abnormal ^{226}Ra concentrations (Granger, 1963). Contacts between mudstone layers and sandstone also show positive ^{226}Ra anomalies and radioactivity, perhaps at considerable distances from ore.	5a. Do either barite or Mn oxide in the host rocks contain ^{226}Ra unsupported by parent U? 5b. Are there positive ^{226}Ra anomalies and higher radioactivity at contact between mudstone and sandstone layers?
6. ^{234}U, ^{222}Rn, and He were mobilized from ores.	6. Other radiogenic daughter products such as ^{234}U, ^{222}Rn, ^{4}He, and ^{210}Pb, also show variable equilibrium relative to ^{231}Pa.	6a. Do soil gases contain Rn anomalies? 6b. Do soil gases contain ^{4}He anomalies? 6c. Do ground waters contain Rn anomalies? 6d. Do ground waters contain ^{4}He anomalies? 6e. Do ground waters contain ^{234}U anomalies? 6f. Do surface waters downslope from outcrop contain ^{234}U anomalies?

Table 2.--Tabular humate-related uranium-deposit model, Grants mineral belt, New Mexico--continued

Genetic concepts	Geologic base	Application questions
K. Preservation of ore deposits.		
1. Deep burial protected the primary ores.	1. The primary ores were preserved by deep burial between Dakota (>95 m.y. age) time and mid-Tertiary (>25 m.y. age) and in some places they are still deeply buried.	1. Was the Morrison Formation deeply buried soon after deposition?
2. Relatively recent weathering of ores has been slowed and prevented by thick overlying sequences of impermeable mudstones and shales.	2. The best-preserved ores are overlain by thick mudstones of Brushy Basin Member and (or) Dakota Sandstone and Mancos Shale beds.	2. Are the host sandstones protected by thick overlying impermeable shale of the Brushy Basin, Dakota, or Mancos?
3. Reduced orebodies were best protected from weathering where they remained beneath the water table even though they were locally destroyed by invasions of oxidizing ground water.	3. Some uranium ores are preserved by virtue of their positions beneath the present (and past?) water table.	3. Is the host sandstone below the ground water table?
4. Oxidation of ores was slowed and prevented in low-dipping host beds.	4. Ores are highly oxidized and destroyed in steeply dipping beds.	4. Is the dip of the host bed less than 5^{o}?
5. The flow of oxidizing ground water that created the oxidized tongues was probably greatest where it moved parallel to major faults, and the flow was impeded by cross faults.	5. Oxidized tongues seem to extend farthest downdip near faults and fault zones subparallel to the regional dip (direction of ground-water flow) and to have been impeded by faults subparallel to the regional strike.	5a. Is the host rock less than 500 m from a major fault? 5b. Is the host rock cut by faults subparallel to the regional dip? 5c. Is the host rock cut by faults transverse to the regional dip?

Table 2A.--Explanatory notes to accompany table 2

(Computer access--WHY)

A2. The Morrison and pre-Morrison sedimentation took place prior to periods of major disruptive epeirogenic deformation, such as the Colorado Plateau, Front Range, Nacimiento, and other uplifts in the foreland region.

B1. This conclusion is according to the conventional interpretation of a broad alluvial fan emanating from the southwest (Craig and others, 1955). More recent studies (C. E. Turner-Peterson, oral commun., 1979) may dictate modification of this depositional interpretation.

B3. Biotite, hornblende, ilmenite, magnetite, and other mafic minerals, derived from granitic and metamorphic provenance terrane, were probably sparingly present in the freshly derived rock. Relict grains and alteration products of some of these minerals may be seen in thin section and in heavy-mineral suites.

B8. The coherency of the mudstone galls suggests that they were not volcanic ash when the banks were undercut. Presumably the ash had been altered to smectite and mixed with epiclastic components prior to transportation(?) and deposition as overbank deposits.

C. Only inferential evidence of transport components of host rock can now be observed in the rocks. The evidence lies in characteristics of the deposited rocks (which are enumerated in the table 2). Therefore, no questions are asked for this part of the model.

