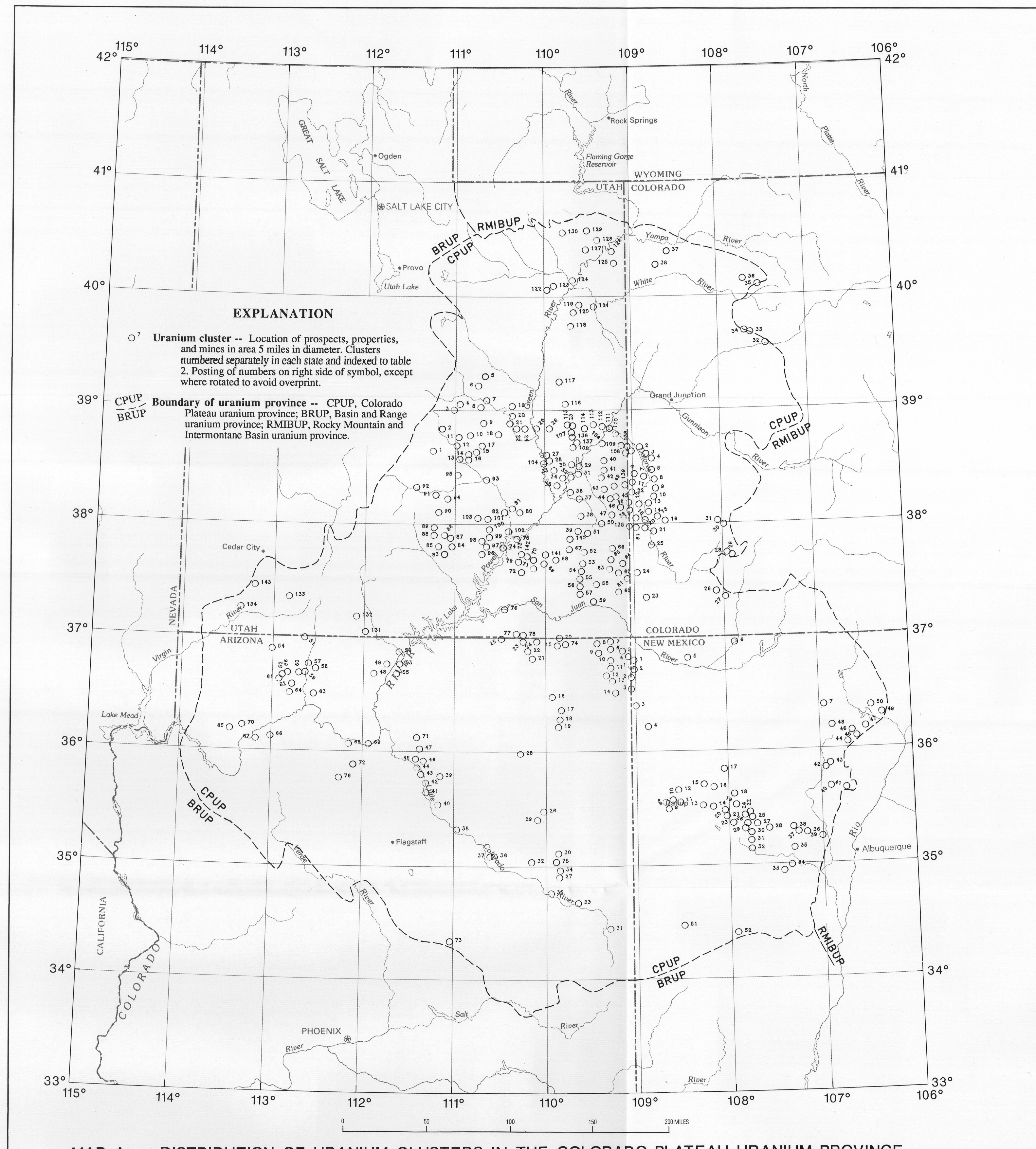
U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

