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THE GEOLOGY OF ARIZONA: ITS ENERGY RESOURCES AND POTENTIAL

By J. Dale Nations, Commissioner
Arizona Oil and Gas Commission
and Associate Professor of Geology
Northern Arizona University
Flagstaff, Arizona

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General Structural and Petrologic Framework of Arizona

Arizona sits astride two major geologic provinces, the Colorado Plateau to the north and the Basin and Range to the south and west. The provinces are characterized by quite different stratigraphic framework and structural patterns, and are separated by a narrow area of transition which is commonly considered a third structural province called the Transition Zone or Central Mountain Region.

The Plateau Province includes the northern third of the state bounded on the south by the Mogollon Rim and on the west by the Grand Wash cliffs in the western Grand Canyon. It extends into southern Utah, southwestern Colorado and northwestern New Mexico. This Province is characterized by predominantly horizontal stratified sedimentary rocks that have been eroded into numerous canyons, plateaus and scarps along which are exposed many colorful rocks ranging in age from Precambrian to Cenozoic. Many of the most famous landscape features such as the Grand Canyon, Black Mesa, Painted Desert and Petrified Forest, and the Mogollon Rim have been carved into these rocks by erosion. Others such as the San Francisco Mountains and the White Mountains have been piled on top of the Plateau by Cenozoic volcanic activity.

Historically the Plateau has been a relatively stable segment of the craton which was periodically inundated by shallow epicontinental seas along the eastern margin of the Cordilleran Geosyncline from late Precambrian time through the Pennsylvanian Period. Beginning in Late Paleozoic time the area was predominantly emergent and blanketed by thick sequences of deltaic, fluvial and eolian sediments throughout the Early Mesozoic, with infrequent inundations by the sea during the Permian. In Late Cretaceous time a marine invasion again occurred, but from the Western Interior Seaway to the east.

South of the Plateau is a relatively narrow band of landscapes called the Transition Zone or Central Mountain Province, characterized by rugged mountains of igneous, metamorphic and deformed sedimentary and volcanic rocks of Precambrian age, with erosional remnants of Paleozoic age. The elevations are generally lower and the crustal rocks have been more severely faulted than in the Plateau Province. The general absence of Mesozoic and Cenozoic rocks indicates a longer period of erosion and/or nondeposition of sedimentary rocks such as are found in the other Provinces. Well known landscape features in the Transition Zone include the Black Hills near Jerome and Prescott, the Mazatzal and Sierra Ancha Mountains around Roosevelt Lake, and the Salt River Canyon between Show Low and Globe. The important copper mining districts extending from Jerome to Morenci, and the uranium occurrences in the Precambrian Dripping Spring Quartzite, are located in this area.

The Basin and Range Province includes the southwestern half of the state bounded on the north and east by the Plateau and Transition Provinces along a line trending northwest-southeast from Lake Mead to Globe. It also extends into southern Nevada, southeastern California and into the states of Sonora and Chihuahua. The characteristic landform of this Province is one of elongated mountain ranges trending northwest-southeast, separated by broad alluvial valleys. The mountains consist of tilted, and sometimes structurally deformed, blocks of Precambrian, Paleozoic, Mesozoic and Cenozoic rocks that are bounded by faults and have been severely eroded. The Paleozoic rocks are predominantly marine limestones, shales and sandstones that were deposited on a shallow marine shelf in the Early Paleozoic and deeper basins in the Late Paleozoic. The Early Mesozoic rocks are predominantly volcanic or plutonic, and those of Cretaceous age are primarily marine sandstones, shales and carbonates, but also include Laramide intrusives. Cenozoic rocks are largely volcanic but also include nonmarine alluvial and lacustrine sediments, and a small area of marine sediments along the southern Colorado River. The valleys are intermontane depressions that have subsided thousands of feet, and are filled with Cenozoic volcanics, alluvium, and lacustrine sediments. Most of the mountain ranges and valleys in the desert region of western and southern Arizona, including the Hualpai Mountains south of Kingman, the Phoenix Mountains north of Phoenix, and the Chiricahua and Santa Catalina Mountains near Tucson, are examples of Basin and Range landforms.