D1. Rb-Sr dates on diagenetic(?) clay minerals suggest host rock deposition occurred 139 ± 12 m.y. ago (Lee and Brookins, 1980).

D7. and 8. Organic matter that remained unwaterlogged probably was not deposited. Large waterlogged pieces probably acted like conglomeratic lag and was deposited in channels with bedload and remained well below the water surface. Fine-grained waterlogged material was probably deposited at the tops of bars and with flood-stage overbank deposits where it was at least periodically above the water table. Organic material that remained under the water table probably tended to coalify, whereas that exposed to the atmosphere probably tended to oxidize and either to disappear or to become silicified.

D11a. Prior to compaction and cementation by quartz overgrowths, clay minerals, and calcite, the permeability must have been even greater.

E1. and E.2. Zones that contained large amounts of decaying and coalifying plant matter and whose pores were filled with humic acid-bearing ground waters were protected from oxidation. Indigenous, sulfate-reducing bacteria produced enough H_2S to alter many of the iron-bearing minerals. Zones that were not protected by organics and bacterial products such as H_2S and CH_4 became oxidized.

Table 2A.--Explanatory notes to accompany table 2--continued

E2. Favorable rocks where exposed at the surface are generally pale to dark buff because of iron oxyhydroxides formed from weathered pyrite, and organic matter is largely destroyed, except for the largest fragments.

E3. Presumably, all glass shards and most other fragments of volcanic materials are largely altered to clays. During alteration the pore solutions are assumed to have been saturated or supersaturated with respect to clay minerals (lithophile metal ions; silica; and alumina) and that some of these precipitated as clays on sand grain surfaces. This seems to have been a pre-ore process.

E4. Low-angle pre-Dakota erosion of the Westwater Canyon (and older rocks) updip from or directly over the deposits exposed a large area that was probably overlain by swampy, paludal terrane as evidenced locally by coal at the base of the Dakota. Humic acids infiltrating from this source could have provided an adequate source of humate.

E6. Quartz overgrowths are generally absent beneath coatings of humate ore, suggesting that most quartz overgrowth deposition followed humate deposition. Quartz overgrowths, however, are common in jordisite-rich zones. Here, the jordisite commonly forms both a thin layer between the detrital quartz grain and the overgrowth and coatings on the overgrowth.

E7. Calcite cement is largely later than humate cement, although one variety in so-called "mottled ore" may be pre-humate.

E8. Kaolinite "nests" are generally smaller and less abundant in the humate-rich ore than in surrounding rocks. The kaolinite appears to be later than the humate. If this kaolinite is genetically and temporally related to kaolinized zones (E4 and E5) below the basal Dakota erosion surface, it provides strong evidence that the humates were introduced prior to basal Dakota time.

E9. Geologic base

These layers of humate are now uraniferous and coextensive with primary ore. It is a moot point whether the uranium was deposited simultaneously with the humate, or later. There seems to be no reason to believe that uranium was deposited before the humate. The source of the humate is also a moot point. Precipitation of the humate could have been caused when solutions containing organic acids came into contact with a solution of either lower pH, or higher divalent and trivalent metal or complex ion concentration, or both.

Table 2A.--Explanatory notes to accompany table 2--continued

E9. Conceptual genetic model

Decaying plant material, as it converts to soil humus, peat, lignite, and coal, partly degrades to organic acids (humic and fulvic acids). These organic acids are commonly soluble in natural waters but can also be precipitated under certain conditions (see E.9, Geologic base, above).

E9. Application question

Care must be taken to distinguish organic humate matter from molybdenum, vanadium, and manganese minerals of similar color. If there is doubt a chemical analysis is required.

F. Uranium could have had either an extrinsic or intrinsic source, and several alternative possibilities exist between each of the listed choices, including multiple sources. The age, temperature of deposition, and probable hydrologic system for ore-solution transport do not point to a magmatic hydrothermal source. Rb-Sr ages of 139 ± 13 m.y. (Lee and Brookins, 1980), and Pb-U ages of about 110-115 m.y. (K. R. Ludwig, oral commun., 1979), and ore fragments in conglomerate at base of the Dakota Sandstone (Nash and Kerr, 1966) in the Jackpile area suggest a pre-Dakota age for ore; therefore, a source in or near Morrison time.

