AZ4

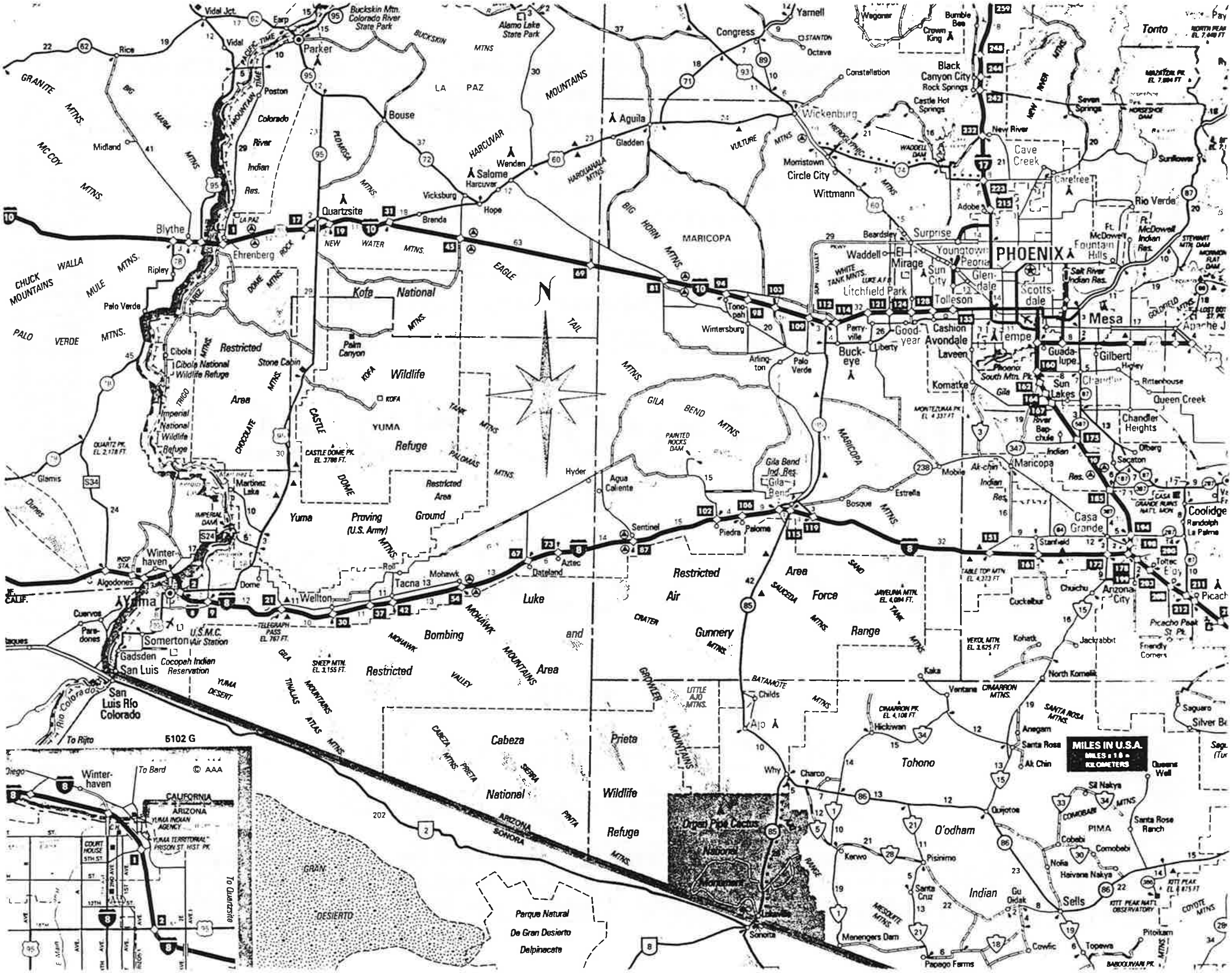
SPRING 2000 FIELD FROLIC TO SOUTHERN ARIZONA

JAN. 26-29, 2000

KARTCHNER CAVERNS AND MISSION COPPER MINE

Plus browsing/shopping at the gem, mineral, and rock shows in Quartzsite;
study of playa lake depositional systems;
and examination of San Andreas fault-induced features.

Field Trip Leaders are alumni Frank Hanna and Louis Jansen with faculty Gene Fritsche and George Dunne


PHOENIX
Scottsdale
Mesa
Tempe
Glendale
Peoria
Wickenburg
Congress
Yarnell
Aguila
Salome
Wenden
Hope
Quartzsite
Parker
Blythe
Ehrenberg
Bouse
Vicksburg
Brenda
Tonopah
Wintersburg
Buckeye
Goodyear
Avondale
Litchfield Park
Tolleson
El Mirage
Sun City
Surprise
Youngtown
Waddell
Wittmann
Circle City
Morristown
Cave Creek
Carefree
New River
Black Canyon City
Rock Springs
Castle Hot Springs
Crown King
Bumble Bee
Tonto
Fountain Hills
Rio Verde
Gilbert
Chandler
Queen Creek
Chandler Heights
Guadalupe
Sun Lakes
Maricopa
Mobile
Casa Grande
Coolidge
Eloy
Picacho
Arizona City
Stanfield
Gila Bend
Paloma
Piedra
Sentinel
Aztec
Dateland
Tacna
Mohawk
Wellton
Dome
Roll
Yuma
Winterhaven
Algodones
Somerton
Gadsden
San Luis
San Luis Río Colorado
Ajo
Why
Sells
Hyder
Agua Caliente
Arlington
Palo Verde
Cibola
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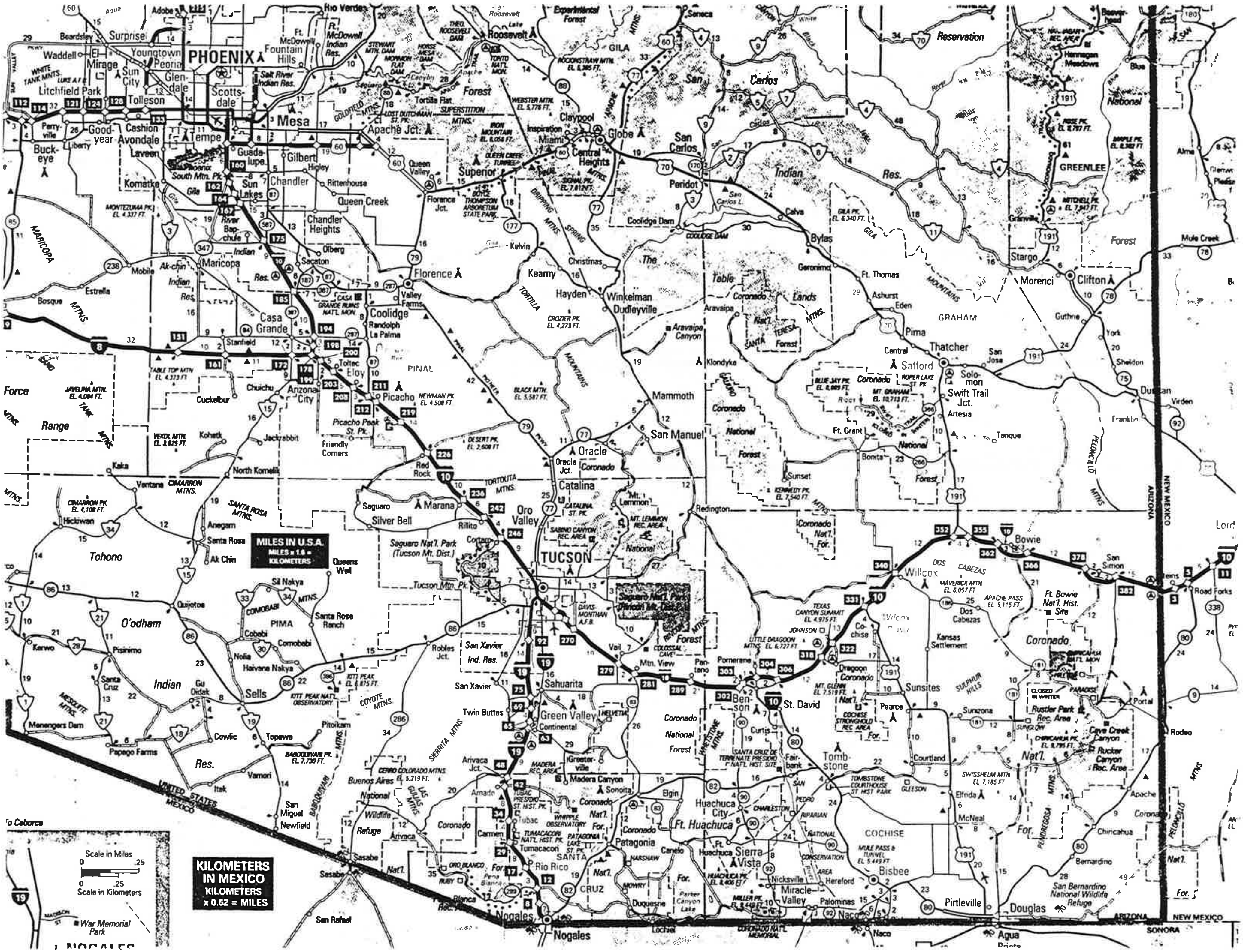
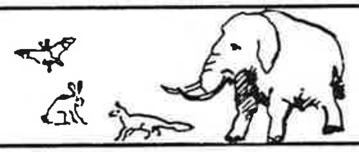
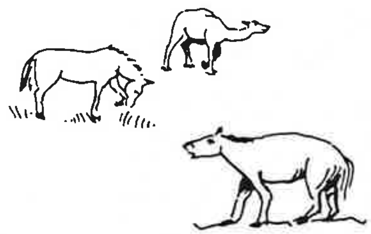
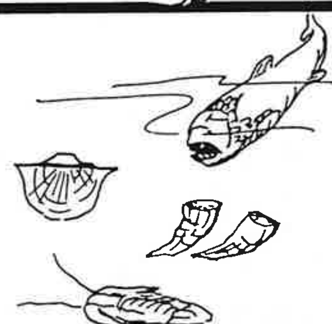
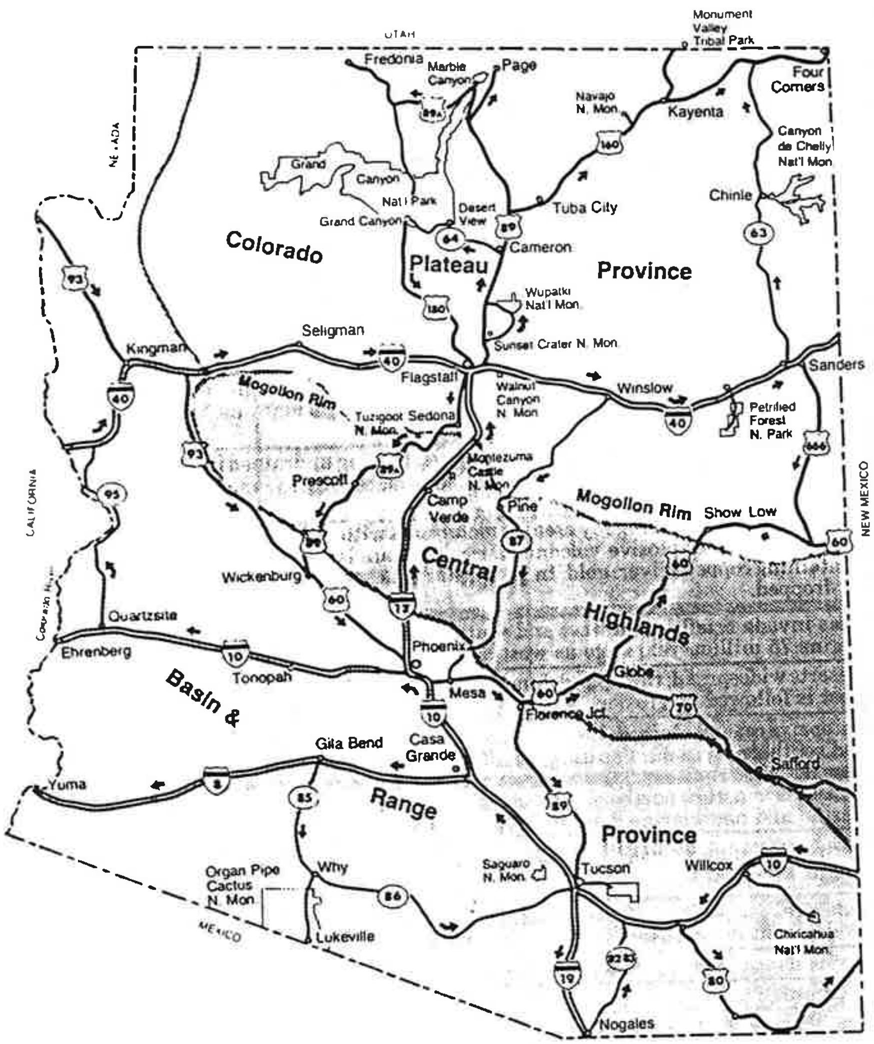
Ripley
Midland
Rice
Vidal
Vidal Jct.
Earp
Poston
Glamis
Cuervos
Sonoita
Constellation
Octave
Gladden
Harcuvar
Bosque
Estrella
Komatke
Laveen
Cashion
Liberty
Kaka
Ventana
Santa Rosa
Ak Chin
Anegam
Quijotoa
Pisinimo
Kervo
Charco
Santa Cruz
Menengers Dam
Papago Farms
Cowlic
Topawa
Pitoikam
Gu Oidak
Komelik
Chuichu
Jackrabbit
Kohatk
Cocklebur
Queens Well
Sil Nakya
Santa Rosa Ranch
Comobabi
Cobabi
Haivana Nakya
Nolia
Saguaro
Silver Bell
GRANITE MTNS.
MC COY MTNS.
BIG MARIA MTNS.
MULE MTNS.
PALO VERDE MTNS.
CHUCK WALLA MOUNTAINS
BUCKSKIN MTNS.
HARCUVAR
MOUNTAINS
VULTURE MTNS.
BIG HORN MTNS.
MARICOPA
GILA BEND MTNS.
EAGLE TAIL MTNS.
NEW WATER MTNS.
KOFA
CASTLE DOME
MOHAWK MOUNTAINS
GROWLER MOUNTAINS
SAUCEDA MTNS.
SAND TANK MTNS.
CABEZA PRIETA MTNS.
SIERRA PINTA
GILA MOUNTAINS
TINAJAS ATLAS MTNS.
YUMA DESERT
LA PAZ
Colorado River Indian Res.
Kofa National Wildlife Refuge
YUMA
Yuma Proving Ground (U.S. Army)
Restricted Area
Cibola National Wildlife Refuge
Imperial National Wildlife Refuge
Luke Air Force Range
Bombing and Gunnery
Restricted Area
Cabeza Prieta National Wildlife Refuge
Organ Pipe Cactus National Monument
Tohono O'odham Indian
PIMA
Gila Bend Ind. Res.
Ak-chin Indian Res.
Salt River Indian Res.
Cocopah Indian Reservation
U.S.M.C. Air Station
Parque Natural De Gran Desierto Delpinacate
GRAN DESIERTO
ARIZONA
SONORA
CALIF.
MILES IN U.S.A.
5102 G
© AAA
Winterhaven
To Bard
CALIFORNIA
ARIZONA
YUMA INDIAN AGENCY
YUMA TERRITORIAL PRISON ST. HIST. PK.
COURT HOUSE
To Quartzsite



PHOENIX
Mesa
Tempe
Scottsdale
Glendale
Peoria
Surprise
Youngtown
Sun City
Tolleson
Litchfield Park
Goodyear
Avondale
Buckeye
Chandler
Gilbert
Queen Creek
Apache Jct.
Superior
Miami
Globe
Claypool
Central Heights
San Carlos
Peridot
Florence
Coolidge
Casa Grande
Eloy
Arizona City
Maricopa
Picacho
Marana
Oro Valley
Catalina
Oracle
San Manuel
Mammoth
Kearny
Hayden
Winkelman
TUCSON
Sahuarita
Green Valley
Tubac
Rio Rico
Nogales
Sells
Willcox
Benson
St. David
Tombstone
Sierra Vista
Huachuca City
Bisbee
Douglas
Safford
Thatcher
Pima
Solomon
Clifton
Morenci
Bowie
San Simon
Duncan
Lordsburg
Road Forks
MARICOPA
PINAL
PIMA
GRAHAM
GREENLEE
COCHISE
SANTA CRUZ
Tohono O'odham Indian Res.
San Carlos Indian Res.
Gila River Indian Res.
Coronado National Forest
Tonto National Forest
UNITED STATES
MEXICO
ARIZONA
NEW MEXICO
SONORA
MILES IN U.S.A.
MILES x 1.6 = KILOMETERS
KILOMETERS IN MEXICO
KILOMETERS x 0.62 = MILES
Scale in Miles
Scale in Kilometers
To Caborca
War Memorial Park

ERA	PERIOD	EPOCH	AGE (mil yr)	DOMINANT LIFE FORMS	EVENTS IN ARIZONA
CENOZOIC Age of Mammals	Quaternary *q*	Holocene	.01		Present erosion cycle gouges Pleistocene and Tertiary deposits. Basalt volcanism continues near San Francisco Peaks and at a few other sites.
		Pleistocene	2		Regional uplift accelerates erosion; cyclic erosion creates terraces. Basalt volcanism occurs in several areas; San Francisco Peaks grow, collapse, and are glaciated. Colorado River flows through to Gulf of California. Pluvial lakes occupy some valleys.
	Tertiary *t*	Pliocene	5		Colorado River turns west, initiates canyon cutting on Colorado Plateau. Little Colorado reverses as recurrent movements lift plateaus. In south, basins fill with stream and lake deposits.
		Miocene			Basin and Range Orogeny 15 to 8 million years ago creates fault-block ranges with NW-SE grain. Basalt volcanism widespread.
			24		Mid-Tertiary orogeny 30-20 million years ago pushes up mountains with NE-SW grain. Metamorphic core complexes form. Colorado Plateau rises; Colorado River flows south, east of Kaibab Arch. Downdropped Verde Valley intercepts northward drainage. Explosive volcanism common, with calderas in Chiricahua and Superstition Mountains.
		Oligocene	38		Tension faulting in south is accompanied by volcanism and intrusion of dikes, stocks, laccoliths. Intermountain valleys fill with debris from mountains. Verde Valley begins to form.
		Eocene	55		Laramide Orogeny ends 50 million years ago, leaving undrained intermountain valleys, some with lakes. No volcanism or intrusions mark "Eocene magma gap." Northbound streams deposit rim gravels.
		Paleocene	63		In south, Laramide Orogeny creates mountains with NE-SW trend: overthrusting may have occurred. Explosive volcanism occurs. Abundant small intrusions appear, some containing copper, silver, gold. In north, plateaus begin to form as large blocks are lifted or dropped.
MESOZOIC Age of Reptiles	Cretaceous K		138		Seas invade briefly from west and south; volcanism widespread. Laramide Orogeny begins 75 million years ago as west-drifting continent collides with outlying plates.
	Jurassic J		205		Deserts widespread; thick sand dune deposits in north. Explosive volcanism in south and west is followed by erosion.
	Triassic R		240		Extensive coastal plain, delta, and dune deposits spread north from mountains in central and southern Arizona. Faulting, small intrusions, explosive volcanism occur in south.
PALEOZOIC Age of Fishes	Permian P		290		Dunes form across northern Arizona, then a western sea invades briefly. Alternating marine and non-marine deposition in south and west.
	Pennsylvanian P		330		Marine limestones deposited in south and south-central Arizona; floodplain and desert prevail in north.
	Mississippian M		365		Widespread deposition of fossil-bearing marine limestone is followed by emergence and development of karst topography with sinks and caves.
	Devonian D		410		Marine deposits form, then are removed from many areas by erosion.
	Silurian S		435		No record.
	Ordovician O		500		Brief marine invasion, then no record.
	Cambrian є				A western sea advances across denuded continent, depositing conglomerate and sandstone, then shale and limestone.
			570		Great Unconformity — long erosion.
PRE-CAMBRIAN pє	Younger		1700		Several episodes of mountain-building and intrusions of sills and dikes are followed by marine and near-shore sedimentation, faulting, and uplift.
	Older				Sedimentary and volcanic rocks accumulate, then are compressed and altered into NE-SW-trending ranges extending beyond Arizona. 1.7 billion years ago granite batholiths intrude these older metamorphic rocks.

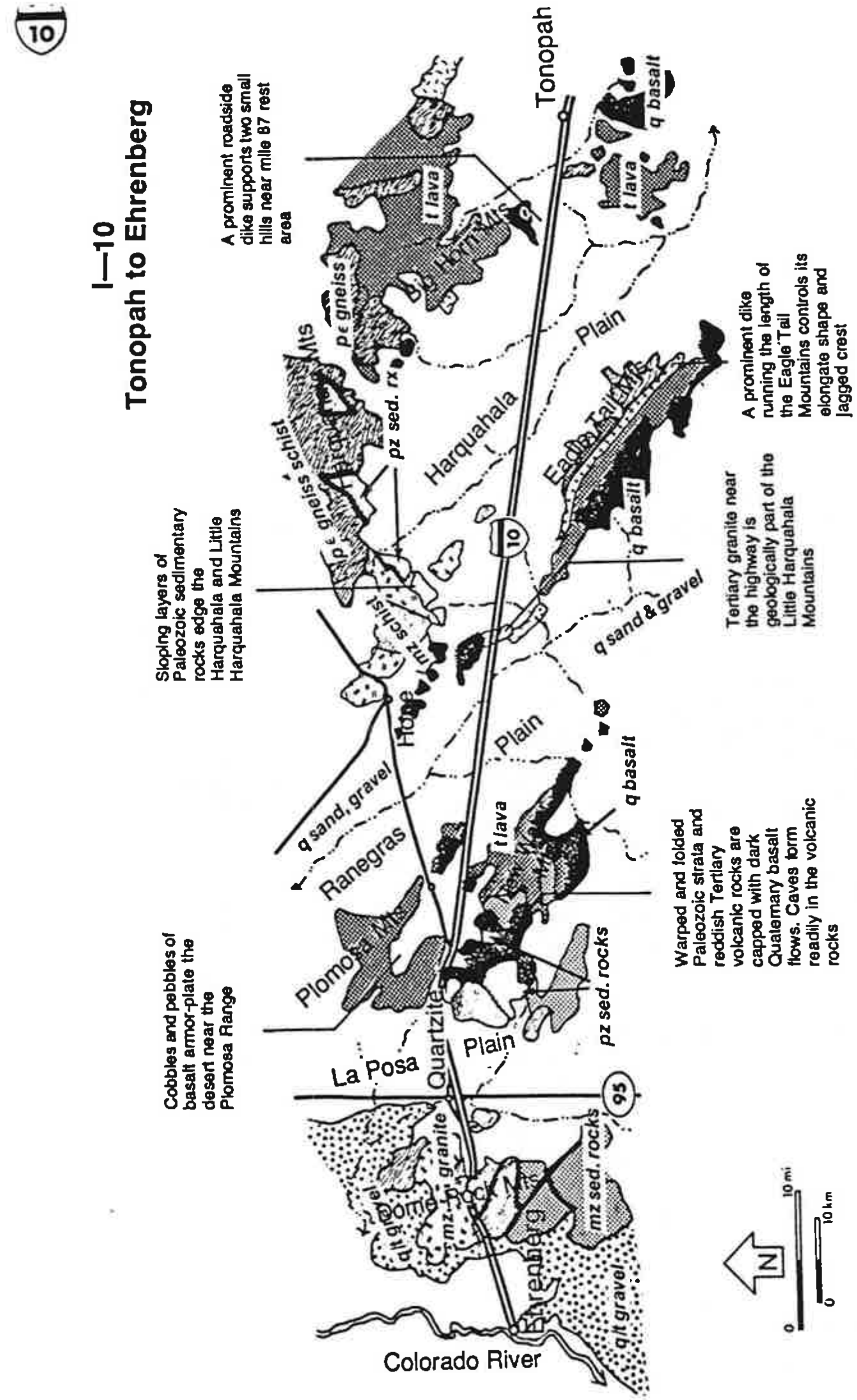


I
Some Geology Basics

Arizona's dry climate and varied topography make it a geologic wonderland, an open textbook of geology. From desert lowland to barren mountaintop, from bent and broken rocks of the southern ranges to the layer-cake strata of the stable northern plateau, about 2 billion years of geologic "happenings" have left their traces for us to piece together into a coherent, albeit patchwork, history.

THREE PROVINCES

In this book, as in many other discussions of Arizona's geology, the state is divided into three regions or provinces: the Basin and Range deserts of southern and western Arizona (Chapter II), the mountainous Central Highlands (Chapter III), and in the north the Colorado Plateau (Chapter IV), named for the river which has so boldly and beautifully carved a canyon through it. In each province, geology plays the major role in governing the spacing and character of hills and mountains, canyons and valleys, cliffs and plains. By governing their habitats, geology has ruled over plant and animal life as well, and much more recently over the ways of man.



Interstate 10
Ehrenberg to Tonopah
(94 miles)

The Colorado is one of the most highly controlled rivers in the world, with portions of its waters assigned to Colorado, Utah, California, Arizona, Nevada, and Mexico. Upstream from Yuma a string of dams controls its flow, preventing floods and providing irrigation water, electricity, and recreation sites. The river no longer floods across its former floodplain, 20 feet or so above the present river level.

West of the mountains I-10 crosses a wide two-level terrace of river deposits formed when the Colorado River carried much more rock material than it does now. The terrace gravels, seen to advantage near miles 4 and 3 where they have been dissected by tributary streams, date from Pliocene and Pleistocene time. Except where mountain ranges cut obliquely through them, these pebbly deposits border the river from Hoover Dam to Yuma, and contribute to our knowledge of the evolution of this greatest of southwestern rivers.

Beyond La Posa Plain, between it and the Colorado River, is one more mountain range: the Dome Rock Mountains. Where I-10 crosses it the range consists of Mesozoic granite and volcanic rocks. A thick, south-tilted faulted sequence of Mesozoic sedimentary rocks — as much as 15,000 feet of them — occurs farther south. The sedimentary rocks record the onset of uplift and volcanic activity in an interesting way: Lower layers consist of conglomerate and sandstone containing claystone and limestone fragments clearly derived from sedimentary rocks; those higher up and therefore younger include sandstone with grains made largely of volcanic rocks, and conglomerate containing fragments of volcanic rock and granite bared by uplift and erosion. Mineral veins in the Dome Rock Mountains have been mined for gold, silver, copper, lead, zinc, molybdenum, and mercury.

La Posa Plain is the last intermountain valley before the valley of the Colorado River. Not far north of the highway there are thick layers of gravel deposited by the Colorado River before it incised its present channel. Some of these deposits contain vertebrate fossils.

Other rocks occur here, too; patches of Paleozoic sedimentary rocks similar to some of those in Grand Canyon. They include the strata that border the highway near the little town of Brenda.

Both the New Water Mountains and the Plomosa Mountains are, like the Eagle Tails, mostly volcanic. Lava and ash flows in these ranges are mid-Tertiary. As a rule of thumb, the ages of the volcanic rocks can be distinguished by their color and their position or **attitude.** If they are reddish in color and tilted steeply, they are older than 17 million years; if they are black and horizontal they are younger than about 15 million years. Also, in these mountains, the reddish Tertiary volcanic rocks show the irregular flow structure of thick, viscous types of lava such as rhyolite. In contrast, the thin, parallel, gray or black flows form from fluid basalt lava. Many black basalt boulders are coated with white caliche deposited by evaporation of the soil water.

South of the highway and converging with it are the Eagle Tail Mountains — again in the volcanic category — with a prominent dike running through them lengthwise like a jagged backbone. The highway crosses a little Tertiary intrusion at the northwest end of the range, in sight of flat-lying Tertiary lava flows, and then drops into another desert valley, the Ranegras Plain.

The Harquahala Mountains north of the highway, and north also of the volcanic ranges, trend SW-NE across the upper end of the Harquahala Plain. Like the Harcuvar, Buckskin, and Rawhide Mountains farther northwest, they run across the general "grain" of this part of Arizona. These transverse ranges all fit into the metamorphic core complex pattern. All are cored with Precambrian gneiss, schist, or granite; most are associated with Tertiary intrusions; some are flanked with Paleozoic or Mesozoic sedimentary rocks. The Little Harquahala Mountains contain major thrust faults that shuffle their Paleozoic, Mesozoic, and Precambrian rocks.

On the west side of the Harquahala Plain are some flood control embankments which hold back floodwater draining from the nearby mountains. As you continue westward you'll see similar embankments bordering canals of the Central Arizona Project, a diversion system that is to bring Colorado River water to the metropolitan and agricultural areas of central Arizona.

The Harquahala Plain west of the Big Horns is another of the broad intermountain basins in this open, less crowded part of the Basin and Range Province, where ranges are smaller and farther from each other. The desert here is surfaced with desert pavement caused by and yet giving a measure of protection from erosion by wind and rain. In warm weather, dust devils spiral skyward, removing what remaining dust they can find. There are not many stream courses in this flat land. Creosote bushes, their root systems poisoning any rivals, are widely spaced except at the edge of the highway.

Most of the volcanic rocks in west central Arizona have been radiometrically dated as early Tertiary. Short, sloping flows may be interspersed with breccia and light tan layers of volcanic ash such as those which slope away from the central **volcanic neck** or **plug** that projects above the Big Horn Mountains. Many do not show such well established relationships with their conduits. Some younger volcanic rocks, mostly basalt, appear both as lava flows and as dikes.

The dark color of the Big Horn Mountains northwest of Tonopah is distinct from the much lighter tones (despite the desert varnish) of granite ranges farther east. The Big Horns mark the northeast limit of a region where rocks lifted in mountain blocks are largely volcanic. True, the volcanic rocks may rest on Precambrian gneiss, schist, and granite that peek out at the margins of some of the ranges, but these are the exceptions rather than the rule.

Interstate 10
Tonopah to Casa Grande
(100 miles)

Along desert washes, including Hassayampa Wash at mile 104, other plants find enough soil moisture to grow; palo verde, mesquite, and varieties of cactus.