MISCELLANEOUS FIELD STUDIES
MAP MF—2080

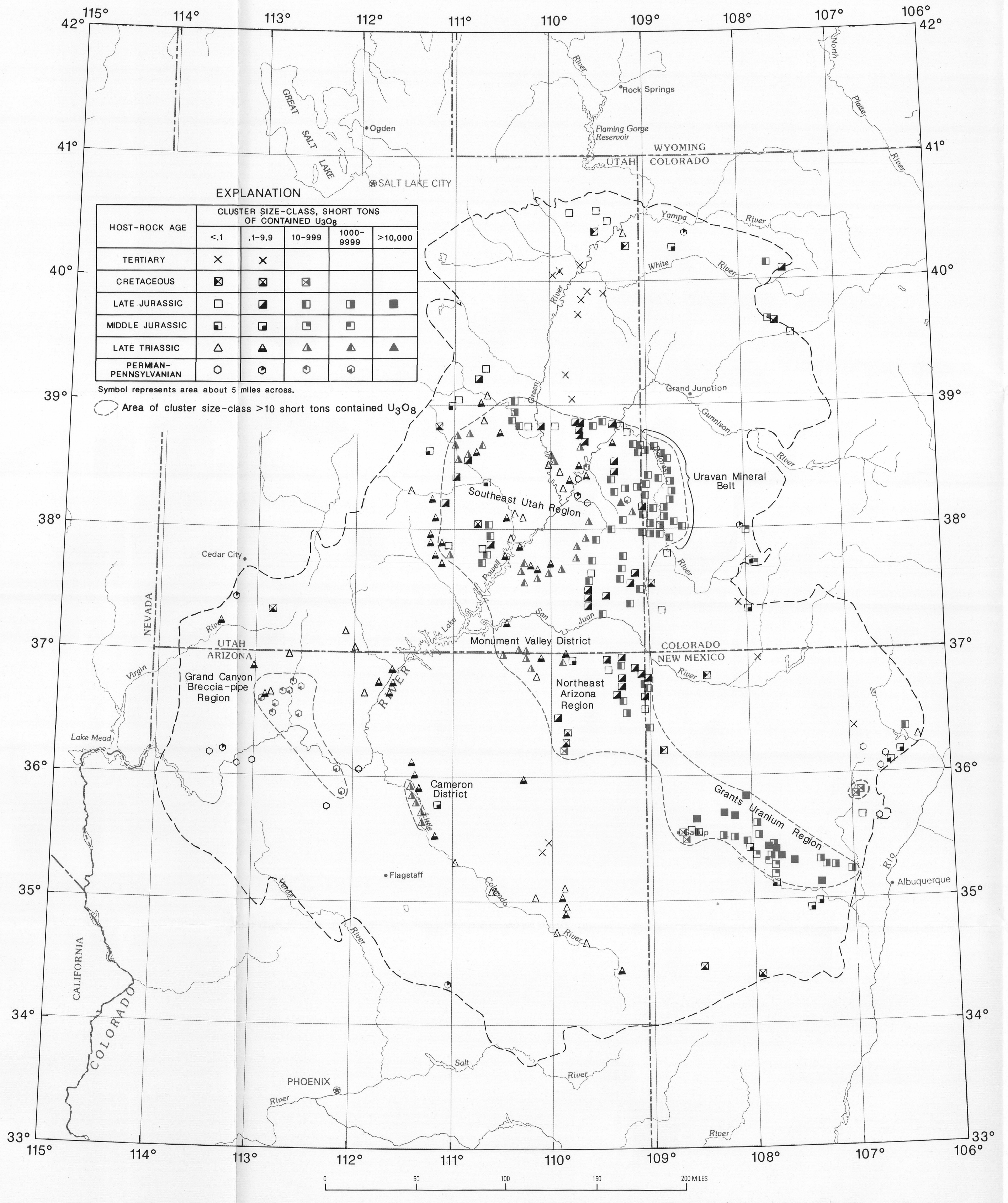


EXPLANATION

○7 **Uranium cluster** -- Location of prospects, properties, and mines in area 5 miles in diameter. Clusters numbered separately in each state and indexed to table 2. Posting of numbers on right side of symbol, except where rotated to avoid overprint.

CPUP / BRUP **Boundary of uranium province** -- CPUP, Colorado Plateau uranium province; BRUP, Basin and Range uranium province; RMIBUP, Rocky Mountain and Intermontane Basin uranium province.

MAP A.-- DISTRIBUTION OF URANIUM CLUSTERS IN THE COLORADO PLATEAU URANIUM PROVINCE



MAP B.-- DISTRIBUTION OF URANIUM CLUSTERS CLASSIFIED ACCORDING TO HOST-ROCK AGE AND SIZE-CLASS IN THE COLORADO PLATEAU URANIUM PROVINCE

By Warren I. Finch, Charles T. Pierson, and Cheryl W. Adkisson

TABLE 2.--*Index to names of uranium clusters shown on map A*

ARIZONA

Cluster number	Cluster name
01	Oak Springs
02	Upper Red Wash
03	Rocky Spring
04	Zona 1
05	North Mesa
06	Black Rock Point
07	John Kee 4
08	Barton 3
09	Sweetwater TP
10	Eurida
11	Sunny Side, Segi Ho Cho
12	Kinusta
13	Cove, East, and West Mesas
14	Lukachukai Mountains
15	Monument No. 2
16	Tom Wilson, Tom Klee
17	Yale Point
18	Begay 1
19	Burnt Corn Wash
20	Harvey Blackwater
21	Koley Black
22	Hunt's Mesa
23	Moonlight, Monument 1
24	Mitchell Butte
25	Tract 17
26	Morale
27	Ruth
28	Hanson 1
29	Bidahochi Butte
30	Navajo
31	Warhoop
32	Sain, Gerwitz
33	Chester
34	Juanita 3
35	Rainbow, Smith
36	Winslow, O'Haco
37	O'Haco-Robinson
38	Calvin Chee
39	Yellow Jeep
40	Amos Chee 1-3
41	Charles Huskon 4
42	Ramco
43	Huskon 3,10
44	Huskon 1
45	Jack Daniels
46	Huskon 20, 34
47	Huskon 5
48	Vermillion
49	Sun Valley
50	El Pequito
51	Kaibab Indian Lease
52	Big Blue, Radon, Rainbow
53	Tommy, June
54	B.P. Group
55	Thomas 1
56	Kathy J
57	Clearwater
58	Pigeon
59	Kanab North and South
60	Hermit
61	EZ-2
62	Hack Canyon
63	Pinenut
64	Arizona 1
65	Copper Mountain
66	Mohawk Canyon
67	Ridenour
68	Orphan Lode
69	Grandview
70	Chapel
71	Earl Huskon
72	Canyon
73	Neptune
74	Bluestone
75	Rock Garden
76	Doty

COLORADO

Cluster Number	Cluster Name
01	Beaver Mesa
02	Tenderfoot Mesa
03	Calamity, North Outlaw, Flat Top
04	South Outlaw
05	Long Mesa, Horse Mesa
06	Buckhorn, Carpenter Ridge
07	Carpenter Flats
08	Uravan, Atkinson Mesa
09	Long Park
10	Monogram Mesa
11	La Sal Creek
12	Anderson Mesa, Little Gypsum
13	Bull Canyon
14	Big Gypsum Creek, Hamm Canyon
15	Long Ridge, Gypsum Gap
16	Klondike Basin
17	Lower and Radium Groups
18	Slick Rock
19	Legin, Charles T. Deremo
20	Spud Patch
21	Horseshoe Group
22	Wray Mesa
23	Karla Kay
24	Roberta Jean, Blue Eagle
25	Arrow Head, Broken Thumb, Rainy Day
26	Shorty Lode
27	Good Hope, Nevada
28	Barlow Group
29	Graysill Group
30	Bear and Fall Creeks-Frazer
31	Black King
32	Revelation Group
33	End of Trail, Lotte
34	Rifle, Garfield
35	S&G 4, Stealy
36	Uranium Peak, Coal Creek
37	Little Star, Starlight
38	Skull Creek
39	Empire