F1. Three 1430 ± 30 m.y.-old granites that crop out south of the Colorado Plateau in Arizona, "when corrected for assumed uranium loss, are anomalously high in uranium *** compared to the average granite" (Ludwig and Silver, 1977). The Lawler Peak Granite once contained 24.2 ppm U; the Ruin Granite; 9.1 ppm U; and the granite at Payson; 4.77 ppm U.

F2. Perhaps 70 percent of the uranium in granites is contained in the minerals biotite and epidote (J. S. Stuckless, oral commun., 1979).

F3. Mudstone clasts derived from undercut stream banks line the bottoms of some cut-and-fill structures in the Westwater Canyon. This attests to the cohesiveness of the clasts and suggests that they were clay-rich mud, not volcanic ash, when deposited (B7, table 2). Perhaps, therefore, volcanic ash in the provenance areas of the streams was being devitrified and leached of its uranium during Westwater Canyon deposition. Air-fall ashes devitrifying in place might release considerable uranium to ambient solutions, particularly under oxidizing conditions.

F3c. If it can be assumed that volcanic ash should have a fairly normal Th-U ratio of about 2 to 5 and, if it is assumed that uranium might be lost during alteration of the ash to clay minerals, then the Th-U ratio of the residual clays should increase. This is because the alteration would probably include oxidation; uranium oxidizes readily and becomes mobile in aqueous solutions whereas thorium does not.

Table 2A.--Explanatory notes to accompany table 2--continued

F3d. Numerous uranium-molybdenum deposits, principally occurring in resurgent volcanic caldera complexes have been described in the Soviet literature. A uranium- and molybdenum-rich volcanic caldera and lake-bed complex at McDermitt, Nev. may be of similar type. Selenium anomalies are common in fine-grained sediments derived from volcanic ash. Therefore, the U-Mo-Se assemblage is compatible with a source from volcanic rocks.

G8. Some of these collapse structures or sandstone pipes are cemented by calcite indicating that carbonate-bearing solutions did traverse the pipes but there is little or no evidence that they provided a conduit for solutions that formed the ore.

G9. Faults and fractures in the Westwater Canyon have typically enhanced permeability parallel to the faults, but fracture coatings and fillings have generally reduced permeability normal to the faults. Isolated calcite-coated fractures in the Brushy Basin mudstones also indicate locally enhanced permeability parallel to fractures. Fractures, almost without exception, displace the primary ore layers, and ore values are virtually unaffected except where altered by later events.

H2. Jackpile ore: Rb-Sr ages = 113 ± 7 m.y (Lee and Brookins, 1980; reportedly remobilized, Brookins, 1979).

^{207}Pb-^{235}U = 94±3 m.y. (Berglof, 1970).

Westwater Canyon ore: Rb-Sr ages = 139 ± 13 m.y. (Lee and Brookins, 1980).

Total Pb-U > 100 m.y. (Granger, 1963).

H3d. A weight ratio of 1:1 for C:U gives a mole ratio of about 20:1, which suggests that groups of about 20 C atoms in the humate molecule possess adequate functional groups or have some other capacity to fix one U atom.

H7. Rb-Sr radiometric age determinations on the chlorite-rich clay minerals associated with ore yields dates of about 139 ± 13 m.y. (Lee and Brookins, 1980).

I3. The red hematitic oxidized tongues are belived by Peterson (1979) and Smith and Peterson (1979) to have been formed during the erosion interval preceeding Dakota deposition. These same oxidized tongues are believed by Saucier (1979) to have been formed in late Tertiary time.

Table 3.--Preliminary list of general questions to apply the tabular humate uranium-deposit model to a new basin

[The questions are keyed alphanumerically to the model in table 2]

A. Pre-host rock conditions and events

1a. Do regional basement rocks contain abnormally uraniferous zircon?

