

**A RÉSUMÉ
of the
GEOLOGY OF ARIZONA**

by

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THE ARIZONA BUREAU OF MINES

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FOREWORD

This "Résumé of the Geology of Arizona," prepared by Dr. Eldred D. Wilson, Geologist, Arizona Bureau of Mines, is a notable contribution to the geologic and mineral resource literature about Arizona. It comprises a thorough and comprehensive survey of the natural processes and phenomena that have prevailed to establish the present physical setting of the State and it will serve as a splendid base reference for continued, detailed studies which will follow.

The Arizona Bureau of Mines is pleased to issue the work as Bulletin 171 of its series of technical publications.

J. D. Forrester, Director
Arizona Bureau of Mines
September 1962

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CHAPTER I: INTRODUCTION

Purpose and Scope

This report is designed to serve as a brief, general account of the geology and mineral deposits of Arizona, especially in connection with the *County Geologic Maps of Arizona**, *Geologic Cross-Sections**, *Outcrop Maps**, *Map of Known Metallic Mineral Occurrences of Arizona**, *Map of Known Nonmetallic Mineral Occurrences of Arizona**, and *Map and Index of Arizona Mining Districts**.

Although reflecting somewhat the author's own opinions, this account utilizes data from numerous sources. Details from published reports are omitted or generalized as far as possible, but extensive references are made to descriptions in the literature. Also, many unsolved problems are indicated.

The geology and mineral deposits of Arizona are big, complex subjects. Although a large amount of information regarding them is available, much more remains to be learned through future detailed field work, laboratory investigations, progress in age determinations, and geophysics.

Previous Work

The present knowledge of Arizona geology has developed from the work of many people.

EARLY EXPLORATIONS (1;2)†

The first notable geologic explorations in this region were by Jules Marcou in the north during 1853 and Thomas Antisell along the Gila River during 1855, incidental to reconnaissance surveys for east-west railway routes. During the next several years, extensive preliminary studies were carried on, particularly in northern Arizona, by J. C. Ives, J. W. Powell, G. K. Gilbert, and G. M. Wheeler, for various Federal organizations. Major Powell's explorations (218) of the Colorado River during 1869–1872 did much to stimulate interest in the geology of the West.

* Published by the Arizona Bureau of Mines, University of Arizona.

† Numbers in parentheses refer to literature cited in Appendix.

WORK BY U.S. GEOLOGICAL SURVEY

The U.S. Geological Survey, organized in 1879, has devoted almost continuous efforts to fundamental studies in Arizona geology, mineral deposits, and water resources. Noteworthy early classics (1;2) resulted from the work of C. D. Walcott, C. E. Dutton, H. E. Gregory, H. H. Robinson, L. F. Noble, and C. R. Longwell, in northern Arizona; T. A. Jaggar and C. Palache, in the Bradshaw Mountains; W. Lindgren, in the Morenci and Jerome districts; F. L. Ransome, in the Globe, Ray, Bisbee, and other districts; B. S. Butler, in several districts; Kirk Bryan and C. P. Ross in southern Arizona; and N. H. Darton for the general region. Many later works by Survey geologists are cited on subsequent pages.

RESEARCH BY UNIVERSITY OF ARIZONA

The University of Arizona has carried on a large share of the geologic research accomplished within the State since 1891. Its first President, T. B. Comstock, who served as Director of the Arizona School of Mines in the University during 1891-1893, was the author of articles (1;2) on Arizona geology and emphasized the need for a geologic map of the Territory.

W. P. Blake, Director of the Arizona School of Mines during 1895-1905 and Arizona Territorial Geologist from 1898-1910, wrote many reports (1;2), from 1856 until 1910, concerning the geology and mineral deposits of the State.

C. F. Tolman followed Blake as a professor of geology at the University from 1905 to 1912 and served as Territorial Geologist from 1910 to 1912. His field work and publications (1;2;195) provided significant new data.

Later teachers of geologic subjects at the University of Arizona during the past generation included F. N. Guild, G. M. Butler, F. L. Ransome, A. A. Stoyanow, R. J. Leonard, B. S. Butler, M. N. Short, C. Schuchert, and W. M. Davis. They contributed greatly to the knowledge of Arizona mineral deposits, stratigraphy, structure, and physiography.

During recent years, expansion of research at the University of Arizona, especially in vertebrate paleontology, geochronology, ground water, and physiography, has brought forth much fundamentally important information.

WORK BY ARIZONA BUREAU OF MINES

The Arizona Bureau of Mines, which was established in 1915 as a department of the University of Arizona, has conducted long-term studies of the geology and mineral deposits of the State. It has published numerous bulletins dealing with mineral districts, areas, and commodities. In cooperation with the U.S. Geological Survey, the Bureau issued the

first Geologic Map of Arizona (63), Darton's *Résumé of Arizona Geology* (61), and geologic maps of all the Arizona Counties (1957-1960).

The County Geologic Maps, on a scale of 1:375,000, represent a stage in the preparation of a new, revised Geologic Map of Arizona, on a scale of 1:500,000, which is to be printed by the U.S. Geological Survey.

Acknowledgements

In the preparation of this report, helpful information and advice relating to various problems were obtained from many persons, especially J. D. Forrester, R. T. Moore, and H. W. Peirce, of the Arizona Bureau of Mines; J. F. Lance, P. E. Damon, J. W. Harshbarger, E. B. Mayo, S. R. Titley, H. W. Miller, Jr., and M. A. Melton, of the University of Arizona College of Mines; and J. R. Cooper, A. F. Shride, S. C. Creasey, J. P. Akers, M. E. Cooley, P. W. Johnson, and L. A. Heindl, of the U.S. Geological Survey.

F. J. McCrory and F. L. Stubbs assisted in compilation of recent metal production data.

The illustrations were prepared by Mrs. Nancy Young, under the guidance of R. T. Moore.

ERAS	PERIODS and EPOCHS	Years x 10 ⁶	MAJOR EVENTS IN GEOLOGIC HISTORY
GENOZOIC	Quaternary	Recent	Volcanism and minor faulting Basin and Range orogeny; Transition Zone and Plateau uplift Volcanism Granitic intrusions Laramide Revolution Nevadan Revolution Volcanism Granitic intrusions Mogollon Highlands in central Arizona
		Pleistocene	
		Pliocene	
	Tertiary	Miocene	
		Oligocene	
		Eocene	
		Late	
MESOZOIC	Cretaceous	Early	
		Jurassic	
	Triassic		
PALEOZOIC	Permian	General uplift Uplift in central Arizona General uplift	
			Pennsylvanian
	Mississippian		
	Devonian		
	Silurian		
	Ordovician		
	Cambrian		
PRECAMBRIAN	Younger	Grand Canyon disturbance; diabasic intrusions Mazatzal Revolution; granitic intrusions	
	Older		
		200	
		550	
		2000+	

Fig. 1. Geologic time scale. Modified from Lance (154).

CHAPTER II: ROCK UNITS, STRUCTURE, AND ECONOMIC FEATURES

Time Divisions

GENERAL STATEMENT (154)

The geologic history of Arizona is preserved in the record of rocks formed during five great eras of geologic time. These are, from oldest to youngest, the Older Precambrian, Younger Precambrian, Paleozoic, Mesozoic, and Cenozoic (Fig. 1). Not all of the events that characterized these time divisions may be recognized at any one place, but the historical sequence can be pieced together by correlating rocks and structures from one area to another.

Divisions of the geologic time scale are not of uniform duration, but rather are intervals characterized by major episodes in the history of the earth and the life on it. The details of geologic history are not known with equal certainty for all parts of geologic time.

METHODS OF DATING AND CORRELATION

Geologic ages and correlations are deduced directly by means of fossils and geochemical (58;59) analyses. Paleozoic and younger rocks may contain fossils of plant and animal life, but Precambrian rocks are almost devoid of recognized fossil remains. Geochemical age determinations of rocks from many parts of the world provide an approximate dating, in years, of events or units in the time scale.

Indirect correlations may be based upon stratigraphic relations such as superposition and unconformities; structural features; sequences of intrusion; lithologic similarity; and regional geologic history. In many instances, the indirect methods are uncertain.

Systems of Folding and Faulting

Throughout geologic time, stresses within the earth's crust have caused folding, fracturing, and faulting. Horizontal compression has produced folds, shear fractures,* and shear faults; the latter designation

*See Glossary (p.113) for definition of terms used in this discussion.

includes thrust faults, strike-slip faults, and some normal faults. Unstressing of the horizontal compression may result in tension fractures and normal faults. All of these features tend to follow systematic directions; the theoretical considerations involved have been discussed extensively in the literature (194;1;2). Their relation to mineral deposition is considered on p.106.

The major folds in Arizona have developed in four general directions, NE.-SW., NW.-SE., N.-S., and E.-W. Not all of these trends may be of first-order importance for each era; thus in Arizona, the dominant directions of folds are NE.-SW. for the Older Precambrian, but NW.-SE. and N.-S. for the Laramide, as discussed on subsequent pages.

The shear fractures and faults may form in as many as eight or more directions. A generalized pattern of them, as observed in many districts, is shown on Fig. 2.

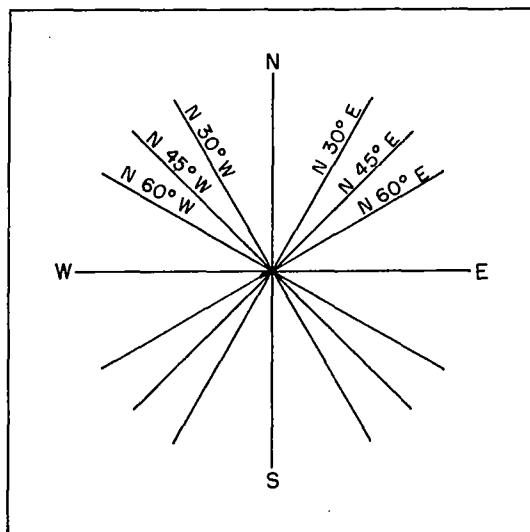


Fig. 2. Generalized pattern of shear-fracture directions.

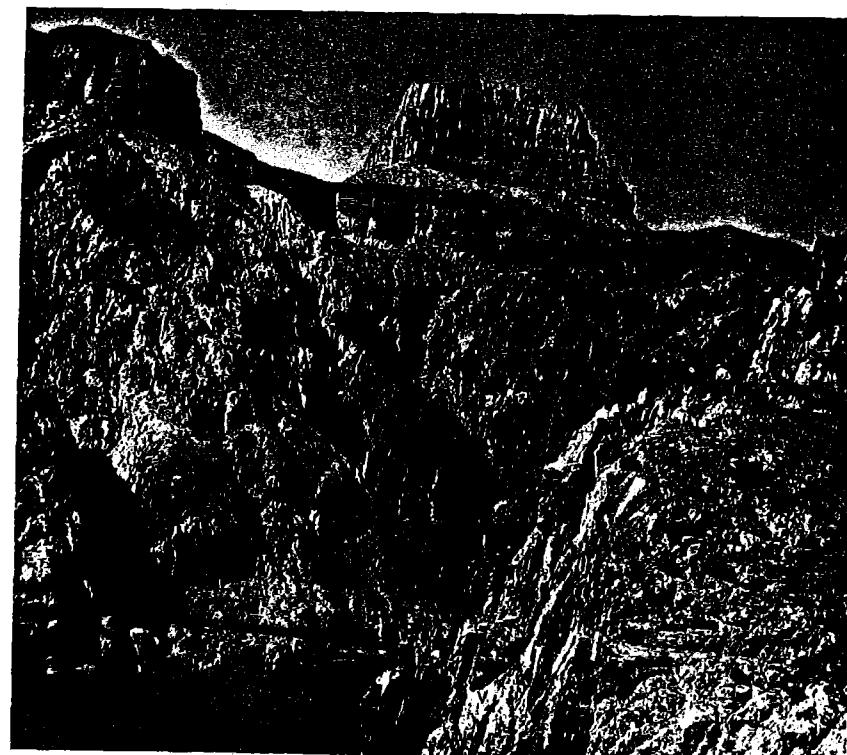
As a matter of geometry, notable variations from these directions may occur in areas where the folds are of a plunging type, or if tilting has occurred subsequent to the folding, fracturing, and faulting; hence, in many areas, the structural trends may appear to be haphazard if the geometric implications are ignored.

Many further aspects of lineament tectonics have been discussed by Mayo (191).

Precambrian Eras

GENERAL STATEMENT

Rocks that have been classified as Precambrian are exposed within the Grand Canyon (Pls. I, VI) and Defiance Uplift of northern Arizona and at numerous places within a belt extending from northwest to southeast through the State, as delineated on the County Geologic Maps* and generalized on the Map of Outcrops of Precambrian Rocks in Arizona.* Also, rocks of this age presumably constitute the fundamental basement which lies concealed to various depths by younger sedimentary and volcanic formations elsewhere in the State.



WESTERN WAYS FEATURES

Plate I. Rocks in the Grand Canyon, east of Bright Angel Creek. View northeastward. R, Redwall limestone; M, Muav limestone; B, Bright Angel shale; T, Tapeats sandstone; V, Vishnu series.

As stated by Anderson and Creasey (8, p.44), "The Precambrian rocks of Arizona, at times, have been termed Archean and Algonkian,

*Published by the Arizona Bureau of Mines.

Designation on Arizona Bureau of Mines County Geologic Maps	CENTRAL ARIZONA		SOUTHERN AND SOUTHEASTERN ARIZONA		Designation on Arizona Bureau of Mines County Geologic Maps	NORTHERN ARIZONA		NORTHWESTERN AND WESTERN ARIZONA		
Diabase (db)	Grand Canyon Disturbance with intrusion by diabase dikes, sills, and irregular bodies		Grand Canyon Disturbance with intrusion by diabase		Diabase (db)	Grand Canyon Disturbance ; diabase intruding Unkar group				
Sandstone and quartzite (ss)	Sandstone and quartzite; Troy quartzite north and northwest of Coolidge Dam (Figure 7)	Thickness in feet	Lower portion of the Troy quartzite between Latitudes 32°30' and 33°30', approximately (Figure 7)	Thickness in feet	Grand Canyon series (Agc)	Grand Canyon series Chuar group: sandstone, shale, basalt, and minor limestone	Thickness in feet	Not recognized		
		0 - 1,250		800 to 1,500			5,120			
Apache group (Au)	UNCONFORMITY		UNCONFORMITY		Grand Canyon series (Agc)	UNCONFORMITY	Unkar group: Dox sandstone 2,297+ Shinumo quartzite 1,564+ Hakati shale 580+ Bass limestone 335+ Hotauto conglomerate 6+ Total Unkar 4,782 to 6,830 Total Grand Canyon series 10,000 to 12,000		YOUNGER PRECAMBRIAN	
Mescal limestone (Am)	Apache group		Apache group							
Lower Apache group (Aq)	Basalt 0-375 Mescal limestone 225-500 Dripping Spring quartzite 400-680 Barnes conglomerate 0-40 Pioneer shale 150-500 Scanlan conglomerate 0-20 Total (local maximum) 1,600				GREAT UNCONFORMITY				OLDER PRECAMBRIAN	
Granite and related crystalline rocks (gr), diorite porphyry (di), pyroxenite (py), and granite gneiss (gn)	Mazatzal Revolution, culminating with intrusions ranging from granitic to gabbroic in composition		Mazatzal Revolution, culminating with intrusions ranging from granitic to gabbroic in composition		GREAT UNCONFORMITY					
Mazatzal quartzite (mq)	Mazatzal quartzite, Maverick shale, and Deadman quartzite		5,400		Mazatzal quartzite (mq)	Mazatzal quartzite, small exposure near Fort Defiance				
Schist (sch), rhyolite (rhy), and greenstone (gst)	Yavapai schist	Alder group: Foliated volcanics and slate		20,000 to 30,000	Pinal schist: Metamorphosed sedimentary and volcanic rocks	Schist (sch)	Vishnu series (Vishnu schist): schist, quartzite, and metavolcanics		25,000+	Unnamed schist: Metamorphosed sedimentary and volcanic rocks
		Red Rock rhyolite, 1,000+ feet					20,000+			
	Yavapai series	Ash Creek group: Basaltic, andesitic, rhyolitic, and dacitic flows and pyroclastic rocks and tuffaceous sedimentary rocks. Locally foliated.		20,000 to 23,500						
		Total Yavapai		41,000 to 54,000						
Granite gneiss (gn)	?		?		?	?		?		
	Granite gneiss		Granite gneiss		Granite gneiss	Granite gneiss		Granite gneiss		

Fig. 3. Tentative correlation of Arizona Precambrian units.

and the same rocks have been placed in both categories by different writers. Butler and Wilson (33, p.11), subdivided the Precambrian rocks of Arizona into older and younger Precambrian, a preferable designation."

The several Precambrian units, as distinguished on the County Geologic Maps of the Arizona Bureau of Mines, are listed and tentatively correlated in Fig. 3. These units are featured separately on the maps only where practicable. For many areas, various Older Precambrian metamorphic rocks are grouped together in the schist category.

OLDER PRECAMBRIAN ERA

INTRODUCTION

Literature. Although much has been learned during recent decades regarding the general features of the Older Precambrian terranes in Arizona, detailed studies of them have been accomplished only for portions of the central and northern regions and for some mountain ranges in the southern part of the State. Reference is made to the following publications:

Central Arizona: Anderson (7); Anderson and Creasey (8); Anderson, Scholz, and Strobell (9); Gastil (91); Wilson (317;318); Damon and Giletti (59).

Northern Arizona: Campbell and Maxson (37); Dings (65); Hinds (107); Noble and Hunter (201); Lance (151); Sharp (263); DuBois (66); Damon and Giletti (59).

Southern Arizona: Cooper and Silver (51); Cooper (48); Damon and Giletti (59); DuBois (67;68); Gilluly (93;94); Lance (152); Peterson, D. W. (211); Peterson, N. P. (213a); Ransome (222;227;229); Sabins (249).

Age assignment. As the Older Precambrian rocks are unfossiliferous, their designation is based upon geologic evidence, both direct and indirect, which may be subject to revision in some localities. Geochemical age determinations have been made for only a small portion of the areas that currently are regarded as Older Precambrian.

Since 1924, when the first Geologic Map of Arizona (63) was published, it has become generally recognized that intense foliation and metamorphism in schist or gneiss, as well as coarse texture in granitic rocks, are not necessarily indicative of extreme geologic antiquity, and it is known also that weak foliation and metamorphism alone do not denote relative youth. Hence, numerous areas, particularly in southwestern Arizona, that formerly were classed as Precambrian, now are mapped as Mesozoic or as Laramide.

GEOSYNCLINAL DEVELOPMENT

At the dawn of legible geologic history, possibly two billion or more years ago, the earth's crust in Arizona presumably consisted for the most

part of rocks of igneous origin. Regional warping and faulting developed in the crust a geosynclinal trough several hundred miles wide. As stated by Cooper and Silver (51), the complete extent of this trough is not known; Damon and Giletti (59) suggest that it extended diagonally northeastward across the site of the present North American continent in the general direction of Schuchert's Sonoran-Ontarian (257) geosyncline.

The long-continued sinking of the geosyncline was accompanied by alternate periods of volcanic activity and sedimentation which built the Older Precambrian series (Fig. 3) to a total thickness possibly exceeding ten miles. The environment of deposition for the Yavapai series may have been either marine or nonmarine or a combination of both (8). The Mazatzal beds are believed to have been laid down in a great delta.



Plate II. Overturned minor folds in Maverick shale, Mazatzal Mountains.

MAZATZAL REVOLUTION

Ending the Older Precambrian era was a long period of major structural deformation, the Mazatzal Revolution (317;318;7;213a), which culminated with large plutonic intrusions of granitic to gabbroic composition. Locally, the invaded rocks were metamorphosed to schist, and portions of the intrusives themselves assumed gneissic structural

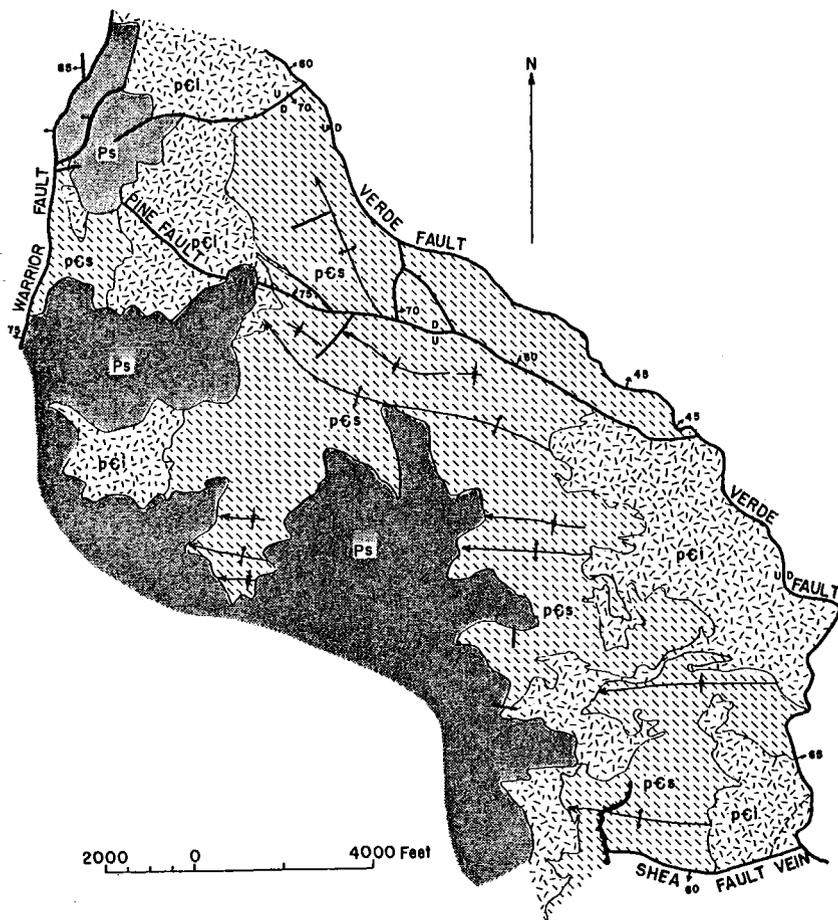


Fig. 4. Tectonic map of a part of the Jerome area. After Anderson and Creasey (8). Pcs, Precambrian sedimentary and volcanic rocks; Pci, Precambrian intrusive rocks; Ps, Paleozoic beds.

lineations. Generally, however, metamorphism was weak except in the vicinities of the large intrusive bodies.

According to Damon and Gilletti (59), geochemical age determinations by the rubidium-strontium method indicate that the Mazatzal Revolution occurred within a period between 1,200 million and 1,500 million years ago. No pre-Mazatzal granite intruding the Yavapai and Vishnu series has been recognized.

Regionally, the Mazatzal Revolution produced major folding and foliation or schistosity which trend prevailingly northeast and locally north or northwestward; minor folding (Pl. II) of west and northwestward trends; thrust faults and steep reverse faults which strike approximately

parallel to the folds; shear faults of general north-south and east-west trends; and steep northwesterly faults.

In the Jerome area (Fig. 4), the northwestward-trending Verde fault zone effected a vertical displacement of 1,000 feet in Precambrian, and 1,500 feet in subsequent, time (8, p.145-149; 231;234). Also, the north-south Shylock fault, west of the area of Fig. 4, had a minimum stratigraphic displacement of 20,000 feet, all in Precambrian time (8). The Precambrian Pine fault resulted in considerable right-lateral displacement of an anticline (Fig. 4).

The Mazatzal Revolution doubtless gave rise to mountain ranges of a magnitude to rival the loftiest ones existing today, and its structural pattern extensively influenced the geologic history of the region throughout all subsequent time.

INTRA-PRECAMBRIAN INTERVAL

Following the Mazatzal Revolution, the region was subjected to erosion which, as calculated by Sharp (263), may have continued for 100 million years or more. The aforementioned mountains were worn down to a peneplain except in areas of highly resistant rock, particularly quartzite, which survived as prominent ridges exemplified in central Arizona and near Ft. Defiance. Ransome (226, p.165-166) demonstrated that the Mazatzal area constituted a northeastward-trending land mass throughout early Paleozoic time. Stoyanow (283, p.462) termed this mass Mazatzal land and implied that it was a northeastward extension of Schuchert's Ensenada land (256). The history of Mazatzal land is summarized by Huddle and Dobrovlny (113).

YOUNGER PRECAMBRIAN ERA

UNITS AND CORRELATION

The Younger Precambrian designation in Arizona includes the Grand Canyon series and Apache group, with formations as listed in Fig. 3. The Grand Canyon series is exposed only within portions of the Grand Canyon, whereas Apache rocks crop out at many places within an area of some 15,000 square miles in the central-southern portion of the State.

The Grand Canyon series, whose structural relations had been noted by J. W. Powell (218;219), was divided by Walcott (301;304) into the Unkar (Pl. VI) and Chuar groups; the Chuar is known only within the area of the big bend northeast of El Tovar. An erosional unconformity below the top of Walcott's Unkar in the eastern locality was reported by Van Gundy (298), who proposed the Nankowep group to include the 400 feet of beds between this surface and the Chuar.

The Apache group (Pls. III, V), together with the Troy quartzite, formerly was classed as Cambrian (226;227), but the work of Darton

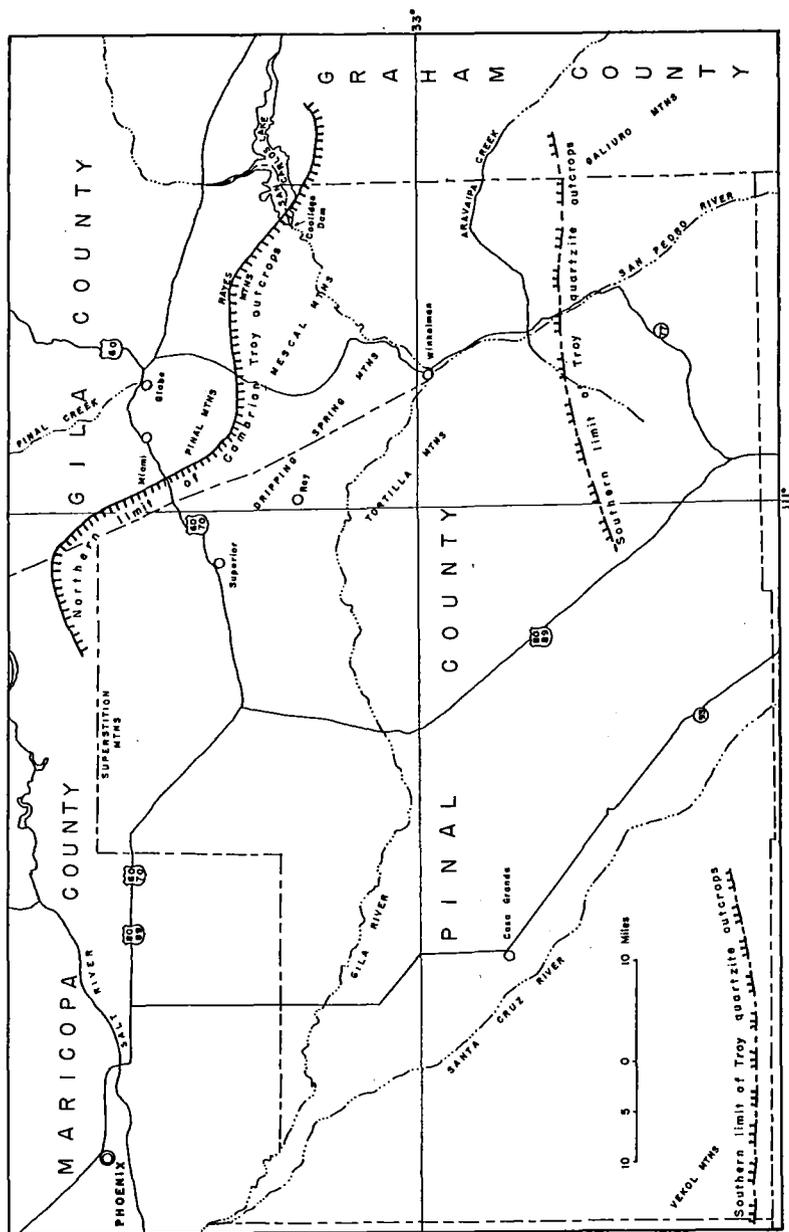


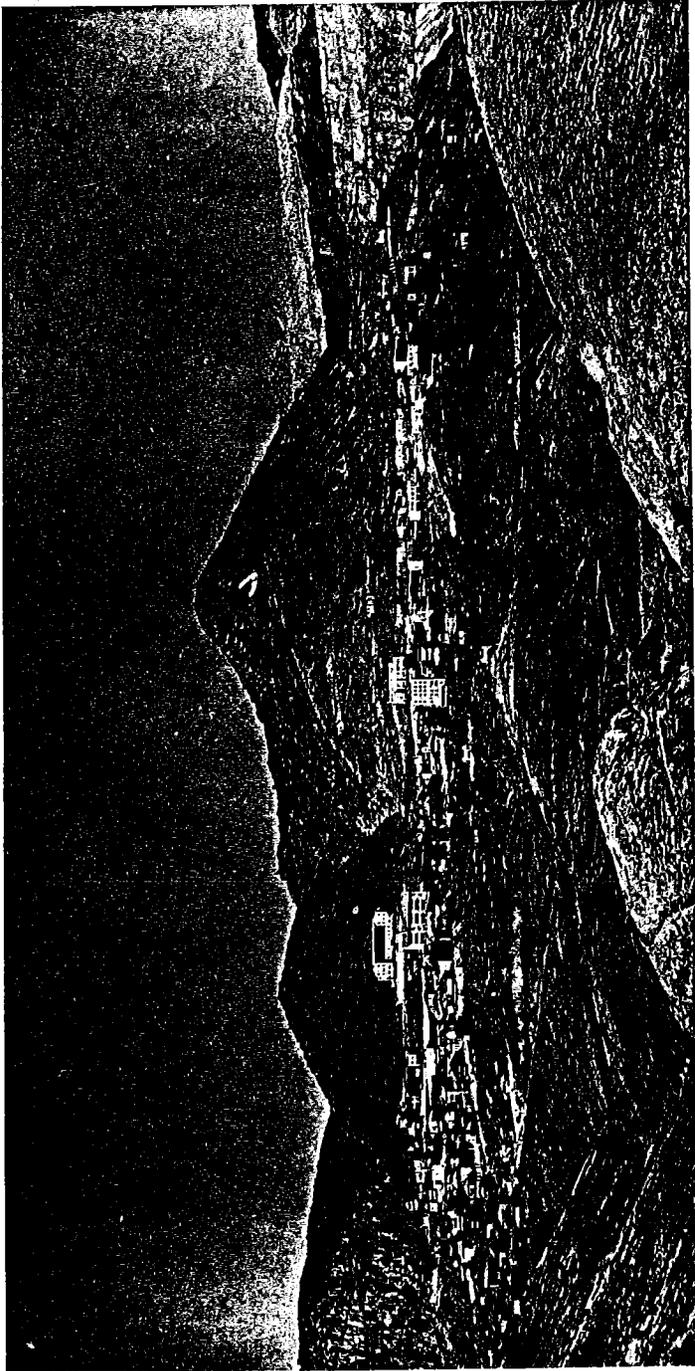
Fig. 5. Approximate northern limits of Cambrian Troy outcrops and southern limits of Precambrian Troy outcrops. Modified from Shride (270).

- (61, p.36) suggested correlation of the Apache with the Grand Canyon series and assignment of much of the Troy section in the Mescal Mountains of Gila County to the Precambrian. Later work by Shride (269) and by Krieger (145) has suggested approximate areal limits for the Precambrian-Cambrian portion of the Troy (Fig. 5). The results of lead isotope determinations on the diabase, which intrudes the older portion of the Troy, are compatible with its assignment to the Younger Precambrian Era (269;270;271).



N. H. DARTON

Plate III. Precambrian rocks in Mescal Mountains. Older Precambrian granite overlain by Scanlan conglomerate.