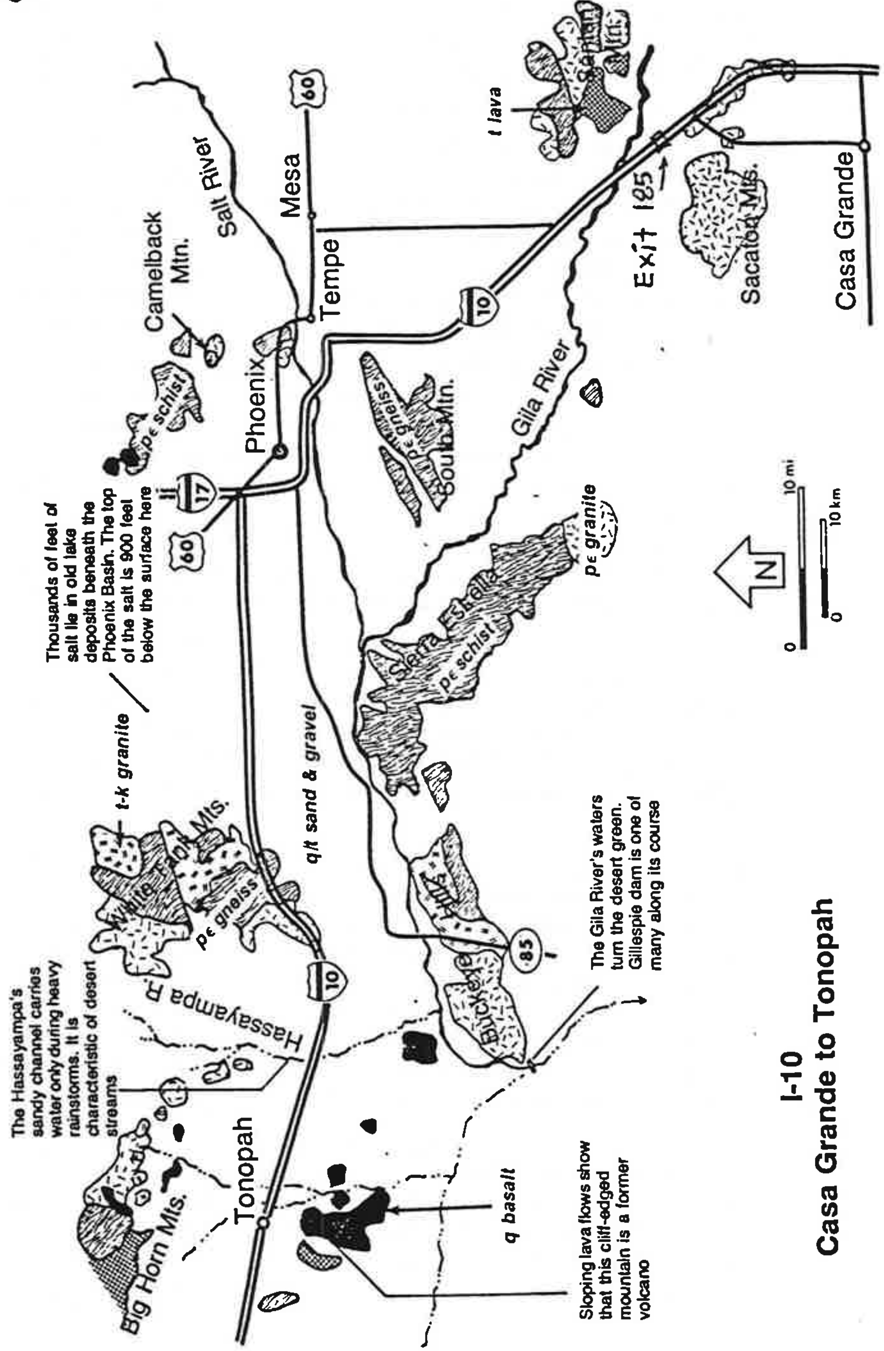
On the arid wasteland of the Tonopah desert the creosote or greasewood bush is almost the only plant that will grow. And it has a few things to tell us about the amount of soil moisture it finds here. These bushes, well adapted to life on the desert, secrete a poisonous substance from their roots, preventing the growth of other plants — of their own or another species — close enough to steal their water. The less the rainfall, the farther the roots of each plant must go to find nourishment, and the farther out the ring of poison. So the farther apart the bushes are on the desert, the less the rainfall. Where they grow near the road the shrubs are large and much closer together than on the desert flat, for they enjoy the benefit of runoff from the highway. In late March and April the highway may be edged with wildflowers sharing this runoff.

Well south of the interstate, and south also of the Gila River, the Buckeye Hills make up a less well known, less well developed or more deeply eroded metamorphic core complex. Dark hills farther west, nearer to Tonopah, are made up of Tertiary volcanic rocks and a few horizontal Quaternary lava flows. Because a nuclear reactor is sited southeast of Tonopah, the geology of this region has been well and thoroughly studied!

The White Tank Mountains north of mile 115 make up a more typical metamorphic core complex, with Precambrian gneiss and granite forming their core and their western slope, and with Tertiary gneiss (or Precambrian rock altered to gneiss that comes up with a Tertiary radiometric date) on the eastern side. The embankment between these mountains and the highway is part of a flood-retarding system designed to collect and store water from desert downpours. This concept is fairly new in Arizona, and embankments in the White Tanks area are the pilot project for others east of Phoenix and farther west near the Harquahala Mountains.

Sierra Estrella, south of the highway about 10 miles away, is a long northwest-southeast ridge of Precambrian gneiss, schist, and granitic rocks. The same rock types make up the eastern end of Buckeye Hills.

At this writing, Interstate 10 was not completed within western Phoenix. Its route turns west at about mile 145, across the Salt River Valley toward the White Tank Mountains and Buckeye Hills. West of Phoenix near Luke Air Force Base, the top of a huge mass of salt (actually **gypsum**, **anhydrite**, and **halite**) rises to within about 900 feet of the surface. This salt accumulated in salt lakes soon after Basin and Range mountain-building, and later was covered with sand and gravel brought in by streams and rivers. It is now being



I-10
Casa Grande to Tonopah

It's quite apparent that in the deserts of Arizona, water tells people where to live and where to farm. The abundant waters of the Salt River dictated the location and prosperity of Arizona's largest city and the communities that surround it — Mesa, Tempe, and others. But growth of the great metropolitan area, which now contains half the state's population, is outstripping the available water supply — both the river water and water pumped from wells. Eighty per cent of this water goes to farming, even though much farmland has been or is being converted to urban use. However, the high cost of energy for pumping water has led to abandonment of some farmland. Now well along in construction, the Central Arizona Project will bring Colorado River water to this area.

The highway crosses the Salt River at mile 151-150. Though dammed upstream, this river brings disaster as well as irrigation benefits to this part of Arizona. Major floods in 1978 and 1980 inflicted heavy damage in the Salt River Valley and the Phoenix agricultural and metropolitan areas. The storm that led to the 1978 flood is considered the most costly in Arizona's history, with homes destroyed, roads and bridges heavily damaged, and 12 fatalities. The 1980 storm closed eight of the area's ten bridges of the Salt River. Water from several dams farther up the river and from deep wells irrigates citrus orchards, cotton and bean fields, and other croplands in the Phoenix area. Pumping of groundwater in the Salt River Valley has led to land subsidence and fissuring.

South Mountain, northwest of mile 160, is a small but typical metamorphic core complex, centered with light-colored granite and surfaced with a sheared, arched carapace of metamorphic rock.

Phoenix Basin, like the Casa Grande Valley, is almost flat. Deep sediments beneath it include lakebeds. Both southeast and west of Phoenix the valley fill also includes thick salt deposits formed in saline lakes.

Exit 185
Go north on 187 1/8 mile to junction with 387.
Turn right on 387 ¾ mile to Tamarack Way
Turn right on Tamarack Way ¼ mile to first dirt track on left.
Turn left and go NE ½ mile to top of pass. Get out and ooh & ahh at the pediment at the foot of the mountain (it's a joke, see. Foot/ Mountain—pedi/ment)

Between mileposts 190 and 180, the highway goes through a small granite range, the Sacaton Mountains, and past Santan Mountain, partly granite, partly Tertiary volcanic rocks, and partly gneiss. Between the two ranges flows the Gila River. Coming from headwaters in eastern New Mexico, the Gila crosses the state of Arizona to join the Colorado River near Yuma. Upstream it has carved a broad, fertile pathway that parallels the edge of Arizona's Central Highlands. Here in the Casa Grande and Phoenix Basins much of its water goes for agricultural use. Downstream, both natural and man-made dams further retard its progress, but by and large its course is controlled by a NE-SW-trending **graben** or downfaulted block that guides it directly across the NW-SE grain of the surrounding basins and mountain ranges.

Blowing dust can be a hazard along this stretch of highway. No doubt dust storms troubled the Hohokam people long before the coming of the white man. Much of the desert's surface dust, as well as fine sand, had already been removed by the wind, leaving a moderately stable, pebbly desert surface — desert pavement — which itself protected finer soil beneath. But man's activities — farming, ranching, building, and driving vehicles (particularly in the last few years off-the-road vehicles) — have destroyed or plowed under the protective pebble pavement, and millions of tons of newly loosened topsoil, including the part that characteristically holds soil moisture and nutrients, can be blown away by a single violent windstorm.

Now a national monument, the Casa Grande ruins — site of earlier agricultural endeavors — can be reached from exit 185. The prehistoric apartment house, built by agricultural people known today as the Hohokam, rises above fields then planted to four staple crops: corn, beans, squash, and cotton.

The broad valley that contains both the town and the ruins of Casa Grande is one of Arizona's richest agricultural areas. Nourished by a spiderweb of irrigation canals bringing water from the Salt River, as well as by subsurface water, farms raise alfalfa, cotton, barley and other grains, and garden crops.

in Jenney, J. P., and Reynolds, S. J., 1989, Geologic evolution of Arizona: Tucson, Arizona Geological Society Digest 17, p. 1-16.

TECTONIC SETTING OF ARIZONA THROUGH GEOLOGIC TIME

by
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ABSTRACT

Located near the southwestern extremity of the North American continental block, Arizona has undergone a complex tectonic evolution influenced by events along both the Cordilleran and Mesoamerican continental margins. The Precambrian basement rocks of Arizona represent Proterozoic continental crust that was formed by magmatism and deformation related to subduction and tectonic accretion south of the Archean core of the continent. Subsequent Precambrian shelf sedimentation covered parts of the previously consolidated crustal block. Most Paleozoic strata were deposited as platform cover extending across the trend of the transcontinental arch between the Cordilleran miogeocline and the Ouachita margin of the continent. Some upper Paleozoic sequences fill downwarped or downfaulted basins that developed within the Ouachita foreland region in response to continental collision along the Ouachita segment of the Hercynian orogenic belt. Thin Triassic terrestrial strata were deposited within the resulting Pangaea supercontinent. By mid-Mesozoic time, Jurassic arc magmatism related to subduction along the Pacific margin of the continent had begun in the southwestern part of the state, whereas amagmatic redbed sedimentation was dominant in the northeastern part of the state. Upper Mesozoic sedimentary strata include Lower Cretaceous deposits of the rifted Bisbee basin at the northwestern extremity of the Chihuahua trough in southern Arizona and Upper Cretaceous deposits of the Rocky Mountain foreland basin in northern Arizona. Laramide magmatism and deformation, most intense in southern Arizona, were related to subduction of oceanic lithosphere at a shallow angle within the mantle beneath the continent during latest Mesozoic and earliest Cenozoic time. Crustal thickening and uplift during the Laramide episode led to widespread Eocene erosion. Subsequent mid-Tertiary arc magmatism and associated extensional deformation, most intense in southern and western Arizona, thinned the overthickened crust to allow subsidence accompanied by syntectonic sedimentation. Late Cenozoic block faulting and basin filling were followed by integration of drainages to form trunk streams emptying into the nascent Gulf of California. Continental drift of the crustal block including Arizona carried the state from tropical latitudes during the Paleozoic to its present location within the temperate zone.

INTRODUCTION

Because of its position near the southwestern extremity of the Precambrian crustal block of the North American craton, the tectonic evolution of Arizona offers special insights into geologic history. In effect, Arizona provides a geographic bridge between the Cordilleran or Pacific margin of the continent and its southern margin, marked during the Paleozoic by the Ouachita orogenic belt and in later times bordered by the Caribbean or Mesoamerican region. The dual tectonic role that Arizona has accordingly played through time makes geologic relations within the state especially complex. Multiple episodes of deformation through geologic time have superposed numerous phases of both contractional and extensional strain upon the crustal block beneath Arizona (Davis, 1981). This paper presents a general overview of the key stages in the tectonic evolution of Arizona and provides a context for the detailed discussions that follow. The focus of the text is maintained on Arizona, whose regional position within a wider tectonic framework has been discussed elsewhere (Dickinson, 1981). Selected references are provided as a guide primarily to recent literature and may slight the contributions of earlier investigators, whose work is cited more fully elsewhere in this volume.

PROTEROZOIC CRUSTAL CONSOLIDATION

The Precambrian basement rocks of the United States can be subdivided into a number of age belts that trend from east-northeast to west-southwest across the midcontinent region (fig. 1). Archean rocks (>2500 Ma) extend from the Canadian Shield into the northern Rocky Mountains but are unknown in the southwestern states. Isotopic investigations of Precambrian exposures and Phanerozoic igneous rocks indicate that Proterozoic basement underlies all of Arizona, including areas where younger cover masks them at the surface (Farmer and DePaolo, 1984). Recent Nd-Sm isotopic studies suggest that the initial formation of Proterozoic continental crust may have occurred slightly earlier than implied by the age belts depicted on figure 1 and that crust as old as 2000-2250 Ma may be present in northwesternmost Arizona (Nelson and DePaolo, 1985). In

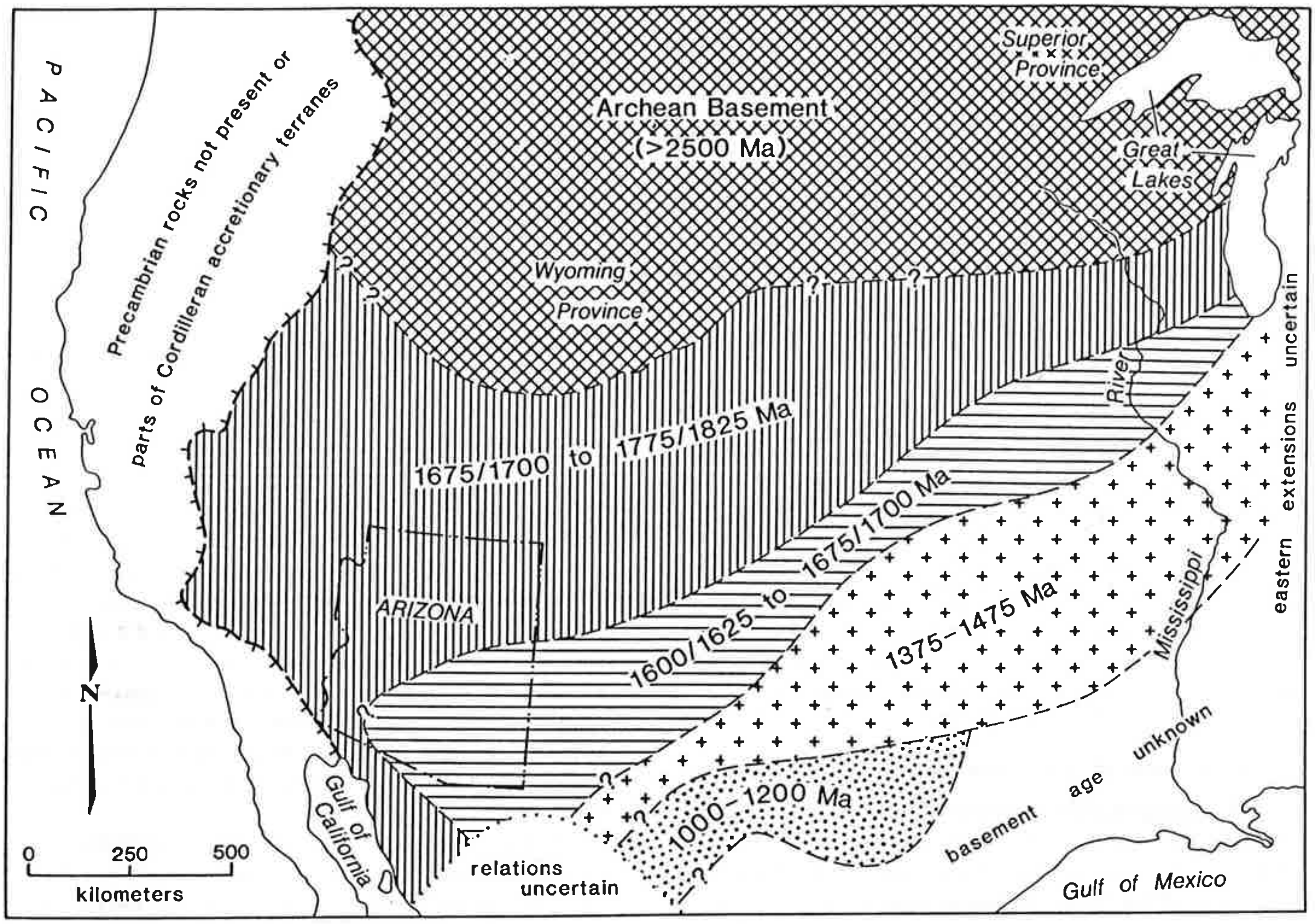

Figure 1. Proterozoic position of Arizona in relation to Precambrian age belts (simplified) of the North American craton. Modified after T. H. Anderson and Silver (1979), Van Schmus and Bickford (1981), J. L. Anderson (1983), Karlstrom and Houston (1984), and Thomas and others (1984).

the following paragraphs, subdivision of Proterozoic time follows the usage of Palmer (1983).

The oldest exposed igneous and metamorphic rocks in Arizona were formed by Early Proterozoic volcanism, sedimentation, plutonism, and deformation during the interval from 1825 to 1625 Ma (Livingston and Damon, 1968; Silver, 1978). Although many details of their geologic history are controversial, there is widespread agreement that the orogenic events responsible for their development involved subduction and arc magmatism (P. Anderson, 1980). This assumption is based upon the lithotectonic association of calc-alkalic volcanics, volcanogenic ore deposits, and granitic plutons with the products of dynamothermal metamorphism. The petrogenesis is generally attributed to the emergence of crustal materials from the mantle within regions where no Archean crustal blocks existed. The initial consolidation of continental crust within Arizona thus apparently occurred about 1750 Ma in response to ancient arc-trench tectonics that quite likely involved amalgamation of multiple magmatic arcs (Condie, 1982). In central Arizona, submarine volcanics in the Yavapai Supergroup of the Prescott-Jerome volcanic belt were succeeded by subaerial rhyolites in the Haigler Group of the New River-Payson volcanic belt, and overlying mature quartzites of the Mazatzal Group evidently reflect shelf or platform sedimentation on the newly formed continental crust (P. Anderson, this volume).

The tectonic processes that led to Proterozoic crustal consolidation in Arizona are still poorly understood. Strongly deformed, dominantly volcanogenic successions in central Arizona have estimated stratigraphic thicknesses locally in excess of 5 km (Donnelly and Hahn, 1981) and are intruded by somewhat younger granitic plutons. Within the region as a whole, however, volcanism and plutonism were broadly coeval during the period of orogenic magmatism. Over large areas farther south, wall rocks are dominantly metasedimentary strata (Condie and DeMalas, 1985), also intensely deformed. With present data, it is difficult to judge whether the various assemblages of Proterozoic rocks in Arizona were built in place by arc-trench systems, possibly including interarc basins and marginal seas, aligned along the southern flank of the Archean continental core, or instead were created elsewhere and accreted tectonically to the continental block. Our present understanding of Phanerozoic orogenic belts suggests that both indigenous and exotic tectonic elements may be represented within the complex Proterozoic terrane of Arizona. In any case, all components of the terrane are inferred to be composed of materials that formed as juvenile crust in Early Proterozoic time but had been deformed and incorporated into a crustal block of continental thickness by mid-Proterozoic time (1500-1600 Ma).

Voluminous granitic batholiths of Middle Proterozoic age were emplaced into the nascent continental crust of Arizona about 1450 Ma (Silver and others, 1977). This intrusive episode occurred much later than the deformation associated with initial consolidation of the crustal profile, and the plutons are in that sense anorogenic bodies. They represent but a segment of an extensive belt of analogous batholiths that extends from the midcontinent region across the southern Rocky Mountains to the Mojave Desert (J. L. Anderson, 1983). With present knowledge, their tectonic affinities are impossible to ascertain with confidence. Analogy with Phanerozoic batholith belts suggests some relationship to crustal subduction or collision within a zone lying to the southeast, away from the Archean core of the continent (Nelson and DePaolo, 1985).

PROTEROZOIC PLATFORM DEVELOPMENT

Following an erosional interval of indeterminate length, Middle Proterozoic sedimentary strata of combined shallow-marine and coastal-plain origin were deposited upon parts of the Arizona basement terrane. Their original extent is uncertain, but sequences as much as 2.5 to 4.5 km thick are preserved in the Grand Canyon (D. P. Elston and McKee, 1982) and in the Apache Group of central Arizona (Shride, 1967). Intercalated basaltic lavas and intrusive diabase sills that provide the only age constraints for the sedimentary strata have yielded isotopic ages of about 1100 Ma (Lucchitta and Hendricks, 1983). Several internal disconformities indicate that basin evolution was complex in detail, but broad facies relations are generally undocumented.

The locally substantial thickness of the Middle Proterozoic succession and the presence of coarse clastics within it suggest that significant crustal deformation accompanied basin development. The nature of any associated tectonism is speculative, but the presence of intercalated basalt flows and diabase sills implies an extensional regime. Somewhat similar successions in the Death Valley region farther west have been related to the subsidence of a rift trough having the general character of an aulacogen (Wright and others, 1976), and a related structure may have extended into the crustal block beneath Arizona.

In central Arizona, approximately half a billion years elapsed between deposition of the youngest preserved Precambrian strata and the onset of Paleozoic sedimentation. Despite the duration of the hiatus, the unconformity beneath the Paleozoic strata of central Arizona displays only slight angular discordance. The widespread structural concordance of Middle Proterozoic and Middle Cambrian strata is dramatic evidence that a remarkably stable continental platform had developed in Arizona by Late Proterozoic time. Block faulting that disrupted the platform surface in the Grand Canyon region prior to Cambrian transgression was probably related to latest Precambrian rifting that delineated the trend of the Cordilleran miogeocline farther west (Stewart, 1972).

EARLY AND MIDDLE PALEOZOIC PLATFORM EVOLUTION

By Late Proterozoic time, Arizona lay within the interior of a vast supercontinent assembled during Proterozoic time (Stewart, 1976; Sears and Price, 1978). Subsequent rifting in latest Precambrian and earliest Paleozoic time spawned a number of separate continental blocks of which North America was one. Passive continental margins evolved subsequently along the Cordilleran and Ouachita margins of the craton as the rifted continents drifted apart. The southwestern projection of the stable continental interior extended into northeastern Arizona as the transcontinental arch. Pre-Pennsylvanian Paleozoic strata of Arizona were deposited in shelf seas and related environments that fringed and covered this continental basement platform (fig. 2).

Paleozoic strata in the center of Arizona do not exceed about a kilometer in aggregate thickness (Peirce, 1976). Sections twice as thick in the northwestern and southeastern corners of the state form the updip limits of sedimentary wedges that thicken toward the old Cordilleran and Ouachita margins of the continental block. Toward the northeast, Paleozoic sequences generally thin along the axis of the transcontinental arch. A thick Paleozoic succession of miogeoclinal character is present to the southwest near Caborca in Sonora, Mexico, but its present location may reflect displacements of uncertain magnitude along post-Paleozoic strike-slip faults (Stewart and others, 1984).

Disconformities within the pre-Pennsylvanian Paleozoic sequence of Arizona indicate that platform sedimentation was discontinuous, marked by repetitive transgression and regression of marine waters. The most distinctive and laterally continuous units within the succession lie at its base and at its top. As the initiation of Paleozoic sedimentation was diachronous, the basal strata are time-transgressive sandstone bodies of partly arkosic but dominantly quartzose composition assigned to the Tapeats Sandstone in the north, the Bolsa Quartzite in the south, and the Coronado Sandstone on the east (Hereford, 1977; Hayes, 1978). These Cambrian clastic units have close counterparts throughout the Cordilleran region and record the initial subsidence of the platform following rifting along the adjacent continental margin. The most widespread marine inundation of Arizona occurred during the Mississippian, when an extensive carbonate platform occupied much of

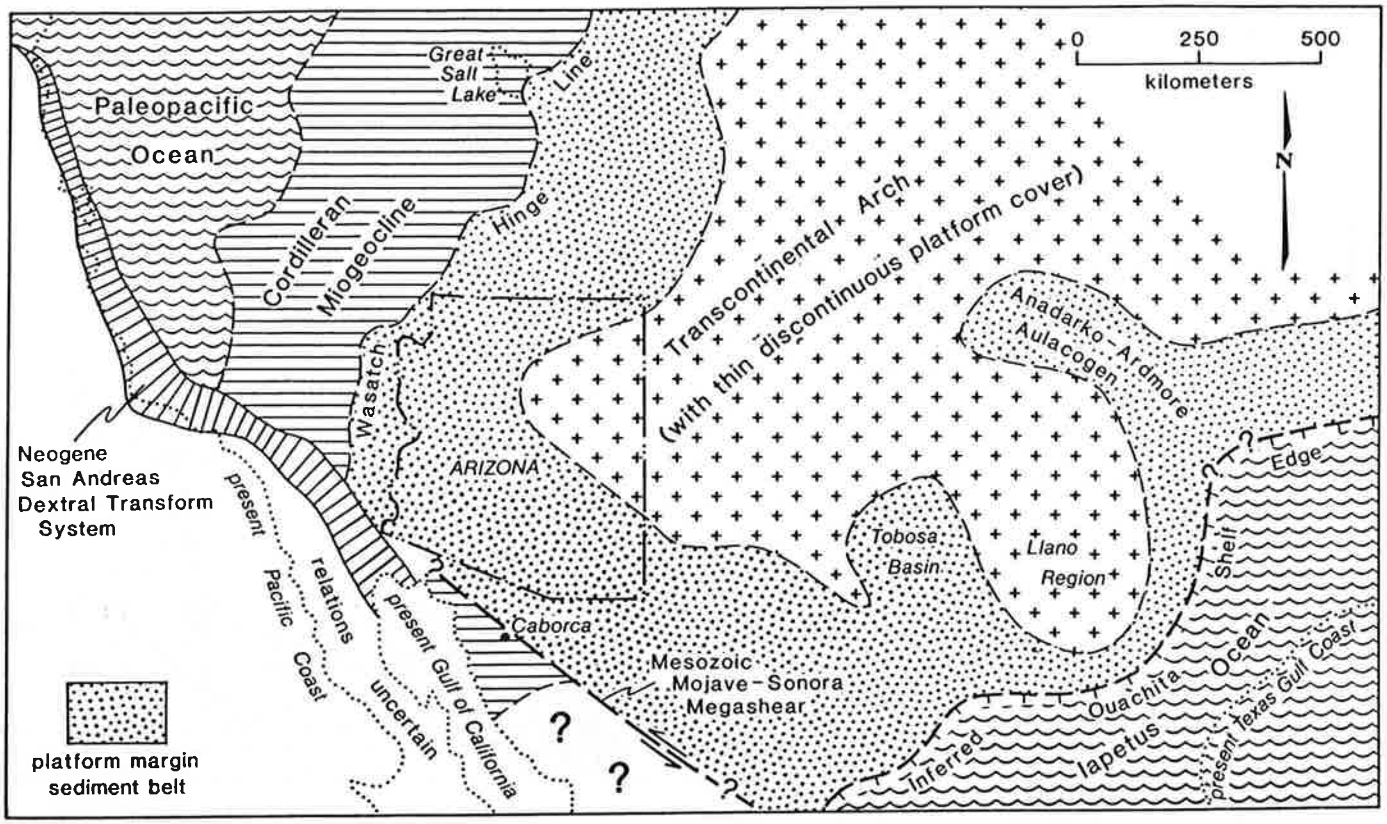

Figure 2. Early to middle Paleozoic position of Arizona in relation to passive continental margins formed by continental rifting in latest Precambrian (to Cambrian) time. Modified after Peiffer-Rangin (1979), Dickinson (1981), Gutschick and Sandberg (1983), and Stewart and others (1984).

Arizona and continued northward along the whole Cordilleran trend (Gutschick and Sandberg, 1983). The correlative Redwall Limestone of the Grand Canyon region and Escabrosa Limestone of southern Arizona form the local stratigraphic record of this vast carbonate province.

LATE PALEOZOIC AND EARLY MESOZOIC BASINS

During middle to late Paleozoic and earliest Mesozoic time, both the Cordilleran and Ouachita margins of the continent were affected by orogenies during which oceanic assemblages of strata were thrust as structurally imbricated allochthons across the edges of the continental block (fig. 3). Along the Cordilleran margin, the Antler and Sonoma orogenies were of Devono-Mississippian and Permo-Triassic age, respectively, whereas the intervening Ouachita-Marathon orogeny occurred during Permo-Pennsylvanian time (Dickinson, 1977). Orogenic events included the development of elongate thrust belts (none of which reached as far into the cratonic interior as Arizona), the subsidence of foreland basins adjacent to the thrust loads, and associated deformation of continental basement at varying distances from the thrust fronts. The full effects of the various pre-Jurassic orogenies along the continental margins upon the basement block beneath Arizona are not yet well understood.

Seemingly, events along the Cordilleran margin had little direct influence on the geologic record in Arizona. For example, the Mississippian Redwall-Escabrosa carbonate platform grew beyond the range of dispersal of orogenically derived clastic sediment into the Antler foreland basin. However, the seaward edge of this vast carbonate province may have been controlled by the flexurally arched flank of the foreland depression. If so, progradation of the edge of the carbonate platform (Rose, 1976) was sufficient to obscure any underlying structural control of its regional position. Similarly, Permian and Triassic platform sedimentation across Arizona displayed no clear evidence of disturbance by the Sonoma event. For example, the widespread Coconino Sandstone (plus Toroweap Formation) and Kaibab Limestone of mid-Permian age (Leonardian to Guadalupian) in northern and western Arizona have their counterparts in the generally correlative and lithologically similar Scherrer Formation and Concha Limestone (plus Rain Valley Formation) of southeastern Arizona (Knepp, 1983). Complex intercalation of laterally extensive Permian strandline and dune facies in central Arizona implies that the region was tectonically stable (Blakey and Middleton, 1983). Moreover, the Lower Triassic Moenkopi Formation contains similar facies of irregular thickness throughout its outcrop area within Arizona, although evidence for local deformation and intercalation of coarse clastics within the

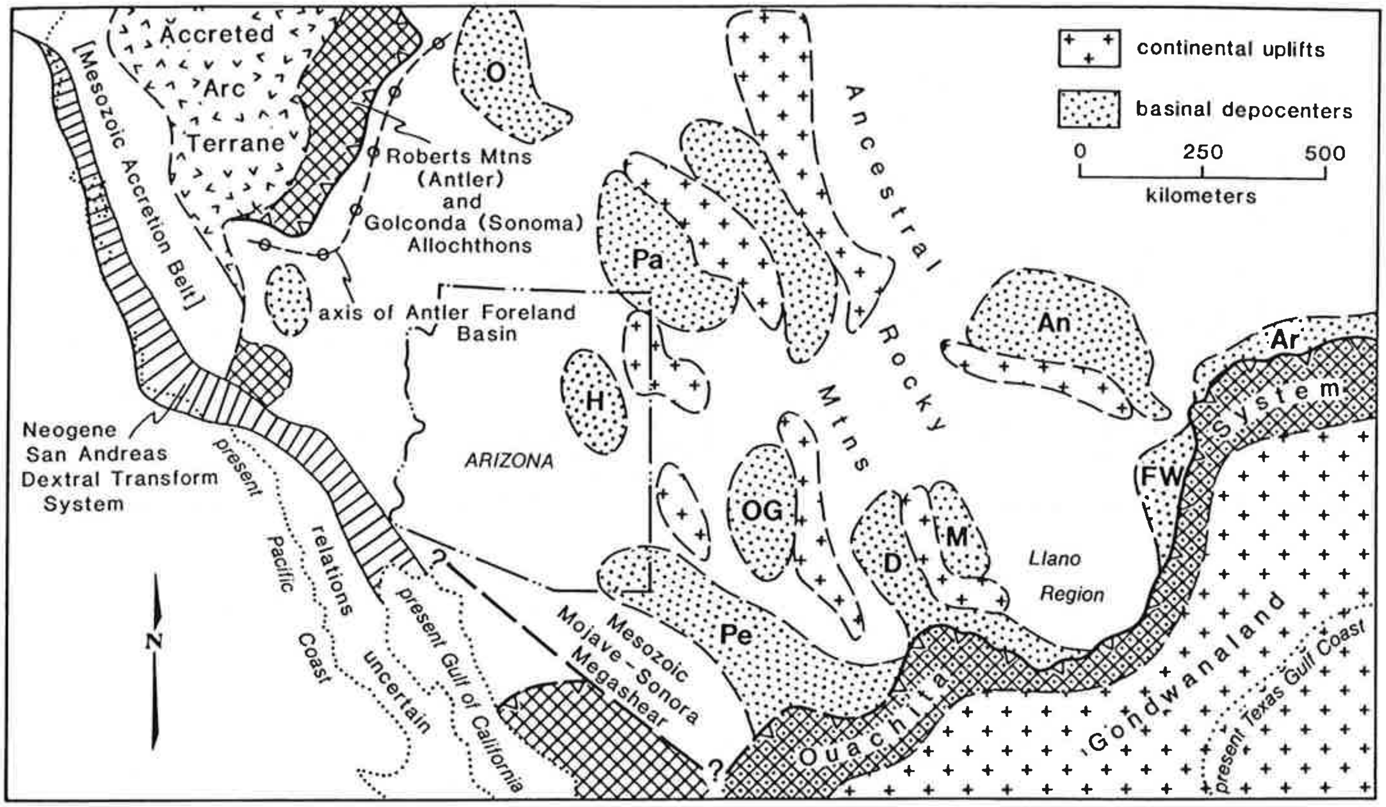

Figure 3. Late Paleozoic position of Arizona in relation to orogenic belts along the Cordilleran and Ouachita continental margins. Modified after Speed (1979), Dickinson (1981), Kluth and Coney (1981), and Dickinson and others (1983). Selected basins: An, Anadarko; Ar, Arkoma; D, Delaware; FW, Fort Worth; H, Holbrook; M, Midland; 0, Oquirrh; OG, Oro Grande; Pa, Paradox; Pe, Pedregosa. The Defiance-Zuni uplift extends into northeastern Arizona.