Major Structural Events

Numerous structural features have been superimposed on the rocks throughout the state, occurring primarily during the Early and Late Precambrian, the Late Mesozoic, and the Late Tertiary. The oldest recognizable deformation, the Mazatzal Revolution, occurred about 1700 million years ago (Brown, et al, 1974) and resulted in the emplacement of large plutonic intrusions and major folding and foliation with prevailing northeast trends. Minor folding, thrust and steep reverse faults were developed with west and northwest trends, and shear faults of general, north-south and east-west trends. Vertical displacements on many Precambrian faults amounted to several thousand feet. The Mazatzal Revolution must have produced mountain ranges many thousands of feet high, but they were eroded down to a featureless plain prior to the deposition of Younger Precambrian sediments of the Grand Canyon Series and Apache Group. The Mazatzal structural pattern influenced subsequent tectonic events throughout the state as the old faults were commonly rejuvenated during later periods of deformation (Wilson, 1962). Many metallic ore deposits were emplaced during the Mazatzal Revolution, particularly in the Transition Zone.

A subsequent, less severe, period of structural deformation occurred at the end of Precambrian time and resulted in folding and faulting of Younger Precambrian sedimentary and volcanic rocks. The result of this deformation, called the Grand Canyon Disturbance, was a series of fault block mountains similar to the Basin and Range structures, along structural trends similar to those of the Mazatzal Revolution. These mountains were eroded away prior to the deposition of Cambrian sediments over much of the state.

The Laramide Orogeny of Late Cretaceous and Early Tertiary time resulted in folding and faulting in the Plateau region, with more intense structural deformation, and the formation of plutonic and volcanic rocks in the Basin and Range Province. The main structural features on the Plateau, e.g. the Kaibab uplift, Black Mesa Basin and Monument uplift, and the major N-S to NW-SE faults are attributed to Laramide compressional deformation. The Laramide deformation in the Basin and Range was much more intense than in the Plateau and resulted in considerable crustal shortening that was accommodated by folding and thrusting, especially in southeastern Arizona. The preponderance of metallic ore deposits, particularly copper, is genetically related to intrusive bodies of Laramide age.

The initiation of crustal extension, with resultant block faulting and volcanic activity in the Basin and Range Province, appears to have occurred about 13-12 million years ago in the Late Miocene (Eberly and Stanley, 1978). This tectonic event which is called the Basin and Range Disturbance resulted in the general collapse of the crust in southern and western Arizona and the formation of deep structural basins. The frequent volcanic activity and erosion of uraniferous volcanic rocks was the apparent source of uranium deposits in the Cenozoic valley fill.

The occurrence of energy resources -- oil and gas, coal, uranium, and geothermal -- are intimately related to the structural and petrologic framework of the state. The proven and potential occurrences of these resources will be discussed in the following pages.

Oil and Gas

Introduction

The objectives of this part of the paper are to summarize the available information on oil and natural gas occurrence and production in Arizona, and to review the prevailing opinions relative to oil and gas potential throughout the state. The information presented is necessarily a brief summary of the most current published literature. The references cited will lead the interested reader to more detailed discussions of the geology and/or potential of specific areas within the state.

The pronounced division of the state into distinct structural provinces imposes a logical organization on any discussion of Arizona geology. The Plateau Province which contains all production to date, and in the opinion of most writers has the greatest future potential, is discussed first. This is followed by consideration of the southeastern corner of the state which is in the Basin and Range Province, but includes the Pedregosa Basin. Last in the order of discussion is the southwestern half of the state, dominated by Basin and Range structure, and is the area of greatest current exploration activity.

