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Comparison of the chemical characteristics of the
uranium deposits of the Morrison Formation
in the Grants uranium region, New Mexico

By

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Geological Survey editorial standards
and stratigraphic nomenclature.

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Abstract

Statistical treatment of the chemical data of samples from the northeast Church Rock area, Ruby deposit, Mariano Lake deposit, and the Ambrosia Lake district indicates that primary ore-forming processes concentrated copper, iron, magnesium, manganese, molybdenum, selenium, vanadium, yttrium, arsenic, organic carbon, and sulfur, along with uranium. A barium halo that is associated with all of these deposits formed from secondary processes. Calcium and strontium were also enriched in the ores by secondary processes. Comparison of the chemical characteristics of the redistributed deposits in the Church Rock district to the primary deposits in the Grants uranium region indicates that calcium, manganese, strontium, yttrium, copper, iron, magnesium, molybdenum, lead, selenium, and vanadium are separated from uranium during redistribution of the deposits in the Church Rock area. Comparisons of the chemical characteristics of the Church Rock deposits and the secondary deposits at Ambrosia Lake suggest some differences in the processes that were involved in the genesis of the redistributed deposits in these two areas.

Introduction

Information concerning the genesis and alteration of various types of uranium deposits can be gleaned from existing analytical data by determining which elements are associated with individual uranium deposits and by comparing the suites of elements associated with different types of deposits. With this end in mind, this report summarizes and interprets data on the elemental composition of mineralized sandstone of the Upper Jurassic Morrison Formation from the Gallup, Ambrosia Lake, and Laguna mining districts (as outlined by Hilpert, 1969) of the Grants uranium region (fig. 1).

A map by Chapman, Wood and Griswold (1974) shows the geology and mines of the Grants uranium region. The geologic setting and stratigraphy of the region, as well as mine locations and descriptions are given by Hilpert (1969) in his report on the uranium resources of northwestern New Mexico. Green (1975) discussed paleodepositional units in the Upper Jurassic rocks of the Gallup-Laguna area, and Kelley (1963) presented the tectonic setting.

Uranium ore in the Grants uranium region occurs mainly in the gently north-dipping sandstones of the Morrison Formation along the Chaco slope, which forms the southern boundary of the San Juan Basin. Some deposits also occur in the Entrada Sandstone and Todilto Limestone of Middle Jurassic age, as well as in the Dakota Sandstone of Late Cretaceous age. Sandstones of the Westwater Canyon Member of the Morrison Formation are the main host for deposits in the Ambrosia Lake district and in the Church Rock area, whereas sandstones in the Brushy Basin Member host the Laguna and Smith Lake deposits.

Two types of uranium ore have long been recognized in the Morrison Formation of the San Juan Basin. One is primary ore, which is also referred to as trend or pre-fault ore; the other type of deposit is termed redistributed, secondary, post-fault or stock ore (Granger and Santos, 1982). Unstructured organic matter (usually referred to as humate or humic material) is intimately associated and coextensive with the primary ore and is widely believed to be critical to the genesis of these deposits. The secondary ore is thought to have been derived from the primary ore and is probably