Moenkopi interval has been reported farther west in the Mojave Desert of California (Walker and Burchfiel, 1983).

By contrast, the Ouachita orogeny apparently left clear imprints of two general kinds on the geologic record in Arizona. Associated in time with the Ouachita event was the development of the Ancestral Rockies uplifts and basins across the region of the southern Rocky Mountains and the Colorado Plateau (fig. 3). These features reflected deformation of the interior of the continental block in response to stresses engendered by crustal collision along the Ouachita-Marathon suture belt (Kluth and Coney, 1981). The Ouachita system was a segment of the Hercynian orogenic belt, along which the Laurasian and Gondwanan continents were united to form the Permo-Triassic supercontinent of Pangaea. The thick Pennsylvanian and Permian successions of the Paradox and Holbrook basins adjacent to the Defiance-Zuni uplift in northeastern Arizona occupy depocenters whose subsidence can be attributed to Ancestral Rockies deformation (Lemke, 1985). In the Paradox Basin, syntectonic Pennsylvanian strata are capped by varied redbeds of the widespread Permian Cutler Formation.

Southeastern Arizona was also affected by tectonic downflexure of the foreland region in front of the Marathon thrust sheets, as they extended along strike into Chihuahua, Mexico. The limestone-bearing Pennsylvanian to Lower Permian section (Horquilla Limestone, Earp Formation, Colina Limestone) of the Pedregosa Basin in southeastern Arizona is thicker (1.5+ km) and more continuous than the Pennsylvanian to Permian redbed sequence (1 km) in the Supai Group and Hermit Shale of the Grand Canyon region in northwestern Arizona. Moreover, deposition of a thin but distinctive interval (Rea and Bryant, 1968) of coarse subaerial clastics ("jelly-bean conglomerate") of earliest Permian (mid-Wolfcampian) age (Armin, 1985b) in the middle of the Earp Formation of the Pedregosa Basin can be attributed to the transient tectonic upflexure of a forebulge adjacent to the downbowed belt of foreland basins (Armin, 1985a). Ouachita foreland deformation within the Pedregosa Basin probably ended before mid-Permian (by Leonardian) time, prior to deposition of the lithologically analogous redbed assemblages in the Epitaph Dolomite of the Pedregosa Basin and the generally correlative Supai Group (including the Schnebly Hill Formation of Blakey, 1979) in the Mogollon Rim region to the northwest (Peirce, this volume).

MIDDLE MESOZOIC MAGMATISM AND REDBED SEDIMENTATION

By mid-Mesozoic time, a persistent regime of subduction and arc magmatism had been established along the western

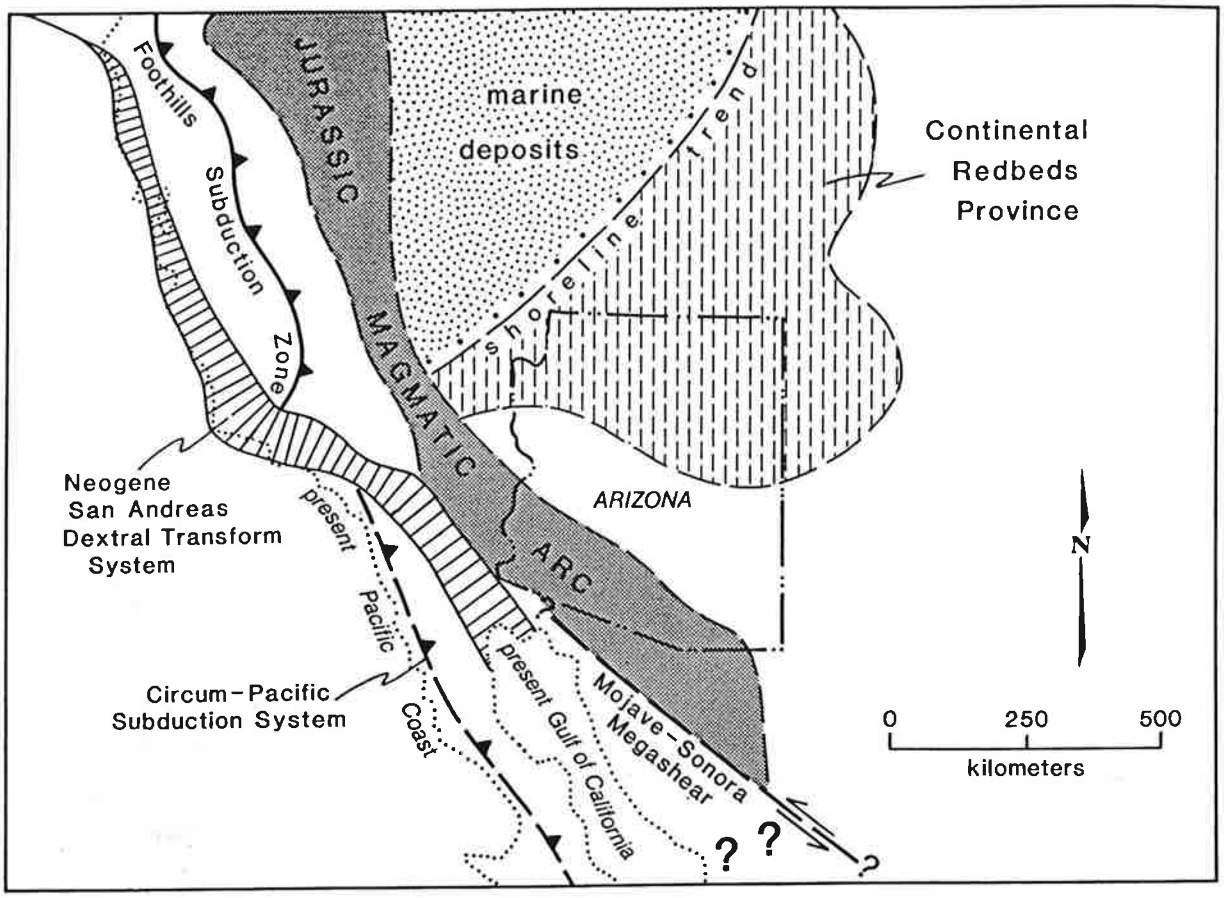

Figure 4. Middle Mesozoic position of Arizona in relation to the subduction zone and magmatic arc of an arc-trench system along the Cordilleran continental margin. Modified after Coney (1978) and Dickinson (1981).

borders of both North and South America. This Cordilleran orogenic system has continued to evolve, through many complex stages (Dickinson, 1976), until it now forms a segment of the globe-girdling circum-Pacific orogenic belt. Arc magmatism related to the subduction of slabs of oceanic lithosphere beneath the continental block played a significant role in the tectonic evolution of Arizona, which was also influenced by varied styles of intra-arc and backarc tectonics. Related subduction complexes, accretionary terranes, and associated strike-slip faults all developed close to the continental margin, but largely farther west than Arizona. In southwesternmost Arizona, however, strike-slip faults related to transform systems along the continental margin are present locally, and deformed Phanerozoic oceanic materials in the Orocopia Schist may represent part of an underthrust subduction complex.

In most segments of the circum-Pacific belt, subduction and arc magmatism linked by evolutionary stages to current tectonic regimes began no earlier than Late Triassic time, but no later than Early Jurassic time. In southern Arizona and nearby parts of California and Sonora, a regionally extensive belt (fig. 4) of Lower and Middle Jurassic arc volcanics and associated plutons is well documented, and evidence for early precursors of Late Triassic age has been reported from widely separated localities outside Arizona (Kistler, 1974; Schweickert, 1976, 1978). Sequences of Jurassic volcanic and volcaniclastic rocks as much as 2.5 to 7.5 km thick and Jurassic granitoid batholiths form significant parts of a number of mountain ranges across the southern third of the state (Hayes and Drewes, 1978; Haxel and others, 1980; Kluth, 1983), except for the southeasternmost corner adjacent to the panhandle of New Mexico. Jurassic magmatism continued in southern Arizona from mid-Early Jurassic (c. 195 Ma) until mid-Late Jurassic (c. 150 Ma) time, but then apparently shifted westward into the region of the Peninsular Ranges Batholith closer to the continental margin (Damon and others, 1981, 1983).

The region of the Colorado Plateau in the northern part of the state was not directly affected by mid-Mesozoic magmatism or tectonism. However, partly volcaniclastic sediment derived from the south or southwest is present in some mid-Mesozoic formations, and volcanic cobbles have yielded Triassic and Jurassic isotopic ages at several localities (Dodge, 1973; Peirce and others, 1985). A laterally extensive blanket of nonmarine redbed formations was deposited across the whole region as complexly intertonguing facies tracts that are difficult to date closely with confidence. The most characteristic strata are Upper Triassic fluvial and associated lacustrine deposits of the Chinle Formation

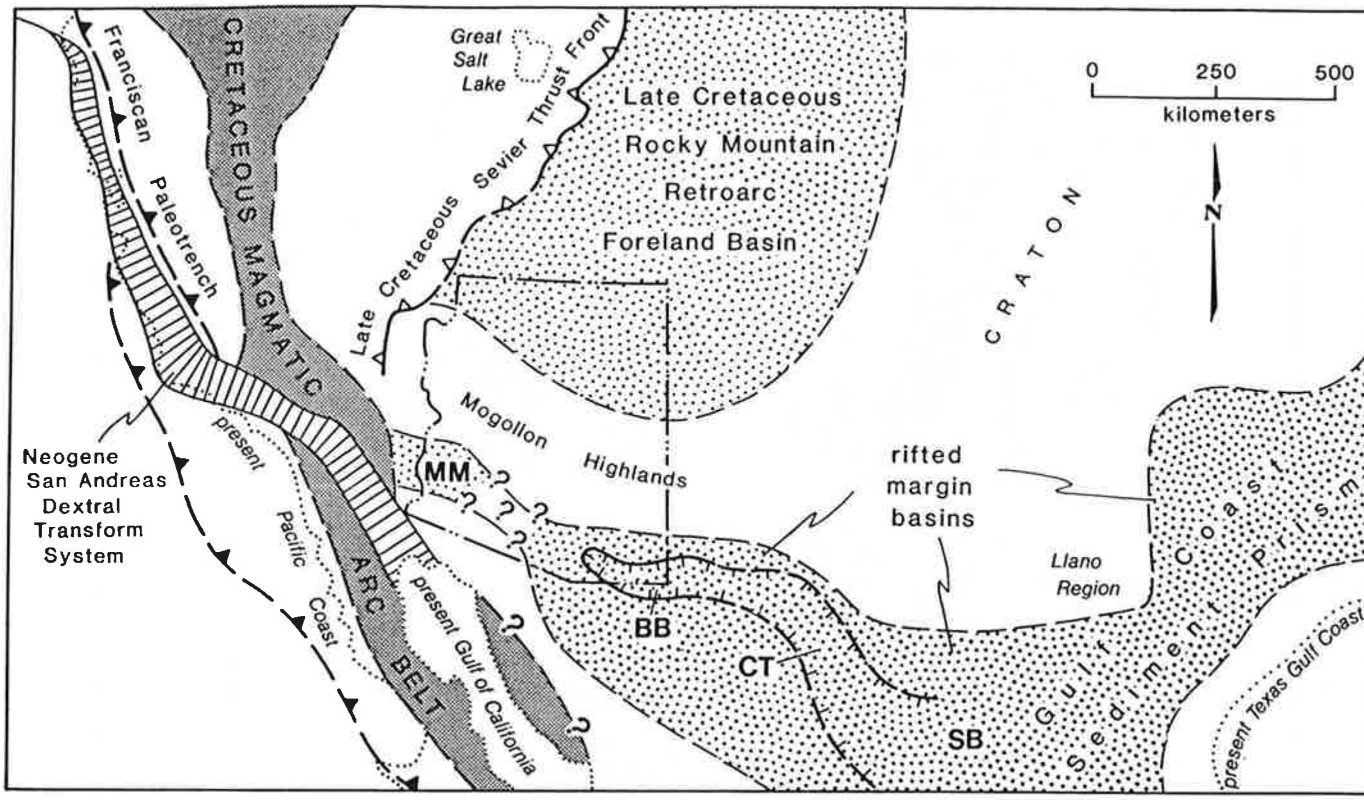

Figure 5. Late Mesozoic position of Arizona in relation to Cretaceous sedimentary basins, the Franciscan paleotrench system, and a Cretaceous magmatic arc delineated by the coastal batholith belt of the Sierra Nevada and Peninsular Ranges. Modified after Dickinson (1981) and Bilodeau (1982). Hachured line denotes Early Cretaceous backarc depocenter (aulacogen) of Bisbee basin (BB) and Chihuahua trough (CT); SB, Sabinas basin; MM, McCoy Mountains Formation and correlatives (see text for discussion).

(Blakey and Gubitosa, 1983), and Lower Jurassic eolian and associated fluvial deposits of the Glen Canyon Group (Kocurek and Dott, 1983). The main Chinle provenance lay to the south and may have included parts of the arc assemblage as far south as Sonora, Mexico (T. H. Anderson and others, 1984; Stewart and others, 1986), but the quartzose dune sands of the Glen Canyon Group were derived from the north. Overlying Middle to lower Upper Jurassic strata of the San Rafael Group include varied fluvial, eolian, and strandline facies (Blakey and others, 1983; Kocurek and Dott, 1983). In several mountain ranges of southern Arizona and southern California, quartzose Jurassic dune sands that were probably related genetically to the extensive Lower to Middle Jurassic eolian strata of the Colorado Plateau region occur interbedded with volcanogenic strata of the magmatic arc province (Bilodeau and Keith, 1979, 1986; Marzolf, 1983). In late Late Jurassic time, fluvial deposits of the Morrison Formation were spread as a sheetlike cover across the entire Colorado Plateau region from highland sources to the west and south along the Cordilleran orogenic system (Brenner, 1983).

LATE MESOZOIC RIFT AND FORELAND BASINS

Major late Mesozoic sedimentary basins of contrasting age and character developed in southern and northern Arizona within the backarc region east of a prominent belt of arc magmatism marked by the Jurassic-Cretaceous batholith belt of California and Baja California (fig. 5). In southern Arizona, subsidence mainly during the Early Cretaceous occurred as a result of backarc crustal extension related to sea-floor spreading within the nascent Gulf of Mexico during the Jurassic (Bilodeau, 1982). In northern Arizona, subsidence mainly during the Late Cretaceous occurred as a result of lithospheric downflexure of the Cordilleran foreland under the structural load of thrust sheets, whose emplacement to the west along the Sevier orogenic belt began in mid-Cretaceous time (Lawton, 1985). The overall geodynamic controls for the contrast in tectonic timing and style of the two types of basins are still poorly understood but were presumably related to major patterns of plate motion during concurrent opening of the Atlantic Ocean and continued circum-Pacific plate consumption.

Lower Cretaceous marine and nonmarine strata up to 3-4 km thick in the Bisbee Group of southeastern Arizona (fig. 5) extend downward without stratigraphic break to include beds intercalated with mid-Upper Jurassic (c. 150 Ma) volcanics and volcaniclastics (Vedder, 1984). These associated volcanogenic strata represent either the youngest local record of the mid-Mesozoic arc assemblage or a succeeding rift assemblage. Poorly dated and partly metamorphosed upper Mesozoic nonmarine strata up to 4-8 km thick in the McCoy Mountains Formation and its correlatives of southwestern Arizona occupy an analogous stratigraphic position immediately above Jurassic volcanics. McCoy strata may be equivalent to the Bisbee Group but are regarded by some as entirely older on the basis of paleomagnetic interpretations (Harding and others, 1983; Harding and Coney, 1985).

The Bisbee basin was a northwesterly extension of the Jurassic-Cretaceous Chihuahua trough, a structural arm of the Gulf of Mexico depression (Bilodeau and Lindberg, 1983). Rifting that formed the oceanic crust of the Gulf of Mexico evidently propagated into the continental block along the Chihuahua trough and Bisbee basin, which together with the Sabinas basin and other depocenters in northeastern Mexico thus represent a complex aulacogen. Facies patterns of coarse synrift deposits in the lower part of the Bisbee Group reflect sedimentation within a rifted region of fault-block topography. The rift phase of tectonic evolution in the Chihuahua trough and Bisbee basin may have been complicated by major sinistral strike-slip motions along a suspected Jurassic paleotransform, the so-called Mojave-Sonora megashear (Silver and Anderson, 1974), inferred by some to cut across northern Mexico from the Mojave Desert region to the Gulf of Mexico (Coney, 1978; Kluth, 1983). Following crustal extension during the rift phase of basin development, upper parts of the Bisbee Group accumulated during passive thermotectonic subsidence of the region that had been affected by crustal thinning. Bisbee sedimentation continued at diminishing rates into early Late Cretaceous time.

No strata equivalent to the main part of the Bisbee Group are present on the Colorado Plateau in northern Arizona, although thin Lower Cretaceous fluvial units are present farther north in Utah above the Upper Jurassic Morrison Formation, which they resemble sedimentologically. Prior to mid-Cretaceous time, the Morrison Formation and older units in northern Arizona were tilted gently to the northeast and beveled beneath an erosion surface of gentle relief. Subsequent mid-Cretaceous transgression of the continental interior seaway deposited basal Upper Cretaceous (Cenomanian) marginal-marine and marine beds of the Dakota Sandstone above a regional unconformity. Progressive overlap of successively older pre-Cretaceous units to the southwest beneath this sub-Dakota unconformity defines the northeast flank of the Mogollon highlands (fig. 5), a broad Cretaceous positive feature in central Arizona (Dickinson and others, this volume). The southwest flank of the Mogollon highlands was more abrupt and apparently coincided with the rifted edge of the Bisbee basin. The asymmetric Mogollon highlands can thus be regarded as a thermotectonically uplifted rift shoulder of the Chihuahua-Bisbee aulacogen. Following the Dakota transgression, marine and marginal-marine strata of the Mancos Shale and Mesaverde Group in northern Arizona represent the southern end of the Rocky Mountain retroarc foreland basin (fig. 5), which developed by broad downflexure of the continental surface throughout an extensive region lying to the east of Sevier thrust plates (Dickinson, 1976).

LARAMIDE MAGMATISM AND OROGENIC DEFORMATION

The most intense orogenic deformation that has affected Arizona since Early Proterozoic time occurred during the Laramide interval of Late Cretaceous and early Cenozoic time. The igneous centers responsible for most of the important porphyry copper mineralization within the state were associated with this Laramide tectonism (Titley, 1981, 1982; Damon and others, 1981, 1983). The Laramide episode of associated magmatism and deformation has been ascribed to the geodynamic effects of a marked change in the angle of dip of a subducted slab of oceanic lithosphere at depth beneath the continental block. Steep slab descent throughout most of Cretaceous time is reflected in the persistent locus of arc magmatism along the main batholith belt of California and Baja California relatively near the Franciscan paleotrench. In latest Cretaceous time, progressive flattening of the angle of slab descent is inferred to have caused the locus of slab-induced melting (where the subducted slab penetrates into the asthenosphere) to shift gradually inland beneath the continent (Coney and Reynolds, 1977; Keith, 1978). This effect allowed the belt of arc magmatism to migrate through Arizona from coastal regions farther west (fig. 6). Concurrently, enhanced compressive and (or) shear interaction between the ultimately subhorizontal subducted slab and the overriding continental lithosphere promoted contractional deformation and crustal thickening across a wide region including Arizona (Dickinson and Snyder, 1978).

Numerous isotopic ages for both volcanic and intrusive rocks establish that Laramide arc magmatism in Arizona began 75 to 80 Ma in mid-Late Cretaceous (Campanian) time and ended about 55 Ma in mid-Early Eocene time. Igneous activity was confined mostly to southern and western Arizona but also involved emplacement of isolated laccolithic stocks and subvolcanic necks within the Colorado Plateau region. The Laramide igneous suite comprises dominantly calc-alkalic rocks of mainly andesitic to rhyolitic composition, characteristic of continental-margin arc provinces. Eruptive centers are recorded by eroded stratovolcano piles and ignimbritic caldera fills (Lipman and Sawyer, 1985), as well as by varied subvolcanic stocks, with associated hypabyssal dike swarms and more deeply eroded granitoid plutons.

Closely following this magmatism of typical arc affinity, the crust of parts of southern and western Arizona was intruded by scattered batholiths of two-mica granite during Early to Middle Eocene time (about 55 to 45 Ma). These peraluminous magmas were doubtless produced by crustal melting (Farmer and DePaolo, 1984), perhaps as dehydration of subducted materials permitted rehydration of the structurally overlying lower crust of Proterozoic age (Reynolds and Keith, 1982), or simply because crustal thickening during Laramide deformation promoted melting within a deep crustal root (Haxel and others, 1984).

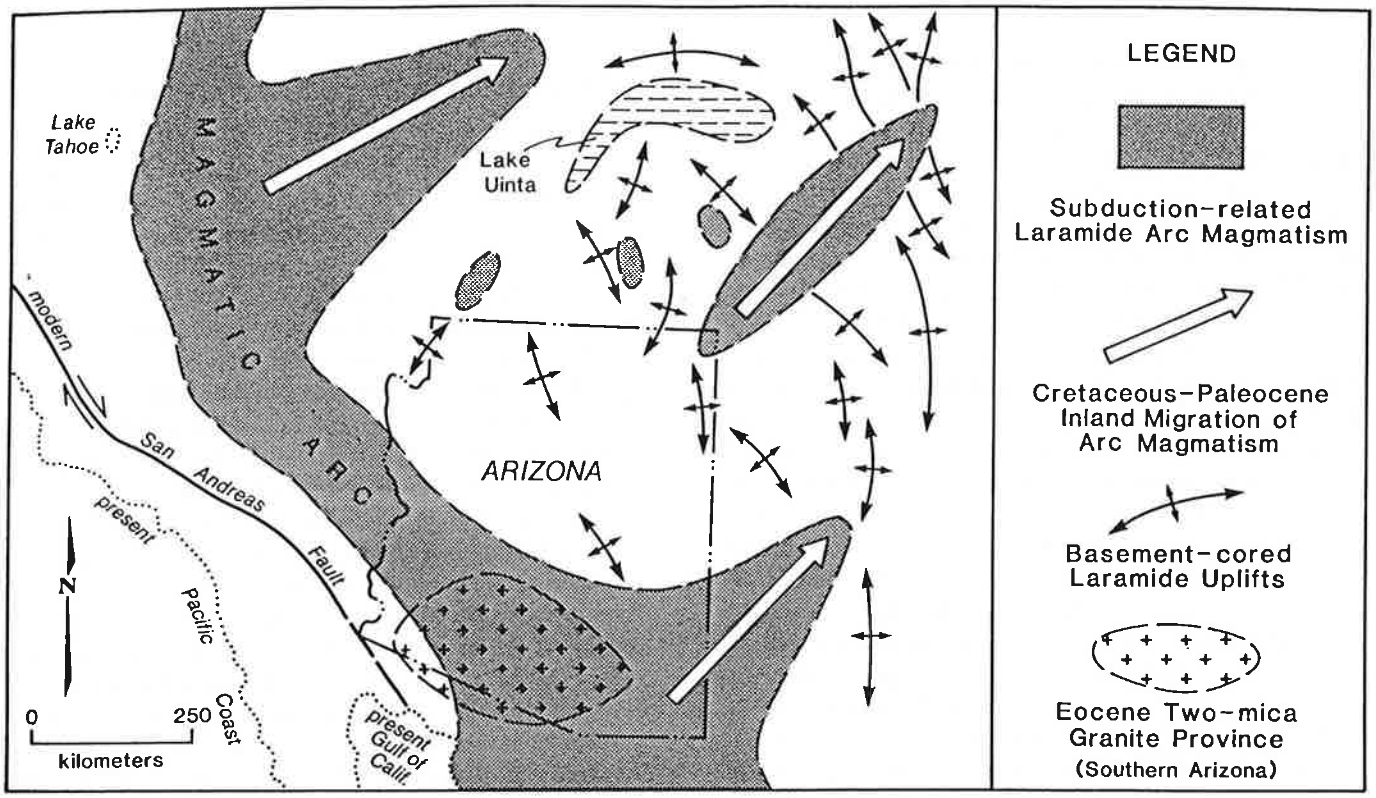

Figure 6. Latest Cretaceous and early Cenozoic position of Arizona in relation to Laramide magmatism and deformation. Modified after Dickinson (1979, 1981), Reynolds (1980), and Keith (1984).

No volcanic equivalents of this intrusive suite are presently known and none may exist, for reduction of confining pressure during the rise of hydrous magma through the crust may force complete crystallization within subterranean magma chambers.

The onset of Laramide deformation was recorded in southeastern Arizona by the deposition of synorogenic clastic successions in locally downfaulted and (or) downfolded basins. These strata, assigned to the Fort Crittenden Formation and correlative units, probably began to accumulate about 75 to 80 Ma during Campanian time, and analogous coarse clastic sequences have been dated as young as near the Cretaceous-Tertiary time boundary (about 65 Ma). Laramide folds and thrust faults involving these and older strata have been mapped in most mountain ranges of southern and western Arizona (Reynolds, 1980; Drewes, 1981), and the monoclinal flexures of the Colorado Plateau region date from the same general episode of deformation. Mylonitic fabrics were developed within shear zones located at deep-seated structural levels during the Laramide deformation (Haxel and others, 1984), and Laramide positive features were probably thrust-bounded basement-cored uplifts (Davis, 1979). Crustal thickening across the southern half of the state was apparently sufficient to induce general regional uplift, and the Eocene landscape is inferred to have been an extensive erosion surface of varied relief. Eocene sediment was transported to the northeast (Peirce and others, 1979; Young, 1979; Cather and Johnson, 1984), against the present grain of the Mogollon Rim, from the uplifted ground of southern and western Arizona toward the Claron basin of southwestern Utah, the Chuska basin of northeastern Arizona, the San Juan basin of northwestern New Mexico, and the Baca basin of western New Mexico (Nations and others, 1985).

MID-TERTIARY MAGMATISM AND EXTENSIONAL DEFORMATION

The post-Laramide period of early Tertiary erosion in southern and western Arizona coincided with a pronounced null in arc magmatism within the Cordilleran region of the western United States. By inference, the descent of subducted oceanic lithosphere beneath the continent was at such a shallow angle that no penetration of the asthenosphere was achieved, and arc magmatism was accordingly suppressed almost entirely. The same time interval, centered on the Eocene, represented the peak of Laramide deformation within the central Rocky Mountains (Chapin and Cather, 1981).

The succeeding mid-Tertiary interval, from the end of the Eocene until mid-Miocene time (about 37 to 15 Ma), was one during which arc magmatism was rejuvenated within Arizona and other parts of the intermountain region and was accompanied and (or) succeeded by widespread extensional deformation (fig. 7). These related magmatic and tectonic events have been ascribed to steepening of slab

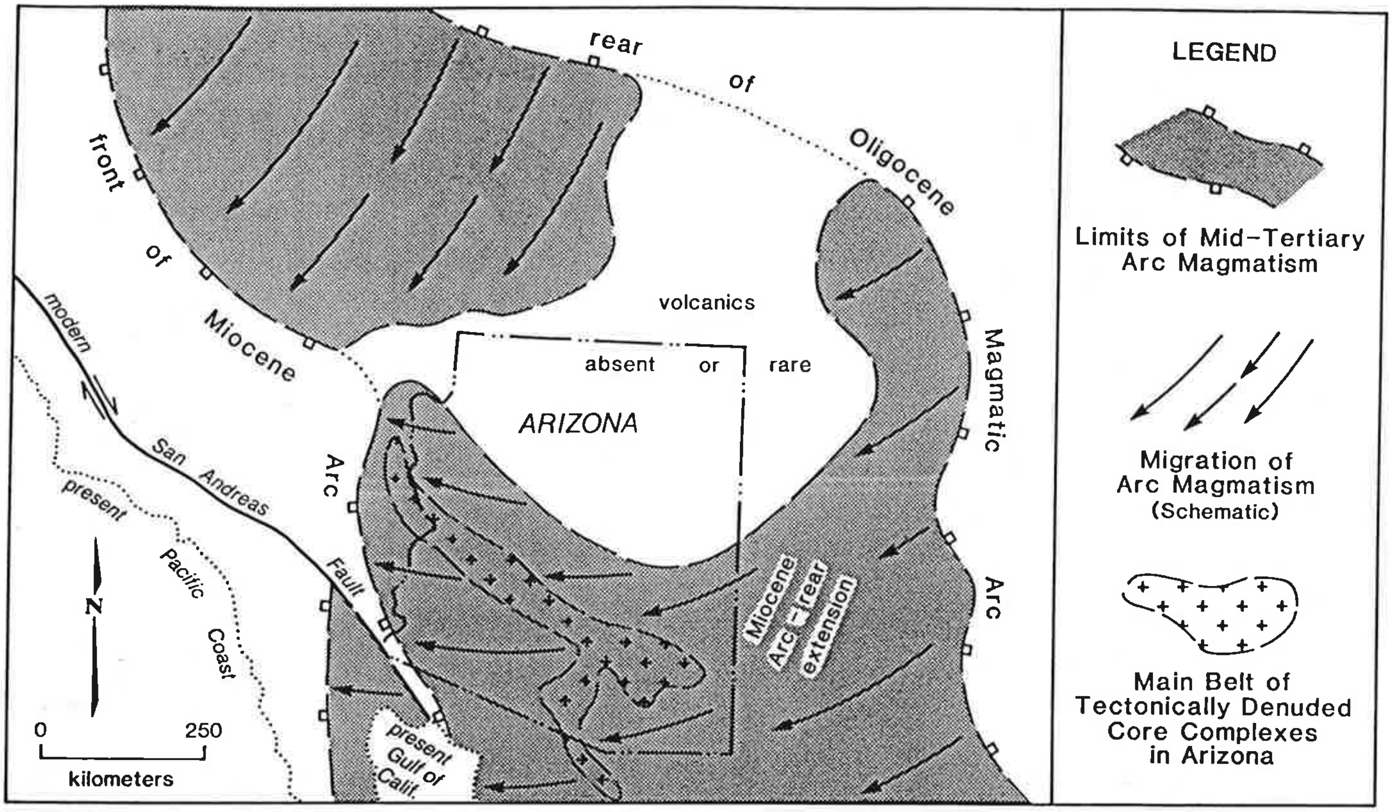

Figure 7. Mid-Cenozoic position of Arizona in relation to migratory mid-Tertiary arc magmatism and associated extensional deformation. Modified after Coney (1979) and Dickinson (1979, 1981).

descent beneath the continental block and thus to a reversal of the geodynamic influences that had earlier caused Laramide deformation (Dickinson, 1981). Consequently, eastward migration of arc magmatism was supplanted by westward migration, and crustal contraction was supplanted by crustal extension. Mid-Tertiary crustal thinning of the previously overthickened crustal profile within the region of intense Laramide deformation in southern and western Arizona allowed subsidence of that previously uplifted region. As neither the magmatic nor the structural aspects of the mid-Tertiary events affected the Colorado Plateau, this episode of subsidence accomplished a reversal of drainage along the Mogollon Rim in central Arizona and established the Colorado Plateau as a positive area relative to the remainder of the state.

