Deposition of Uranium in Salt-Pan Basins

By KENNETH G. BELL

SHORTER CONTRIBUTIONS TO GENERAL GEOLOGY

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ABSTRACT

Drainage waters carry minute quantities of uranium into oceans, inland seas, and lakes, and when bodies of water evaporate completely in desiccating salt-pan basins, the uranium must be deposited together with all other dissolved materials. The ratio of uranium to total evaporite sediments is approximately $1:2 \times 10^7$. The distribution of uranium in salt-pan basin sediments is not completely known. Some organic-rich muds, and phosphatic sediments deposited in desiccating basins may contain uranium in amounts as large as 0.0X percent. Uranium may be adsorbed on clays that are deposited with some evaporite sediments. These muds, phosphatic sediments, and clays may remove nearly all of the dissolved uranium from the water of some basins. Anhydrite, gypsum, halite, and potassium-bearing evaporite minerals probably are the least uraniferous of all rocks in the earth's crust; their uranium contents generally are less than 0.00001 percent. Within salt-pan basins where oxidizing conditions tend to prevail, and no significant amounts of organic-rich muds, clays, and phosphatic sediments are deposited, highly soluble uranium salts remain in solution and are deposited only as the basin finally is completely desiccated. These final highly soluble evaporite sediments are not likely to be preserved because they are subject to removal by wind erosion and leaching.

INTRODUCTION

Waters draining lands commonly carry minute amounts of dissolved uranium. Unless drainage waters have traversed highly uraniferous terranes, their contents of uranium generally are fractions of a part per billion (Fix, 1956; Judson and Osmond, 1955; Adams, 1954; Rona and Urry, 1952). This uranium is carried into lakes, inland seas, and the oceans.

Ocean water contains traces of uranium; the amounts vary slightly, depending upon total salinity, depth, and position with respect to shore line. Uranium contents ranging from 0.36 to 3.5 parts per billion (ppb), oil 0.36 to 3.5×10^{-9}, for ocean water from different localities have been reported by various authors (Hernegger and Karlik, 1935; Föyn and others, 1939; Koczy, 1950; Nakanishi, 1952; Rona and Urry, 1952; Stewart and Bentley, 1954; Rona and others, 1956). There are few published data on the uranium contents of waters from saline lakes and inland seas. Stewart and Bentley (1954) have reported uranium contents of 4.7 to 5.3 micrograms per liter (4.7 to 5.3 ppb) in water samples from Great Salt Lake, Utah. Some samples from the Salton Sea, Calif., that were analyzed in the U.S. Geological Survey laboratories contained about 10 ppb of uranium (Butler, A. P., Jr., written communication, 1947). Tourtelot (1955) has stated that highly alkaline water from lakes in western Nebraska contains 12 to 100 ppb of uranium. The concentration of uranium in ocean water is about a 10-fold increase over that in drainage waters, and the concentration in some saline lake waters is greater.

The amount of uranium that can be deposited within a salt-pan basin normally is very small. If the figure of 0.1 ppb, indicated by Fix (1956) to be approximately the average uranium content for water of major streams in the United States, is considered to represent drainage waters in general, then 10 billion tons, or 7.4 million acre-feet, of water must evaporate for each ton of uranium deposited during complete desiccation. An approximate comparison between the amount of uranium and the total amount of evaporite sediments that can be deposited from a given volume of water can be obtained by considering the composition of the ocean. If the quantity of 35 grams per kilogram (35,000,000 ppb) for the total salinity of ocean water (Sverdrup and others, 1942, p. 176–177 and 219) and a uranium content of 1.5 ppb are used, and desiccation is assumed to be complete, a simple calculation shows that for every ton of uranium deposited about 23 million tons of evaporite sediments are deposited. If the uranium is assumed to be uniformly distributed in the evaporite sediments the content would be less than 0.00001 percent.

If an undrained basin that initially held a lake, an inland sea, or a detached body of ocean water becomes completely desiccated, all the dissolved material is deposited, mostly in the form of saline or evaporite sediments; a minute portion of the dissolved matter may be adsorbed on clastic and organic sediments. Uniform, uninterrupted desiccation would cause progressive deposition of the most abundant minerals in the general sequence: calcium carbonate (as calcite or limestone) and calcium phosphate (as forms of apatite or dispersed in other minerals), calcium sulfate (as gypsum and anhydrite), sodium chloride (as halite), potassium chloride (as sylvite), and magnesium chlorides and sulfates; other less abundant minerals may be deposited. This idealized sequence rarely is obtained because desiccation generally is neither uniform nor uninterrupted; cyclic repetition of parts of the sequence may occur many times, mainly because of influxes of water into the basin. An important result of influxes of water is the increasingly high concentration of very soluble salts in the residual liquid as desiccation reduces the volume and causes precipitation of slightly and moderately soluble salts (evaporite minerals); the influxes also may bring substantial amounts of detrital and organic sediments into the basin. Complete desiccation can be expected to result in deposition of a final, uppermost thin layer containing the most soluble evaporite minerals.