WESTERN WAYS FEATURES

Plate IV. Jerome. View northwestward. q, Older Precambrian quartz porphyry; P, Paleozoic limestone; T, volcanic rocks of Hickey formation, separated from q by the Verde fault. Underground workings of United Verde mine extend to a depth of 4,000 feet below the open pit, UV.

Fossil remains found in the Younger Precambrian beds suggest the types of earliest life known in Arizona. They include fragments of possible mollusks, trilobites, and stromatoporoids (303;304) in the Chuar; medusa in the Nankoweap (298); casts of jelly-fish in the Chuar and Bass; algal structures in the Bass (151); and abundant fossil algae or stromatolites in the Mescal (313;62;270).

STRUCTURAL DEVELOPMENT

General statement. During and after the Intra-Precambrian erosion interval, the region underwent geosynclinal warping which provided a basin for marine deposition of the Younger Precambrian strata.

Possibly, the Apache group and Grand Canyon series represent branches of one large geosyncline, although the locality of their junction is not evident. The Apache strata in central Arizona wedge out northwestward abruptly against Mazatzal quartzite of the Christopher Mountain area, 16 miles east of Payson, but their northeastward continuation is hidden under later strata of the Plateau. Also, the extent of the Grand Canyon series beneath the Paleozoic and later beds is not exposed. The fact, that fossil stromatolites from the Mescal limestone have been identified by Rezak (270, p.87) as forms common in the Belt series of northwestern Montana, invites speculations regarding the Younger Precambrian paleogeography.

Mild folding and erosion (270) affected the Apache beds prior to deposition of the Precambrian portion of the Troy quartzite.

Grand Canyon Disturbance. Younger Precambrian time in Arizona approached an end with a period of structural deformation, generally known as the Grand Canyon Disturbance, which culminated with extensive intrusion by diabasic sills and dikes. This deformation is expressed in structural features of types and trends similar to those of the Mazatzal Revolution, although of much weaker development. Its structural effects are better exemplified in the Grand Canyon series (223;199) than in the Apache group, and the diabasic intrusive activity seems to have been relatively greater in the Apache.

As determined by Walcott (302;303), the Unkar and Chuar beds in the eastern part of the Grand Canyon were folded before Cambrian time into a northeastward-plunging syncline more than 18 miles broad, and the Unkar was invaded by a "dolerite" (diabase) sill. The principal break in this area is the Butte fault, of curving north-northwest strike and steep dip; on its eastern side the relative movement was up, possibly 4,000 feet, during the Grand Canyon Disturbance and down, 2,200 feet, in post-Paleozoic time. The fault dies out abruptly at either end (61, p.186).

In the Grand Canyon north and east of El Tovar, the Disturbance gave rise to tilted fault blocks of northwestward trend (176;199), which



WESTERN WAYS FEATURES

Plate V. Rocks of Apache group in Salt River Canyon. View downstream, across curves of U.S. Highway 60. T, Troy quartzite; db, diabase; M, Mescal limestone; D, Dripping Spring quartzite.

resemble Basin-Range structures. Faults of northeast and northwestward strikes show large Precambrian, and reversed post-Paleozoic, displacements. The Wheeler monoclinial fold (199) in the Shinumo area trends northeastward and passes into a thrust fault; the compressive forces that formed it apparently acted from the southeast. Darton (61) noted that the diabase, which invaded the Unkar beds, resembles lithologically the Apache diabase.

In central Arizona, the Grand Canyon Disturbance resulted in folds, normal faults, and reverse faults of north, northwest, northeast, and eastward trends within the Apache beds. As noted by Shride (270), the strongest folding and faulting occurred along belts generally several miles apart and of north or northwesterly trends; this deformation was followed with intrusion by minor dikes and extensive sills of diabase (Pl.V) which locally rival the invaded sedimentary beds in volume. The intrusive bodies caused relatively little metamorphism. Shride (270) concluded that the diabase, by wedging apart the strata, locally gave rise to numerous faults.

ECONOMIC FEATURES OF ARIZONA PRECAMBRIAN

OLDER PRECAMBRIAN

The ore deposits of the Jerome (Pl.IV) or Verde district (8;234) consist of replacements and veins that were formed during Older Precambrian time and probably are related genetically with igneous intrusive activity of the Mazatzal Revolution. Oxidation and notable supergene enrichment of their upper portions were consequences of the long periods of erosion that antedated the Cambrian Tapeats sandstone. Figures regarding production of copper and other metals from the Verde district are listed in Table 10.

The Iron King (8) veins containing zinc, lead, silver, gold, and copper ore, near Humboldt; the Cherry Creek gold-quartz veins (8;316), east of Dewey, Yavapai County; various manganese deposits (80;81); the Pikes Peak iron deposits (79); and iron deposits in Delshay Basin (226, p.155-156), Gila County, are believed to be of Older Precambrian age.

Pegmatite deposits, presumably Older Precambrian, contain a wide variety of useful minerals, such as those of feldspar, quartz, mica, beryl, lithium, columbium-tantalum, and rare-earths, in the White Picacho district (118); feldspar and quartz, in the southern part of the Cerbat Mountains (333); mica in the northern part of the Hualpai Mountains (333); and columbium-tantalum, in the Aquarius Range (196).

Older Precambrian rocks at many places contain metalliferous deposits that originated during the Laramide (Late Cretaceous-Early Tertiary) interval. Examples include the copper-ore bodies at Ray (227), Miami (227;213a), and Inspiration (227;213a), which are replacements largely in Pinal schist; the Old Dick and Copper King zinc-lead-copper

replacement bodies, and the Hillside vein containing lead and gold-silver ore, in Yavapai schist of the Bagdad area (9); gold-quartz veins, in schist at the Vulture mine, in granite at the Congress and Octave mines, and in granitic or metamorphic rocks of several other districts (316); precious and base-metal veins and replacements in the Cerbat (65;254) and Hualpai Mountains, in granitic and metamorphic rocks; mercury-bearing veins and replacements in the Alder series, of the Mazatzal and Phoenix mountains (158;160;225), and tungsten deposits (319;130;55; 56;57) in granitic and metamorphic rocks.

Older Precambrian granite and gneiss at several localities have been quarried for building stone (333), and schist has been used in wall-facings.

YOUNGER PRECAMBRIAN

Regarded as of Younger Precambrian age are the chrysotile asbestos veins (313;270;279) in central Arizona and in the Grand Canyon; iron deposits in the Sierra Ancha area (226, p.155), Gila County; and iron deposits in the Canyon Creek-Ft. Apache Indian Reservation area, of southwestern Navajo County (278).

Younger Precambrian rocks are hosts for copper, zinc, lead, silver, and manganese deposits of Laramide (Late Cretaceous-Early Tertiary) age, as for example in the Superior (268;275;327) and Globe (221;213; 213a;157) areas.

Mescal limestone was used extensively in construction of Roosevelt dam.

Pre-Paleozoic Interval

Following the Grand Canyon Disturbance, a long period of erosion beveled the Precambrian rocks to a peneplain.

As interpreted by Sharp (263), at least 95 per cent of this peneplain in the Grand Canyon area has a relief of less than 150 feet, and the remainder consists of monadnocks of resistant granite and quartzite which rise to a maximum height of 800 feet. He concluded that the erosion was accomplished mainly under humid conditions by the agencies of chemical weathering and running water. Also, he calculated that in places it removed at least 15,000 feet of rock during a period estimated as approximately of 100 million years duration.

Where exposed elsewhere in Arizona, the pre-Paleozoic erosion surface generally is characterized by little or no relief. At places in the central portion of the State, however, remnants of the ridges of Mazatzal land, carved during the Intra-Precambrian interval, survived this final Precambrian erosional period and remained as prominences well into the Paleozoic Era.

Paleozoic Era

DISTRIBUTION AND TYPES OF ROCKS

Strata of Paleozoic age crop out extensively within the Plateau*, Transition Zone*, and southeastern segment of the Basin and Range Province*, but they appear very sparingly elsewhere in the State, as shown on the County Geologic Maps† and the Map of Outcrops of Paleozoic and Mesozoic Rocks in Arizona.† Their continuation beneath younger rocks may be projected in a general way from surface and drill-hole data for the Plateau area (Cross-Sections† No. 1-6) but is relatively obscure for the Basin and Range Province where the rocks have been subjected to folding, faulting, and igneous intrusion.

The several periods and formations within the Paleozoic record for Arizona are tabulated on subsequent pages. On the County Geologic Maps of the Arizona Bureau of Mines, some of these rock units are combined locally, as occasioned by limited areas of outcrop and availability of information.

South of Lat. 33°30', the Paleozoic beds are dominantly marine calcareous deposits, but northward, the upper portions of the stratigraphic sections (Fig. 6) include significant units of continental sandstone and shale.

Paleozoic igneous rocks are lacking in Arizona, so far as known.

DEVELOPMENT

GENERAL STATEMENT

An important element in Paleozoic history was the Defiance positive area, in east-central Arizona, which extended southwestward as Mazatzal land. Portions of the Defiance area remained essentially above sea level into Permian time.

The Cordilleran geosyncline in Nevada profoundly influenced the seaways of northwestern and northern Arizona. As interpreted by Nolan (202) and McKee (180), its general site appears to have become increasingly unstable from late Paleozoic into middle Mesozoic time.

Owing to the scarcity of outcrops of Paleozoic rocks throughout much of southwestern Arizona, the shore lines that may have existed there at various periods are but vaguely inferred.

Northwest of the Defiance-Mazatzal land area, the southeastern limb of the deepening Cordilleran geosyncline extended into Arizona; in the southeastern portion of the State, the Sonoran geosyncline developed (Figs. 7, 8). Within these structural troughs, Paleozoic sedimentation was relatively thick, as exemplified by 5,240 feet of strata at Bisbee,

* Defined on p.87 and Fig. 13.

† Published by the Arizona Bureau of Mines.

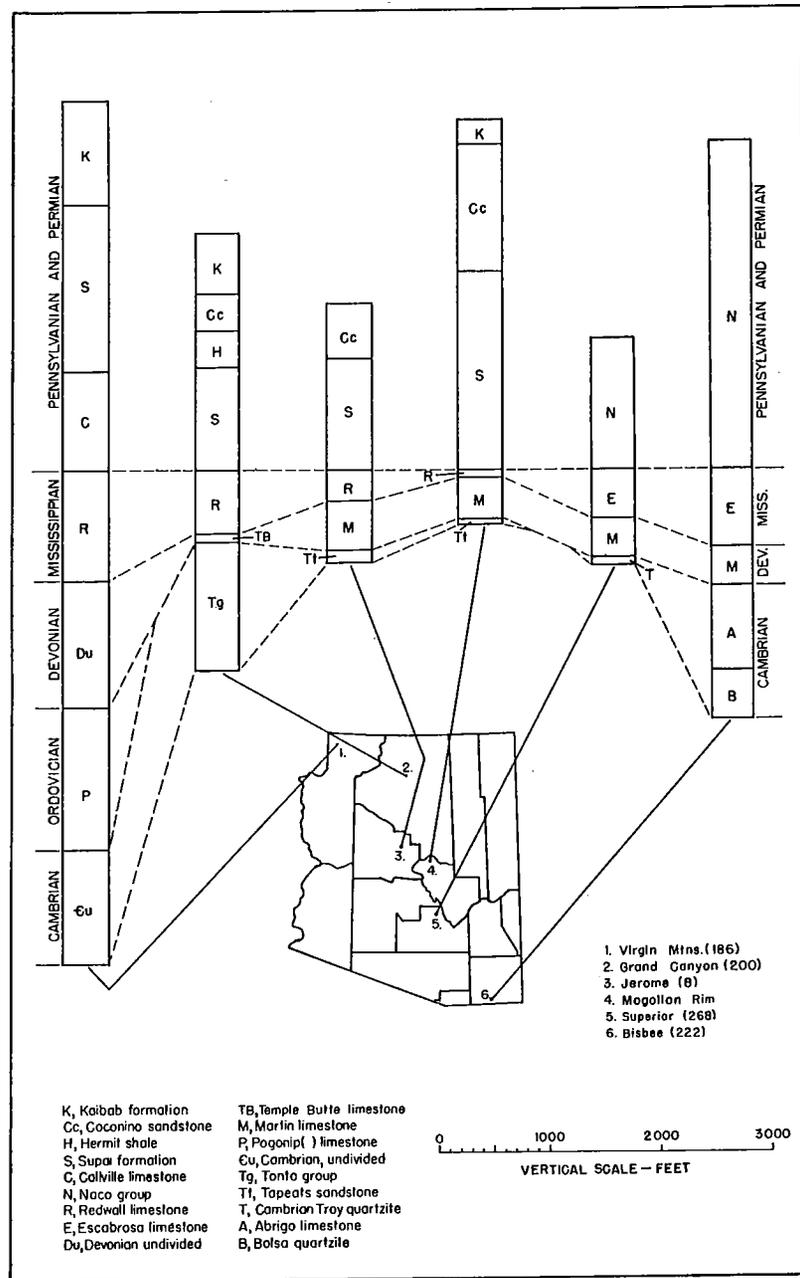


Fig. 6. Some columnar sections of Arizona Paleozoic rocks. Compiled by R. T. Moore

7,600 feet in the Chiricahua-Dos Cabezas Mountains, and 7,857 feet in the Virgin-Beaver Dam Mountains (see also Fig. 6).

Repeated invasions and withdrawals of the seas defined the geologic periods, Cambrian through Permian.

LIFE

As indicated by fossil remains, life in Arizona during Paleozoic time included such marine animals as brachiopods, mollusks, corals, sponges, trilobites, and fishes (154). Also, reptiles and amphibians had appeared by the end of the Era. The principal invertebrate index fossils are listed in the Appendix.

CAMBRIAN SYSTEM

The areas of land and sea within this region during the Cambrian period are sketched provisionally on Figure 7.

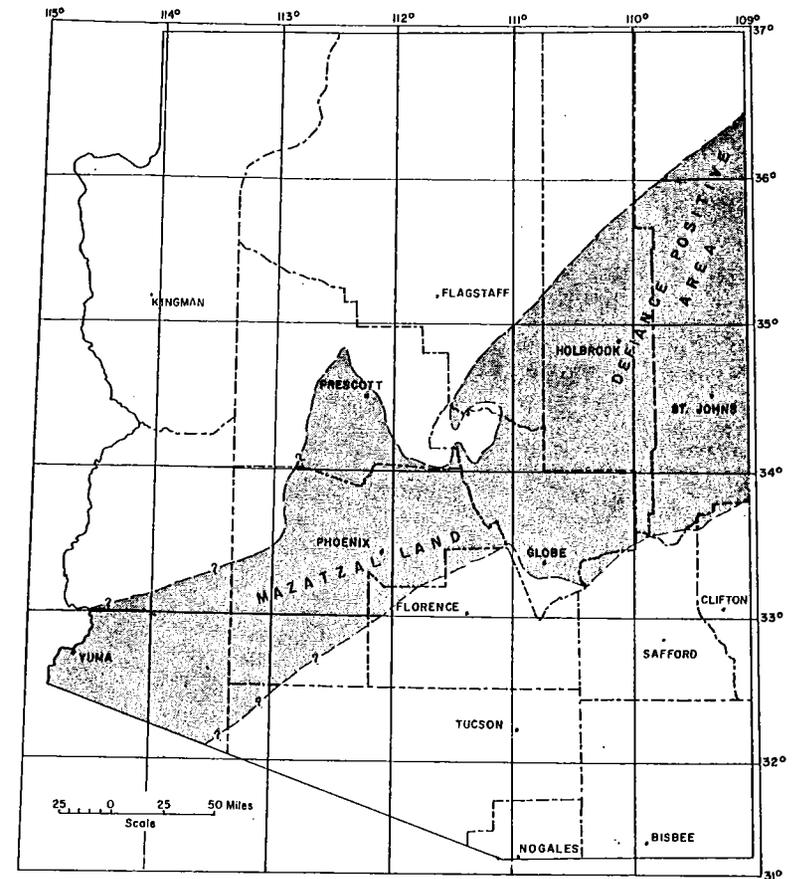
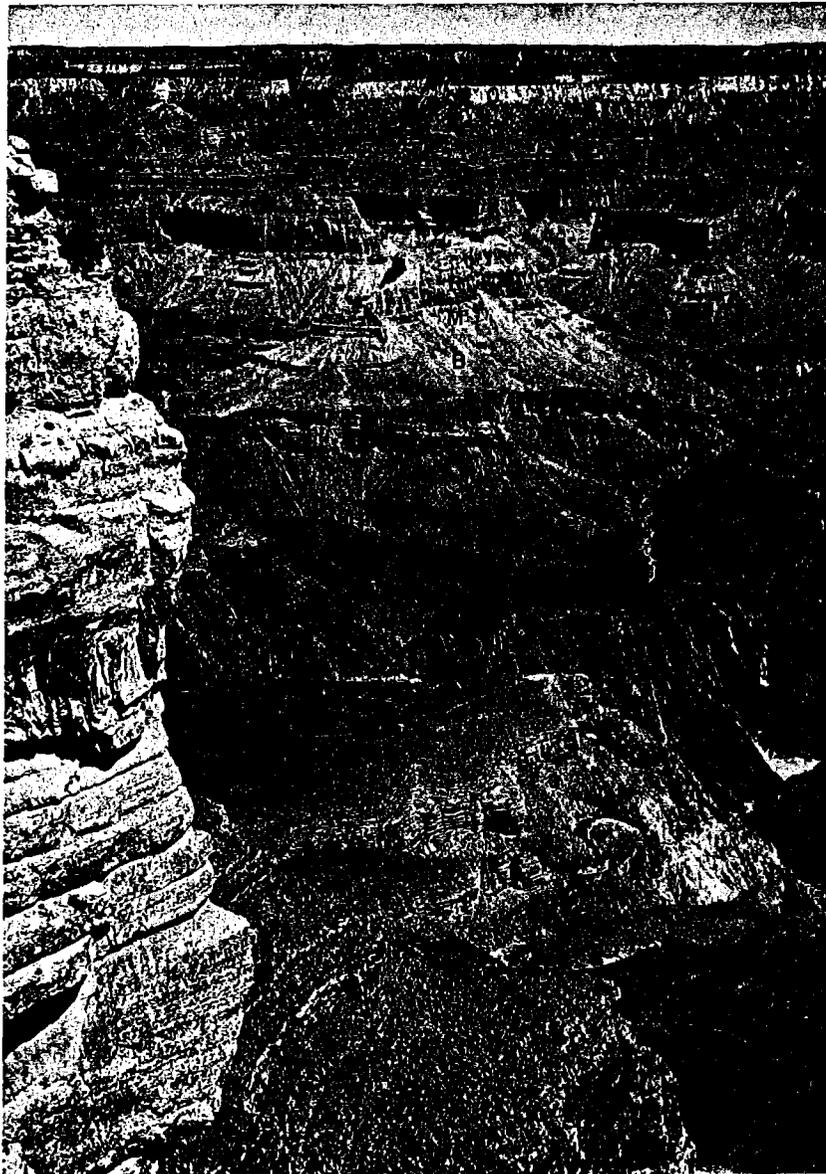
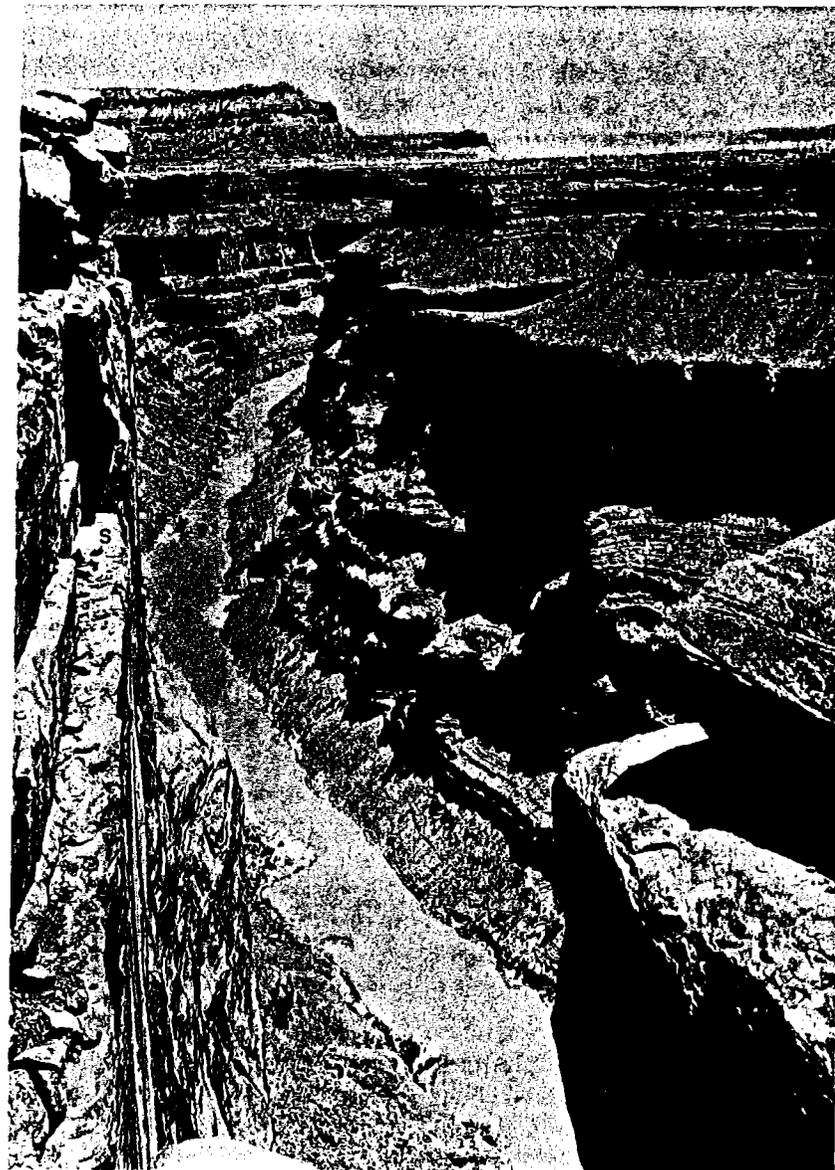


Fig. 7. Cambrian areas of land and sea in Arizona (Land areas shaded).



WESTERN WAYS FEATURES

Plate VI. Geologic section in the eastern part of the Grand Canyon. View north-westward, opposite El Tovar. Skyline is Kaibab Plateau surface. K, Kaibab limestone and Toroweap formation; C, Coconino sandstone; H, Hermit shale; S, Supai formation; R, Redwall limestone; M, Muav limestone; B, Bright Angel shale; T, Tapeats sandstone; Uq, Shinumo quartzite; Uh, Hakatai shale; Ub, Bass limestone; V, Vishnu series.



RAY MANLEY

Plate VII. Paleozoic strata in the Grand Canyon, near Toroweap Valley. View upstream. K, Kaibab limestone and Toroweap formation; Cc, Coconino sandstone; H, Hermit shale; S, Supai formation; Cv, Calville limestone; R, Redwall limestone; M, Muav limestone; B, Bright Angel shale.

Characteristically, deposition thickened progressively northwest and southeastward from the indicated land mass.

As noted by McKee (180, p.488), the sea did not invade southern Arizona until late-Middle Cambrian, whereas it covered the northern region of the State in Middle or Lower Cambrian time.

The Cambrian System (109) is represented by the Tonto group in northern Arizona and by the Troy, Bolsa, Coronado, and Abrigo units in southern Arizona.

Tonto group. The Tonto group, of Middle and Lower Cambrian age, comprises the outcrops designated on Arizona Bureau of Mines County Geologic Maps as Cambrian in northern Mohave County, the Grand Canyon (184), northwestern Yavapai County, and northern Gila County.

As divided by Noble (200) for the Grand Canyon region, the Tonto group (Pls. VI, VII) from base to top includes the Tapeats sandstone, 628 feet; Bright Angel shale, 391 feet; and Muav limestone, 473 feet thick. Southeastward, the upper two of these formations thin out near Latitude 35° (61, p.40), and the Tapeats sandstone wedges out abruptly against Older Precambrian rocks in Gila County. Northwestward, mainly through thickening of its limestone portion, the Cambrian section measures 2,200 feet in the Virgin Mountains, Mohave County (186).

Troy quartzite. The Troy quartzite originally was regarded as of Cambrian age and extending intermittently from the northern portion of the Santa Catalina Mountains into northern Gila County (226). Later, Darton (61, p.36) showed that much of the Troy section in the Mescal Mountains probably is of Precambrian age. On the Arizona Bureau of Mines Geologic Map of Gila County, the Troy quartzite in the Globe area is designated as Cambrian, in accord with N. P. Peterson (213); more recent work (270;145), however, indicates the northern limit of the Cambrian Troy to be south of the Pinal Mountains (Fig. 5). As concluded by Shride (270), the Cambrian portion of the Troy clearly seems to represent sandy, clastic facies of the Bolsa-Abrigo sequence, and the name, Troy, more appropriately might be restricted to beds of Younger Precambrian age.

Bolsa, Coronado, and Abrigo units. South of the southern limits of Troy quartzite (Fig. 5), the Bolsa quartzite forms the basal portion of the Cambrian sequence in Pinal, Pima, Santa Cruz, Cochise, and Graham Counties. The Coronado quartzite in Greenlee County is considered as generally equivalent to the Bolsa. For several localities south of the aforementioned limits, the basal quartzite has been referred to as Troy in earlier literature.

The Abrigo limestone, which overlies the Bolsa quartzite with gradational contact, commonly includes a sandstone or quartzite member at the top and becomes increasingly sandy northward. Gilluly (94, p.25) noted

that the Abrigo seems to have been deposited in relatively very shallow water, and that the Cambrian sequence in southeastern Arizona was the result of a single sedimentary cycle, with the Bolsa representing the transgressive phase of the marine invasion and the clastic beds at the top of the Abrigo the regressive phase.

Fossil evidence indicates Middle Cambrian age for the Bolsa quartzite (84, p.66), and Middle to Upper Cambrian for the Abrigo limestone (94). These units, particularly the Abrigo, show considerable stratigraphic variation over southern Arizona. Their thicknesses at several localities, together with references to detailed descriptions, are listed in Table 1.

Table 1. Data for Bolsa quartzite and Abrigo limestone.

LOCALITY	THICKNESS IN FEET		REFERENCE*
	BOLSA OR EQUIVALENT	ABRIGO	
Bisbee	430	770	222
Tombstone Hills	440	844	94
Swisshelm Mts.	300		76
Chiricahua Mts.	600		248
Dos Cabezas Mts.	460		248
Clifton	250		166
Little Dragoon Mts.	480	800	48;49
Whetstone Mts.	400	749	283;94
Santa Catalina Mts.	350	750	283;270
Tucson Mts.	700	640	26;30
Waterman Mts.	220	718	174
Slate Mts.	450	520	175
Vekol Mts.	195	360	175
Growler Mts.	880 (approx.)		

* Reference numbers apply to list on p.119-133.

ORDOVICIAN SYSTEM

The Ordovician system is represented by the Longfellow and El Paso limestones in southeastern Arizona, and possibly by the Pogonip (?) limestone in northwestern Arizona.

Longfellow and El Paso limestones. In the Clifton-Morenci district, Greenlee County, the Longfellow limestone of Upper Cambrian-Lower Ordovician age lies conformably upon the Coronado quartzite and is 400 feet thick (166).

At several localities in eastern Cochise County, Bolsa quartzite and Abrigo limestone are overlain by a limestone unit which attains thicknesses of 350 feet in the Dos Cabezas Mountains (61;123;248); 715 feet in the northeastern Chiricahua Mountains (248); and 435 feet in the Swisshelm Mountains (74;75). As indicated by fossils, the basal portion of this limestone section is Upper Cambrian, and the remainder of it is

Lower Ordovician. The unit as a whole has been correlated with the Longfellow and El Paso limestones.

Pogonip(?) limestone. A dolomitic limestone unit 216 feet thick, which overlies undifferentiated Cambrian dolomitic limestone in the Virgin Mountains, was tentatively correlated with the Lower and Middle Ordovician Pogonip formation by McNair (186). As concluded by Moore (197), this unit wedges out south and eastward within a few tens of miles.

PRE-DEVONIAN DISCONFORMITY

A regression of the seas marked the end of the Cambrian Period in Arizona, and, except for the areas covered during Ordovician, most of the region apparently remained near sea level until Middle or Late Devonian time.

No Silurian rocks have been identified in the State.

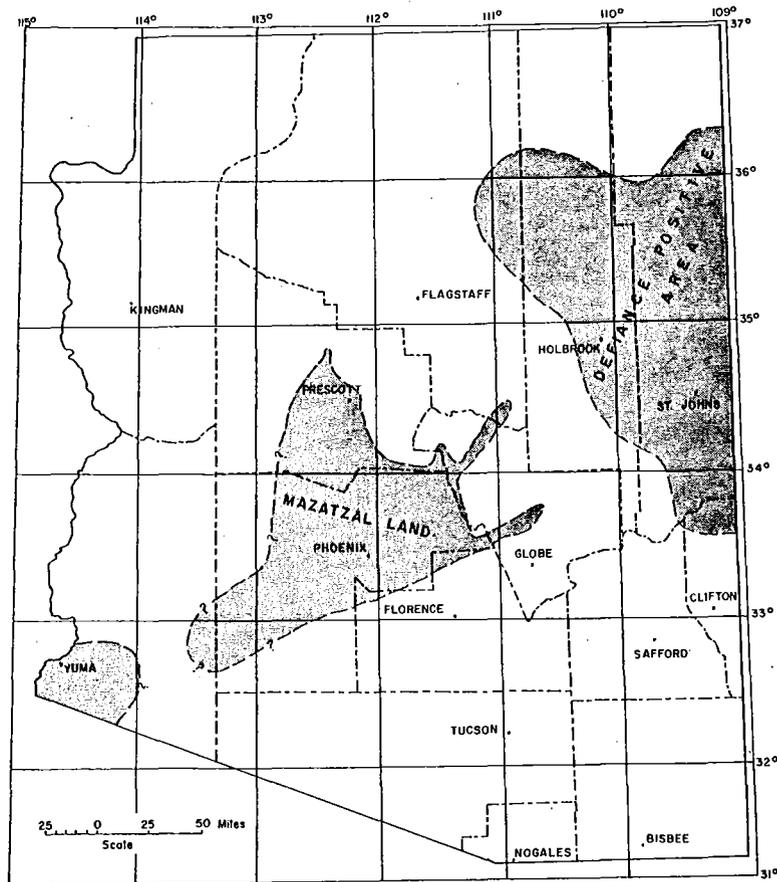


Fig. 8. Devonian areas of land and sea in Arizona (Land areas shaded).

DEVONIAN SYSTEM

Development. In Devonian time, Arizona was flooded by epicontinental seas except for the Defiance-Mazatzal land masses and possibly some local island areas (Fig. 8). Sedimentation was thickest within the areas of the expanding Sonoran and Cordilleran geosynclines. Throughout Arizona, the Devonian beds rest upon an erosional surface and show little or no angular discordance with the underlying early Paleozoic rocks. In the Globe area, this erosional surface has a relief of possibly 1,200 feet (213a).

Formations. On the County Geologic Maps* and Cross-Sections*, most of the areas designated as "Carboniferous and Devonian," and many of those in the "Paleozoic undivided" category, contain Devonian strata. The main recognized formational names are the Martin limestone and Morenci shale (Upper Devonian) in southern Arizona; the Martin formation (Middle? and Upper Devonian) in central Arizona; Temple Butte limestone (Upper? Devonian) in the Grand Canyon area; and the Muddy Peak limestone (Upper Devonian) in the Virgin Mountains.

As noted by Stoyanow (283), the proportion of clastic or sandy materials within the Martin formation of central Arizona increases northward; thus the "sandstone and quartzite" unit on the Geologic Map of Gila County includes local channel-fillings of Devonian sandstone as much as 250 feet or more thick (270).

Some representative thicknesses and references to detailed stratigraphic descriptions are listed in Table 2.

Table 2. Data for Devonian formations.