Northern Arizona

The only production and, based on current knowledge, the greatest oil and gas potential in Arizona is in the Plateau Province of northern Arizona. All of the area was located on a shelf throughout the Paleozoic which separated the Cordilleran Geosyncline in Nevada from the emergent Transcontinental Arch in New Mexico. The Paleozoic sedimentary rocks record a fluctuating shoreline resulting in a discontinuous sequence of marine sediments interrupted by unconformities and/or nonmarine sediments. All the Paleozoic systems except the uppermost Permian, are terminated toward the New Mexico border either by onlap or erosional truncation along the western margin of the Defiance Uplift and thinned southward over a positive area in central Arizona. Most of the Paleozoic systems thicken toward the Paradox Basin in southeastern Utah in the Four Corners region (Lessentine, 1965). During the Triassic and Jurassic the area was buried by predominantly nonmarine sediments, but was submerged beneath the shallow Western Interior Seaway in Late Cretaceous (Cenomanian-Turonian) time, only to become emergent again in latest Cretaceous time.

Several writers (Brown and Lauth, 1958; Conley, 1974; and Peirce, et al, 1970: Lessentine, 1965) have interpreted the oil and gas potential of Paleozoic rocks in northern Arizona. This paper is an updated summary of their work and that of other authors.

Production Summary

All oil and gas production and known reserves in the state are confined to Apache County in the Colorado Plateau. Forty wells have produced oil in this area of 10 fields, the largest of which is Kerr-McGee's Dineh-bi-Keyah with 20 wells completed in a Tertiary sill intruded into Pennsylvanian marine strata. Fifteen of the additional 20 wells produced from Pennsylvanian strata, 4 from Mississippian, and 1 from Devonian (Peirce, 1970, p. 99). Structurally, the Dineh-bi-Keyah Field is on the flank of the Defiance Uplift and all others are on the same structural trend in the southern margin of the Paradox Basin. To the west in Coconino and Mohave Counties an eastward regional thinning of Cambrian-Pennsylvanian, and local thinning and over the Kaibab positive, creates potential stratigraphic and structural traps (Peirce, 1970, p. 100; Brown and Lauth, 1958).

Structure

The Colorado Plateau in northern Arizona is a relatively undisturbed structural province but has been downwarped into two major structural basins -- the Black Mesa Basin and the Paradox

Basin. The Paradox Basin barely extends into Arizona but all of the Arizona oil and gas production is confined to it. The Black Mesa Basin is bounded on the east by the Defiance Uplift (positive since Precambrian) on the north by Monument Upwarp, on the west by Kaibab Plateau and on the south by the Mogollon Slope, all Laramide in age (Brown and Lauth, 1958). Several folds and faults with predominantly N-S or NW-SE trends cross the region (Lessentine, 1965; Kelley, 1958).

Oil and Gas Potential in Northern Arizona

Brown and Lauth (1958) summarized the oil and gas potential as follows:

> "The largest oil and gas wells have been and shall probably continue to be found along the southern edge of the Paradox Basin in its foreland facies zone. The Pennsylvanian formations have good potential along the southern edge of the Black Mesa Basin. Based upon shows in wells, petroliferous indications along the outcrop areas and the regional thickening of the Mississippian, Devonian and Cambrian. Potential producing reservoirs may be developed in rocks of these systems."

Southwestward from the Four Corners area, the Pennsylvanian-Permian strata grade laterally to redbed and limestone facies in the Black Mesa Basin, where the Devonian and Mississippian marine strata appear to be most favorable for oil and gas. These strata wedge out to the east against the Defiance Uplift and to the south against the Mogollon Slope, creating favorable conditions for stratigraphic traps (Peirce, 1970). In rocks of Permian age the Fort Apache member of the Supai Formation, the De Chelly member of the Cutler Formation and the Coconino Sandstone have excellent potentials for shallow production. Brown and Lauth (1958) further outlined potential producing areas on isopach maps of Paleozoic and Cretaceous systems in Arizona.