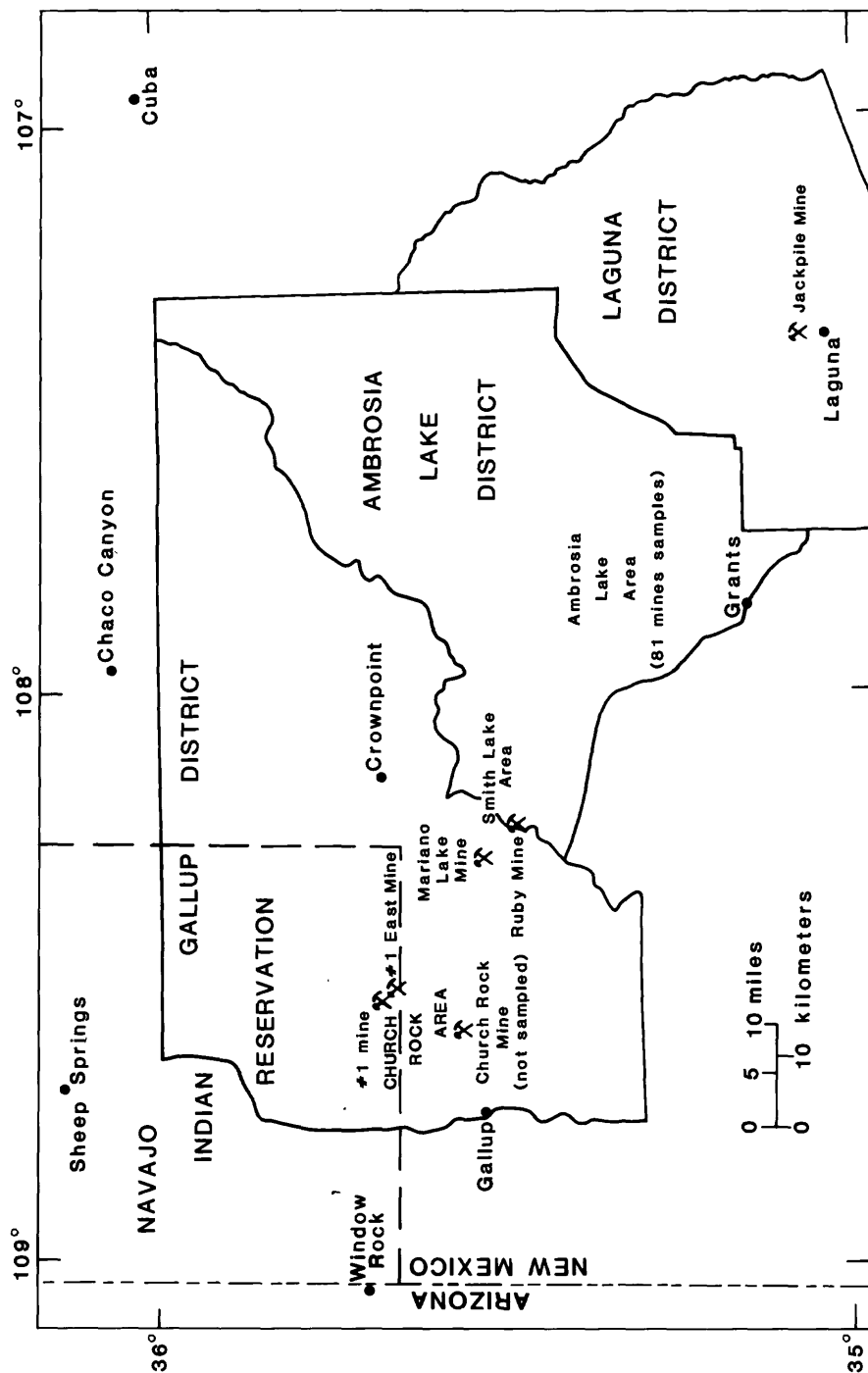


Figure 1.--Index map of Grants uranium region, New Mexico.

genetically similar in many ways to roll-type uranium deposits. Pyrite is believed to be critical to the genesis of roll-type ore (Granger and Warren, 1969). The deposits in the Church Rock area may represent a third type of ore in the San Juan Basin. Age determinations (Ludwig and others, 1982) indicate that these deposits are younger than the primary ore in the Grants uranium region and unlike primary ore, the deposits in the northeast Church Rock area do not contain abundant organic matter (N. Fishman, oral commun., 1982). The deposits in the northeast Church Rock area lie near a regional oxidation front (Saucier, 1980). This suggests that oxidizing solutions may have been involved in the genesis of these deposits. Oxidizing solutions probably also were involved in the genesis of the redistributed deposits at Ambrosia Lake; however, the sulfide content of the deposits in the northeast Church Rock area is much lower than in the redistributed deposits in the Ambrosia Lake district (E. Santos, oral commun., 1982). Therefore, the Church Rock deposits may represent a type of ore that differs in genesis or alteration from primary ore, but also differs from redistributed ore of the Ambrosia Lake district. The proximity of oxidized rock to these deposits suggests that all of the deposits included in this study have been reworked to some degree by oxidizing solutions.

A different type of alteration is believed to have affected the Laguna area. Data in Beck and others (1980) indicate that a number of elements including Al, Fe, Mg, Ca, Na, K, Ti, Mn and Sr have been leached from the host sandstone in the Laguna district. Adams and Saucier (1981) attribute this leaching to post-Morrison--pre-Dakota weathering processes.

Sources of information

This study summarizes geochemical information from over 800 mineralized samples from the Morrison Formation in the Gallup, Ambrosia Lake, and Laguna districts. These mineralized samples were collected by members of the U.S. Geological Survey from various mines in the following areas: 1) northeast Church Rock area (Church Rock #1 and #1 East mines) of the Gallup district - 80 samples collected by N. S. Fishman and E. S. Santos; 2) Mariano Lake deposit in the western part of the Smith Lake area, Gallup district - 98 samples collected by N. S. Fishman and R. L. Reynolds and J. F. Robertson; 3) Ruby deposit in the eastern part of the Smith Lake area, Ambrosia Lake district - 81 samples collected by J. F. Robertson and N. S. Fishman; 4) 31 mines and some drill core from the Ambrosia Lake district - 514 samples collected by H. C. Granger, E. S. Santos, F. B. Moore, and B. G. Dean; and 5) Jackpile deposit in the Laguna district - 50 samples collected by R. H. Moench and J. S. Schlee (their Table 8).

