Cenozoic Sediments, Volcanics, and Related Uranium in the Basin and Range Province of Arizona

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Concentrations of uranium in Cenozoic deposits of Arizona occur with carbonaceous and siliceous matter in light-colored, calcareous mudstones or fetid carbonates that were deposited in lacustrine, paludal or low-energy floodplain environments. Although uranium was deposited throughout the Cenozoic, the largest uranium resources in the state occur in the Date Creek basin in fine-grained sediments associated with ignimbrite volcanism of the mid-Tertiary orogeny. This concentration may be related to the coincidence of three factors: low-energy environments where fine grained, carbonaceous, lacustrine or paludal sediments were accumulating; exposure of large areas of alkalic Precambrian granite; and, extrusion of large volumes of relatively alkalic and silicic volcanics of the mid-Tertiary ignimbrites.

In 1975, Union Oil Co. announced that the Anderson mine in southern Yavapai County, Arizona, contained 80 million pounds of uranium buried beneath rocks of the Date Creek basin (Sherborne and others, 1979; Eng. Min. Jour., 1978). This discovery, coupled with the increased price of uranium, touched off a flurry of exploration activity throughout the Basin and Range province of Arizona (Peirce, 1977). Much of the leasing and claim staking was directed at the Date Creek basin and surrounding areas, although many other occurrences in southern and western Arizona attracted attention.

Keith (1970) reported about 90 uranium occurrences in Tertiary rocks in the Basin and Range province of Arizona. Most of these had been briefly described in one-page preliminary reconnaissance reports of the Atomic Energy Commission. Approximately 27% of the reported occurrences were in young, basin-fill sediments, 40% were in older, tilted sediments, and 33% were in mid-Tertiary volcanics.

Because the uranium at the Anderson mine occurs in mid-Tertiary sediments, a preliminary investigation focused on other sediments of similar age in the Basin and Range province of Arizona (Scarborough and Wilt, 1979). That investigation consisted of a survey of the literature describing various Tertiary formations, examination of outcrops of uraniferous Tertiary sediments, and determination of ages of intercalated volcanics.

Earlier papers by Cooley and Davidson (1963), Heindl (1962), and Sell (1968) correlated Cenozoic rock units according to rock type, structural involvement, and sequence. Eberly and Stanley (1978) refined the earlier subdivisions, which had applied only to southeastern Arizona, by obtaining age dates on pertinent volcanics in southwestern and south-central Arizona. Their paper dealt primarly with basin-fill deposits of the last 13 million years, although a stratigrapic summary diagram (Eberly and Stanley, 1978) showed three subdivisions of mid-Tertiary deposits that are used in this paper.

This paper concentrates on the three subdivisions of mid-Tertiary deposits, particularly those rocks that contain uranium, and only briefly reviews early and late Cenozoic rocks. Early Tertiary rocks involved in the Laramide orogeny include intrusives, volcanics and very minor volumes of sediments; they are discussed in the literature pertaining to porphyry copper deposits

(Titley and Hicks, 1966; Jenney and Hauck, 1978). Rocks younger than the mid-Tertiary sediments discussed here have been treated in summary articles by Eberly and Stanley (1978) for southwestern Arizona, by Peirce (1976) for salt deposits in Arizona, and by Scarborough and Peirce (1978) for southeastern Arizona.

Although the emphasis of this paper is on uranium deposits in mid-Tertiary sediments, details of uranium occurrences in volcanics of the same age and in younger basin-fill deposits are supplied so that comparisons can be made with those in mid-Tertiary sediments. Although the economic justification for this paper is uranium, the primary purpose is to work out a geologic framework of Tertiary deposits that can be applied statewide regardless of the commodity in demand at the moment.

GEOLOGIC FRAMEWORK

The middle and late Cenozoic record in Arizona is dominated by two major tectonic events—a mid-Tertiary orogeny and a Basin-and-Range disturbance. The stratigraphic record of the mid-Tertiary orogeny of Eberly and Stanley (1978) is characterized by large volumes of intermediate volcanics (commonly andesite, rhyolite and tuff) with variable volumes of coarse clastics and lacustrine deposits. Associated tectonism, plutonism, and metamorphism were not investigated for this preliminary report. Oligocene and lower and mid-

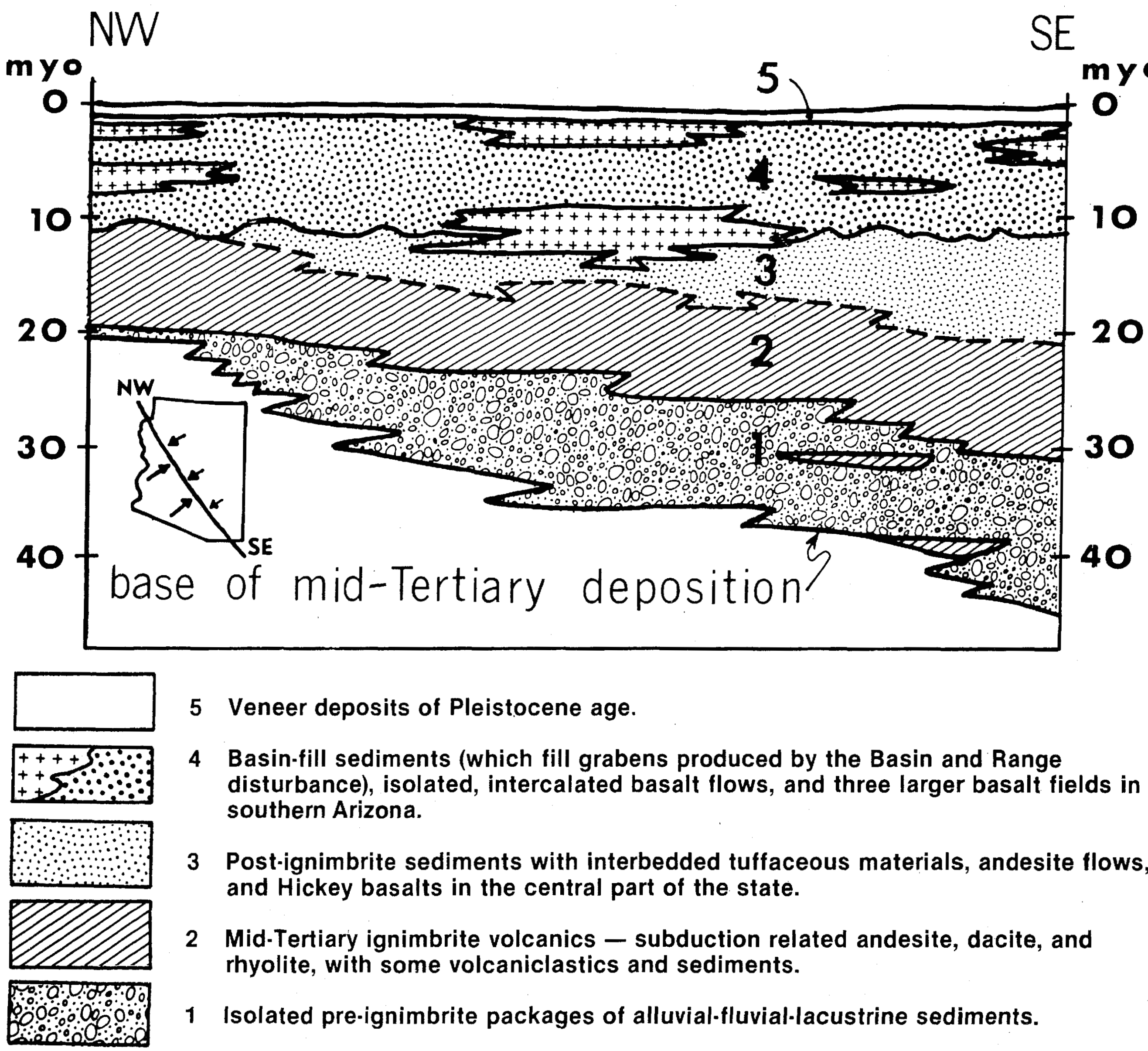

Fig. 1—Highly simplified NW-SE cross section through Arizona's Basin and Range province showing middle and late Cenozoic framework.

dle Miocene rocks deposited during the mid-Tertiary orogeny unconformably overlie more deformed rocks deposited before or during the Laramide orogeny of Cretaceous and Paleocene age. The mid-Tertiary rocks are in turn, unconformably overlain by undeformed basin-fill deposits of late Miocene and Pliocene age that were deposited during the Basin and Range disturbance.

The Basin and Range disturbance (Scarborough and Peirce, 1978) is restricted in this paper, as it was in Gilbert's (1875a, 1928) original discussions, to that episode of high-angle normal faulting that blocked out the present physiography. Basin-fill deposits resulting from this tectonism consist of large volumes of sediments and basalt. These basin-fill deposits are relatively undeformed, in contrast with pre-upper Miocene rocks that were affected by Basin and Range faulting and some earlier structural events.

Subdivisions

In any area, the stratigraphic record of the mid-Tertiary orogeny can be subdivided, using the amount of volcanism, into three categories—pre-ignimbrite, ignimbrite, and post-ignimbrite. These subdividions correspond respectively to the lower, middle, and upper Unit I of Eberly and Stanley (1978). The names of the three categories are informally based on ignimbrite volcanism in order to contrast them with later basaltic volcanism. Stratigraphic products of the Basin and Range disturbance include basin-fill sediments and basalt and comprise a fourth category that is the youngest of the four major subdivisions used in Figure 1 and Table 1.