Several wells have been drilled on and adjacent to the Holbrook "Anticline" without success but interest and activity continue there due to structural and stratigraphic complexity associated with evaporite facies in the upper Supai Formation and the presence of older Paleozoic strata (Peirce, 1970; McCaslin, 1976a).

Several other large, and largely untested, areas of the Plateau are known to contain Paleozoic rocks with some potential. Peirce (1970) suggests several areas, e.g. the Coconino Plateau south of Grand Canyon with Devonian and Mississippian potential; northwestern Arizona north of Grand Canyon, with a thick lower Paleozoic section and Paleozoic rocks buried beneath the White Mountain Volcanic Field. Conley (1974, 1975) summarized the history of oil and gas exploration in Arizona including the locations of stratigraphically significant wells, tabulated production data for oil, gas and helium, and noted that shows of oil or natural gas have been observed in rocks of all Phanerozoic geologic systems known in northern Arizona except the Jurassic and Tertiary. He concluded that "this part of the state has many large unexplored or incompletely explored areas having the basic factors normally considered requisite for oil and gas accumulation," and that "northern Arizona can be considered as an attractive unexplored onshore area offering potentially large accumulations of oil from a variety of traps in Paleozoic rocks."

Southeastern Arizona

The greatest exploration activity for oil and gas in southern Arizona has been concentrated in Cochise County in the extreme southeastern corner of the state. The Pedregosa Basin is characterized by a thick (over 2,000 feet) sequence of Pennsylvanian rocks with distinct deep marine basin facies of limestone and mudstone, flanked by marginal porous dolostone (reefs?) and shelf carbonates. The similarities between this basin and the Permian Basin have attracted attention to its potential. The additional thickness of Permian and Lower Cretaceous rocks known to be in the basin increase its potential as a petroleum province. Over 40 petroleum exploration wells have been drilled in the Arizona portion of the Pedregosa Basin resulting in some encouraging shows but no commercial production (Thompson, et al, 1978). Conley and Stacey (1977) mapped well locations and summarized subsurface data, Peirce and Scurlock (1972) and Scurlock (1973) published information on formation tops and drillstem tests, and Aiken and Sumner (1974) wrote a summary report on the oil and gas potential of southeastern Arizona, including geophysical maps and cross sections. The exploratory wells drilled to Paleozoic or Precambrian rocks along with formation tops and oil and gas shows are tabulated by Thompson, Tovar and Conley (1978). They rank the Horquilla Formation (Pennsylvanian) and Martin (Devonian) as the highest potential in southeastern Arizona based upon the best shows in the Horquilla and good reservoir characteristics in the Martin dolostone and sandstone. Lower Cretaceous sedimentary rocks (Bisbee Group) up to 10,000 feet thick were deposited as a delta complex on the margin of a sea that extended to the southeast into Mexico. It contains a limestone unit, the Mural Limestone, ranging from 300 to 800 feet thick, that is reefoid in places and yields a fetid odor on fresh fracture (Peirce, et al, 1970).

Structure

Structural complications have been imposed on the Pedregosa Basin by Laramide thrusting and wrench faulting, but the most severe modifications have resulted from Mesozoic and Cenozoic igneous intrusions and Late-Tertiary Basin and Range extensional faulting (Thompson, et al, 1978; McCaslin, 1976b).

Potential

Many of the wells have been drilled on Basin and Range horsts where reservoirs tend to be flushed by ground water, and the best prospects lie in the graben where chances for oil and gas preservation are better (Thompson, et al, 1978). None of the wells have tested the deeper parts of the basins in Cochise County where thick sections of Paleozoic rocks should be encountered at depths of below 10,000 feet. Future exploration should also evaluate the potential of the Lower Cretaceous objectives in favorable locations (Thompson, et al, 1978).

Southwestern Arizona

The recent discoveries of economic accumulations of oil and gas in the Basin and Range region of Nevada (McCaslin, 1974, 1976c, 1977, 1978; and Kamen-Kaye, 1978) and rapidly accumulating data on subsurface structure and stratigraphy in southwestern Arizona (Eberly and Stanley, 1978; Scarborough and Peirce, 1978) has provided a previously unavailable data base for increased evaluation of this part of Arizona as a potential petroleum province.