In addition to the mineralized samples, more than 700 unmineralized samples were used to provide background values of the abundances of elements against which the abundances of elements in mineralized samples were compared. In order to remove the effects of regional variations in the chemistry of the rocks from our comparisons, mineralized sample suites were compared to background sample suites from the same area. Thus, there are different background sample sets in each area. In the Ambrosia Lake area, many of the samples from the background set contained high concentrations of Mo, Se and equivalent uranium which suggest the samples were affected by mineralization. Consequently, a second background set of samples from the

southern part of the San Juan Basin, but distant from ore, was compiled and used for comparisons. This second background set is included in table 1. For the Laguna area, the background data set of unmineralized or weakly mineralized samples consisted of data from 14 samples taken from table 10 of Moench and Schlee (1967). Background data for the other areas were obtained from the U.S. Geological Survey's RASS (Rock Analysis Storage System) computer files. Further details of the nature of the data from the Church Rock area including geometric deviation, number of values below the limits of determination and the minimum and maximum values in the data sets are presented in Spirakis and others (1983). Similar information for the Mariano Lake and Ruby deposits is contained in Pierson and others (unpublished data) and Spirakis, Pierson, and Granger (1981) gives the same type of information for the Ambrosia Lake area. Information for mineralized samples in the Laguna area was taken from Moench and Schlee (1967).

Nature of the geochemical data

Analytical results for most elements in most of the samples were obtained by semiquantitative three-step or six-step emission spectrography (Myers and others, 1961). Many of the analyses performed since the late 1970's were by quantitative Induction-Coupled Plasma or "Direct Reader" spectrographic methods. For those elements not adequately determined by spectrographic methods, the following quantitative procedures were used: uranium by neutron activation or by radiometric or fluorimetric methods; selenium by X-ray fluorescence, sulfur, organic carbon by induction furnace techniques and mineral carbon, arsenic, ferrous iron, and ferric iron by wet chemical methods.

The semiquantitative spectrographic data (Myers and others, 1961) are presented as midpoints (0.15, 0.3, and 0.7 for 3-step and 0.15, 0.2, 0.3, 0.5, 0.7, and 1.0 for six-step) of geometric brackets whose boundaries are 0.12, 0.26, 0.56, and 1.2 for three-step and 0.12, 0.18, 0.26, 0.38, 0.56, 0.83, and 1.2 for six-step. Thus there are either three or six brackets for every order of magnitude; the boundaries and midpoints for higher or lower values are the same except for the position of the decimal. In three-step data, about 60 percent of the results will be in the correct bracket. The precision of a reported value in six-step data is approximately plus-or-minus one bracket at the 68 percent confidence level and plus-or-minus two brackets at the 95 percent confidence level.

Over the period of time of about 25 years during which the samples used in this study were submitted for analysis, there were some changes in the analytical techniques and limits of determination for some elements. These changes necessitate that some caution be used in comparing analytical results obtained at different times, but our conclusions as to how various elements are affected by mineralization or alteration are based, to a large extent, on comparisons of analytical data of similar age. Thus while some of the analytical results may have varied with time, the conclusions are unlikely to have been affected significantly.

Treatment of the geochemical data

In the studies of individual districts, areas, or deposits (Spirakis, Pierson, and Granger, 1981 for Ambrosia Lake; Pierson and others, for the Ruby and Mariano Lake deposits; and Spirakis and others, for the Church Rock area) samples from each district, area, or deposit were first separated into suites of sandstone and mudstone. The sample suite of mudstones from the Ambrosia Lake area was the only mudstone group that contained a sufficient number of mineralized mudstones to allow comparisons between mineralized and unmineralized mudstones. The suites were then broken into four arbitrary groups which range from highly mineralized to essentially unmineralized. The groups were defined with respect to uranium content as follows: 1) greater than 1000 ppm U; 2) greater than 100 ppm U (which includes greater than 1000 ppm U); 3) less than 100 ppm U; and 4) less than 20 ppm U.

With the aid of a computer, the geometric means and deviations for each of the elements in the four groups were calculated for each deposit, area or district. The computations are straightforward for data sets in which all analytical results are within the range of determination of the technique used. Where qualified values are present, special methods of computation had to be used. Qualified values in the analytical data are of the three following types: 1) not detected (N); 2) present in an amount less than the lower limit of determination for that element (L); and 3) present in an amount greater than the upper limit of determination for that element (G). For cases where data are either singly censored on the left (data contain qualified values of L and/or N but not G), or on the right (data contain qualified values of G but neither L nor N), a method devised by Cohen (1959, 1961) that has been computerized by VanTrump (1978) was used to estimate geometric means and deviations. In this procedure, log normality of the data is presumed and the geometric means and deviations, which should be considered as estimates, are calculated from the following quantities: 1) geometric means and deviations of the unqualified values; 2) the numerical value of the limit of determination; and 3) the number of qualified values in the data. In Cohen's method, N's are not distinguished from L's and as the percentage of qualified values increases the accuracy of the geometric mean decreases. Those elements with many qualified values are noted in table 1.