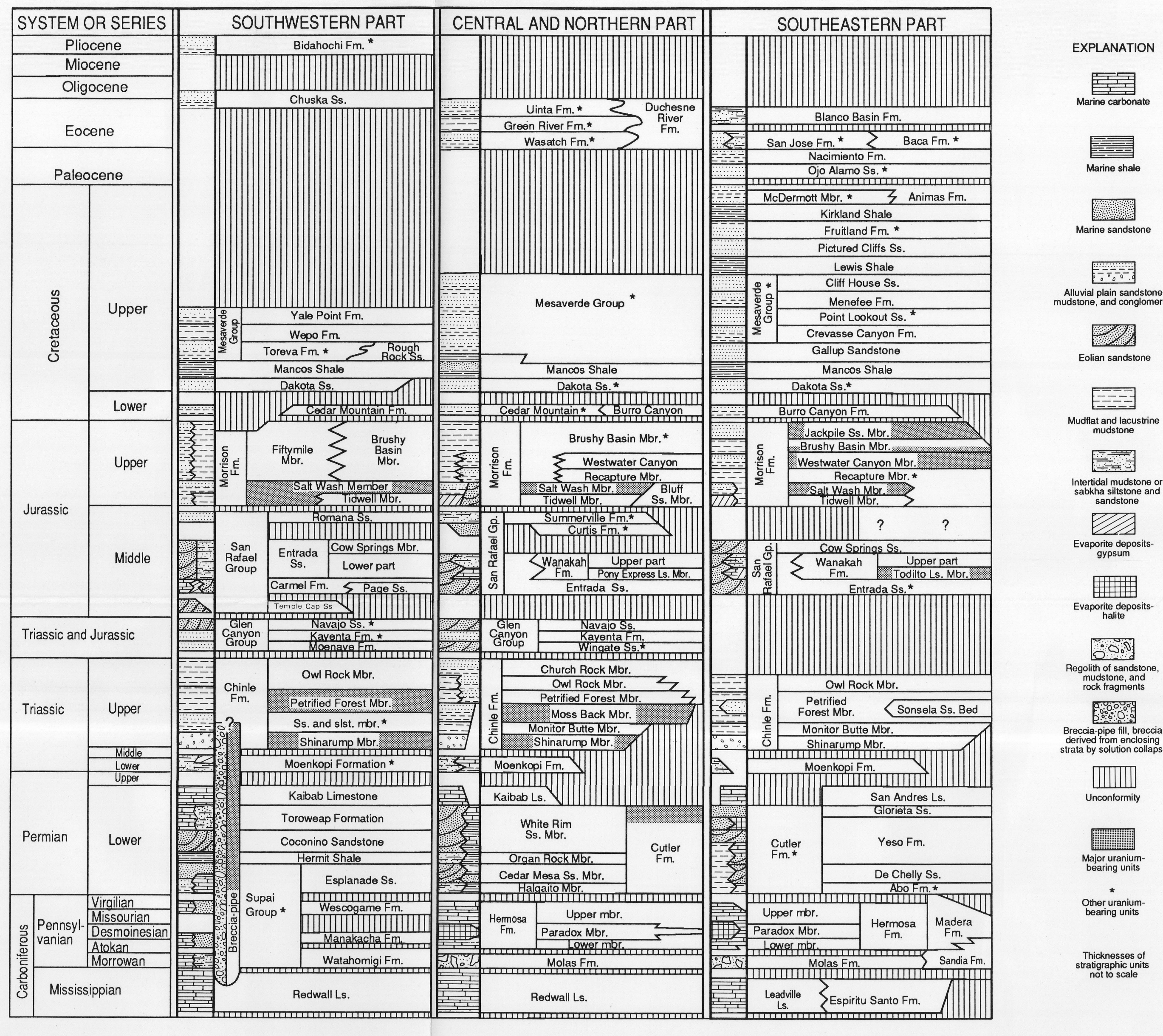
NEW MEXICO

Cluster Number	Cluster Name
01	Beclabito Dome
02	King Tutt Mesa
03	Enos Johnson
04	Adee B. Dodge
05	Boyd
06	Chitton and Son
07	Carbon and Log
08	Hogback
09	Becenti, Diamond
10	CD & S
11	Foutz, Westwater
12	Church Rock
13	Mariano Lake
14	Ruby
15	Dalton Pass
16	Crownpoint
17	Nose Rock
18	Borrego Pass
19	West Largo
20	Evelyn
21	Elkins
22	Ann Lee
23	Haystack
24	Dysart, Section 23
25	Cliffside
26	Poison Canyon
27	Johnny M, Marquez
28	Mt. Taylor
29	Faith, Hope, Barbara J
30	Red Bluff
31	F-33
32	Horace, Quemazon
33	Crackpot, Paisano
34	Sandy
35	Jackpile, Paquate, St. Anthony
36	Rio Puerco
37	San Antonio Valley
38	Marquez Canyon
39	Bernabe-Montano
40	Collins
41	Spanish Queen
42	La Ventana Mesa
43	Butler
44	R.A. Nos. 1 & 2
45	Arroya del Aqua
46	Hillfoot, Midcontinent
47	Box Canyon
48	Corral
49	Trejo Sanchez
50	Lucky Dog, Yeso
51	Hogback, Varnunm
52	Midnight, Red Basin