Pre-ignimbrite sediments are distinguished by an absence of volcanic clasts of mid-Tertiary age and by a general lack of interbedded volcanics except for relatively scattered, thin flows or tuff. These lower and middle Oligocene rocks mostly consist of light-colored fanglomerate, which in places contains a limestone or fine-grained clastic member.

The ignimbrite deposits consist of large volumes of intermediate to silicic volcanics, most of which are andesite, rhyolite, and ash-flow tuff. This ignimbrite package is Oligocene or late Oligocene to early Miocene in age and appears to be time transgressive across Arizona from east to west (Fig. 1). Included within the thick and areally extensive volcanics are some thick fanglomerate units and thin sedimentary lenses.

Post-ignimbrite sediments are characterized by intercalated volcanics that are fewer, thinner, and more mafic than those in earlier ignimbrite deposits. The post-ignimbrite sediments are more deformed than younger sediments of similar composition and are Middle Miocene in age.

Basin-fill deposits consist of large volumes of undeformed sediments filling basins created by the Basin and Range disturbance. Associated localized volcanic flows are chemically very mafic and consist of low-silica, true basalts. Basin-fill deposits are Late Miocene and Pliocene in age.

A widespread but very slight angular unconformity marks the top of the basin-fill unit. Veneers of generally coarse grained clasts occur on this unconformity and are of Pleistocene age.

LOWER BOUNDARY

Mid-Tertiary rocks rest unconformably on a great variety of older rocks. Examples of every rock formation, ranging from Laramide copper-bearing porphyry and volcanics to Precambrian granite and schist, were exposed by erosion before the Middle Tertiary. A paleogeologic map of the specific rocks underlying each mid-Tertiary deposit would be almost as complex as the present geologic map of Arizona. This complexity is avoided in Figure 2 by mapping only the youngest sedimentary rocks that underlie mid-Tertiary rocks in any region.

Prior to the Middle Tertiary, extensive erosion exposed Precambrian rocks in a northwest-trending swath across the state just south of the Mogollon Rim. Some of this erosion occurred during Mesozoic time in that part of southern Arizona called the Mogollon Highlands by Harshbarger and others (1957) and Cooley and Davidson (1963). Some of the erosion occurred during the Early Tertiary and may be related to a Late Eocene erosion surface (Epis and Chapin, 1975) that occurs in much of the southwestern United States. Some of the large areas of Precambrian rocks shown in Figure 2 were exposed during Early and Middle Tertiary time and may be related to the distribution of uranium in any sediments of that age. Much of this Precambrian rock is alkalic granite and contains somewhat high percentages of potassium and uranium (Malan and Sterling, 1969; Sterling and Malan, 1970).

A deposit that probably formed during this Eocene erosion is a section of "rim gravels" that crops out on the Mogollon Rim at the southern edge of the Colorado Plateau province (Peirce and others, 1979). Fine-grained sediments of the same age occur farther north and east in New Mexico, where the Baca Formation has produced uranium (Chenoweth, 1976). These deposits are also discussed by Bornhorst and Elston (this volume).

PRE-IGNIMBRITE SEDIMENTS

Sediments deposited before the massive outpouring of ignimbrite are distinguished by a lack of clasts of mid-Tertiary volcanics, although clasts of many other rock types, including Laramide volcanics, are represented. Some fanglomerate units contain mineralized clasts eroded from Laramide porphyry copper-deposits. Volcanics associated with pre-ignimbrite sediments are rare or absent, but when present, consist of very thin andesite flows or ash-flow tuff. Pre-ignimbrite sedi-

Table 1. Geologic Framework of Cenozoic Rocks in Arizona's Basin and Range Province.

Category	General Age	Sedimentary Rock Record	Volcanic Rock Record	Character of Uranium	Tectonics
VENEER	0-2 m.y.	pediment gravel terrace gravel alluvial fans	low-silica basalt minor tuff	rare in soils	undeformed rarely cut by high-angle faults
BASIN-FILL	2-10 m.y.	clastics and evaporites filling Basin and Range grabens	low-silica basalt minor distal air-fall ash beds	fine-grained clastics mudstone, white marl, green silica pods	undeformed except in deepest levels
POST-IGNIMBRITE	10-15 m.y.	light-colored mudstone, tuffaceous sediments, reworked tuff, some fanglomerate	some basalt minor ash-flow tuff and air-fall ash beds	fine-grained sediments, marl, tuffaceous sediments, bedded dolomite	tilted sections dip 5-20° many undeformed sections
IGNIMBRITE	15-30 m.y.	mostly thin, lensoidal units in volcanics a few thick red-colored fanglomerates and mega-breccia slide blocks	voluminous, subduction-related, intermediate, ignimbrite volcanics, andesite and rhyolite	in carbonaceous, siliceous, fine-grained, sediments in fractures and shear zones in alkalic volcanics	tilted sections dip 15-40° some sections gently arched or warped
PRE-IGNIMBRITE	25-40 m.y.	light-colored fanglomerate some local fetid limestone devoid of mid-Tertiary clasts	scattered, thin intermediate composition flows and dikes	in fine-grained, light-colored sediments	tilted sections dip 15-40°
LARAMIDE	45-75 m.y.	Mogollon "rim gravels," clastics of Eocene and perhaps Paleocene age	voluminous, calc-alkalic volcanics and plutonics	with Cu/Mo vein systems of porphyry copper acidic plutons	complex compressional tectonics

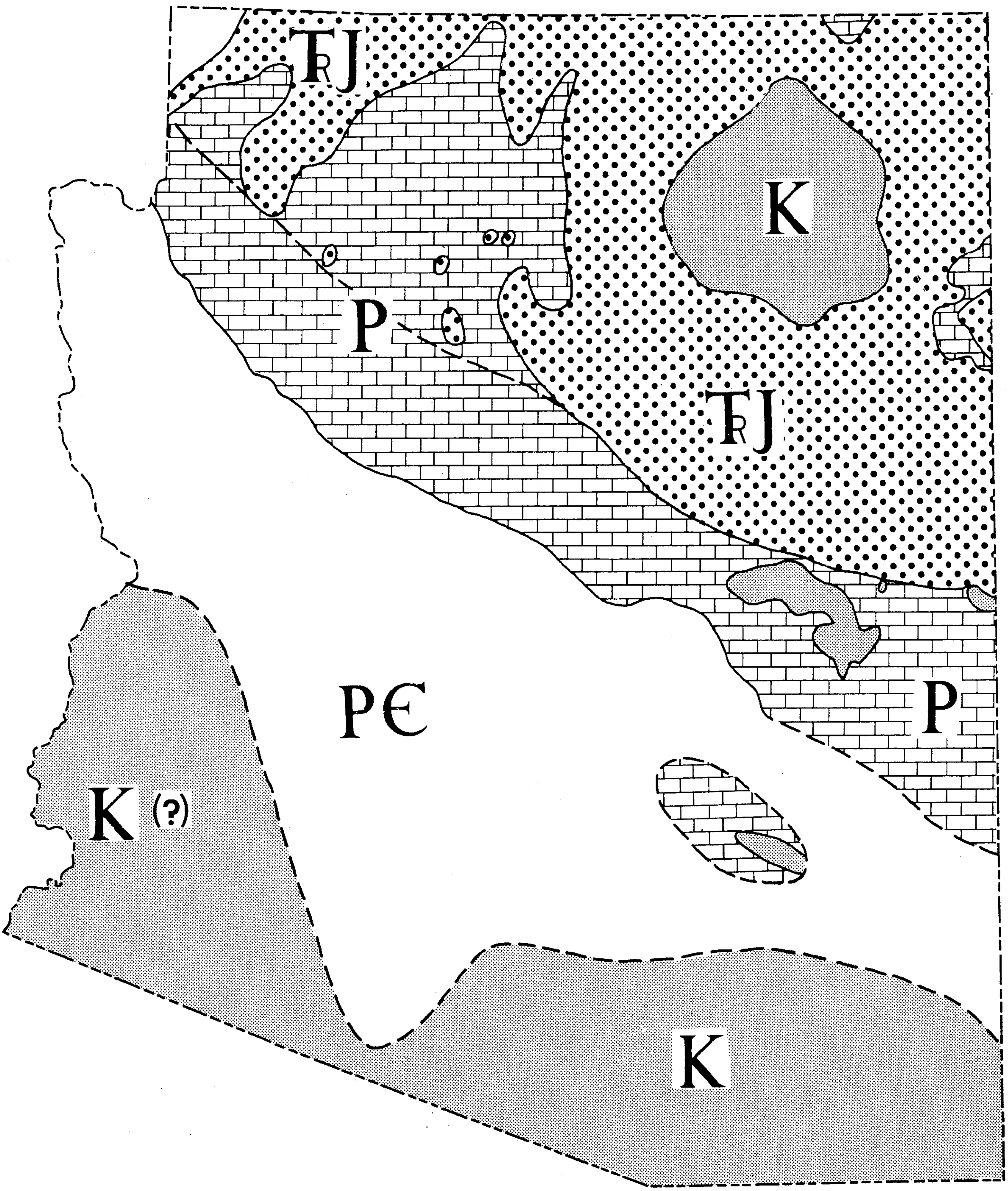

Fig. 2—Youngest rocks that underlie the mid-Tertiary unconformity in Arizona. P€ = Precambrian; P = Paleozoic; ŦJ = Triassic-Jurassic; K = Cretaceous. This diagram, although simplified, shows well the swath through the central part of the state from which the entire Phanerozoic section, except rocks, is missing.