Marine Paleozoic rocks are preserved in the mountain blocks of southern Arizona, therefore they may be preserved in the intervening basins (Peirce, 1970). Indeed, Paleozoic and Mesozoic marine rocks may be preserved in basins between mountain blocks from which they may have been completely removed by erosion. Such rocks may have contained oil and gas which could still be trapped in those rocks at depth or may have migrated into younger basin fill deposits or even volcanic rocks as in the Miocene tuff reservoirs of the Eagle Springs Field in Nevada which has produced over 3 million barrels of oil (Petrol. Inf., 1976) and the recently discovered Trap Spring Field, also in volcanics. Scarborough and Peirce (1978) reported the geometry and lithology of fill in several southern Arizona basins, which commonly consists of impermeable claystones and evaporites with interbedded or marginal facies of sandstone and conglomerate. Eberly and Stanley (1978) utilized data from surface outcrops, extensive subsurface samples and seismic profiles to interpret the Cenozoic stratigraphy of southwestern Arizona. Correlations were based on radiometric dates on interbedded volcanics and by reference to unconformity surfaces. They subdivided the essentially all nonmarine Cenozoic section into two unconformity-boundary units, Unit I including all rocks deposited between the beginning of post-Laramide alluviation, about 53 million years ago (Early Eocene), and the onset of Late Miocene (13-12 m.y. ago) block faulting (Basin and Range disturbance). Unit I rocks were greatly modified by volcanism and faulting during the

Basin and Range disturbance, resulting in a regional unconformity which forms the lower boundary for Unit II. The rocks of Unit II were deposited in subsiding fault troughs or grabens, as clastic material eroded from adjacent highlands was carried into them by interior drainage systems, and as salts were left by evaporation of water in the basins. Evaporites accumulated to great thicknesses in some basins, e.g. 6000 feet in Picacho Basin, 3600 feet+ in Luke Basin, and 4000 feet in Red Lake Basin in the northwestern corner of the state (Scarborough and Peirce, 1978).

The Overthrust Belt Across Arizona?

An exciting new interpretation of Arizona's Basin and Range Province has been proposed by Anschutz Corporation. They have projected the Laramide overthrust belt that has recently yielded major discoveries in the Northern Rockies (several articles in 1977-78 Oil and Gas Journal), across central Arizona from the northwestern corner to the southeastern corner, in the belief that the surface rocks have been thrust northeastward over younger, potentially petroleum-bearing rocks. Anschutz has leased over four million acres on this trend across central Arizona and is currently conducting extensive seismic work in the area.

Coal

Occurrence

Coal is Arizona's most abundant fuel energy resource. It is essentially restricted to rocks of Cretaceous age, with the main reserves concentrated in the Black Mesa Field in northeastern Arizona. Several smaller deposits of only local economic significance occur at scattered locations in eastern Arizona, all Cretaceous except one in Late Paleozoic rocks exposed along the Mogollon Rim.

The most extensive coal reserves occur in Late Cretaceous rocks that have been preserved in a structural basin with considerable topographic relief (6000 to 8000 feet elevation) called Black Mesa. The coal beds crop out around the periphery and on the eroded top of the mesa, defining an areal extent of about 3200 square miles. The coal is interbedded with sandstones and shales of the Dakota Sandstone, Toreva Formation and Wepo Formation, which along with the unproductive marine Mancos Shale and terrestrial Yale Point Sandstone form a combined thickness of 1700 feet. All these rocks dip toward the center of the Black Mesa Basin resulting in burial of the coals in the Dakota Sandstone (up to 1700 feet), the Toreva Formation (up to 1000 feet) and the Wepo Formation (between 325 and 800 feet) (Peirce, 1970). Total coal reserves beneath Black Mesa have been estimated at 21.25 billion short tons, with strippable coal within 130 feet of the surface at about one billion tons (Peirce, 1970). The application of subsurface mining techniques below 130 feet would increase the recoverable coal from the area. Coal seams in the Dakota Sandstone average 2-4 feet thick with an observed maximum of 9 feet along the southwestern margin of the mesa. The thickest coal in the Toreva Formation is 6-7 feet thick in the northwestern rim of the mesa. The Wepo Formation contains the best quality coal in Black Mesa, and occurs nearer to the surface than the Toreva or Dakota. It contains at least ten coal beds that individually exceed three feet in thickness. This formation is currently being mined by Peabody Coal Company at the northern margin of Black Mesa (O'Sullivan, 1958; Peirce, 1970).