UTAH

Cluster Number	Cluster Name
01	Helm
02	Dog
03	Unnamed
04	Copper Rock, White Star
05	Cottonwood, Cedar Ridge
06	School Section 36
07	Buckhorn
08	Dexter
09	Wickiup
10	Consolidated, Green Vein, Hertz
11	Lucky Strike, Conrad
12	Dirty Devil
13	Delta
14	Cistern Group
15	Little Erma
16	Canary
17	Temple Mountain
18	Cliff Dweller
19	Sinbad
20	Vanura
21	Rainy Day
22	School Section 2
23	Cie Dog
24	Mohawk
25	Cooper King
26	Sunday
27	Cottonwood
28	A Group
29	Atomic King
30	Mile High
31	Colorado 1
32	Highbench, Lockhart, Lula
33	Taylor Canyon
34	C Group
35	Soda Roll
36	Cutler
37	Hart
38	Conglomerate
39	Horseshoe
40	Valley View
41	Blue Goose
42	Yellow Circle
43	San Juan, Rattlesnake
44	MiVida
45	Big Buck
46	Divide
47	Jimbo Bob
48	Wyoming
49	Pandora
50	Happy Jack
51	Rainbow
52	Lucky Lady
53	Buckskin
54	Cottonwood
55	Lonesome
56	Sunshine
57	Sandy
58	Tree
59	Ike
60	Pete
61	Lone Wolf
62	Blue Jay
63	Bradford Canyon
64	Dusty
65	Strawberry
66	Blue Eagle
67	King Edward, Notch
68	Okie
69	Hideout
70	Found
71	Maybe
72	Hershey, Markey
73	Happy Jack
74	Black Oxide
75	Jomac
76	Whirlwind
77	Taylor Reid
78	Mitten 1
79	Cub
80	Hatch Canyon
81	Happy Canyon
82	Poison Spring Canyon
83	Yellow Jacket
84	Rainy Day
85	Black Widow
86	Stud Horse, Hope
87	Dream
88	Horse Head
89	Midas, Centipede
90	Oak Creek
91	Oyler
92	Birch Springs
93	Copper Queen
94	Billy's Dream
95	Big Jim
96	Tony M
97	Delmonte
98	Happy Shep
99	Woodruff
100	Trachyte
101	Congress
102	Ekkers
103	Section 6, 32S-11E
104	Horsethief
105	Shinarump
106	Red Head
107	Slick Rock
108	Corvusite
109	Polar Mesa
110	Glory Hole
111	Junction
112	Squaw Park
113	Cactus Rat
114	Yellow Cat
115	Eagle
116	Pine Tree
117	Lyon
118	Blue Knolls
119	Willow Creek
120	Horse Ear
121	Brenda
122	Keg
123	Eureka
124	Happy Landing
125	Bonniebell, Snow
126	Eagle Nest
127	Devils Cave
128	Jensen Draw
129	Steinaker Draw
130	Blackie 1
131	Radiance
132	Balboa
133	Bullock
134	Silver Reef
135	Wilson
136	Bertha 5
137	Dime
138	Cedar Point
139	La Sal Creek
140	Abe
141	Mirador
142	Jacobs Chair
143	Kolor

Table 1. Mississippian to Pliocene stratigraphic units in selected parts of the Colorado Plateau Uranium Province showing the uranium-bearing and adjoining units, and their lithologies and depositional environments (expanded and modified after Fred Peterson in Granger and others, 1988).



DISTRIBUTION OF URANIUM DEPOSITS IN THE COLORADO PLATEAU URANIUM PROVINCE -- A CLUSTER ANALYSIS

INTRODUCTION

The Colorado Plateau Uranium Province (CPUP) is defined by the distribution of uranium deposits, chiefly the sandstone-type, in upper Paleozoic and Mesozoic sedimentary rocks within the Colorado Plateau physiographic province (Granger and others, 1986). The uranium province is bordered by widely distributed and mostly minor uranium deposits in Precambrian and Tertiary rocks and by outcrops of Tertiary extrusive and intrusive igneous rocks. Based on isotopic and other evidence, Granger and others (1986) have proposed that the CPUP deposits were formed mainly during three mineralizing episodes: (1) the first was a major, widespread episode at about the end of Triassic time, ~210-200 Ma, that resulted in deposits in the Coconino, Supai (locally of group rank), Cutler, and Chinle Formations; (2) the second was a minor, more localized episode in mid-Jurassic time, ~155-150 Ma, that resulted in deposits in the Todilto Limestone Member of the Wanakah Formation and perhaps the Entrada Sandstone; and (3) the third and dominant episode occurred at about the beginning of Cretaceous time, ~135 Ma, and resulted in the deposits in the Morrison and Dakota Formations (Granger and others, 1986; Granger and Finch with contributions by others, 1988). A fourth episode of mineralization is here proposed to have occurred during Late Cretaceous and Tertiary time, partly in relation to the Laramide orogeny. This episode resulted in the redistribution of older primary uranium deposits, especially in the Morrison Formation in the San Juan Basin, and in the formation of new deposits in the Upper Cretaceous and Tertiary sedimentary rocks and in faults in older rocks. This fourth episode was related to the mineralization in the Tertiary and Precambrian rocks that border the Colorado Plateau, and it was probably more widespread in the western United States, extending into the *Rocky Mountains & Intermontane Basins* Uranium Province (RMIBUP), to the east and north, and into the Basin & Range Uranium Province (BRUP), to the south and west (map A).