Some minerals and compounds in an evaporite sequence may be intermixed to a considerable degree. Calcium phosphate is likely to be dispersed in calcite (or limestone). Calcite and gypsum or anhydrite may be intimately mixed or occur in alternating, thin, relatively pure layers. Sylvite commonly is mixed with halite. After desiccation has ceased, redistribution of material may result in the formation of secondary minerals that may be intermixed with the primary minerals; polyhalite, carnallite, and other minerals that are double salts may be formed in this manner. Redistribution of material may tend to concentrate some elements in thin zones. The physical chemistry of the formation of evaporite minerals, both during and after desiccation, is not fully known.

There is no analytical evidence that conclusively indicates that uranium minerals are deposited from saline water simultaneously with anhydrite, gypsum, halite, sylvite, and other minerals of similar solubility. As desiccation proceeds and minerals of increasing solubility are deposited, the concentration of uranium in the water should increase, and uranium minerals should be deposited with the final, most soluble evaporite minerals. Clays, shales, and organic sediments that are interbedded with some evaporite sediments commonly contain slightly greater amounts of uranium, probably held by adsorption or chemically combined with organic matter, than the evaporite minerals themselves. Any calcium phosphate minerals that are deposited can be expected to contain small amounts of uranium held in isomorphous substitution for calcium.

Most of the uranium that enters lakes, inland seas, and oceans with drainage waters probably is carried as highly soluble uranyl ions or in complex ions containing a uranyl radical. Inasmuch as uranium salts that might be present in lake or ocean waters are highly soluble, a tremendous concentration of such ions must occur before any evaporite uranium minerals are deposited. The hydrous forms of uranyl chloride ($UO_2Cl_2 \cdot 3H_2O$) and uranyl sulfate ($2UO_2$ $SO_4 \cdot 7H_2O$) are soluble to the extent of several parts of the salt to one part of water; sodium and potassium chlorides are soluble to the extent of about 0.35 parts of the salt to one part of water at 20° C (Chemical Rubber Publishing Co., 1956, p. 622–623, 596–597, 570–571). The deposition of halite, sylvite, and other saline minerals of similar solubility begins long before saturation points of hydrous uranyl salts are reached.

A desiccating body of water, particularly if it is shallow, generally is well aerated and therefore maintains an oxidizing environment. This condition is indicated by the common presence of ferric oxides as impurities in evaporite sediments. The oxidizing environment maintains the dissolved uranium in the highly soluble uranyl form. A reducing environment, caused by stagnation of part of the body of water or by an influx of putrefying organic matter, is either a local or a temporary condition. Where a reducing environment exists some uranium may be reduced to the tetravalent state and be deposited with organic-rich muds, or some uranium in the uranyl state may be sorbed by organic matter and subsequently become reduced to the tetravalent state. Many evaporite deposits include no sediments that could have been deposited only under reducing conditions. Reduction or sorption of uranyl uranium and its incorporation in nonsaline reduzates is strictly the result of a local condition that exists temporarily during desiccation of some salt-pan basins. It is probable that in most basins only a small part of the uranium in the water is removed by this mechanism.

Shortly after the desiccation of a salt-pan basin begins, the water becomes permanently saturated with the carbonate ion in equilibrium with calcium except for short intervals occurring immediately after large influxes of water. The carbonate ion is an effective agent for holding the uranyl ion in solution. Whether or not it plays a significant role in maintaining the solubility of uranium in desiccating basins is a moot question. It is probable that the concentration of carbonate ion considerably exceeds that of the uranyl ion until possibly such time as desiccation is almost complete. The excess of carbonate ion enhances the solubility of the uranyl ion, but in an oxidizing environment the uranyl ion is so soluble that the presence of carbonate may not be significant. Also, little seems to be known concerning the effect of the carbonate ion on the adsorption of uranium by clays and other substances.

URANIUM IN EVAPORITE MINERALS AND DEPOSITS

Thin beds of limestone or marlstone may be deposited during the initial stage of desiccation in a salt-pan basin. The uranium content of such limestone and marlstone generally is in the order of 0.0001 percent, or less, except where the rock is appreciably phosphatic.