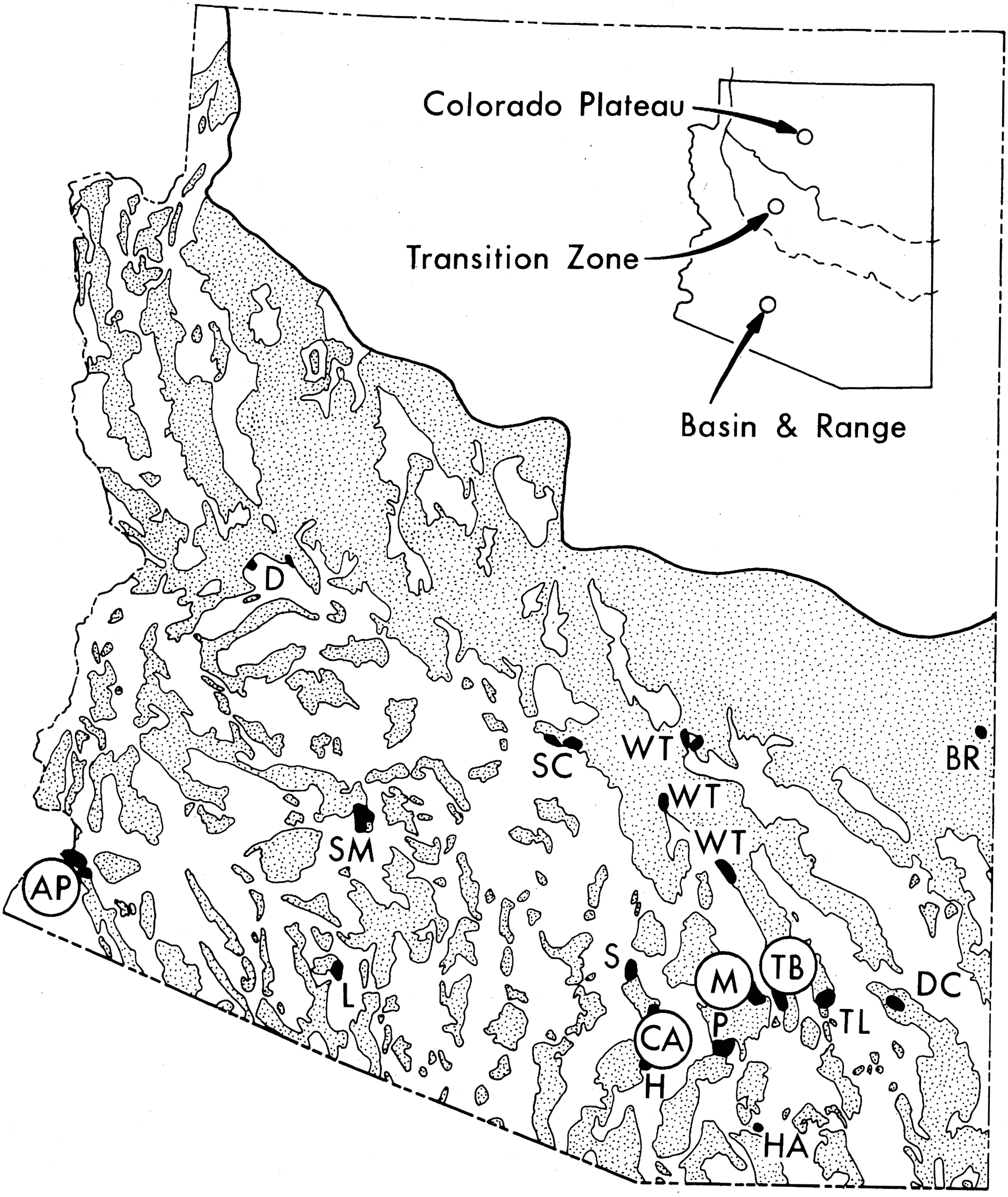

Fig. 3—Pre-ignimbrite sediments and minor volcanics (in black). Insert map shows boundaries of physiographic provinces used in this paper. Stipple pattern shows present mountain ranges. Clear areas are present valleys.

ments generally consist of conglomerate, either as alluvial-fan accumulations ranging from 2,000 to 10,000 ft (650-3,400 m) thick or as relatively thin, basal conglomeratic units underlying the ignibritic volcanics.

Pre-ignimbrite Fanglomerate

The reddish-brown fanglomerate that is typical of the pre-ignimbrite sediments generally lacks reported uranium. The Whitetail Conglomerate (WT, Fig. 3) is a pre-ignimbrite sediments that was first described by Ransome (1903) in the Globe area, where it ranges widely in thickness. Other examples of pre-ignimbrite fanglomerate include the Helmet Fanglomerate (H, Fig. 3); Cooper, 1960), which occurs beneath 29-m.y.-old Turkey Track andesite in the Sierrita Mountains (Damon and Bikerman, 1964), the Locomotive Fanglomerate (L, Fig. 3; Gilluly, 1946) which underlies 25-m.y.-old Ajo Volcanics (Jones, 1974), and other similar conglomerates throughout southern Arizona (Fig. 3). A fanglomerate in the Ray and Mammoth area (WT, Fig. 3), is known to be 30 to 40 m.y. old and is believed to be equivalent to the Whitetail Conglomerate (Cornwall and others, 1971; Krieger and others, 1979). One fanglomerate sequence, named the Sil Murk Formation by Heindl and Armstrong (1963), contains a basal 500-foot (170-m) thick section of red aeolian sandstone and an upper, less deformed group of 27-m.y.-old volcanics (Eberly and Stanley, 1978).

Uranium-bearing Pre-ignimbrite Formations

In the pre-ignimbrite sediments, uranium occurs in fine-grained members of the fanglomerate sequence. The fine-grained facies generally consists of light-colored to greenish mudstone, calcareous shale, and limestone with some gypsiferous beds. The presence of red fanglomerate and monolithologic megabreccia overlying or underlying fine-grained members indicates that nearby areas had high relief.

The 2,000-foot-thick (700 m) Mineta formation (Chew, 1952; Clay, 1970), which occurs on the east slope of the Rincon Mountains (M, Fig. 3), contains several uranium prospects (Bissett, 1958; Granger and Raup, 1962; and Thorman and others, 1978). The Mineta formation consists of a lower, gray to red, conglomerate member; a middle, dark gray cherty limestone and varicolored mudstone member; and an upper, detrital member of red arkose and light-colored gypsiferous mudstone and evaporites. These beds dip 30° to 60° northeast and contact older rocks along high-angle faults to the west. The Mineta formation is Oligocene in age and is overlain by a "Turkey Track" andesite which was dated as 26.9 m.y. old (Shafiqullah and others, 1978). Uranium mineralization and radioactivity up to 100 times background values occur discontinuously within the Mineta formation over a strike length of four miles. Rocks in the Mineta formation that contain uranium include thin, dark gray and white mudstone lenses that are intercalcated within the thick lower conglomerate; dark gray, fetid limestone and variegated shale in the middle member; and the sheared contact between these two members. Uranium also occurs at the Blue Rock claim (Thorman and others, 1978) in a northeast-dipping shear zone that may have experienced some movement into the Laramide orogeny.

The Teran basin area in the southwestern Galiuro Mountains (TB, Fig. 3) is across the San Pedro Valley from the outcrops of Mineta formation and contains a similar, but thicker, sequence of lower fanglomerate, middle mudstone, shale, and sandstone, and upper fanglomerate. The sequence is overlain by Galiuro Volcanics, which locally date back 28 m.y. (Creasey and Krieger, 1978). Uranium anomalies that are two to three times background values occur in yellow to brown, gypsiferous mudstone in the middle, fine-grained unit; anomalous limestone beds have been reported but not yet confirmed.

The Pantano Formation of Brennan (1962) and Finnell (1970) is equivalent in age to the Mineta formation and occurs in several extensive exposures in pediments east of Tucson (P, Fig. 3). It contains all the lithologies of the Mineta formation, plus a lower fetid limestone and

AP	Redbeds of Adair Park
BR	Blue Range area of White Mountains
CA	Limestone at Cardinal Avenue
DC	Volcanic flow in Dos Cabezas Mountains
H	Helmet Fanglomerate
HA	Ash flow north of Huachuca Mountains
L	Locomotive Fanglomerate
M	Mineta Formation
P	Pantano Formation
S	Safford conglomerate
SC	Conglomerate under Superstition volcanics
SM	Sil Murk Formation
TB	Sediments of Teran Basin
TL	Three Links conglomerate
WT	Whitetail Conglomerate
D	Older volcanics and sediments of Date Creek basin
M	Uranium occurrences

thick red claystone member. It is devoid, however, of uranium occurrences except for an isolated limestone remnant at Cardinal Avenue in southwest Tucson that once may have been part of the Pantano Formation.

The limestone at Cardinal Avenue, in the southern Tucson Mountains (CA, Fig. 3) (Brown, 1939; Grimm, 1978), occurs in an isolated syncline that is exposed on a stripped pediment surface south of Valenica Road. Carnotite fracture coatings and anomalous radioactivity up to five times background occur in strongly fetid, gray to buff limestone. Interbedded light-colored mudstone lacks anomalous radioactivity. These lacustrine beds are probably of Tertiary age and may correlate with limestone in the Mineta or Pantano Formation (Grimm, 1978).

Redbeds at Adair Park in the southern Laguna Mountains north of Yuma (AP, Fig. 3) consist of a thick, coarsening-upward sequence consisting of a lower section of sandstone and gypsiferous mudstone, a middle section of red floodplain and alluvial fan deposits, and a thick upper unit of boulder conglomerate and monolithologic breccia. The redbeds are of Oligocene or older age, as indicated by the fact that they are unconformably overlain by the light-colored clastics of the Kinter Formation, which contain a 23-m.y.-old ash (Olmsted and others, 1973). Anomalous radioactivity occurs in the lower part of the redbed sequence in orange and yellow, mottled gypsiferous mudstone. A high-angle fault brings the redbeds into contact with older crystalline rocks.