Mid-Tertiary arc magmatism of generally alkali-calcic character began in southwestern New Mexico near the beginning of Oligocene time, and its inception swept irregularly westward through central and southern Arizona during Oligocene and earliest Miocene time (Shafiqullah and others, 1978; Reynolds and others, 1986). Andesitic to latitic lavas and rhyodacitic to rhyolitic domes and ignimbrite sheets are characteristic components of the regional igneous suite, which locally includes granitoid plutons as well. Although the westward migration of arc magmatism implies renewal of relatively steep slab descent beneath the region, the position of the rejuvenated magmatic belt still lay well east of the locus of analogous Cretaceous igneous activity near the Pacific Coast. Mid-Tertiary ignimbrite outcrops in southeastern Arizona can be regarded as erosional outliers of the vast ignimbrite plateau of the Sierra Madre Occidental farther south. Basaltic andesites erupted during Early Miocene time at scattered localities throughout southwestern New Mexico and southeastern Arizona have been interpreted to reflect a tendency for incipient interarc rifting along the continental flank of the magmatic belt (W. E. Elston and Bornhorst, 1979).

Mid-Tertiary extensional tectonics that began while the Oligocene-Miocene volcanism was underway and continued until about mid-Miocene time (c. 15 Ma) produced dramatic structural effects that reflect significant crustal extension and thinning. Steeply tilted homoclines of mid-Tertiary volcanics and coarse nonmarine clastics abut downdip into basement rocks along low-angle normal faults that were active during the deposition of the clastic sediments. Displacements on such faults amounted to as much as several kilometers. Analogous mid-Tertiary deformation also placed unmetamorphosed mid-Tertiary and older strata, together with unconformably underlying Precambrian basement, directly against so-called core complexes (fig. 7), composed of more deep-seated plutonic and metamorphic rocks of varying ages (Coney, 1980; Davis, 1980). The contacts between cover rocks and core rocks are denudational detachment faults now displaying gently dipping to subhorizontal attitudes. Tectonic

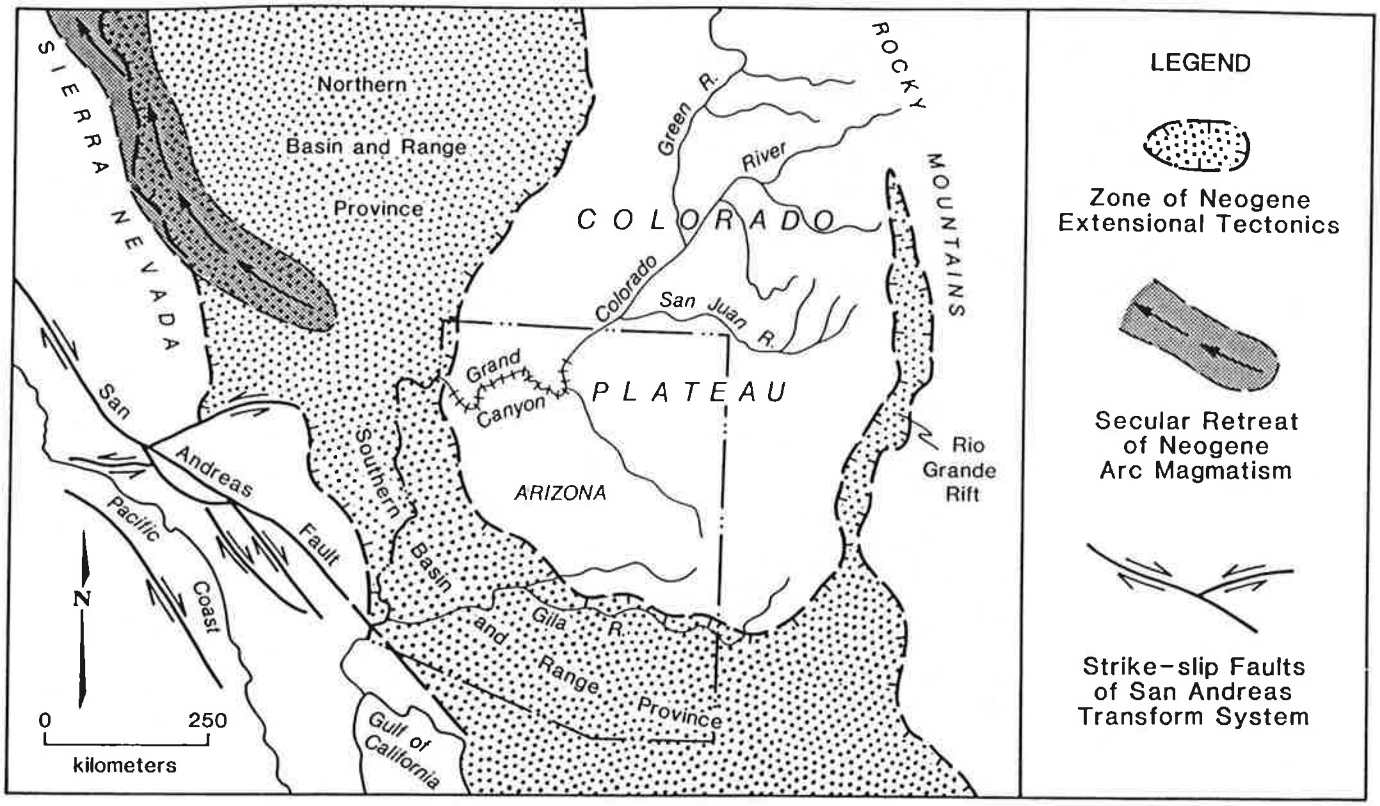

Figure 8. Late Cenozoic position of Arizona in relation to the Basin and Range province and the Colorado Plateau of the intermountain region. Modified after Dickinson (1979, 1981).

denudation of the core complexes was accomplished by movements of as much as several tens of kilometers along deeply rooted shear zones that experienced brittle fracture at shallow structural levels but accommodated ductile shear to produce mylonitic fabrics at structural levels deep within the crust (Rehrig and Reynolds, 1980; Davis, 1983; Spencer, 1984; Reynolds and Spencer, 1985). Such mylonitic zones are now exposed to view near the upper surfaces of the tectonically denuded core complexes, where they occur beneath kinematically related detachment faults and are overprinted by brittle deformation and chloritic alteration adjacent to the detachment faults. Mylonitic fabrics inherited from Laramide deformational events also occur within the interiors of some core complexes.

LATE CENOZOIC BLOCK FAULTING AND SUBSIDENCE

Volcanics and sediments of Late Miocene age (about 12 to 5 Ma) in southern and western Arizona are generally not strongly tilted but are disrupted by normal faulting of the Basin and Range Province (Shafiqullah and others, 1980). Basin and Range extensional tectonism in the intermountain region (fig. 8) has been generally coeval with development of the San Andreas transform system along the continental margin (Eaton, 1979). The generation of associated generally basaltic volcanism has thus not been related to subduction but rather to upwelling of mantle beneath the region of crustal extension in the absence of a subducted slab at depth (Dickinson and Snyder, 1979). A secular eastward expansion of the region containing scattered basaltic eruptive centers may have been related to gradual enlargement of the area lacking a subducted slab beneath it as the San Andreas transform lengthened progressively with time (Seager and others, 1984).

Basin and Range faulting formed numerous local nonmarine basins elongated generally from north to south in southern and western Arizona (Scarborough and Peirce, 1978). Thicknesses of basin fill imply structural relief of 2-4 km between the pre-mid-Miocene basin floors and adjacent mountain blocks, and the floors of the deeper basins are now 1-2 km below sea level (Eberly and Stanley, 1978). Some basins with interior drainage have continued to fill with Neogene sediment up to the present time. Other basins that record net accumulation of sediment up through some part of Pliocene time are now undergoing dissection by integrated drainages such as that of the Gila River. Drainage integration was probably not possible on a regional scale until the nearby Gulf of California began to open within the San Andreas transform system near the Miocene-Pliocene time boundary (Shafiqullah and others, 1980; Nations and others, 1985). As major Basin and Range deformation in Arizona predated opening of the Gulf of California, most syntectonic sediments were probably associated with bolson systems confined within individual structural depressions. In some way not yet well understood geodynamically, development of the rhombochasmic Gulf of California structural depression may have terminated major extensional strain within the nearby Basin and Range Province of Arizona.

The most important modern drainage in Arizona is that of the Colorado River, whose immense delta lies at the head of the Gulf of California. As drainage into that transtensional rift trough was impossible much before Pliocene time, the striking canyons incised into the Colorado plateau by the river and its tributaries are evidently Pliocene and younger erosional features, at least in their present form. The major incision of the Grand Canyon itself probably occurred about 5 Ma, near the Miocene-Pliocene time boundary (Nations and others, 1985). Although positive relative relief of the Colorado Plateau had been established by mid-Tertiary time (Peirce and others, 1979), further crustal thinning and relative subsidence of the adjacent Basin and Range Province doubtless occurred in response to Neogene extensional faulting. The Transition Zone of central Arizona delineating the edge of the relatively undisturbed Colorado Plateau block is thus evidently a composite tectonic boundary whose morphology reflects a combination of mid-Tertiary and Neogene extensional effects (Zoback and others, 1981) whose relations are still not fully understood (Eaton, 1982). The present absolute elevation of the Colorado Plateau (fig. 8) probably incorporates the effects of broad regional uplift of the entire intermountain region in response to Neogene upwelling of anomalously hot mantle having a lower density than is normal for subcontinental mantle (Damon, 1979).

EFFECTS OF CHANGING PALEOLATITUDE

The successive tectonic settings of a particular crustal segment, such as Arizona, are a function of locally evolving plate boundaries and plate interactions, as discussed above. However, the overall paleogeographic setting is a function not only of local tectonics but of changing paleolatitude in response to continental drift. Significant aspects of the stratigraphy and paleogeomorphology of Arizona cannot be understood without reference to the paleowander path of the continent. During Phanerozoic time, Arizona moved through about 60 degrees of paleolatitude (fig. 9) and an uncertain amount of paleolongitude. The shifting configurations of surrounding or nearby crustal blocks have also influenced aspects of paleogeography, such as prevailing oceanic currents and terrestrial climatic patterns.

Paleomagnetic data on the APW (apparent polar wander) path of the North American craton and published reconstructions of the global configurations of the various continental blocks through time allow a general appraisal of the changing paleogeographic setting of Arizona during the Phanerozoic. Its Precambrian setting is much more uncertain, but Arizona probably lay in tropical or subtropical latitudes during most of the time that its Proterozoic rocks were formed (fig. 1).

The carbonate-rich lower and middle Paleozoic sequence (Cambrian to Mississippian) accumulated while the Arizona portion of the continental platform (fig. 2) was washed by warm tropical to equatorial seas in which carbonate-secreting organisms must have been abundant. Associated quartzose sand is the type of detritus delivered to such shelf seas from nearby emergent but low-lying land areas subjected to deep weathering in warm humid climates.

Pennsylvanian and Permian successions include an initially bewildering array of offshore carbonates, terrestrial and strandline redbeds, sabkha and brine-pool evaporites, and quartzose sandstones of both marine and eolian origin. The assemblage can be reconciled with a paleogeographic picture of Arizona situated within the tropical trade-wind belt along the northwestern fringe of the immense Pangaean landmass (fig. 3). Shelf seas producing carbonate sediment are inferred to have fringed trade-wind deserts where redbed and evaporite associations were developed in the lee of extensive Hercynian highlands. Immense quantities of quartzose sand were transported longshore from more northerly (then northeasterly) reaches of the Cordilleran margin under the influence of oceanic circulation driven by the trade winds. The same prevailing wind pattern drove some of the sand onshore into coastal and interior dune fields.

As Arizona moved rapidly into and through the subtropics during early to middle Mesozoic time, the redbed succession of the Colorado Plateau was deposited within a subtropical desert belt (fig. 4). Knowledge of the exact latitudinal positions of Arizona at various stages during this drift phase is clouded by uncertainties concerning the Jurassic paleowander path of North America (Steiner, 1983; Gordon and others, 1984: May, 1985). The eolian sandstones and associated braided fluvial deposits of the Glen Canyon Group evidently represent the record of a vast erg that extended inland from an embayed shoreline protected by offshore island arcs lying to the west (Kocurek and Dott, 1983). During deposition of the succeeding San Rafael Group, regional transgression restricted the size of the erg but did not affect the arid to semiarid nature of bordering terrestrial environments.

Beginning in Late Jurassic time, the paleolatitudinal position and paleogeographic setting of Arizona have been generally compatable to those of the present day. Throughout that period, Arizona has remained within the temperate zone of prevailing westerlies (fig. 9). Consequently, its climate has remained subject to the rain shadows of various highland barriers that have stood to the west from time to time. As now, however, the marine influence of the Gulf of Mexico, and of the Atlantic Ocean generally, has been a constant potential moderator of aridity. During late Mesozoic time (fig. 5), the presence of the great interior Cretaceous seaway of the mid-continent, and of the extensive marine embayments of northern Mexico, would have enhanced these ameliorating effects. Nevertheless, the intermittent development of Mesozoic and Cenozoic

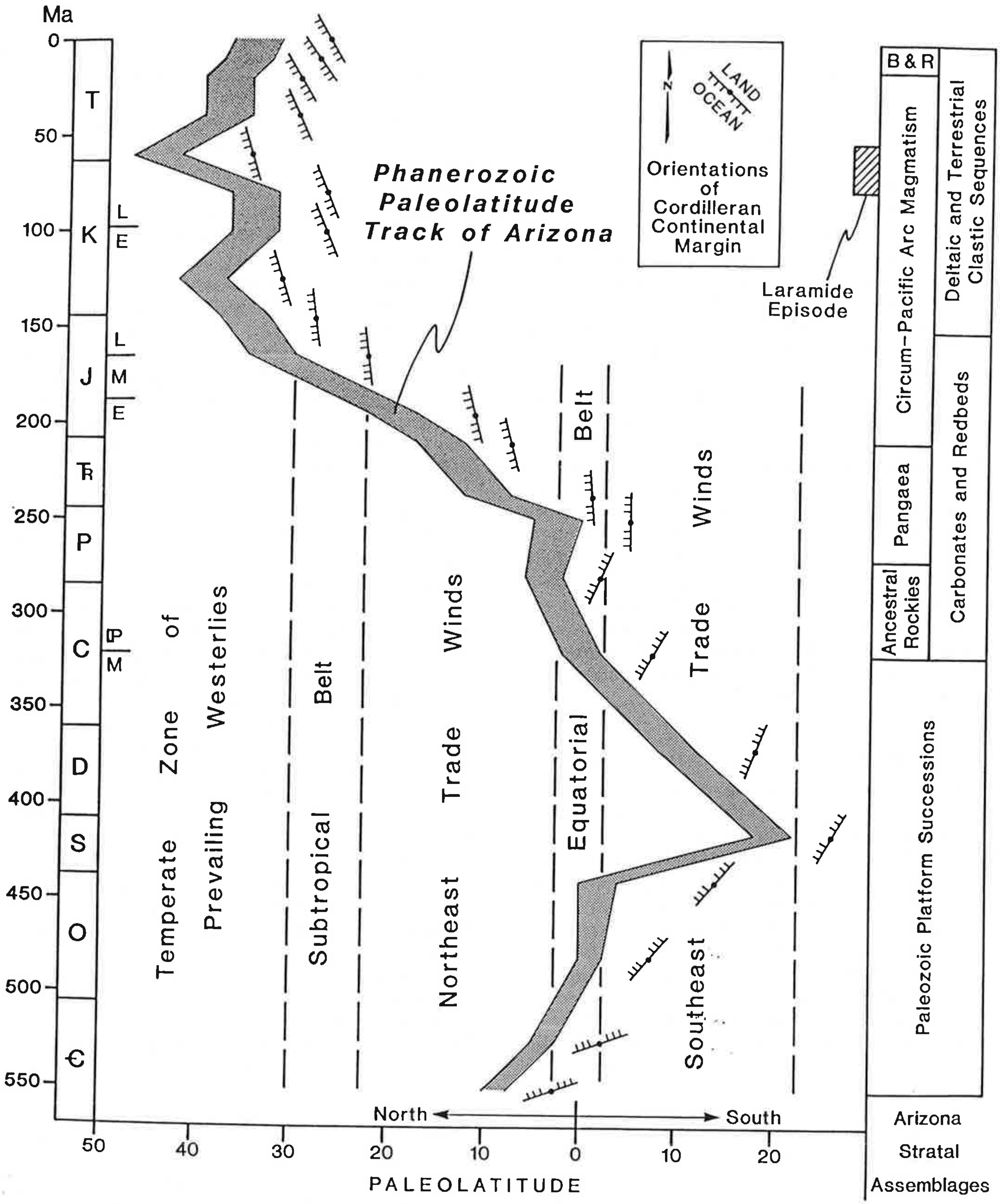

Figure 9. Changing paleolatitude of Arizona and orientation of the nearby Cordilleran continental margin through Phanerozoic time (see text for discussion). Approximate paleolatitudes interpolated from paleocontinental maps of Smith and others (1981) with ages adjusted to DNAG scale (Palmer, 1983). "B & R" denotes Basin and Range tectonism.

highlands of varied origins in southern and western Arizona has taken place within an essentially persistent climatic regime. As a result, piedmont fanglomerates and more distal fluvial and lacustrine deposits ranging in age from latest Jurassic to Holocene display remarkably similar sedimentological features throughout the region.

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Overview of Proterozoic Metamorphism in Arizona

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ABSTRACT

Proterozoic rocks in Arizona preserve a range of peak metamorphic temperatures (300-750 °C) and consistently low pressures (~3 kbar) across a complex assemblage of tectonic blocks and orogenic provinces. Peak metamorphism in the Mojave Province, California and northwestern Arizona, and in the Yavapai Province, central Arizona, occurred during the 1.7 Ga Yavapai orogeny. Rocks in the Mojave Province preserve granulite facies assemblages (600-750 °C, 2-3.5 kbar). Rocks in the Yavapai Province preserve greenschist to amphibolite facies assemblages; peak conditions ranged from 580-650 °C, 2-2.5 kbar in the northwest (Hualapai block) to approximately 400 °C, 2-3 kbar in the southeast (Green Gulch, Big Bug, Ash Creek blocks). The general increase in metamorphic temperatures toward the northwest crudely corresponds with an increase in the surface exposure of 1.7 Ga synmetamorphic plutons. Local amphibolite facies domains ("hot spots") with temperatures as high as 650 °C are preserved near syntectonic plutons in the Hualapai and Big Bug blocks. The greenschist facies Ash Creek and Green Gulch blocks contain no 1.7 Ga plutons and display only non-penetrative 1.7 Ga deformational fabrics.

Metamorphism in the Mazatzal Province, southeastern Arizona, occurred during the 1.66-1.60 Ga Mazatzal orogeny. Assemblages indicate a range in peak conditions from the lowermost greenschist facies (less than 300 °C, 2 kbar) in the northwest (Mazatzal block) to greenschist or lower amphibolite facies (420-460 °C, 2-3 kbar) in the southeast (Sunflower and Pinal blocks). Amphibolite facies assemblages occur near syntectonic plutons in the Sunflower and Pinal blocks. The increase in metamorphic grade from northwest to southeast may reflect a foreland to hinterland transition, with a slightly increased depth of exposure and an increased component of plutonic heat to the southeast.

The Proterozoic of Arizona may represent a broad low-P, high- (but variable) T metamorphic terrane in which many of the anomalously high temperatures primarily reflect the effects of synmetamorphic plutons. Ambient regional metamorphic conditions away from plutons, at least in the Yavapai and Mohave Provinces, were in the greenschist facies (~400 °C, 2.5 kbar). The metamorphic data are consistent with a model involving the (1.74 - 1.60 Ga) convergent accretion of thin, warm, dominantly arc-related crust to the margin of North America with important pulses of plutonism and thermal metamorphism at 1.7 and 1.66-1.60 Ga. Plutonic heat may have also played a role in partitioning deformation between blocks and block boundaries, and thus, may have contributed to the overall block-structure of the region.

INTRODUCTION

Proterozoic rocks in Arizona are part of a broad orogenic belt in which dominantly juvenile crustal materials were accreted to the margin of Laurentia between 1.8 and 1.6 Ga (Hoffman, 1988; Bowring and Karlstrom, 1990). The rocks are exposed in a northwest-trending cross-sectional transect of the orogenic belt (Fig. 1). Based on geologic, geochemical, and geochronological data, the transect has been subdivided into three orogenic provinces which have been further subdivided into eight structural blocks separated by shear zones (Karlstrom and Bowring, 1988). A major goal of recent research has been to understand the history and tectonic significance of this distinctive block architecture.

Metamorphic analysis offers the potential to add new insights into the evolution of and relationships between the crustal blocks and provinces. Preliminary data indicate that some block boundaries represent metamorphic discontinuities. However, few metamorphic studies have been carried out, and only recently have quantitative metamorphic data become available to compare metamorphic conditions and histories across the block bounding shear zones. The purposes of this paper are: (1) to summarize available metamorphic data from each of the major crustal blocks in the Arizona transect, (2) to compare, where possible, the character and timing of metamorphism across the block and province boundaries, and (3) to highlight areas where future metamorphic studies will be most critical for evaluating tectonic models.

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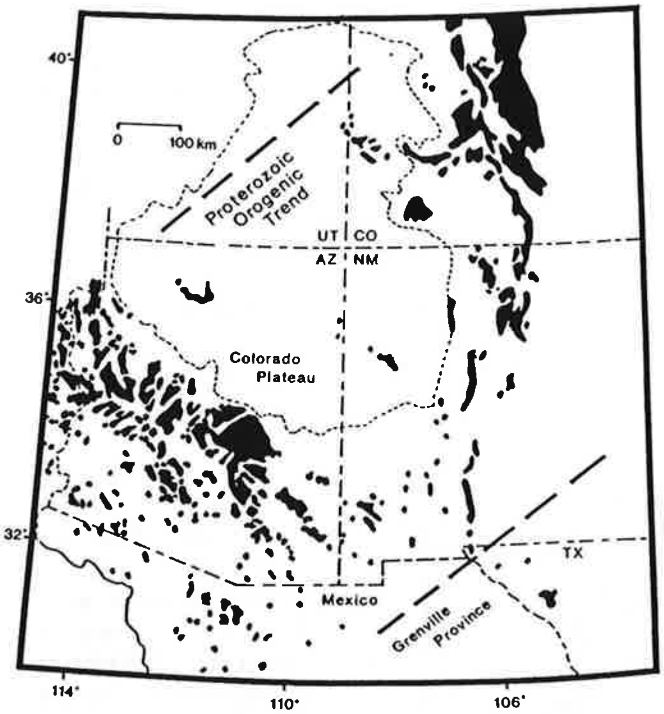

Figure 1. Distribution of Proterozoic rocks in southwestern North America showing the approximate boundaries of the Early Proterozoic orogenic belt. Modified from Williams (1990).

GEOLOGIC BACKGROUND

Proterozoic rocks in southwestern North America are part of a broad orogenic belt that extends from southern California to Labrador, Greenland, and the Baltic Shield (Hoffman, 1988). A variety of metamorphosed volcanic, sedimentary, and plutonic rocks are exposed, but isotopic data suggest that most of the rocks were juvenile materials when they were added to the Archean nucleus of North America at 1.8-1.6 Ga (DePaolo, 1981, Bennett and Depaolo, 1987). The Transition Zone of Arizona (Fig. 1,2) exposes a 500 km long transect ("Arizona transect") across the Proterozoic orogen (Karlstrom and Bowring, 1988).

The Arizona transect has been divided into three orogenic provinces: (1) the Mojave Province, which contains isotopic evidence for significant involvement of older crust (Wooden and others, 1988; Chamberlain and Bowring, 1990; Wooden and DeWitt, this volume); (2) the Yavapai Province which contains dominantly juvenile rocks deformed at approximately 1.7 Ga; and (3) the Mazatzal Province, deformed at approximately 1.65 Ga (Karlstrom and Bowring, 1988). Each of the provinces has been divided into tectonic blocks bounded by major shear zones (Fig 2. ; Karlstrom and Bowring, 1988). Eight blocks are recognized in Arizona, the Mojave block in the Mojave Province, the Hualapai, Green Gulch, Big Bug, and Ash Creek blocks in the Yavapai Province, and the Mazatzal, Sunflower, and Pinal blocks in the Mazatzal Province. The blocks are geographic segments of the orogen that have been interpreted to show differences in tectonic history relative to each other. Understanding differences and similarities between blocks remains the key to understanding the orogenic history. The blocks may represent some combination of the following: (1) independent terranes assembled during convergent tectonism, (2) low-strain domains formed by deformation partitioning within a single tectonic terrane, or (3) domains of differential uplift and adjustment after, perhaps long after, a collisional orogeny (Bowring and Karlstrom, 1990).

In the Mojave and Yavapai Provinces, at least two major fabric-forming deformation phases can be distinguished (Albin and Karlstrom, this volume; Burr, this volume; Karlstrom and Bowring, this volume). Phase 1 is characterized by northwest-striking, steeply to shallowly dipping foliations. Karlstrom and Bowring (this volume) interpreted these fabrics to reflect shortening across a north- to northwest-trending magmatic arc, perhaps in two separate events, one at 1.74-1.735 Ga and the other at 1.72-1.70 Ga. Phase 2 is characterized by upright northeast-trending folds and a variably developed, northeast-striking, steeply dipping foliation, typically with a steeply plunging mineral lineation. These structures are interpreted to reflect shortening across a northeast-trending margin during the 1.7 Ga Yavapai orogeny (Karlstrom and Bowring, this volume). Block-bounding shear zones commonly record northwest-side-up shearing during this phase of deformation (Darrach, 1988; Karlstrom and Bowring, this volume; Burr, this volume).

Rocks in the Mazatzal Province are characterized by variably developed, northeast-striking, steeply dipping deformational fabrics, formed during the 1.66-1.60 Ga Mazatzal orogeny. The orogeny is believed to represent the development and deformation of a northeast-trending continent margin arc, south of the now assembled Yavapai Province (Karlstrom and Bowring, this volume).

Granitoids are abundant throughout the Proterozoic orogen in Arizona, comprising as much as 50% of the exposed terrane. They provide important age constraints on deformation and metamorphism. More importantly, they played a significant role in localizing deformation and metamorphism and in stabilizing the newly formed Proterozoic crust. A wide range in age and composition is exposed, but four ages may be particularly important. (1) 1.74-1.73 Ga plutons, primarily granodiorites and diorites, locally appear to post-date the development of early northwest-trending fabrics in the Mojave and Yavapai provinces. (2) 1.7 Ga granite and quartz monzonite plutons are present in all three provinces, and are generally synchronous with phase 2 shortening in the Mojave and Yavapai provinces (Karlstrom and Bowring, this volume). (3) 1.66 - 1.63 Ga granitoids occur in the Mazatzal Province, particularly in the Sunflower and Pinal blocks, and may

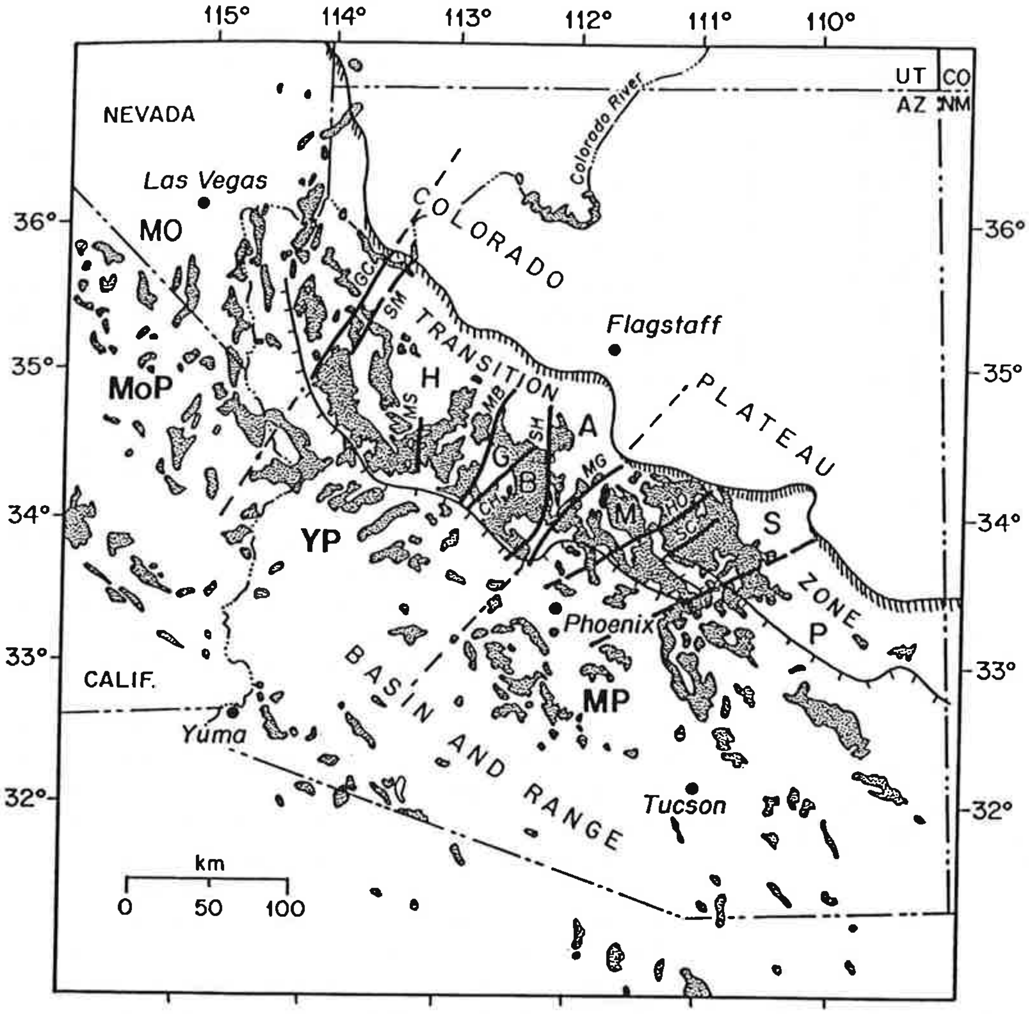

Fig. 2. Generalized map of Proterozoic rocks in Arizona showing the location of orogenic provinces and tectonic blocks. Dashed lines represent approximate province boundaries: MoP-Mojave Province, YP-Yavapai Province, MP-Mazatzal Province. Block abbreviations: MO-Mojave, H-Hualapai, G-Green Gulch, B-Big Bug, A-Ash Creek, M-Mazatzal, S-Sunflower, P-Pinal. Major Proterozoic shear zones: GC-Gneiss Canyon, SM-Slate Mountain, MS-Mountain Springs, MB-Mesa Butte, CH-Chaparral, SH-Shylock, MG-Moore Gulch, SC-Slate Creek. Modified from Karlstrom and Bowring (1988).

define the hinterland of the Mazatzal orogenic belt. Plutons in this age range also occur as post-deformational plutons in the Mojave Province (Wooden and Miller, 1991). (4) 1.4 Ga "anorogenic" granitic plutons are present in all three provinces and may correspond to an important period of uplift and stabilization of the Proterozoic crust (Bowring and Karlstrom, 1990).