The cluster concept

Of the more than 10,000 uranium prospects, properties, and mines in the United States, more than 4,000 of them occur in the Colorado Plateau Uranium Province. To show so many localities on small-scale maps would render the maps unreadable. Large-scale maps at different scales, showing uraniferous occurrences are available for most areas, but to re-evaluate them using the current definition of a deposit, given below, would be an onerous task. Uranium occurrence data range from chemical and radiometric analyses of mineralized rock at a sampled locality to production and reserves of ore for a mining property. To understand the distribution and intensity of mineralization, ideally a uranium deposit needs to be defined geologically and metallogically. Because of the very nature of uranium deposits, especially the sandstone-type, it is very difficult to define a deposit (American Society for Testing and Materials, 1983). A uranium deposit is a volume of naturally occurring uranium-bearing material that has geologic continuity; it may have a systematic reoccurrence of uranium-bearing concentrations that form a recognizable entity. For the purposes of this study, a strict cutoff grade of 0.03 percent chemical U_3O_8 (radiometric analyses are disregarded) is used to define a deposit and to select localities to include in a cluster of deposits.

In order to show the distribution of occurrences, a cluster concept was established. A cluster is the group of all of the properties (deposits) within an area of about 25 square miles. A cluster may contain only one property or a hundred or more; it is commonly named after the most prominent property. Nearly all clusters contain only uranium deposits of one stratigraphic unit and structural type. The cluster concept allows a regional analysis of uranium deposits, based on mutual similarities and hierarchical relations.

The size of the cluster is the total tons of contained U_3O_8 determined from production and reserves of all of the deposits within the cluster. Production data are primarily from the U.S. Department of Energy (DOE) records for 1947 through 1982; production data prior to 1947 are meager and are from files and published reports. Much of the uranium in ore mined for radium and vanadium prior to 1947 went into tailings piles and was later recovered, but no allocation as to cluster can be assigned. Between 1943 and 1947, the Army Corps of Engineers recovered 2,698,000 pounds of U_3O_8 from ores mined for vanadium and from pre-existing tailings (U.S. DOE, 1982). The DOE production records are for mining properties; a property may represent one, part of one, or parts of more than one geologically defined uranium deposit. Many properties are adjacent to one another, so it is commonly impossible to separate out individual deposits. Furthermore, outside and between mining limits are extensions of lower-grade material. Because of these features, delineation of a uranium deposit is very difficult, if not impossible, in many places. Uranium-ore-reserve data are commonly unavailable, so the size for many clusters is low but, as new reserve data become available, the sizes of clusters will be adjusted upwards in the computer file. In order to make the unevenness of data less of a problem, each cluster is classified according to broad size classes, as shown on map B.

Each cluster is assigned a dominant host-rock age and an episode age of mineralization. Isotopic age determinations have been made on only a few deposits. These data are extrapolated to similar deposits in the same host rock in order to classify the age of mineralization for each cluster. Geologic ages for both host rock and age of mineralization are coded in the database according to the numeric system in Swanson and others (1981).

The cluster concept will lead to a number of useful research activities, such as grade-tonnage studies, relation of cluster-size distribution to various geologic features, and resource assessment.

Scope and purpose

A project is underway to create a modern computer data base for the distribution of uranium deposits in the conterminous United States. Two phases are planned. Phase I will create a computer database to plot small-scale maps (scales larger than 1:250,000); this can be done in a relatively short time. Phase II will expand Phase I to create a related computer database in order to plot large-scale maps (scales smaller than 1:250,000); this phase will require a long time to complete because of the large number of properties (deposits).

This map of the CPUP is the first of a series of planned maps for Phase I, which include RMIBUP and BRUP maps. The Arizona portion of BRUP is part of a report on uranium in Arizona (Wenrich and others, 1989). Plans for Phase II are not firm, but the cluster concept created for Phase I may be expanded to serve Phase II's purpose; however, before it is initiated, the difficult task of defining a uranium deposit, for purposes of plotting, will need to be addressed and solved (see below).

This report is a "new generation" compilation and wholly supercedes the Colorado Plateau portion of the preliminary map of uranium provinces in the conterminous United States (Byers and Finch, 1984). From an historical point of view, the present map significantly advances the knowledge of the distribution of the deposits shown on the map by Finch (1955), published more than 30 years ago.

Method of compilation

The general method of determining a cluster was to use a square template scaled at 5 mi x 5 mi; the template was positioned to best fit the occurrences plotted on the reference map. The latitude and longitude for the center of the cluster, which is not necessarily over a known deposit, was entered into the file. In a few cases, some deposits lay just outside the cluster template. Instead of establishing a new cluster, these satellite properties were included in the nearest cluster, especially in large mining districts. In one place, major production was from deposits in the Triassic Chinle and Permian Cutler Formations within the cluster area: cluster UT-45 for the Cutler deposits was offset 2.5 miles northeast of cluster UT-44 for the Chinle deposits to avoid complete overlapping of symbols (map A). In a few places, slight overlapping of symbols is evident, mainly because of difference in stratigraphic position or size class. The size of symbols on maps A and B equal an area about 5 mi. across.

Data for each cluster have been entered into computer files using the GSMRDS database (Taylor and others, 1986). The cluster database is periodically updated. The base for maps A and B was digitized using GSMAP (Selner and others, 1986). Data in the GSMRDS files were plotted using the program DBASE2MA to establish a latitude-longitude point file. Maps A and B are computer plots.

Not all of the properties in the DOE production data file are locatable; about 500 remain to be located. Only those located as of January 1, 1989 are included in this report. As new information on property locations is received, the computer files will be updated and new computer-generated maps can be plotted for maps A and B.