FORMATION AND LOCALITY	FEET	REF.	FORMATION AND LOCALITY	FEET	REF.
Martin limestone:			Muddy Peak ls.:		
Bisbee	340	222	Virgin Mts.	552	186
Tombstone	230	94	Temple Butte ls.:		
Little Dragoon Mts.	270	48;49	Grand Canyon	0-100	301
Swisshelm Mts.	615	77	Martin formation:		
Chiricahua Mts.	342	248	Dripping Spr. Mts.		
Empire Mts.	300	88	(Pi. VIII)	340	215
Sierrita Mts.	440	149	Superior	354	268
Tucson Mts.	350	30	Black River	333	113
Waterman Mts.	385	174	Roosevelt Dam	451	113
Vekol Mts.	200+	175	Oak Cr.,		
Morenci shale:			S.W. Navajo Co.	89	113
Morenci	175	166	East Verde River	388	113
			Jerome	465	8
			Little Harquahala Mts.	180	

* Issued by the Arizona Bureau of Mines.



TAD NICHOLS

Plate VIII. Paleozoic formations in the southern portion of the Dripping Spring Mountains, Gila County. View northeastward. A fault displaces the formations on the left in reference to those on the right.

DEVONIAN-MISSISSIPPIAN DISCONFORMITY

The end of the Devonian period in Arizona was marked by an interval of non-deposition and erosion; at some localities the disconformity at the base of the Mississippian is well pronounced, but in southeastern Arizona it is not obvious.

MISSISSIPPIAN SYSTEM

Development. During Mississippian time, the areas of the Sonoran and Cordilleran geosynclines expanded, but portions of the Defiance-Mazatzal areas remained as land masses.

Formations. On the County Geologic Maps* and Cross-Sections*, Mississippian rocks are included in the categories of "Carboniferous and Devonian" and "Paleozoic undivided." The principal standard formational names are as follows:

SOUTHERN AND SOUTHEASTERN ARIZ. CENTRAL AND NORTHERN ARIZ.

Mississippian and Pennsylvanian

Tule Spring limestone

Upper Miss. or Lower Penn. (?)

Black Prince limestone

Upper Mississippian

Paradise formation

Lower and Upper (?) Miss.

Escabrosa limestone (Pl. VIII)

Lower Mississippian

Modoc limestone

Lower Mississippian

Redwall limestone

(Pls. I, VI, VII)

Representative thicknesses of these formations, together with selected references to detailed stratigraphic descriptions are given in Table 3.

MISSISSIPPIAN-PENNSYLVANIAN DISCONFORMITY

A disconformity, but no angular unconformity, separates the Mississippian from the Pennsylvanian strata in Arizona. It is lithologically obscure in much of southeastern Arizona (94:249), but elsewhere in the State it commonly is marked by a surface of erosion with relief of 30-50 feet in many places, as described by Huddle and Dobrovolney (113), Anderson and Creasey (8), Hughes (114), and Noble (200).

PENNSYLVANIAN AND PERMIAN SYSTEMS

Division. The division between Pennsylvanian and Permian in Arizona is defined by fossil evidence within a conformable series of beds. At many places this time-break transgresses lithologic contacts and is difficult to map.

*Published by the Arizona Bureau of Mines

Table 3. Data for Mississippian formations.

FORMATION AND LOCALITY	FEET	REF.	FORMATION AND LOCALITY	FEET	REF.
Escabrosa limestone:			Paradise formation:		
Bisbee	800	222	Chiricahua Mts.	195	283
Tombstone Hills	786	94	Redwall limestone:		
Dragoon Mts.	729	94	Roosevelt Lake	175	113
Chiricahua Mts.	730	248	Black River	297	113
Empire Mts.	600	88	Salt River, Hwy. 60	189	113
Sierrita Mts.	550	149	Upper Tonto Creek	28-45	113
Tucson Mts.	600	26	Jerome	286	8
Vekol Mts.	435	175	Little Harquahala		
Dripping Spr. Mts.	552	215	Mts.	150	
Castle Dome			Grand Canyon		
Mine area	365	214	(eastern)	404	182
Modoc limestone:			Grand Canyon		
Clifton	182	166	(western)	800	200
Tule Spr. limestone:			Virgin River	500+	235
Clifton	500	165	Black Prince limestone:		
			S.E. Ariz.	168	48;49

Table 4. List of Pennsylvanian and Permian formations.

SOUTHERN ARIZONA		NORTHERN ARIZONA	
Naco group:		Permian (Pls. VI, VII)	
Permian		Kaibab limestone	
Rain Valley formation		Toroweap formation	
Concha limestone		Coconino and DeChelly	
Scherrer formation		sandstones (Pls. IX, XI)	
Epitaph dolomite		Hermit shale	
Colina limestone		Permian and Pennsylvanian	
Permian and Pennsylvanian		Supai fm. (Includes Ft. Apache ls.	
Earp formation		in southeastern portion)	
Pennsylvanian		Callville limestone (Pl. VII)	
Horquilla limestone			
NORTHEASTERN ARIZONA			
Monument Valley (209)	Black Mesa Basin (209;25;296;99;308)	Defiance Plateau (209)	
Permian, Cutler formation	Permian, Cutler group	Permian	
Hoskininni sandstone	Hoskininni sandstone	DeChelly ss.	
DeChelly sandstone	DeChelly and Coconino ss.		
Organ Rock tongue	Organ Rock tongue		
(Pl. X)	Cedar Mesa sandstone		
Cedar Mesa sandstone	Halgaito formation		
Halgaito tongue	Permian and Pennsylvanian	Supai Fm.	
	Rico-Supai formations		
	Pennsylvanian		
	Hermosa fm. (Naco) Includes		
	Paradox fm.		

Table 5. Data for Pennsylvanian and Permian formations.

FORMATION AND LOCALITY	FEET	REF.	FORMATION AND LOCALITY	FEET	REF.
<i>Naco group:</i>			<i>Kaibab limestone:</i>		
Rain Valley formation,			Grand Canyon		
Mustang Mts.	500+	31	Marble Gorge		
Concha limestone			(Pl. XII)	250	178
Chiricahua Mts.	730	248	Bright Angel Tr.	296	178
Gunnison Hills	129	95	Toroweap Valley,		
Waterman Mts.	510	174	T.33 N.,R.7 W	571	178
Scherrer formation			Aubrey Cliffs	123	178
Chiricahua Mts.	150	248	Virgin Mts.	330	186
Gunnison Hills	687	95	<i>Toroweap formation:</i>		
Waterman Mts.	422	174	Oak Cr. Canyon	247	178
Epitaph dolomite			Little Colo. R.	35	178
Tombstone Hills	783	94	Toroweap Valley	425	178
Colina limestone			Virgin Mts.	426	186
Chiricahua Mts.	535	248	<i>Coconino sandstone:</i>		
Tombstone Hills	633	94	Mogollon Rim		
Earp formation			N. of Pine	1,150	
Chiricahua Mts.	2,700	248	Holbrook	620	177
Tombstone Hills	595	94	G. Canyon,		
Whetstone Mts.	800	305	Bass Tr.	330	200
Waterman Mts.	893	174	Little Colo. R.	600	61
Horquilla limestone			Lees Ferry	57	177
Pedregosa Mts.	2,115	74	Seligman	700	177
Chiricahua Mts.	1,600	248;249	Toroweap Valley	96	177
Tombstone Hills	1,000	94	Kanab Cr., Upper	15	177
Whetstone Mts.	1,400	305	N. Grand		
Vekol Mts.	520	175	Wash Cliffs	30	197
<i>Naco group undiv.:</i>			<i>DeChelly</i>		
Growler Mts.	255±		<i>sandstone (210):</i>		
<i>Naco group,</i>			Pine Sprs.,		
<i>Penn. undiv.:</i>			Apache Co.	300	209
Tucson Mts.	1,000	26	Canyon DeChelly	800	209
Superior	1,200+	268	Monument Valley	330	209
Coolidge Dam	1,400	305	<i>Hermit shale:</i>		
Salt R., Hy. 60	770	112	G. Canyon,		
Fossil Creek	475	112	Bass Tr.	332	200
Union-Cont.			Toroweap Valley	1,053	185
Aztec well,			Seligman	80	200
T15 N.,R18 E.	545	112	<i>Supai formation:</i>		
<i>Kaibab limestone:</i>			Carrizo Cr.	1,490	112
N. of Snowflake	1	178	Fossil Cr.	1,730	112
Meteor Crater	150	178	Sycamore Can.	1,665	8
			Union-Cont.		
			Aztec well,		
			T.15 N.,R18 E.	2,470	112
			Grand Canyon,		
			Bass Tr.	953	200

Development. Pennsylvanian sedimentation in Arizona was thickest within the areas of the Sonoran and Cordilleran geosynclines and apparently lacking on the Defiance positive area. The southwestern margin of the Paradox basin, superimposed across the southeastern shelf of the Cordilleran geosyncline in Pennsylvanian time, extended into northern

Apache and Navajo Counties. Various effects of this tectonic activity upon the character and extent of Pennsylvanian-Permian sedimentation in the Four Corners region have been discussed by Wengerd and Matheny (308). For other details of Pennsylvanian paleogeography, reference is made to the works of McKee (180), Wanless (306), Hanover and Pye (99), and Kottowski (144).

Permian rocks are thickest in the northwestern portion of the State and in relatively small basins west of St. Johns and Flagstaff (180). They are thinnest on the Defiance area, where Supai strata rest directly upon Precambrian rocks and surround a small outcrop of Precambrian quartzite (61;96).

The Pennsylvanian and Permian beds consist largely of marine limestone in southern Arizona, but clastics and red beds of deltaic, flood-plain, and sand-dune (236) origin interfinger increasingly within them towards the Mogollon Rim and constitute a large portion of the section throughout the northeastern half of the State. Evaporites, mainly gypsum or salt, are relatively common in the Permian.

Formations. The principal standard formations, from youngest to oldest, are given in Table 4.

Some representative thicknesses are given in Table 5. For detailed stratigraphic descriptions, the reader is referred to the works cited.

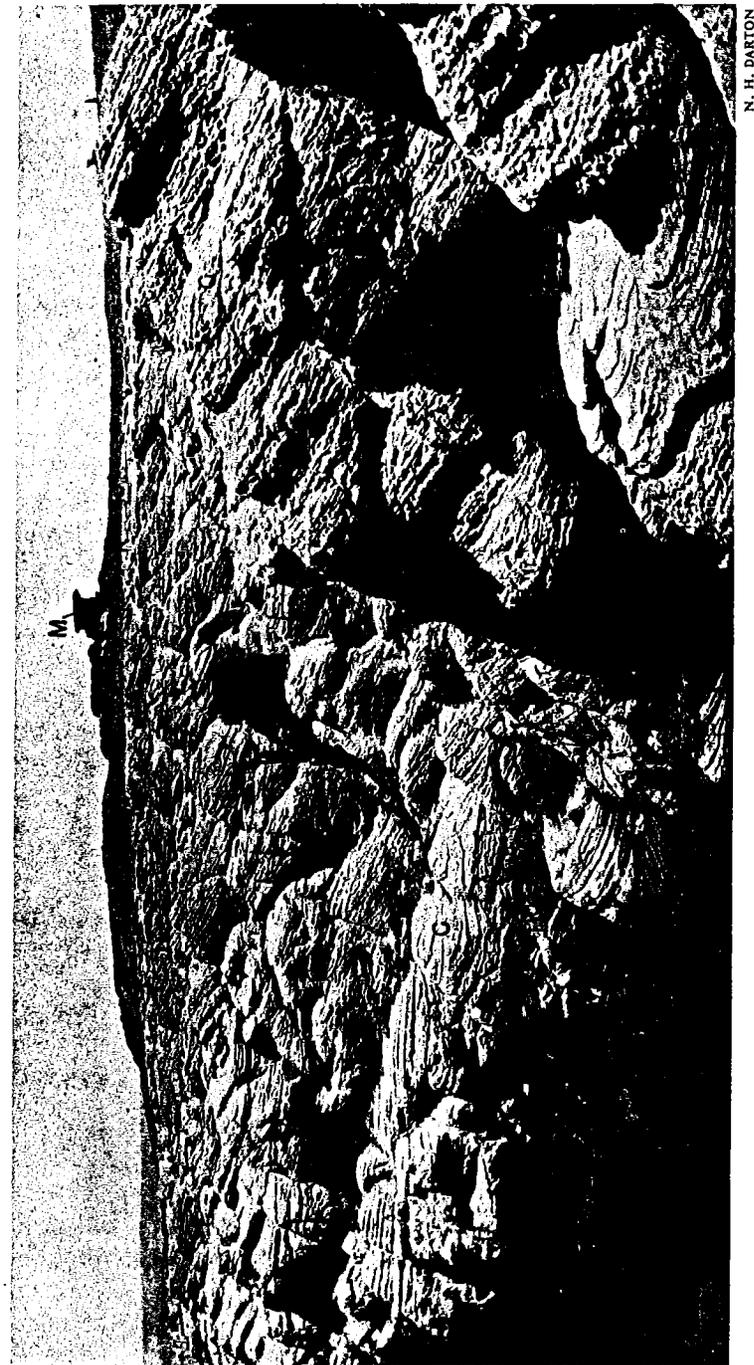
ECONOMIC FEATURES OF PALEOZOIC

METALLIC ORES

No metalliferous deposits of Paleozoic origin are known to occur in Arizona, but, for many districts, post-Paleozoic mineralization was extensive within the Cambrian, Devonian, Mississippian, Pennsylvanian, and Permian limestones. It formed numerous ore bodies of copper, zinc, lead, gold, silver, and manganese, as exemplified in the Bisbee (222;122;295 108;81), Tombstone (35;81), Morenci (165;166;34), Globe (157;213; 213a;81), Superior (268;275;327), Pima (228;325;292;293;116;124;173; 241;253;50;149;150), Silver Bell (276;265;240;3), Courtland-Gleeson or Turquoise (224;312), Christmas (246;215;71), Johnson or Cochise (48; 49), Seventy-Nine (246;131;132), Helvetia (255;54), Aravaipa (245;326), Swisshelm (90), Warm Springs (287), and Bentley or Grand Gulch (106), areas. The copper and iron deposits of Swansea (16) and Planet (16;331), gold and copper deposits near Parker (316;72), and gold deposits in the Harquahala area (316) are regarded as Laramide.

The Supai, Hermit, and Coconino beds are host rocks for the Orphan uranium-bearing diatreme (20), on the south rim of the Grand Canyon, near El Tovar.

Many tungsten-bearing veins and replacements occur in the Paleozoic strata of southeastern Arizona (319;57).



N. H. DARTON

Plate IX. Coconino sandstone (C) with prominent cross-bedding, four miles southeast of Winslow. M, Moenkopi formation; K, thin sandy bed representing the Kaibab limestone.

OIL AND GAS

Petroleum and natural gas are produced from discoveries made during 1954-1958 in the Hermosa-Paradox units (24;25;220), northeastern Apache County. Also within that area, commercial quantities of oil and gas have been found in Mississippian and Devonian beds.

Important reserves of helium occur in the Coconino sandstone, south of Navajo Station, Apache County (102;64).

NONMETALLICS

Noteworthy resources of nonmetallics in the Paleozoic formations are listed as follows:

Flagstone, building and ornamental stone, in Coconino and DeChelly sandstones (333;208).

Building stone, in Kaibab limestone formation (333).

Marble (333) for building and ornamental stone and roofing granules, in Escabrosa and other Paleozoic limestones of southeastern Arizona, as for example, in the Chiricahua Mountains (206), northern Santa Catalina Mountains, Tortolita Mountains, Sierrita Mountains, Dragoon, and Duquesne areas.

Cement material, in the Paleozoic limestones; used currently in plants at Rillito and Clarkdale, and formerly in a plant at Roosevelt Dam.

Limestone for lime manufacture, used currently in plants near Globe, Hayden, Morenci, and Nelson, and formerly near Tucson, Flagstaff, and Drake.

Limestone for smelter flux.

Sandstone and quartzite for use in smelting.

Gypsum, in Permian limestones of Empire, Sierrita, and Santa Rita Mountains (333).

Salt, in Supai formation. Especially abundant within Supai of south-central Navajo and Apache Counties; reported to be 1,000 feet thick in a well on Pinta dome, south of Navajo station (25).

Dolomite (333), in portions of Kaibab, lower Redwall, Martin, Muav, and Bright Angel formations.

Lignite, in Supai formation near Fossil Creek, Yavapai County (226, p.160).

Silica of high purity, in Coconino sandstone of Meteor Crater.

Permian-Triassic Unconformity

Throughout the Plateau Province, a great unconformity exists at the base of the Lower and Middle(?) Triassic Moenkopi formation. Because this stratigraphic break involves the interval between the Paleozoic and Mesozoic eras, it has received much attention and has been described

for various localities in more than 30 papers (181). It is marked by irregular erosion surfaces or channels, by basal conglomerates, and, in some areas, by angular discordance; extending from the lower part of the Permian to the middle stage of the Lower Triassic, its time-span may be calculated in terms of some tens of millions of years (181).

Within northeastern Arizona, the hiatus becomes progressively greater from west to east (4). Thus, in the vicinity of Holbrook, the unconformity is cut partly on Coconino sandstone; and, in the northern portion of the Defiance Uplift, where the Moenkopi is absent, the Upper Triassic Chinle formation rests on DeChelly sandstone.

Mesozoic Era

ROCK TYPES AND DISTRIBUTION

Rocks mapped as Mesozoic cover much of the Plateau and crop out in numerous areas within southeastern and southwestern Arizona, but they are scarce or lacking within central portions of the State, as shown on the County Geologic Maps* and the Map of Outcrops of Paleozoic and Mesozoic Rocks in Arizona*. The units assigned to the Triassic, Jurassic, and Cretaceous Systems of the Mesozoic on the County Geologic Maps* are discussed on subsequent pages.

The sedimentary rocks consist of sandstone, shale, conglomerate, and minor limestone. Their environments of deposition ranged through non-marine, near-shore, and marine.

Igneous and metamorphic rocks of known or inferred Mesozoic age occur at many places in southeastern and southwestern Arizona.

MESOZOIC LIFE

As stated by Lance (154, p.88), Arizona's Mesozoic life has provided some of the best-known vertebrate fossil localities of the world. Notable among the animals were crocodiles, dinosaurs, and armored amphibians from the Triassic and Jurassic of the northeastern part of the State.

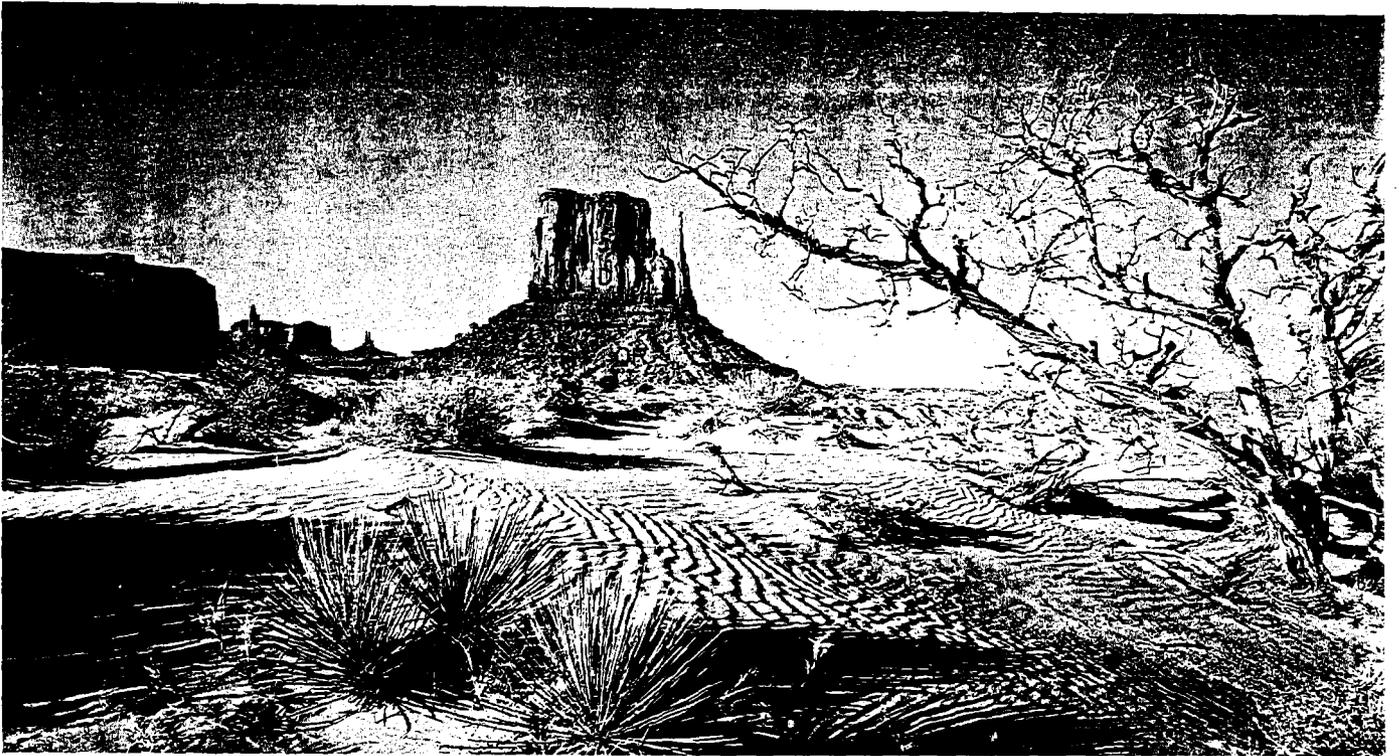
Invertebrate index fossils of the Cretaceous are listed in the Appendix.

TRIASSIC AND JURASSIC SYSTEMS

INTRODUCTION

Triassic and Jurassic strata, as determined by fossils, occur extensively within the Plateau Province. Also, many outcrops of sedimentary and metamorphic rocks elsewhere in the State may belong in these subdivisions of the Mesozoic, but no fossil evidence for their assignment has been announced.

* Published by the Arizona Bureau of Mines.



CHUCK ABBOTT

Plate X. Mitten Butte, Monument Valley. D, DeChelly sandstone; OR, shale and sandstone of Organ Rock tongue. Ripple-marked dune sand in foreground.



WESTERN WAYS FEATURES

Plate XI. Canyon DeChelly. Rock is DeChelly sandstone, locally cross-bedded.

Igneous rocks at several places in Cochise County are regarded as Triassic or Jurassic on indirect evidence (94;49).

Distinctions among the Triassic and Jurassic beds have been complicated somewhat by gradations in lithology, interfingering of units, and instability of paleontological interpretations.

STRUCTURAL DEVELOPMENT

Areas of Deposition. The general areas of Triassic land and sea in this region are sketched on Fig. 9. The Jurassic pattern generally was similar to the Triassic except that seas extended farther south in the northern portion of the State (180). Many details regarding the Triassic and Jurassic physiography are given by Harshbarger, Repenning, and Irwin (100).

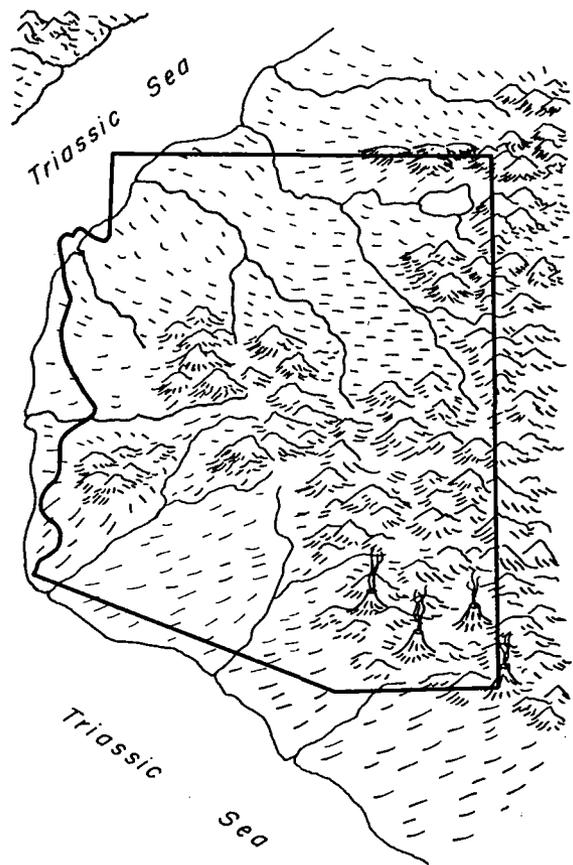
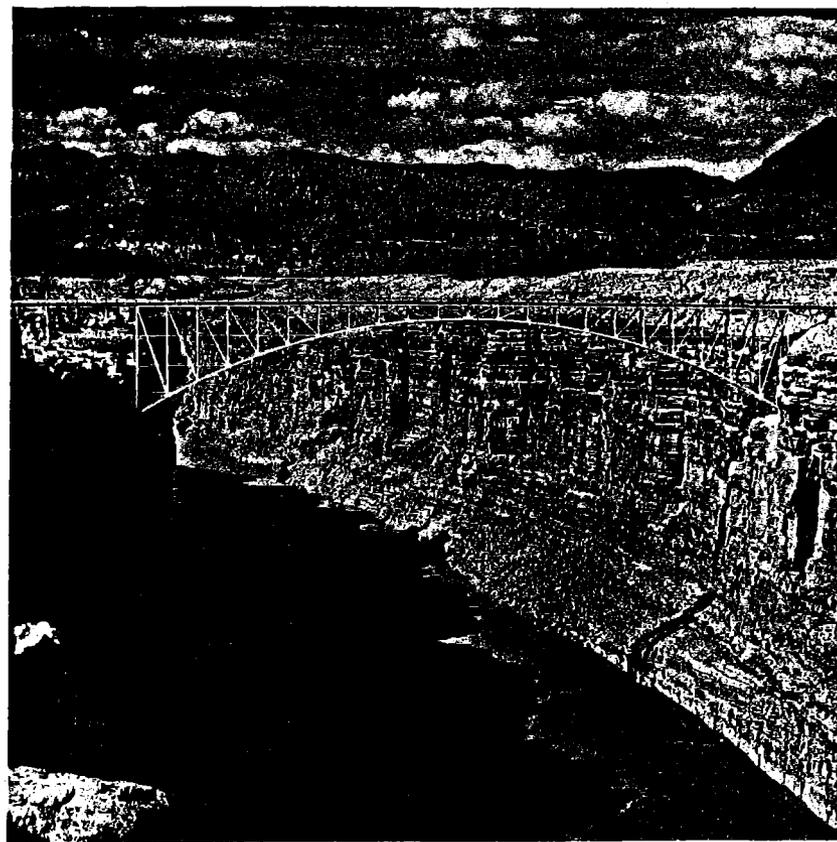


Fig. 9. Triassic areas of land and sea in Arizona. After Lance (154). Seas invaded northwestern Arizona early in the Triassic, and possibly the southwestern part of the State during later Triassic-Jurassic time.



WESTERN WAYS FEATURES

Plate XII. Marble Canyon, Colorado River. Skyline is Paria Plateau surface. N, Navajo sandstone, underlain by Kayenta, Moenave, and Wingate formations, in the Vermillion Cliffs; C, Chinle and Shinarump beds; K, Kaibab limestone, underlain by Toroweap formation and Coconino sandstone.

Southern Arizona. In Sonora, within 100 miles south of the Arizona boundary (47), the Triassic-Jurassic Barranca formation is more than 7,200 feet thick (137). The western portion of the geosyncline, in which the Barranca formation accumulated, probably was linked with marine Triassic and Jurassic basins of California and Nevada, as concluded by King (137); its northern shelf probably included portions of southwestern and southern Arizona, somewhat as suggested by Tenney (288) and Eardley (70). Also the thick series of locally metamorphosed strata in Yuma and southern Pima Counties, shown on the County Geologic Maps* as Mesozoic undivided, may include Triassic or Jurassic units (332).

* Published by the Arizona Bureau of Mines.

In Cochise County, as stated by Gilluly (94), the interval between Permian and Early Cretaceous, at least 70 million years long, was marked by a period of strong crustal deformation and subsequent invasion by magmas of granitic and monzonitic composition in the Mule Mountains and southern Dragoon Mountains areas; andesitic and dacitic volcanic rocks were erupted locally in the Dragoon quadrangle and probably also in some areas farther south. Of these rocks, the intrusive bodies were mapped as Triassic or Jurassic by Gilluly (94), and the volcanic eruptions were referred to the Triassic or Jurassic by Cooper (49).

In the Mule Mountains (108), the Dividend fault (Pl. XV), with a displacement of 2,000 to 5,000 feet, brings Paleozoic and Early Cretaceous beds on the southwest against Pinal schist on the northeast. Invading the zone of this fault are the Sacramento Hill porphyry stock and the Juniper Flat granite (Pl. XV), which are regarded as Triassic-Jurassic (94). Lower Cretaceous strata unconformably overlie the Juniper Flat granite, and the schist on the northeast side of the Dividend fault.

Schmitt (251) proposed the term, Nevadan Revolution, for the Triassic-Jurassic epoch of orogeny and igneous activity in the Southwest.

Northern Arizona. The following summary regarding Triassic and Jurassic history in northern Arizona is quoted from Lance (154):

Triassic and Jurassic rocks of northern Arizona are dominantly redbeds, laid down along the margins of seas that existed to the north and northwest during most of the two periods. Streams flowing from highlands in central and southern Arizona (Fig. 9) deposited mud and sand that produced such spectacular formations as the Chinle, which contains the Painted Desert and Petrified Forest. Great blankets of dune deposits such as the Navajo sandstone give evidence of arid, desert wastelands that occupied the area from time to time.

The shifting patterns of deposits attest to some crustal movements as well as changing climates in Triassic and Jurassic time. A sharp uplift in central Arizona produced the Mogollon Highlands in middle Triassic time (100). This uplift followed approximately the trend of the present Mountain Region, and is recorded by the great sheet of Shinarump conglomerate that was spread northward as far as southern Utah. Also, gentle folding in northern Arizona is indicated by the fact that the Upper Cretaceous Dakota sandstone was deposited on an erosion surface that bevels Jurassic and older beds.

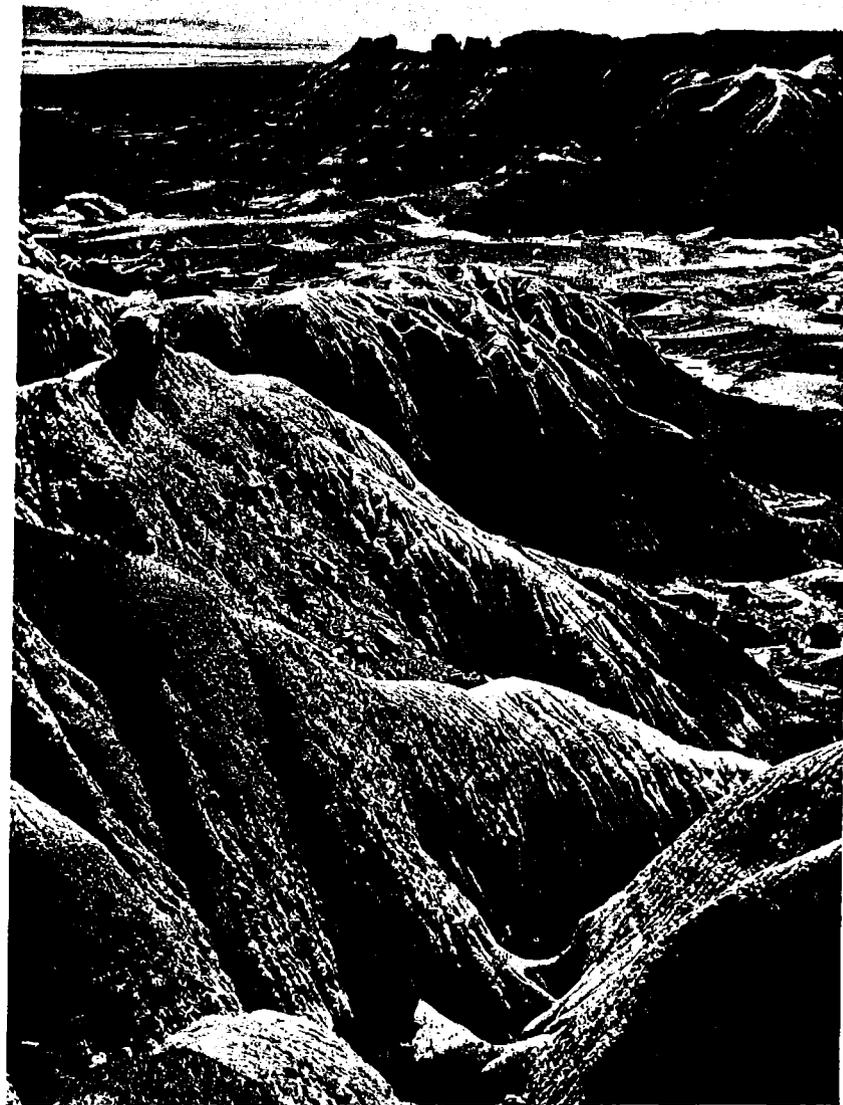
The orogeny that initiated the Virgin Mountains began after Jurassic, and before Late Cretaceous, time (169;170).