Ocean water contains phosphorus in amounts ranging from 0.001 to 0.1 mg per kg, or 1 to 100 ppb (Sverdrup and others, 1942, p. 176). Complete precipitation of this phosphorus in the form of marine apatite produces about 0.005 to 0.5 milligrams of the phosphate mineral. The waters of some lakes and inland seas contain more phosphorus than the ocean waters. It has been established that marine phosphatic sediments generally contain small and variable amounts of uranium, and some phosphatic sediments deposited from saline lake waters are also uraniferous. Investigations by Altschuler and others (1958) have shown that sedimentary marine apatite typically contains between 0.005 and 0.02 percent uranium that is considered to be in the apatite structure in isomorphous substitution for calcium. Deposition of phosphatic sediments from saline waters therefore provides a mechanism for removal of uranium.

Pure phosphate minerals are not characteristic constitutents of evaporite deposits because the small quantities of phosphates present generally are dispersed in other evaporite minerals, but all the dissolved phosphate must be deposited in any basin that becomes completely desiccated. The relatively low solubility of the phosphate minerals causes them to be deposited simultaneously with the carbonate minerals, and consequently in an evaporite sequence a large portion of the phosphatic constituents are deposited early and are found in thin beds of slightly phosphatic marlstone or limestone. By use of the values given by Sverdrup and others (1942, p. 176) for the phosphorus content of ocean water and the data of Altschuler and others (1958) for the uranium content of marine phosphatic sediments it can be seen that the phosphatic constituent removes a variable portion of the available uranium (0.005 to 0.5 milligrams of phosphate mineral containing between 0.0000003 and 0.0001 milligrams of uranium, whereas the available uranium averages approximately 0.002 milligrams per kilogram of ocean water). Phosphatic sediment that rests upon the bottom for a long period of time continues to take up uranium, and reworked marine apatite may contain as much as 0.1 percent of this element (Altschuler and others, 1958). Under some conditions the phosphatic sediments may remove essentially all of the uranium from the saline water; under other conditions only a small fraction of the available uranium may be removed. Evaporite minerals that are deposited after the bulk of the carbonate minerals generally contain mere traces of phosphates; such minute quantities of uranium as are in gypsum, anhydrite, halite, and sylvite could be associated with phosphatic impurities.

Large amounts of calcium sulfate minerals are deposited during the early stages of desiccation of salt-pan basins that initially are filled with ocean water. Gypsum is deposited during desiccation of lakes and inland seas that are characterized by sulfate-rich waters. Many thick deposits of anhydrite and gypsum occur in nearly pure form, that is, they contain less than 20 percent of other materials. If organic matter and clays are not the major impurities, these deposits are essentially devoid of uranium. As indicated below, the sulfate minerals hold only minute traces of uranium, and the uranium content of impure anhydrite and gypsum rocks is contained in the clay, organic matter, and other substances, and not in the sulfate minerals.

Many deposits of anhydrite become partly or wholly converted to gypsum by the hydrating action of ground and surface waters, therefore, a question arises concerning the possibility that uranium might be leached during the hydration. This action undoubtedly can occur, but it is probable that the anhydrite held no significant amount of uranium. Gamma-ray logs of test wells drilled through evaporite sequences indicate that anhydrite and halite strata show, in general, the lowest levels of radioactivity of all sedimentary rocks. Examples of this low radioactivity are found in gamma-ray logs of many wells drilled through evaporite-mineral deposits in the Paradox basin of southwestern Colorado and southeastern Utah and in the Delaware basin of southeastern New Mexico.

On the west slope of the Humboldt Range, Pershing County, Nev., there are large outcrops of gypsum, one of which has an area of about a square mile. The principal impurities in this gypsum are carbonate minerals. The outcrops are covered by a layer of weathered gypsum a few inches thick mixed with a small amount of wind-deposited sediment derived mostly from dust and salt flats of the adjacent Humboldt Sink. Radioactivity measurements made on the outcrops with a scintillation counter gave readings of approximately 0.003 milliroentgens per hour when the instrument was held about 2 feet above the weathered gypsum surface. The readings were almost nil where taken inside some prospect tunnels. The small amount of energy measured on the outcrop probably was predominately cosmic radiation. A similar condition exists in White Sands National Monument, N. Mex., where dunes of gypsum sand cover large areas. A scintillation counter gave no measurable reading during a traverse of some of these dunes (A. P. Pierce and J. W. Mytton, U.S. Geological Survey, oral communication, 1957).