1b. Are crystalline basement rocks abnormally uraniferous?

1c. Do associated strata contain uranium deposits?

1d. Do Pb-isotope analyses of the nearby basement rocks show loss of U?

2a. Are both marine and continental strata represented in sequence beneath the potential host rock? (This question may not be relevant in other basins.)

2b1. Is the potential host rock part of a red-bed sequence?

2b2. Is there evidence of a primary (early diagnetic) red facies of the potential host unit?

2c. Is the regional angular discordance between the host rock and the immediately underlying sequences less than 2^{o}?

3a1. Does the distribution of the potential host rock essentially coincide with a present-day basin?

3a2. Is the potential host rock near the source-edge of the basin?

3b1. Is there evidence of uplift of areas marginal to the potential host rock's depositional basin?

3b2. Are the sedimentary structures in the potential host sandstone compatible with a positive area adjacent to the foreland?

B. Source of host rock constituents

1a. Do isopachs of potential host rock unit suggest a sediment source in extensively uplifted basin margins?

1b. Do paleostream directions suggest a sediment source in extensively uplifted basin margins?

2. Do granite terranes lie in the general directions indicated by 1a and 1b?

3a. Is the potential host sandstone feldspathic or arkosic?

Table 3.--Preliminary list of general questions to apply the tabular humate uranium-deposit model to a new basin--continued

B. Source of host rock constituents--continued

3b. Are altered amphiboles and (or) magnetite present in the potential host rock?

4. Are granitic pebbles present but rare in the potential host rock?

5. Are chert grains and pebbles present but sparse?

6. Are volcanic clasts present?

7. Are intercalated mudstones in potential host sandstones largely bentonitic clay?

8. Are mudstone galls present in channel sandstone units?

9a. Was there contemporaneous volcanism in adjacent regions?

9b. Is there evidence of contemporaneous wind directions from the volcanic terrane?

9c. Are pyroclastic components of the potential host rock compositionally similar to the contemporaneous volcanic rocks in adjacent regions?

9d. Are pyroclastic components of the potential host rock of intermediate to acid composition?

10. Are there bentonitic beds in the unit directly over the potential host rocks?

11. Are larger fossil-plant fragments largely devoid of roots and branches?

12. Are sparse nonwoody fossil plant molds and imprints in mudstone facies?

C. Transport of host rock constituents

1-3. No questions (see Appendix A).

4. Does the potential host rock thicken and become sandier along folds, indicating contemporaneous influence of structure on sedimentation?

5a. Is there a prominent disconformity at the base of the potential host rock?

5b. Are there higher energy sediments above the disconformity than below?

6. No question (see Appendix A).

Table 3.--Preliminary list of general questions to apply the tabular humate uranium-deposit model to a new basin--continued

D. Deposition of host rock

1a. Is there evidence that the potential host rock was deposited as a wedge-shaped alluvial complex?

1b. Is there evidence that the potential host rock was deposited by a distributary alluvial system?

2. Are the sedimentary structures of the potential host rock those of braided streams?

3. Is there evidence for localized thick sandstone bodies in a trunk channel system within the potential host unit?

4. Is there high-energy epiclastic material above intraformational scour surfaces at or above the base of the potential host unit?

5. Is the bulk of the potential host unit composed of medium- to coarse-grained sandstone that displays trough, cross-bedded, and horizontal lamination typical of fluvial rocks?

6a. Are mudstone beds intercalated with potential host sandstone beds but subordinate to them?

6b. Is there a critical sandstone-mudstone ratio range as well as a critical number of sandstone-mudstone alterations?

7. Do thick bentonitic mudstone layers immediately overlie the potential host sandstone?

8. Are large pieces of woody fossils partly carbonized?

9. Are fine grains of detrital fossil-plant material sparse in the potential host rocks, especially the very fine grained ones?