When qualified values are found in the data, most of the elements involved are singly censored on the left, although a few are singly censored on the right. Inasmuch as Cohen's technique cannot be applied to doubly censored data sets, the method used when necessary to reduce data to singly censored sets was to arbitrarily replace the G values with values of the midpoint of the next higher bracket in the geometric series used to report the results of three-step or six-step spectrographic analyses. Cohen's technique was then applied to estimate the geometric means and deviations.

In order to identify statistically significant differences between geometric means of elements among the various mineralized and unmineralized groups, a "t" test described by Natrella (1963, chapter 3, pp. 26-27) was used. This test is appropriate because it does not presume equal variances for the two groups being compared. Computations to identify significant differences between data sets involve the number of samples, geometric deviations and geometric means of each data set. The larger the numbers of

Table 1.--Geometric means for sample suites containing greater than 100 ppm uranium.
[In parenthesis next to each element is the amount of that element in the background sets discussed in the text.]

Element	Smith Lake Area			Primary	Secnndary	Mudstones	Laguna Jackpile ⁵
	Church Rock ¹	Mariano Lake ²	Ruby ³	Ambrosia Lake ⁴	Ambrosia Lake	Ambrosia Lake	
<u>%</u>							
Fe	.74 (.89)	1.67 (.85)	1.19 (.55)	.96 (.77)	.82 (.77)	1.87 (2.65)	.22 (.14)
Mg	.16 (.23)	.14 (.12)	.18 (.13)	.21 (.17)	.16 (.17)	1.05 (1.40)	.08 (.04)
Ca	.18 (.36)	.21 (.15)	.96 (.31)	1.19 (.40)	1.93 (.40)	.68 (.79)	.12 (.05)
Ti	.09 (.11)	.13 (.12)	.10 (.12)	.10 (.10)	.09 (.10)	.24 (.23)	.08 (.07)
Al	4.55 (4.43)	5.55 (5.31)	5.27 (4.85)	3.55 (3.60)	4.20 (3.60)	5.11 (6.38)	1.5 ⁺ (--)
Na	.96 (.67)	.81 (.74)	1.22 (1.32)	1.15 (.63)	1.19 (.63)	.76 (.64)	.3 ⁺ (--)
K	2.52 (2.33)	2.74 (2.47)	3.09 (3.14)	2.41 (2.41)	2.44 (2.41)	2.71 (2.80)	1.5 ⁺ (--)
Total-C	-- (--)	-- (--)	.65 (.06)	.60 (.14)	.36 (.14)	.27 (.09)	-- (--)
Org C	L (L)	.30 (.02)	.43 (.05)	.32# (.065)	.048* (.065)	.33 (.048)	-- (--)
Min C	L (L)	L (L)	** (**)	.17 (.035*)	.40 (.035*)	.060 (.086)	-- (--)
Fe ₂ O ₃	-- (--)	.83 (.41)	.57 (.65)	2.80 (.62)	-- (--)	-- (--)	-- (--)
FeO	-- (--)	.67 (.47)	.53 (.10)	-- (--)	-- (--)	-- (--)	-- (--)
Total-S	.045 (.011)	.49 (.07)	.27 (.01*)	.55 (L)	-- (L)	-- (--)	-- (--)
<u>ppm</u>							
Mn	81.4 (154.3)	82 (43)	355 (249)	264 (174)	226 (174)	356 (109)	55.3 (12.7)
Ba	811 (664)	820 (782)	907 (1052)	669 (560)	826 (560)	394 (386)	617 (300)
Be	1.19* (.89*)	1.27* (L)	1.88 (1.75)	1.08* (.65*)	.54* (.65*)	3.78 (1.69)	1.5 ⁺ (L)
Co	.72* (.42*)	1.50* (L)	3.38* (1.29*)	-- (--)	-- (--)	-- (--)	7.0* (L)
Cr	-- (--)	4.58 (5.92)	-- (--)	5.21 (7.77)	4.95 (7.77)	14.6 (21.5)	3.0 (L)
Cu	4.39 (5.53)	6.21 (5.08)	5.12 (4.22)	8.46 (4.10)	7.60 (4.10)	20.8 (19.8)	6.19 (3.58)
Mo	L (L)	27 (5.5*)	1.67* (L)	21.8* (5.10)	3.6* (5.10)	570 (7.2)	3.0 ⁺ (L)
Ni	2.45* (4.39*)	1.48* (L)	4.40 (3.58)	L (L)	L (L)	-- (--)	-- (--)
Pb	21.4 (14.6)	38 (12.9)	21* (5.9*)	45 (13.4)	12* (13.4)	77.2 (12.4)	32.8 (L)
Sr	108 (130)	98 (78)	178 (124)	177 (94)	196 (94)	229 (361)	29.3 (9.5)
V	117 (37)	808 (106)	642 (185)	634 (52)	1517 (52)	1166 (98.7)	482 (49)
Y	7.16 (9.61)	18 (L)	18 (10.8*)	16.3 (13)	11.5* (13)	14.4 (33.2)	7.0 ⁺
Zr	-- (--)	120 (99)	113 (28*)	93 (112)	83 (112)	107 (161)	108 (100)
Ga	5.85* (4.90*)	9.6 (7.83)	10 (3.9*)	4.42 (9.9)	3.76* (9.9)	18.49 (9.46)	-- (--)
Yb	L (L)	1.88 (1.14)	.89*	-- (--)	-- (--)	-- (--)	-- (--)
Se	L (L)	20.4 (9.49)	11.57 (1.89)	59.65 (7.65)	15.4 (7.65)	79.9 (6.7)	1 ⁺ (--)
U	1487 (32)	1280 (42)	1068 (28)	1817 (18)	1273 (18)	606.6 (17.1)	1500 (29)
As	L (L)	23.1 (3.67)	5.36 (1.40)	38 (--)	-- (--)	-- (--)	20 ⁺ (--)
eU	974 (292)	--	1505 (89)	1828 (19)	1103 (19)	1414 (47.3)	-- (--)