Secondary uranium minerals have been found in a few bedded gypsum deposits, for example in the Paradox member of the Hermosa formation in Gypsum Valley, San Miguel County, Colo., and in the Brule formation, Dawes County, Nebr. These uranium minerals are epigenetic and have been introduced by ground and surface waters. The Brule formation is nonmarine, and its gypsiferous member was deposited from a lake of sulfate-rich water in which the salinity apparently did not reach the point where minerals more soluble than gypsum were deposited. A field examination in sec. 3, T. 34 N., R. 47 W. showed that anomalous radioactivity, and uranium minerals, occur at scattered points along the gypsum outcrop where there are intermittent ground-water seeps. The flow of water is insufficient to make surface streams, except during unusually wet periods, but does cause small landslides and collapse of steep slopes. The uranium minerals are carnotite, autunite, and sabugalite [$Hal(UO_2)_4(PO_4)_4 \cdot 16\ H_2O$] (Dunham, 1955). They are concentrated on the surfaces of the outcrops and in the thin soil mantle where the ground water evaporates. Where there is no evidence of ground-water seepage, neither anomalous radioactivity nor uranium minerals can be found.

Two samples of the bedded gypsum from the Brule formation contained 0.0008 and 0.0001 percent of uranium (Nos. 260461 and 260462, table 1). Sample no. 260461 was light brown, had a strong fetid odor, and contained a small amount of organic matter that probably had sorbed the apparently anomalous amount of uranium; sample 260462 was white and odorless. The samples contained about 5 percent of acid-insoluble matter. The waters that formed the Brule lake drained a terrane characterized by sedimentary deposits containing an abundance of volcanic ash and therefore probably contained greater-than-average quantities of uranium. This condition is reflected in the abnormally high uranium content of the gypsum. It is unlikely that the minute, although anomalous, amount of uranium in this gypsum accounts for the secondary uranium minerals on the surfaces of the outcrops and in the topsoil. It is more likely that the uranium in the secondary minerals is leached from tuffaceous clays in the vicinity and is deposited on the outcrops and in the topsoil where the water evaporates.

Anhydrite is anomalously radioactive within or in the vicinity of some petroleum and natural gas fields, for example, in the Permian formations of the Panhandle field of Texas. Investigations have shown that the radioactivity originates in uraniferous organic substances that have been epigenetically emplaced in secondary anhydrite; the primary anhydrite, which was deposited as an evaporite sediment, is no more uraniferous than primary anhydrite found elsewhere (A. P. Pierce, U.S. Geological Survey, oral communication, 1957).

The uranium contents of some typical deposits of anhydrite and gypsum are presented in table 1. Three samples (Nos. 252251, 252252, and 260461) contained small amounts of organic matter. These three samples contained anomalous quantities of uranium, which possibly were sorbed by the organic matter.

Saline minerals, such as halite, sylvite, carnallite, and others of similar solubility contain so little uranium that the amount cannot be determined with pre-

TABLE 1.—*Uranium content of typical deposits of anhydrite and gypsum*

[Analysts: D. L. Ferguson, H. H. Lipp, W. J. Mountjoy, C. G. Angelo, J. P. Schuch, and E. J. Fenelly.]

Sample No.	Material	Acid-insoluble matter percent	SO_4 percent	Uranium percent
252250	Anhydrite			0.0001
252251	do			.0004
252254	do			.0002
260459	Gypsum	10.2	35.5	.0001
260460	Anhydrite	.5	39.9	.0001
260461	Gypsum	5.0	40.1	.0008
260462	do	5.9	41.8	.0001

NOTE.—Sources of samples:

252250. Sample of core chips, Shell Oil Co.'s Desert Creek No. 1 well, SW¼SE¼NW¼ sec. 2, T. 42 S., R. 23 E., San Juan County, Utah, depth 5,122½ ft.

252251. Same as source of sample 252250; depth 5,124½ ft.

252254. Sample of core chips, Reynolds Metal Co.'s Hatch No. 1, sec. 4, T. 39 S., R. 24 E., San Juan County, Utah, depth 5,797–5,799 ft.

260459. Sample from prospect tunnel, W½ sec. 27, T. 26 N., R. 32 E., Pershing County, Nev.

260460. Sample from abandoned Regan mine, approximately 12 miles south of Yerington, Nev.

260461. Sample from outcrop of gypsiferous member of Brule formation, W½ sec. 3, T. 34 N., R. 47 W., Dawes County, Nebr.

260462. Sample from same locality as sample 260461.

cision by standard methods of chemical analysis. There are but few published data on this subject. Kemény (1941) has reported that the uranium contents of rock salt, sylvite, and carnallite from Germany and Austria, determined by radiometric methods, average 0.0006 percent (6×10^{-10} g/g). Gentner and others (1954) have reported a uranium content of 0.00001 percent (1×10^{-10} g/g) for sylvite from Buggingen, Germany; the determination was made by a method of counting alpha tracks on an emulsified plate. A few samples of potash ores, consisting mainly of halite, sylvite, and polyhalite, from the Carlsbad district, New Mexico, have been tested for uranium in the Geological Survey laboratories. The uranium contents of the samples were less than 0.0001 percent, so no attempt was made to determine them precisely. All uranium determinations by the Geological Survey laboratories were made by fluorometric methods.