10. Is the potential host sandstone interdigitated with distal and overlying facies?

11. Are the host sandstones good ground-water aquifers and is there evidence that they were more permeable than now?

E. Alteration and preparation of host rock

1. Is the potential host unit characterized by diagenetic red color and the absences of organic matter and pyrite?

2. Is the potential host unit characterized by bleaching, disseminated pyrite, and coalified plant fossils?

3. Does the potential host rock contain authigenic montmorillonite or relict glass shards?

Table 3.--Preliminary list of general questions to apply the tabular humate uranium-deposit model to a new basin--continued

E. Alteration and preparation of host rock--continued

4. Was the potential host rock slightly tilted, beveled, and covered by succeeding sedimentary rocks?

5. Are the rocks immediately below the beveled surface bleached, leached, and kaolinized?

6. Are quartz overgrowths present in the potential host sandstone?

7. Are the potential host rocks calcareous?

8. Are kaolinite nests common in the potential host sandstone?

9a. Does the potential host sandstone contain authigenic organic material (humate)?

9b. Does the potential host sandstone contain abundant coalified or silicified fossil wood?

9c. Are carbonaceous lacustrine mudstone beds intercalated with or overlying the potential host sandstone?

9d. Are coal beds found in the formation that truncates the potential host sandstone?

F. Source of uranium

1a. Do originally uranium-rich granitic rocks occur in the potential-host-rock provenance region?

1b. Is there geochemical evidence that the granites in the provenance region were leached of uranium?

2. Were minerals, such as epidote and biotite, that may have contained labile uranium highly altered or destroyed in the potential host rock?

3a. Are there bentonitic beds in the potential host rock?

3b. Are there thick bentonitic beds above the potential host rock?

3c. Do clays or mudstones in and above potential host sandstone have high Th-U ratios?

3d. Are either Se or Mo anomalously high in clays in the potential host unit, or associated with anomalous uranium occurrences in the host unit?

Table 3.--Preliminary list of general questions to apply the tabular humate uranium-deposit model to a new basin--continued

G. Transport of uranium and humate

1a. Are the potential host sandstones presently permeable?

1b. Is there evidence that the flow of possible mineralizing solutions through potential host sandstones was restricted by confining mudstone layers?

2. Is there evidence, such as diagenetic minerals, that the potential host sandstone was more permeable in the past?

3a. Is present ground-water recharge updip from surface exposures?

3b. Is the potential host sandstone less than half the distance to the center of the basin.

4. Are there humate layers peneconcordant with host-rock stratification?

5. Do mudstone beds overlying or interlayered with potential host sandstone contain volcanically derived constituents that appear to have devitrified in place?

6a. Are there sandstone pipes in the potential host unit?

6b. Is there evidence that these pipes were conduits of mineralizing solutions?

7. Do sandstone pipes extend beneath the potential host unit into potential sources of uranium?

8. Are there faults in the potential host unit that pre-date the next overlying unit?

9a. Do any faults contain "primary" humate?

9b. Are there primary uranium minerals in any faults?

H. Primary uranium and associated mineral deposition

1a. Are there known uranium deposits that are elongate subparallel to the strike of the host unit?

1b. Is the potential host unit truncated by younger formations, and are known deposits subparallel to the truncation line?

1c. Are there potential host sandstones near an edge of the truncation zone?

2a. Do isotopic ages indicate that uranium was deposited relatively early in host-rock history?

Table 3.--Preliminary list of general questions to apply the tabular humate uranium-deposit model to a new basin--continued

H. Primary uranium and associated mineral deposition--continued

2b. Do clasts of primary ore occur in overlying rocks?

2c. Do essentially all faults displace primary uranium-mineral concentrations?

3a. Is primary humate in the potential host rock uraniferous?

3b. Is coffinite the chief primary uranium mineral?

3c. Is there evidence for a urano-organic complex?

3d. Is the weight ratio of C:U in unaltered humate about 1?

4. Do samples of either humate or barren potential host rock contain anomalous V, Mo, or Se?

5. Do potential host rocks contain jordisite or anomalous Mo?

6a Are either pyrite or marcasite present but unevenly distributed in ore?

6b. Are U-sulfide S ratios erratic in ore?