Uranium Exploration Guides—Pre-ignimbrite sedimentary rocks contain anomalous radioactivity and uranium mineralization in light-colored shale, gypsiferous mudstone, or fetid limestone. The uraniferous, fine-grained rocks are always light-colored (gray, yellow, or green, rather than red) despite their inclusion in a redbed sequence. Known occurrences of uraniferous rocks are very thin, discontinuous, and generally weakly radioactive. Exploration for uranium is complicated by the scattered nature of the faulted and steeply dipping remnants now exposed in isolated pediments at the edges of the mountain blocks. If other remnants are present in the basin blocks, they may be buried by thousands of feet of basin-fill sediments. The distribution of reported uranium occurrences and claims centers around the Rincon Mountains and surrounding areas of southeastern Arizona, where the typical fanglomerate of the pre-ignimbrite rocks contains a fine-grained member, as in the Mineta formation.

IGNIMBRITE

The base of the ignimbrite package is defined by the lower contact of voluminous andesite flow sequences. The andesites are unconformably overlain by massive rhyolite ash flows made up of true ignimbrite of the "ignimbrite flare-up" of Coney (1976). The beginning of this mid-Tertiary volcanism coincides with the end of the "magmatic gap" of Damon and Mauger (1966), which occurred between the end of Laramide magmatism and the beginning of mid-Tertiary magmatism (Damon and others, 1964). The top of the ignimbrite package is gradational with post-ignimbrite sediments, although angular unconformities occur in some places.

Ignimbrite volcanism swept across the state from east to west, and hence the ignimbrite deposits are time transgressive. Coney and Reynolds (1977) and Keith (1978) believe this volcanism resulted from subduction of a slab whose dip angle became progressively steeper.

Mid-Tertiary Volcanic Fields

A Ajo
B Black Mountains
C Chiricahua
G Galiuro
K Kofa
S Superstition
T Tumacacori
V Vulture Mountains
W White Mountains

Uranium in Veins in Volcanic Rocks

1 Chuichu area (M & M group)
2 Superstitions (Cardinal claim)
3 Quijotoa Mountains (Copper Squaw claim)
4 Ruby area (Iris, Purple Cow claims)
5 Pajarito Mountains (Sunset, White Oak claims)
6 Patagonia area (Four Queens, Alto claims)
7 Southern Pinaleno Mountains (Golondrina claim)
8 Pearce volcanics (Fluorine Hill claim)
9 Douglas area (Last chance claim)

Formations

MD Mount Davis volcanics
PM Patsy Mine volcanics
RA Rillito andesite
TT Turkey Track andesite
P Pacacho Peak volcanics

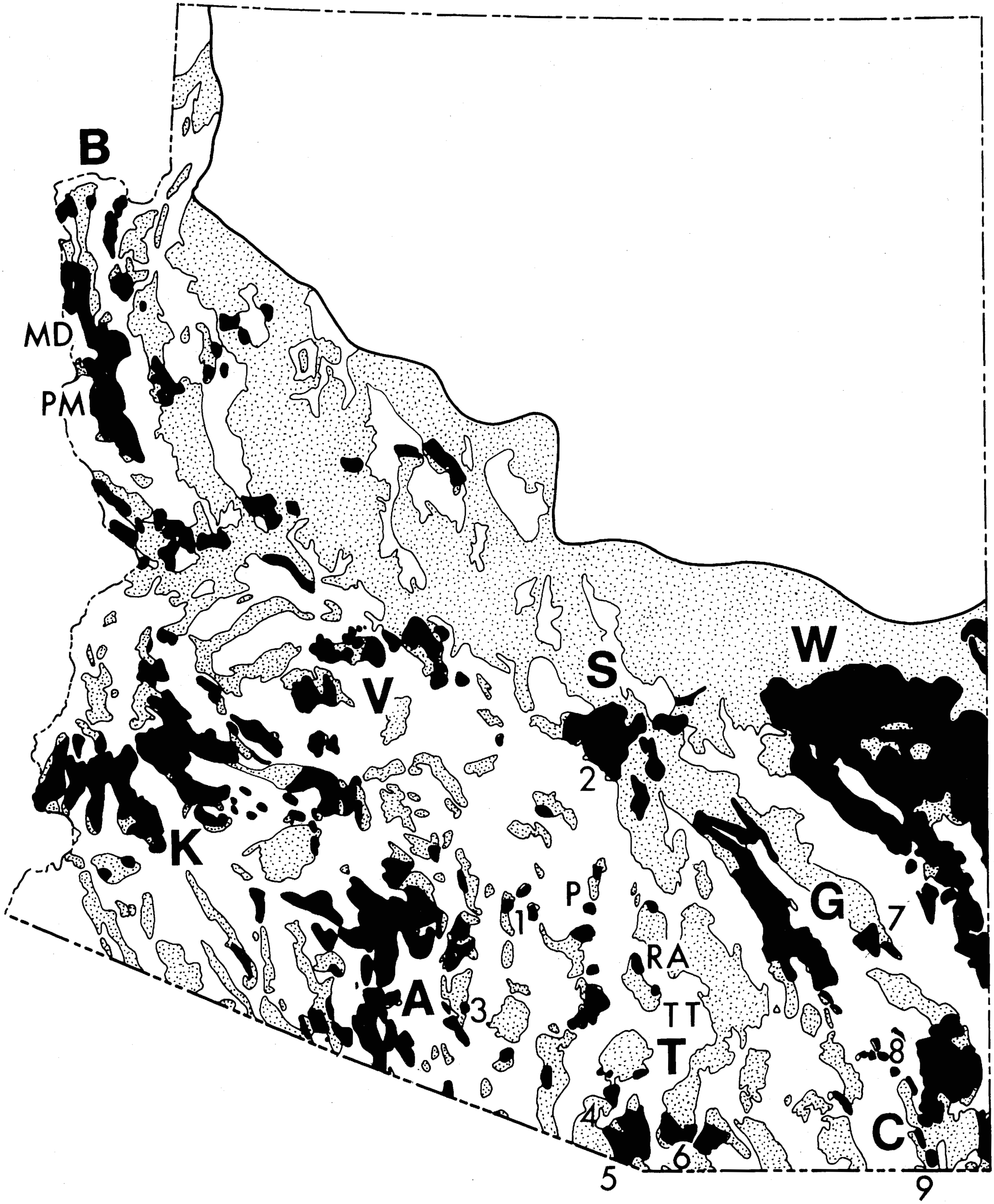

Fig. 4—Ignimbrite volcanics (in black). Stipple pattern shows present mountain ranges. Clear areas are present valleys.

Ignimbrite volcanism in the Blue Range of the White Mountains in eastern Arizona occurred between 37 and 23 m.y. ago (Ratte and others, 1969). In the Chiricahua Mountains of southeastern Arizona, volcanism extended from 28 to 24 m.y. ago (Marjaniemi, 1968). Ignimbrite volcanism in southwestern Arizona occurred from 16 to 13 m.y. ago (Shafiqullah and others, 1980), and, in the Black Mountains of northwestern Arizona, from 19 to 11 m.y. ago (Anderson and others, 1972; Anderson, 1978). Most of the volcanics in the Basin and Range part of the state were extruded between 30 and 15 m.y. ago.

Ignimbritic Volcanics

Ignimbritic volcanics have initial $^{87}Sr/^{86}Sr$ ratios that are higher than 0.705 and generally are between 0.7069 and 0.7096 (Shafiqullah and others, 1978). A comparison of these high intitial strontium ratios with ratios of mantle rocks and of crustal granite suggests that the magmatic source for the ignimbritic volcanics was neither exclusively primitive mantle material (0.703) nor exclusively Precambrian sialic basement rocks (Damon, 1971; Damon and Shafiqullah, 1976) which have much higher initial ratios. Lipman and others (1971) suggest that the massive, mid-Tertiary silicic volcanics were derived from the subducted Farallon plate. Regardless of the exact source of the magmatic material, it is apparent from K_2O/SiO_2 data that mid-Tertiary magmatism was related to subduction of a plate that was being overriden by the North American plate (Keith, 1978).

Major ignimbrite volcanic fields are shown in Figure 4 and include the Superstition field (Peterson, 1968; Stuckless and Sheridan, 1971) and the Chiricahua field (Marjaniemi, 1968; Drewes and Williams, 1973), both of which contain hypothesized calderas. Other extensive areas of mid-Tertiary volcanics that may represent major fields are the Ajo region (the Ajo volcanics of Gilluly, 1937, 1946), the Galiuro Mountains (the Galiuro Volcanics of Simons, 1964, and Creasey and Krieger, 1978), the Kofa Mountains and surrounding areas (Jones, 1915; Wilson, 1933), the Vulture Mountains (Rehrig and others, 1980; Shafiqullah and others, 1980), the Tumacacori-Atascosa area (Nelson, 1968), the Blue Range area of the White Mountains (Ratte and others, 1969), and the Black Mountains of northwestern Arizona (Ransome, 1923; Thorson, 1971; Anderson and others, 1972; Anderson, 1978; Longwell, 1963).