Bentonitic clays in the Late Triassic of Arizona (6) may represent air-borne volcanic ash from a source in Nevada or California (171).

SEDIMENTARY UNITS

General statement. For the Triassic and Jurassic beds of the Plateau, the following units, from oldest to youngest, are distinguished on the County Geologic Maps*: Moenkopi (Pls. IX, XIX) formation (Early

and Middle(?) Triassic); Shinarump conglomerate and Chinle formation (Late Triassic); Glen Canyon group (Late Triassic and Jurassic); San Rafael group (Middle and Late Jurassic); and Morrison formation (Late Jurassic).



WESTERN WAYS FEATURES

Plate XIII. Chinle formation, Painted Desert. Petrified wood in foreground.

* Issued by the Arizona Bureau of Mines.



A. E. TURNER, BUREAU OF RECLAMATION

Plate XIV. Navajo sandstone, Glen Canyon dam site. View downstream.



RAY MANLEY

Plate XV. Lavender open-pit mine. View northwestward, along Dividend fault, with Bisbee in background and Lowell in central foreground. S, Pinal schist; P, Paleozoic beds; J, Juniper Flat granite; g, porphyry of Sacramento Hill stock; M, Cretaceous Morita beds, unconformably overlying the units S, J, and g.

Moenkopi formation. The Moenkopi formation (61;181;4;307) consists of non-marine, locally gypsiferous, sandy and silty redbeds interfingering with minor amounts of marine calcareous strata. Its thickness, which diminishes from approximately 1,600 feet in northwestern Mohave County (197) to zero in eastern and southeastern Apache County, is listed as 854 feet near Fredonia, 756 feet in the House Rock Valley area, 168 feet near Snowflake, and 330 feet in the vicinity of Flagstaff.

Shinarump conglomerate. The Shinarump conglomerate, which now is regarded as the basal member of the Chinle formation (277), rests disconformably upon Moenkopi beds at most places and upon DeChelly sandstone in eastern Apache County. The Shinarump contains sandstone, conglomerate, and shale. Its thickness generally ranges from 50 to 100 feet but attains more than 350 feet in Monument Valley (78). Details of the Shinarump have been described in the literature (96;61;183;78 197;307).

Chinle formation. The Chinle formation (96;61;4;42;307) is made up of shale, clay sandstone, and minor amounts of limestone. It is about 915 feet thick in the House Rock Valley area. In northeastern Arizona it thickens southeastward from 850 feet in the northern Echo Cliffs to 1,500 or more feet east of Holbrook. With its variety of red, pink, brown, purple, and gray tints, the formation is renowned for scenery, as exemplified on the Painted Desert (Pl. XIII) of Coconino, Navajo, and Apache Counties. Also, the Chinle is well known for its abundance of fossil wood, particularly within the Petrified Forest National Monument, south of Adamana.

Glen Canyon group. Resting disconformably upon the Chinle beds is the Glen Canyon group (100;307;164). Some characteristics of its formations (Pls. XII, XIV) from base to top are tabulated as follows:

Wingate sandstone (Late Triassic): Red-orange to brown sandstone and shale; the sandstone is cross bedded in part. Thickness is 925 feet in Hopi Buttes area but diminishes westward, eastward, and northward.

Moenave formation (Late Triassic?): Red, orange, and brown cross-bedded sandstone and shale. Rests upon eroded surface of Chinle formation and intertongues with Wingate sandstone. Thickness variable; 384 feet at Moenave, west of Tuba City, and 540 feet in House Rock Valley area.

Kayenta formation (Late Triassic?): Red-brown to purple sandstone, mudstone, and minor limestone. In places rests upon eroded surface of Wingate sandstone. Thickness ranges from 144 feet near Kayenta to about 300 feet in House Rock Valley and 678 feet on Ward Terrace, southeast of Cameron.

Navajo sandstone (Late Triassic(?) and Jurassic): Pale-brown to orange cross-bedded sandstone with minor cherty limestone. Intertongues with Kayenta formation. Thickness ranges from 1,700 feet in Paria Plateau to 15 feet near Chinle village, Apache County.

San Rafael Group. The San Rafael group (100) rests disconformably upon the Glen Canyon group. Some very generalized data of its formations from base to top are tabulated as follows:

Carmel formation: Greenish-gray sandstone alternating with grayish-red to brown siltstone. Thickness generally ranges from 100 to 200 feet but decreases in eastern, southern, and southwestern portions of the Navajo Country.

Entrada sandstone: Orange-pink to reddish sandstone and red silty sandstone. Thickness ranges from 200 to 490 feet, approximately.

Summerville formation: Grayish orange-pink to reddish brown sandstone, silty in lower portion. Intertongues with Cow Springs sandstone, which occupies its stratigraphic position in southwestern portion of the Navajo Country. Thickness variable from 125 to 265 feet.

Bluff sandstone: Gray cross-bedded sandstone occurring in northeastern portion of Apache County. Intertongues with Cow Springs sandstone and grades into Summerville formation. Thickness ranges from 47 to 64 feet.

Cow Springs sandstone: Greenish-gray to yellowish-gray cross-bedded sandstone. Interfingers with Summerville and lower portions of Morrison formation. Thickness, 342 feet at type locality, 35 miles southwest of Kayenta.

Morrison formation. Overlying the San Rafael group with local conformity is the Morrison formation (96;52;100;281) of sandstone, mudstone, and varicolored sandy shale. The Morrison is about 555 feet thick at Marsh Pass and 725 feet at Yale Point, on the edge of Black Mesa; southwestward, it wedges out and intertongues with the Cow Springs sandstone.

ECONOMIC FEATURES OF THE TRIASSIC AND JURASSIC

Southern and western Arizona. The ore-bearing replacements and veins in the Bisbee (Pl. XV) or Warren district (222;251;295;108) and Courtland-Gleeson or Turquoise district (312;94) are believed to be connected genetically with monzonitic intrusive bodies of pre-Early Cretaceous,

Triassic or Jurassic (Nevadan) age. Data regarding production of copper and other metals from these districts are listed in Table 10.

Other ore deposits in southern and western Arizona may be related likewise to intrusives of Nevadan age, but definite evidence of such a correlation is not available.

Northern Arizona. Uranium and vanadium mineralization occurs, mainly as replacements, in the Chinle formation between Cameron and St. Johns, between Ganado and Chinle village, and in Monument Valley (117;335; 20;78;18). Uranium deposits in the Morrison formation of the Chuska and Carrizo mountain areas have been described (188;282). The primary or hypogene uranium mineralization in the Cameron area possibly is of Laramide age.

The replacement copper deposits of the White Mesa district, T.37 N., R.9-10 E., Coconino County, have been explored within the Navajo sandstone (96;190). Their primary mineralization possibly was associated genetically with Laramide intrusive activity at depth.

Placer gold, very finely divided, appears to be distributed sparsely within the Chinle formation throughout extensive areas (161;330).

The following nonmetallic mineral resources in Triassic and Jurassic formations have been described as of potential importance:

Limestone for lime or cement, beds in Chinle formation (133).

Bentonitic clay, in Chinle formation (334).

Clay for brick and tile, in Chinle and Morrison formations (111).

Kaolin, in Morrison and Cow Springs formations (111).

Gypsum, in Moenkopi formation (10;333).

Building stone and flagstone, in Moenkopi (208;333), Chinle, Wingate, Moenave, Kayenta, Navajo, and Morrison formations (208).

Natural aggregate, in Shinarump member of Chinle formation (134).

Sand and crushed stone, from various formations (98).

PRE-CRETACEOUS UNCONFORMITY

From northeastern Arizona to the southwestward, an erosional surface at the base of the Cretaceous cuts across progressively older rocks (100) that had been uplifted and deformed during the Nevadan Revolution. Thus the units, immediately beneath the Cretaceous, range in age from Late Jurassic in northern Apache, Navajo, and Coconino Counties to Older Precambrian in southern Arizona. The angular discordance associated with this unconformity, although generally slight, is notable in some localities, as for example in the Mule Mountains (222;94). In the latter area, the pre-Cretaceous surface exhibits marked irregularity.

CRETACEOUS SYSTEM

INTRODUCTION

On the Arizona Bureau of Mines County Geologic Maps, the assignments of sedimentary, volcanic, and intrusive rocks to the Cretaceous System are based upon evidence that is direct for some areas and more or less indirect for others. Correlations according to formational names are made only for sedimentary beds in northern Apache, Navajo, and Coconino Counties and for some volcanic rocks in southwestern and northwestern Arizona. Also, no distinction between Early and Late Cretaceous is featured on the maps, but these two subdivisions of the System are discussed on subsequent pages.

Early Cretaceous. In Arizona, rocks regarded as Early Cretaceous are limited to the region of the Sonoran geosyncline south of Latitude 32°30' and east of Longitude 112°15'. The sedimentary beds consist of shallow marine, near-shore, and continental types which are suggestive of deposition in a sea which advanced progressively northwestward. Interbedded with them at some localities are volcanic rocks, which implies crustal unrest.

As interpreted by McKee (180), the Cordilleran geosyncline did not exist after the Triassic-Jurassic Nevadan Revolution; during the Early Cretaceous, former shelves and basins of deposition in northwestern and northern Arizona received no sediments, so far as known.

Late Cretaceous. A Late-Cretaceous sea occupying the Rocky Mountain geosyncline successively advanced and retreated across northern Arizona (180). It spread southward into Gila County and possibly (216;83) into Pinal, Graham, and Greenlee Counties. Its invasions are recorded by sandstone and shale of marine and non-marine types. Volcanic rocks, indicative of crustal unrest, are abundant within the sequence in southeastern Gila, northeastern Pinal, and northwestern Graham Counties.

A notable basin of Late Cretaceous deposition is indicated by a succession of non-marine and near-shore sandstone, shale, conglomerate, and limestone, conformably underlain by volcanic rocks, in the eastern portion of the Santa Rita Mountains (284). The Late Cretaceous beds of the Tucson Mountains (26;138;139;140) may be related to this basin of deposition; but definite correlative evidence is lacking. Possibly, central Cochise County also received Late Cretaceous sediments, but, if so, they were removed by erosion (94).

Crustal unrest, presumably extending from Triassic or Jurassic into Late Cretaceous time, is indicated by the widespread occurrence of igneous rocks in southern and western Arizona, which are classed as Cretaceous on the County Geologic Maps of the Arizona Bureau of Mines.

EARLY CRETACEOUS STRATIGRAPHY

Cochise County. Of the Early Cretaceous units in Arizona, the Bisbee group and Bisbee formation in Cochise County are best known.

The Bisbee group in the Mule Mountains (222;94) consists, from top to base, of the following formations:

Cintura formation of brown to red sandstone and shale with minor limestone; thickness 1,800 feet.

Mural limestone; thickness 517 to 700 feet.

Morita formation, lithologically similar to the Cintura, with some lenses of limestone in lower portion; thickness 1,800 to 3,000 feet (Pl. XV).

Glance conglomerate; thickness commonly less than 100 feet but ranges up to 600 feet or more; absent in some places.

As the Mural limestone thins out north of the Mule Mountains, Gilluly (94) proposed for the group in central Cochise County the name, Bisbee formation. It generally consists of buff, brown, and red sandstone, shale, conglomerate, and minor limestone. At Tombstone (35;94) it is more than 3,000 feet thick and has a prominent novaculitic member at the base and several relatively thin limestone members in the lower portion. Northwest of Courtland, andesitic and other volcanic rocks appear to be associated with the basal portion of the section (94). In the vicinity of Dragoon, the Bisbee formation is more than 3,000 feet thick and is overlain by 4,900(?) feet of volcanic and clastic sedimentary rocks, presumably of Early or Late Cretaceous age (49). In the Chiricahua Mountains, its thickness exceeds 3,500 feet, including a maximum of 1,000 feet of conglomerate at the base and 220 feet of limestone in the middle portion (249).

Other areas. A composite section of Early Cretaceous rocks in the southwestern flank of the Whetstone Mountains and the Cienega Wash area of the Empire Mountains is reported to be 15,000 feet thick (250). The Whetstone section reportedly totals more than 10,000 feet with limestone predominating in the lower 1,460 feet, and sandstone and shale in the remainder (198;250).

On the southwestern flank of the Huachuca Mountains, the Parker Canyon section shows 7,600 feet of Early Cretaceous beds which include a northward-thinning limestone member approximately 250 feet in maximum thickness (198).

SECTIONS INCLUDING EARLY AND LATE CRETACEOUS ROCKS

Patagonia Mountains. Northwest of Duquesne, Paleozoic limestone is overlain by approximately 10,000 feet of Early and Late Cretaceous rocks of which the lower 7,000 feet consists of flows, breccia, and tuff of rhyolitic to andesitic composition (198).

Santa Rita Mountains. Northwest of Patagonia, the Adobe Creek section contains 1,430 feet of sandstone and mudstone, considered as Early Cretaceous; 1,300 feet of Late(?) Cretaceous sandstone and conglomerate; and 4,400 feet of Late Cretaceous sandstone, conglomerate, limestone, and shale (198).

Tucson Mountains. In the mountain range immediately west of Tucson, purplish andesites, 2,000 to 5,000 feet thick and regarded as Early Cretaceous, are overlain successively by red beds and arkose, 3,000 feet or more thick, of which the upper portion is designated as Late Cretaceous (26;30;138;139;140).

LATE CRETACEOUS SECTIONS

Greenlee County. The Late Cretaceous Pinkard formation of sandstone and shale attains a thickness of 500 feet or more in the Morenci area (166).

Deer Creek-Christmas area. A series of volcanic rocks interbedded with Late Cretaceous strata occurs in northeastern Pinal, northwestern Graham, and southern Gila Counties (38;227;229;245;246). Its maximum thickness is about 1,500 feet, of which approximately one-third consists of sandstone, shale, and conglomerate, and the remainder of andesite, andesite breccia, and tuff. The sedimentary beds, which occur mainly in the lower portion of the section, may be equivalent to the Pinkard formation (245;246).

Northern Arizona. Late Cretaceous units are represented by the Dakota sandstone, overlain successively by the Mancos shale and Mesaverde group, in the Black Mesa region of Navajo, Apache, and Coconino Counties; and by the Dakota sandstone northwest of Glen Canyon and northeast of St. Johns.

The Dakota consists of gray or pale-orange sandstone with some shale. In Black Mesa the formation ranges from about 50 to 120 feet thick (239;205).

The Mancos, composed of gray, yellow, or blue silt, clay, and fine-grained sandstone, is 670 feet thick in the northeast portion of Black Mesa but becomes thinner southwestward. Its lower contact is gradational, and it intertongues with the overlying Toreva formation (239;205).

The Mesaverde group (239;205;310) from base to top includes the Toreva formation, Wepo formation, and Yale Point sandstone. The Toreva consists of gray sandstone with varicolored shale and ranges from 140 to 325 feet thick. The Wepo formation, comprising gray to brown siltstone, mudstone, and sandstone, together with coal, ranges in thickness from 743 feet on the west to 318 feet on the northeast. The Yale Point sandstone consists of yellowish-gray sandstone 300 feet thick near Marsh Pass, but thinning and intertonguing with the Wepo southward.

Cental Arizona. Undifferentiated sandstone and shale, in southern Apache, southern Navajo, southeastern Coconino, and northeastern Gila Counties, unconformably overlie Permian beds and contain Late Cretaceous fossils; this series, in part, may be Dakota (100). At the head of Carrizo Creek and south of Heber, it is 300 feet thick (61). Its details near Pinedale are described by Veatch (299).

CRETACEOUS IGNEOUS ROCKS

General Statement. Those igneous rocks indicated as Cretaceous on the County Geologic Maps* are volcanic except for granite in several areas of the Sierrita Mountains, Pima County.

These volcanics range from intermediate to felsic in composition, with the andesitic type predominant. In addition to this somewhat distinctive lithology, they characteristically tend to be faulted, folded, altered, and locally mineralized. In many places rocks of inferred Late Cretaceous or Early Tertiary ages invade them.

Where direct evidence is lacking, many geologists are inclined to assign all volcanic rocks in most areas of southern and western Arizona to the Tertiary, as has been customary for many years; hence differences of opinion are reflected on the County Geologic Maps* along the Pima-Maricopa boundary northeast of Ajo and the northern portion of the Pinal-Graham boundary.

In southeastern Arizona, volcanic rocks are assigned to the Cretaceous on stratigraphic evidence, as stated on previous pages, and by projection of lithologic and structural similarities into neighboring areas. Thus, for example, in the Peña Blanca area of the Atascosa Mountains, southwestern Santa Cruz County, andesite of a lithology common to the Cretaceous lies with pronounced angular unconformity beneath rhyolite of supposed Tertiary age.

For most areas of southwestern and western Arizona, the evidence for Cretaceous volcanism is inconclusive from a stratigraphic standpoint and admittedly tenuous, but the testimony of structural history seems worthy to consider. As described on previous pages, much of southern and western Arizona presumably was occupied by the northeastern shelf or margin of a Triassic-Jurassic geosyncline. Following the break-up of this feature by the Nevadan Revolution, structural instability may well have prompted extensive volcanic activity during Cretaceous time; ample evidence of crustal unrest is offered by the shifting patterns of lithology and thickness among Cretaceous beds in southeastern Arizona, and the abundance of volcanics stratigraphically related to them.

Brief data regarding volcanic rocks in some areas of southwestern and western Arizona are summarized in following paragraphs.

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Ajo area. The Concentrator volcanics of deformed andesitic and keratophyric rocks, possibly 3,000 or more feet thick near Ajo, were assigned to the Cretaceous(?) by Gilluly (93) on the bases of "lithologic similarity to rocks of known age and lengths of time required for different geologic events." Also, this unit is separated by angular unconformity from overlying Tertiary(?) rocks and intruded by quartz monzonite of probable Tertiary (93) or Laramide age.

Sauceda Volcanics. In southern Maricopa and southwestern Pima Counties, a unit of deformed rocks, termed the Sauceda volcanics on the County Geologic Maps,* consists mainly of rhyolite, latite, and andesite and is more than 1,500 feet thick. In T.10 S., it intertongues with andesite, likewise thick.

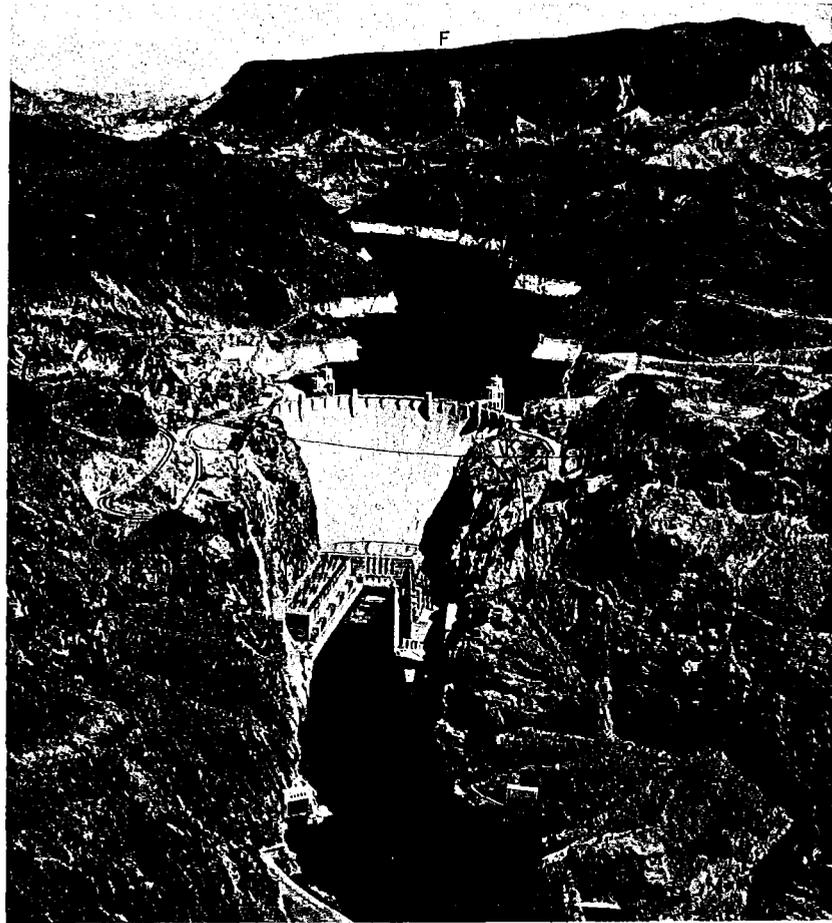
Yuma County. In the Castle Dome and Kofa (SH) Mountains, a series of deformed flows, breccias, and tuffs, 2,000 or more feet thick, lies unconformably upon sedimentary beds of Mesozoic, possibly Triassic or Jurassic, age. Its lower portion is predominantly andesitic, and its upper division, termed the Kofa volcanics on the Geologic Map of Yuma County*, is mainly andesitic to rhyolitic. This series has been intruded by granitic rocks, as well as by numerous dikes and plugs, of presumed late Mesozoic and Laramide ages.

Western Mohave County. Resting upon Older Precambrian rocks in the Black Mountains is a thick sequence of volcanic rocks (Pl. XVI) that long have been regarded as Tertiary (254;230;159). Granitic bodies and numerous dikes and plugs intruding portions of this volcanic pile were assigned likewise.

In the Oatman district, the lower portion of the series consists of andesite and trachyte, approximately 5,000 feet thick, together with a unit, comprising about 1,600 feet of latite, andesite, and siliceous flows, that is termed the Gold Road volcanics on the Geologic Map of Mohave County.* Rhyolitic flows and tuffs, 1,500 or more feet thick, lie unconformably upon the lower members in some sections and upon Older Precambrian in others. A monzonitic stock invades the andesite and probably also the Gold Road volcanics; its original cover, which must have been at least one-half mile thick, was stripped away prior to eruption of the rhyolite.

The andesite and Gold Road units show more intense alteration than the rhyolite and contain gold-quartz veins that do not extend above the pre-rhyolite unconformity. These differences, together with the magnitude of the aforementioned unconformity, strongly suggest that the

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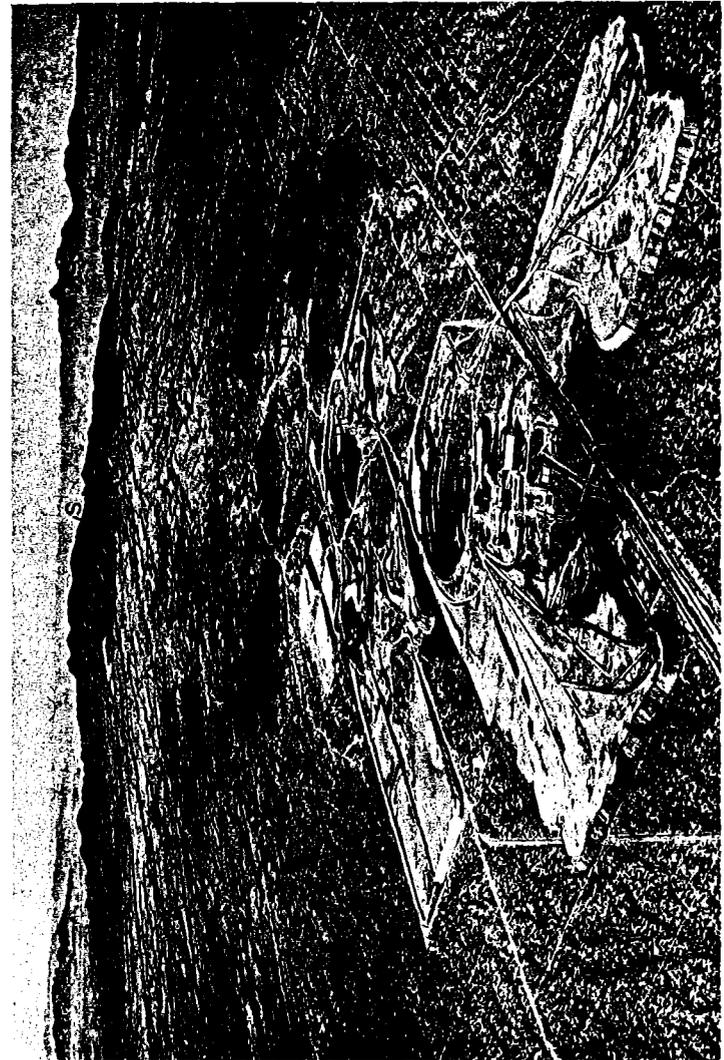
BUREAU OF RECLAMATION

Plate XVI. Hoover dam, on Colorado River. F, Fortification Hill, capped by Quaternary basalt; T, Tertiary sedimentary beds; K, Cretaceous andesitic rocks.

andesite and Gold Road units are Cretaceous, the monzonitic stock is Laramide, and the rhyolite sequence is Tertiary.

ECONOMIC FEATURES OF THE CRETACEOUS

Metallic Ores. No metalliferous deposits of pre-Laramide Cretaceous origin are recognized in Arizona, but the rocks of known and inferred Cretaceous age were hosts for important mineralization of Laramide or later ages. Examples are replacements and veins containing silver, gold, lead, copper, and manganese at Tombstone (35;81); copper, zinc, lead, silver, and gold in the Pima (Pl. XVII) district (325;116;124;149;150;50); and veins with gold and silver in the Black Mountains (230;159;316);



PETER BALESTRERO

Plate XVII. Mission (M) and Pima (P) open-pit mines, on pediment area of Sierrita Mountains. View southwestward, in 1961. V, Palo Verde, D, Daisy, and H, Mineral Hill, shafts; X, San Xavier shaft (behind hill); L, Paleozoic limestone; K, Cretaceous quartzite and arkose; g, Laramide granodiorite; S, Sierrita Mountains; B, Baboquivari Mountains; A, Altar Valley.



Plate XVIII. Mesozoic granite (G) and schist (S), Gila Mountains, Yuma County.
View southwestward.

gold-quartz veins in the Kofa Mountains (316); veins and replacements containing silver and lead in the Silver district, Trigo Mountains (315;316), Yuma County; silver in the Cerro Colorado area, Pima County; and manganese in the Bouse Hills, Trigo Mountains, and Aguila areas, Yuma County (80).

Nonmetallics. Building stone has been quarried from the Mancos and Mesaverde beds (208).

Mineral Fuels. Coal has been mined from the Dakota sandstone and Mesaverde formation (310;220;146), and small amounts have come from Late Cretaceous beds in the Deer Creek (38;220) and Pinedale areas (299;220).

UNDIFFERENTIATED MESOZOIC

INTRODUCTION

Sedimentary, schistose, gneissic, and granitic rocks in Yuma and southwestern Pima Counties and volcanics in western Santa Cruz and southern Pima Counties are assigned through indirect evidence to the Mesozoic on the County Geologic Maps.* As stated on a previous page, the sedimentary rocks, and the schist also, may be Triassic or Jurassic.

GENERAL FEATURES

Sedimentary rocks. The sedimentary rocks comprise a deformed series, several thousand feet thick, of shale, sandstone, quartzite, limestone, and conglomerate. Pebbles in the conglomerate of the New Water Mountains, Yuma County, contain Permian and earlier fossils (315;179). This series, intruded by numerous dikes and in places by granitic rocks, has undergone metamorphism of variable intensity and locally grades into schist.

Schist. The rocks mapped as schist for the most part have been derived from sedimentary beds of a lithology similar to that of the aforementioned sedimentary unit into which it locally grades. Except in a few areas, this schist (Pl. XVIII) neither is strongly foliated nor intensely metamorphosed and, as a whole, it resembles no unit in the Precambrian, Paleozoic, or Cenozoic of Arizona.

Gneiss. The gneiss consists mainly of granitic and sedimentary rocks that have been weakly foliated. It intertongues with, and appears to be younger than, the schist.

Volcanic rocks. The series designated as Mesozoic volcanics comprises flows, tuff, and breccia, intercalated with sandstone and shale. These rocks are more altered and deformed than are the beds, regarded as Cretaceous, which seem to overlie them.

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Granitic rocks. Intruding the sedimentary, schistose, and gneissic units it granite (Pl. XVIII) which in southern Yuma County has a sodic composition and almost white color. According to Paul Damon (204), of the University of Arizona, geochemical work on lithologically similar granite, occurring about ten miles southwest of Lukeville, indicates an age of 80-85 million years, which would assign it to Middle or Late Cretaceous.

The Chico Shunie quartz monzonite, southwest of Ajo, was assigned to the Mesozoic(?) by Gilluly (93) on indirect evidence.

ECONOMIC FEATURES

The sedimentary series constitutes the host rocks for ore deposits of presumed Laramide age, as, for example, lead-fluorspar veins in the Castle Dome and Middle mountains (315); veins containing gold and copper in the Plomosa Mountains and north of Vicksburg (16), Yuma County; cinnabar veins in the Dome Rock Mountains (160); and manganese (80) and replacement iron deposits (16) in the Plomosa Mountains.

The schist is a host rock of numerous gold-quartz veins, as exemplified in the Fortuna mine area (315;316), Yuma County; and of some lead and copper deposits (16). Marble of potential importance occurs in schist south of Dome (315), Yuma County.

The gneiss contains gold deposits (315;316) in various places.

The granite is a host rock for gold-bearing veins in several areas. South of Dome, it has been quarried for railroad ballast (315).

Laramide Interval

INTRODUCTION

A period of mountain-making deformation, uplift, and igneous activity, which is termed the "Laramide or Rocky Mountain Revolution," began in Late Cretaceous and extended into Cenozoic time.

In Arizona, Laramide folding and faulting were relatively moderate for the Plateau but intense for the Basin and Range Province. For the Transition Zone, Laramide features have not been distinguished separately from those of the later Cenozoic.

Laramide igneous activity is marked by batholiths, stocks, dikes, plugs, and volcanic rocks, especially within the Basin and Range Province. For this latter region, the orogeny is not clearly separable from the Triassic-Jurassic Nevadan Revolution; furthermore it appears to blend with the crustal unrest and igneous activity of middle to late Cenozoic time.

Thus, the Laramide has no recognized definitive time limits, and its convenient usage to designate an interval is not accepted officially by the U.S. Geological Survey; many geologists tend to assign its features in

Arizona entirely to the Tertiary, and granitic rocks are so designated for several areas on the Geologic Map of Cochise County.*

Schist, gneiss, volcanic, and sedimentary rocks in several areas are regarded as of Tertiary-Cretaceous age.

LARAMIDE FEATURES IN THE PLATEAU PROVINCE

STRUCTURE

General Statement. As interpreted by Hunt (115), the Plateau Province had been a shelf area in pre-Cenozoic time. At the beginning of the Cenozoic and during early Tertiary, the Plateau area was a basin or trough, probably not far above sea level, and surrounded by newly formed mountains; this depression had been formed by folding that began in Late Cretaceous and continued during the early Tertiary. After Eocene time, there occurred epeirogenic uplift, faulting, and igneous activity, which have continued intermittently to the present (115).