7. Do Mg and chlorite abundances correlate inversely with montmorillonite in ore?

8a. Are kaolinite nests present in barren rock?

8b. Do kaolinite nests seem to be later than ore minerals?

I. Modification of primary uranium ores

1. Is there physical evidence that primary ore was formed prior to the sedimentation of the next succeeding formation?

2. Are there remanants of trend orebodies as indicated by their parallel orientation but obvious reduced size and modified shape?

3a1. Is there a red hematitic oxidized zone in the potential host sandstone?

3a2. Are there uranium deposits adjacent to margins of the hematitic oxidized tongue?

3b1. Do the redistributed deposits have a roll-front form?

3b2. Are the roll-front bodies stacked along faults and fractures?

Table 3.--Preliminary list of general questions to apply the tabular humate uranium-deposit model to a new basin--continued

I. Modification of primary uranium ores--continued

3c1. Are the weight ratios of organic C-U far less than 1 and the Mo content low in the redistributed deposits?

3c2. Do the redistributed deposits contain both coffinite and uraninite?

3c3. Are FeS_2, V, and Se enriched in the redistributed deposits?

3c4. Are there Se bands at the edges of the redistributed deposits?

J. Recent modifications of primary and redistributed deposits

1a. Are surface exposures or shallow drill samples of the potential host rock pale-buff sandstone that contains hydrous iron oxides or gypsum?

1b. Are there secondary uranyl minerals in the zone of weathering?

1c. Do either surface exposures or shallow drill-hole samples of the potential host rock contain relict humate, either uraniferous or non-uraniferous?

1d. Is the average grade of uranium samples low compared to normal unoxidized ore?

2. Are surface exposures of the potential host rock abnormally uraniferous?

3. Do either ground water in or surface water downslope from the outcrop of the potential host sandstone contain uranium anomalies?

4. Do surface or ground waters contain ^{226}Ra anomalies?

5a. Do either barite or Mn oxide in the potential host rock contain anomalous ^{226}Ra?

5b. Are there positive ^{226}Ra anomalies and higher radioactivity at the contact between mudstone and sandstone layers within the potential host unit?

6a. Do soil gases contain Rn anomalies?

6b. Do soil gases contain ^{4}He anomalies?

6c. Does ground water contain Rn anomalies?

6c. Does ground water contain ^{4}He anomalies?

6e. Does ground water contain ^{234}U anomalies?

6f. Do surface waters contain ^{234}U anomalies?

Table 3.--Preliminary list of general questions to apply the tabular humate uranium-deposit model to a new basin--continued

K. Preservation of uranium deposits

1. Were the potential host rocks deeply buried soon after deposition?

2. Are the potential host sandstone beds directly overlain by thick impermeable rock units?

3. Is the potential host sandsstone below the present ground-water table?

4. Is the dip of the potential host beds less than 5°?

5a. Is the potential host rock more than several kilometers from a major fault?

5b. Is the potential host rock cut by faults essentially parallel to the regional dip?

5c. Is the potential host rock cut by faults transverse to the regional dip?

Table 4.--Data needed to answer questions in table 2

A1a.	Uranium analyses of zircons from basement rocks.
A1b.	Uranium analyses of basement rocks.
A1c.	Knowledge or location of uranium deposits in associated strata.
A1d.	Pb-isotope analyses of nearby basement rocks.
A2a.	Presence or absence of marine and continental sequence below host.
A2b1.	Presence or absence of red-bed sequence in host unit.
A2b2.	Knowledge of primary red-bed facies in host unit.
A2c.	Angular discordance between host rock and sequence of underlying rocks.
A3a1.	Evidence for subsidence during host-rock sedimentation.
A3a2.	Distance from southern edge of host rock basin.
A3b1.	Evidence of uplift of nearest margin of basin.
A3b2.	Direction of resultant current directions of host unit (cross-beds, lineation trends, channel trends, etc.).
B1a.	Isopach map of Westwater Canyon Member.
B1b.	Stream directions (isopach map, outcrop readings).
B2.	Geologic map of adjoining region to south.
B3a.	Feldspar content of host rock.
B3b.	Altered amphibole and magnetite content of host rock.
B4.	Granite-pebble content of host unit.
B5.	Chert-pebble content of host unit.
B6.	Volcanic clasts in host unit.
B7.	Smectite (bentonitic) clay content of intercalated mudstone.
B8.	Mudstone-gall content of host sandstone.
B9a.	Paleogeographic map of adjacent region.