Uranium Exploration Guides—The distribution of ignimbritic volcanics may be related to the occurrence of uranium in fine-grained sedimentary rocks that are intercalated within the volcanics. Keith (1979a) made a preliminary study of the relationship of metallogenesis to subduction-related magmatic types. He suggested that the slightly more calcic mid-Tertiary magmatism in southern Arizona is related to lead-silver mineralization and that the slightly more alkalic mid-Tertiary magmatism in the northwestern part of the state is related to copper-gold mineralization. The more alkalic rocks are more potassic and probably are slightly richer in uranium than the calcic rocks. The coincidence of large volumes of uranium in ignimbrite-associated sedimentary rocks in the Anderson mine area with the slightly more alkalic mid-Tertiary magmatism makes the relationship between uranium and the chemistry of alkalic volcanic rocks worthy of further investigation. A loose spatial relationship between uranium and highly potassic rocks, such as the ultrapotassic trachyte that occurs in the Vulture Mountains of central western Arizona (Rehrig and others, 1980), is also intriguing.

Occurrences of uranium in mid-Tertiary volcanics are also shown in Figure 4. Although many of these occurrences have not yet been examined, several generalizations follow from an analysis of the descriptions in the preliminary reconnaissance reports of the Atomic Energy Commission. Uranium occurs in more silicic volcanics, such as rhyolite prophyry, tuff, perlite and dacite; these silicic rocks are also more highly potassic than basic rocks. Reported uranium minerals include carnotite, kasolite, autunite, uranophane, uraninite, and "gummite." They generally are found on fracture surfaces or in large scale shear zones and, in some cases occur in the presence of excess silica that occurs as silicification, opal, or quartz veins. Although radioactivity ranges from two to 200 times the background values, mineralized zones appear to be spotty and may not contain economic concentrations of uranium.

Coarse-grained Ignimbrite-related Sediments

Some ignimbrite sequences contain intercalated sections of coarse-grained clastic deposits that contain no reported uranium occurrences. Examples of these clastic deposits are shown in Figure 5 and include the Hackberry Formation of Schmidt (1971) in the Hayden and Ray areas (HF, Fig. 5), and the Kinter Formation (Olmsted, 1972; Olmsted and others, 1973) in the Yuma area (K, Fig. 5). In addition, some of the fanglomerates discussed under pre-ignimbrite sediments grade into ignimbritic volcanics, making it necessary to include their upper parts in the ignimbritic package (H,L,SM, Fig. 5).

A typical unit consisting of coarse-grained clastics interbedded with ignimbritic volcanics is the Hackberry Formation of Schmidt (1971) in the Ray and Hayden areas. This 10,000-foot-thick (3,300 m) formation consists of massive conglomerate deposited in debris flows, alluvial fans and plains, and large "megabreccia" slide blocks (Krieger, 1977). The Hackberry Formation contains andesite that is correlated with 35-m.y.-old Galiuro volcanics (Creasey and Krieger, 1978). The Hackberry Formation contains no known uranium occurrences.

Fine-grained Ignimbrite-related Sediments

Although sediments are a volumetrically insignificant part of the ignimbrite package, they are very important because fine-grained sediments are the host rock for the largest uranium resources yet found in Cenozoic rocks in Arizona.

Formations with Minor Uranium Anomalies—Some sedimentary rocks that are intercalated with mid-Tertiary rhyolite and tuff contain mudstone and locally fetid and cherty limestone which have redioactivity measuring up to two times background values. At the Clanton Hills, west of the Gila Bend Mountains (CH, Fig. 5; Wilson, 1933; Ross, 1922), a basal rhyolite dated at 23 m.y. old (Eberly and Stanley, 1978) is overlain by a sequence consisting of basal red arkosic sandstone and mudstone overlain by cherty limestone, more arkose, a rhyolite ash-fall tuff and breccia, and a capping cherty limestone. Uranium anomalies of 1.5 times background values occur in the locally fetid, partially brecciated, thin limestone (Scarborough and Wilt, 1979).

Similar lithologies occur in the nearby Gila Bend Mountains (GB, Fig. 4), where a silicic volcanic flow of probably latest Oligocene age occurs in a section of calcareous arkosic sandstone and thin, dark gray, fetid limestones, which are only locally and mildly radioactive.

Formations with Uranium Occurrences—Fine-grained sedimentary rocks of the Anderson mine area (AM, Fig. 6; Reyner and others, 1956; Peirce, 1977; Otton, 1977a, 1977b, 1978; Sherborne and others, 1979) contain the largest quantity of uranium resources in the state. An estimated 80 million pounds of U_3O_8 occur in the Date Creek basin (Engineering and Mining Journal, 1978), and much more uranium may be present, although some of it may not be recoverable. The uranium occurs in an upper member of the Anderson Mine Formation in carbonaceous mudstone and siltstone interbedded with tuffaceous shale, mudstone, marl and limestone. The uranium-bearing member overlies a lower arkose member which unconformably overlies the Arrastra volcanics (Sherborne and others, 1979). The age of the uranium-bearing rocks at the Anderson mine is early to middle Miocene, based on the presence of fossils of the rhinoceros *Diceratherium* and tall camel *Oxydactylus* (Lindsay and Tessman, 1974) of Hemingfordian age. The uranium-bearing lacustrine and paludal rocks at the Anderson mine are unconformably overlain by the 13.2-m.y.-old Cobwebb basalt (Shafiqullah and Damon, 1979). An Early Miocene age for the uranium-bearing Anderson Mine Formation is consistent with its tentative correlation with the Chapin Wash Formation (Reyner and others, 1956; Peirce, 1977; and Otton, 1977a). The Chapin Wash Formation consists of pink to red mustone, siltstone, and arkosic sandstone (Lasky and Webber, 1949) that are interbedded with Miocene (17.9-m.y.-old) volcanic rocks described by Shackelford (1976) and Gassaway (1972).

The uraniferous Artillery Formation (Lasky and Webber, 1949; Otton, 1977b, 1978) of the Bill Williams River area, at the northwest edge of the Date Creek basin, may roughly correlate with the lower part of the section in the subsurface of the Date Creek basin southeast of the Anderson mine (Otton, 1978, personal commun.; Sherborne and others, 1979). The Artillery Formation is a 2,500-foot-thick (800 m) sequence of basal red arkosic conglomerate, middle light-colored calcareous shale, mudstone, marl, and upper monolithologic breccia. The middle fine-grained part of the Artillery Formation contains abundant uraniferous limestone and mudstone that have been extensively explored for uranium.

Numerous preliminary reconnaissance reports of the Atomic Energy Commission indicate that the sediments and tuff of the Muggins Mountains east of Yuma are uraniferous. However, because most of these uranium occurrences are inside a military reservation, access can be gained only after obtaining various official permissions. Older published accounts (Wilson, 1933; Lance and Wood, 1958; Wood, 1958) briefly describe a section of arkose, shale, limestone, breccia, and tuff that yields dates of 21.9 m.y. (Damon and others, 1968). The uranium is apparently associated with the fine-grained clastics and limestones.

Several uranium claims near Black Butte in the Vulture Mountains (BB, Fig. 6; Hewett, 1925; Kam, 1964) are located in a light-colored sequence of mudstone and vitric ash that is capped by a middle Miocene volcanic flow. The fine-grained sediments overlie a section of andesite and rhyolite tuff that is underlain by a thin, basal arkosic conglomerate. The section crops out at the west edge of the Vulture Mountain block and might continue to the west under alluvium. Uranium occurs in laminated, calcareous mudstone and locally in thin, fetid and cherty limestone.

A uraniferous, tilted sedimentary package is exposed in the southern part of the Big Sandy Valley (BS, Fig. 5) at the Catherine and Michael claim (Granger and Raup, 1962) on the east side of the valley. Similar sediments also occur in the subsurface on the west side of the valley, where they are covered by flat-lying, basin-fill deposits. In one place the 6,000-foot-thick (2,000 m) sequence consists of a basal unit of light red arkosic conglomerate, a middle unit of thick arkosic sandstone, and an upper unit of vitric ash, green mudstone, gray limestone, and brown marlstone. A tilted basalt that occurs high in the fine-grained section is 12.2-m.y.-old (Shafiqullah and Damon, 1979). Uranium occurs in many scattered localities, usually within limestone or marlstone that contains abundant black chert nodules and silicified palm roots.