These meager data do not indicate enrichment of uranium in evaporite sediments. They do not warrant any conclusions regarding the proportionate rate at which uranium is deposited during stages of desiccation represented by halite and sylvite.

The clays and the iron and aluminum oxides that are deposited with saline minerals probably as a rule are considerably more uraniferous than the saline minerals themselves. Some information about the distribution of uranium between water-soluble evaporite minerals and water-insoluble matter was obtained by analyzing several samples taken from a drill core recovered from potassium-bearing beds in the Salado formation of Permian age, Delaware basin, N. Mex. The samples were cut from a 19-foot length of core from a stratigraphic section that includes two thin zones having large contents of clays. The clays evidently were deposited when large influxes of sediment-bearing water entered the basin. The analytical data are presented in table 2.

The sections of core were split lengthwise, and one part was crushed and mixed to provide material for analysis. Uranium in the total sample was determined by a fluorometric method. The samples were then separated into water-soluble saline minerals, water-insoluble but acid-soluble saline minerals, and water- and acid-insoluble matter by the following procedure: The samples were leached by weighing 1 gram of the substance into a tared sintered glass crucible of medium porosity, 10 ml of water were added, the slurry was stirred briefly, and the resulting solution was drawn by vacuum into a volumetric flask; this procedure was repeated ten times for a total of 100 ml of water; the water-soluble evaporite minerals, such as halite and sylvite, and a small portion of the slightly water-soluble minerals, such as polyhalite and anhydrite, were dissolved in the water leachate; the crucible and contents were then dried under a vacuum of less than 1 cm of mercury in a desiccator containing anhydrous calcium sulfate, were weighed, and the leaching procedure repeated with 1:1 hydrochloric acid; the acid leachate contained most of the polyhalite and the calcium sulfate minerals, as well as phosphate and carbonate minerals; the water- and acid-insoluble matter remaining in the crucible consisted of clay minerals and other clastic sediments, which were then dried and weighed.

An attempt was made to determine the uranium contents of the water-soluble leachates by the fluorometric method, but the quantities of uranium present were below the threshold of the procedure used, or less than 0.00002 percent. Uranium in the acid leachates was determined, but there is no assurance that the values obtained are indicative of the uranium contents of the water-insoluble but acid-soluble minerals; some of this uranium may have been adsorbed on clays and was removed by the acid. Uranium in the water- and acid-insoluble matter was obtained by difference, and again there is no assurance that the values indicate the true quantities of uranium because some uranium may have been removed by the acid.

The data presented in table 2 indicate that most of the uranium is concentrated in the water-insoluble but acid-soluble matter and the water- and acid-insoluble matter. The water-soluble matter contains extremely small amounts of uranium, the amount being less than 0.00002 percent of the total sample for all samples analyzed. The uranium contents of the water-insoluble but acid-soluble matter are very small and show a positive correlation with the total uranium contents of the samples; the latter feature may be an indication of extraction of uranium from the water- and acid-insoluble matter by the acid.

One sample (No. 254465, table 2) is of especial interest because it represents a clay-rich zone about 6 inches thick. Unfortunately about three-quarters of the material from this zone was lost during drilling; that which was recovered was completely consumed in the various chemical analyses. The megascopically visible constituents of the sample were coarse crystalline halite, sylvite, and polyhalite, and galls and stringers of greenish-gray clay consisting of montmorillonite, illite, and kaolinite and (or) chlorite. The analytical data (table 2) indicate the presence of a surprisingly large amount of uranium; two splits of the core contained 0.0078 and 0.038 percent uranium,

TABLE 2.—*Chemical and mineralogic determinations on samples from a drill core of an evaporite deposit Potash Company of America drill-hole-151, Sec. 12, T. 20 S., R 33 E., Lea County, N. Mex.*

[Analysts: W. T. Mountjoy, H. H. Lipp, and C. G. Angelo, U.S. Geological Survey. Clay minerals indentified by A. J. Gude, U.S. Geological Survey.]