Regional metamorphism coincided with the 1.7 Ga phase 2 deformation in the Mojave and Yavapai Provinces and with the 1.65 Ga deformation in the Mazatzal Province. Peak metamorphic conditions vary significantly across the Arizona transect (Anderson, 1989; Bowring and Karlstrom, 1990). Two regional gradients have been noted. In the Mojave and Yavapai provinces, metamorphic conditions increase from southeast to northwest, from greenschist facies conditions in the Ash Creek block to granulite facies conditions in the Mojave block. In the Mazatzal Province, peak metamorphic conditions apparently increase from northwest to southeast, but conditions in the Pinal block (farthest southeast) are still poorly constrained.

METAMORPHIC DATA

The block architecture of the Arizona transect (Karlstrom and Bowring, 1988) provides a useful geographic and tectonic framework for evaluating the metamorphic conditions across the region. In addition to the province-scale metamorphic gradients, metamorphic discontinuities have been observed at several block boundaries (Karlstrom and Bowring, 1988; Bowring and Karlstrom, 1990). In fact, the discontinuities have been used in part to define several of the blocks. In the following section, metamorphic data are summarized and evaluated, block by block, from northwest to southeast. The data are also briefly summarized in Table 1.

Metamorphic data presented here come from a variety of sources including published manuscripts, unpublished M.S. and Ph.D. theses, and preliminary results of ongoing investigations. Several detailed investigations are currently under way to evaluate metamorphic relationships within blocks (i.e. Karlstrom and others, 1990; Williams and Karlstrom, 1990; Williams, 1991) and across block-bounding shear zones such as the Gneiss Canyon shear zone

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MIDDLE TERTIARY TECTONICS OF ARIZONA AND ADJACENT AREAS

by
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ABSTRACT

Middle Tertiary tectonics in the Basin and Range Province of Arizona and adjacent parts of southeastern California and southern Nevada were dominated by large-magnitude lithospheric extension accommodated at upper crustal levels primarily by formation of and movement on regional, low-angle normal (detachment) faults. Unidirectional tilting of upper-plate fault blocks over large areas referred to as tilt-block domains reflects the geometry and movement direction of underlying detachment faults. Large displacements on detachment faults resulted in denudation and isostatic uplift of lower-plate mylonitic crystalline rocks that are now exposed in archlike structural culminations known as metamorphic core complexes. Mylonitic fabrics in these complexes formed by ductile shear along the deeper, downdip projections of detachment faults. Crustal extension occurred in the lower crust beneath the Transition Zone, which was probably tilted one to two degrees to the southwest as a result of greater crustal thinning beneath its southwestern margin. Relative elevation changes between the Basin and Range Province and Colorado Plateau occurred in association with tilting of the Transition Zone and were marked by a reversal in drainage direction and formation of many of the basic features of modern Arizona physiography. Crustal extension was accompanied by widespread, dominantly silicic magmatism that migrated from east to west across Arizona. Both extension and the westward sweep of magmatism are inferred to be related to steepening and perhaps disintegration of the subducted lithospheric slab beneath southwestern North America.

INTRODUCTION

The middle Tertiary tectonic evolution of Arizona and adjacent areas was dominated by two processes: lithospheric extension and a resurgence of magmatism following a 10- to 30-Ma period of magmatic quiescence. Both extension and magmatism were related to the evolving plate-tectonic setting of the continental margin of western North America, which is fairly well understood based on marine magnetic-anomaly data and global plate reconstructions (Atwater, 1970; Jurdy, 1984).

Middle Tertiary magmatism and extensional deformation in the Basin and Range Province of Arizona (fig. 1) and adjacent areas overprinted crust that had experienced previous periods of magmatism and compressional deformation. The most significant earlier period of widespread magmatism, compressional deformation, and inferred crustal thickening was in middle to Late Cretaceous and early Tertiary time. The fact that mid-Tertiary tectonism occurred largely in areas that had experienced earlier deformation and magmatism (the Colorado Plateau consistently escaped significant deformation) suggests that the earlier tectonic history of the crust exerted control over the locus of later mid-Tertiary activity. The nature of this

Figure 1. Map of the major physiographic provinces of Arizona.

control is only very general, however, as specific mid-Tertiary faults and related structures generally do not have any obvious relationship to older structures (e.g., Wernicke and others, 1985).

The Basin and Range Province extends from the Snake River Plain in Idaho southward through Arizona into Mexico. It is characterized by numerous, typically north-trending (± 30°) ranges bounded by Cenozoic sedimentary basins that are as deep as several kilometers. Whereas high-angle normal faults bounding one or both sides of these ranges have been recognized as characteristic features of the Basin and Range Province for some time (e.g., Nolan, 1943; Stewart, 1971, and references therein), low-angle normal faults have only been widely recognized since the 1970s (e.g., Anderson, 1971; Armstrong, 1972) and are now considered to be fundamental structural features of the region (Crittenden and others, 1980; Frost and Martin, 1982). High-angle normal faults did not accommodate more than about 20 to 30 percent extension (Stewart, 1980) and possibly much less in parts of Arizona and southeastern California, yet 50 to 100 percent extension is indicated by paleogeographic reconstructions (Hamilton and Myers, 1966; Hamilton, 1969), inferred changes in crustal thickness (Hamilton, 1978), and strike-slip fault displacements (Wernicke and others, 1982). Low-angle normal faults accommodated much of the large-magnitude crustal extension.

In Arizona and perhaps most areas of the Basin and Range Province, low-angle normal faulting preceded formation of large, range-bounding, high-angle normal faults. Middle Tertiary crustal extension associated with low-angle normal faulting was directed east-northeast-west-southwest in Arizona and much of the southern Basin and Range Province, whereas late Tertiary extension associated with high-angle normal faulting was directed in an east-west to east-southeast-west-northwest direction (Zoback and others, 1981). In Arizona, this change in extension direction and style was approximately coeval with a change from dominantly intermediate and silicic magmatism in an intra-arc setting to dominantly basaltic magmatism following cessation of subduction and development of the San Andreas transform system (Lipman and others, 1972). Changes in extension direction were possibly the result of a component of right-lateral shear associated with the San Andreas transform system superimposed on the extensional tectonic regime of the Basin and Range Province. The cause of the change in style of extension is not understood, but was possibly cooling and strengthening of the distended lithosphere (England, 1983).

In this paper we review evidence for the nature and character of mid-Tertiary magmatism, space-time patterns of magmatism, and the character and timing of extensional deformation. Reversal of the relative elevations of the Colorado Plateau and the Basin and Range Province also occurred in mid-Tertiary time and must be incorporated into any synthesis of mid-Tertiary tectonics in Arizona and the southwest. We do not discuss high-angle normal faulting and associated basaltic magmatism that occurred after about 13 Ma (late Tertiary and Quaternary).

MAGMATISM AND PLATE-TECTONIC SETTING

Between Oligocene and middle Miocene time, many areas in the Basin and Range Province were blanketed by hundreds to thousands of meters of volcanic rocks and were punctured by calderas, granitic plutons, and numerous dikes. The volcanic sections are dominated by silicic to intermediate flows and pyroclastic rocks, including widespread silicic ash-flow tuffs (Shafiqullah and others, 1978, 1980; Damon, this volume; Nealey and Sheridan, this volume). True basalts are sparse in middle Tertiary volcanic fields in southeastern Arizona, but are more common in central and west-central Arizona where some volcanic fields are fundamentally bimodal in composition (e.g., Suneson and Lucchitta, 1983; Capps and others, 1985). Volcanism in many areas was synchronous with middle Tertiary tectonism, as demonstrated by synvolcanic angular unconformities and by the restriction of some volcanic units and synvolcanic sedimentary deposits to fault-bounded troughs or half grabens. In other areas, volcanism was either earlier or was spatially separated from tectonism, as indicated by regionally extensive volcanic units that were erupted across large areas of low relief.

Volcanic rocks are locally associated with dikes and subvolcanic intrusions, some of which represent magmatic conduits for the volcanics. Deeper level middle Tertiary plutons, some as large as 15 km in diameter, are more widely distributed than previously appreciated and are present in Arizona in the Dos Cabezas, Swisshelm, Pinaleno, Santa Teresa, Dragoon, Santa Catalina, Tortolita, Picacho, South, White Tank, Belmont, Little Ajo, Painted Rock, Palomas, and Black Mountains, and Bouse Hills (Shafiqullah and others, 1978, 1980; Marvin and others, 1978; Keith and others, 1980; Banks, 1980; Erickson, 1981; Rehrig, 1982; Reynolds, 1985; Reynolds and others, 1985; R. Tosdal and G. Haxel, personal commun., 1985). The apparent lack of large middle Tertiary plutons in some uplifted crustal blocks, such as the Harcuvar and Harquahala Mountains, indicates that such plutons do not underlie the entire region, but were generally isolated, point sources of magma and heat.

Although there is general agreement that the main pulse of magmatism occurred between 30 and 15 Ma, there has been some disagreement about the precise timing of the change to fundamentally basaltic magmatism related to the Basin and Range disturbance (Damon and Mauger, 1966; Lipman and others, 1972; Elston, 1976; Coney and Reynolds, 1977; Shafiqullah and others, 1980; Damon and others, 1984). The timing of this switchover is clearly indicated on a plot of initial $^{87}Sr/^{86}Sr$ ratio (Sr_0) versus age

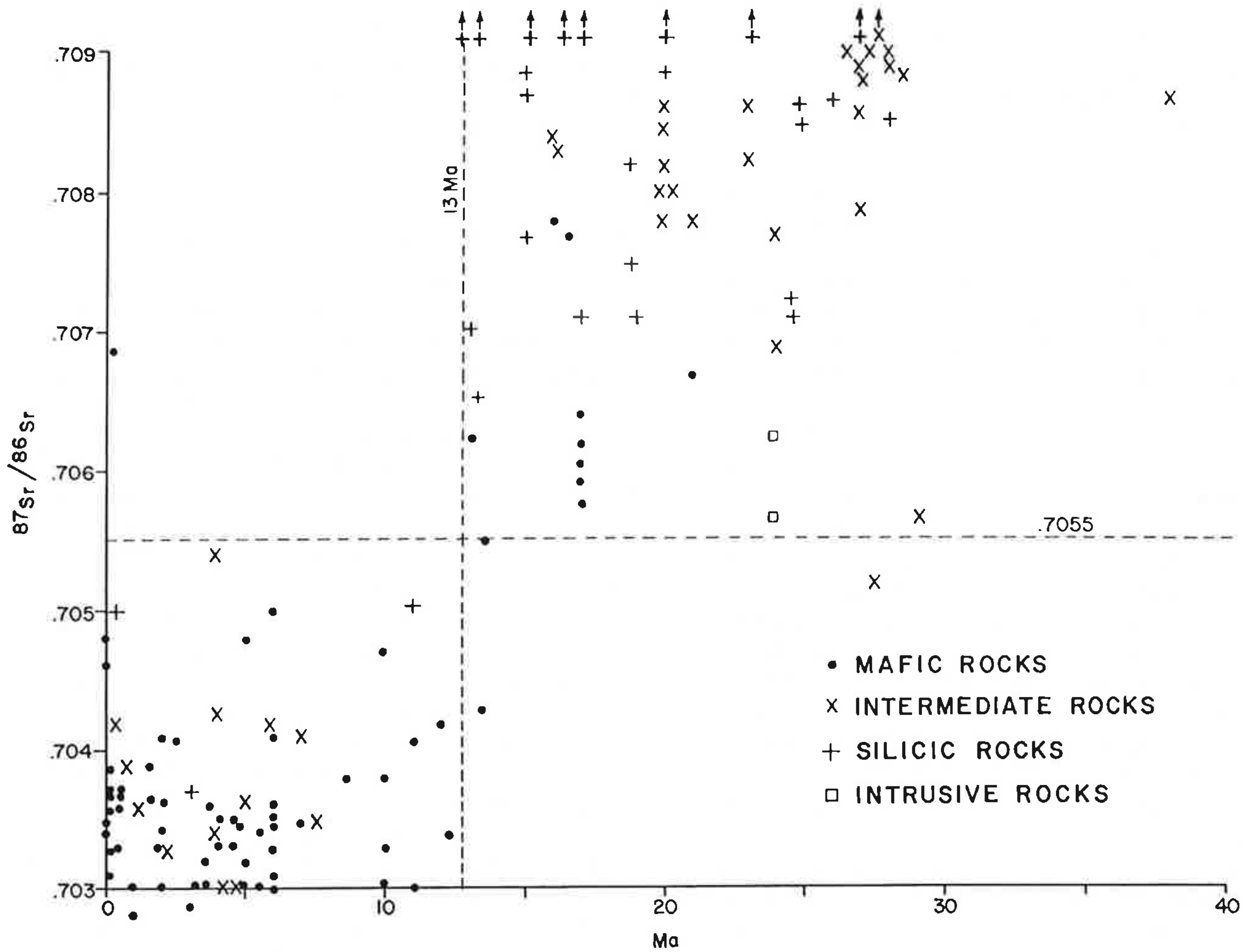


Figure 2. Plot of age versus initial $^{87}Sr/^{86}Sr$ for post-40-Ma igneous rocks in Arizona. Note that igneous rocks older than 13 to 15 Ma have initial $^{87}Sr/^{86}Sr$ ratios greater than 0.7055, whereas those younger than 13 to 15 Ma have initial $^{87}Sr/^{86}Sr$ ratios less than 0.7055. Data from various sources, most of which are listed in Reynolds, Florence, and others, (1986) or Sheridan and Nealey (this volume).

for post-40-Ma igneous rocks in Arizona (fig. 2). This plot reveals that a fundamental change in magma chemistry occurred at 13 to 15 Ma (see also Annis and Keith, 1986). Magmatic rocks formed prior to this time are characterized by Sr_0 of greater than 0.7055 (averaging 0.7086; see Damon, this volume). Magmatic rocks formed after this time, including the dacitic to rhyolitic rocks of the San Francisco and Hackberry Mountain volcanic fields, generally have Sr_0 of less than 0.7055 (see references in Reynolds, Florence, and others, 1986). The magmatic change at 13 to 15 Ma is also reflected by major changes in mineralogy, petrochemistry, metallogeny, and overall lithologic abundances of the magmatic rocks (Keith and Wilt, 1985; Annis and Keith, 1986). In essence, igneous suites older than 13 to 15 Ma are mostly alkali-calcic to calc-alkalic, are compositionally diverse, and contain minor true basalts (except in central and west-central Arizona), whereas those younger than 13 to 15 Ma are dominated by alkaline basalts with only local intermediate to felsic rocks. The precise age of the switchover varies slightly with geographic area; it is 15 Ma in central Arizona, 12.5 Ma in the Castaneda Hills of west-central Arizona, and probably 11 to 12 Ma in the Lake Mead area.

The initiation, climax, and termination of middle Tertiary magmatism were diachronous across Arizona and adjacent states. A compilation of all radiometric age determinations in Arizona (Reynolds, Florence, and others, 1986) and adjacent areas confirms that the main pulse of magmatism and volcanism is time transgressive from east to west across southern New Mexico and Arizona (fig. 3; Coney and Reynolds, 1977; Dickinson, 1979; Damon and others, 1981; Lipman, 1981; Seager and others, 1984; Reynolds, Welty, and Spencer, 1986). Magmatism began in southern New Mexico at 40 to 36 Ma, crossed the Arizona-New Mexico border before 30 Ma, and had transgressed westward across southeastern Arizona by 25 Ma (Reynolds, Welty, and Spencer, 1986). At about 25 Ma, the simple westward progression of magmatism was complicated by the apparent initiation of significant volcanism in southwestern Arizona and southeastern California synchronous with continued magmatism in southeastern Arizona. By 20 Ma, the locus of magmatism had shifted

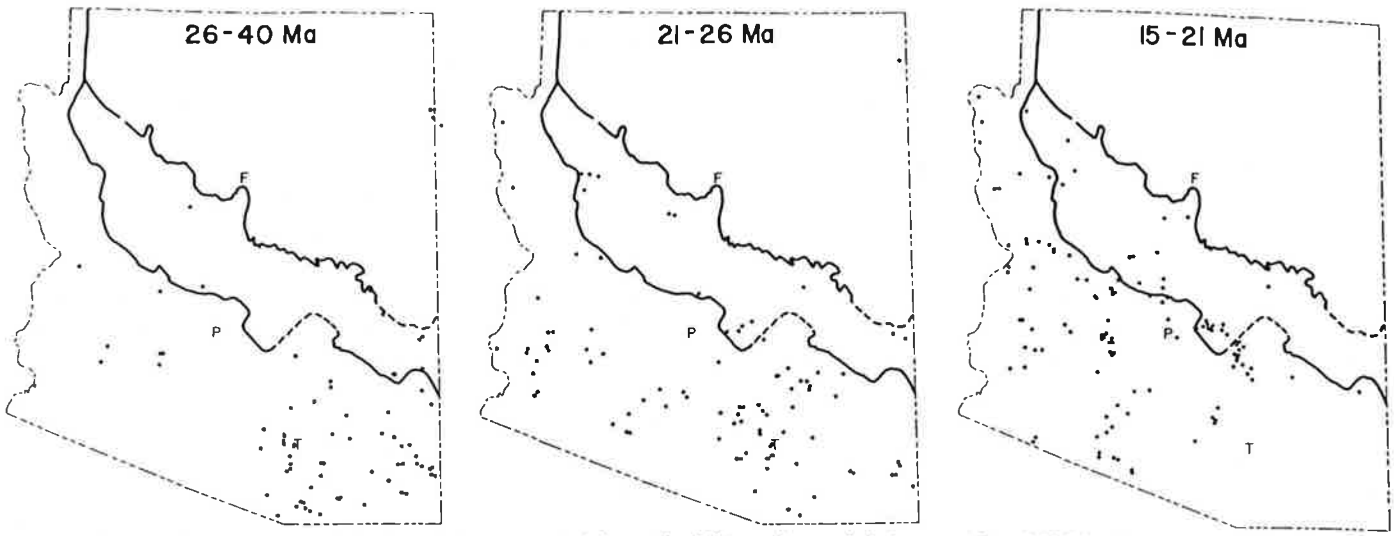


Figure 3. Maps showing distribution of K-Ar dates in Arizona for different time periods between 40 and 15 Ma. The maps include only those dates that can be reasonably regarded as the true emplacement age of the dated igneous rock (see comments in Reynolds, Florence, and others, 1986). The maps demonstrate that middle Tertiary magmatism was concentrated in eastern Arizona between 40 and 27 Ma, was widespread between 21 and 27 Ma, and was largely restricted to western Arizona after 21 Ma. Magmatism therefore migrated westward with time. T=Tucson, P=Phoenix, F=Flagstaff.

westward out of southeastern Arizona and into western Arizona, southeastern California, and coastal Sonora. An analogous westward progression of magmatism across northern Arizona may be represented by the emplacement of diatremes and alkalic rocks in northeastern Arizona at 25 to 30 Ma and subsequent eruption of similar alkaline rocks in central and northwestern Arizona at 20 to 25 Ma (fig. 3; see references in Reynolds, Florence, and others, 1986). The clear westward younging of volcanism contradicts the conclusions of Glazner and Supplee (1982) who proposed that magmatism throughout Arizona migrated northward with time.

Space-time patterns of Cretaceous and Tertiary magmatism can be related to changes in plate-tectonic setting. Based on the interpretation that calc-alkaline and alkali-calcic magmatism was triggered by subduction and that magmatism occurs at the Earth's surface above areas where the top of a subducted slab comes into contact with the asthenosphere (depth typically 80-150 km, e.g., Barazangi and Isacks, 1976), migrating patterns of magmatism at convergent plate margins can be used to determine the changing inclination of a subducted slab. During the Late Cretaceous and early Tertiary Laramide orogeny, the eastward sweep of magmatism across Arizona is interpreted as a consequence of a decreasing dip of an east-dipping subduction zone (Coney, 1976; Coney and Reynolds, 1977; Dickinson and Snyder, 1978; Dickinson, 1981). The decrease in dip has been attributed to rapid convergence between the North American and Farallon plates, rapid westward absolute motion of North America, and possible subduction of aseismic ridges (Coney, 1976; Keith, 1982; Henderson and others, 1984). By Eocene time, the subducted slab had a very shallow dip that resulted in complete cessation of all magmatism in Arizona except crustally derived, peraluminous, two-mica granites (Keith and Reynolds, 1980, 1981). The westward return sweep of magmatism from 40 to 20 Ma was probably a result of an increase in dip of the subducted plate (Coney and Reynolds, 1977; Dickinson, 1981; Lipman, 1981). The widespread distribution of volcanism at 20 Ma may reflect complete foundering or breaking up of the subducted slab (Coney and Reynolds, 1977). The termination of middle Tertiary magmatism and switch to fundamentally basaltic volcanism was probably a response to cessation of subduction due to creation of the lengthening North America-Pacific transform and resulting growth of a no-slab window beneath Arizona (Lipman and others, 1972; Shafiqullah and others, 1978, 1980; Dickinson and Snyder, 1979; Lipman, 1981; Damon and others, 1984).

Plate-tectonic setting, migration patterns, and geochemistry of middle Tertiary magmatism in Arizona provide constraints on the origin of the magmas. Keith (1978, 1982; see also Keith and Wilt, 1985) has presented evidence that changes in alkalinity, both in time and in space, are supportive of a steepening subduction zone. These migration patterns and alkalinity variations cannot be accounted for by models that attribute middle Tertiary magmatism to nonsubduction-related crustal melting due to mantle diapirs (see review by Elston, 1976) or Mesozoic crustal thickening (Glazner and Bartley, 1985). Such models also do not account for geochemical differences between Eocene peraluminous granites, which are known to be crustal melts, and middle Tertiary igneous rocks, which were derived in part from the mantle (Farmer and DePaolo, 1984). However, modeling of possible mantle and crustal contributions to middle Tertiary magmas using Sr, Nd, and Pb isotopes (Farmer and DePaolo, 1984) is hindered by uncertainties about the isotopic signatures of lower versus middle crust and of lithospheric mantle versus asthenospheric mantle. The local presence of relatively radiogenic late Tertiary basalts with Sr_0 of up to 0.7055 demonstrates that the mantle below Arizona is compositionally heterogeneous (Leeman, 1982).

CRUSTAL EXTENSION

Middle Tertiary tectonic activity in Arizona was dominated by widespread normal faulting and fault-block rotation that accommodated major northeast-southwest to east-northeast—west-southwest crustal extension. Movement occurred on low- to high-angle normal faults, and many high-angle normal faults are known or suspected to be truncated downward by, or to flatten downward and merge with, major detachment faults. Detachment faults in Arizona and the southwest have several to several tens of kilometers of displacement and are the most important structural features of mid-Tertiary age in the Basin and Range Province.

Upper-plate rocks above major detachment faults are, in most cases, tilted dominantly in one direction—toward the breakaway fault and opposite to the direction of upper-plate displacement (fig. 4). Areas of uniform tilt direction are referred to as tilt-block domains (fig. 5) and are known or inferred to be representative of distension above one detachment fault or several faults that dip regionally in the same direction. Tilting and distension above detachment faults produced numerous half grabens and associated asymmetric sedimentary basins that received abundant clastic detritus from nearby upper-plate rocks. Conglomerate, sandstone, and siltstone, in many areas with associated volcanic rocks and sedimentary breccias representing catastrophic debris avalanches (e.g., Krieger, 1977), are typical. Sedimentary and volcanic sequences within some half grabens are progressively less tilted upsection because sedimentation occurred during tilting.

Lower-plate rocks typically consist of plutonic and high-grade metamorphic rock exposed in antiformal or domal

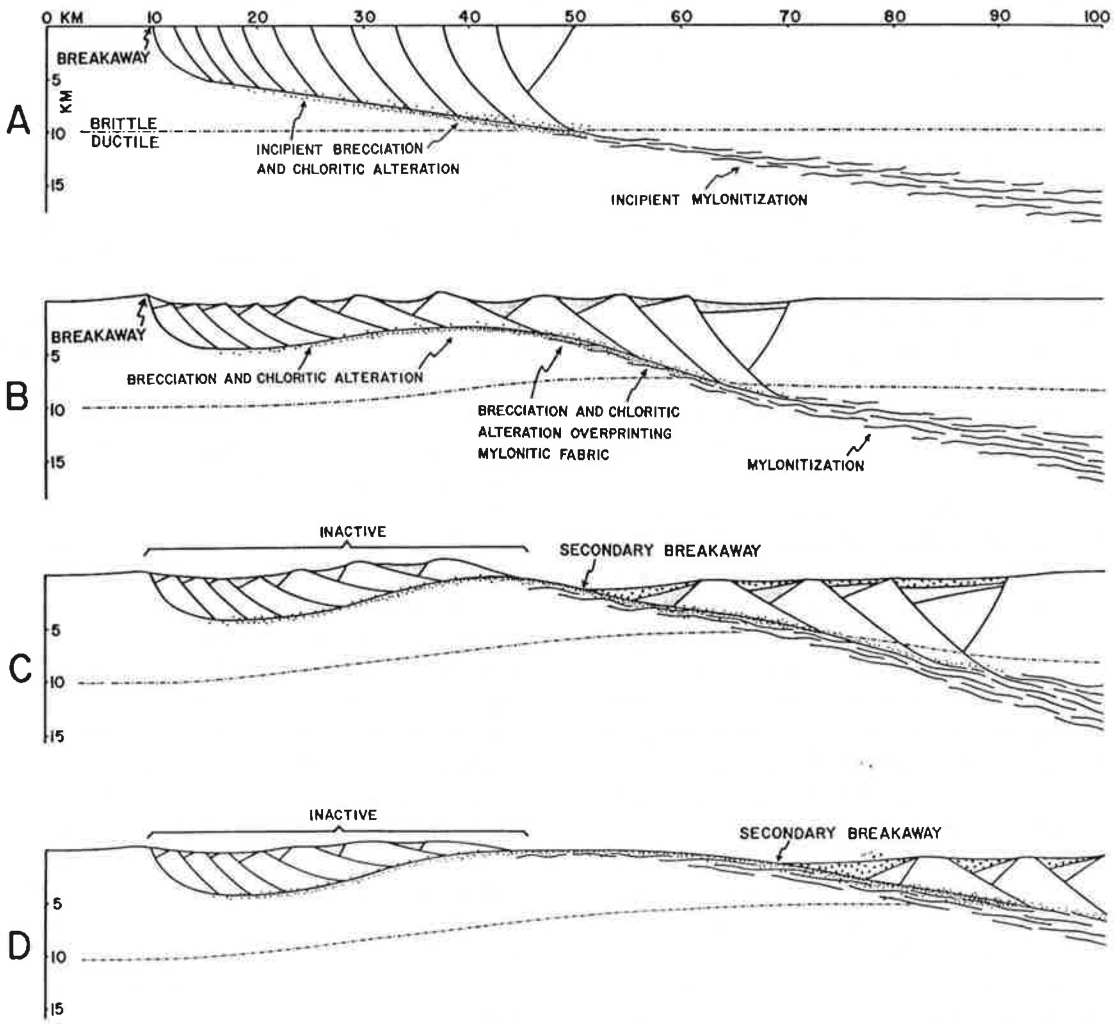


Figure 4. Evolutionary cross sections of a hypothetical detachment fault-ductile shear zone and the formation of a metamorphic core complex. (A) Detachment fault is shown as initially planar below 5 km and listric above. The detachment fault projects downward across the brittle-ductile transition to become a ductile shear zone. (B) Isostatic uplift of the lower plate due to denudation leads to arching of the footwall. Footwall rocks originally mylonitized below the brittle-ductile transition rise isostatically through the transition and are overprinted by brittle structures adjacent to the detachment fault. Syntectonic sediments fill grabens and half grabens. (C) Continued arching and uplift of the footwall result in termination of detachment-fault movement to the left of the arch and formation of a secondary breakaway to the right. In some complexes, displacement of the arch *above* moderately dipping listric normal faults results in further arching due to reverse drag. Syntectonic sediments locally include clasts derived from the lower plate adjacent to the secondary breakaway.