Table 4.--Data needed to answer questions in table 2--continued

B9b.	Wind directions in associated eolian sandstone.
B9c.	Composition of Upper Jurassic volcanic rocks in adjacent region and composition of Morrison host volcanic debris.
B9d.	Composition of Morrison volcanic debris.
B10.	Presence of nearly pure smectite (bentonite) in Brushy Basin.
B11.	Large fossil-plant content of host sandstone.
B12.	Fossil-plant mold, imprint, and leaf content of mudstone interbedded with host sandstone.
C4.	Isopach map of host rock (Jmw (Westwater Canyon), Jmb (Brushy Basin), Jmbjs (Jackpile).
C5a.	Prominent disconformity at base of Westwater Canyon.
C5b.	Grain size of basal host unit beds.
D1a1.	Isopach map of host rock (Jmww (Westwater Canyon), Jmbb (Brushy Basin), Jmbbj, Brushy Basin).
D1a2.	Grain size of host rock.
D1b.	Paleocurrent direction in host rock.
D2a.	Bedding character of host sandstone.
D2b.	Graded bedding presence or absence.
D2c.	Isopach map of sandstone within host unit.
D3.	Isopach map of sandstone within host unit (net sandstone?).
D4a.	Conglomerate presence or absence.
D4b.	Mudstone gall presence or absence.
D4c.	Scour surface presence or absence.
D5a.	Average grain size of host sandstone.
D5b.	Sedimentary structures of host sandstone.
D6a.	Abundance of intercalated mudstone.
D6b.	Sandstone-mudstone ratio.

Table 4.--Data needed to answer questions in table 2--continued

D6c. Number of sandstone-mudstone alternations.

D7a. Smectite (montmorillonite) layers above host.

D7b. Presence of volcanic fragments or relict shards.

D8. Presence of large coalified plant fragments.

D9. Presence of fine grains of plant fragments.

D10. Relation of host sandstone with distal facies.

D11a. Permeability of sandstone--now, past.

D11b. Aquifer quality of host sandstone.

D11c. Consolidation of host sandstone.

D11d. Presence of impermeable acquitardes.

E1a. Color of host sandstone.

E1b. Color of associated mudstone.

E1c. Evidence for alteration of ilmenite-magnetite and other mafic minerals.

E1d. Presence or absence of carbonized plant matter.

E1e. Presence or absence of pyrite or pseudomorphs.

E2a. Color of host sandstone.

E2b. Color of associated mudstone.

E2c. Presence or absence of coalified fossil wood.

E2d. Presence or absence of pyrite, marcasite, or goethite.

E2e. Presence or absence of leucoxene or anatase.

E2f. Evidence of alteration of ilmenite-magnetite and other mafic minerals.

E2g. Presence or absence of fresh-looking biotite.

E3. Kind of clay mineral.

E4. Tilting and truncation history of host.

Table 4.--Data needed to answer questions in table 2--continued

E5a.	Clay minerals below truncated surface.
E5b.	Pyrite and mafic mineral content of rocks immediately below bevel surface.
E6.	Presence or absence quartz overgrowths.
E7a.	Presence or absence calcite.
E7b.	Character of calcite.
E8.	Presence or absence kaolinite nests.
E9a.	Presence or absence humate impregnation.
E9b.	Presence or absence coalified plants.
E9c.	Presence or absence carbonaceous mudstone in and overlying host.
E9d.	Presence or absence of coal at or near base of Dakota.
F1a.	Thorium and uranium analyses of granite in provenance region.
F1b.	Uranium analyses of zircon from host rock or granite in provenance region.
F2.	Biotite and epidote content of host sandstone.
F3a.	Clay mineralogy of mudstones in host unit.
F3b.	Clay mineralogy of mudstones in overlying host sandstone.
F3c.	Th-U ratio of clay in and above host sandstone.
F3d1.	Se and Mo content of ore and geochemical samples.
F3d2.	Se and Mo content of clay in and above host sandstone.
G1a.	Permeability of barren and mineralized sandstone.
G1b.	Distribution of mudstone layers.
G2.	Diagenetic mineral effect on original permeability.
G3a.	Present-day ground-water recharge.
G3b.	Distance in kilometers of cell center from Dakota truncation of Morrison.