Production

Although coal mining on Black Mesa dates back to prehistoric times, large scale mining did not begin until 1970 when Peabody Coal Company started production on a 14,000 acre lease (0.7% of Black Mesa's total area) on tribal lands at the north side of Black Mesa (Peirce, 1975). Since then they have been providing coal for two generating plants, the Mohave plant near Bullhead City, Nevada via a 275 mile slurry pipeline, and the Navajo plant near Page, Arizona via an 80 mile long railroad. Nearly 11.5 million tons had been produced at the end of 1977 and an additional 10 million tons are proposed for 1978 production. The projected production from the Peabody lease is 12.5 million ton/year for approximately 32 years (Peabody Coal Co., personal correspondence, Nov. 17, 1978).

Hale (1976) estimated that 16 million tons of strippable coal underlie each square mile of the Peabody lease and that it contains the energy equivalent of 71 million barrels of crude oil per square mile.

Uranium in Arizona

Introduction

Numerous occurrences of uranium are known throughout Arizona, with past production primarily from Triassic and Jurassic strata on the Colorado Plateau, but with current increasing exploration and development in the Basin and Range Province. This paper will summarize the mode of occurrence, past production and current activity of uranium exploration and production in Arizona. The sources of this information are primarily Butler and Byers (1969), Keith (1970), Peirce (1977 a & b, 1978).

Occurrence

Uranium deposits in Arizona are of two general types; peneconcordant with sediments, veins and fracture fillings. The most abundant and generally most productive are the peneconcordant deposits which are mainly in sandstone and conglomerate of continental origin. They consist of masses of rocks impregnated with uranium oxides, commonly in association with vanadium and sometimes iron, lead and zinc. The uranium content ranges from trace amounts to several percent, but the average grade of ore mined has been about 0.29 percent U_3O_8 (Butler and Byers, 1969).

The emplacement of uranium minerals in sedimentary rocks has resulted from post-depositional precipitation from ground water solutions, in pore spaces or as replacement of grains, cement or fossil plant material. The most significant production has been from Mesozoic age terrestrial sediments laid down by slow moving, braided and meandering fresh water streams on deltas, alluvial plains or flood plains; or they are in restricted basins or near shorelines (Keith, 1970).

The Colorado Plateau production in Arizona has come predominantly from two Mesozoic formations, the Triassic Chinle Formation (53%) and the Jurassic Morrison Formation (28%), with the remaining 19% from various other stratigraphic units and veins (Butler and Byers, 1969). The following brief discussion summarizes the occurrences and production of uranium in these Mesozoic systems.

Chinle Formation (Upper Triassic): (more than 1.6 million tons production)

Deposits in the Chinle Formation occur mostly in the basal (0-150' thick) Shinarump Conglomerate Member composed of sand and gravel that was spread by meandering streams over an extensive erosional surface cut into the underlying Moenkopi Formation (Lower Triassic). Many small and medium-sized deposits are in similar lenticular channel-filling sandstones in the lower part of the Petrified Forest Member (Butler and Byers, 1969). The uranium ore bodies are localized in conglomeratic sandstone that fills stream channels scoured from the Moenkopi Formation. It is probable that the uranium was precipitated from ground water flowing through the permeable channels in localities formerly occupied by plant material (Birdseye, 1958). Deposits in the Chinle Formation are concentrated in two areas of major production, one in Monument Valley and the other near Cameron in the valley of the Little Colorado River, with other smaller deposits in Chinle outcrops elsewhere on the Colorado Plateau (Butler and Byers, 1969; Keith, 1970).