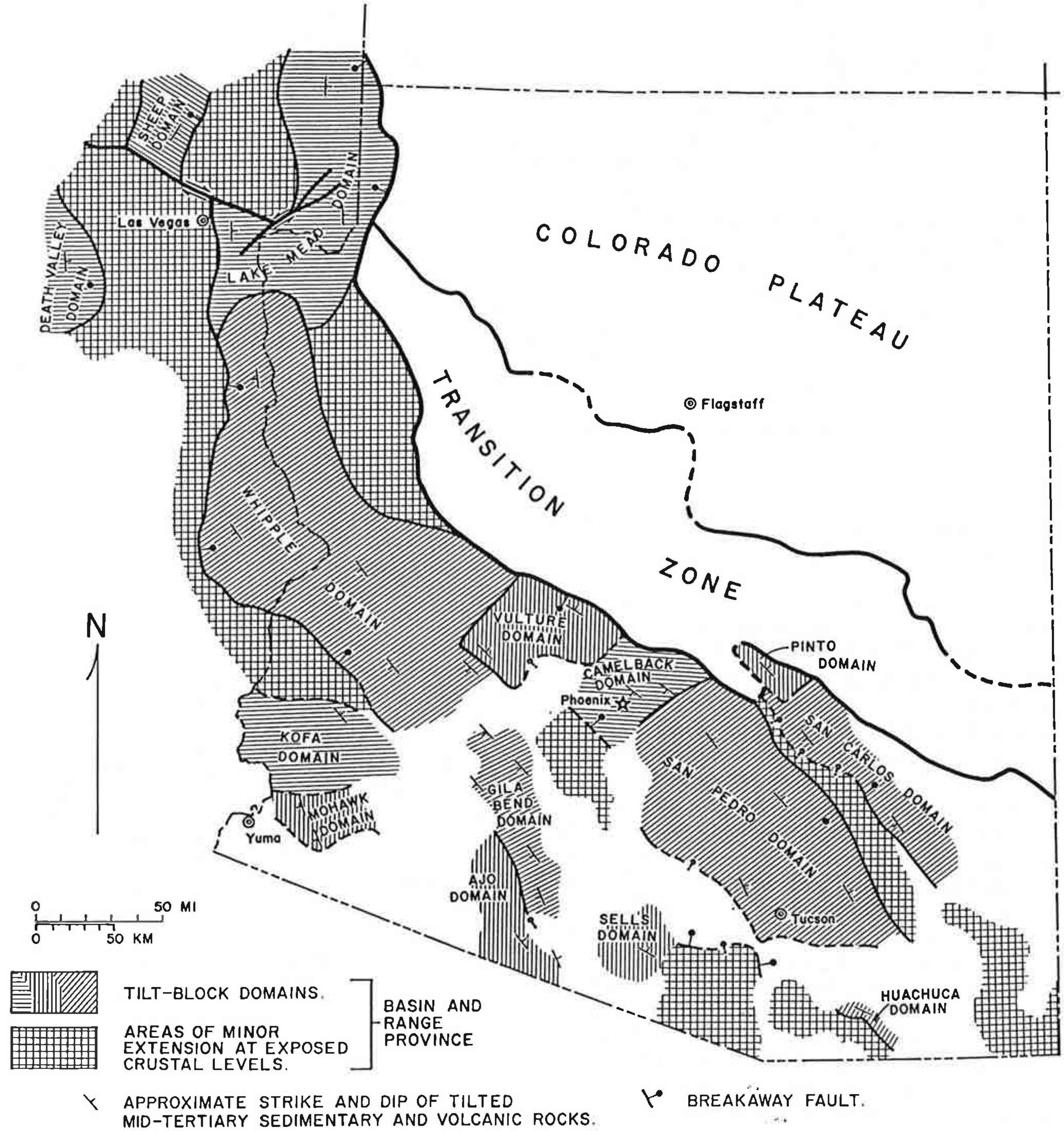


Figure 5. Mid-Tertiary tilt-block-domain map of Basin and Range Province in Arizona and adjacent parts of Nevada and California.

uplifts termed "metamorphic core complexes" (figs. 6, 7; Crittenden and others, 1980). A penetrative, lineated, mylonitic fabric that progressively dies out downward is a characteristic feature of metamorphic core complexes in Arizona. Mylonitic lineation is generally parallel to the direction of upper-plate displacement and distension, and the sense of shear during mylonitization, as indicated by S-C fabrics and other asymmetric petrofabrics (fig. 7; e.g., Berthe and others, 1979; Simpson and Schmid, 1983; Lister and Snoke, 1984), is the same as the sense of shear inferred for the overlying detachment fault based on offset indicators and tilt directions of upper-plate fault blocks (Reynolds, 1985; Davis and others, 1986; fig. 5). The mylonitic fabric ranges from being well developed over the entire uplift to being restricted to a small area along the edge of the uplift. Mylonitic and nonmylonitic rocks within a few tens to hundreds of meters below the detachment fault are fractured or brecciated and contain secondary chlorite,

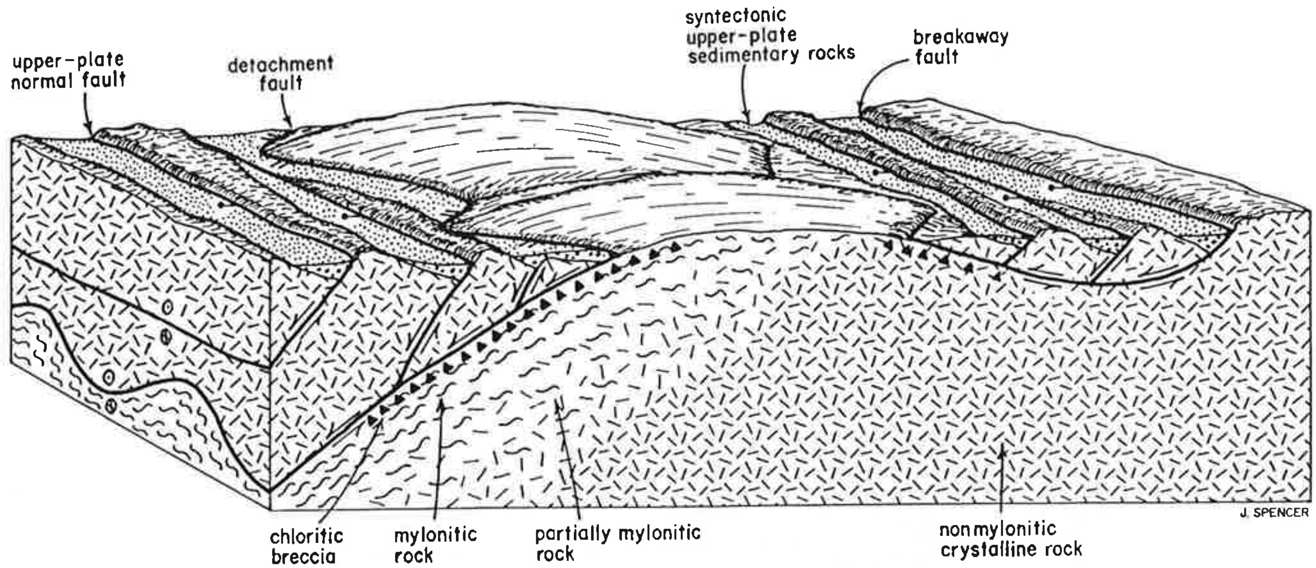


Figure 6. Idealized block diagram of a metamorphic core complex.

epidote, and hematite. Lower-plate rocks within a few centimeters to locally as much as several meters below the detachment fault commonly have been converted to hard, flinty cataclasite.

All of these structures and associated lithologies are best explained in the context of an evolving crustal shear zone (fig. 4; Wernicke, 1981; Davis, 1983; Davis and others, 1986). According to the shear-zone model, large-magnitude normal displacement on gently dipping shear zones resulted in tectonic denudation and isostatic uplift of footwall rocks that resided at depths of perhaps as much as 15 km before fault movement. Footwall rocks initially below the brittle-ductile transition (temperatures greater than about 300° C corresponding to depths greater than about 5 to 15 km) underwent ductile shearing along the downdip projection of detachment faults, resulting in formation of lineated mylonitic fabrics that die out downward away from the shear zone. As a result of tectonic denudation and associated isostatic uplift, the lower plate cooled and passed upward through the brittle-ductile transition, and deformation style changed from ductile shearing to brittle faulting and related brecciation. This change occurred at about the closure temperature for argon in biotite, and K-Ar biotite ages from lower-plate rocks record the approximate age of this transition. Hot water circulated through freshly shattered rocks near and along the fault, resulting in hydrothermal alteration and growth of chlorite and epidote. Continued uplift and cooling was associated with formation of a thin (typically 10-100 cm) layer of microbreccia adjacent to the fault surface, and finally with formation of fault gouge (Davis and others, 1986). In some areas, lower-plate mylonitic rocks were completely denuded by detachment faulting, and clasts of mylonitic rock, eroded from below the fault, were deposited in basins formed by ongoing tilting of upper-plate fault blocks (e.g., Spencer, 1984; Spencer and Reynolds, 1987).

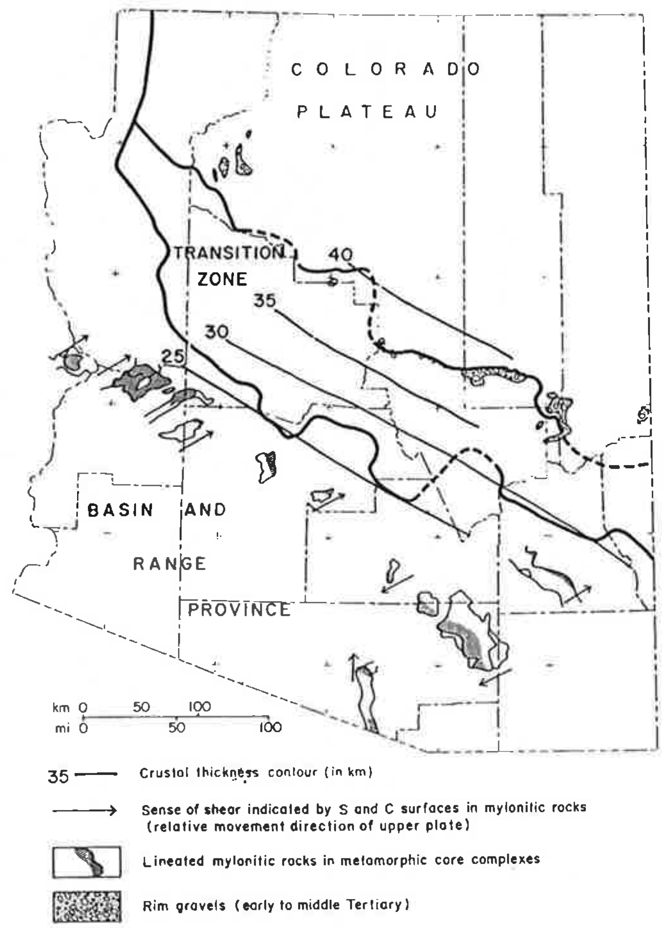


Figure 7. Map of Arizona showing crustal thickness changes associated with the Transition Zone and location of metamorphic core complexes and early to middle Tertiary rim gravels. The rim gravels are located along the presently topographically high margin of the Colorado Plateau and were deposited by northeast-flowing streams that drained the presently topographically lower Transition Zone and Basin and Range Provinces. The arrow next to each metamorphic core complex indicates the direction the upper plate moved based on sense-of-shear indicators in mylonitic rocks.

Detachment faults typically have a complex, undulatory form that appears to represent an interference pattern between two sets of approximately perpendicular folds or warps (fig. 6; Cameron and Frost, 1981). The axes of one fold set, typically represented by a single broad upwarp in any individual complex, are perpendicular to mylonitic lineation and the direction of displacement on the detachment fault. These folds or warps appear to be largely, if not entirely, the product of some combination of (1) differential isostatic uplift due to tectonic denudation, and (2) reverse drag above a deeper, concave-upward detachment fault (Spencer, 1984). Periodic, shorter wavelength corrugations with axes parallel to the direction of transport on the detachment fault and to mylonitic lineation are of uncertain origin. Some corrugations are probably true folds, whereas others are probably primary irregularities of fault surfaces.

Southeastern Arizona

Santa Catalina-Rincon-Tortolita-Picacho Mountains Area. Major displacement on detachment faults in southeastern Arizona resulted in unroofing and uplift of lower-plate mylonitic rocks from depths where rocks deformed ductilely and where muscovite and biotite were open to argon loss. Mylonitic rocks characterized by a strong east-northeast-trending lineation and mid-Tertiary K-Ar ages are exposed in the southwestern Rincon, Santa Catalina, Tortolita (figs. 8, 9), and Picacho Mountains. In all of these areas, the mylonitic rocks are known or inferred to have been overlain by a Tertiary detachment fault.

Lower-plate mylonitic fabrics with a characteristic gentle dip and northeast- to east-northeast-trending lineation have been overprinted on a wide variety of rock types. Mylonitic rocks in the Rincon and Santa Catalina Mountains were largely derived from Porphyritic Proterozoic granite and Eocene Wilderness-suite, garnet-muscovite-bearing granites, whereas those in the Tortolita and Picacho Mountains were also derived from large middle Tertiary plutons (Keith and others, 1980; Davis, 1980; Banks, 1980; Rehrig, 1982). Mylonitic fabrics are best developed along the southwest side of each range and are remarkably consistent in character, lineation trend, and overall sense of shear (top to the southwest). These mylonitic fabrics were formed by noncoaxial, ductile shear along deep levels of the detachment faults now exposed along the southwest side of the ranges. Mylonitic fabrics formed within the main top-to-the-southwest shear zones in each range are locally overprinted by small- to large-scale shear zones with antithetic (top-to-the-northeast) shear. These antithetic shear zones are either conjugate zones (Naruk, 1987) or are related to folding of the shear zone about an axis perpendicular to lineation (Reynolds and Lister, 1987).

We make a sharp distinction between these middle Tertiary fabrics and older, in part pre-Eocene mylonitic fabrics present on the east side of the Rincon and Santa Catalina Mountains (Keith and others, 1980; Bykerk-Kauffman, 1986; Bykerk-Kauffman and Janacke, 1987). These older fabrics, which occur in Proterozoic granitoids, middle Proterozoic and Paleozoic sedimentary rocks, and Late Cretaceous to early Tertiary plutons, are probably related to Laramide compression (Thorman and Drewes, 1981).

The Catalina fault northeast of Tucson places a variety of rock types, including Precambrian crystalline, Paleozoic and Mesozoic metasedimentary, and Tertiary sedimentary rocks, over lower-plate mylonitic granitic and gneissic rocks (Pashley, 1966; Drewes, 1977). The stratigraphically highest, tilted conglomerates contain clasts of mylonitic rock derived from the lower plate (Pashley, 1966), which indicates that the lower plate was locally denuded and exposed to erosion before faulting ended. The San Pedro fault on the east side of the Rincon Mountains places similar upper-plate rocks on a lower plate of tectonized Paleozoic and Mesozoic metasedimentary rocks that do not have a lineated mylonitic fabric and that are cut by dikes of undeformed muscovite granite related to the 45-50-Ma Wilderness-suite granites (Lingrey, 1982). The similarity of upper-plate units above the Santa Catalina and San Pedro detachment faults, which sit above the same, structurally continuous lower plate, supports the interpretation that the two faults are correlative, and that the fault surface is broadly arched about a northwest-trending axis. Upper-plate granodiorite on both sides of the Rincon Mountains is, in part, correlative with the Precambrian Johnny Lyon granodiorite in the Johnny Lyon Hills just east of the Rincon mountains (Silver, 1978; Lingrey, 1982). In the northwestern Johnny Lyon Hills, a pre-mid-Tertiary thrust fault places the granodiorite over Paleozoic and Mesozoic rocks (Cooper and Silver, 1964; Drewes, 1974; Dickinson, 1986). This thrust fault, and rocks above and below it, is preserved in fault blocks above the Catalina and San Pedro detachment faults, which suggests at least 20-30 km of west-southwest displacement of upper-plate rocks (e.g., Lingrey, 1982, fig. 52). The breakaway of the San Pedro-Catalina detachment fault, or of a structurally deeper, southwest-dipping normal fault, is exposed east of the Rincon Mountains in the southwestern Galiuro Mountains (Dickinson and others, 1987) and in the Johnny Lyon Hills and Little Dragoon Mountains (Cooper and Silver, 1964; Dickinson, 1984).

We infer that the Catalina fault projects beneath middle Tertiary and older rocks of the Tucson Mountains. The overall gentle northeast dip of these rocks is probably the result of antithetic rotation that accompanied relative top-to-the-southwest translation of rocks above the Catalina fault. Restoration of 20 to 30 km of transport places rocks in the Tucson Mountains approximately over the forerange of the Santa Catalina Mountains prior to detachment faulting. Total displacement could have been 40 km or more.

Low-angle normal faults are also exposed north and west of the Santa Catalina Mountains between the San Manuel

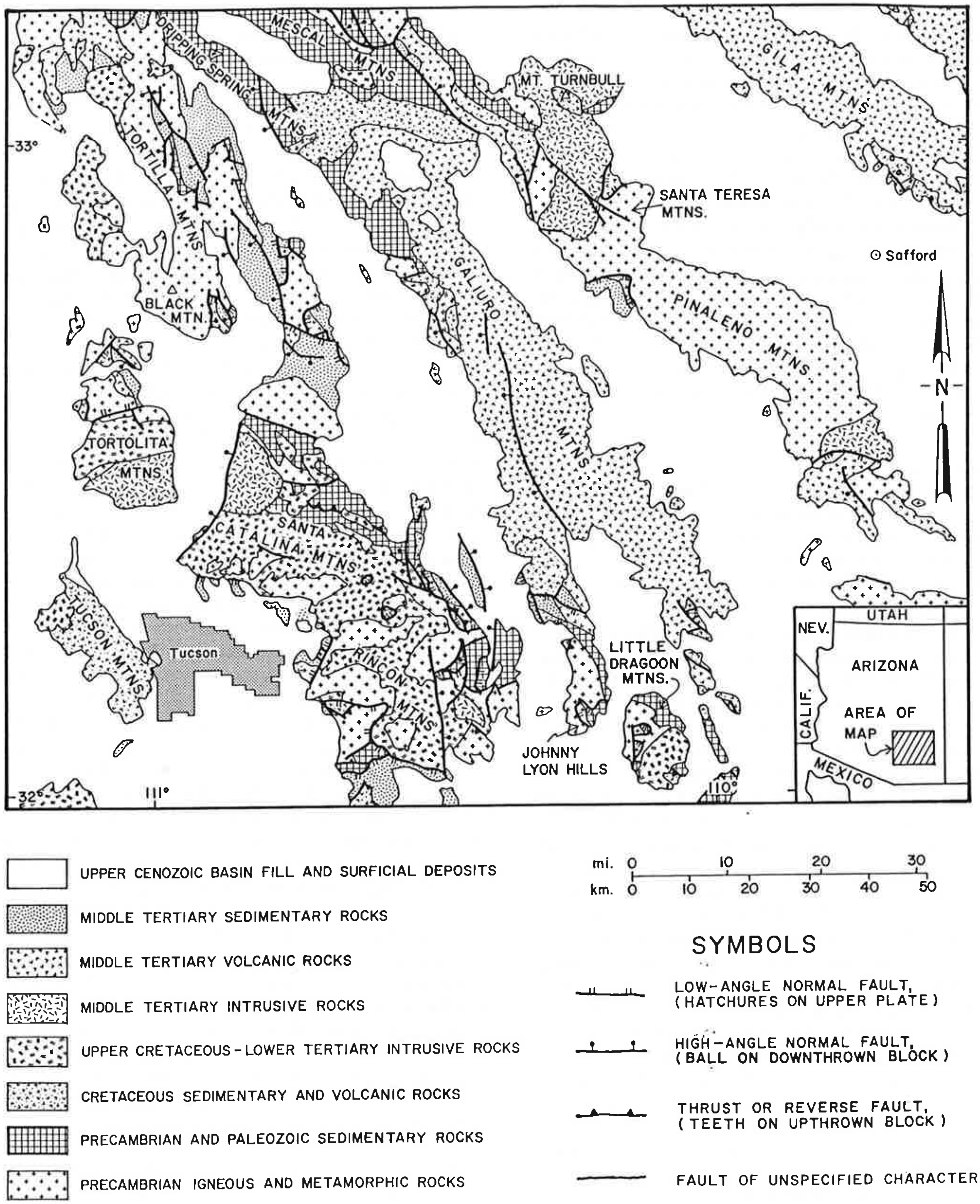


Figure 8. Simplified geologic map of part of southeastern Arizona.

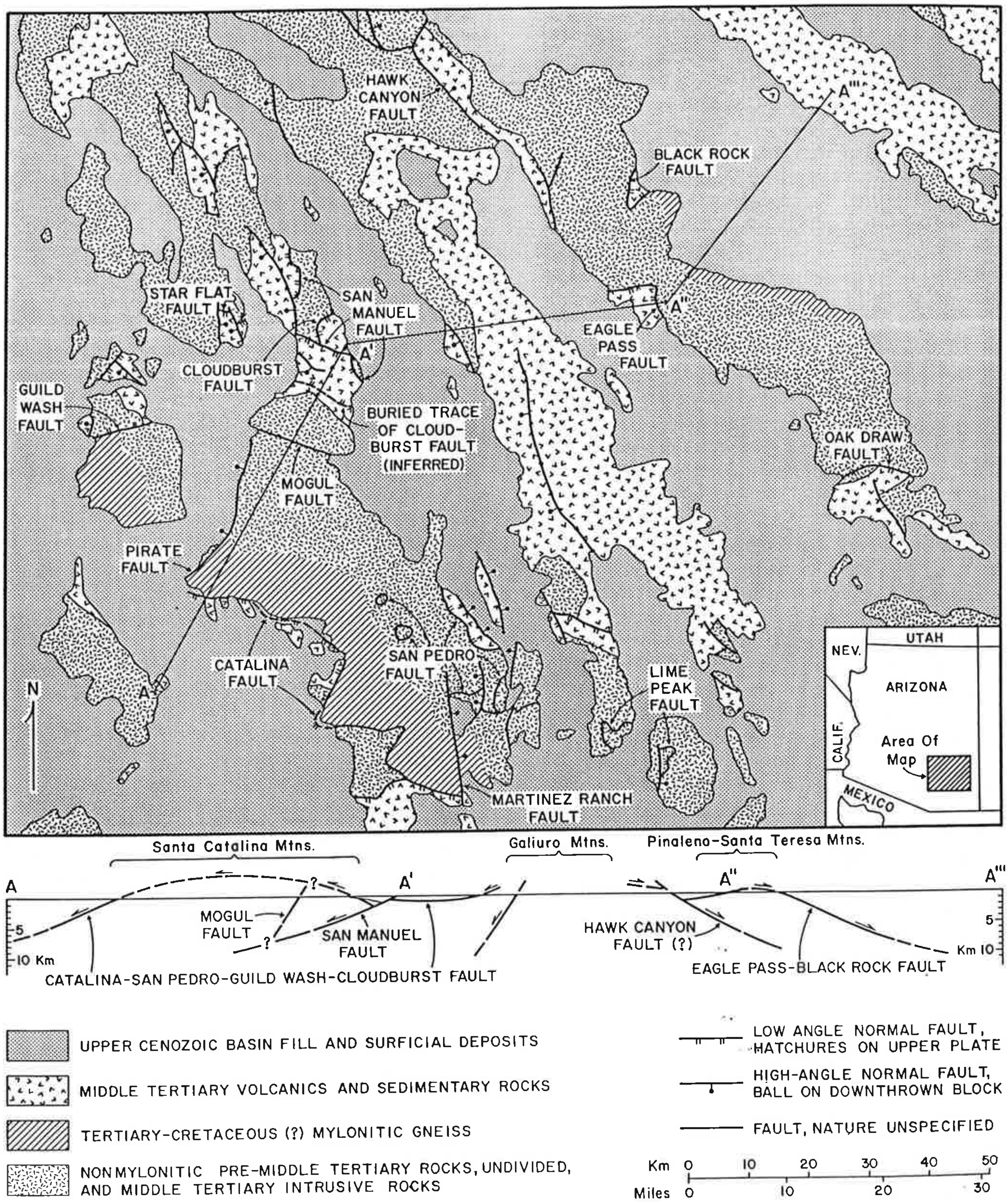


Figure 9. Tectonic map and cross sections showing major mid-Tertiary tectonic features in part of southeastern Arizona. The northern segment of the San Manuel fault, as shown here, was named the Camp Grant fault by Krieger (1974b). We correlate the Camp Grant fault with the San Manuel fault based on geographic proximity, lithologic similarity of upper and lower plates associated with each fault segment, and the fact that both faults cut the same footwall block.

area and the Tortolita Mountains (figs. 8, 9). In the San Manuel area, the subhorizontal Cloudburst fault places sedimentary and volcanic rocks of the mid-Tertiary Cloudburst Formation over Precambrian granitic rocks, and the fault is cut by the gently to moderately southwest-dipping San Manuel fault (Creasey, 1965). The Star Flat fault, located east of Black Mountain, places volcanic and sedimentary rocks of the Cloudburst Formation over Precambrian granite (Krieger, 1974a). Correlation of the Star Flat fault with the Cloudburst fault is suggested by the fact that both faults place tilted Cloudburst Formation over largely Precambrian crystalline rocks and that the two faults are separated by only 10 km, a distance that would be less if displacement on the younger San Manual-Camp Grant fault (Krieger, 1974b; fig. 9) were restored. The Guild Wash detachment fault in the northern Tortolita Mountains places upper-plate Tertiary volcanic and sedimentary rocks (Banks and others, 1977) that are probably correlative with the Cloudburst and San Manuel Formations (Dickinson, 1983) over typically mylonitic, lower-plate crystalline rocks forming most of the Tortolita Mountains. If the Guild Wash fault is correlative with the Star Flat and Cloudburst detachment faults, as suggested by similar upper- and lower-plate lithologies and geographic proximity of the three faults, then the Cloudburst-Star Flat-Guild Wash detachment fault appears to cut structurally deeper into lower-plate, mylonitic and nonmylonitic crystalline rocks to the southwest in the western Tortolita Mountains.

Correlation of the Guild Wash and Cloudburst faults raises an interesting geometrical problem. The Cloudburst fault is offset about 2.5 km by the San Manuel fault (Lowell, 1968), and the down-dropped, southwest continuation of the Cloudburst fault is buried under San Manuel Formation and is not exposed. Three possible geometries for the southwestward continuation of the Cloudburst detachment fault are: (1) it projects beneath the Santa Catalina Mountains and is at a much deeper structural level than the Catalina fault; (2) it projects beneath the Oracle granite north of the Mogul fault, is offset by south-side-up movement on the Mogul fault, and projects over the Santa Catalina Mountains to connect with the Catalina detachment fault; and (3) it continues upward to the base of the San Manuel Formation, which postdates the fault and buries its trace, and projects over crystalline rocks on both sides of the Mogul Fault to connect with the Catalina fault. The first geometry is considered unlikely because it would allow correlation of the Guild Wash fault with the Cloudburst fault only if the Santa Catalina and central and southern Tortolita Mountains are in the upper and lower plates, respectively, of the Cloudburst fault. This seems highly unlikely given the structural and lithologic similarity of crystalline rocks in the two areas. In other words, we view the first geometry outlined above as prohibitive of a correlation between the Guild Wash and Cloudburst faults. Because we favor this correlation, we find this first geometry unlikely. The second geometry is considered unlikely because it would require major movement on the Mogul fault after detachment faulting, making the Mogul fault a young Basin and Range fault of anomalous trend and peculiarly reduced geomorphic expression. We thus favor the third geometry, as shown in the cross section of figure 9, which correlates the Guild Wash, Star Flat, Cloudburst, Catalina, and San Pedro detachment faults. This geometry is consistent with major movement on the Mogul fault before, not after, detachment faulting. This pre-detachment movement could have been south-side-down in order to account for the fact that the footwall of the detachment fault is middle Proterozoic Oracle Granite north of the Mogul fault, but includes upper Proterozoic and Paleozoic metasedimentary rocks south of the Mogul fault. Alternatively, a pre-mid-Tertiary thrust fault lies beneath the Oracle granite north of the Mogul fault and has been offset by pre-detachment south-side-up movement of the Mogul fault to a position where the thrust fault projects over rocks south of the Mogul fault (Keith, 1984).

The San Pedro fault is locally cut by younger, west-dipping normal faults, and the Cloudburst fault is likewise cut by the southwest-dipping San Manuel fault. These younger faults project beneath the Santa Catalina and Rincon Mountains, and movement on them has resulted in southwestward displacement of crystalline rocks in the Santa Catalina-Rincon Mountains relative to the Galiuro Mountains. The west flank of the Galiuro Mountains forms the breakaway zone for the regionally southwest-dipping Catalina and related detachment faults (Dickinson and others, 1987). This breakaway zone trends about N. 30° W. in contrast to the N. 50° W. trend of the belt of uplifted, arched, lower-plate rocks exposed in the Rincon, Santa Catalina, Tortolita and Picacho Mountains. This 20-degree discordance, with northward-increasing distance between the Galiuro Mountains breakaway and the belt of uplifted mylonitic crystalline rocks, is possibly the result of northward-increasing displacement on faults such as the San Manuel fault that would have accommodated counterclockwise movement of the Rincon-Santa Catalina-Tortolita-Picacho Mountains relative to the Galiuro Mountains. If so, the Rincon Mountains are least displaced by younger normal faults, and a northeast-trending cross section through the range to the Galiuro Mountains would be dominated by a single, warped detachment fault (e.g., Spencer, 1984). In contrast, ranges to the northwest such as the Tortolita and Picacho Mountains have possibly undergone major translation above underlying, southwest-dipping normal faults, and a cross section through one of these ranges to the Galiuro Mountains could contain several southwest-dipping imbricate detachment faults. The combined amount of transport on these imbricate faults, including the Picacho detachment fault, is not necessarily substantially different than the amount of transport on just the Catalina detachment fault in the Rincon Mountains.

Pinaleno-Santa Teresa Mountains Area. Two detachment faults are exposed in the area of the Santa Teresa

Mountains about 100 km northeast of Tucson (figs. 8, 9; Blacet and Miller, 1978; Rehrig and Reynolds, 1980; Davis and Hardy, 1981). Both faults displace a similar sequence of steeply southwest-tilted upper-plate rocks above a structurally continuous lower plate and are inferred to be correlative. Crystalline rocks of the Pinaleno Mountains are continuous with lower-plate rocks in the Santa Teresa Mountains and are strongly overprinted by a lineated mylonitic fabric at the northeast foot of the range (Swan, 1976; Thorman, 1981; Naruk, 1986). The top-to-the-northeast sense of shear indicated for the mylonites by macroscopic shear-zone geometry and by S-C structures (Naruk, 1986; Kligfield and others, 1984) is consistent with the southwest tilt of fault blocks above the Eagle Pass and Black Rock faults (fig. 9) and strongly suggests that the Pinaleno mylonite zone is mid-Tertiary and related to shear at deeper levels of the Eagle Pass-Black Rock detachment fault.

The Santa Teresa Mountains are structurally continuous to the north with the Mount Turnbull block, which is in the hanging wall of the moderately northeast-dipping Hawk Canyon normal fault (Willden, 1964). Rocks above the fault, including middle Tertiary volcanics and overlying San Manuel-like, postvolcanic fanglomerate, dip approximately 40° to the southwest. This requires moderate tilting of at least the western part of the Mt. Turnbull block by rotational movement above the Hawk Canyon fault. The southwest dip of the Eagle Pass fault is possibly due to rotation above a southeastward continuation of the Hawk Canyon fault or related faults that are now buried under younger basin fill in Aravaipa Valley.

The Hawk Canyon fault and related northeast-dipping normal faults continue to the northwest through the Hayes and Mescal Mountains to the vicinity of Globe. These faults project beneath the Globe Hills and San Carlos area and probably account for the overall southwest dip of Proterozoic and Paleozoic strata in these areas.

Summary of Extensional Tectonics in Southeastern Arizona. In summary, the extensional tectonics of the area north and east of Tucson were dominated by displacement above two major detachment faults, the Eagle Pass-Black Rock detachment fault and the Catalina-San Pedro-Guild Wash-Star Flat-Cloudburst detachment fault. Upper-plate rocks are displaced away from the Galiuro Mountains, and the flanks of the Galiuro Mountains approximately coincide with the inferred breakaway faults for both detachment systems. The mirror-image symmetry of mid-Tertiary structures about the axis of the Galiuro Mountains is further accentuated by younger moderate-angle normal faults that dip away from the Galiuro Mountains and project beneath adjacent ranges (cross section in fig. 9).

Central Arizona

In the South Mountains, a key locality for extension-related deformation in central Arizona (fig. 10), gently dipping mylonitic fabrics with the regionally extensive east-northeast-trending lineation have been dated by U-Th-Pb, Rb-Sr, and K-Ar methods at 25 to 20 Ma (Reynolds and Rehrig, 1980; Reynolds, 1985; Reynolds, Shafiqullah, and others, 1986). A top-to-the-east-northeast sense of shear in the mylonitic rocks matches the east-northeast transport direction of rocks above the overlying South Mountains detachment fault. The kinematic and timing relationships indicate that mylonitization and detachment faulting represent a ductile-to-brittle continuum of simple shear on a gently northeast-dipping, normal shear zone (Reynolds, 1985; Davis and others, 1986). The detachment fault projects in the subsurface to the northeast beneath southwest-dipping Tertiary volcanic and clastic rocks near Phoenix and Tempe and is visible on seismic reflection profiles (Frost and Okaya, 1986). The stratigraphic succession in the upper-plate Tertiary rocks, which are composed of a lower, coarse-grained sedimentary breccia, a middle sequence of fluvial red beds, and upper volcanics dated at 17 Ma, suggests that tectonism began before, and continued after, the local inception of volcanism (Scarborough and Wilt, 1979; Schulten, 1979).

Geologic relationships in the White Tank Mountains to the west of Phoenix (fig. 10) are similar to those in the South Mountains (Reynolds, 1980; Rehrig and Reynolds, 1980). Gently dipping mylonitic fabrics with an east-northeast-trending lineation are moderately well developed in the eastern third of the range and have been overprinted on Precambrian gneiss, Tertiary plutons, and middle Tertiary dikes. The overall sense of shear in the mylonites is interpreted to be top-to-the-east-northeast, although thin, late-kinematic shear zones have the opposite vergence (Reynolds and Lister, 1987). A detachment fault has not been recognized, although chloritic-breccia-style brittle structures are present along the eastern edge of the range. We infer that an unexposed detachment fault, correlative with the South Mountains detachment fault, originally overlay the range and dipped east-northeast beneath the volcanic rocks north of Phoenix.