Uranium has also been reported from fine-grained

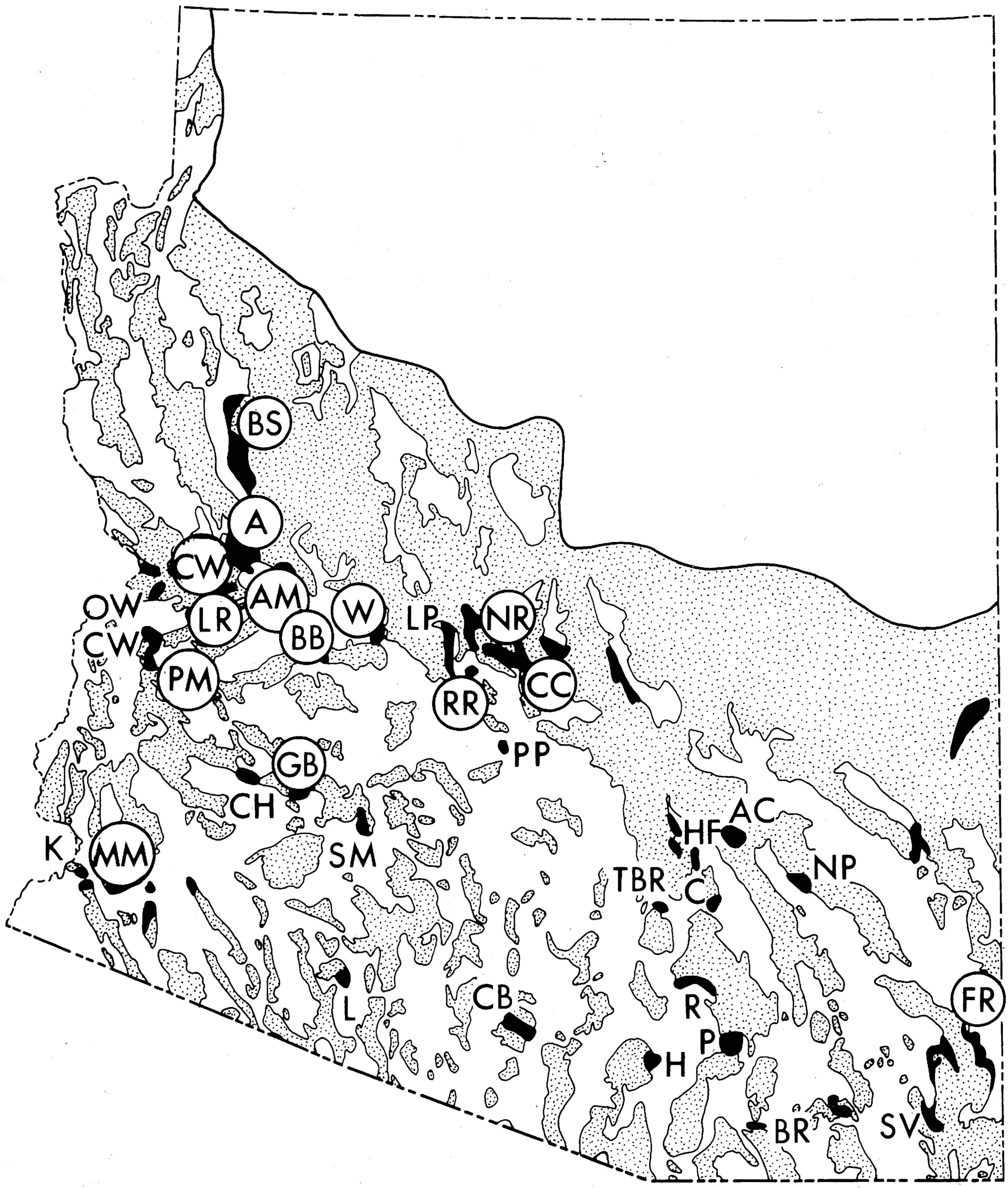

Fig. 5—Sediments associated with ignimbrites (in black). Stipple patterns shows present mountain ranges. Clear areas are present valleys.

sediments intercalated within volcanics north of Phoenix. The ignimbrite section in the Lake Pleasant-Horseshoe Dam area north of Phoenix consists of a mixture of tabular andesite flows, thick proximal air-fall tuff, reworked tuff and tuffaceous sediments, and buff-colored mudstone. These rocks locally are gently warped and beveled and, in several places, are capped by 13-m.y.-old basalt (Shafiqullah and Damon, 1979) similar to Hickey basalt. Uranium anomalies occur in thin, aphanitic dolomite beds within the mudstone sequences of several of these sections. In places, the dolomite contains silica-replacement features, but the most uraniferous dolomite outcrops are devoid of silicification. Four outcrop areas are known from the region: one near a rifle range north of Phoenix (RR, Fig. 5); another near New River (NR, Fig. 5); and two areas near Cave Creek (CC, Fig. 5), one of which is just north of town and another along the south edge of New River Mesa.

These dolomitic occurrences are important because large areas of similar carbonates and mudstone may exist beneath the capping Hickey basalt all along the transition zone between the Colorado Plateau province and the Basin and Range province. Although potentially extractable volumes of uranium are known at only one of these sites, the area may not yet have been sufficiently explored.

Uranium Exploration Guide—Fine-grained sediments associated with ignimbrite in the Date Creek basin contain the largest uranium resources in the state. The presence of such large resources in an area that had unpromising surface manifestations promotes hope that similar occurrences may be concealed beneath other valleys. Host rocks of the uranium occurrences are fine-grained, calcareous shale or limestone deposited in low-energy paludal or lacustrine environments (Fig. 6). The rocks are generally bleached or light colored, contain carbon in the form of carbonaceous trash, plant roots, or fetid limestone, and contain siliceous material as silicified plant roots, agate or opalized wood, or chert nodules or veinlets.

Fine-grained clastic and carbonate rocks of similar type appear to be limited to an east-west swath across the center of the state from near the mouth of the Bill Williams River to just north of Phoenix. The presence of low-energy deposits in the central and central-western part of the state may relate to an underlying tectonic cause.

Subdued topography existed in an area farther south in central Arizona during Late Miocene and Pliocene time. Peirce (1976) called this structurally low zone the Gila Low. A persistent tendency toward lowness in a broad region of central Arizona may have persisted from Early Miocene time and might have had an influence on uranium deposition in fine-grained host rocks.

POST-IGNIMBRITE SEDIMENTS

Post-ignimbrite sediments were deposited after the bulk of ignimbrite volcanics were extruded; they are distinguished by a lack of ignimbrite or by diminished amounts of volcanic interbeds. Post-ignimbrite sediments usually contain thin, reworked tuffaceous mate-

A	Artillery Formation
AC	Apsey Conglomerate
AM	Anderson Mine Formation
BB	Sediments at Black Butte
BR	Redbeds at Babocomari Ranch
BS	Older sediments of Big Sandy Valley
C	Cloudburst Formation
CB	Sediments of Comobabi
CC	Sediments near Cave Creek
CH	Limestones in Clanton Hills
CW	Chapin Wash Formation
FR	Faraway Ranch Formation
GB	Limestones in Gila Bend Mountains
H	Upper Helmet Fanglomerate
HF	Hackberry formation
K	Kinter Formation
L	Upper Locomotive Fanglomerate
LP	Sediments near Lake Pleasant
LR	Lincoln Ranch beds
MM	Muggins Mountains beds
NP	Redbeds of northern Pinaleno Mountains
NR	Carbonates of New River area
OW	Older redbeds in Osborne Wash
P	Upper Pantano Formation
PM	Limestone in Plomosa Mountains
PP	Redbeds of Papago Park, Phoenix
R	Rillito I
RR	Redbeds near rifle range, Lake Pleasant
SM	Upper Sil Murk
SV	Tuff in Swisshelm Valley
TBR	Redbeds near Three Buttes
W	Sediments near Wickenburg

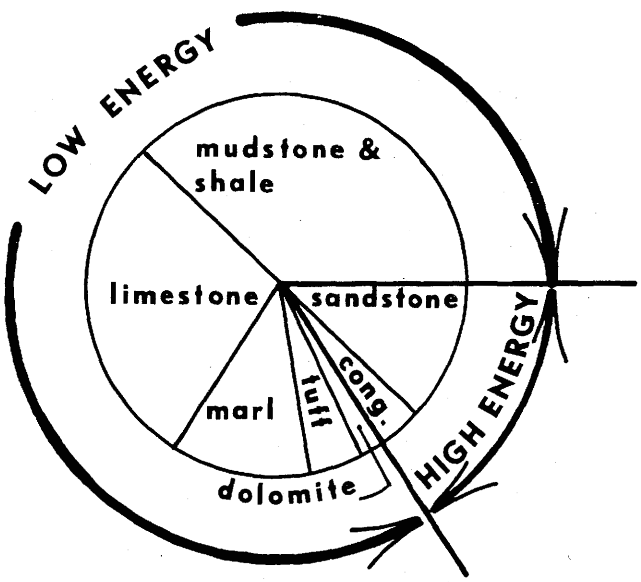

Fig. 6—Proportions of various uranium-bearing mid-Tertiary sedimentary host rocks in Arizona's Basin and Range province.

rial or proximal tuff facies. The base of the post-ignimbrite package is sometimes marked by angular unconformities, but the contact is locally gradational and reflects the gradual waning of ignimbrite volcanism. The tops of the post-ignimbrite deposits are assumed to be major unconformities that mark the onset of Basin and Range faulting. The ages of the lower and upper contacts of the post-ignimbrite subdivision vary from place to place, although the upper boundary or the onset of Basin and Range tectonism appears to have been fairly sudden at about 12 to 11 m.y. ago (Eberly and Stanley, 1978; Peirce, 1976; Anderson et al, 1972) throughout the state.

Coarse-grained Post-ignimbrite Sediments

Anomalous uranium has not been reported from fanglomerate, sandstone, or basalt of the post-ignimbrite subdivison. These units, as shown in Figure 7, crop out in slightly more valleyward parts of the pediments than previous subdivisions. However, even though these rocks occur in the topographic valleys, they are structurally part of the mountain or horst blocks. These middle Miocene rocks have been cut by Basin and Range faults. The part of the unit in the horst block was exposed to erosion and pedimentation while the part in the graben block was buried by basin-fill deposits.

Facies in the fanglomerates of the post-ignimbrite package are partly, but not totally, related to present valley configuration.

The composition of clasts in several conglomerates records unroofing of adjacent mountain blocks in the middle Miocene. Thin layers of reworked tuff are very common in strata of this subdivision and relate to the more proximal tuff facies.