¹Spirakis and others, 1983

²Pierson and others, unpublished data

³Pierson and others, unpublished data

⁴Spirakis and others, 1981

⁵Computed from data for 50 samples, from Moench and Schlee, 1967 (Table 8).

+ Indicates mean from mill pulp data Moench and Schlee, 1967 (Table 7).

* Data may be in error owing to percentage of qualified values being greater than 30 percent or to presence of multiple detection limits.

L Data set contained too many values below the limit of determination to permit the mean to be estimated.

** Geometric mean not presented because of extremely high geometric deviations.

-- No data.

Dark samples were preferentially selected for analysis for organic carbon in this set thus introducing a bias.

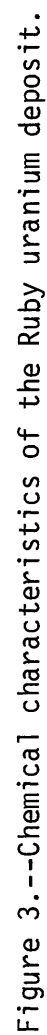
samples and the smaller the geometric deviations, the less the differences in geometric means must be to be significant. The differences referred to in the text and figures are significant at the 95 percent confidence level.

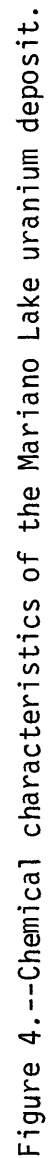
Observations and discussions

Table 1 presents the geometric means of each of the elements studied in the Church Rock area, the Ruby deposit, the Mariano Lake deposit, the Laguna district, the primary deposits of the Ambrosia Lake district and the secondary deposits of the Ambrosia Lake district. It also contains information on mineralized mudstones at Ambrosia Lake and data from the background sample sets. Figure 2 summarizes our observations about the behavior of various elements in the Church Rock area. Our observations concerning the increase, decrease, or lack of change in abundance of various elements in the Ruby deposit, Mariano Lake deposit, Laguna district, Ambrosia Lake primary deposits, and Ambrosia Lake secondary deposits are presented in figures 3, 4, 5, 6, and 7, respectively. With the exception of the deposits in the Laguna district, which may have been altered by post-Morrison--pre-Dakota weathering, many elements in the organic-rich primary deposits (Ruby, Mariano Lake, and Ambrosia Lake) exhibit a similar behavior. In these deposits, copper, iron, magnesium, manganese, molybdenum, lead, selenium, strontium, vanadium, yttrium, arsenic, organic carbon, and sulfur are enriched in the mineralized rock (both greater than 1000 ppm uranium and greater than 100 ppm uranium) relative to adjacent unmineralized rock (both less than 100 ppm uranium and less than 20 ppm uranium). Enriched does not necessarily imply a relation to primary ore-forming processes.