A higher structural level of middle Tertiary deformation is exposed in the Big Horn, Belmont, Vulture, and Hieroglyphic Mountains. In the western Big Horn Mountains, volcanic rocks dated at 20 to 16 Ma (J. Spencer, unpublished K-Ar data) dip moderately to gently to the southwest and are cut by northeast-dipping normal faults (Capps and others, 1985). Toward the east, in the eastern Big Horn and Belmont Mountains, the volcanics dip moderately to steeply to the northeast and are cut by southwest-dipping, low- to high-angle normal faults. Unconformities within the volcanic sequence indicate that volcanism was synchronous with normal faulting and tilting. Coarse sedimentary breccia and landslide-type megabreccia derived from fault scarps and oversteepened volcanic sections were deposited in the larger half grabens after the main pulse of silicic volcanism. Gently tilted to flat-lying basalts dated at 15 to 15.5 Ma occur north and south of the range and mark the termination of the main episode

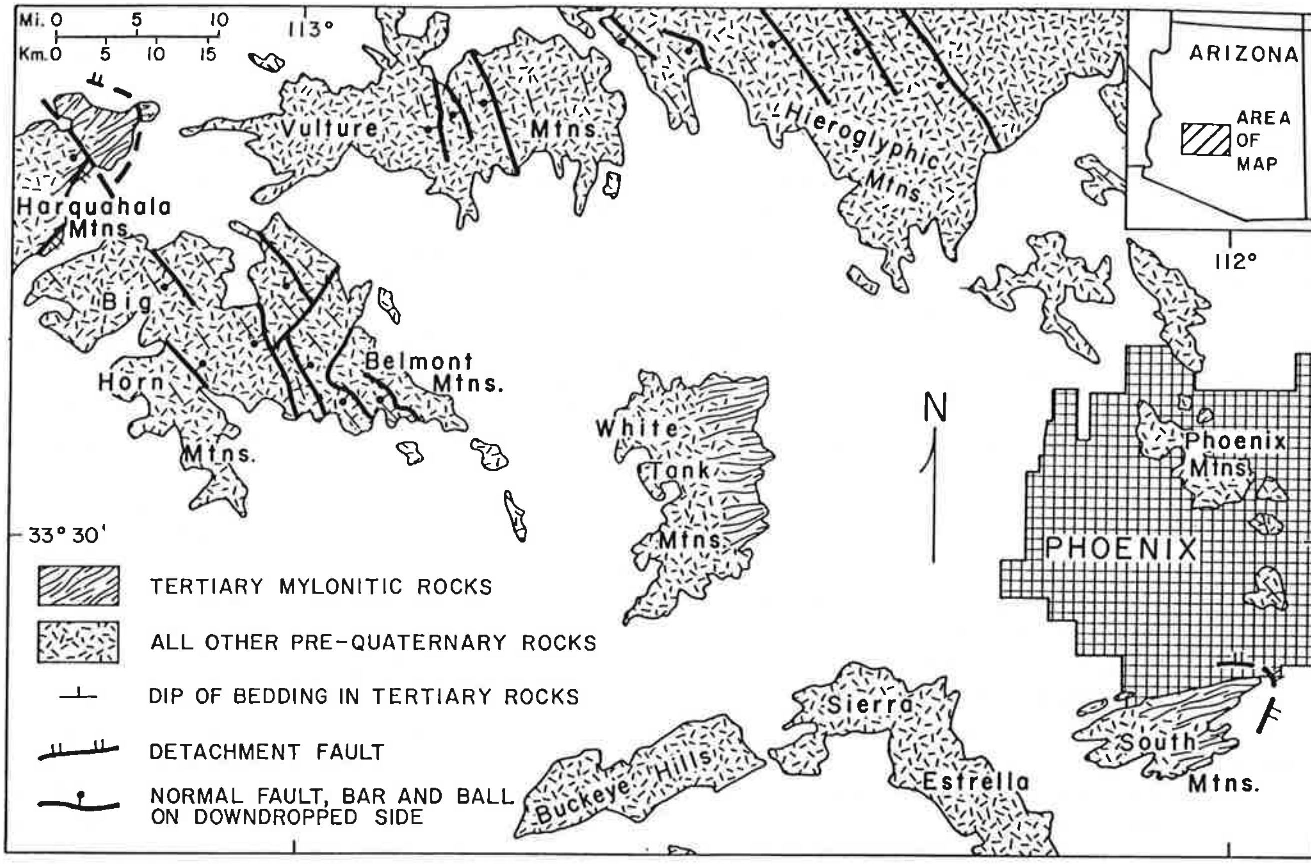


Figure 10. Map of central Arizona showing locations of mountain ranges and major Tertiary fabrics and structures.

of tilting (Scarborough and Wilt, 1979; Shafiqullah and others, 1980).

A nearly identical geologic setting has been documented in the Vulture Mountains to the northeast, where silicic volcanic rocks dated at 26 to 16 Ma dip moderately to steeply to the northeast and are cut by southwest-dipping, low- to high-angle normal faults (Rehrig and others, 1980). Termination of normal faulting and tilting is tightly bracketed by a 16-Ma date on a postfaulting potassic dike and a 13.5-Ma date on flat-lying basalt. Northeast-dipping volcanic rocks and southwest-dipping normal faults continue to the northeast through the Wickenburg and Hieroglyphic Mountains to the southwest edge of the Bradshaw Mountains (Capps and others, 1986; Stimac and others, 1987; Grubensky and others, 1987). Some of the southwest-dipping normal faults in the Wickenburg Mountains are very low angle, have displacements of approximately 3 to 5 km, and truncate higher angle normal faults in the overlying tilted Tertiary rocks (Stimac and others, 1987). The uniform northeast dip direction over the entire region from the central Bighorn Mountains to the Hieroglyphic Mountains suggests several possibilities: (1) the southwest edge of the Bradshaw Mountains is marked by the trace of the breakaway portion of a major southwest-dipping detachment fault or fault system that projects southwestward beneath the Hieroglyphic, Vulture, and Big Horn Mountains; (2) the northeast dip of the Tertiary units is due to movement on southwest-dipping antithetic faults related to a northeast-dipping detachment fault or fault system; or (3) northeast tilting occurred above a regionally southwest-dipping detachment fault or fault system that intersects a regionally northeast-dipping detachment fault or fault system. Northeast-dipping detachment faults in (2) or (3) would possibly link the South Mountains—White Tank detachment fault with the Bullard detachment fault of west-central Arizona. Resolution of these three possibilities is possible only by seismic reflection profiling.

Whipple Tilt-block Domain

One of the most extensive areas of detachment faulting, tilted upper-plate fault blocks, and tectonically denuded mylonitic and nonmylonitic rocks in western North America forms part of western Arizona and adjacent southeastern California and southernmost Nevada. This area composes the Whipple tilt-block domain, an area of approximately 25,000 km^2 in which Tertiary fault blocks dip predominantly to the west or southwest.

The Whipple tilt-block domain extends parallel to the strike of tilt-blocks (N-S to NW-SE) from the central Eldorado Mountains and northern Black Mountains in southernmost Nevada and northwestern Arizona, respectively, southward along the Colorado River and into west-central Arizona as far southeast as the Big Horn and Little Horn

Mountains (fig. 11). The nature of the northern and southern boundaries of the tilt-block domain is not known, although the boundaries could represent strike-slip faults in the lower plate that separate the Whipple tilt-block domain from areas with detachment faults of opposite dip (west or southwest) and sense of displacement (top to the west or southwest).

The southern part of the Whipple tilt-block domain contains a single regional detachment fault of great lateral extent and several smaller low-angle normal faults of more restricted lateral extent and displacement. The regional detachment fault is the Whipple-Buckskin-Rawhide-Bullard detachment fault (Davis and others, 1980, 1982; Carr and others, 1980; Dickey and others, 1980; Rehrig and Reynolds, 1980; Shackelford, 1980; Reynolds and Spencer, 1985; Spencer and Reynolds, 1987; fig. 12). Its northern continuation is probably represented by the basal detachment fault in the Chemehuevi (John, 1982), Sacramento (McClelland, 1982; Spencer, 1985a), Homer (Spencer, 1985a), Dead, Newberry (Mathis, 1982), and southern Eldorado (Volborth, 1973) Mountains (fig. 11). Multiple detachment faults in some of these northern ranges could represent northward bifurcations of the Whipple-Buckskin-Rawhide-Bullard detachment fault. Displacement on the Whipple-Buckskin-Rawhide-Bullard detachment fault is estimated to be about 40 to 60 km (Reynolds and Spencer, 1985).

Structurally deeper detachment faults appear to project beneath the Whipple-Buckskin-Rawhide-Bullard detachment fault in the southern part of the Whipple tilt-block domain. These faults include the Plomosa (Scarborough and Meader, 1983) and Moon Mountains detachment faults and low-angle normal faults exposed in the Riverside (Hamilton, 1964; Carr and Dickey, 1980; Lyle, 1982), Big Maria (Hamilton, 1982, 1984) and Arica (Baltz, 1982) Mountains (fig. 12). All of these northeast-dipping faults could extend beneath the Whipple-Buckskin-Rawhide-Bullard detachment fault (imbricate detachment faults) or could curve upward to connect with it forming a single warped regional detachment fault (fig. 12). A seismic-reflection profile from the area north of the Turtle Mountains (Frost and Okaya, 1986) dramatically confirmed that the concave-upward, curved geometry of the detachment fault predicted by Howard, Stone, and others (1982), and not an imbricate fault geometry, is the correct geometry for the detachment fault in the vicinity of the Turtle Mountains. Preliminary results of a COCORP seismic reflection survey across the Plomosa-Buckskin Mountains area suggest that the Plomosa detachment fault does not project at depth beneath the Buckskin Mountains (E. Hauser, personal commun., 1987), consistent with hypothesized profiles 2 and 3 in figure 13.

The Whipple tilt-block domain, including lower-plate rocks distended or unroofed by movement on the Whipple-Buckskin-Rawhide-Bullard detachment fault and subsidiary low-angle faults, is bounded on the west by an area that does not contain significant Tertiary extensional faults at surficial levels. This unextended area includes the central Kofa, southern Plomosa, southern New Water, and Dome Rock Mountains in Arizona, most of the Big Maria Mountains, the Little Maria, McCoy, Granite, Iron, Old Woman, and Piute Mountains, and the Piute Range, all in California, and the McCullough Mountains in southern Nevada (zone A in fig. 11). Upper-plate rocks of the Whipple tilt-block domain are separated from the unextended area by one or more breakaway faults that dip regionally eastward or northeastward. It should be noted that the unextended area itself probably sits above the deep-seated projection of detachment faults to the southwest in the central Mohave Desert area (Dokka and Glazner, 1982), and southern Colorado River trough (Garner and others, 1982), but surficial manifestations of extension above these faults are minor or not recognized.

The eastern boundary of the Whipple tilt-block domain is a zone in which normal faulting and fault-block rotation are progressively less significant toward the east (zone E in fig. 11). This zone includes ranges such as the Cerbat, Hualapai, and Poachie Mountains that are composed of large, slightly tilted to untilted, structurally coherent fault blocks that probably lie many kilometers above the northeastward, down-dip projection of the Whipple-Buckskin-Rawhide-Bullard detachment fault and related detachment faults.

The Whipple tilt-block domain can be approximately divided into three belts (zones B, C, and D in fig. 11)—a central belt of uplifted lower-plate rocks bounded on each side by belts of tilted upper-plate rocks. The eastern belt (zone D) is the tapered end of a wedge of upper-plate fault blocks above an east-dipping detachment fault or faults that project at depth toward zone E and the Transition Zone-Colorado Plateau (zones F and G, respectively). The western belt (zone B) is a detached, synformal keel of upper-plate fault blocks above a master detachment fault that projects over the central belt (zone C; see also Spencer, 1984). Zone B also includes tilted fault blocks above possible low-angle normal faults that project beneath the central belt (zone C) of uplifted lower-plate rocks.

Mid-Tertiary volcanic and sedimentary rocks in upper-plate fault blocks of the Whipple tilt-block domain were deposited between about 30 and 15 Ma. These mid-Tertiary rocks rest depositionally on Precambrian crystalline rocks and less commonly on younger metamorphic and igneous rocks. Sedimentary and volcanic rocks representing the time interval from about 100 to 30 Ma are completely absent; this indicates that the area was topographically high and undergoing erosional denudation before extensional faulting. Because the formation of sedimentary basins and deposition of coarse clastic sediments above rotating normal-fault blocks is viewed as a manifestation of crustal extension, the age of these tilted sedimentary and volcanic rocks is interpreted as the time of extensional faulting. K-Ar dates of tilted volcanic rocks in the Whipple Mountains

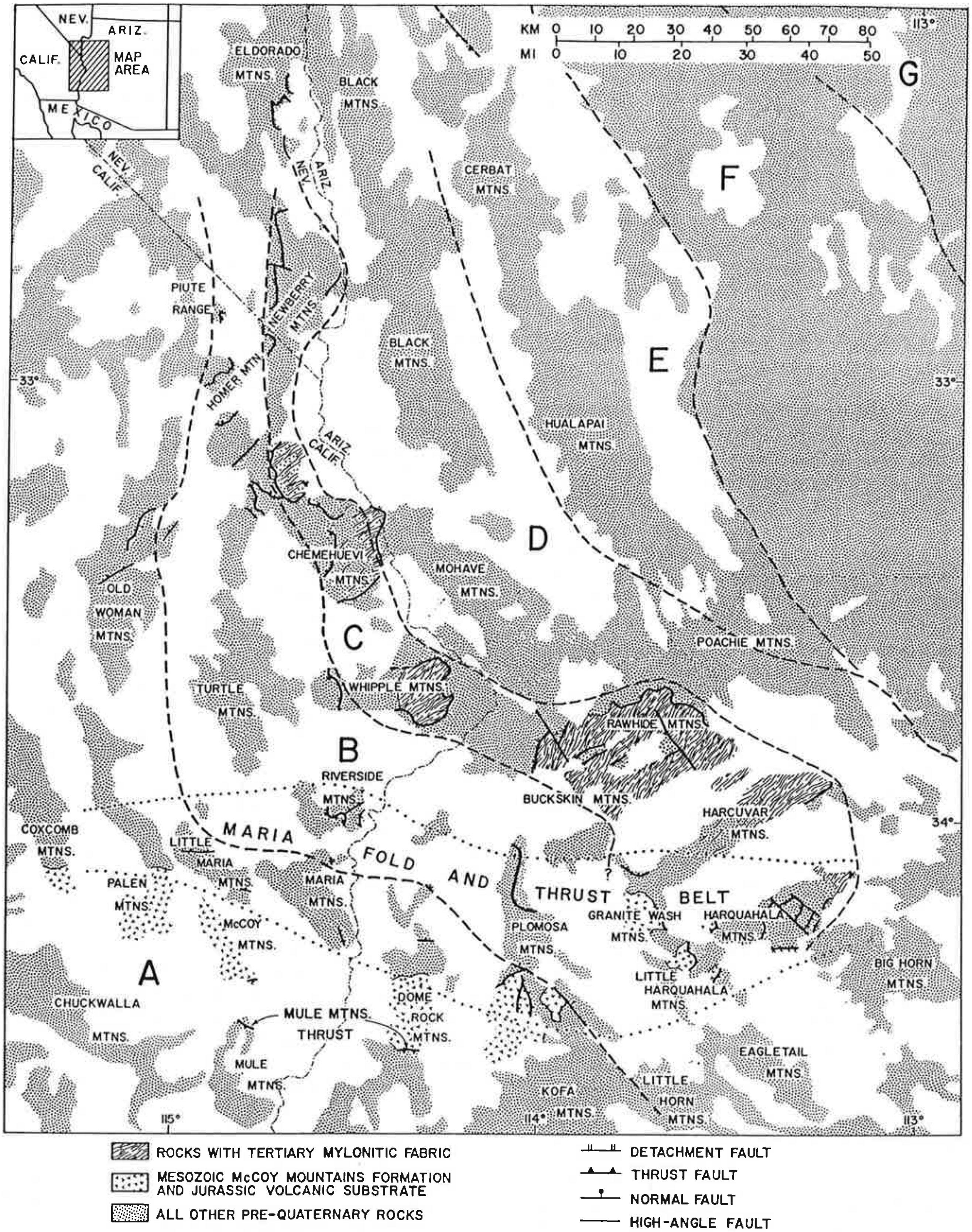


Figure 11. Generalized tectonic-domain map for mid-Tertiary structures in the Whipple tilt-block domain and surrounding area. (A) Area of minor extension at surficial levels, (B) synformal keel of distended upper-plate rocks above warped regional detachment fault, (C) zone of archlike uplifts of lower-plate rocks forming metamorphic core complexes, (D) wedge-shaped extensional allochthon of moderately to highly tilted and extended upper-plate rocks, (E) area of slight to moderate extension characterized by large fault blocks with little or no tilt, (F) Transition Zone, and (G) Colorado Plateau.

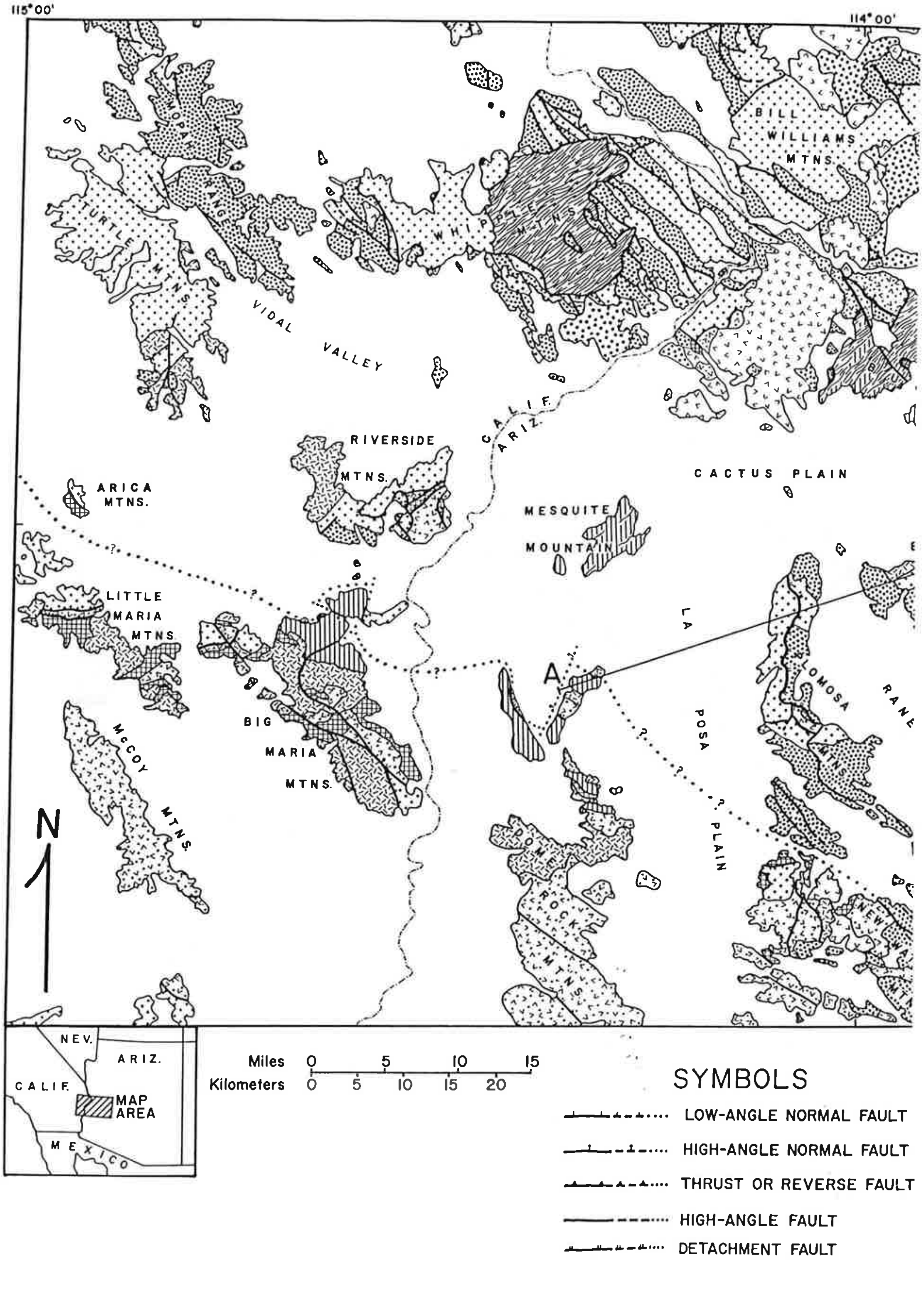
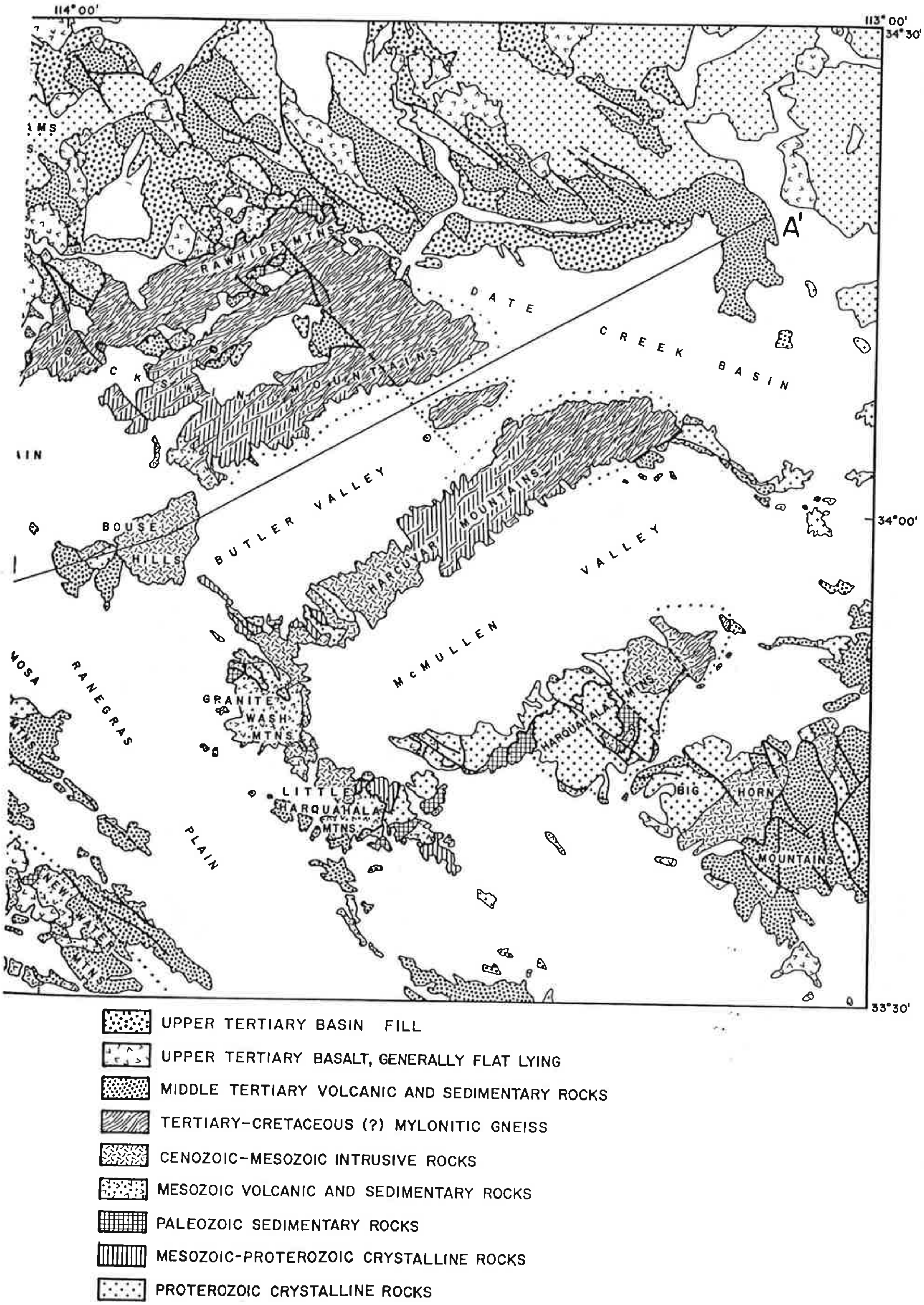


Figure 12. Simplified geologic map of west-central Arizona and adjacent parts of southeastern California.


114° 00'
113° 00'
34° 30'
34° 00'
33° 30'
A'
RAWHIDE MTNS
BUCKSKIN MOUNTAINS
DATE CREEK BASIN
BUTLER VALLEY
BOUSE HILLS
HARCUVAR MOUNTAINS
McMULLEN VALLEY
RANEGRAS PLAIN
GRANITE WASH MTNS
LITTLE HARQUAHALA MTNS
HARQUAHALA MTNS
BIG HORN MOUNTAINS
NEW WATER MTNS
UPPER TERTIARY BASIN FILL
UPPER TERTIARY BASALT, GENERALLY FLAT LYING
MIDDLE TERTIARY VOLCANIC AND SEDIMENTARY ROCKS
TERTIARY-CRETACEOUS (?) MYLONITIC GNEISS
CENOZOIC-MESOZOIC INTRUSIVE ROCKS
MESOZOIC VOLCANIC AND SEDIMENTARY ROCKS
PALEOZOIC SEDIMENTARY ROCKS
MESOZOIC-PROTEROZOIC CRYSTALLINE ROCKS
PROTEROZOIC CRYSTALLINE ROCKS

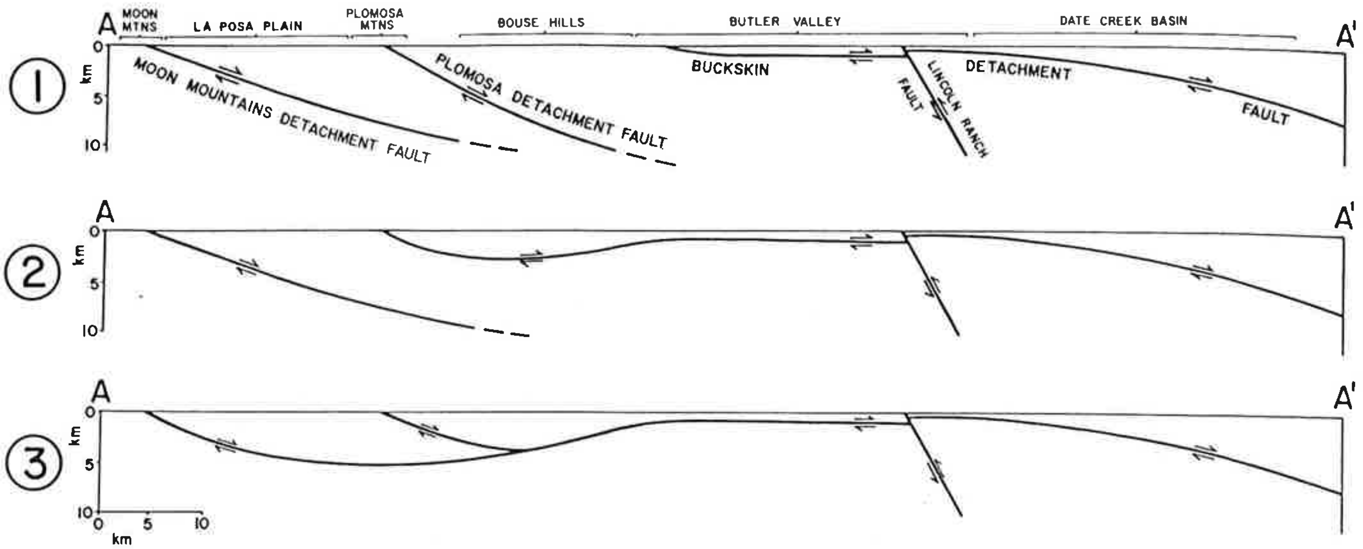


Figure 13. Three possible subsurface detachment-fault geometries for cross section A-A′ in figure 12.

tiltblock domain fall within a range of 32 to 12 Ma, although most dates fall in the range of 22 to 15 Ma (Frost and Martin, 1982, and references in Reynolds, Florence, and others, 1986), which is interpreted as the time of the most active extensional faulting.

The uplifted, lower-plate rocks exposed in the core complex belt of the Whipple tilt-block domain (zone C in fig. 11) have been variably overprinted by a weak to strong mylonitic foliation with a N. 50° to 60° E.-trending mylonitic lineation. Mylonitic fabrics are especially well developed in the Whipple, Buckskin, Rawhide, and Harcuvar Mountains (fig. 11). Mylonitization occurred largely if not entirely by top-to-the-northeast shear along the downdip projection of the regional detachment fault during mid-Tertiary time (Davis and others, 1986; Wright and others, 1986). The subhorizontal, undulating mylonitic foliation in the Whipple, Buckskin, Rawhide, Harcuvar, and Harquahala Mountains and the overlying regional detachment fault define at least eight northeast-trending arches that have axes parallel to mylonitic lineation and to the inferred direction of displacement of the upper plate (Rehrig and Reynolds, 1980; Davis and others, 1980; Frost, 1981a, 1981b). The geometric alignment between arch axes and mylonitic lineation is strongly suggestive of a genetic relationship between the two features, although the nature of this relationship and the origin of the arches is not clear.

The two elongate, east-northeast-trending arches in the Whipple Mountains are doubly plunging (Frost, 1981a), and the three east-northeast-trending arches in the Rawhide and Buckskin Mountains have long, horizontal crests that roll over to plunge gently to moderately beneath alluvium and upper-plate rocks along the northeast and southwest ends of the arches. The arches of the Harcuvar and Harquahala Mountains have approximately horizontal crests that roll over to plunge gently northeastward at the northeast ends of the ranges. Mylonitic foliation also rolls over to a southwest dip in the southwestern Harcuvar Mountains (Rehrig and Reynolds, 1980; Reynolds and Lister, 1987).

Two processes probably account for formation of the broad, north-northwest-trending monoclinal or anticlinal warps of the elongate east-northeast-trending arches and are responsible for the plunge at their ends: (1) differential isostatic rebound due to differential tectonic denudation (Rehrig and Reynolds, 1980; Howard, Stone, and others, 1982; Spencer, 1984), and (2) reverse drag (Hamblin, 1965) above deeper listric normal faults (Spencer, 1984; see also Bartley and Wernicke, 1984, and Gans and others, 1985). If the Plomosa fault extends under the Buckskin Mountains, reverse drag above this fault or above listric faults that merge downward with the Plomosa fault could be responsible for the southwest plunge of the arches in the southwestern Buckskin Mountains (fig. 13, cross section 1). However, the monoclinal warp at the northeast end of the Buckskin, Rawhide, and Harcuvar Mountains is too far (60-80 km) from the trace of any possibly structurally lower detachment faults to be due to reverse drag above such faults. Possibly the monoclinal flexure at the northeast ends of the east-northeast-trending arches is the result of differential isostatic rebound, and the monoclinal flexure at the southwest ends could have been produced by differential isostatic rebound or reverse drag, or both.

In summary, the dominant tectonic process affecting the Whipple tilt-block domain was detachment and distention of an enormous extensional allochthon and its displacement to the east relative to the lower plate. Rocks forming the eastern belt of tilted upper-plate fault blocks (zone D in fig. 11) were displaced from a position over the central belt of lower-plate rocks that underwent isostatic uplift due to denudational faulting (zone C in fig. 11). Another way of visualizing this process is to consider the lower plate as having been drawn up and out from beneath the distending upper plate. The largest exposed, tilted fault block in the Whipple tilt-block domain is in the Mohave Mountains in

PEDIMENTS and the "PEDIMENT PROBLEM"

Pediments are gently sloping, concave-upward graded surfaces of transportation cut indiscriminately across rocks of varying lithology, usually covered with a thin veneer of alluvium in transit. In form and function a pediment is similar to an alluvial fan, except that a pediment is erosional and a fan is constructional.

Pediment slopes range from 1° to 7°, as do fan slopes, increasing toward the mountain front. Headward portions of pediments may penetrate into a mountain mass, isolating segments of the range (***Inselbergs***) and possibly intersecting with pediments from the other side of the range at ***pediment passes***. The pediment form, like that of an alluvial fan, is a good example of a water-spreading ***wash slope*** (concave upwards, convex plan). Functionally, it distributes and dissipates water and sediment.