Within the Plateau Province of Arizona, the Laramide structural features are folds and faults which trend prevailing in north to north-westward, and locally in transverse, directions (Fig. 10).

Folds. The folds comprise generally broad anticlinal domes, synclinal basins, and monoclines; as a rule, the anticlines are asymmetrically steeper on their eastern flanks. The main deformation probably was caused by compressional forces which resulted in arching of the strata above thrust or steep reverse faults in the basement rocks, as suggested by Baker (13;14) and exemplified in Cross-Sections* No. 2 and 3.

Faults. The exposed faults in the Plateau Province are mainly of steep or vertical dip. Displacements on them range from a few feet to more than 1,500 feet; in some cases they grade into monoclinical flexures. The faults are believed to have developed, at least in part, during the process of Laramide folding, and additional displacement occurred along many of them during Cenozoic time. Presumably the more important breaks are of Precambrian heritage; for example, the Butte fault (61;302;303), in the eastern portion of the Grand Canyon, shows from 400 to 4,000 feet of Precambrian displacement which was reverse in reference to its post-Paleozoic normal, possibly right-lateral, movement.

The principal faults, as indicated on Fig. 10, occur west of Longitude 111°. They effect progressive relative depression of the beds on both sides of the Kaibab uplift, and the Grand Wash fault marks the western boundary of the Plateau Province. Their individual features are discussed briefly under the Cenozoic section on subsequent pages.

Kaibab uplift. The Kaibab uplift (12;285;126;127;128) is an asymmetrical compound anticline (Fig. 10) whose arcuately concave steep eastern

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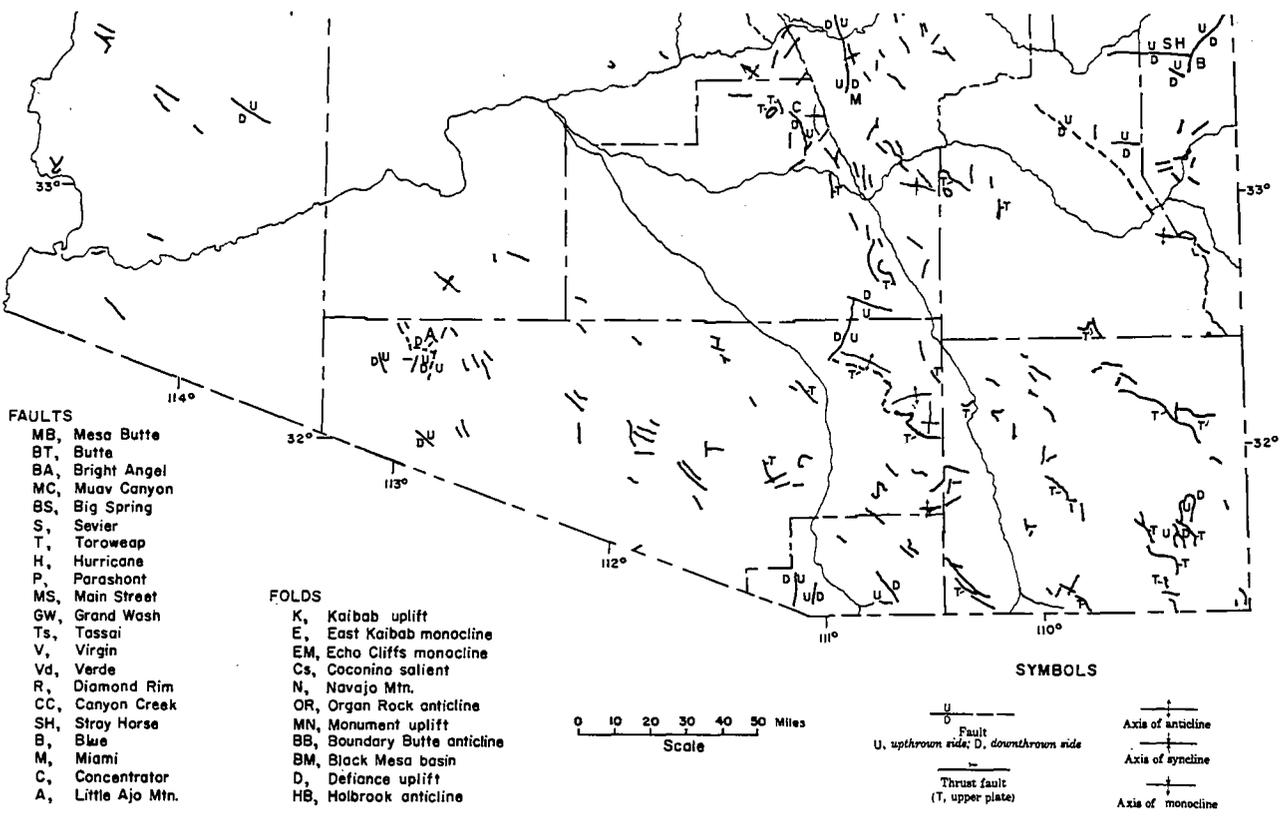
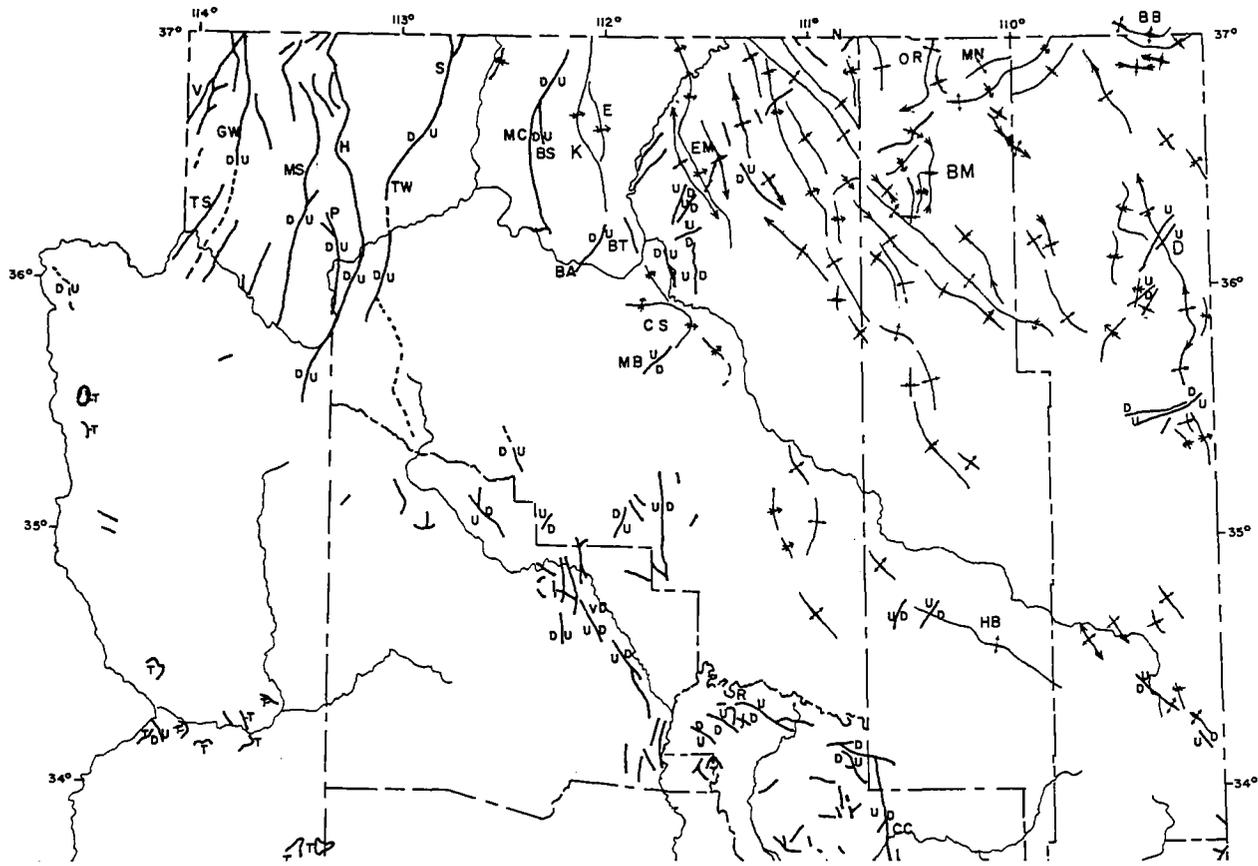


Fig. 10. Tectonic map of Arizona, generalized.

flank is termed the East Kaibab monocline (12). Along the line of Cross-Section No. 2*, this large anticline, together with associated faults, constitutes a structural rise of 5,000 feet.

Coconino salient. As interpreted by Kelley (126;127;128), the Coconino salient (Fig. 10) may have resulted from the pushing of a deep-seated block northeastward and upward between flanking shear zones that lie beneath the Grand View and Coconino monoclines; thus the zone of the Mesa Butte fault (Fig. 10) would have been the principal accommodating break for this deep-seated movement. The original structural relief of the Coconino salient appears to have been reduced by the arcuate fault that bounds its northeastern tip (128).

Echo Cliffs monocline. Separated from the East Kaibab monocline by a narrow, shallow syncline is an asymmetric anticlinal fold termed the Echo, or Echo Cliffs, monocline (96). With an arcuately concave, steep eastern flank, it makes a structural depression which amounts to 2,500 feet along the line of Cross-Section No. 2* but diminishes southward.

Black Mesa basin. The Black Mesa basin consists of a large compound downwarp traversed by several broad minor folds of northwestward trend (Fig. 10). As shown in Cross-Section No. 3*, its maximum structural depression amounts to 3,000 feet.

Monument uplift (96;13;14). Extending from Utah into Arizona is the Monument uplift which, in the vicinity of Latitude 37°, effects a maximum structural rise of approximately 3,000 feet and brings Supai beds to the surface. The Comb Ridge monocline forms its southeastern flank. West of it is the Organ Rock anticline (Fig. 10).

Defiance uplift (126;127;128;66). Superimposed upon the Defiance positive area and rising gently from the eastern margin of the Black Mesa basin is the Defiance uplift, a broad asymmetrical anticline (Fig. 10) whose steep, locally overturned eastern flank is termed the Defiance monocline. Its maximum structural relief in Arizona amounts to approximately 5,000 feet.

Boundary Butte anticline (13;14). Trending S.65°E., the eastern portion of the Boundary Butte anticline lies within the Four Corners area of Arizona (Fig. 10 and Cross-Section* No. 3).

Mogollon slope. In the area extending southward from the Defiance uplift and Black Mesa basin, the strata prevailingly dip at low angles northeastward except where interrupted by several folds of northwestward trend, as shown on the Geologic Maps of Apache, Navajo, and Coconino Counties*. The folds probably are Laramide, but the final



N. H. DARTON

Plate XIX. Hurricane Cliffs, northern Mohave County, View eastward. B, Quaternary basalt; M, Moenkopi formation, separated from Hermit shale (H) by Hurricane fault along cliff base; K, Kaibab limestone, Toroweap formation, and thin Coconino sandstone.

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northeastward tilting is regarded by Lance (153) as a middle to late Cenozoic effect superimposed upon pre-Cretaceous features (p.74).

IGNEOUS ROCKS

No igneous rocks between Precambrian and late Miocene or early Pliocene have been recognized on the Plateau in Arizona. If, however, the primary mineralization of the uranium and copper deposits is considered as Laramide, it may be presumed that Laramide intrusive bodies are present at depth. As interpreted by Bollin and Kerr (20), the exposed igneous rocks in the Cameron area appear to be later than the uranium.

THE LARAMIDE IN THE BASIN AND RANGE PROVINCE AND TRANSITION ZONE

STRUCTURE

General Statement. As pointed out by Suess (286) and by Butler (32) and exemplified in Cross-Sections* No. 2, 5, and 6, the Precambrian rocks rise some thousands of feet higher in the Mountain Region than in the adjoining Transition Zone and Plateau (outlined on Fig. 13). It appears that Laramide folding and faulting effected greater uplift in the Mountain Region than in the Desert Region.

The Laramide structural details of the Basin and Range Province in Arizona are inherently complex, and furthermore they have been isolated, modified, concealed, or obliterated at many places by later Cenozoic structural events, sedimentation, and volcanism. Hence, our present concepts of the relations are based partly upon inference.

Descriptions of Laramide and later structural features for various areas are contained in the references cited in Table 6.

Folding in the Mountain Region. In its southeastern portion, which corresponds to the area of the Sonoran geosyncline, the Mountain Region probably represents a complexly faulted anticlinorium.

Detailed work by Gilluly (94) in central Cochise County has shown that a major deformation occurred perhaps during the first half of the Tertiary. He says (94, p.160): "It seems that any reasonable reconstruction of the rocks to depth on the basis of their present attitudes and distribution requires that the observed crust was shortened by several miles." Much of this compression was accommodated by folding of the Cretaceous and older rocks throughout southeastern Arizona.

Except for a few localities, the Laramide folds trend northwestward. Most of them are of open type, but some are isoclinal and locally overturned (Fig. 11). Several of the folds are indicated on Fig. 10, and also by dip-and-strike and other conventional symbols on the County Geologic

* Issued by the Arizona Bureau of Mines.

Table 6. References for Laramide and later structural features.

AREA	REFERENCE
Bisbee	222;295;108
Tombstone	35;94
Central Cochise County	94
Swisshelm	90
Chiricahua, Dos Cabezas Mts.	248;249;192
Dragoon quadrangle	48;49
Morenci	165;166
N. Graham County	245;23;104;105
Arivaipa, Deer Cr.	245;326
Globe	221;211;213;213a
Miami, Ray	229;328;213;213a
Superior	268;275;327
Dripping Spr. Valley	227;229
Tortilla Mts.	17;259
San Manuel	258;329
Copper Creek	147;148
Santa Catalina Mts.	195;22;207;67;68
Tucson Mts.	26;30;139;140;217
Silver Bell	265;240;242
Waterman	174
Sierrita	228;325;149;150
Empire	5;88
Helvetia, Rosemont	54;101
S. Yuma County	315
Planet	331
Artillery Mts.	156
Oatman	230;159
N. Black Mts.	254;168;169;172
Virgin Mts.	169;170;197
Jerome; Verde Valley	8;163;297;120

Maps*. Some are featured in Cross-Sections* No. 1, 2, 3, 7, 8, and many are mentioned in the literature (p.119-133).

In the northwestern segment of the Mountain Region, the exposed rocks south of Latitude 36° consist of metamorphics, intrusives, and volcanics within which the folding that probably occurred has not been demonstrated. North of Latitude 36°, within the reaches of the Cordilleran geosynclinal area, the orogeny (170) that had been initiated between Jurassic and Late Cretaceous underwent further development during the Laramide; its folding is exemplified in the Virgin Mountains (197;332).

Folding in the Desert Region. It is suggested that broad open folding of dominantly northwest to northward trend may have been developed over the Desert Region of Arizona (Fig. 13) during Laramide time. West of Tucson and south of T.8 S., for example, one belt of structurally high ranges appears from Longitude 111° to the Gila and Salt River Meridian, and another lies west of the Sonoita Valley and Growler Mountains; between these two belts the ranges are structurally low except for the Gunsight Hills, Little Ajo Mountains, and Growler Pass areas.

* Issued by the Arizona Bureau of Mines.

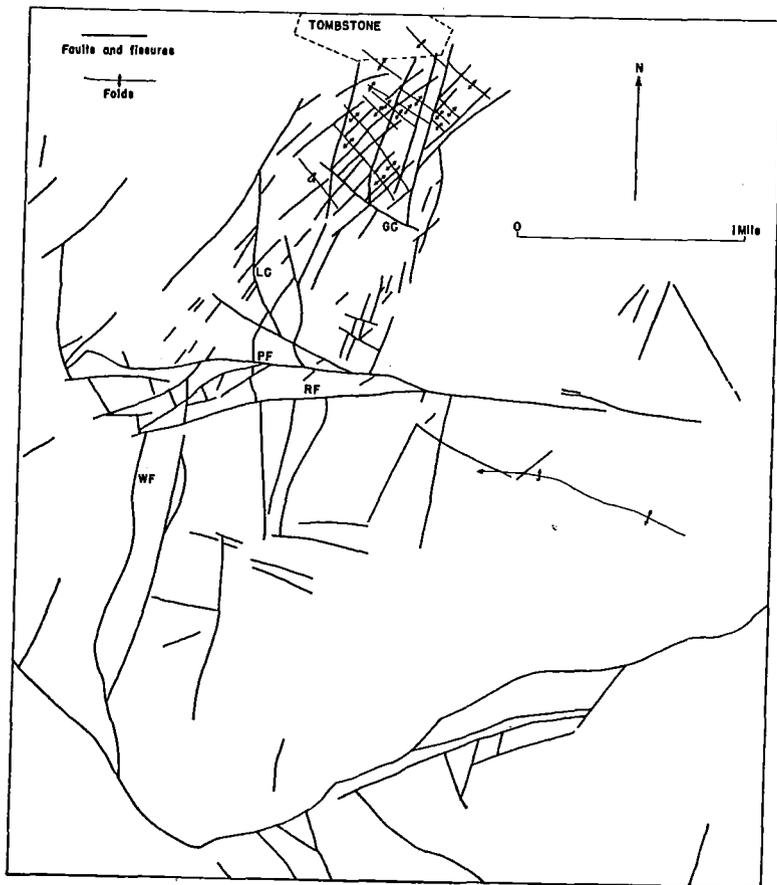


Fig. 11. Tectonic map of the Tombstone area. After Butler, Wilson and Rasor (35). GC, Grand Central fault; LC, Lucky Cuss fault; PF, Prompter fault; RF, Rattlesnake fault; WF, West boundary fault.

Faulting. As stated by Longwell (171, p.427), "Of several misconceptions that persist regarding Basin Range structure, none is more erroneous than the view that most of the faulting was concentrated in late Cenozoic time."

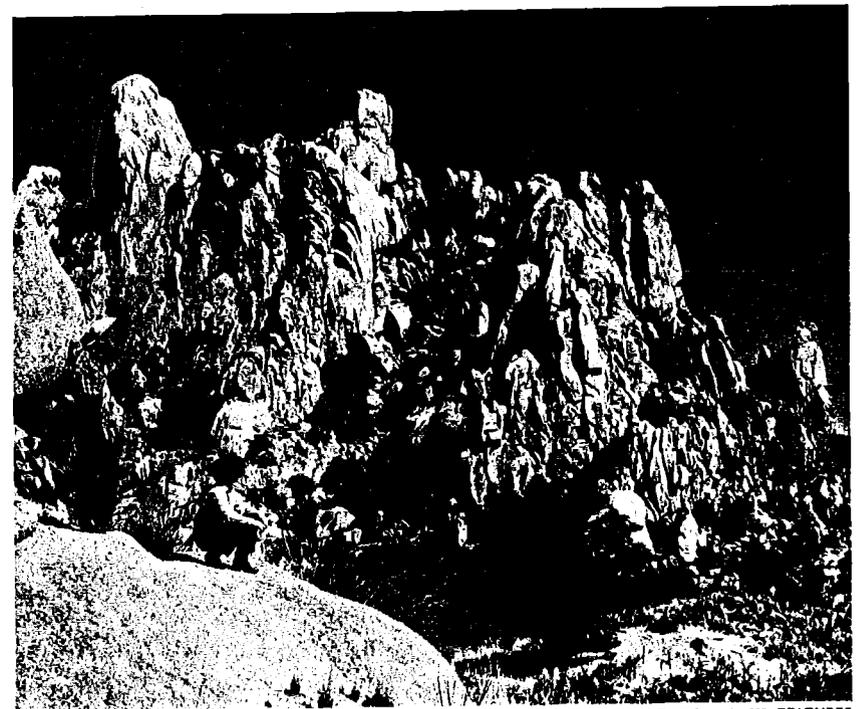
It is believed that a large proportion of the faults, which include normal*, reverse*, strike-slip*, and thrust* types, in the present mountain areas and in the concealed basal rocks of the intervening basins, were active during Laramide time. However, many details, including the extent of their renewal during later Cenozoic, are not clear. The general pattern of the faults and fractures is discussed on p.6. Some individual features

* Defined in Glossary (p.113-117).

are considered briefly under the Cenozoic section on subsequent pages, and many are described in the references specified on p.65.

The best-known shear breaks are those of the general E.-W. and N.-S. categories, with local deviations to N.70°W. and N.20°E. trends. Reverse and lateral movements are shown on some in the E.-W. class, as exemplified by the 4,000 feet of reverse, and much larger horizontal, displacements on the Prompter fault (Fig. 11) at Tombstone (35;94). Lateral and reverse, as well as normal, displacements occur among faults of the other directional categories, especially those of the general N.-S., E.-W., and northwesterly trends.

The known Laramide and later thrusts are confined to the southeastern and western regions, as indicated on Fig. 10. In the southeastern portion they are associated geographically with the relatively intense folding that characterizes the site of the Sonoran geosyncline. The western region is on a segment of the shelf of the former Cordilleran geosyncline north of Latitude 36° and possibly within the unstable region of a pre-existing Triassic-Jurassic geosyncline south of Latitude 36°. Most of the thrusts trend northwest to northerly and effected northeast or eastward displacements, but some trend westerly and moved northward. In



WESTERN WAYS FEATURES

Plate XX. Laramide granite, Cochise Stronghold, Dragoon Mountains.

places, as the Dragoon Mountains (94) for example, several thrusts are imbricate, folded, and otherwise complex. Overturning of beds in association with thrusting is exemplified in the Dragoon Mountains (94) and southeast of Superior (328).

MAJOR INTRUSIVES

Batholiths and stocks, indicated as Laramide "granite and related crystalline intrusive rocks" on the County Geologic Maps* and the Map of Outcrops of Laramide Rocks in Arizona*, occur at numerous places within the Basin Ranges of Arizona. These intrusive rocks range chiefly from granitic to dioritic in composition. They were localized by deep-seated structural features. Thus, for example, the Stronghold granite (Pl. XX) in the Dragoon Mountains is roughly central to a culmination of thrust sheets and was emplaced by permissive rather than forceful injection, as demonstrated by Gilluly (94). Among other major intrusive bodies localized by thrust faults are the Uncle Sam porphyry (94) at Tombstone; diorite, granite, and syenite in the Pima district (149;150); and the Amole Peak stock in the Tucson Mountains (26). Many examples of localization by faults and folds are suggested by alignments of contacts.

MINOR INTRUSIVES

Dikes, sills, and plugs, mapped as Laramide, likewise are of widespread occurrence. These rocks range from acidic to basic in composition. The dikes were localized by zones of weakness, chiefly faults, the plugs by intersections of such zones, and the sills along bedding planes or slips.

VOLCANIC ROCKS

Eruptive rocks in several areas are designated as Tertiary-Cretaceous on the Geologic Maps* of Cochise and Pima Counties. Also, those volcanics in southwestern Maricopa and western Pima Counties, which are regarded diversely as Cretaceous or Tertiary (p.52), are indicated on the Map of Outcrops of Laramide Rocks in Arizona*. These rocks generally range from rhyolitic to andesitic in composition.

METAMORPHIC ROCKS

Metamorphosed sedimentary and igneous rocks in several areas, mainly of Pima County, are mapped as Laramide gneiss and schist.

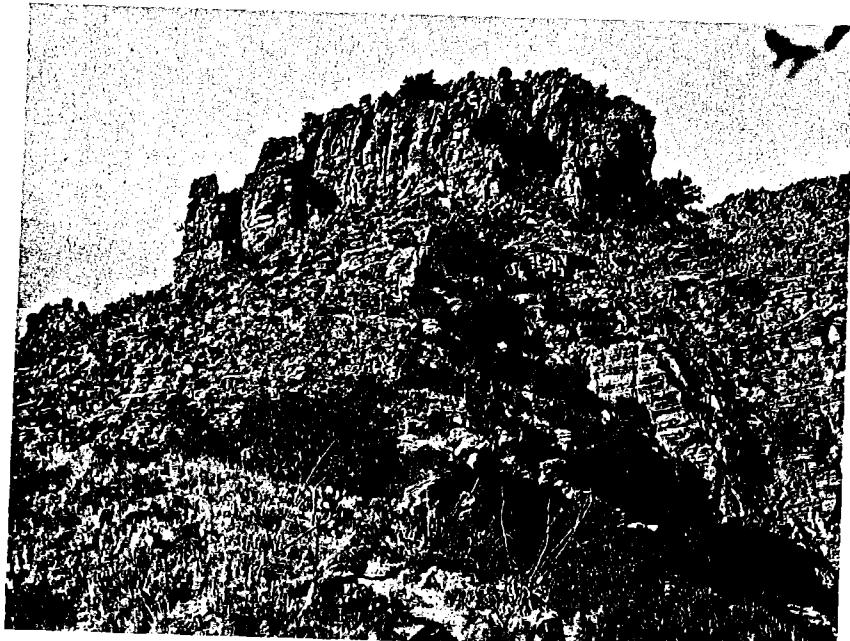
In general, the gneiss (Pl. XXII) is coarsely banded or laminated and of granitic texture, but locally it is schistose. In the Santa Catalina Mountains (195;22;207;67;68), it includes folded Precambrian, Paleozoic, and Cretaceous(?) rocks that were permeated partially, metamorphosed, and replaced locally by Laramide granite.

* Issued by the Arizona Bureau of Mines.



PHELPS DODGE CORPORATION

Plate XXI. New Cornelia open-pit mine, Ajo. View southward. Concentrator and smelter in foreground. L, Little Ajo Mountains; G, Growler Mountains.



WESTERN WAYS FEATURES

Plate XXII. Laramide Gneiss, Santa Catalina Mountains.

The unit designated on the County Geologic Maps* as Laramide schist comprises deformed sedimentary and igneous rocks of Mesozoic aspect. They have undergone mild to locally strong metamorphism, which presumably was effected by Laramide granitic intrusions.

SEDIMENTARY ROCKS

A series of tilted, faulted, commonly reddish-brown to gray conglomerate, sandstone, shale, and local thin limestone, together with some intercalated basalt and andesite, rests unconformably upon Precambrian, Paleozoic, Mesozoic, and intrusive Laramide rocks at numerous places in southern and western Arizona. This series is designated as the TKs unit on the County Geologic Maps*.

Features of these rocks in the Artillery Mountains (156) region (Mohave County), southern Yuma County (27;315), the Papago country (27), lower Gila region (244), and Salt River Valley (162) have been described in the literature. The series in the Artillery Mountains is at least 2,500 feet thick and was named the Artillery formation by Lasky and Webber; there it contains fossil palm roots of early Eocene(?) age (156). In all of its separate areas, the TKs unit (Pl. XXIV) has generally

* Issued by the Arizona Bureau of Mines.

similar features of texture and induration. Its composition suggests deposition in local desert basins that were undergoing somewhat continuous, slow depression relative to rising adjacent mountains (93). The possible magnitude of relative sinking for such basins is exemplified in the Ajo area by the thickness, at least 6,000 and possibly 12,000 feet, of the Locomotive fanglomerate (93). This formation, which interfingers with the Ajo volcanics and is not distinguished from them on the Geologic Map of Pima County*, seems to be of the TKs category.

It is reemphasized that age assignments, based other than upon fossil evidence or geochemical determinations, are not very satisfactory; hence, in some of the map localities, the TKs designation possibly includes beds as young as Miocene or as old as Triassic-Jurassic.

ECONOMIC FEATURES OF THE LARAMIDE

Mineralization, believed to be genetically associated with Laramide stocks of generally monzonitic composition, is of first-order importance in Arizona. It formed many ore bodies in Precambrian, Paleozoic, and Mesozoic host rocks, as mentioned on pages 19, 34, 47, 54, 58. These ore bodies mostly were localized or controlled by Laramide structural features, particularly northwesterly folds, E.-W. and N.-S. faults and fractures, and northeasterly fissures. Laramide diatremes or breccia pipes (9;73) also were important loci for mineralization, as exemplified by the Copper Creek (147;148), Silver King (327), and Orphan (20) ore deposits.

Also, the stocks themselves were host rocks for Laramide hypogene mineralization of the great porphyry copper deposits in the Morenci (34;165;166), San Manuel (258;329), Ajo (93; Pl. XXI), Miami (227; 229;213a), Ray (227;229), Esperanza (253) (Pima district), Silver Bell (240;242), Bagdad (9), and Lone Star (Safford) areas. The veins at Mammoth (Tiger) occur in quartz monzonite and rhyolite (53).

The TKs unit contains barite veins of Laramide or later age northeast of Mesa (280) and manganese deposits in western Arizona (80). Also, it constitutes the bed rock for gold placers in the Dome, Laguna, and Muggins areas of Yuma County (315;330).

Gneiss from the Santa Catalina Mountains is used for flagstone and other constructional purposes.

Cenozoic Era

GENERAL DISTRIBUTION OF ROCK UNITS

Cenozoic formations cover a large percentage of Arizona. The Tertiary and Quaternary sedimentary units are most widespread within

* Issued by the Arizona Bureau of Mines.

Symbols on Arizona Bureau of Mines County Geologic Maps		Age		Basin and Range Province and Transition Zone		Plateau Province	
Sedimentary	Igneous	Quaternary	Recent	Principal Units		Principal Units	
QT, QTB	QT, QTV, QTB			b, j (1; 2)	Verde fm. (20; 163)	v; rel. thin	v; rel. thin
QT, QTB				b, r, l (1; 2)	Hickey fm. (8; 163)	1,400	v - 750*
QT, QTB				r, i, d; a; b; i (294; 1; 2)	Sandstone cgl (156)	1,200	v - 660.
TK					Chopin Wash fm. (51)	v - 2,000	700-1,800
TK					White tail cgl (227; 229)	v - 1,500	
TK						v - 1,250	
TK						v - 2,800*	v - 1,000*
TK						?	?
TK						v - 6,000*	

Explanation:	
Volcanic rocks,	i - Minor-intrusive rocks
a - andesitic	v - variable
b - basaltic	Numbers in parenthesis refer to literature cited in Appendix.
l - latitic	
d - dacitic	
r - rhyolitic	

Fig. 12. Tentative correlation of Arizona Cenozoic units.

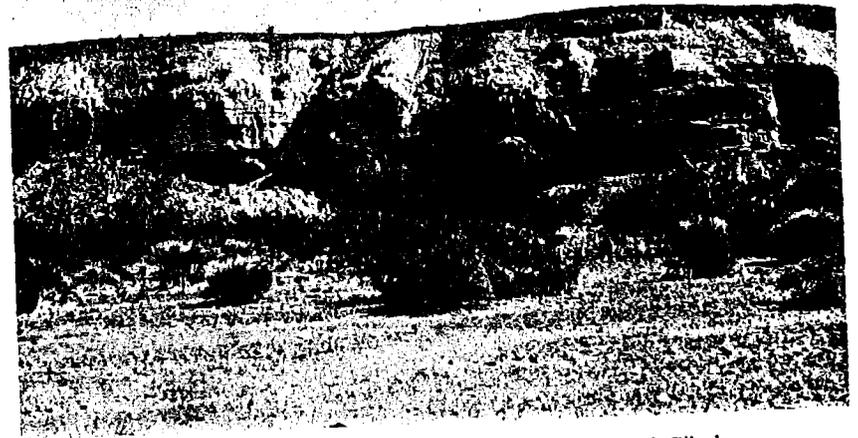


Plate XXIII-A. Marine Tertiary beds, southeast of Cibola.



Plate XXIII-B. Tertiary conglomerate in northeastern Maricopa County.

- the Basin and Range Province, as shown on the County Geologic Maps. These sediments represent continental deposits so far as known, except for Marine Tertiary beds (Pl. XXIII-A) in the Cibola area (314;315) of western Yuma County. The extensive distribution of volcanic and minor-intrusive rocks is featured on the Map of Outcrops of Tertiary and Quaternary Igneous Rocks in Arizona*.

* Issued by the Arizona Bureau of Mines.

The principal units, as distinguished on the County Geologic Maps*, are listed and correlated in Fig. 12. Their age assignments are based upon fossil data for only some of the localities; for other areas, the ages are deduced from indirect evidence with various degrees of certainty and may be subject to change.