Morrison Formation (Upper Jurassic): (800,000 tons production)

Uranium ore in the Morrison Formation in Arizona is essentially restricted to the Salt Wash Sandstone Member, which crops out in the vicinity of the Carrizo and Lukachukai Mountains in the extreme northeastern corner of the state. It consists of lenticular lenses of sandstone interbedded with mudstone. 85% of the ore mined from the Morrison in Arizona has come from the Lukachukai Mountains (Butler and Byers, 1969).

Toreva Formation (Upper Cretaceous) and Tertiary Basins

A few productive deposits have been found in fluvatile sandstone interbedded with carbonaceous siltstone in the lower member of the Toreva Formation on the northeastern margin of Black Mesa (Butler and Byers, 1969). However, the easily located surface exposures of uranium ore along exposures of productive Mesozoic rocks have probably been found, therefore more recent exploration has shifted to other objectives including Paleozoic rocks along the Mogollon Rim (Peirce, 1977, 1978) and Cenozoic rocks in the Basin and Range Province (Peirce, 1977). The greatest industry activity has been concentrated recently in western Arizona (e.g. Anderson Mine, Yavapai Co.) where the ore occurs in Miocene lacustrine volcaniclastic sedimentary rocks in association with carbonaceous materials. Estimated reserves are greater than Arizona's cumulative production of U_3O_8 (Peirce, 1977) i.e. 15-50,000 tons U_3O_8, (Meehan, 1978). The ore emplacement is believed to be an early diagenetic event, resulting from the compaction and dewatering of uranium-rich volcanic lake sediments with precipitation of uranium caused by contact with a strongly reducing paludal environment. The ore occurs in several mineralized beds which are generally 1-3 meters thick, but locally range up to 11 meters, and commonly reaches an aggregate thickness of 15 meters. The ore grade ranges from 0.03% to 0.10% U_3O_8 with an average of about 0.06% (Peirce, 1978).

Earlier production from Tertiary rocks in this vicinity came from the Uranium Aire deposit consisting of two beds of mineralized lacustrine carbonaceous mudstone, and the smaller Masterson group and Lucky Four deposits (Butler and Byers, 1969).

Numerous occurrences of uranium in the Basin and Range Province of the southwestern half of Arizona have been reported. Most are associated with lake deposits consisting of interbedded sandstone, shale, mudstone, bentonitic clays, gypsum and volcanic ash or tuff. Carbonaceous material, opalitic silica and calcium carbonate are common associates. Most have received little more than superficial reconnaissance examination and only two have been thoroughly prospected. Considering the vast amount of Cenozoic sediments in the southwestern half of Arizona, the possibilities for additional potential resources in the numerous basin areas cannot be excluded (Keith, 1970).

Other Modes of Occurrence

Diatremes and Breccia-pipes

These explosion and/or collapse formed masses of fractured rock have been one of the major types of uranium occurrence in Arizona but due to small size and difficulty of exploration, they do not have the future potential comparable to the peneconcordant deposits previously discussed.

The main occurrences of diatremes are in the Hopi Buttes and Monument Valley areas, and many of the uranium deposits are associated with infilling lacustrine limestone, sandstone, and volcanic ash rather than the breccia. Most deposits are low grade and have produced only a few tens of tons.

The most productive deposit in breccia-pipe structures is the Orphan Mine on the south rim of the Grand Canyon, which has produced about 500,000 tons of good grade uranium ore. It, and other breccia pipes in the area, originated by the collapse of solution caverns in the Mississippian

Redwall Limestone, with the resultant collapse of the overlying strata as a breccia-filling. Several such structures are exposed, and many others must occur on the Plateau, but because of their small size and concealed outcrops they will be difficult and expensive to find (Keith, 1970).