Acknowledgements

The chief maps and reports used to compile the clusters are listed in the selected references. C. W. Adkisson and C. T. Pierson, U.S. Geological Survey, provided computer printouts of summaries of property production data for states and counties from the very large U.S. Department of Energy 1947-1982 production file. I also thank Taesin Chung and Luther Smith, Energy Information Administration, DOE, Washington, D.C., for providing the DOE production-data-file tape. W. L. Chenoweth, Consulting Geologist, Grand Junction, Colorado, was very helpful in providing locations of many mining properties. R.B. Taylor was particularly helpful in establishing and modifying the GSMRDS file for the special purposes of this study as well as in solving other computer-related problems.

STRATIGRAPHIC DISTRIBUTION

All the uranium deposits in the CPUP are in sedimentary rocks that range from Pennsylvanian to Tertiary in age (table 1). There are nine major uranium-bearing stratigraphic units and 15 other units with small and less important uranium deposits. The major uranium ore-bearing units are the Lower Permian uppermost Supai (assigned group rank in the Grand Canyon area), Hermit, Coconino, and Cutler Formations; Upper Triassic Chinle Formation; Middle Jurassic Entrada Sandstone and Todilto Limestone Member of the Wanakah Formation; the Upper Jurassic Morrison Formation; and Upper Cretaceous Dakota Sandstone. The uranium deposits hosted in Permian rocks are mostly in the Grand Canyon region of northern Arizona and eastern Utah (map B). Deposits in Triassic rocks are scattered throughout eastern Utah and in the Cameron and Monument Valley districts of northern Arizona. The deposits hosted in mid-Jurassic rocks are localized in the Grant uranium region and in a narrow belt in the easternmost part of the CPUP in Colorado. The Morrison uranium deposits are most widespread and occur throughout eastern Utah, in the Uravan mineral belt of Colorado, in northeast Arizona, and in the Grants uranium region (map B). The Dakota uranium deposits are restricted to the southwestern edge of the Grants uranium region (clusters NM-8 NM-9, map A; Chenoweth, 1989). These deposits are in coaly portions of sandstone channels and are small (map B). To the east, smaller Dakota deposits occur within Morrison uranium clusters NM-11 and NM-12. A significant amount of uranium (about 100 tons U_3O_8) was recovered from fault zones in the Dakota Sandstone above large concentrations of primary uranium ore in the Morrison Formation at the Church Rock mine (cluster NM-12, map A). This Dakota uranium ore was formed by redistribution of underlying primary Morrison ore (see below).

TYPES OF DEPOSITS

The uranium deposits are of several types based on their structural relations to the host rock and on their genesis. Nearly all of the deposits have epigenetic relations to the enclosing rock.

Most of the productive deposits are classified as sandstone-type deposits, which are epigenetic concentrations of uranium minerals that generally impregnate sandstone, are locally associated with humate, and replace fossil wood and mineral grains. The edges of mineralized bodies are peneconcordant to sedimentary structures and lithology; most commonly the bodies are tabular. Roll features are common at the edges of many ore bodies; rolls are of two types, each with a different genesis. One roll type, common in the Salt Wash Member of the Morrison Formation, was formed under reducing conditions, possibly at the interface of two solutions during diagenesis shortly after sedimentation (Granger and Santos, 1986). The second type of roll, commonly called a solution-front roll, was formed by an advancing oxidizing solution-front downdip from an exposure at the surface. This type of roll is similar to those in Tertiary rocks in Wyoming (Harshman, 1972) and Texas and was formed in mid-Tertiary time by redistribution of the earlier formed tabular ores, particularly in the Westwater Canyon Member ores of the Grants uranium region.

The epigenetic sandstone deposits in the Grants uranium region, New Mexico, are of two types -- primary and redistributed. The primary deposits consist of uraninite or coffinite formed under reducing conditions. Redistributed deposits consist of coffinite formed by an advancing oxidizing solution-front. Other evidence for redistribution is the occurrence of remnant deposits in the Grants uranium region. The grade of primary deposits averages about 0.22 percent U_3O_8, the remnant deposits about 0.20 percent, and the redistributed deposits about 0.16 percent (McCammon and others, 1986). Both primary and redistributed deposits can be weathered to produce high-valent secondary uranium minerals.

The second most important type of deposit is the uranium-bearing solution-collapse breccia pipes in the Grand Canyon region of northern Arizona (Wenrich, 1985) (map B). The solution-collapse breccia pipes extend upward from the Mississippian Redwall Limestone into the Upper Triassic Chinle Formation. They were formed when a karst topography developed beginning in Late Mississippian time, and collapse continued intermittently until the early stages of sedimentation of the Chinle Formation. The ores are believed to have developed in Late Triassic time in the breccia adjacent to the relatively impermeable units of the enclosing red beds of the Hermit Shale and Supai Group (table 1). The ores developed as annular rings and as core fillings in the pipes that are generally about 300 ft in diameter; the height of the orebodies encompass as much as 700 vertical ft of the pipes. Although not genetically related to the Grand Canyon breccia pipes, it is noteworthy that in the Grants uranium region, the Woodrow uranium deposit (included in cluster NM-35, map A) is in a solution-collapse pipe in the Morrison Formation.

A third type of deposit was formed during the redistribution of the primary sandstone-type ores in mid-Tertiary time when some uranium and associated metals were deposited as veins in faults. Some of these form rich ores, such as some deposits at Temple Mountain, Utah (cluster UT-17, map A). Most of the veins formed during this time are small. Many of them encompass several stratigraphic units that are commonly the same ones that contain the sandstone-type deposits.

A fourth structural and genetic type of uranium deposit consists of bedded uraniferous shale; the uranium is most likely syngenetic. The principal example is the La Ventana deposit (cluster NM-42, map A) in northwestern New Mexico. The grade of this deposit is low and generally uniform throughout the shale. Fairly large amounts of contained uranium are in the bedded deposits.