Locations of formations in the post-ignimbrite package are shown in Figure 7. The Nogales Formation (NF, Fig. 7; Drewes, 1972) consists of 7,000 ft (2,400 m) of light-colored fanglomerate, tuff, sandstone, and basalt flows, one of which yields a K/Ar date of 12.6 m.y. (Simons, 1974). The San Manuel Formation (SM, Fig. 7) (Heindl, 1962; Creasey, 1967; Schmidt, 1971; Krieger and others, 1974) is a fanglomerate that unconformably overlies the Oligocene Cloudburst Formation (28.3 m.y.; Shafiqullah and others, 1978); the San Manuel Formation is unconformably overlain by basin-fill sediments. Other examples of coarse-grained post-ignimbrite sediments shown in Figure 7 include the Big Dome Formation (BD, Fig. 6; Krieger and others, 1974), the Daniels Conglomerate (DC, Fig. 7; Gilluly, 1946) near the Ajo, the Hell Hole Conglomerate (HH, Fig. 7; Simons, 1964), and the Rillito III beds (RIII, Fig. 7) of Pashley (1966).

Fine-grained Post-ignimbrite Sediments

Light-colored mudstone, limestone, and marl that are interbedded with vitric ash and tuffaceous sediments of the post-ignimbrite subdivision contain scattered uranium occurrences. These unnamed formations were deposited unconformably on tilted andesite sequences or basalt-flow complexes that range in age from 26 to 14 m.y. The sediments are, in turn, unconformably overlain by undeformed, fine-grained, basin-fill deposits.

In the Lake Pleasant area (LP, Fig. 7), a sequence of about 1,000 ft (350 m) of white, gently folded, tuffaceous sediments and a grayish-brown cherty limestone and minor mudstone contains carnotite stains on fracture surfaces. These beds unconformably lap up against mesas that are capped by basalts believed to be 13 to 14 m.y.

BD	Big Dome Formation
CM	Sediments at Chalk Mountain
DC	Daniels Conglomerate
HD	Sediments at Horseshoe Dam
HH	Hell Hole Conglomerate
LP	Sediments at Lake Pleasant
NF	Nogales Formation
R_{III}	Rillito III beds
RB	Roskruge basalt
RW	Ripsey Wash formation
SB	Swisshelm basalt
SM	San Manuel Formation
HD	Uranium occurrence

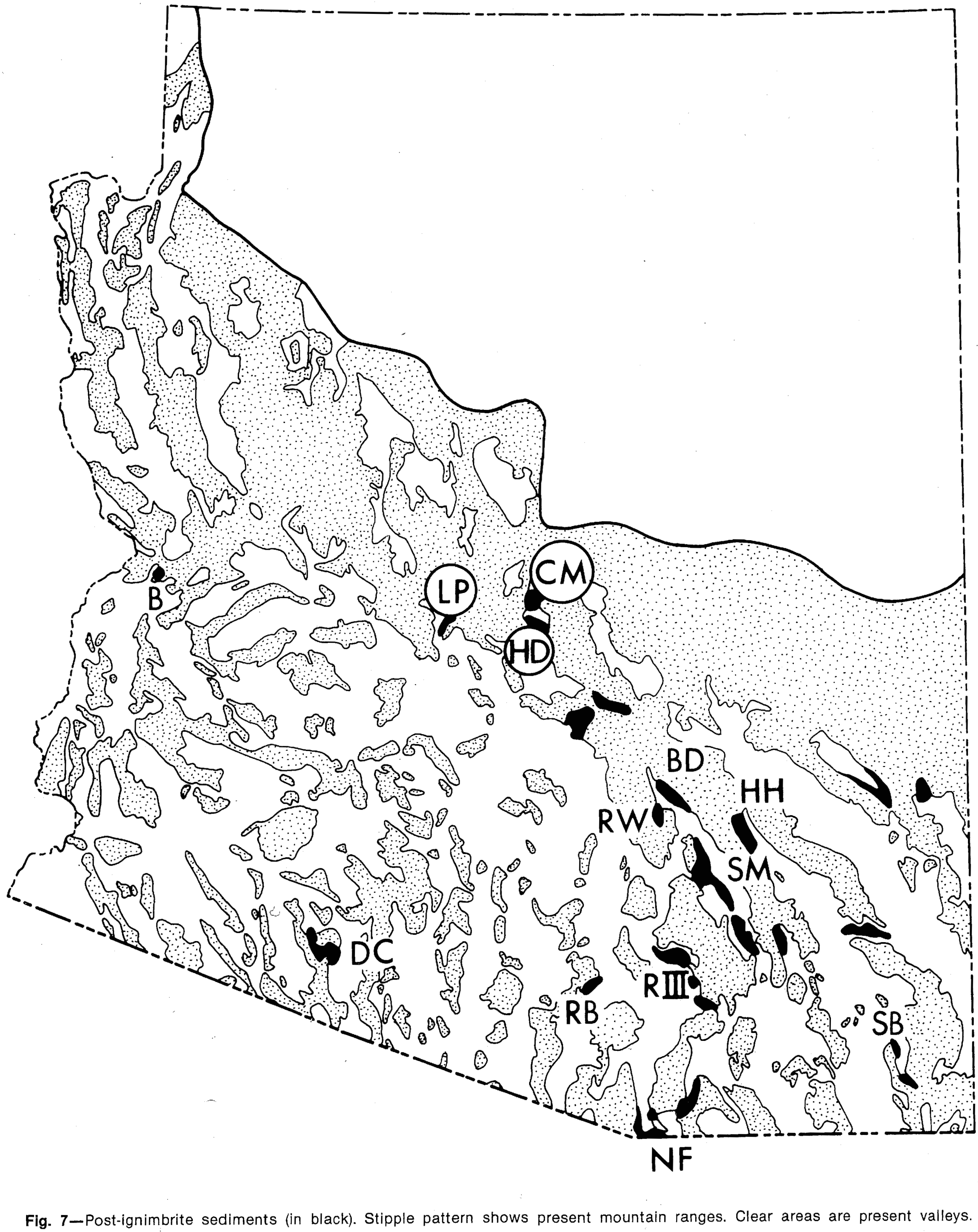

Fig. 7—Post-ignimbrite sediments (in black). Stipple pattern shows present mountain ranges. Clear areas are present valleys.

old. The light-colored beds are unconformably overlain by flat-lying, fine-grained, basin-fill sediments near the center of Lake Pleasant Valley.

Near Horseshoe Dam (HD, Fig. 7), a southwest-dipping section of light-colored tuffaceous units, calcareous units, and marl is underlain by a middle Miocene andesite flow exposed at the Horseshoe Dam abutments. The contact of this section with younger, undeformed, basin-fill sediments is a high-angle fault. Disseminated uranium is found in some of the mudstone and calcareous units in association with silica-replacement pods. Uranium also occurs near high-angle faults that bound the section to the south and west. At Chalk Mountain (CM, Fig. 7), a few miles north of Horseshoe Dam, a slighly deformed, light-colored, tuffaceous and marly section contains carnotite as fracture coatings. This section may relate to the Lake Pleasant section, rather than to the section at Horseshoe Dam.

Uranium Exploration Guides

The coarse-grained sediments of the post-ignimbrite subdivision in southern and eastern Arizona appear to have little uranium potential. More promising prospects for this post-ignimbrite package occur in fine-grained rocks that crop out in the 50-mile-wide transition zone that parallels the boundary between the Colorado Plateau and Basin and Range provinces. An association between sediments containing uranium and basalt and white vitric tuff is common in large areas of unexplored terrain. The lack of large volumes of mineralization in known occurrences does not necessarily preclude future major discoveries.

In addition to its occurrences in mid-Tertiary rocks, uranium also occurs in Tertiary fault zones. Uranium occurs in a low-angle, west-dipping fault on the west end of the Buckskin Mountains of western Arizona (B, Fig. 7), where it occurs in pods of limonite associated with alteration and copper mineralization. Some of these gently dipping faults or dislocation surfaces appear to have affected rocks as young as middle Miocene (Davis and others, 1977).

BASIN-FILL DEPOSITS

Basin-fill deposits are distinguished from older sediments by their lack of tilting or folding. The base of basin-fill deposits is assumed to be a major unconformity now buried under thousands of feet of sediments. The top is above the highest level of valley-fill deposits and unconformably underlies thin Pleistocene deposits. The age of basin filling ranges from 13 or 10 m.y. to approximately 2 m.y. Summary articles describing these units for southwestern Arizona include Eberly and Stanley (1978) and, for southeastern Arizona, Peirce (1976) and Scarborough and Peirce (1978).