Calcium might also be an element that is typically enriched in these organic-rich primary deposits (again with the exception of the deposits at Laguna). It is enriched in the mineralized rock in the Ruby and Mariano Lake deposits compared to the adjacent unmineralized or weakly mineralized rocks but it is not enriched in the mineralized rock in the Ambrosia Lake district compared to the adjacent unmineralized rocks. Table 1 shows that the geometric mean of calcium in the primary deposits of the Ambrosia Lake area is higher than in the other primary deposits and calcium in the Ambrosia Lake deposits is enriched relative to a suite of samples distant from the ore. This background sample suite is included in table 1 and described in Spirakis, Pierson, and Granger (1981). The suite of samples distant from ore, however, contains a high proportion of outcrop samples; so it is possible that calcium was leached from the suite of samples distant from ore rather than enriched in the ore. Calcium is also enriched in the ore in the Laguna district but the background samples in the Laguna district may have been leached of calcium by post-Morrison--pre-Dakota weathering. Thus the behavior of calcium is not certain but on the basis of the enrichment of calcium in the primary ores in the Ruby, Mariano Lake and Laguna deposits and on the high calcium content of the primary deposits in the Ambrosia Lake district compared to other deposits, it seems appropriate to include calcium among the elements typically enriched in primary deposits.

A comparison of the geometric means of barium in all of the deposits included in table 1 with the geometric means of barium in a background set of samples distant from ore (Spirakis, Pierson, and Granger, 1981) suggests that barium is 50 to 100 percent higher in these ores than in the background.





Compared to the average barium content of sandstones in Turekian and Wedepohl (1961), barium in these ores is enriched by a factor of 10. Thus including barium among the elements enriched in the primary ores is justified.

All of the elements enriched in these organic-rich deposits were not necessarily incorporated into the deposits at the same time. Data from the mineralized mudstones at Ambrosia Lake and paragenetic relationships in sandstones provide some clues as to which elements were involved in processes that formed the organic-rich primary ores and which elements are associated with later events. In some places in the Ambrosia Lake area, organic-rich uranium-vanadium deposits extend from sandstones into the adjacent mudstones. A comparison of the chemical data from these mineralized mudstones to the nearby non-mineralized mudstones shows that organic carbon, vanadium, uranium, selenium, molybdenum, beryllium, and manganese are enriched in the mineralized mudstones. Other elements including aluminum, barium, calcium, copper, iron, strontium, and magnesium are enriched in the organic-rich deposits in sandstones but are not enriched in the parts of the deposits that extend into the mudstones. Some of these chemical differences between mineralized sandstones and mineralized mudstones might be related to the degree of compaction of the sediments at the time the elements were introduced into the deposits. It is likely that compaction, once complete, would preclude the migration of organic carbon into the mudstones and would impede the ingress of mineralizing solutions into mudstones; compaction, however, would have a much smaller effect on the permeability of sandstones. Thus, it is likely that organic carbon, uranium, vanadium, selenium, molybdenum, beryllium, and manganese were all emplaced in the mudstones and adjacent mineralized sandstones in an early, pre-compaction, mineralizing event. Paragenetic relations (P. Hansley, oral commun., 1982) indicate that barite, anhydrite and most calcite formed after the organic-rich ore. This is consistent with the interpretation that compaction prevented barium, calcium, and strontium from entering the mudstones in a post-mineralization event. If compaction did indeed prevent post-mineralization solutions from entering the mudstones, then the difference between elements enriched in the mineralized mudstones and the elements enriched in the sandstone parts of the deposits can be used to tie compaction into the paragenetic sequence and is evidence for mineralization shortly after sedimentation.

A possible enrichment of aluminum and magnesium, which occur in ore-stage clay minerals, and chlorite, and iron and copper, which occur in ore-stage sulfides, might have been masked by the high initial concentration of these elements in the mudstones. Sulfur and arsenic also may have been emplaced during the organic-rich, ore-forming event, but no data concerning the abundance of sulfur and arsenic in the mineralized mudstones are available. Lead probably was not transported to the deposits in either the primary organic-rich, ore-forming event or in the later event but instead was generated in place by radioactive decay of uranium. Consequently, the deposits at Church Rock, which are predominately Pleistocene in age (Ludwig, and others, 1982), and the secondary sandstone deposits, at Ambrosia Lake which are Tertiary in age (Granger and Santos, 1982) are not enriched in lead. Yttrium is enriched in all of the organic-rich deposits but it is not enriched in the mineralized mudstones, nor is it enriched in the Church Rock deposit or the secondary deposits at Ambrosia Lake which formed in mineralizing events that postdate the primary ore. Thus, there is no evidence

as to the timing of the enrichment of yttrium.