Sample No.	Sample interval (depth)	Principal minerals	Water-soluble saline minerals	Water- and acid-insoluble matter	Acid-soluble but water-insoluble saline minerals (by difference) [1]	Uranium (as percent of total sample)				Chemical composition (as percent of total sample)											
						Total	In water leachate	In acid leachate	In insoluble matter (minimum by difference)	$CO_3^=$	Water leachate						Acid leachate of water-insoluble matter [2]				Approximate summation
											Ca^{++}	Mg^{++}	Na^{++}	K^+	$SO_4^=$	CL^-	Ca^{++}	Na^+	K^+	$SO_4^=$	$PO_4^=$	
254463	2,258 ft 0 in to 2,262 ft 4 in.	Halite	99.85	0.10	0.05	0.00008	<0.00002	<0.00001	0.00005	------	0.56	0.29	35.75	3.93	2.85	52.28	0.06	<0.02	0.02	<0.02	<0.0005	101.8
254464	2,262 ft 4 in. to 2,263 ft 8 in.	Polyhalite	67.2	.65	32.15	.00012	<.00002	.00002	.00008	------	9.18	2.80	1.12	10.00	43.50	1.78	3.78	.02	2.78	17.50	.007	91.3
[3] 254465	2,263 ft 8 in to 2,264 ft 2 in.	Halite, sylvite, montmorillonite, Illite, kaolinite and (or) chlorite, carbonate minerals.	71.6	19.4	9.00	.038	------	------	------	2.61	1.60	3.06	9.14	9.17	7.60	27.85	1.70	<.02	.07	1.06	------	83.2
						[3].0078	<[3].00002	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------
						------	------	[3].04	------	------	------	------	------	------	------	------	------	------	------	------	[3].041	------
254466	2,264 ft 2 in to 2,264 ft 10 in.	Halite	99.49	.47	.04	.00006	<.00002	<.00001	.00003	------	.47	.29	35.75	4.90	2.05	56.45	.04	<.02	<.02	.05	<.0005	100.5
254467	2,264 ft 10 in to 2,268 ft.	Halite, sylvite	99.05	.88	.07	.00004	<.00002	<.00001	.00001	------	.12	.62	22.25	22.60	2.12	52.10	.04	<.02	<.02	.02	.001	101.0
254468	2,268 ft to 2,273 ft 6 in.	Halite, sylvite, clay minerals.	94.3	3.9	1.80	.00065	<.00002	.00007	.00056	------	.24	.47	26.25	14.00	1.38	52.00	.78	.15	.02	.75	.009	99.9
254469	2,273 ft 6 in to 2,274 ft 6 in.	Halite, sylvite, montmorillonite, Illite, kaolinite and (or) chlorite.	61.9	32.7	5.40	.00011	<.0002	<.00001	.00008	------	.56	2.07	13.46	4.42	3.30	28.90	.24	<.02	.08	.29	.004	90.2
254470	2,274 ft 6 in to 2,277 ft.	Halite	98.3	.89	.81	.00004	<.00002	<.00001	.00001	------	.71	.34	36.75	1.62	3.30	55.95	.17	.02	.02	.38	<.0005	100.2

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[1] Acid-soluble but water-insoluble saline minerals include carbonate and phosphate minerals, and part of any polyhalite, gypsum, and anhydrite in the sample.

[2] Mg^{++} and Ol^-, were present, are in amounts of less than 0.01 percent in all samples.

[3] Partial analyses were made of three portions of the sample.

or 78 and 380 (ppm); the acid-soluble matter of a third split, obtained after removing water-soluble matter, contained an amount of uranium corresponding to 0.040 percent (400 ppm) of the sample. The range of values is attributed to the coarse heterogeneous character of the material and the improbability of making three identical splits of the core. This sample contained about 19 percent water- and acid-insoluble matter, about 2.6 percent carbonate as $CO_3^=$, and about 0.041 percent phosphate as $PO_4^{\equiv}$.

Above average quantities of uranium and phosphate were found in the second thin clay-rich zone represented by samples 254468 and 254469 (table 2). The amount of uranium in sample 254468 was 0.00065 percent (6.5 ppm) and of phosphate as $PO_4^{\equiv}$ was 0.009 percent (90 ppm).

These clay-rich samples contained no visible uranium minerals and no fluorescent substance. Some uranium undoubtedly was combined with the phosphate constituent, but the amounts of uranium found seem to be considerably in excess of what reasonably could be accounted for by this combination. Some of the uranium could have been adsorbed on clays, and a finely dispersed uranium mineral could have been present.

The clay-rich zones undoubtedly represent interruptions in the desiccation of the basin caused by large influxes of water carrying dissolved matter and much fine-grained sediment. Such influxes could have resulted from occasional floods that washed the adjacent terrain. When the floods subsided, desiccation immediately was resumed; fine-grained suspended clastic sediments settled to the bottom and became mixed with the initial evaporite layer which contained some phosphatic and carbonate constituents. This action provided at least two mechanisms for removal of uranium from the basin water, adsorption on clays, and combination with phosphatic constituents. It seems probable that most of the uranium thus removed was already in the basin prior to the influx that brought in the clays.