DEVELOPMENT

CHARACTER OF RECORD

As summarized by Lance (153, p.155),

The Cenozoic era in Arizona was a time of complex geological activity. Structural movements, volcanic and igneous activity, erosion, and sedimentation all acted upon pre-existing geologic features to form the present plateaus, mountains, valleys, and drainage patterns. Because of the scarcity of known fossils in Cenozoic continental sediments, the sequence of events is known in only the most general way.

Structural details tend to be obscured by a general scarcity of persistent marker beds in the sediments and by areal discontinuity among members of the volcanic sequences.

STRUCTURAL EVENTS

Relation to sedimentation. Laramide folding and faulting in southern Arizona continued into Miocene time (153). Developments of tectonic basins or troughs, which did not necessarily coincide with present-day intermontane valleys, are indicated by TKs unit (p.70); by Eocene(?) sediments southeast of St. Johns (238); by deposits, not older than late Oligocene or younger than middle Miocene (153), near Redington (41) in northeastern Pima County and near Wellton (336;155) in southwestern Yuma County; and by other Miocene(?) units such as the Pantano formation of eastern Pima County (21), the Helmet fanglomerate in the Sierrita Mountains (50), the Whitetail conglomerate (227;229;213a) in Gila and Pinal Counties, and the Datil formation in southeastern Apache and northeastern Graham Counties (238).

Relation to Drainage (141;142;193). According to Lance (153),

Major drainageways in Arizona developed after the Laramide uplift of mountains in Utah and Colorado, and extended generally southwest across the State by middle Cenozoic time. This drainage produced erosion surfaces older than the Bidahochi formation on the Plateau, and perhaps some features now preserved in central and southern Arizona.

Regional uplift, accompanied by flexing and faulting, increased during or slightly before Miocene and was largely completed by the end of Miocene or in early Pliocene (153;297); among its effects were gentle northeasterly tilting of the Plateau and further arching of the Mountain Region (p.64). As interpreted by Lance (153),

* Issued by the Arizona Bureau of Mines.

This uplift served to disrupt the southwesterly drainage. Gorges were cut in the rising mountains before complete disruption occurred, and some of these gorges form a part of the present drainage system. Formation of the present Basin-and-Range topography in the southern part of the State was also essentially a Miocene event, and some of the disrupted drainage was diverted into newly formed basins. Pediments and other erosion surfaces were locally developed before the Pliocene basin fill accumulated.

Continuing structural movement, volcanic activity, and diversion of waters by overflow during the Pliocene resulted in complex changes of the drainage pattern. The reduction of stream gradients or blocking of the valleys allowed the deposition of hundreds to thousands of feet of sediments (121) during much of the Pliocene. The fine-grained character and stratigraphic relationships of these sediments suggests that much of the material was brought into the valleys by through-flowing rivers.

Sedimentation in some of the valleys continued until middle Pleistocene time. Coarse deposits in the form of alluvial fans and pediment gravels were shed from the mountains in middle and late Pleistocene (153).

Much of the earlier Cenozoic sediments (Pl. XXIII-B) is mantled by Quaternary gravel, sand, and silt.

IGNEOUS ACTIVITY

General statement. Igneous rocks assigned to Eocene, Miocene, Pliocene, Pleistocene, and Recent ages are represented in Arizona (Fig. 12). Those featured as Laramide have been discussed briefly on p.68.

Later Cenozoic igneous activity is expressed by volcanic (Pls. XXV, XXVII-XXIX) and minor-intrusive (Pl. XXVI) rocks of extensive distribution; by late Miocene or early Pliocene laccolithic intrusions (97; 311), mainly porphyries of intermediate composition, in the Carrizo Mountains, San Francisco volcanic field (243) and probably beneath Navajo Mountain (in Utah and northeastern Coconino County, Fig. 10); and by diatremes, which have been recognized in the Gila Valley near San Carlos (187), as well as in the Hopi Buttes (97;311;266) collapsed-structures. This activity seems to have been localized generally by Laramide and earlier tectonic influences. Thus, the volcanic cones, necks, plugs, and diatremes mark deep-seated structural intersections; and the dikes came up along fissures or other zones of weakness.

The Cenozoic igneous rocks of many Arizona areas have been described in the literature (1;2).

Eruptive Rocks. The eruptive rocks issued partly from central vents at many places, and to an unknown extent from dikes. Distinctions among various Cenozoic eruptives — rhyolite, dacite (Pl. XXV), latite, andesite, and basalt — are indicated on the County Geologic Maps* where feasible.

Large central-type volcanoes, marked by currently extinct cones (Pl. XXIX), craters, necks, or plugs, are best exemplified in the San

* Issued by the Arizona Bureau of Mines.

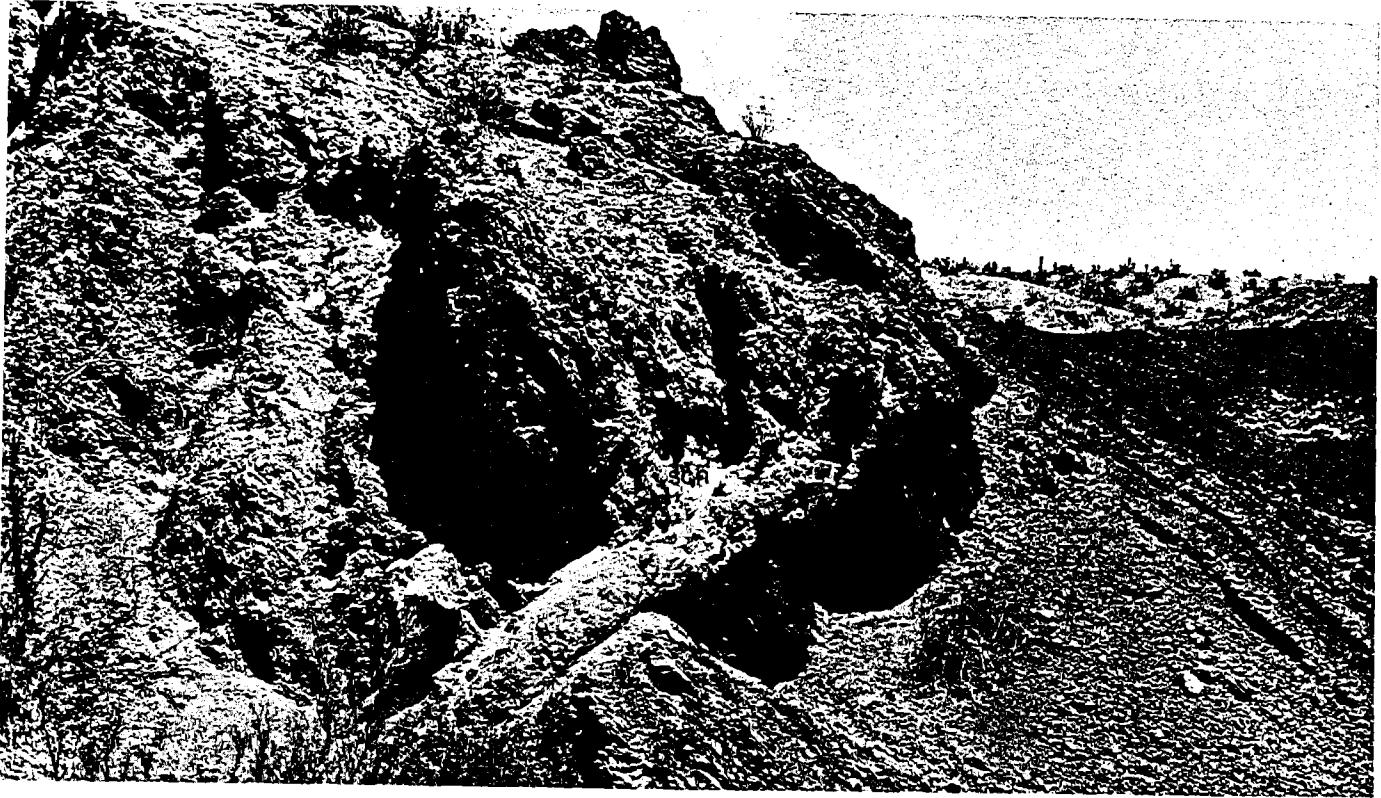
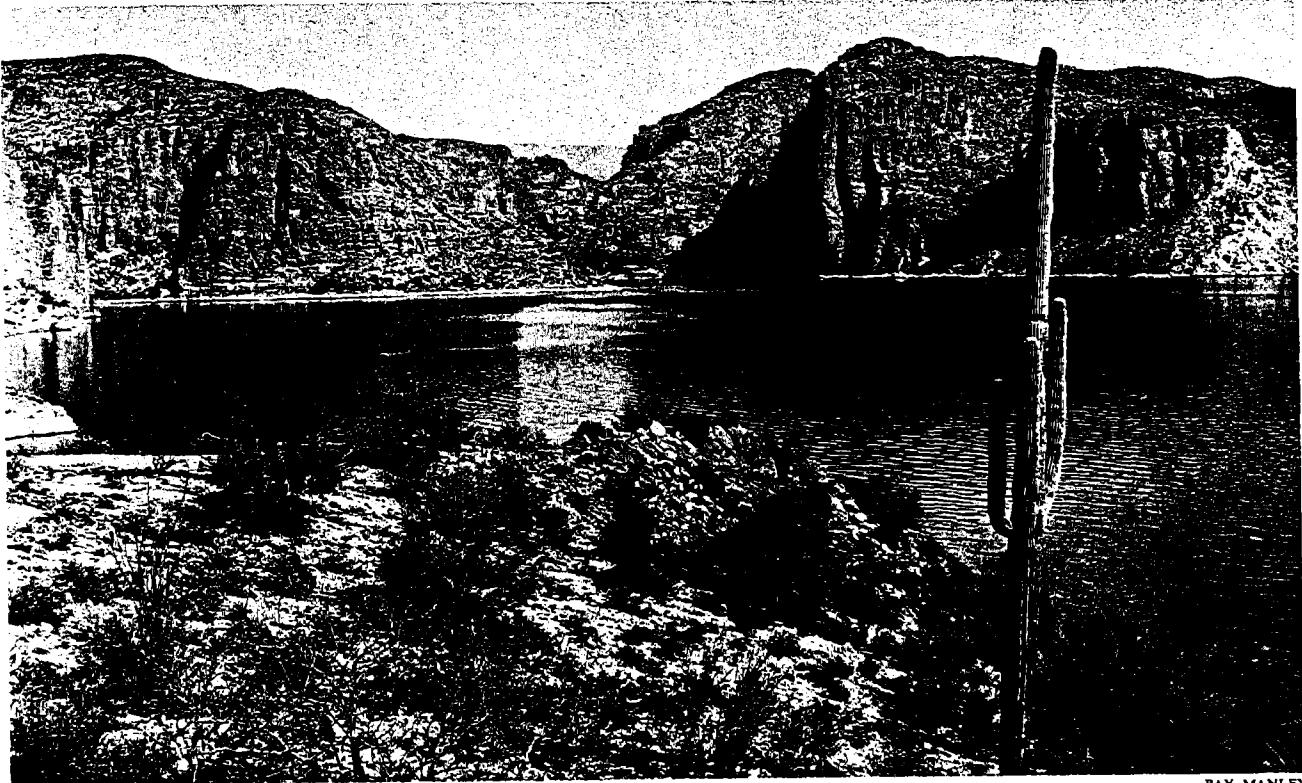


Plate XXIV. Thrust fault in northeastern Yuma County. TKs, Tertiary-Cretaceous beds in footwall; sch, Precambrian schist in hanging wall.



RAY MANLEY

Plate XXV. Dacite bluffs along Canyon Lake, Salt River.

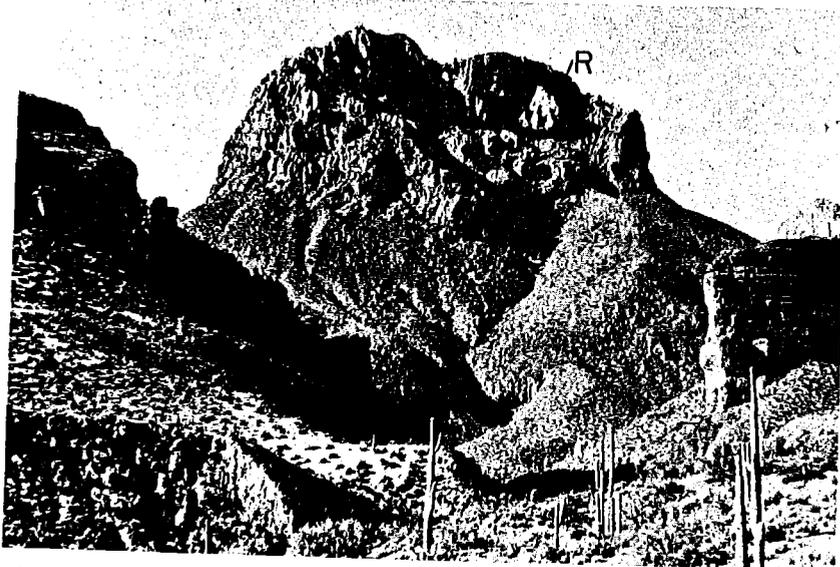


Plate XXVI. Hell's Peak, southwest of Ray. View southwest, down Walnut Canyon. R, Tertiary rhyolite plug, more than 1,000 feet in diameter; T, Tertiary rhyolitic tuff.

San Francisco volcanic field, which lies upon a broad structural dome in southern Coconino County. The San Francisco Mountain volcano (Pl. XXVII), at the close of its activity, rose to 8,800 feet above the surrounding Plateau surface; this volcano, together with Kendrick, O'Leary, Sitgreaves, Bill Williams, Mormon Mountain, and several small cones, erupted some 86 cubic miles of basalt, andesite, latite, dacite, and rhyolite, as flows and pyroclastics, presumably during the Pliocene and early Pleistocene (243). Also, about 200 basalt cones ejected some 20 cubic miles of flows, cinders, and tuff during middle Pleistocene and Recent time (243); for one of these cones, Sunset Crater, the date of eruption was 1064 or 1065 A.D. (272).

Central eruptions, mainly basaltic, produced extensive flows and pyroclastic material in east-central Arizona. More than 200 Recent cinder cones occur on the basalt plain along the northern margin of the White Mountains. In the mountains south of this plain, Tertiary and Quaternary volcanics form a sequence 4,000 or more feet thick.

Other noteworthy central eruptions for northern Arizona took place in the Mt. Floyd, Uinkaret Plateau (143), Shivwits Plateau (197), Mohon Mountains, and Hopi Buttes (97;311) areas. Volcanics, associated with the Hopi Buttes, occur intercalated with Pliocene Bidahochi beds (97;237).

Late Cenozoic eruptions poured over the Plateau escarpment south of the White Mountains; between Fossil and Beaver creeks, Yavapai

County; south of Ash Fork; and south of Seligman. They also flowed into the Grand Canyon at Toroweap Valley (185), as well as into the present canyons of White and Black rivers.

Within the Basin and Range Province (294), central eruptions of late Cenozoic age occur prominently, as for example at Batamote and Childs mountains (93) near Ajo, and in the Sentinel, Pinacate (315;89; 119), Crater Mountains, Table Top, Cabeza Prieta, Parker, Kingman, and San Bernardino Valley areas.

Minor-intrusive bodies. Cenozoic volcanic plugs or necks, dikes, and sills, exposed by erosion at numerous places, constitute locally spectacular features. Notable examples for northeastern Arizona (96;97;311) include Agathla, Church Rock, Chiastla, Tyende dikes, Wildcat Peak, Black Rock, and the Hopi Buttes, prevailing of basic composition. Within the Basin and Range Province, minor-intrusive bodies of rhyolitic (Pl. XXVI) to basaltic composition are well displayed, especially in T.3-4 S., R.11-12 E.; at Picacho, T.9 S., R.9 E.; in the Triplets and Gila Mountains areas of Graham County; and in the Peloncillo, Galiuro, Picket Post, Weavers Needle (Superstition Mountains), and Wickenburg Mountains areas.

SOME CENOZOIC TECTONIC FEATURES

Introduction. Deformation in Arizona during the early Cenozoic is regarded as Laramide (p.58). The later disturbances, which include faulting throughout the State, and folding restricted mainly to the Basin and Range Province, seem generally to blend with the Laramide, as discussed on previous pages.

As a comprehensive summary of present information regarding the Cenozoic tectonics would be voluminous, only some samples or generalizations of them are given in this résumé.

Examples of compressional effects. In southwestern Mohave County (156), folding together with thrust faulting affected beds as young as Eocene(?) and possibly continued through Pliocene time.

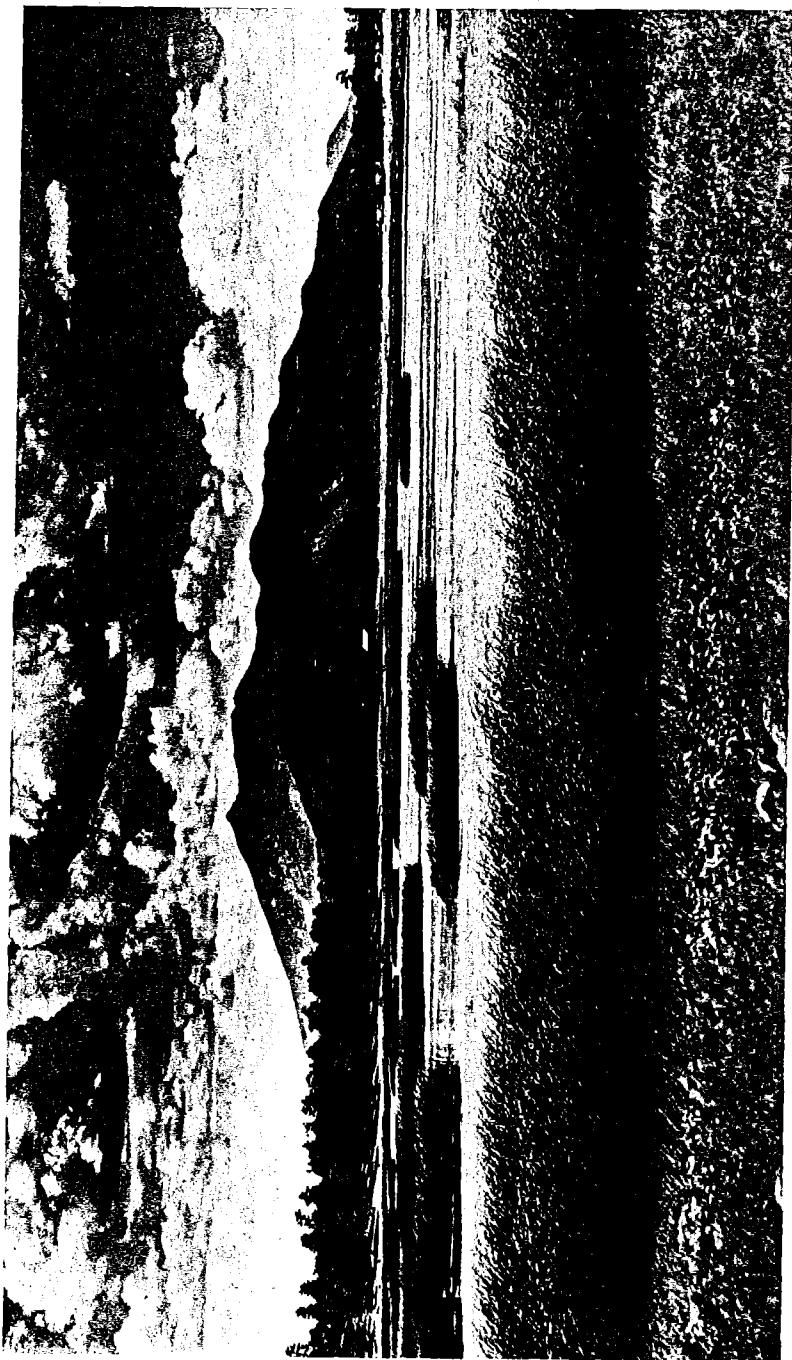
East of Yuma (332), Pliocene(?) and older formations are cut by faults showing reverse and lateral displacements.

In the Ray area (227;229), Gila conglomerate and Miocene dacite form a shallow syncline. Southwest of Ray (328), the dacite has been sharply and deeply folded in the Spine syncline.

South of Kelvin, Gila conglomerate was thrust over older rocks, and in turn overridden by Paleozoic beds (17;259).

The San Manuel thrust fault cuts folded Gila conglomerate (329).

Along the southwestern base of the Santa Catalina Mountains, Miocene(?) Pantano beds occur thrust over older rocks (195).



ESTHER HENDERSON

Plate XXVII. San Francisco Mountains, north of Flagstaff.



Plate XXVIII. Quaternary volcanic rocks along Burro Creek, Mohave County. View upstream. B, basalt; t, tuff.

Table 7. Some Cenozoic and Laramide faults.

FAULT	DESIGNATION ON FIG. 10	MAX. CENOZOIC AND LARAMIDE DISPLACEMENT, FT.	REFERENCE
Mesa Butte	MB	250+	12
Butte	Bt	2,200	302;303;12
Bright Angel	BA	175	12
Muav Canyon	MC	350	285
Big Spring	BS	1,000	285
Sevier	S	1,400	143
Toroweap	Tw	632	185
Hurricane (Pl. XIX)	H	1,500	69
Parashont	P	1,100	197
Main Street	MS	200	197
Grand Wash	GW	16,000	168
Tassai	Ts	5,000	168
Virgin	V	7,000	197
Verde	Vd	1,500	8
Diamond Rim	R	750±	
Canyon Creek	CC	600±	
Stray Horse	SH	500+	
Blue	B	1,500±	
Miami	M	1,500+	213;213a
Concentrator	C	2,000+	275;327
Little Ajo Mtn.	A	10,000±	93

Basin Ranges. In Arizona the Basin Ranges for the most part represent fault blocks (227;213a;93;332) of complex internal structure which were elevated in reference to adjacent, relatively depressed basins, plains, or valleys. Many of them seem to be bounded on one or more sides by faults that may occur either within continuous zones or partly en echelon. These boundary faults mostly are concealed by late alluvium or lava flows. The displacements effected by such faulting, which range from relatively small amounts to several thousands of feet, are regarded as dominantly of normal type, but they also include reverse, thrust, and lateral movements in several localities.

Many of the fault blocks exhibit prominent tilting. Various theories regarding this phenomenon have been advanced (300;93;194). The writer believes that the tilted fault blocks represent faulted limbs of folds (322). Reflecting the inherently complex regional structure, the Basin Ranges trend in diverse directions, as shown on the County Geologic Maps.*

The Basin and Range orogeny extended mainly from early or middle Miocene (p.74) into Pliocene (153), and continued less markedly into Pleistocene, time.

CENOZOIC LIFE

Life in Arizona during Tertiary and Quaternary time is known from fossil localities. As stated by Lance (154),

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Plants, fish, birds, fresh-water mollusks, and mammals indicate that the climate was generally similar to that of today, but somewhat more humid. The abundance of fossils in some localities shows that herds of several types of extinct camels, horses, rhinoceroses, and antelopes roamed the State at times, and were preyed upon by a variety of ancestral carnivores. In the late Pleistocene, more than ten thousand years ago, early man came to Arizona, where he found and hunted animals such as mammoths, ground sloths, tapirs, camels, bison, and horses.



TAD NICHOLS

Plate XXIX. S. P. volcanic crater and basalt flows, San Francisco volcanic field.

ECONOMIC FEATURES OF THE LATER CENOZOIC

SCOPE OF DISCUSSION

The following brief summary necessarily is limited to mineral commodities. Although ground water and soils within the later Cenozoic formations obviously are of first-order importance, they constitute special fields in geology beyond the scope of this résumé.

INFLUENCE ON PRE-EXISTING DEPOSITS

Later Cenozoic events were important from the standpoint of pre-existing ore deposits.

Post-Laramide erosion served to expose ore bodies, but later sedimentation, volcanism, and faulting concealed an unknown number of the exposures, especially on pediments (Pl. XVII), as exemplified by major discoveries in the San Manuel (258) and Pima (292;293;87) mining areas.

A noteworthy record of the later Cenozoic effects is offered by the Miocene(?) Whitetail (Pl. XXX) conglomerate (227;213a), which accumulated within local basins in northeastern Pinal County and southwestern Gila County. It marks an erosion cycle that persisted sufficiently long to remove an estimated thickness of one-half mile or more of rock which once covered the Laramide porphyry masses now exposed in the region, and also to permit extensive oxidation and enrichment of the

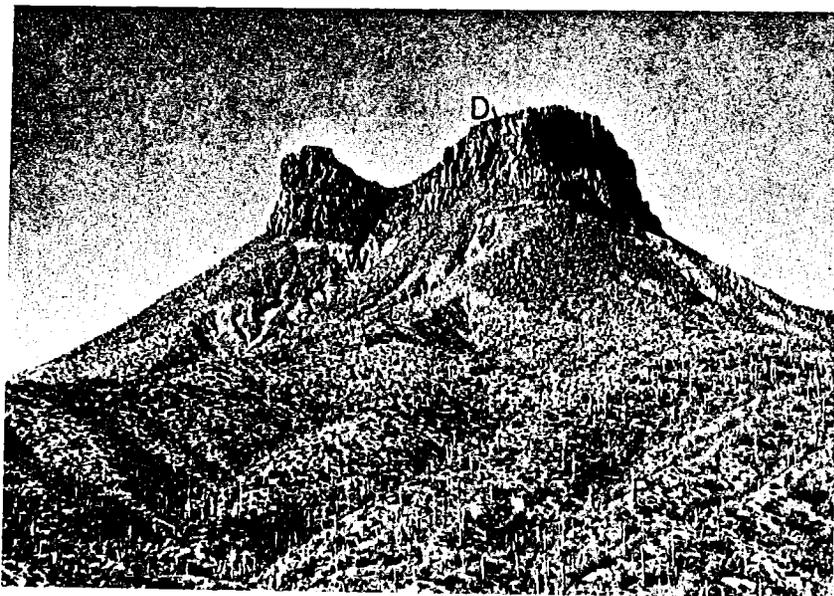


Plate XXX. Teapot Mountain, northwest of Ray. D, dacite; W, Whitetail conglomerate; P, Precambrian Pinal schist.

copper deposits in the Ray, Superior, Miami, and Globe areas. After Whitetail sedimentation, the region was subjected to folding and faulting which preceded and followed eruptions of the overlying Miocene dacite (328).

The depths of oxidation and supergene enrichment were modified by later Cenozoic structural movements. A tabulation of some 44 Arizona mines or districts indicates that the lower level of Post-Laramide general oxidation coincides with present water levels in only 20 per cent of the cases; it is considerably either above or below in 80 per cent of them.

LATER CENOZOIC METALLIFEROUS DEPOSITS

Manganese. Sedimentary deposits of manganese in the Pliocene(?) Chapin Wash formation, Artillery Peak area, constitute huge low-grade reserves that were productive during recent years (156;80;39). Notable occurrences in probable Pliocene beds east of Eherenberg (80) also have been worked. Manganiferous veins and brecciated zones in Tertiary volcanics are of commercial importance in several districts (80;81).

Placers. Gold placers (330) were formed during later Cenozoic time in many Arizona districts, outside of the Plateau Province. Most of these placers occur on, or associated with, Cenozoic pediments.

Oxidized copper minerals of placer origin are mined from the Whitetail conglomerate of the Copper Butte area (320), southwest of Ray.

The Emerald Isle oxidized copper deposits (290;291;260), northwest of Kingman, possibly represent placer material that has undergone extensive solution and redeposition.

Float and placer material have yielded silver ore in the Globe-Richmond Basin area, and tungsten ore (319) in the Camp Wood (Eureka district) and Little Dragoon areas.

Some alluvial deposits in southern and western Arizona, especially within southern Pinal County, have attracted attention as possible resources of iron oxides and various other heavy minerals.

NONMETALLICS (333)

Sand and Gravel. Of major commercial importance are the sand and gravel deposits that accumulated during later Cenozoic time throughout the State (39;129).

Clay materials. Bleaching clay in the Bidahochi formation is mined on a large scale near Sanders, Apache County (135;136). Bentonitic clay occurs in several localities (333;334) and clay, used for brick and other structural purposes, is abundant among the Cenozoic sedimentary beds (333).

Volcanic cinders and pumice. Notable cinder deposits occur in south-central Coconino County, southern Apache and Navajo Counties, south-eastern Cochise County, and portions of Yavapai County. Pumice or pumicite has been mined from near Flagstaff and Williams and northeast of Safford (333).

Stone. Cenozoic volcanic rocks are a source of crushed stone and building stone (333;98;134).

Cement materials. Shaly material and limestone from the Verde formation are used for making cement at Clarkdale.

Miscellaneous. Other nonmetallic mineral resources (333) in Arizona Cenozoic formations include gypsum, perlite (40), sodium sulfate (120), salt, diatomaceous earth, strontium sulfate, and alunite.

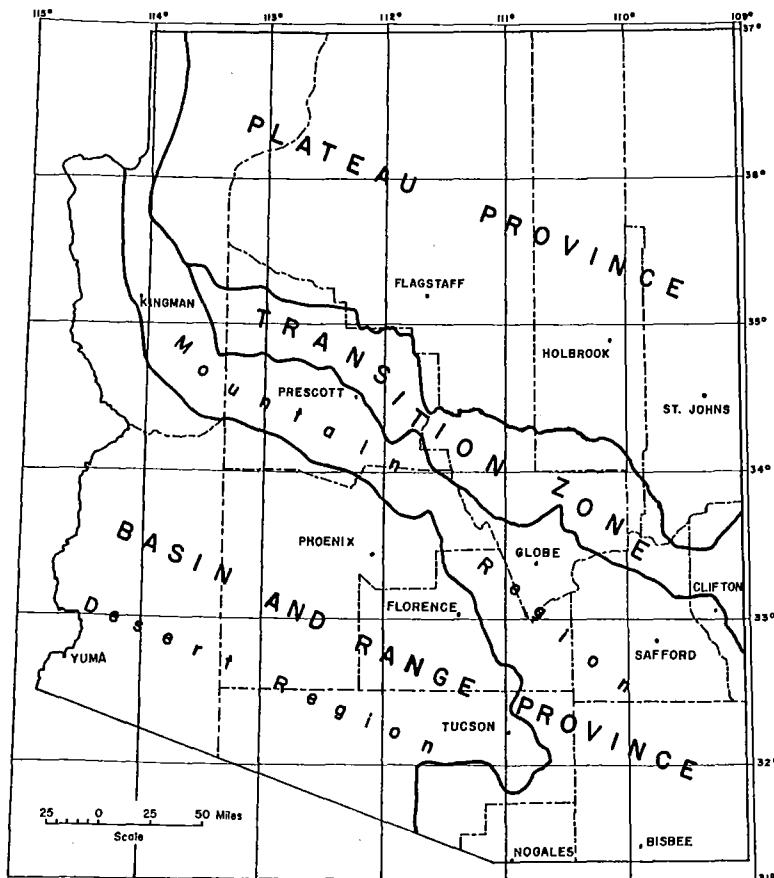


Fig. 13. Physiographic provinces in Arizona.

CHAPTER III: PHYSIOGRAPHY

General Features

AREA AND RIVER SYSTEM

Arizona includes an area of 113,956 square miles, with maximum dimensions of 392 miles from north to south by 338 miles from east to west.

Approximately 90 per cent of this area is drained by the Colorado River system, whose principal Arizona tributaries are the Little Colorado and Virgin rivers in the north, and the Bill Williams and Gila rivers in the central and south portions. The segment of the main Colorado River within and bordering Arizona amounts to 715 miles in length. It is a large, perennial stream, but other rivers in the State mostly are intermittent though at times subject to great floods.

PROVINCES REPRESENTED

As implied by its spread of altitude from 100 feet at Yuma to 12,611 feet above sea level on San Francisco Mountain, north of Flagstaff, Arizona exhibits spectacular physiographic contrasts. Its area lies within two of the major physiographic provinces of the southwestern United States. As shown on Fig. 13, approximately the northeastern half of the State is in the Colorado Plateau; this province extends as a large area into Utah, Colorado and New Mexico. On the southwest, south of Latitude $35^{\circ} 30'$, the Plateau is separated by a transitional zone from the Basin and Range Province, which in turn extends from the Columbia Plateaus of Oregon and Idaho southward into Mexico and eastward to the Great Plains in New Mexico and Texas.