This segregation of elements enriched in the organic-rich deposits into pre- and post-compaction groups provides a basis for speculation as to the nature of the primary ore-forming process and of the alteration of the primary ore. One possibility for the primary ore-forming event is that an organic-rich solution migrated through the still uncompact sediments and through adsorption onto the mobile organic material, scavenged from minerals and volcanic glass along its path many of the elements that were enriched in the ore before compaction. Organic matter in this solution would establish a low redox potential of the solution so that U, V, and other elements sensitive to reduction would have to be transported in a reduced state as an organic complex. Reactions of this solution with volcanic glass in the sediments would produce an alkaline pH. Devitrification of volcanic glass provides a source of silica for the paragenetically early quartz overgrowths and an alkaline pH would enhance the solubility of mobile organic matter. One constraint on this hypothesis is that the organic-rich solution would have to traverse and react with a sufficient volume of sediment to account for the concentration of elements in the ore. The feasibility of this can be examined by considering the scavenging of vanadium to form a deposit. If 5 ppm vanadium per unit volume of rock (about 10 percent of the vanadium in this work) was leached from the rock as the organic-rich solution passed, then the solution would have to travel 1000 feet to pick up enough vanadium to form a deposit 10 feet thick and averaging 500 ppm vanadium. One thousand feet does not appear to be an unreasonable distance for mobile organic material to migrate through uncompact sediments. Thus, the hypothesis seems plausible. It might be possible to identify migration routes of the proposed scavenging solutions by recognizing the deficiency of vanadium and other elements along the solution's path. However, the variability of the vanadium content of unmineralized parts of the Morrison Formation (as shown by the geometric deviation of the mean in Spirakis, Pierson, and Granger, 1981) indicates that analyses of a large number of samples would be required to detect a difference of a few parts per million in the vanadium content between populations of leached and unleached rocks.

A proposal by Granger and Warren (1981) for the nature of the mineralizing solutions in the Uravan area and for the vanadium-uranium deposits in the Entrada Formation might also apply to the deposits in the San Juan Basin. They suggest that mineralization occurred where an organic-rich solution that transported vanadium and aluminum encountered a magnesium-rich solution. Magnesium in the magnesium-rich solution triggered mineralization by displacing vanadium and aluminum from the adsorption sites on the mobile organic material. In this model, uranium is transported in the magnesium-rich solution and is precipitated through reduction by both organic matter and trivalent vanadium. It is possible that magnesium could trigger the precipitation of the ore even if only one solution was involved provided that colloidal organic matter in the solution migrated slower than the solution. Magnesium and other dissolved species in the solution then would catch up with the organic matter and would fill the available adsorption sites. Once the sites were full, any additional magnesium brought in by the solution would displace vanadium and aluminum and initiate the precipitation of the deposits. At present, our lack of knowledge as to which elements and in what concentrations may be transported in organic complexes without precipitating

the organic material prevents information as to which elements were involved in the initial mineralizing event from further defining the nature of the mineralizing process.

The elements enriched in the primary ore in sandstones but not in the mineralized mudstones (barium, calcium and strontium) were probably introduced in a post-compaction alteration of the primary ore. The occurrence of barium and calcium in sulfates (barite and anhydrite) and the association of barite with oxidized rock (Adams and Saucier, 1981) suggest that the post-compaction solution was oxidizing.

Barium is the only element identified here as enriched in and around all of the deposits included in this study. Other data (Pierson, Spirakis, and Peterson, unpublished data) show that relative to unmineralized sandstones near or distant from ore deposits, barium is not enriched in the primary tabular deposits of the Henry Mountains mineral belt in Utah. The Henry Mountains deposits are believed to have remained below the water table since they formed and therefore they are nearly pristine (F. Peterson, oral communication, 1982). Thus the absence of barium enrichment in these unaltered deposits supports the contention that the barium anomaly is a product of alteration.

The origin of the barium halo may involve some of the processes described by Granger and Warren (1969) for the genesis of roll-type uranium deposits. According to their model, the initial products of pyrite oxidation by near-surface oxygen-bearing solutions are partly oxidized sulfur species. Under conditions of limited oxygen supply, the partly oxidized species slowly disproportionate to sulfate and sulfide. As Plummer (1971) pointed out, barium and sulfate are extremely insoluble together in any one low-temperature solution. Consequently, if the oxidizing solution contains barium, then the oxidation of pyrite (which is an abundant component of the ores) to sulfate will precipitate barium as barite. Because the oxidation of partly oxidized sulfur species to sulfate is a slow process, the partly oxidized species may migrate away from the oxidizing ore deposits before sulfate is produced and barite precipitated. Thus barite precipitates in a halo in and around the ore deposits.

The barium anomaly is a potentially useful prospecting guide for partly oxidized primary uranium-vanadium ore deposits in the Grants mineral belt and elsewhere. Because the halo originates from secondary processes, application of this prospecting guide is restricted to deposits that have been partly oxidized.