Stagnant, anaerobic conditions may exist temporarily within the water of parts of some desiccating salt-pan basins. If there is an influx of fine-grained clastic sediments and organic matter during such periods, organic-rich dark muds or limy muds may be deposited and ultimately become shales. Some of such shales that are slightly phosphatic may be anomalously radioactive and contain uranium in the range of 0.00X to 0.0X percent. On the other hand, organic-rich muds can be deposited in oxidizing environments, and subsequently a zone in which reducing conditions exist may form in them although the uppermost layer of mud and the water above it remain in an oxidizing condition; under these circumstances the reducing zone is insulated from the main body of water, and the only uranium that can be sorbed is that in the connate water, consequently the muds do not become significantly enriched in uranium. Uranium-rich muds generally are deposited in reducing environments, and if the bottom surface remains in a reducing condition, sorption of uranium in a particular layer may continue for as long as water can move freely past or through it.

In the Paradox basin of southwestern Colorado and southeastern Utah some thin beds of euxenic dark-gray and black shale are interspersed among the carbonate and saline deposits of the Paradox member of the Hermosa formation. They are good marker beds for stratigraphic correlation because they show anomalously high radioactivity on gamma-ray logs. The characteristics and possible origin of these dark-shale beds have been discussed by Wengerd and Strickland (1954). The uranium contents of a few samples of some of these dark-shale beds and of the dolomites and anhydrite that enclose them have been determined. These data are presented in table 3. The samples were chipped from drill cores and represent the only material that was available at the time of this investigation. The most uraniferous sample, No. 252252, contained 0.0057 percent uranium. In general, the uranium contents of these shale beds are about an order of magnitude higher than those of the enclosing dolomites and anhydrite. Probably some uranium is sorbed by organic matter and phosphatic sediments and thereby is removed from the saline during the deposition of sediments such as those that formed the shales in the Paradox member. This mechanism operates only temporarily in a few basins and probably removes only a small part of the dissolved uranium from the water.

TABLE 3.—*Uranium contents of euxenic dark shales and enclosing dolomites and anhydrite from the Paradox basin.*

[Analysts: G. G. Angelo, J. P. Schuch, and E. J. Fennelly]

Sample No.	Depth (feet)	Description	Uranium percent
Shell Oil Co.'s North Boundary Butte No. 1 Well, C SW¼ NE¼ sec. 33, T. 42 S., R. 22 E., San Juan County, Utah			
252220	4,212	Limy gray shale	0.0009
252221	4,615	do	.0007
252222	4,617	do	.0009
252223	4,618½	do	.0013
252224	4,620½	Shale and dolomite, anhydrite	.0005
252225	4,621½	Dolomite	.0004
252226	4,622	do	.0011
252227	4,623	do	.0003
252228	4,625	Dolomite, anhydrite	.0003
252229	4,628	Limy gray shale	.0006

TABLE 3.—*Uranium contents of euxenic dark shales and enclosing dolomites and anhydrite from the Paradox basin*—Continued

Sample No.	Depth (feet)	Description	Uranium percent
Superior Oil Co.'s No. 1-28 Navajo Well, C NW¼ NW¼ sec. 28, T. 41 S., R. 26 E., San Juan County, Utah			
252230	6,048–6,049	Shaly dolomite	0.0006
252231	6,053–6,054	do	.0006
252232	6,055–6,056	Gray shale	.0007
252233	6,056–6,057	do	.0007
252234	6,057–6,058	do	.0008
252235	6,058–6,059	do	.0006
252236	6,058–6,060	Black shale	.0006
252237	6,061–6,062	do	.0010
252238	6,062–6,063	do	.0010
252239	6,063–6,064	do	.0010
252240	6,064–6,065	do	.0012
252241	6,065–6,066	do	.0007
252242	6,067-6,068	do	.0006
252243	6,068–6,069	do	.0007
252244	6,069–6,070	do	.0011
252245	6,070–6,071	do	.0032
252246	6,071–6,072	do	.0013
252247	6,072–6,073	Shaly dolomite	.0007
252248	6,073–6,074	Dolomite	.0002
Shell Oil Co.'s Desert Creek No. 1 Well, SW¼ SE¼ NW¼ sec. 2, T. 42 S., R. 23 E, San Juan County, Utah			
252249	5,122½	Anhydrite	0.0001
252250	5,124½	do	.0001
252251	5,126	Gray shale	.0004
252252	5,127	Black shale	.0057
252253	5,128½	Dolomite	.0001
Reynolds Metal Co.'s Hatch No. 1 Well, sec. 4, T. 39 S., R. 24 E., San Juan County, Utah			
252254	5,797–5,799	Anhydrite	0.0002
252255	5,799–5,799¼	Black shale	.0017
252256	5,799¼–5,800	Shaly dolomite	.0005