Vein Type Deposits

Vein deposits that have been evaluated most thoroughly occur in the Younger Precambrian Dripping Spring Quartzite that crops out in the Central Mountain Region of Arizona. Production has amounted to only about 23,000 tons averaging 0.23 percent U_3O_8, and has not been economically sound. However, it continues to be investigated as a host for low-grade deposits, and some production was recently achieved by solution mining (Chenoweth, 1978). The mineralization is genetically related to a Precambrian diabase sill in the Apache Group.

Numerous other small vein-type occurrences have been found in association with intrusive and extrusive rocks in the Basin and Range Province. The host rocks are mainly Precambrian granitic and rhyolitic rocks, but some have been found in Mesozoic intrusives and a few in Precambrian schist. None now known could be economically mined (Keith, 1970). However, such igneous and metamorphic environments continue to attract increasing exploratory attention in Alaska, the Basin and Range, the Rocky Mountains, in the Canadian Shield and in the Appalachians. The margins of plutons in northeastern Washington, northern Idaho, the Rocky Mountains and the Basins and Range are areas of active exploration (Chenoweth, 1978).

Keith (1970) summarized, in some detail, the economic aspects and production potential of uranium in Arizona, although economic changes since then have certainly favorably altered conditions for the explorationists and producers.

Geothermal Resources in Arizona

Investigation of Arizona geothermal resources began in 1971 when state and federal agencies, utility companies and private interests began geological and geophysical exploration for resources. During that year, Wright (1971) prepared a review of the status of geothermal resources in Arizona, in which he listed 12 selected areas of thermal springs with temperatures ranging from 85°C to 40°C. He concluded that thermal waters in the Basin and Range are closely associated with faults and have probably resulted from the cycling of surface waters. Harshbarger (1972) suggested the occurrence of thermal waters in areas of relatively recent volcanism and faulting indicates a potential for the occurrence of geothermal energy. The USGS circular, Assessment of Geothermal Resources of the United States (White and Williams, 1975) records eight identified hot water convection systems in Arizona, one with temperatures above 150°C and seven with 90°C to 150°C.

An investigation of geothermal energy resources in Arizona was begun in 1977 as a joint effort between the University of Arizona, Geosciences Department; the Bureau of Geology and Mineral Technology, Geological Survey Branch; and the U.S. Energy Research and Development Administration, Division of Geothermal Energy. The main emphasis of the current program will be on locating sources for hot water convection systems (up to 150°C) and hot, dry, crystalline rock (>200°C), to be utilized as space and process heating (Hahman, 1977). Geothermal projects initiated are: preparation of a Landsat lineament map of Arizona, scale 1:1,000,000, with emphasis on Quaternary fractures; geophysical study of the Basin and Range Province of Arizona with respect to geothermal models, depth to basement, and structural analysis; and the study of over 10,000 chemical analyses of ground water in Arizona for high and low temperature geothermal reserves. The Geological Survey and Mineral Technology is compiling a special library on geothermal energy (Hahman, 1977).

A preliminary map of the geothermal resources in Arizona was published in February 1978 by the Geological Survey Branch. It is a compilation of existing data printed on a USGS 1:1,000,000 scale base map. It depicts hot springs (30°C), cinder cones and extrusive volcanic rocks 3,000,000 years and younger, state and federally designated known geothermal resource areas, regions of high chemical geothermometers, high heat flow (>2.5 HFU), and moderate (>36°C/km) and high (>150°C/km) geothermal gradients.

Perhaps the most promising location, with bottom temperatures of 163°C and 184°C and discharge estimated at 19000 l/min at depths below two kilometers, in two wells about 1 kilometer apart, near Chandler in Maricopa County. Other sites with good potential are in Yuma, Cochise, Graham and Greenlee Counties (Frank, 1977).

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