EPISODES OF URANIUM MINERALIZATION

Isotopic age determinations suggest that the major deposit types resulted from four important episodes of mineralization. They are (1) Late Triassic episode, (2) Middle Jurassic episode, (3) Early Cretaceous episode, and (4) Middle Tertiary episode. Smaller, less significant episodes probably took place.

The Late Triassic Episode

The earliest significant uranium mineralizing episode evidently occurred about 210-200 Ma (Ludwig and others, 1984, 1986; Miller and Kulp, 1963; Berglof, 1970), shortly after deposition of the Upper Triassic Chinle Formation. During this episode, deposits of highly diverse character were formed in the Coconino Sandstone, Supai Group, and Cutler and Chinle Formations (table 1). The Coconino-Supai deposits occur in the Grand Canyon area of northern Arizona within collapsed and brecciated sandstone and siltstone that fills pipes that bottom in the underlying cavernous Mississippian Redwall Limestone. Recent studies of ores from the solution-collapse breccia pipe deposits have shown that in only one pipe is there any U/Pb isotope age older than about 200 Ma, specifically about 260 Ma for the Canyon pipe (cluster AZ-72, table 1 ; Ludwig and Simmons, 1988). Thus, there must have been, at least locally, a second earlier period of mineralization for the breccia pipe ores. This will require a re-evaluation of the concept of the Late Triassic episode.

The principal Cutler deposits are in easternmost Utah (clusters UT-29, 32, 45, map A) and generally occur in red or partly bleached arkosic sandstone in areas where the Chinle Formation rests unconformably on the Cutler (table 1). The orebodies are somewhat tabular and are elongate parallel to fluvial sedimentary structures. Primary ore contains uraninite but, in oxidized ore, much of the uranium seems to be fixed by films of iron oxides that coat sand grains. There is little doubt that these Cutler deposits are genetically related to the overlying Chinle deposits.

The Chinle deposits principally occur in northern Arizona and eastern Utah in the Shinarump, Petrified Forest, and Moss Back Members (table 1, map B). The orebodies generally are elongate and occur in paleochannel fillings of sandstone and conglomeratic sandstone. The Monitor Butte and Petrified Forest Members contain abundant devitrified, argillized volcanic ash, which was the probable source rock for uranium in the deposits of this episode.

The Middle Jurassic Episode

A relatively small, localized mineralizing episode probably occurred about 155-150 Ma (Berglof, 1970) and produced deposits in the Middle Jurassic Todilto Limestone Member of the Wanakah Formation in northwestern New Mexico (clusters NM-23, 25, 29-34, 45, 47, map A) and probably in the Entrada Sandstone in western Colorado (clusters CO-27-30, 34, map A). Shortly after deposition of the Todilto, uraninite and a little coffinite, locally accompanied by fluorite, barite, and vanadium-oxide minerals, were deposited along the axial trends of intraformational folds in the Todilto. The source of the uranium is uncertain.

Deposits in the Entrada Sandstone have not been dated, so it is not known which mineralizing episode produced them. They are uraniferous vanadium deposits in flat-bedded and cross-bedded eolian parts of the Entrada. They occur near the top of the Entrada, along a narrow north-trending belt (clusters CO-27-30, 34, map A) that marks the western edge of deposition of the overlying Pony Express Limestone Member of the Middle Jurassic Wanakah Formation in southwest Colorado, which is stratigraphically equivalent to the Todilto Limestone Member in northwest New Mexico (table 1). The uraniferous vanadium ore occurs in peneconcordant tabular layers that contain vanadium oxides, and roscoelite and other vanadium clay minerals. The spatial relation of these deposits to the limestone of Todilto age indicates a temporal relation to the Todilto deposits and suggests they belong to this episode.

The Early Cretaceous Episode

The most intense mineralizing episode occurred at about 135 Ma, after deposition of the Upper Jurassic Morrison Formation. During this episode, the sandstones including the Jackpile Sandstone, Brushy Basin, Salt Wash, and Westwater Canyon Members of the Morrison were extensively mineralized in eastern Utah, western Colorado, and northwestern New Mexico (table 1). The Pb-U ages of uranium minerals in the Westwater Canyon indicate a minimum age of about 132 Ma (Ludwig and others, 1984). Studies of Jackpile- (Brookins, 1980) and Salt Wash-hosted ores (K.R. Ludwig, oral commun., 1985) suggest apparent minimum ages of deposition closer to 115 Ma, but with a wide range of error. The decision to include all these deposits in one mineralizing episode is arbitrary but permissible.

Most of the deposits form peneconcordant tabular layers within the host sandstone beds. One model proposes the precipitation of uranium during diagenesis at an interface of two solutions, commonly between brine and freshwater (Goldhaber and others, 1990). In the Grants uranium region, where the ore is associated with humate, a lacustrine-humate model has been proposed instead of the solution-interface model (Turner-Peterson, 1985). The basis of the lacustrine-humate model is that the overlying Brushy Basin volcanic mudstones were the source of the humate, and either the uranium traveled as a urano-organic complex and precipitated directly or later passage of uranium-bearing oxidizing ground water enriched the humate to ore grade. In host rocks characterized by syngenetic detrital organic matter, a single ore-forming solution is called upon to precipitate uranium under reducing conditions. The Brushy Basin Member, which contains an abundance of devitrified, argillized, and locally zeolitized volcanic ash, is commonly pointed to as the most likely source rock for most of the uranium in the Morrison-hosted deposits.

The Tertiary Episode

Isotope age determinations on the redistributed ores in the Westwater Canyon Member of the Morrison Formation range from 3.4 to 18.0 Ma and suggest that these ores formed in several stages ranging from 10 to 13 Ma (Ludwig and others, 1984). Saucier (1980) suggested two main stages, one in late Oligocene or early Miocene (~24 Ma) and a second in Pliocene (5 Ma) or Holocene (0.010 Ma). The latter would be due to weathering because of recent exposure of ore-bearing beds by erosion. The faulting due to the Laramide orogeny would place a maximum time of mineralization for veins in faults (Moench and Schlee, 1967).