The data presented above indicate that the distribution of uranium in sediments deposited in desiccating salt-pan basins is not uniform and is not completely known. In attempting to determine the distribution, a major difficulty arises from the fact that the amounts of uranium and its compounds involved are very small in comparison to the total bulk of sediments. It is known that in some salt-pan-basin deposits uranium is not uniformly distributed among the various sedimentary materials but is relatively enriched in clays, in phosphatic sediments, and in some beds of organic-rich, dark shale that were deposited in reducing environments. It is possible that in some basins essentially all of the dissolved uranium can be removed from solution by inclusion in clays and phosphatic and organic sediments. Within basins where such sediments are not deposited, or are deposited in very small amounts, it seems most likely that a substantial part of the uranium must remain in solution until the bittern finally evaporates.

The probability that the concentration of uranium increases continuously in the water of some salt-pan basins even though substantial amounts of clays, phosphatic sediments, and carbonate and evaporite minerals are deposited is indicated by the comparatively high concentrations of uranium in the waters of the Salton Sea, Calif., and Great Salt Lake, Utah. Much of the water entering Great Salt Lake drains terranes to the east and northeast that are composed in part of highly phosphatic formations (Phosphoria and Park City formations). Rather extensive deposits of calcareous oolites that contain small amounts of phosphatic material are found along parts of the shore, and the oolites still are being formed; black, organic-rich clays are being deposited along other parts of the shore (Eardley, 1938). The uranium contents of the oolites and black clays are unknown. Even though these sediments are types that commonly are enriched in uranium from solution, the lake water has about twice the concentration of uranium as does ocean water. The concentration of uranium in the Salton Sea (10 ppb) is about four times that of ocean water.

It already has been pointed out that within desiccating salt-pan basins oxidizing conditions tend to prevail and reducing conditions tend to be localized and often are of brief duration. As a consequence, most of the dissolved uranium is maintained in the highly soluble uranyl state. The uranyl salts are so highly soluble that it is reasonable to assume that the water in a basin must evaporate completely to cause deposition of uranium that is not sorbed by clays, organic matter, and phosphatic sediments. If the water never evaporates completely it is unlikely that any uranium salts will be deposited. If a basin becomes completely desiccated, a small but appreciable amount of uranium minerals should be deposited in a final layer of highly soluble evaporite minerals. Such uraniferous deposits apparently are unknown; the reason is that they are readily susceptible to removal.

The surface of a dried-up basin, or even a partly dried-up basin, is subject to wind erosion that can remove considerable amounts of sediment. Anyone who has been in the vicinity of the Bonneville salt flats of Utah, or the smaller salt flats in the Carson and Humboldt Sinks of Nevada, in the Mohave and Death Valley areas of California, or the bolsons of west Texas on windy days can attest to the fact that wind moves large amounts of evaporite minerals. An indication of the amount of evaporite material that can be so moved is given by Eardley and others (1957, p. 1151) in discussing wind erosion in the Bonneville basin of Utah. They stated: "The writers postulate that the wind removes about 3,000,000 tons of salt annually from the Great Salt Lake desert. This is carried by the wind out of the drainage basin." It is reasonable to assume that an exposed layer of uraniferous evaporite minerals could be removed by wind within a very short period.

Uraniferous evaporite minerals would have to be covered by some other kind of sediment immediately after they were deposited in order to be preserved from wind erosion. Even then, these very soluble minerals would be leached by the first passage of water through the sediments. This water would remove the highly soluble salts, including uranium salts, from the places of initial deposition and transport them laterally or downward, thereby dispersing them through much larger volumes of rock and sediment, or it would bring them to the surface to form deposits of efflorescent minerals that subsequently would become dispersed.

There is little possibility that a final deposit of uranium-rich evaporite sediments can be preserved in a salt-pan basin.

SUMMARY

In summary, it can be stated that evaporite sediments deposited in salt-pan basins are probably the least uraniferous of all rocks. Their uranium contents average less than 0.00001 percent. This condition results from (1) the paucity of uranium in ocean and surface waters, (2) the oxidizing environments that generally exist within the evaporating bodies of water, (3) the great solubility of uranyl chlorides and sulfates and uranyl carbonate complexes, and (4) the likelihood that any uraniferous evaporite sediments that might be deposited are removed by wind erosion or by leaching. Analytical work that would indicate whether uranium is deposited at a fairly uniform rate throughout the desiccation of a salt-pan basin or tends to remain in solution until the basin finally dries out has not been done. Theoretical considerations indicate that in some basins most of the uranium can be removed from solution through sorption by clays, phosphatic sediments and organic-rich muds; in other basins the bulk of the uranium should remain in solution until such time as desiccation is almost complete.

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