4 - 0 m.y. old basalt

9 - 4 m.y. old basalt

14 - 9 m.y. old Hickey basalt

Volcanic Fields and Formations

CB Cottonwood basalt
CWB China Wash basalt
FB Fortification basalt
HBV Hopi Buttes volcanic field
PB Pinacate volcanic field
SB Sentinel volcanic field
SBV San Bernardino volcanic field
SF San Francisco volcanic field
WM White Mountain volcanic field

Basin-fill Sediments

B Bouse Formation
HL Hualapai Limestone
L Littlefield formation
MC Muddy Creek Formation
O Osborne Wash formation
Q Quiburis Formation
S Safford Basin beds
SD St. David Formation
T Tonto Basin beds
V Verde Formation

Uranium Occurrences

1 Virgin River Valley
2 Lake Mead area
3 Verde Valley
4 Tonto Creek area
5 San Pedro Valley
6 Safford area

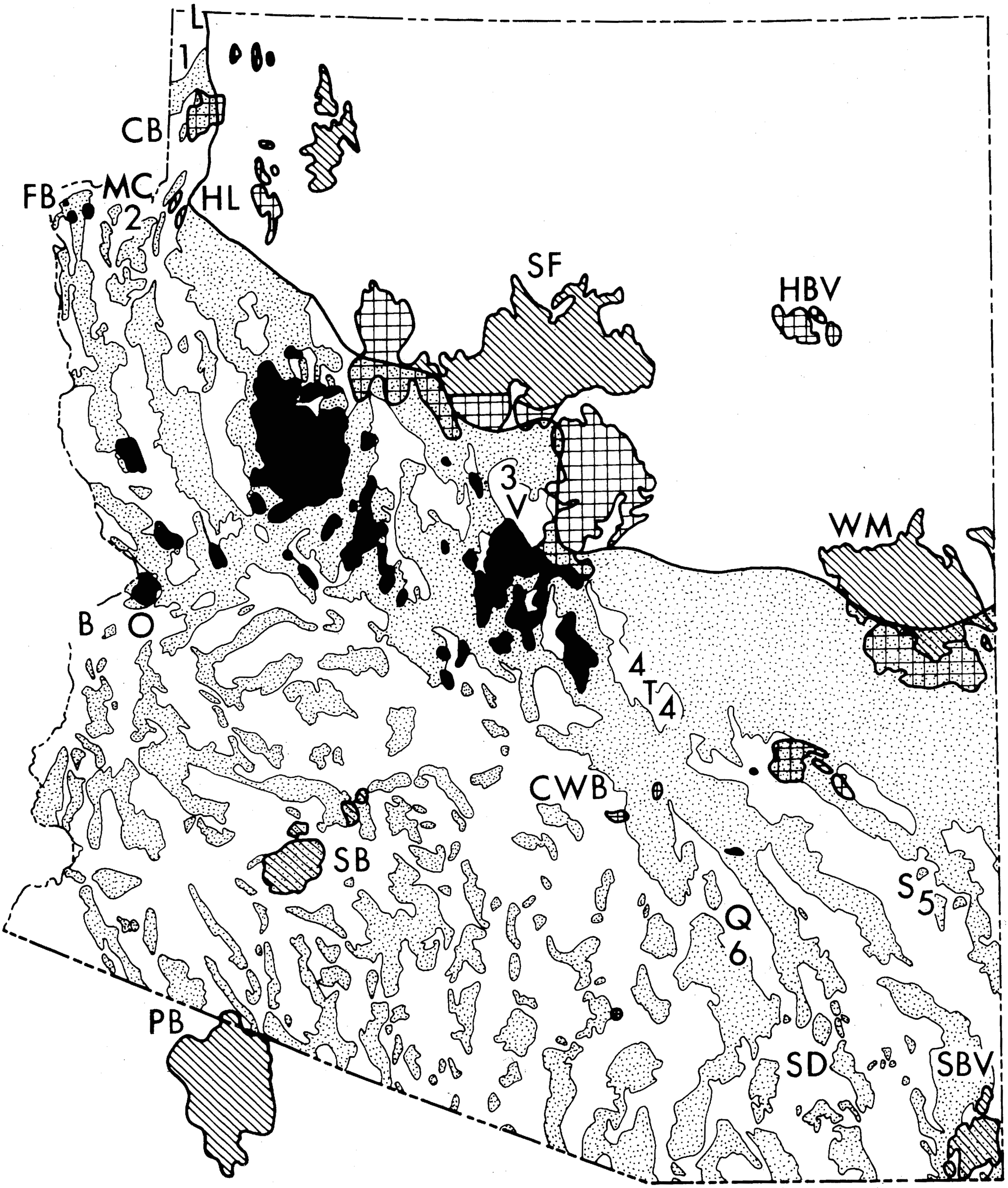

Fig. 8—Basin-fill sediments (clear areas) and volcanics (as above patterns). Stipple pattern shows present mountain ranges.

Basin-Range Volcanics

Basalt extruded after the inception of Basin and Range faulting is true basalt rather than the higher silica basaltic andesite that characterizes the volcanism related to subduction zones. The $^{87}Sr/^{86}Sr$ initial ratios of 0.705 or less are similar to primitive mantle ratios (Shafiqullah and others, 1978). This similarity suggests the magma may have leaked upward from the mantle through deep-seated Basin and Range faults and experienced little or no mixing with crustal materials.

Figure 8 shows that volcanism at the edge of the Colorado Plateau generally moved progressively northward onto the Plateau during the Tertiary. This pattern is best shown within the San Francisco and White Mountain volcanic fields. In the Basin and Range province, Late Tertiary basaltic volcanic rocks are scattered in several fields, as shown in Figure 8.

The earliest basaltic volcanism is represented by the Hickey basalt in the central part of the state. Most of the early basalt dates from 13 to 9 m.y. ago (Shafiqullah and others, 1980), although some flows are as old as 14 m.y. Hickey basalt chemistry and strontium initial ratios are more closely allied to strontium initial ratios of the Basin and Range volcanics than to ratios of mid-Tertiary ignimbrite (Shafiqullah and others, 1978; Keith, 1979b). These relationships support a model in which Basin and Range block faulting began at or near 13 m.y. ago, around the time of initial Hickey basalt extrusion.

Basin-fill Sediments

Undeformed basin-fill sediments exhibit facies relationships that are consistent with present-day valleys and thus developed within the general framework of present-day physiography (Heindl, 1962). Basin-fill sediments consist of fanglomerate at the edges of basins and of low energy facies, including anhydrite and salt, in the valley centers (Peirce, 1976). Examples of basin-fill formations include the Quiburis Formation of the San Pedro Valley, (Q, Fig. 8; Heindl, 1963), the Gila Conglomerate of eastern Arizona (Gilbert, 1875), and the Muddy Creek Formation of northwestern Arizona and Nevada (Longwell, 1928, 1963; MC, Fig. 8). Most basin-fill deposits have not been named or studied in detail because they are poorly exposed. The Bouse Formation of the Yuma area (B, Fig. 8; Metzger and Loeltz, 1973; Metzger and others, 1973) was deposited during a Pliocene marine invasion from the Gulf of California.

Uranium Occurrences — Uranium occurs in light-colored, fine-grained, lacustrine mudstone or marl with some tuffaceous interbeds and with abundant silica as chert, agate, or opal. The distribution of these uraniferous basin-fill deposits is shown in Figure 8. They are exposed in valleys whose sedimentary deposits have experienced dissection during the Pleistocene. It is quite possible that most other valleys which have not yet been downcut will contain similar fine-grained uranium-bearing, lacustrine sediments.

In the Virgin River Valley, the Littlefield Formation (L, Fig. 8; Moore, 1972) contains carnotite on fractures in a sequence of sandstone, clay, silt, and gypsum that is below the 6.7 to 4.6-m.y.-old Cottonwood Basalt (Damon and others, 1968). In the Lake Mead area, the Muddy Creek Formation (MC, Fig. 8; Longwell, 1963) contains carnotite and uranophane on bedding planes in tuffaceous limestone, marl, lacustrine mudstone and sandstone, and opalized, cherty limestone with abundant gypsum.

The Verde Formation (V, Fig. 8; Twenter and Metzger, 1963), in the Verde Valley, consists of lower mudstone and upper marlstone and has concentrations of carnotite on fractures in calcareous marl in the vicinity of Cottonwood. Uranophane occurs in fractures in paludal mud and lignite in the Tonto Basin area (T, Fig. 8) where the sediments lap onto beveled granites of the Sierra Ancha. Uranium also occurs in the upper parts of the Quiburis Formation (Q, Fig. 8; Agenbroad, 1967), in the San Pedro Valley east of the Santa Catalina Mountains. The uranium occurs in calcareous lakebeds containing minor chalcedony. Uranophane and carnotite also occur on fractures in light-colored tuff, clay, and nodular, opal-bearing lakebeds of the Late Pliocene 111 Ranch beds in the Safford area (S, Fig. 8).

CONCLUSIONS

Uranium occurs in middle and Late Tertiary pre-ignimbrite, ignimbrite, post-ignimbrite, and basin-fill sediments of Arizona. In each group of rocks, the uranium is apparently concentrated in fine-grained sediments that were deposited in lacustrine, paludal, or low-energy floodplain environments. Light-colored calcareous mudstone or fetid carbonates are the most favorable host rocks, especially in the presence of carbonaceous material and of silica in the form of chert nodules or stringers.

If the kinds of sediments that are favorable host rocks for uranium are present in each of the packages, why does the ignimbrite category, as exemplified by the sediments in Date Creek basin, contain so much more uranium than any of the other subdivisions? The principal difference between the four packages of deposits is the characteristic that was used to define them—the amount and type of volcanism. The package that contains the most uranium resources is the one with the largest volume of ignimbrite volcanism.

If ignimbrite volcanism occurred throughout the Basin and Range portion of Arizona, why are the major known resources found in central and western Arizona? This part of Arizona differs from eastern and southern Arizona in three aspects:

1) The time of mid-Tertiary volcanism was slightly later in the west and the possibility exists that the volcanism in the west was slightly more alkalic than that farther east.

2) The western and central area also coincided with exposures of large areas of Precambrian alkalic granite.

3) During the middle Miocene the area received fine-grained sediments suggesting that low-energy depositional sites were subjected to continued subsidence; thus, lacustrine and paludal environments persisted and resulting carbonaceous mudstones were preserved.

The slightly higher uranium contents in alkalic and silicic volcanic and granitic rocks that could have been exposed to leaching processes may have combined with appropriate reducing environments to trap uranium, with a tectonic setting to preserve the resulting deposits. These three factors could have coincided in western and central Arizona during the later part of the mid-Tertiary in order to produce a large deposit such as the Anderson mine.

Exploration for other deposits similar to those of the Anderson mine should focus on areas combining the following factors: fine-grained sediments with carbonaceous and siliceous matter; exposures of alkalic Precambrian granite; and large volumes of alkalic volcanics of the ignimbrite package.

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Table of Contents