CLUSTER DISTRIBUTION BY SIZE-CLASSES

The largest size-class, >10,000 tons U_3O_8, occurs only in two areas: a group of mines in the Morrison Formation in the Grants uranium region, NM (clusters NM-12, 15, 16, 17, 21, 25, 27, 28, 35, map A; Holen and Finch, 1982) and a single cluster in the Triassic Chinle Formation in eastern Utah (cluster UT-44, map A).

The second largest size-class, 1000-9999 tons U_3O_8, is concentrated in the Salt Wash Member of the Morrison Formation in the Uravan Mineral Belt, the Westwater Canyon Member in the Grants uranium region, and the breccia pipes of the Grand Canyon region (map B). The remainder are scattered in Arizona and Utah.

The third largest size-class, 10-999 tons U_3O_8, is concentrated mainly in Utah, the Uravan Mineral Belt, northeast Arizona, and the Grants uranium region (map B). A line drawn around this general concentration forms a reversed comma-shaped area (map B) that lies between two major tectonic lineaments, the Zuni and Uncompahgre, which appear to mark the position of major mixed lithofacies that were favorable for epigenetic uranium deposition (Green, 1988). The northern circular area in east-central Utah and including the Uravan Mineral Belt in Colorado is roughly coincident with the outline of the Paradox basin, as shown by Hite (1961).

The next to lowest size-class, 0.1-9.9 tons U_3O_8, is scattered throughout the CPUP, but a marked concentration is noted in Utah (map B).

The lowest size-class, <0.1 ton U_3O_8, occurs mainly outside of the mining areas. This is in part due to inconsistent compilation of occurrences in mining areas. Most clusters of this size-class are represented by only one or two deposits.

MINING AND PRODUCTION

The ore deposits in the CPUP were mined first for radium, then for vanadium, and last for uranium. Radioactive minerals were first identified on the Colorado Plateau in the Morrison Formation at Roc Creek (cluster CO-7, map A) Colorado in 1898 (Coffin, 1920). Small amounts of carnotite ore were mined and milled in the Slick Rock area (cluster CO-18, map A), San Miguel County, Colorado from 1901 to 1904 (U.S. Atomic Energy Commission, 1951; Chenoweth, 1980). From 1911 to 1923, deposits of radioactive minerals, mainly in the Morrison Formation, were extensively mined for radium. In 1923 the Belgian Congo became the world's source for radium and mining of the Colorado Plateau ore deposits for radium ceased. Although sporadic mining and milling of the ores for vanadium continued, large-scale mining for vanadium was begun in 1936, and continued until 1945, mainly in the Morrison and Entrada Formations in western Colorado. From 1943 through 1946, about 1,349 tons U_3O_8 were recovered from the treatment of tailings at various vanadium mills on the Colorado Plateau (Chenoweth, 1988). None of this uranium recovery can be assigned to specific mines.

Mining of the Colorado Plateau deposits was begun a third time in 1947, when the U.S. Atomic Energy Commission initiated its program of developing a domestic supply of uranium. Production has been continuous since 1947. Production peaked in 1960 and again at a higher level in 1980, but in 1986 it was lower than in 1956 (EIA, 1987, table 23). Total CPUP production from 1947 through 1982 was 266,600 tons of U_3O_8 (U.S. DOE, 1978-1983). Of the principal host rocks, about 82 percent of the CPUP production has been from the Morrison Formation; in particular, about 58 percent has been from the Westwater Canyon Member of the Morrison in the Grants uranium region of New Mexico (map B). This region has been the largest production center in the U.S. and has yielded more than 40 percent of the Nation's total. The largest uranium mine in the U.S. was the Jackpile mine, which yielded more than 50,000 tons of U_3O_8 from 1954 to 1982 (cluster NM-35, map B). Nearly 10 percent of the total CPUP production through 1982 has been from the Chinle Formation. The Permian host formations have yielded over 5 percent. The Entrada and Todilto totaled about 1.5 percent, and the remainder was from the Dakota Sandstone and Tertiary formations.

DISTRIBUTION OF RESERVES AND UNDISCOVERED RESOURCES

In 1986, the Reasonably Assured Resources (RAR, reserves) for the Colorado Plateau at the lowest forward-cost category (\$30/lb U_3O_8) were more than 60 percent of the total for the entire U.S. (EIA, 1987, table 17). About 85 percent of the 1986 CPUP RAR is in the Grants uranium region; the remainder is largely in the Grand Canyon breccia pipe region of northern Arizona (map B).

The U.S. Department of Energy assessed the undiscovered uranium resources of the Nation in the late 1970's under the National Uranium Resource Evaluation (NURE) program. In their 1980 assessment report, they give the potential resources by host rock unit (U.S. DOE, 1980, table 11). Of the total of 1,343,275 mean tons of U_3O_8 at \$100/lb or less classed as probable, possible, and speculative resources, about 66.5 percent is mostly in the Westwater Canyon Member of the Morrison Formation and lesser amounts in the Brushy Basin and Recapture Members, all in the San Juan Basin, New Mexico; about 10 percent is in the Salt Wash Member of the Morrison Formation, mainly in eastern Utah and western Colorado; about 1.4 percent is in the Todilto Limestone Member of the Wanakah Formation in the San Juan Basin; about 0.5 percent is in the Entrada Sandstone in western Colorado; about 13 percent is in the Chinle Formation, mainly in eastern Utah; about 6 percent is in Permian formations, mainly in collapse breccia pipes in northern Arizona; and the remaining 2.5 percent is in Cretaceous and Tertiary formations.

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