Broadly considered, the physiographic provinces in Arizona are consequences of structure. In the Plateau Province, the Paleozoic and later beds have undergone only moderate deformation; in the Transition Zone, they are more faulted than in the Plateau; and in the Basin and Range Province, the rocks have been more intensely deformed and occur as numerous relatively elevated and depressed blocks.

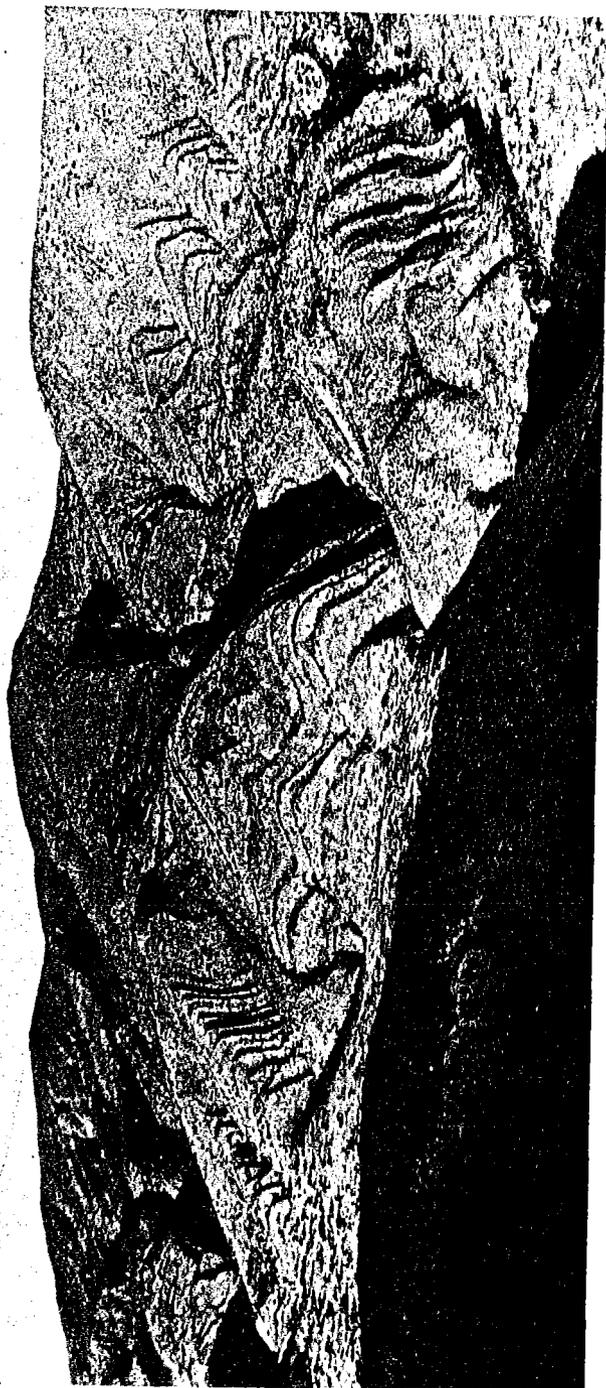


Plate XXXI. Slopes on steeply dipping Paleozoic limestone, Mescal Mountains.

N. H. DARTON

As stated or implied on previous pages, the physiographic provinces and major drainageways in Arizona appear to have been established during Miocene to early Pliocene time, and were accentuated or otherwise modified by later events of deformation, volcanism, erosion, and sedimentation. Longwell (169) showed that the course of the Colorado River west and south of the Plateau may date from late Miocene or early Pliocene; he suggested that an early drainage in the Plateau area may have been diverted to the present course of the river, partly by volcanism and partly by crustal disturbances (115).

PHYSIOGRAPHIC PROCESSES

CONDITIONING FACTORS

Although influenced primarily by structural features (Pls. XXXI, XXXIII), erosion and sedimentation are markedly conditioned by the interrelated factors of climate and vegetative cover (27).

Fahrenheit temperatures (261) range from 120° or more in summer for southwestern Arizona to 50° or more below zero in winter for the highest mountains of the State. Daily summer temperature variations may amount to 55° or more in the southwestern portions.

Annual precipitation varies from less than 5 inches in the western portion to more than 30 inches at high elevations; roughly half of the State receives less than 10 inches per year (261).

Subject to local conditions of precipitation, forests tend to grow at altitudes of 6,500-12,000; pinon-juniper trees at 5,000-7,000; and chaparral thickets at 4,000-5,500 feet (262). Depending upon soil conditions, grasses may thrive below altitudes of 6,500, and desert shrubs below 5,000 feet (262). Steep slopes, especially below altitudes of 4,000 feet, carry little soil and commonly lack vegetative cover.

MECHANICAL EROSION

Owing to aridity, weathering and erosive processes in Arizona are dominantly mechanical rather than chemical (27). Diurnal fluctuations of temperature appear to be highly effective in surface disintegration of rocks, particularly where vegetative cover is thin or lacking. Headward down-cutting and lateral planation by streams are the principal erosive processes; wind action, although effective in deflation, transportation, and deposition of dust or sand, is believed to cause only minor amounts of sculpturing on hard rocks.

Rock character generally is reflected by erosion. The homogeneous, coarse textures, such as of granite, commonly result in rounded forms; relatively hard, unfractured units stand out prominently; and limestone or other carbonate units in an arid climate resist erosion because fractures in them tend to heal.

Basin and Range Province

RANGES

The Basin and Range Province (Fig. 13) is characterized by numerous mountain ranges which rise abruptly from broad plain-like valleys or basins (231). These mountain masses attain altitudes of a few hundred feet to more than 10,000 feet above sea level and measure from a few miles to 100 miles in length by less than a mile to more than 20 miles in breadth. Owing to the influence of aridity on erosive processes (p.89), their topography becomes progressively more sharp and rugged southwest and westward.

Only within particular areas are the ranges approximately parallel to one another. Northeast of a line drawn from Topock to Phoenix, they reflect somewhat the trends of the neighboring Plateau margin; southwest of this line, and also throughout southeastern Arizona, they show pronounced contrasts of alignment among various areas.



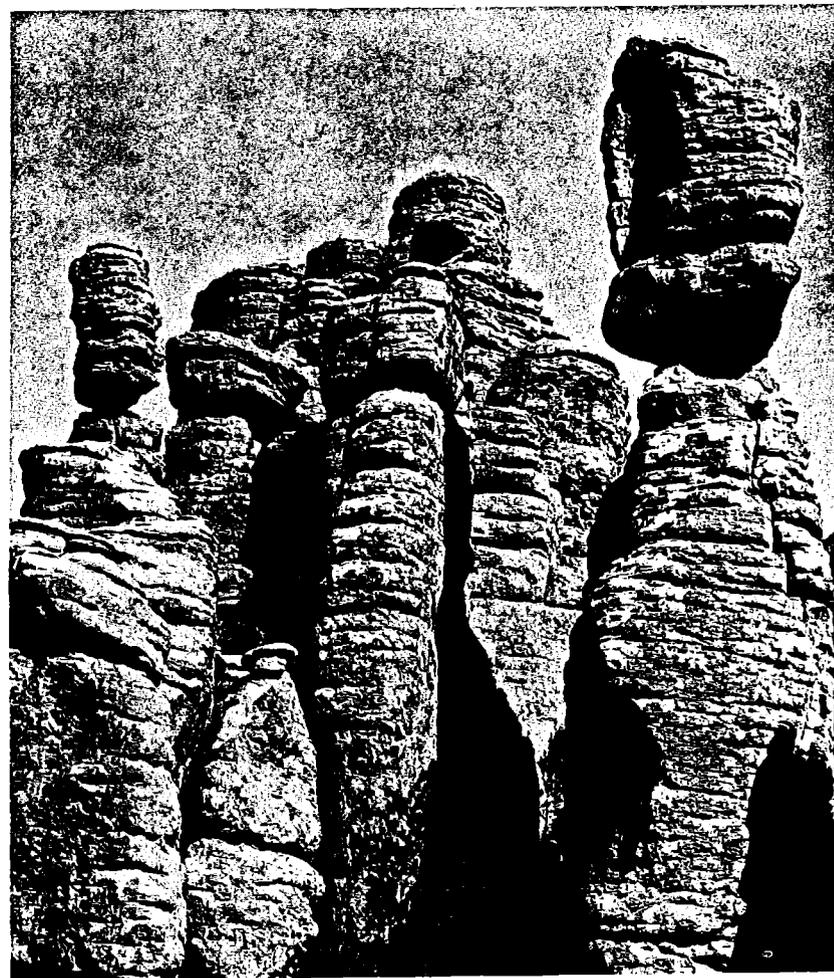
Plate XXXII. Recent arroyo-cutting on plain southwest of Palomas Mountains.

PEDIMENTS

The semi-planar, sloping, locally hilly, rock-cut surfaces that occur along the margins of many of the ranges are termed pediments (Pl. XVII). They are believed to have resulted largely from lateral planation by streams and partly from sheet-flood erosion (29).

BASINS

The intermont valleys (27;121) or plains in many sections are wider than the mountains, and some are more than 30 miles across (Pl. XXXV).



WESTERN WAYS FEATURES

Plate XXXIII. Erosional features in Chiricahua National Monument. Rock is rhyolitic welded tuff, upon which erosion has been influenced by joints and bedding-plane surfaces.

The valley floors rise from approximately 100 feet near Yuma to 5,000 feet above sea level in the Sulphur Spring Valley of southeastern Arizona; many of them show maxima of 1,200 to 2,000 feet of relief between axis and margin. Their general plain-like surfaces were formed through combined deposition and erosion by sheet floods, meandering streams, and wind action.

Most of the intermont valleys are dissected by drainage systems tributary to the Colorado River, and only a few closed basins, bolsons,



WESTERN WAYS FEATURES

Plate XXXIV. Santa Rita Mountains, in the Mountain Region of the Basin and Range Province. View eastward across Santa Cruz Valley.

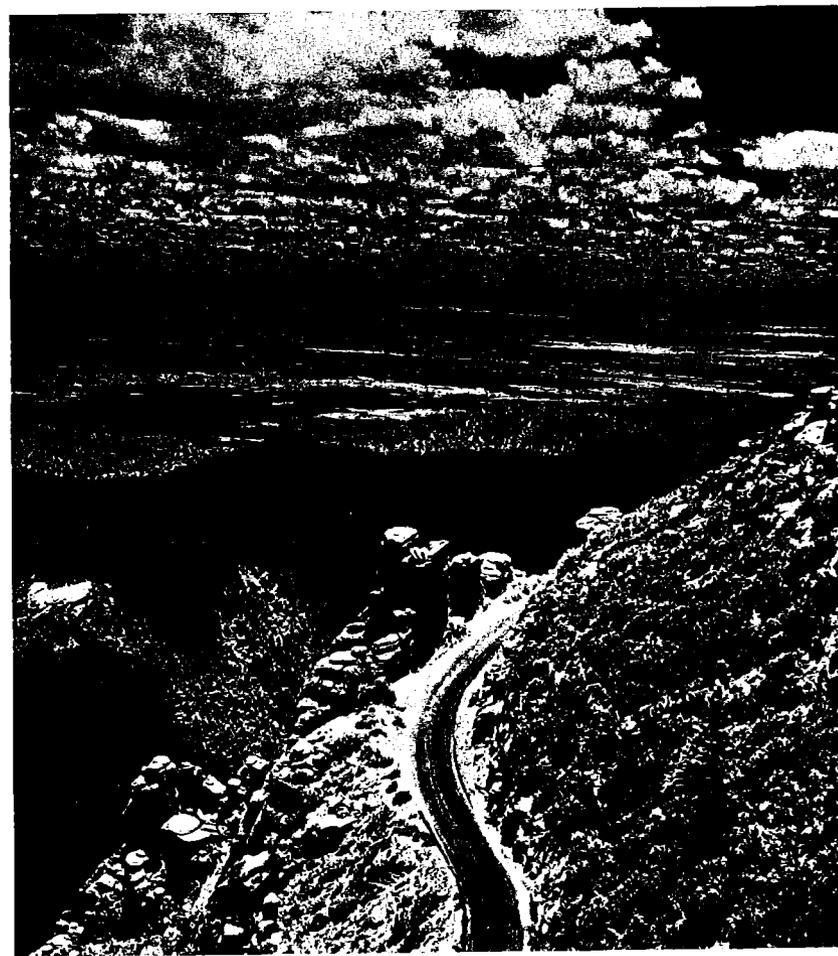
or playas ("dry lakes") remain. Terraces occur at one or more levels along the major streams, as discussed by Bryan (27), Smith (273), and Gilluly (94).

Recent channel trenching (Pl. XXXII) or arroyo-cutting (28;309) in southern Arizona valleys has been attributed to removal of vegetation, the climatic cycle, and killing of the beavers.

REGIONAL SUBDIVISIONS

MOUNTAIN REGION

The widest and highest of the mountain ranges occur within an irregular, northwestward-trending belt adjacent to the Transition Zone



WESTERN WAYS FEATURES

Plate XXXV. Plain of Santa Cruz Valley, viewed southwestward from Santa Catalina Mountains. Rock in foreground is Catalina gneiss.

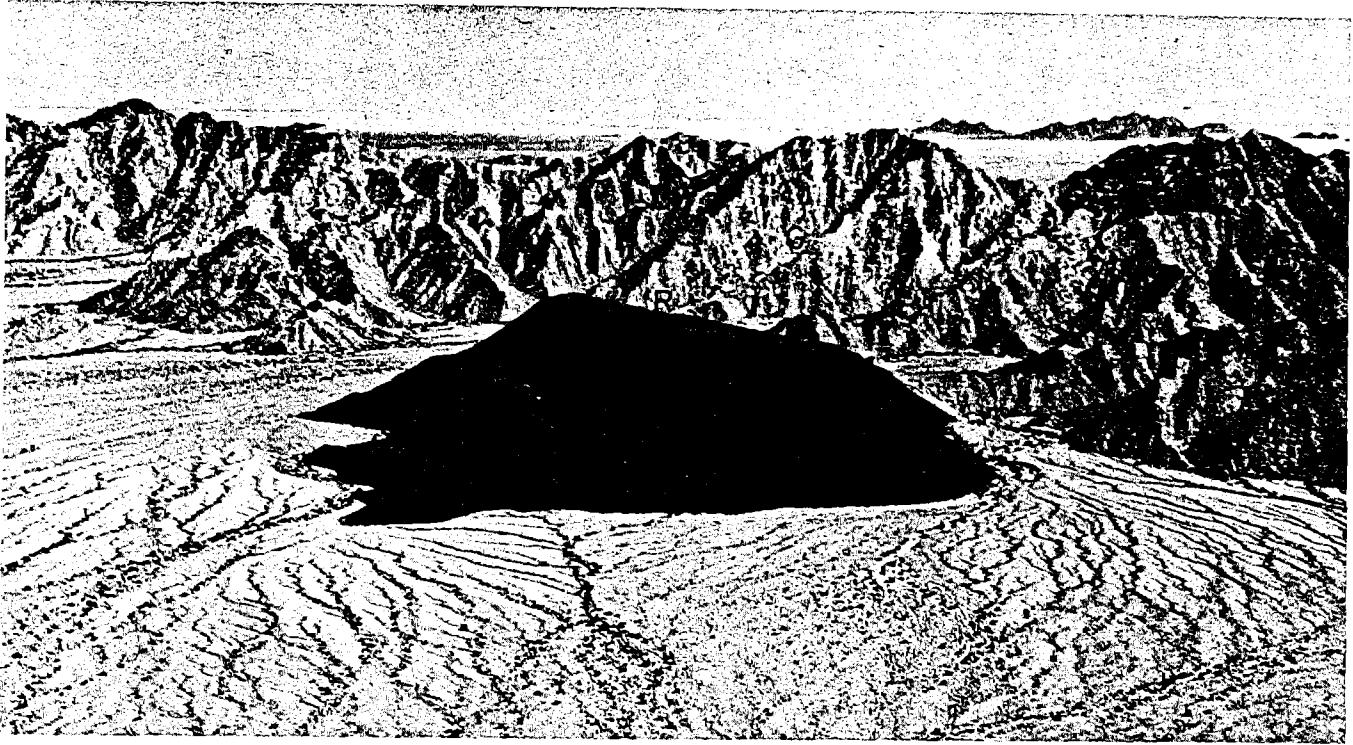
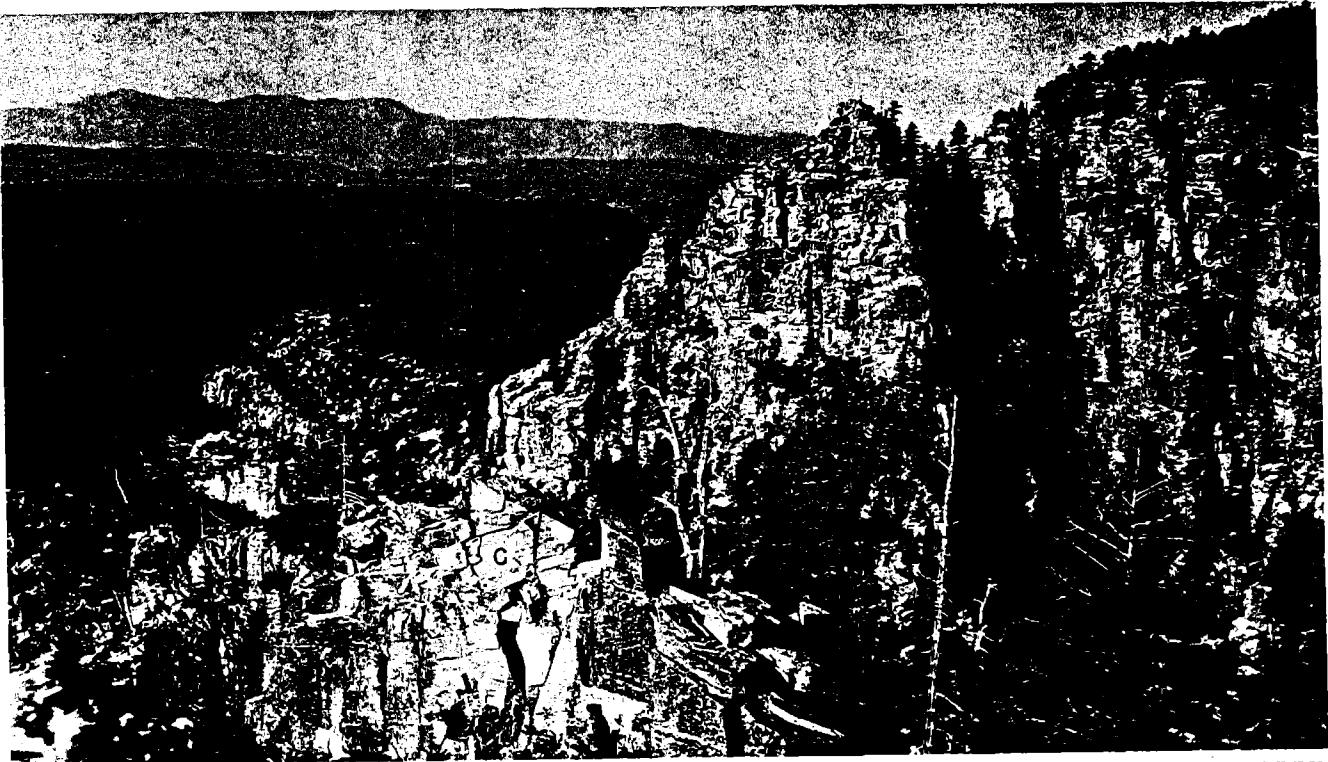


Plate XXXVI. Desert-Region physiography, Tinajas Altas Mountains. View southwestward. Butler Mountains and Yuma Desert in distant background. R, Raven Butte, of Quaternary basalt; G, Mesozoic granite.



WESTERN WAYS FEATURES

Plate XXXVII. Mogollon Rim (foreground) and Transition Zone, east of Payson. View southwestward, with Mazatzal Mountains in distance. C, Coconino sandstone. PC, Precambrian rocks.

and plateau (Fig. 13); Ransome (229) termed it the Mountain Region. Its highest Peak, Mt. Graham, is 10,713 feet above sea level or about 7,800 feet above Safford, in the adjacent Gila Valley. Mt. Lemmon in the Santa Catalina, Mt. Wrightson in the Santa Rita (Pl. XXXIV), and Miller Peak in the Huachuca mountains, rise to more than 9,000 feet, but most other peaks of the Mountain Region do not exceed 8,000 feet in altitude.

DESERT REGION

The portion of the Basin and Range Province southwest of the Mountain Region lies within the Sonoran Desert (229) and is known as the Desert Region (Fig. 13). Here, general altitudes are lower, mountains are more sharply carved (Pl. XXXVI), and valleys or plains are more extensive areally than in the Mountain Region.

Transition Zone (332)

The Transition Zone (Fig. 13) has a somewhat arbitrary width of 50 miles in its southeastern segment but narrows in northwestern Arizona, near Latitude 35° 30'. Topographically, it is more rugged than the Plateau, outside of the Grand Canyon. In general the Transition Zone is lower in altitude than the Plateau, although some of its mountains rise as high as the Plateau rim (Pl. XXXVII).

Faulting and erosion since middle Tertiary time have affected this zone in many places and separated it physiographically from the Plateau, which it structurally resembles in that its strata lie essentially flat except for local flexing. Headward erosion by tributaries of the Gila, Salt, and Bill Williams rivers has carved it into deep canyons or valleys and steep-sided mountains. In accord with their lithology and structure, these mountains generally are flat-topped or mesa-like in the areas of sedimentary and volcanic rocks which prevail over most of this region; sharp and rugged in metamorphic terranes; and rugged to rounded in crystalline rocks. Three great valleys in the Transition Zone, the Chino, Verde, and Tonto, were formed as the results of relative downfaulting plus erosion.

Plateau Province

GENERAL FEATURES

In Arizona, the Plateau Province comprises several individually named plateaus together with valleys, buttes, and cliffy mesas; its general surface is surmounted in several localities by high volcanic mountains and deeply incised by canyons of the Colorado River system (43;44). Except for canyons and valleys, the region as a whole lies above 5,000, much of it exceeds 6,000, and some areas attain more than 9,000 feet

in altitude. The southwestern margin or "Rim" of the Plateau is marked by ruggedly indented cliffs from a few hundred to more than 1,500 feet high (Pl. XXXVII). In places, as north of Clifton and southeast of Camp Verde, the cliffs are concealed by younger lava flows.

The following description of Plateau physiography has been abstracted, with slight modifications, from Lance (154):

The Plateau Province is a land of spectacular landscape that almost everywhere reveals the geologic framework and history with graphic clarity. The Grand Canyon (60;61;189), one of the great scenic wonders of the world, is essentially a textbook of geology in itself. Here a mile-deep slice, carved by the Colorado River into the Plateau rocks, exposes a complex history of geologic events spanning the several eras of geologic time (Pls. I, VI, VII, XII).

The sedimentary beds are nearly horizontal over large areas, but have been locally flexed by broad warps and sharp monoclinical folds and broken by faults. A gentle northward tilt carries the Arizona section beneath younger rocks of the high plateaus of the northern extension of the province in Utah. Erosion during most of the Cenozoic has etched out the major structural features in a remarkable way. Many of the sedimentary rocks are persistent units across the Plateau, but some are lenticular on a broad scale, or show marked lithologic changes laterally, indicating the effects of local basins and swells in the sedimentational history.

A convenient subdivision of the Plateau, for purposes of this discussion, includes the Grand Canyon Region, the Mogollon Slope, and the Navajo Country. The Grand Canyon area includes the individual plateaus north and south of the Canyon itself and the Marble Platform on the east. The Mogollon Slope is the up-tilted southern portion of the Plateau, northward from the Mogollon Rim to the Little Colorado River Valley. The Navajo Country comprises the mesas, plateaus, buttes, and valleys of the northeast portion of the State and coincides approximately with the Navajo and Hopi Indian Reservations.

GRAND CANYON REGION

The Grand Canyon Region consists largely of a series of terrace-like plateaus, elongated north and south, separated from each other by faults and monoclines. The highest of these is the Kaibab Plateau (Pl. VI), which is a structurally uplifted area (p.59), with both the topography and geologic section stepped down to east and west. To the west the successively lower steps, north of the Colorado River, are the Kanab, Uinkaret, and Shivwits plateaus. The Shivwits is bounded on the west by the Grand Wash Cliffs, a great structural break that overlooks the Basin and Range Province. Most of the land south of the Colorado River is included in the Coconino Plateau, with the San Francisco volcanic uplift on the east and a series of down-dropped benches on the west. The surfaces of the Kaibab and the Coconino plateaus descend to the east along the East Kaibab monocline to the Marble Platform (Fig. 10).

The Colorado River flows westward across the area, locally turning to follow boundaries between the major and minor structural blocks. Tributary canyons are dissecting the plateaus both north and south of the river. North of the river are impressive escarpments, as along the Vermillion Cliffs (Pl. XII).

Cenozoic volcanic fields cover large areas of the Plateau on both sides of the river. Locally the great sheets of basalt are surmounted by cinder cones and stratovolcanoes. San Francisco Mountain (Pl. XXVII) near Flag-

staff includes the highest point in the State, and its lofty peaks held glaciers at least twice during the Pleistocene (264).

Some volcanic flows pass unbroken across the major faults, showing that no renewed movement has occurred since the eruptions, but some flows have been broken by late Cenozoic faults (44).

MOGOLLON SLOPE

In the Mogollon Slope, the strata dip gently north and northeast toward the Black Mesa basin.

The White Mountains volcanic pile covers the edge of the Plateau on the southeast, and late Cenozoic flows extend in tongues northward toward the Little Colorado River valley.

A spectacular feature of the area is Meteor Crater. This mile-wide, bowl-shaped depression is believed to have been formed either by the impact of a prehistoric meteorite or by a vapor explosion of volcanic source (61;267).

NAVAJO COUNTRY

The plateaus, buttes, mesas, and canyons of the Navajo Country are in many ways similar to those of the Grand Canyon Region, but consist of mostly younger rocks and reflect different structural controls. Two major features dominate the area, the great downwarp of Black Mesa Basin and the Upwarped Defiance Plateau.

Eastward from the Marble platform, the principal features are the Echo Cliffs, Kaibito Plateau, Black Mesa, Chinle and Beautiful valleys, and Defiance Plateau. The structural relief is greater than the topographic relief across the area.

The dominant land forms of the area are carved largely from brightly colored beds. Deep canyons fringe the mesas. Canyon DeChelly, cut across the Defiance Uplift into the bright Permian redbeds, rivals the Grand Canyon in scenic beauty, although not in size. Locally, particularly in the Hopi Buttes area, the landscape is dominated by volcanic necks which represent the congealed material solidified in the throats of Pliocene volcanos now exposed by erosion.

CHAPTER IV: ECONOMIC GEOLOGY

Introduction

The scope of this discussion is limited to some more or less general comments regarding Arizona mineral deposits. Salient economic features related to the several geologic Eras are mentioned on p.19,34,47,54,58, 71,84. Descriptions of numerous individual districts and deposits may be found in the literature which is cited in the Appendix.

Geographic Distribution Of Deposits and Districts

Qualitatively, the mineral deposits are classed as metallic, nonmetallic, oil, gas, and coal. Their geographic distribution is shown on the *Map of Known Metallic Mineral Occurrences of Arizona** and *Map of Known Nonmetallic Mineral Occurrences of Arizona.** Numerous individual mines are featured on the County geologic maps.*

The general locations of mining districts are indicated on the *Map and Index of Arizona Mining Districts.** At one time a mining district was, in a sense, a local governmental unit with fairly definite boundaries determined by local usage; at present, however, the governmental aspect of a mining district largely has disappeared, and in many instances the boundaries are decidedly indefinite (247).

The more important metal-producing districts other than uranium, as well as numerous nonmetallic occurrences, are found within the Basin and Range Province and Transition Zone (Fig. 13). Within the Plateau Province are important deposits of uranium-vanadium, nonmetallics, and coal; some of base metals; and the comparatively recent discoveries of petroleum, natural gas, and helium.

* Issued by the Arizona Bureau of Mines.

Historical Summary

ABORIGINAL PERIOD

As described by Forrester (85;86), Arizona Indians are known to have carried on noteworthy mining from 1,000 A.D. until about the middle of the sixteenth century for such resources as salt, building stone, pottery clay, pigments, ornamental stones, and materials for making tools and weapons. Significant examples were the Indian mining of oxidized copper ore at the sites of the Jerome (8) and Ajo (93) mines.

SPANISH PERIOD

During 1539 until the Gadsden Purchase in 1853, active exploration by Spanish and Mexican prospectors resulted in the finding of many silver and gold deposits in Arizona, as far north as Jerome in 1585 (8) and as far southwest as Castle Dome (315), Yuma County. Also, they were aware of the Ajo copper deposits at least as early as 1750 (93). The value of production by Spanish mining from these discoveries is not known.

AMERICAN PERIOD (39)

EARLY OPERATIONS

The early American prospecting and mining in Arizona were primarily for gold and silver; owing to the remoteness of this region, base metals and nonmetallics were unattractive. The ardent search for gold and silver, however, led to discoveries of copper, lead, zinc, and other deposits that eventually acquired commercial importance. Prior to the completion of railroads across southern Arizona in 1881 and northern Arizona in 1882, a few small-scale copper-mining and smelting operations were conducted under adverse conditions, as for example in the Ajo, Planet, and Clifton-Morenci areas.

DISCOVERIES AND DEVELOPMENTS

Some important mineral discoveries (or rediscoveries) after 1853, as well as the initiation of subsequent large or significant developments of them, are given in Table 8.

PRODUCTION TOTAL (39)

The total value of all minerals obtained in Arizona from 1858 through 1961 is approximately as follows:

Commodities	Value	Per cent of Total Value
Metals	\$8,163,474,000	96.23
Nonmetallics	318,110,000	3.75
Mineral Fuels	1,949,000	0.02
Total	\$8,483,533,000	100.00

Table 8. Some important mineral discoveries and developments.

District, area, or deposits	Discovery date	Date of approximate start of large or significant development
Ajo	1854	1911
Gold placers E. of Yuma	1858	
Oatman	1862	
Gold Road	1900	1900
Tom Reed	1904	1904
United Eastern	1915	1915
Planet, Swansea	1863	1910
Bradshaw Mts.	1863	1875
Cerbat Mts.	1863	1882
Vulture	1863	1867
Clifton-Morenci	1864	1880;1937
Silver Bell	1873	1904;1952
Silver King	1873	1876
Globe	1874	1878;1903
Miami	1874	1904;1912
Magma (Superior, Pioneer)	1874	1910
Twin Buttes	1875	1880
Pima ore body	1950	1955
Jerome	1876	1883
United Verde Ext.	1914	1915
Tombstone	1877	1880
Bisbee	1877	1880;1951
Mammoth (Tiger)	1879	1886;1934
Ray	1880	1907;1954
Bagdad	1882	1928;1942
Asbestos, Gila County	1883	1914
Congress	1887	1889
Harquahala	1888	1891
Uranium deposits	1890	1948
Pearce	1895	1895
King of Arizona	1896	1897
Tungsten deposits	1896	1915;1940
Mercury, Mazatzal Mts.	1911	
Helium	1927	1960
San Manuel	1944	1948
Petroleum and natural gas	1954	1958

Mineral Deposits

INTRODUCTION

Arizona is particularly well-endowed with mineral resources that have yielded bountifully. Improved methods of prospecting, mining, metallurgy, and transportation have served to maintain or augment the general reserves, other than of gold ore, in response to commercial demands. Also, new uses for various minerals and for radioactive and less-common metals, as developed especially during the past twenty years, have added to the list of potential markets.