A comparison of the chemical characteristics of the deposits in the northeast Church Rock area with the chemical characteristics of the organic-rich deposits in the Ambrosia Lake, Mariano Lake and Ruby areas yields information as to the behavior of elements during redistribution by oxidizing solutions. Some elements, such as Ca, Mn, Sr, and Y, are depleted in the deposits of the Church Rock district compared to adjacent unmineralized or weakly mineralized rock but are enriched in the primary deposits included in this study. Other elements, including Cu, Fe, Mg, and Pb are enriched in the primary ores of Ambrosia Lake, Ruby, and Mariano Lake but show no significant change in their abundances in the deposits of the Church Rock district

compared to the adjacent unmineralized rock. If the deposits in the northeast Church Rock district were derived from primary (organic-rich) deposits and if the elements that are enriched in the Ambrosia Lake, Ruby, and Mariano Lake deposits are indeed typical of primary ores of the San Juan Basin, then presumably these elements were also once enriched in the deposits in the Church Rock district. Their present lack of enrichment in the deposits of the Church Rock district suggests that organic carbon and the elements Ca, Cu, Fe, Pb, Mg, Mn, Sr, and Y were separated from the uranium in the Church Rock deposits during redistribution.

Only 13 of the 76 mineralized samples from the Church Rock area contain detectable concentrations of molybdenum. One sample contains 855 ppm molybdenum. In the Ruby deposit, about half of the mineralized samples contain detectable amounts of molybdenum; the highest concentration is 1200 ppm. Approximately two thirds of the samples of primary ore from the Ambrosia Lake district and four fifths of the mineralized samples from the Mariano Lake deposit contain detectable concentrations of molybdenum. The maximum recorded value of molybdenum in the data from the Ambrosia Lake deposits is 15,000 ppm; in the Mariano Lake deposit the maximum is 3000 ppm. Selenium has a similar distribution. The proportions of mineralized samples containing more than 10 ppm selenium is 25 percent in the northeast Church Rock area, 50 percent in the Ruby deposit, 70 percent in the Mariano Lake deposit, and 90 percent in the primary ores in the Ambrosia Lake district. Both molybdenum and selenium are seldom detected in barren rocks. These data indicate that compared to barren rocks, molybdenum and selenium are enriched in the deposits included in this study (with the exception of molybdenum in secondary ores at Ambrosia Lake and possibly both molybdenum and selenium in the Laguna district); however, the enrichment in the deposits of the northeast Church Rock area and to a lesser extent the Ruby deposit (which has been more oxidized than the deposits in the Mariano Lake or Ambrosia Lake areas (M. Green, oral commun., 1982)) is only sporadic. The sporadic nature of the distributions of selenium and molybdenum in these reworked deposits indicates that molybdenum and selenium were in part separated from uranium by oxidizing solutions. Thus molybdenum and selenium are included among the elements leached by oxidation.

Vanadium is enriched in the Church Rock deposits compared to the adjacent unmineralized rocks, but the very low geometric mean of vanadium in the Church Rock deposits compared to the organic-rich deposits suggests that to some extent, vanadium also has been separated from uranium during oxidation.

The separation of uranium from other elements can be attributed to differences in the chemical mobility during oxidation between uranium and other elements. For example, uranium is highly mobile under oxidizing conditions, but magnesium that is largely incorporated in clay minerals and chlorite in primary ore deposits is not. Thus during alteration by oxidizing solutions, uranium may have been mobilized from a primary (humate-rich) deposit in the vicinity of the Church Rock district and reprecipitated in the present Church Rock deposit; in the process, immobile magnesium was left behind and magnesium was separated from uranium.

Some of the elements including Ca, Cu, Fe, Mn, Se, and Sr that were separated from uranium in the Church Rock deposits are the same elements that are enriched in the secondary deposits in the Ambrosia Lake district. The enrichment of these elements in the secondary ores at Ambrosia Lake indicates that these elements are mobile in the redistribution process. The separation of Ca, Cu, Fe, Mn, Se, Sr, and V from uranium in the Church Rock deposits and the concentration of these same elements in the secondary ores at Ambrosia Lake supports the contention that the primary ores are the source of many of the elements in the secondary deposits and suggests some different processes were involved in the formation of the Church Rock deposits than in the formation of the secondary deposits at Ambrosia Lake. Although molybdenum was leached from the ore in the Church Rock district, and probably to a lesser extent from the Ambrosia Lake district, molybdenum concentrations are not known to occur in association with the secondary ores (Spirakis, Pierson, and Granger, 1981). This may be due to the migration of molybdenum farther down hydrologic gradient than other elements associated with secondary ores (Day, Spirakis, Zech, and Kirk, 1982).

Although the chemical characteristics of the deposits provide some insights into the ore-forming processes, detailed mineralogic and paragenetic studies will be required to confirm the ideas presented here.

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