Table 4.--Data needed to answer questions in table 2--continued

G4.	Character of humate layers.
G5.	Evidence for volcanic debris in Westwater Canyon and Brushy Basin mudstone.
G6a.	Is a sandstone pipe present?
G6b.	Evidence of mineralizing-solution path.
G7.	Extent of sandstone pipe below base of Morrison.
G8.	Presence of pre-ore (late Morrison) faults.
G9a.	Do faults and fractures offset primary humate layers?
G9b.	Do faults and fractures offset primary uranium layers?
H1a.	Shape and orientation of known uranium deposits.
H1b.	---do.---
H1c.	Distance from truncated edge of Morrison.
H2a.	Isotopic ages of primary ore minerals.
H2b.	Presence or absence of clasts of Morrison uranium ore in Dakota.
H2c.	Relation of ore to faults.
H3a.	Presence or absence of uranium in humate.
H3b.	Presence or absence and abundance of coffinite.
H3c.	Absence of X-ray pattern in uraniferous humate.
H3d.	C:U weight ratio in primary humate.
H4.	V, Mo, and Se analyses of rocks and ores.
H5.	Mo analyses and jordisite mineralogy.
H6a.	Presence or absence of pyrite in uranium-bearing rock.
H6b.	U-sulfide S ratio in uraniferous rock.
H7.	Mg analyses and abundance of chlorite and montmorillonite in uraniferous rock.
H8a.	Presence or absence of kaolinite nests in barren rock.

Table 4.--Data needed to answer questions in table 2--continued

H8b.	Paragenesis of kaolinite and uranium minerals.
I1	Presence or absence of primary ore clasts in younger rocks.
I2.	Presence or absence (loction) of remanent-trend ore.
I3a1.	Presence or absence of red hematitic oxides sandstone.
I3a2.	Presence or absence of U deposits at edge of tongue.
I3b1.	Presence or absence of roll-type characteristics.
I3b2.	Relation of rolls to faults and fractures (stacked-ore).
I3c1.	Analyses of organic C and Mo from ore samples.
I3c2.	Coffinite and uraninite mineralogy.
I3c3.	Analyses of FeS_2, V, and Se from ore samples.
I3c4.	Morphology of Se concentrations.
J1a.	Presence or absence of hydrous iron oxides and gypsum.
J1b.	Presence or absence of secondary U minerals.
J1c.	Presence or absence of relict humate.
J1d.	Average grade of U deposit (samples).
J2.	Radiometric data of outcrop.
J3.	Uranium analysis of ground water.
J4.	^{226}Ra analysis of surface and ground water.
J5a.	^{226}Ra analysis of barite and Mn oxide.
J5b.	^{226}Ra analysis of sandstone-mudstone contacts
J6a.	Rn analysis of soil gas.
J7b.	He analysis of soil gas.
J6c.	Rn analysis of ground water.
J6d.	He analysis of ground water.
J6e.	^{234}U analysis of ground water.

Table 4.--Data needed to answer questions in table 2--continued

J6f.	^{234}U analysis of surface water.
K1.	Evidence of burial of Morrison soon after deposition.
K2.	Thickness of Brushy Basin (for upper Brushy Basin sandstone such as Jackpile, also of Dakota and Mancos) shales.
K3.	Position of host sandstone relative to present ground-water table.
K4.	Dip of host beds.
K5a.	Fault map of basin, measure distance to major fault.
K5b.	Fault map of basin.
K5c.	Fault map of basin.