METALLIFEROUS DEPOSITS

COMMODITIES AND MINES

The principal metals produced in Arizona are copper, gold, silver,

zinc, lead, molybdenum, uranium, manganese, tungsten, vanadium, and mercury. Approximately 176 lode metal mines and 5 placers in the State were operated during 1960 for a yield valued at \$378,047,000 (129), as compared with 1,024 lode mines and 276 placers operated during 1940 for a yield valued at \$82,483,000.

Copper. Arizona's output of copper has ranked first among the United States since 1910, and it accounts for one-half of the Nation's present annual production of that metal (129;39).

Prior to 1910, rock containing less than two per cent of copper generally was not considered as ore. Since that time, advancement in mining and metallurgical methods has continued to lower the grade that can be worked at profit; currently, the bulk of Arizona's yield comes from ores that average less than one per cent of copper.

For 1960, Morenci, San Manuel, New Cornelia, Bisbee, and Ray, listed in order of rank, provided 68 per cent; Inspiration, Esperanza (in Pima district), Silver Bell, Magma, Copper Cities (in Globe-Miami district), Pima, Bagdad, Miami, Old Dick (in Eureka district), and Castle Dome (in Globe-Miami district) accounted for 30 per cent of the total production (129).

Gold. Placers (330) were the main source for gold mined in Arizona until after the Civil War period; their yield continued to be considerable until about 1885, but thereafter it was of very minor importance except during periods of depression in base-metal markets. Placers have accounted for approximately one-thirtieth of the total gold production.

After 1885, siliceous lode ores led in the output of gold from the State until 1924 (72); thereafter until 1941, gold as a by-product from copper, lead, and zinc ores exceeded that of the siliceous type only during periods of high base-metal prices. The major gold-quartz districts, listed according to rank of production, were in the Black Mountains (Mohave County), Congress, Vulture, Bradshaw Mountains, Kofa, Harquahala, Fortuna, and Cerbat Mountains areas (316).

Since 1940, most of the gold taken from Arizona has been of the by-product category. Jerome was one of the leading sources of it until 1952. During 1960, some 97 per cent of the State's gold was supplied by the Bisbee, Ajo, Iron King (Humboldt), San Manuel, Magma, and Morenci mines (129).

Silver. Early silver bonanzas, especially in the Tombstone (35), Pearce (274;72), Silver King (327), Cerbat Mountains (254), Bradshaw Mountains (167), White Hills (254;72), Richmond Basin (19), Vekol (289), and Silver (315) district (southern Trigo Mountains) areas, greatly influenced Arizona history; during 1878-1887, the value of silver mined in the State exceeded that of gold.

Since 1903, the output of silver has come mainly as a by-product of base-metal ores. During 1960 (129), the leading silver producers in Arizona were the Iron King (Humboldt), Bisbee, Ajo, Morenci, and Magma mines.

Zinc (39;323;324). Arizona zinc production began in 1905 but was retarded for many years by the complex character of ores and the generally low prices for the metal. Successful adaptation of the flotation process for zinc-ore concentration since 1925, along with a higher average metal price after 1940, greatly encouraged zinc mining; and more than 92 per cent of Arizona's zinc output has occurred during the past 20 years. Its value exceeded that of gold mined in the State for the period 1943-1961. The zinc has come principally from the Bisbee, Iron King, Cerbat Mountains, Pima, Harshaw, Superior, Mammoth (Tiger), Jerome, Ruby, Eureka, Johnson, Patagonia, and Dragoon Mountains areas. The Iron King mine was the leading producer in 1960 (129).

Lead (39;323). The production of lead began in Arizona sometime about 1854 (324), chiefly as a by-product of silver mining. Notable among the very earliest lead mines were the Mowry and others in southern Arizona, but no reliable data of their output are available. In Yuma County, the Castle Dome and Silver districts (315;324) together probably yielded 7,000,000 or more pounds of lead prior to 1883. For the period 1883-1890, the Arizona lead output amounted to 20,700,000 pounds.

Lead mining has responded generally to metal prices, and, as with zinc, it has benefitted from improved methods of concentration. Arizona's lead has been supplied largely from the Bisbee, Mammoth (Tiger), Cerbat Mountains, Harshaw, Iron King, Ruby, Pima, Tombstone, Banner, and Arivaipa areas. The Iron King mine and the Flux mine (Harshaw district) accounted for most of the output for 1960 (129).

Molybdenum. The expanding uses and demands for molybdenum since 1914 encouraged its mining in Arizona. Some was produced from the Mammoth (Tiger) and other areas, but since 1933 essentially all of it has been recovered as a by-product of treating copper ores, especially from the Miami, Inspiration, Morenci, Silver Bell, San Manuel, Bagdad, and Pima district mines.

Uranium. Since 1942, Arizona has produced significant quantities of uranium from the Plateau Province (11) and the Transition Zone, together with small amounts from the Basin and Range Province (129).

Manganese (80;81). Prior to 1915, manganese-silver ores were mined in Arizona for use as smelter flux. Subsequent production of manganese ore for other uses was considerable during times of war, and it was greatest in 1953-1959. During the latter period, Government purchases

encouraged an increased output, especially of low-grade ore, from most of the Counties; with the termination of this program, however, manganese mining in the State almost ceased.

The Artillery Peak deposits (156) of southern Mohave County are rated as among the first four or five largest low-grade manganese reserves in the United States.

Tungsten (319;55;56;57). The mining of tungsten ore in Arizona began about 1900 but was of relatively small importance except during World War I and after 1930. Production has been erratic, but was pronounced under the Government purchasing program of 1951–1956; since then, it has been very small.

Vanadium. Some vanadium was mined in Arizona prior to 1945 from the Mammoth (Tiger) (212;53) and other areas, but more recently it has been recovered extensively from uranium ores of northeastern Arizona.

Mercury (160). Deposits of mercury were discovered in the Dome Rock Mountains by 1878 or earlier, in the Copper Basin district (Yavapai County) during the late eighties, in the Mazatzal Mountains in 1911, and in the Phoenix Mountains in 1916. Most of the output has come from veins in the Mazatzal Mountains.

PRODUCTION SUMMARY

From the standpoint of value of production, Arizona's leading metal was gold during 1858–1877, silver throughout 1878–1887, and copper for all of the years after 1887. Metal output by principal districts and by Counties is listed in Tables 10 and 11; a summary of it for the whole State is as follows (39):

Commodity	Value in Dollars	Per cent of Total value
Copper	\$7,102,961,000	87.01
Gold	337,361,000	4.14
Silver	280,789,000	3.44
Zinc	212,514,000	2.60
Lead	119,689,000	1.46
Molybdenum	39,500,000*	
Uranium	38,047,000**	
Manganese	23,761,000*	
Tungsten	7,150,000*	1.35
Mercury	1,202,000*	
Vanadium	500,000*	
Total, 1858–1961	\$8,163,474,000	100.00

* Including estimates

** For 1954–1961 only; includes estimates

TYPES OF DEPOSITS

The commercially important metallic deposits in Arizona are classified as replacements, veins, pegmatites, and mechanical concentrations. Representative examples of these four types are cited on p.19-85.

Replacements. The replacements range from irregular masses and disseminations to tabular or vein-like forms. Their ore and gangue minerals have replaced pre-existing host rock. Where occurring within sedimentary rocks in the vicinity of intrusives, the replacements commonly are termed contact or pyrometamorphic deposits. Replacements may occur in any type of rock where structural conditions are favorable. Those in limestone are of special interest because of their abundance and relatively high grade.

Veins. A vein or lode, as used in this résumé, consists of a crack, fissure, bedding slip, or foliation slip, which is occupied by subsequent mineral matter. More broadly, the term has been defined to include any well-defined zone or belt of mineral-bearing rock in place. Veins are formed by replacement of their wall rocks as well as by filling of open spaces.

Pegmatites. Pegmatites (9;118) are coarse-grained igneous rocks of either vein-like or irregular shape. They appear to have been formed by solutions during very late stages in the crystallization of their parent magmas, and to be transitional between igneous rocks and veins.

Mechanical concentrations. The mechanical concentrations include placers, float, and other sedimentary concentrations.

ORIGIN

The original ore and gangue minerals of the replacement bodies and other vein masses were deposited by hydrothermal solutions emanating from igneous sources. Subsequent oxidation to various depths (p.85), with or without secondary enrichment by ground-water solutions, has affected many of the deposits (p.84).

It has long been recognized that the primary or hypogene ore deposits tend to be grouped around igneous intrusive bodies, particularly stocks. As summarized by B. S. Butler (33),

The association as now seen is dependent first on the depth below the surface at which the igneous body came to rest, and second, on the amount of erosion that has occurred since the deposits were formed.

It is probable that the different depth relations were present in each major period of igneous activity, and the deposits as we now see them are what is left after various stages of erosion.

The deposits have characteristics indicative of their depth of formation aside from their relation to the intrusive bodies. The deep deposits are in shear zones, and the ore minerals have largely formed as a replacement of the sheared rock. This contrasts with the filling of fissures or the filling and replacement of breccia zones or breccia pipes in deposits formed nearer the

surface. The minerals in the deep deposits are coarsely crystalline, whereas those formed near the surface are likely to be finer grained.

There is also a difference in the degree of separation of the metals. The deep deposits may have copper and zinc in the same lode, whereas nearer the surface the copper deposits are commonly in or very close to the intrusive body and contain little zinc or lead, and zinc and lead deposits are some distance from the intrusive bodies and are low in copper.

Different areas in the Southwest have been eroded to very different depths relative to the surface when intrusion took place at the different periods. The Older pre-Cambrian rocks have been deeply eroded, and over wide areas any near-surface deposits of that age have been removed. The pipelike deposits of Jerome and the shear deposits in adjacent areas suggest formation in a zone between deep and shallow.

In contrast with the deeply eroded pre-Cambrian, the later deposits are within and closely grouped about stocks, as exemplified at Bisbee and Morenci-Metcalf, Arizona. The more deeply eroded stocks seem to have had much of the lodes removed with the upper parts of the stocks. The Schultze granite stock, for example, between Superior and Miami, is nearly barren of mineral deposits within and around its central portion, but at either end where the roof of the stock plunges beneath the sedimentary cover valuable deposits are present.

The later deposits are in or associated with fissures, breccia zones, or breccia pipes, as contrasted with the shear-zone replacements of the deeper deposits, and there is more tendency for separation of the metals in districts where copper, zinc, and lead are present. The veins fill fissures with only slight replacement, and vein minerals, especially the quartz, have the fine-grained, banded texture that suggests rapid change and rapid deposition. Characteristically, the deposits change rapidly with depth (252).

These near-surface types are well exemplified by the Oatman and Mammoth deposits of Arizona.

ASSOCIATED STRUCTURAL FEATURES

General statement. Deformation of the earth's crust was a primary factor in localizing the intrusive masses and in controlling ore deposition within favorable rocks.

The effects of horizontal compressional stresses, as expressed by shear faults* and fractures, folds, bedding slips*, thrust faults*, and tension fissures*, are particularly important. Not all of these effects may readily be evident in all of the districts, although commonly two or more types of them are prominent, and more obscure ones may be found by detailed mapping.

Shears. The shear faults and fractures trend systematically (p.6 and Fig. 2) and dip generally steeper than 45°. Of their two strongest systems, one strikes in a general E.-W., and the other in a general N.-S., direction. They were sufficiently deep-seated to have dikes and stocks commonly invading them.

The shear faults may show either or both horizontal and vertical components of displacement, which is normal on some, but reverse on

others; their displacements may range from a few feet to several thousands of feet. Those in Paleozoic and later rocks are believed to have been localized mainly by zones of weakness in the Older Precambrian crust.

Folds, bedding slips, and thrust faults. The folds may break into steeply dipping reverse faults, low-angle thrusts, or normal faults. Folded areas may be underlain by reverse and thrust faults. Bedding slips (35) commonly accompany folding. As a rule, one or more of these structural features in a given area have been complicated or obscured by subsequent geologic events.

Tension fissures. In many Arizona districts, fissures of little or no displacement strike northeast and northwest; they are interpreted as tensional resultants of horizontal compression. Their development appears to be regional rather than local.

The northeast fissures commonly extend in echelon patterns rather than continuously for long distances. In most of the districts where they have been mapped, there is strong evidence that they constituted channels of access for the mineralizing solutions; ore shoots commonly occur where northeast fissures intersect favorable rocks within anticlines, beneath impervious beds or bedding slips, or where they cross shear faults and fractures.

OXIDATION AND SUPERGENE ENRICHMENT

Alteration by weathering has been an important factor in the value and development of numerous ore deposits. The early production of metals in Arizona came largely from oxidized ores that were amenable to simple methods of metallurgical treatment. To a varying extent, many metal occurrences may or may not be productive because of changes that have resulted from weathering.

It is beyond the scope of this résumé to outline comprehensively the complex subjects of oxidation and supergene enrichment. For available information regarding them, reference is made to the literature (1;2;227;213a).

NONMETALLIC DEPOSITS (333;39)

INTRODUCTION

The mining and preparation of nonmetallics have expanded into one of Arizona's major mineral industries, especially during recent decades, along with the increase in construction and other industries within the southwestern and western United States. For example, the total value of output in Arizona for sand and gravel now exceeds that for gold, and its annual value has ranked second only to copper since 1954.

*See Glossary (in Appendix) for definitions of terms.

TYPES OF DEPOSITS

Sand and gravel, lime, gypsum, and sodium sulfate represent sedimentary deposits; cement materials are chiefly sedimentary, but may include also igneous and metamorphic types; stone is either sedimentary, igneous, or metamorphic rock; clays are derived by alteration, and are further classified as either residual or transported sediments; chrysotile asbestos, barite, and fluorspar occur as hydrothermal veins; commercial feldspar, amblygonite (118), spodumene (118), and quartz are mined chiefly from pegmatites; cinders, pumice, and tuff are of volcanic origin; perlite is a volcanic rock, probably intrusive; and mica comes chiefly from pegmatites, but to a limited extent also from plutonic and metamorphic rocks.

PRODUCTION

Although most of the Arizona mineral substances used for construction purposes are consumed locally, some of the nonmetallics, such as bentonite, asbestos, feldspar, barite, sodium sulfate, Coconino flagstone, fluorspar, and mica, have found their chief markets outside the State.

The total value, partly estimated, of the principal nonmetallic commodities produced in Arizona is listed in Table 9.

Table 9. Production of Arizona nonmetallic commodities (39)

COMMODITY	VALUE*
Sand and gravel, 1917-1961	\$106,750,000
Cement, 1905; 1949-1961	60,005,000
Stone, 1889-1961	44,041,000
Lime, 1894-1961	31,205,000
Bentonite, 1925-1961	24,500,000
Chrysotile asbestos, 1914-1961	15,820,000
Clay products, 1894-1961	11,000,000
Feldspar, 1923-1961	4,750,000
Cinders, pumice, 1949-1961	7,373,000
Gypsum, through 1961	4,108,000
Barite, 1929-1961	2,614,000
Gem stones, through 1961	1,526,000
Misc. clays, 1949-1961	1,725,000
Sodium sulfate, 1920-1933	865,000
Perlite, 1946-1961	828,000
Fluorspar, 1902-1961	583,000
Mica, 1949-1961	417,000
Total	\$318,110,000

* Including estimates.

Table 10. Value* of copper, gold, silver, zinc, and lead produced by Arizona districts.

DISTRICT	YEARS	COPPER	GOLD	SILVER	ZINC	LEAD	TOTAL VALUE
Globe-Miami	1878-1957	\$1,289,155,000	\$ 4,776,000	\$ 13,034,000	\$ 31,000	\$ 352,000	\$1,307,368,000
Morenci-Metcalf	1872-1957	1,228,849,000	5,622,000	8,471,000	.....	6,000	1,242,948,000
Bisbee	1880-1957	1,038,256,000	58,283,000	63,887,000	47,011,000	30,410,000	1,237,847,000
Ajo	1854-1957	642,521,000	30,573,000	8,523,000	.....	.....	681,617,000
Jerome	1883-1957	571,939,000	38,780,000	40,121,000	8,781,000	90,000	659,711,000
Ray	1911-1957	521,505,000	1,033,000	2,422,000	.....	1,166,000	526,157,000
Superior	1875-1957	229,929,000	12,500,000	24,750,000	8,711,000	375,000	276,265,000
Mammoth	1881-1957	70,516,000	11,295,000	1,261,000	10,195,000	14,009,000	107,276,000
Bagdad	1887-1957	60,261,000	2,225,000	1,612,000	5,803,000	620,000	70,521,000
Silver Bell	1881-1957	67,861,000	38,000	1,100,000	1,042,000	163,000	70,204,000
Pima	1907-1957	30,945,000	28,000	2,467,000	14,080,000	8,601,000	56,121,000
Big Bug	1867-1957	13,723,000	17,231,000	10,840,000	35,037,000	15,960,000	92,811,000
San Francisco	1863-1951	.....	47,830,000	2,080,000	.....	.....	49,910,000
Tombstone	1879-1957	500,000	5,517,000	30,000,000	88,000	2,700,000	38,805,000
Harshaw	1880-1957	784,000	65,000	6,073,000	14,268,000	10,229,000	31,419,000
Wallapai	1863-1957	1,289,000	5,016,000	7,067,000	11,920,000	5,168,000	30,460,000
Johnson	1882-1957	14,942,000	4,000	468,000	9,739,000	3,000	25,156,000
Banner	1905-1957	14,176,000	626,000	518,000	469,000	2,266,000	18,055,000
Patagonia	1858-1957	5,542,000	50,000	2,327,000	3,590,000	2,727,000	14,231,000
Turquoise	1880-1955	9,366,000	654,000	743,000	1,144,000	637,000	12,544,000
Oro Blanco	1873-1957	337,000	2,626,000	2,797,000	2,068,000	2,704,000	10,532,000
Pearce	1895-1929	.....	2,535,000	7,990,000	.....	.....	10,525,000
Other Districts	1854-1957	42,516,000	70,530,000	25,481,000	8,147,000	13,197,000	159,871,000
All Districts	1854-1957	5,854,912,000	317,857,000	264,047,000	182,155,000	111,383,000	6,730,354,000
All Districts	1854-1960	6,720,450,000	332,230,000	276,137,000	205,800,000	118,453,000	7,653,070,000
All Districts	1854-1961	\$7,073,010,000	\$337,361,000	\$280,789,000	\$212,516,000	\$119,688,000	\$8,023,364,000

* Includes estimates.

Table 11. Value* of copper, gold, silver, zinc, and lead produced by Arizona Counties.

COUNTY	YEARS	COPPER	GOLD	SILVER	ZINC	LEAD	TOTAL VALUE
Apache	1956-1960	5,000	73,328,000	107,192,000	\$ 59,132,000	\$ 36,998,000	\$ 5,000
Cochise	1879-1960	1,164,291,000	6,000	24,000	.....	14,000	\$1,441,141,000
Coconino	1911-1960	969,000	5,354,000	12,621,000	501,000	2,669,000	1,013,000
Gila	1875-1960	1,441,122,000	211,000	431,000	3,572,000	3,974,000	1,462,267,000
Graham	1873-1960	776,000	7,254,000	12,874,000	15,000	75,000	8,964,000
Greenlee	1872-1960	1,394,262,000	9,348,000	868,000	.....	621,000	1,414,480,000
Maricopa	1858-1960	1,275,000	58,491,000	12,045,000	13,121,000	5,441,000	12,112,000
Mohave	1863-1960	3,928,000	1,000	6,000	.....	.....	93,026,000
Navajo	1958-1960	279,000	36,226,000	17,198,000	18,544,000	10,134,000	287,000
Pima	1854-1960	958,343,000	28,118,000	33,051,000	19,007,000	16,025,000	1,040,445,000
Pinal	1875-1960	1,055,354,000	2,885,000	11,459,000	21,697,000	18,639,000	1,151,755,000
Santa Cruz	1858-1960	10,192,000	92,840,000	65,558,000	70,204,000	22,775,000	64,872,000
Yavapai	1862-1960	682,725,000	16,395,000	1,874,000	6,000	1,088,000	934,102,000
Yuma	1858-1960	6,729,000	1,573,000	936,000	.....	.....	26,092,000
Undistributed	1854-1960	.....	.....	.....	.....	.....	2,509,000
Total	1854-1960	\$6,720,450,000	\$332,230,000	\$276,137,000	\$205,800,000	\$118,453,000	\$7,653,070,000

* Includes estimates.

APPENDIX

SOME MARINE INVERTEBRATE PALEOZOIC AND MESOZOIC INDEX FOSSILS OF ARIZONA*

This list includes many of the more abundant and easily identified index fossils found in Arizona. Either singly or collectively, the fossils listed under each System may be used to identify the rocks of that System. They are not presented here in any order indicating zonal occurrence or relative importance in broad correlation use, although many of them form widely distributed zonal indices.

Cambrian

Brachiopoda

- Dicellomus politus* Hall
- Dolichometopus productus* (Hall and Whitfield)
- Billingsella coloradoensis* (Shumard)
- Lingulella lineolata* (Walcott)
- Micromitra (Paterina)* spp.

Arthropoda (Trilobites)

- Alokistocare* spp.
- Crepicephalus texanus* (Shumard)
- Neolenus* sp.
- Saukia* sp.

Ordovician

Coelenterata

- Calopoecia* sp.
- Nyctopora* sp.
- Palaeophyllum thomi?* (Hall)
- Reuschia* sp.

Brachiopoda

- Dalmanella* cf. *D. hamburgensis* Walcott
- ##### Mollusca
- Eccyliomphalus multiseptarius* Cleland
 - Rafistoma trochiscus* White

* Prepared by Halsey W. Miller, Jr., University of Arizona, Tucson.

Devonian

Coelenterata

- Acervularia davidsoni* Edwards and Haime
- Coenites prolifica* (Hall and Whitfield)
- Pachyphyllum woodmani* (White)

Brachiopoda

- Atrypa reticularis* (Linné)
- Camarotoechia endlichi* (Meek)
- Cyrtia cyrtiniformis* (Hall and Whitfield)
- Spirifer hungerfordi* Hall
- Spirifer whitneyi* Hall

Mississippian

Protozoa

- Plectogyra* spp.

Coelenterata

- Syringopora aculeata* Girty

Bryozoa

- Archimedes* spp.

Brachiopoda

- Chonetes loganensis* Hall and Whitfield
- Leptaena rhomboidalis* (Wilckens)
- Rhipidomella* spp.

Mollusca

- Straparollus luxus* (White)

Echinodermata

- Orophocrinus* sp.
- Pentremites* sp.
- Platycrinus* sp.

Pennsylvanian

Protozoa

- Fusulina* spp.
- Frusulinella* spp.
- Millerella* spp.
- Profusulinella* spp.
- Triticites* spp.

Coelenterata

- Chaetetes milleporaceous* Edwards and Haime
- Michelinea "eugenia"*

Brachiopoda

- Mesolobus* spp.
- Spirifer rockymontanus* Marcou

Permian

Protozoa

- Parafusulina* spp.
- Schwagerina* spp.

Brachiopoda

- Dictyoclostus bassi* McKee
- Dictyoclostus meridionalis* McKee

Mollusca

- Euomphalus* aff. *pernodus* Meek and Worthen
- Perrinites* sp.

Cretaceous (lower)

Mollusca

- Acanthohoplites* sp.
- Arctica* spp. (large forms)
- Dufrenoyia* sp.
- Stoliczkaia* sp.
- Trigonia reesidei* Stoyanow

Cretaceous (upper)

Mollusca

- Collignonicerias* spp.
- Inoceramus* spp.
- Metoicoceras* sp.
- Sciponoceras gracile* (Shumard)
- Mammites nodosoides* (Schlotheim)

GLOSSARY OF SELECTED TERMS*

Acidic. An adjective used to denote a rock of siliceous composition; felsic.

Agglomerate. Volcanic fragments of coarse to fine texture, generally unsorted and more or less firmly cemented.

Alluvial fan. The outspread deposit of boulders, gravel, and sand left by a stream where it has passed from a gorge out upon a plain or open valley bottom (227).

Andesite. A volcanic rock, generally of dark-gray color and intermediate in composition between rhyolite and basalt (227). The extrusive equivalent of diorite.

Anticline. A fold or arch of bedded or layered rock, dipping in opposite directions from an axis.

Anticlinorium. A series of folds, so grouped that taken together they have the general outline of an arch.

Arkose. A sedimentary rock composed of material derived from disintegrated granitic rock.

Basalt. A common lava of dark color and of great fluidity when molten. It is less siliceous than rhyolite and contains much more iron, calcium, and magnesium (227). The extrusive equivalent of gabbro.

Base Metal. A metal, such as copper, lead, or zinc, which is less valuable than the precious metals, gold and silver.

Basic. Mafic.

Batholith. A huge mass of plutonic rock, several tens of square miles in area.

Bedding slip. A fault that is parallel to the bedding.

Breccia. A mass of naturally cemented angular rock fragments (227).

Breccia pipe. An elongated body of breccia in a diatreme.

Clastic. Formed from fragments of rocks.

Collapsed structure. A surface sink underlain by a diatreme.

Continental deposits. Sedimentary deposits laid down within a general land area and deposited in lakes or streams or by the wind (227).

Cross-bedding. An oblique or inclined layering in some sedimentary rocks which may form a considerable angle with the true bedding planes (227).

Dacite. A quartz andesite. The extrusive equivalent of quartz diorite.

Deformation. Any tectonic change in the original shape of rock masses; folding, jointing, and faulting.

Diabase. A dark intrusive rock having the same composition as basalt but, on account of its slower cooling, a more crystalline texture (227).

* Prepared for the lay reader, rather than for the professional geologist or engineer. More complete definitions are contained in various publications (82;110;227;36).

Diatreme. A vent or pipe-like structure blown through rock by gases, presumably of volcanic origin (82).

Dike. An upright or steeply dipping sheet of igneous rock that has solidified in a crack or fissure in the earth's crust (227).

Diorite. An even-grained intrusive igneous rock consisting chiefly of feldspar, hornblende, and very commonly black mica (227).

Dip. The angle of slope of a rock layer, vein, or fissure, measured from a horizontal plane.

Disconformity. A hiatus, commonly an erosion surface of considerable magnitude, without angular discordance between contiguous beds.

Epicontinental. Situated upon a continental plateau or platform, as an epicontinental sea (82).

Epeirogenic. Pertaining to the rising or sinking of extensive tracts of the earth's crust.

Era. A division of geologic time of the highest order, comprising one or more periods (82).

Fanglomerate. Firmly cemented alluvial-fan material.

Fault. A movement or displacement of the rock on one side of a fracture or break in the earth's crust past the rock on the other side (227).

Fault zone. A tract of more or less parallel faults constituting a major fault structure.

Felsic. Pertaining to or composed dominantly of feldspathic minerals and quartz.

Fold. A bend or warp in rock layers or beds (227).

Foliation. The banding or lamination of metamorphic rocks as distinguished from stratification (82).

Footwall. The lower wall of a fracture or of an ore body.

Formation. A rock unit, or a series of units, grouped together for purposes of description and mapping (227).

Fracture. A general term for any kind of a break, caused by shear stress or tensile stress, in a rock mass. Fractures include faults, shears, joints, and fracture cleavages.

Gabbro. A holocrystalline plutonic rock consisting essentially of calcic-sodic feldspar and pyroxene.

Geomorphology. The study of geologic history and structure through the interpretation of topographic forms.

Geosyncline. A region that subsided through a long period of time by means of folding or faulting or both, while contained sedimentary and volcanic rocks accumulated.

Gneiss. A rock resembling granite but with its mineral constituents so arranged as to give it a banded appearance. Gneiss does not split as freely and evenly as schist (227).

Granite. A granular plutonic rock composed essentially of quartz, feldspar, and mica; its feldspar is largely orthoclase or microcline, commonly together with some plagioclase.

Greenstone. A noncommittal term for metamorphosed mafic igneous rocks.

Hanging wall. The upper wall of a fault or of an ore body.

Isoclinal. Dipping in the same direction.

Keratophyre. A felsic igneous rock containing albite, chlorite, epidote, and calcite.

Laccolith. A mass of igneous rock of lenticular cross-section, which has been forced between strata so as to raise the overlying beds in the form of a dome (82).

Laminated. Sheeted into thin layers.

Latite. Volcanic rock between trachyte and andesite in composition. The extrusive equivalent of monzonite (82).

Lineament. A linear feature.

Mafic. Pertaining to or composed dominantly of the ferromagnesian rock-forming minerals.

Magma. The fused liquid material that solidified as igneous rocks (227).

Member. A division of a formation, generally of distinct lithologic character or of only local extent (82).

Metamorphic rock. Rock that has been changed in the earth by heat, pressure, solution, or gases (227).

Metavolcanics. Volcanic rocks that have been metamorphosed.

Minor intrusives. Volcanic plugs or necks, dikes, and sills.

Monocline. A simple bend in bedded rocks which is equivalent to one side of an arch or sag (227).

Monzonite. An intrusive igneous rock of general granitic appearance but containing a larger proportion of calcic feldspar than granite. There is commonly quartz present, and the rock then is a quartz monzonite, which is intermediate in composition between granite and quartz diorite (227).

Normal fault. A fault along which the hanging wall has been depressed relatively to the footwall (82).

Novaculite. A very fine-grained quartzose rock of sedimentary origin.

Open Fold. A fold in which the limbs form a large angle to each other, as opposed to isoclinal.

Orogeny. The process of mountain building.

Overturn. Tilted past the vertical.

Paleontology. The science that deals with the life of past geologic ages. It is based upon the study of fossil remains of organisms.

Peneplain. A land surface of slight relief and relatively gentle slopes; almost a plain.

Period. The unit of geologic time of the second rank; a division of an era (82).

Physiography. Physical geography; geomorphology.

Plug. A mass of igneous rock formed in the vent of a volcano (82).

Plunging fold. A fold in which the axis is not horizontal.

Plutonic. A general term for those rocks that have crystallized in the depths of the earth, and have therefore assumed, as a rule, the granitic texture (82).

Porphyry. Any igneous rock in which certain crystals (phenocrysts) are distinct from a fine-grained matrix (groundmass) (227).

Positive area. An area that has not tended to sink.

Pyroclastic. Applied to rocks made up of igneous rock fragments produced by explosive volcanic action. Tuffs and volcanic breccias are pyroclastic rocks (227).

Pyroxenite. A granular igneous rock consisting largely of pyroxene.

Quartzite. A rock composed of sand grains cemented by silica into an extremely hard mass (227).

Reverse fault. A fault along which the hanging wall has been raised relatively to the footwall (82).

Rhyolite. A lava, generally of light color, corresponding in chemical composition to granite; the extrusive equivalent of granite (227).

Rock. Any naturally formed aggregate or mass of mineral matter, whether or not coherent, constituting part of the earth's crust (82).

Schist. A metamorphosed rock that splits more easily in certain directions than in others. Schist splits more evenly and freely than gneiss (227).

Shear fracture. A fracture caused by shearing stresses, as contrasted with one caused by tension.

Sill. A sheet of igneous rock intruded in an attitude more nearly horizontal than vertical and as a rule between beds of sedimentary rock (227).

Stock. An intrusive body of igneous rock, smaller than a batholith.

Strike. The course or bearing of the outcrop of an inclined bed or structure on a level surface; it is perpendicular to the direction of dip (82).

Strike-slip fault. A fault on which the net slip is practically in the direction of the fault strike (82).

Supergene. Applied to ores or ore minerals that have been formed by generally descending water. Ores or minerals formed by downward enrichment (227).

Syenite. A rock similar to granite but containing a higher proportion of alkali feldspar relative to silica.

Syncline. A downward of bedded or layered rock; the opposite of anticline.

System. The stratigraphic term for *period*. (227).

Tectonic. Pertaining to structure (227).

Tension fissure. A fissure caused by tension.

Thrust fault. A reverse fault that dips less than 45° from the horizontal.

Trachyte. A volcanic rock between rhyolite and latite in composition; the extrusive equivalent of syenite.

Tuff. A rock consisting of small or fine-grained volcanic fragments.

Unconformity. A hiatus, commonly an erosion surface, of considerable magnitude between contiguous beds.

Volcanics. Volcanic rocks.

Wrench fault. A nearly vertical strike-slip fault.

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