The distal margin becomes a ***suballuvial bench***, often convex upwards, as it passes beneath the basin fill, ending perhaps at the buried high-angle fault separating the mountain block from the basin block (***horst and graben***). Pediments end upslope usually at the ***mountain front*** at an abrupt slope change called the ***piedmont angle***.

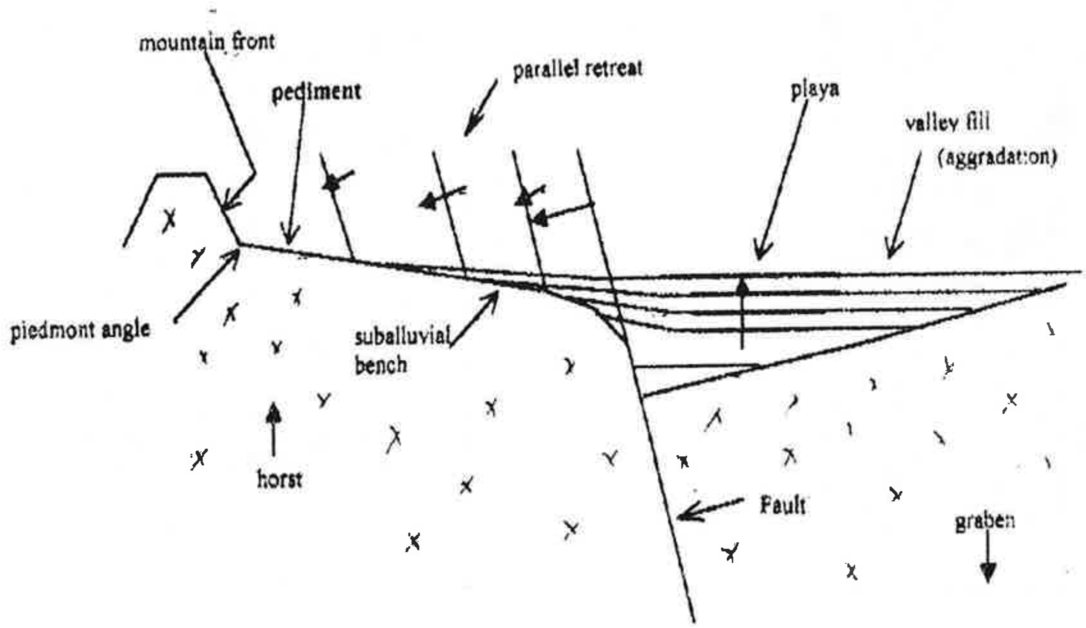
Pediments are usually found in arid regions, but are not necessarily an arid landform. Many suggest that they are formed under much different climatic conditions and are therefore ***relict*** or that they were formed beneath a mantle of weathering products or alluvium and are therefore ***exhumed***.

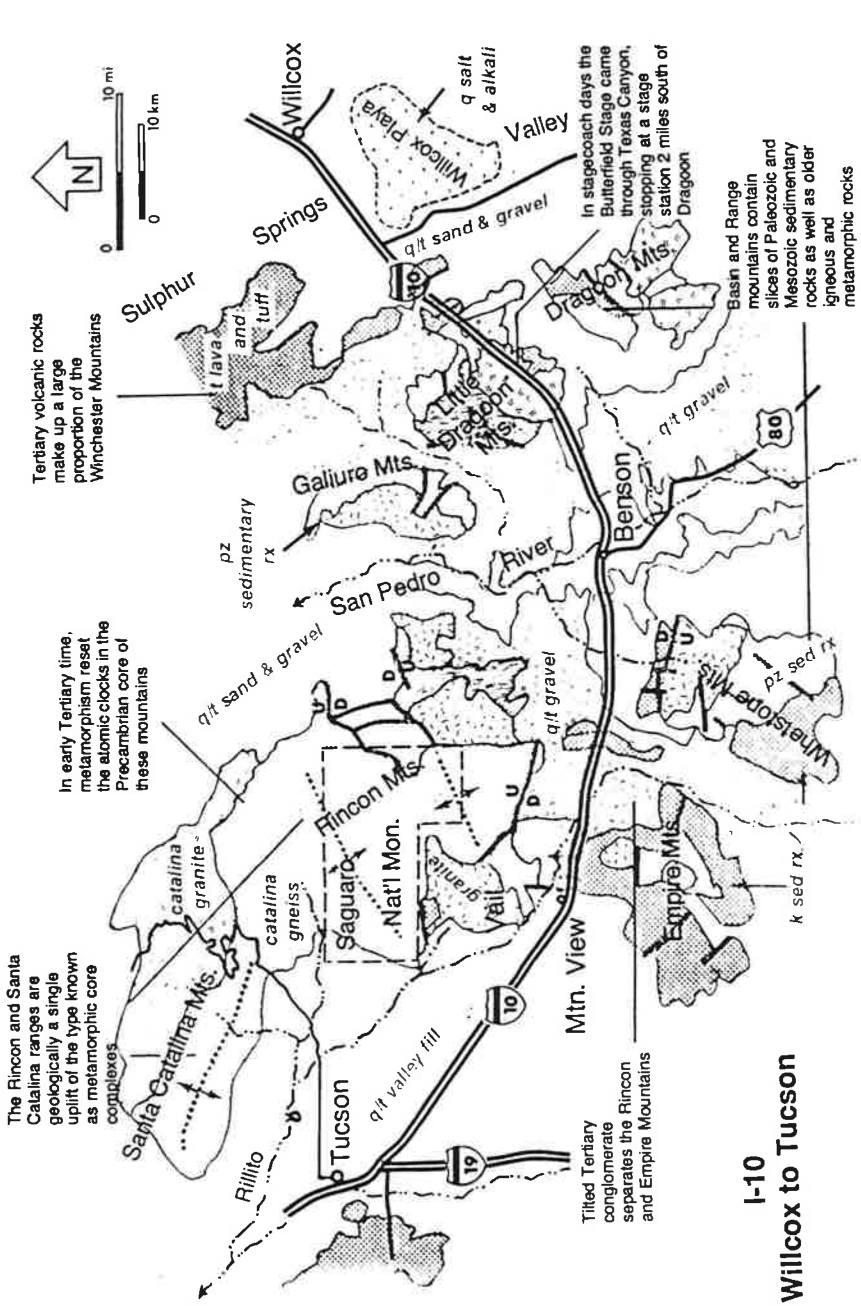
The **"Pediment Problem"** refers to the processes that formed the pediment and those that currently operate there. Many workers have suggested methods of ***slope retreat*** and pediment planation that seem logical and reasonable, but none have satisfactorily explained the creation and maintenance of the sharp piedmont angle.

Various mechanisms include: Lateral planation by organized streams emerging from the mountain front migrating laterally across the bedrock. This cannot account for the sharp piedmont angle. Sheetfloods and rillwash certainly occur and move large amounts of sediment keeping the surface free from accumulation, but must be subsequent to the morphology. Weathering of different sorts including subaerial and suballuvial and maybe under different climatic conditions; these are very hard to study but ultimately may explain the piedmont angle as a concentrated microclimate weathering phenomenon. Lithology and structure may seem obvious influences, but are unrelated as pediments are formed on all rock types, fractured or not, often many miles from the nearest fault.

The method of slope retreat is directly related to the pediment-forming process, but this most fundamental concept in geomorphology is still theoretical and not completely agreed on even when it does not relate to pediments. Some workers believe a parallel-retreat model for the mountain front works best in arid climates leaving behind a pediment surface as the mountain mass becomes smaller, and others favor a slope replacement or slope decline model but with less conviction.

Finally, all agree with the obvious morphology--that the exposed bedrock surface between the steep mountain front and the gently sloping alluvial plain--called a pediment, is coincident with a graded slope that merges with valley fill a closed-basin playa, or the floodplain of a master stream draining the valley.


mountain front
pediment
parallel retreat
playa
valley fill
(aggradation)
piedmont angle
suballuvial
bench
horst
Fault
graben



I-10
Willcox to Tucson

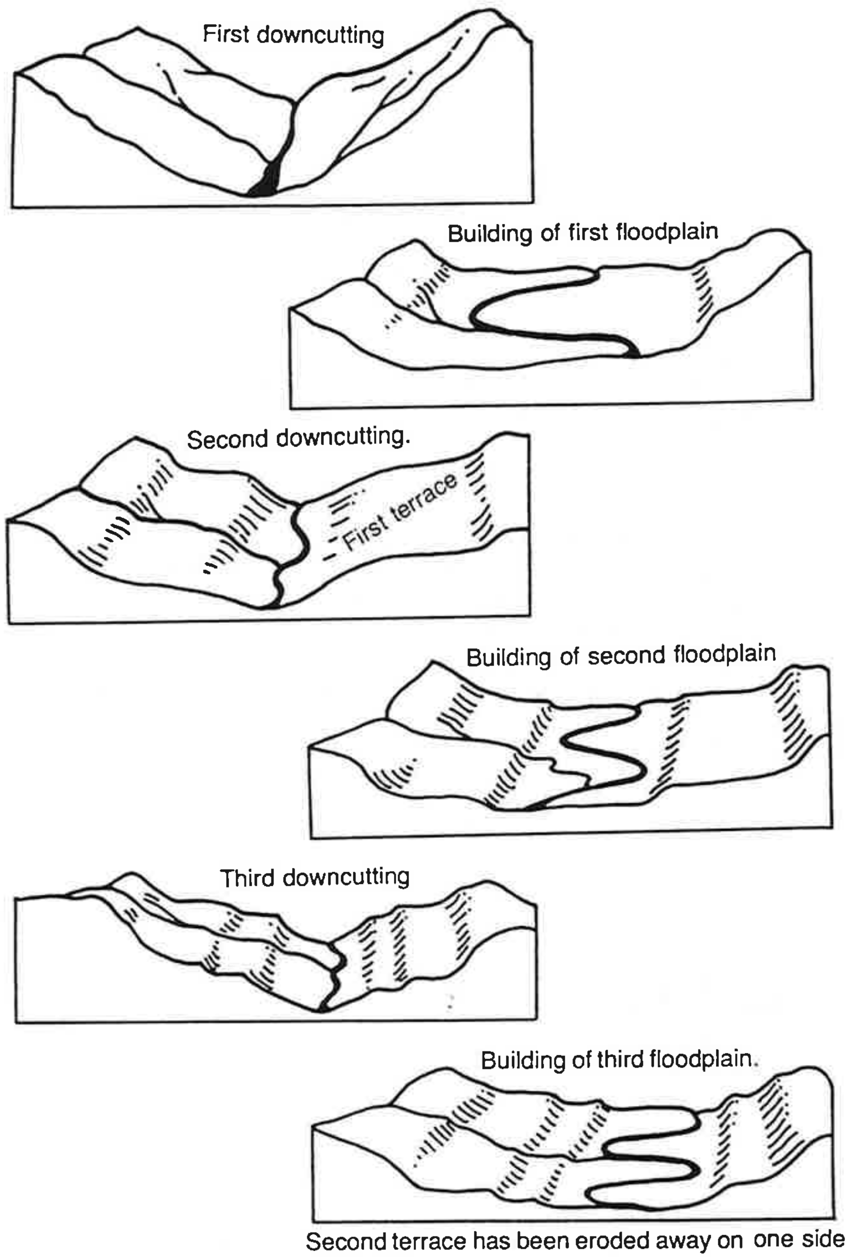
In Texas Canyon, spheroidal weathering rounds huge joint-edged blocks of porphyry. The pink-orange blush on the boulders results from breakdown of iron-bearing minerals; freshly broken surfaces are light gray.

Interstate 10
Willcox to Tucson
(90 miles)

For a brief discussion of the Sulphur Springs Valley and Willcox Playa, see the preceding section. Dunes now mark the ancient lake shore near Willcox. Valley fill here is about 2000 feet thick — lake deposits and sloping layers of silt, clay, sand, and gravel washed from the surrounding mountains: the Pinalenos, Dos Cabezas, and Chiricahuas on the east, the Galiuros and Dragoons on the west.

East of Willcox the highway climbs across a broad, undulating alluvial surface which merges imperceptibly with eroded pediments at the base of the Little Dragoon (north of the highway) and Dragoon Mountains. At the north end of the Dragoons, in faulted and metamorphosed Paleozoic rocks, marble has been quarried. The Dragoons also contain many old mines that once produced copper, gold, zinc, lead, and silver. Ghost towns and abandoned shafts are scattered through this range, once the hideout of the legendary Cochise.

The Little Dragoons just north of the highway are also rich in copper-lead-zinc ores. The mine on their east flank, near the contact between Paleozoic rocks and pink granite porphyry of the main mountain, has been in operation off and on since 1881. On their west flank, the Tungsten King mine produced tungsten ores from a mass of coarse granite porphyry.



As many as three terrace levels border the San Pedro River. Each represents a period during which an overburdened stream widened its channel and filled it part way with rock debris, followed by a period of downcutting.

The highway continues through the pass between the Little Dragoon Mountains and the Dragoons themselves. Both these ranges are fault blocks, and both contain intricately faulted arrays of Precambrian schist and Paleozoic and Mesozoic sedimentary rocks surrounding Laramide intrusions.

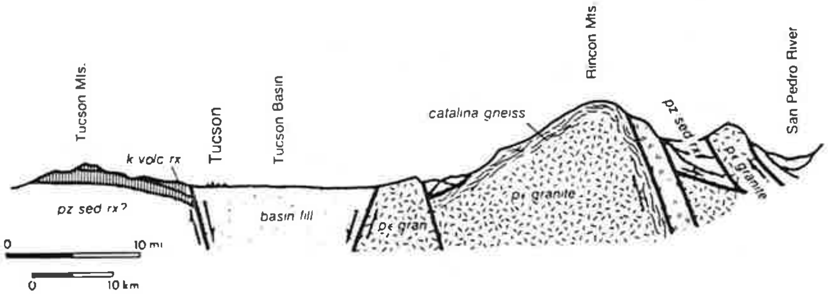
Texas Canyon, west of the pass, penetrates one of these intrusions, and west of milepost 319 the highway travels through a wonderland of rocks that you may have seen before in western films or TV shows. Huge monoliths of quartz monzonite porphyry, looking much like granite but with large crystals of feldspar poking out like warts on a toad, are shaped by processes of jointing and weathering. Intersecting joints divide the rock into rectangular blocks, and then, even before they are exposed, weathering processes widen the joints and round the corners of the blocks. Further rounding of the separated boulders is accomplished by **spalling** or **sheeting**, also called **exfoliation**. Both processes are still taking place.

Beyond Texas Pass the highway descends gradually into the San Pedro Valley. Watch the roadcuts and the walls of deep ravines that parallel the road. Try to pick out the transition between the eroded mountain pediment beveled on partly decomposed granite and the bouldery gravels of the valley fill. Despite the differences in processes — erosion *versus* deposition — the desert surface crosses smoothly from pediment to valley fill near mile 316-315.

The San Pedro Valley, a deep graben downfaulted between the adjacent ranges, was lake-filled in Pliocene time; silty pink lake deposits are eroded into **badlands** west of Benson. In them have been discovered a rich variety of Pliocene and early Pleistocene fossil vertebrates: fish, turtles, lizards, snakes, birds, squirrels, rabbits, gophers, mice and rats, wolves, horses, peccaries, llamas, and camels! Such an abundance of animals confirms what the lake deposits tell us: that the climate here was once quite a bit wetter than at present. After the lake's demise, the deposits were blanketed with coarse gravel and cobbles, and then within the last 700,000 years dissected again by the river. The present river channel cuts through some of the former floodplain deposits. Along a terraced river valley such as this, the highest terraces are the oldest, the lowest are the youngest.

To the right as the highway climbs out of the San Pedro Valley are hills marked by low gray ridges of Precambrian and Paleozoic sedimentary rocks. They lie against 1.6 billion-year-old Precambrian schist and granite, southern Arizona's equivalent of the dark rocks of Grand Canyon's Inner Gorge, rocks that seem to be the foundations of this part of the continent and that are often referred to by geologists as the Precambrian **basement**. Here they extend out onto the eroded upper portions of the Rincon Mountain pediment, but they are gravel-covered and hard to see at highway speeds.

Both the Empire and the Whetstone Mountains south of the highway are made up of relatively undeformed but quite steeply tilted Paleozoic and Mesozoic sedimentary rocks. Low hills of Precambrian granite mark the north end of the Whetstones. The mustard-colored soils near the highway are derived from volcanic ash that is probably Oligocene in age, about 25-30 million years old.



Section north of I-10, Benson to Tucson

As you come between the Empire Mountains and the Rincons, you can see that a large ridge stands away from the main Rincon Mountain mass. Edged with faults, this ridge dropped about 5000 feet relative to the Rincons, possibly before the rise of the great metamorphic core complex of the Rincons. The sliding surface — thought by some geologists to be the sole of a much more extensive overthrust fault — extends south across the highway at mile 295. Movement along this fault took place sometime between 14 and 10 million years ago.

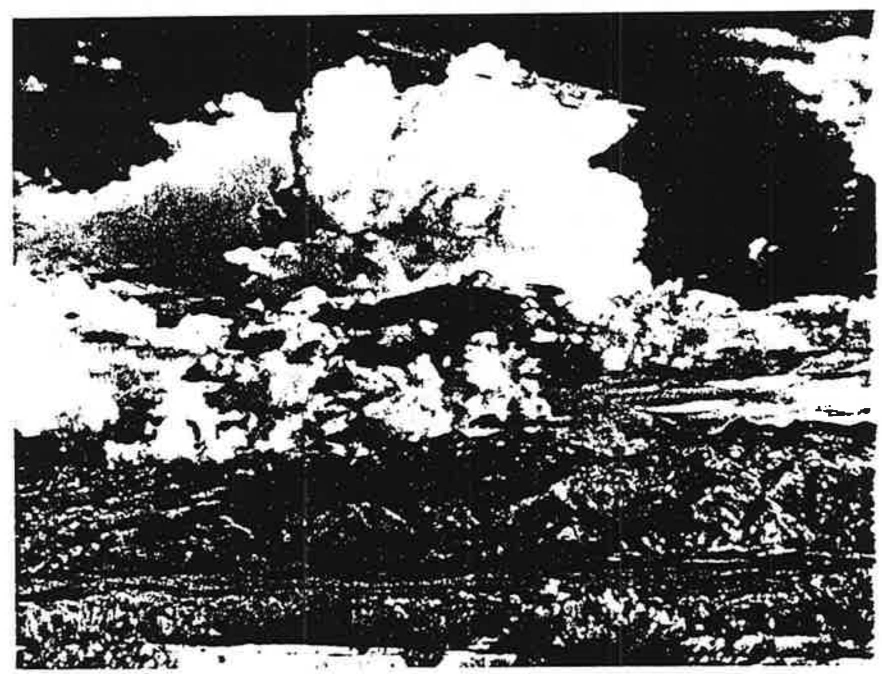
Other detached wedges of Precambrian gneiss and slices of Paleozoic and Mesozoic rocks border the south and west sides of the Rincon's bulbous granite core, which is encased in a carapace of highly sheared rock — a typical metamorphic core complex. Near Vail, one of the Paleozoic slices holds Colossal Cave, a limestone solution cavern decorated with stalactites, stalagmites, and other types of cave ornaments (see next section). East of Mountain View, Mesozoic sedimentary rocks extend across the highway and are visible in highway cuts as tilted layers sliced by numerous faults. Without these exposures, one would be hard put to discern the faulting here!

Entering Tucson's wide valley, I-10 drops gradually across the broad, gentle slopes that surround the Rincon and Empire Montains. Thousands of feet of valley fill — about 7000 feet under Tucson — conceal the real bases of the desert ranges. Roadcuts near mile 284-283 show some of the fill quite well, with typical stony Pliocene-Pleistocene gravel overlying an irregular, hilly surface cut in light colored, tilted volcanic rocks, reddish clay, and gravel.

Because there is no central river draining it, Tucson Basin seems unusually flat-floored. Its eastern half is drained by Pantano Wash, its north edge by the Rillito (Little River), and its western portion by the Santa Cruz River. The town originally sprang up on the banks of the Santa Cruz, which a century ago flowed all year around. Tucson has grown to fill the entire northern end of the basin. All of its water now comes from deep wells, and the water table has dropped markedly over the years. The rivers now flow only after heavy rains or snowmelt.

Open pit copper mines south of Tucson are in the Pima Mining District, discussed under I-19 Tucson to Nogales. Clockwise around the Tucson Basin from these mines are the Tucson, Santa Catalina, and Rincon Mountains, discussed under Saguaro National Monument (Chapter V) and Tucson and Vicinity, and the Empire and Santa Rita Mountains, described under I-19 Tucson to Nogales and AZ 82-83 Nogales to I-10.

The forerange of the Santa Catalinas, an anticline of banded gneiss, hides the domelike granite core of a large metamorphic core complex.
Tad Nichols photo.



Tucson and Vicinity

The mountains around Tucson offer several interesting excursions: to Sabino and Bear Canyons and Mt. Lemmon in the Santa Catalina Mountains, to the Tucson Mountains and the Arizona Sonora Desert Museum, to Saguaro National Monument (discussed in Chapter V), and to Colossal Cave at the base of the Rincon Mountains. Longer trips are also possible: to Oracle and the Pinal Pioneer Parkway (see US 89 Florence to Tucson); to Nogales (see I-19 and AZ 82-83); and to Kitt Peak (see AZ 86).

The Museum of Geology at the University of Arizona displays many beautiful minerals from Arizona mines, as well as other geologic specimens. A major rock and mineral show takes place in Tucson each February.

SABINO AND BEAR CANYONS

These two canyons, both now city parks, slice through the Catalina Gneiss that makes up the forerange of the Catalinas — part of the great Rincon-Catalina-Tortolita metamorphic core complex. The gneiss seems to lean up against the dark, forested dome of Mt. Lemmon, high point of the mountains (9157 feet), but it is actually around part of an anticline separated from the dome by a deep valley in part occupied by the east and west forks of Sabino Creek and by Sycamore Creek, a tributary of Bear Creek. With some severely deformed Precambrian and Paleozoic sedimentary rocks (still exposed near the summit of Mt. Lemmon), the gneiss seen in Sabino and Bear Canyons was altered by immense pressures, high temperatures, and the upward thrust of the mountain core. It formed from the granite of the summit dome and probably also, in part, from sedimentary rocks that once lay above that granite.

Tumbled boulders of Catalina Gneiss add to Sabino Canyon's beauty. They fell from the canyon walls during an 1887 earthquake.

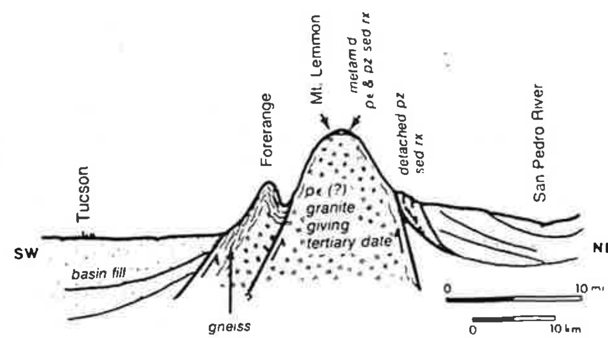
The gray Catalina Gneiss is attractively banded, with white quartz veins of all sizes. It is a particularly resistant rock except along joint planes, where crushing and signs of movement are present.

Streams in these canyons, only partly fed by springs near the summit and in the valley behind the forerange, do not always flow. Their canyons appear basically V-shaped from a distance, but from close up are seen to be modified by the cliff-forming tendency of several strong, vertically fractured bands of gneiss. Lichens and desert varnish on the cliffs conceal the true gray color of the rock, which does however show up well on stream-washed boulders.

Both Sabino and Bear Canyons give access by trail to the valley behind the forerange and the main dome beyond it. At Seven Falls up Bear Canyon, Sycamore Creek tumbles into deep pools, super sized **potholes** formed as swirling water scoured solid rock with sand and boulders. Smaller potholes can be found in both canyons.

CATALINA HIGHWAY TO MT. LEMMON

Visible from Tucson as a rounded granite dome, Mt. Lemmon rises to 9157 feet. Weather up there is 20 degrees cooler than in the desert around Tucson. Rainfall is higher, and a conifer forest darkens the summit and upper slopes. In front of the dome is the rocky ridge of the Santa Catalina forerange, separated from the dome by a deep east-west cleft that to a great extent controls the direction of streams that pass through the forerange onto the desert floor. Together the dome and the forerange make up the Catalina part of the huge Rincon-Catalina metamorphic core complex, the largest in the Basin and Range region.



Section across the Santa Catalinas Mountains

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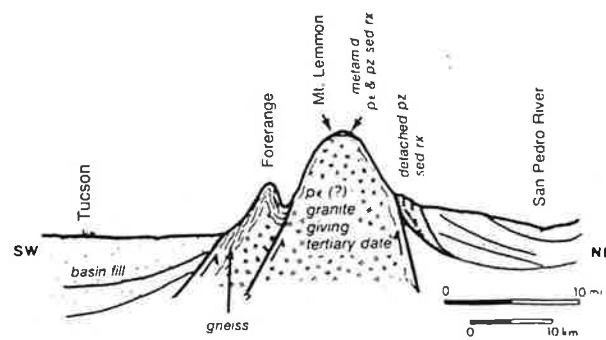


Section across the Santa Catalinas Mountains

The Catalina Highway, branching from East Tanque Verde Road, crosses the hidden fault at the base of the Santa Catalinas and climbs through banded dark and light gray Catalina Gneiss, well exposed in roadcuts and natural outcrops, that makes up the forerange. Some of these rocks may have formed from Precambrian granite, which appears in its original form only at the north end of the range. Others are banded in ways that suggest derivation from sedimentary rock layers that once overlay the granite. The forerange gneiss forms a steep anticline along the face of the mountains, with **dips** — the direction and angle at which the layers slope downward — expressed in layering or foliation.

As the highway climbs through the forerange the crest or axis of this anticline can be seen; beyond milepost 2 the dip is reversed. The gray gneiss, with dark and light veins, shows up well in cliffs visible from milepost 2 or mile 4-5.

The central core of the Catalinas is massive granite, probably Laramide in age but so altered by heat, pressure and movement during mountain-building stresses that its atomic calendar was reset to give a post-Laramide age. At the same time a faint layering was created, so that the rock could now be called a **gneissic granite**. The highway reaches some of the granite (we'll call it that) near milepost 6, just beyond Molino Basin Picnic Area, and then comes to its main mass, much less fractured, between miles 10 and 11. It is well exposed near another picnic area at mile 12-13. Chunky crystals of glassy quartz and feldspar, sparkly flakes of black and white mica, and occasional dark brown crystals of **garnet** make up this rock. In places it is banded by **pegmatite veins** containing larger crystals of the same minerals. Everywhere it is cut with several sets of joints; along some, crushed white sand shows that movement has taken place.

Along this road there are many fine examples of weathering processes that gradually turn the granite into loose sand. Along joints and faults where water can penetrate the rock, the rock begins to decompose, with mica crystals changing chemically to clay, and with

With a fanciful hand erosion has carved strange figures in granite along the Catalina Highway.

the bonding of quartz and feldspar crystals gradually loosening. In the fine fissures, water freezing on wintry nights forces the rock apart; on a small scale it separates individual crystals. Tree roots pry apart boulders, and plants release acids that further break down crystal bonds. Near and above mile 14 such weathering has carved strange pillars or **hoodoos** that tower above the road and march down the mountainside.

Below the ground surface, similar weathering takes place, and chemical decomposition turns the granite into loose sand. Rounded, half-buried knobs are very typical of weathered granite terrains.

On the north side of the Catalinas, and visible from the vista point at milepost 18, are dipping Precambrian and Paleozoic sedimentary rocks fringing the north side of the mountain core. Elsewhere, particularly near the summit, these rocks were caught up in the metamorphism that affected the core of the range. Near Summerhaven and along the summit ridge from mile 20-25 some of the same rocks, severely folded and metamorphosed, have been recognized as part of the carapace of the metamorphic core complex. The northern part of the summit is cut by many dikes, some of dark **diabase**, some of lighter, coarsely crystalline pegmatite.

Many small streams begin life as springs and little ponds up here near the top of the mountain, where rainfall is several times heavier than on the desert below. Carving V-shaped canyons down through the granite, the streams join others that flow parallel to the mountain front, behind the forerange, between the granite and its gneiss carapace. They then cut through the forerange as Soldier Creek, Sabino Creek, Bear Creek, and other delightful canyons.

TUCSON MOUNTAINS

(see also Saguaro National Monument in Chapter V)

This small range is composed of Tertiary intrusive and volcanic rocks bordered by faulted, folded Paleozoic and Cretaceous sedimentary rock. Flat-lying basalt flows make up "A" Mountain, while Safford Peak at the north end of the range is a **volcanic neck**. Cat Mountain Rhyolite — partly volcanic ash hardened into tuff — forms Cat Mountain and other parts of the range near Ajo Road (AZ 86). Dikes cut across and along the range. Small, light-colored hills on both sides of the range are Paleozoic limestone. The southern part of the range is a confused mixture of lava flows, layers and patches of volcanic ash, volcanic breccia, and blocks of Paleozoic limestone — such a hodge-podge that it is defined as the Tucson Mountain Chaos!

On the west side of the Tucson Mountains, in the Avra Valley, the Arizona Sonora Desert Museum (and zoo) tells the tale of life on the desert; recently added earth science exhibits explain the geologic history of this part of Arizona. Nearby is the western section of Saguaro National Monument, as well as "Old Tucson," a one-time movie set maintained as an outdoor museum of the old west.

COLOSSAL CAVE

Dissolved in Mississippian rock — the Escabrosa Limestone — of a detached block of Paleozoic sedimentary rocks on the west side of the Rincon Mountains, Colossal Cave is a typical small solution cavern, well decorated with stalactities, stalagmites, and other cave ornaments.

From the parking lot near the entrance to the cave, one can look out at this **detachment**, which with others makes up the foothills of the Rincons. Above the cave entrance massive layers of Escabrosa Limestone form a steep slope; younger, thinner limestone layers lie above, and parts of the sequence are repeated below, with large and small folds complicating the picture. Whether they were dragged along the side of an uplift under the weight of a mile or more of overburden, or were moved into position by other means (we don't yet know the answer to this knotty problem), the detached blocks did not retain their shape but squeezed and folded, rumpled or broke, depending on their resistance to the stresses involved.

To the southwest and west, bordering a small valley, are reddish brown slopes of the Pantano Formation, parts of which are mined for clay. Granite over the hill to the north is Precambrian, whereas the Catalina Gneiss covering the main mountain mass has had its atomic calendar reset to about 30 million years.

Rincon Peak is one of two parallel anticline ridges (shown on the map of I-10 Wilcox to Tucson), with the foliation of the gneiss arching up over them. A syncline comes between them at Rincon Valley.

Colossal Cave itself, limited in extent by the size of the block of Paleozoic sedimentary rocks, was dissolved by groundwater seeping through joints in the Escabrosa Limestone, probably early in Pliocene time. (The tour guide may tell a different story.) Groundwater solution occurred most readily right at the surface of the groundwater, where acidified rain water trickling through joints in the limestone most readily dissolved it. As the land rose, lower levels of the cave were excavated. Sometime after solution of the cave, the water drained away. From then on, rainwater trickling through

In limestone caverns like this one in the Santa Catalina Mountains, water dripping from the ceiling builds slender, icicle-like stalactites *and stubbier* stalagmites. Flowstone *(background) forms as water seeps across cavern walls.* Tad Nichols photo.

overlying limestones, dissolving calcium carbonate from them, began to decorate the cave. **Dripstone** and **flowstone** ornaments built up where this trickling water came into the cave, dripping from the ceiling or flowing thinly down the walls. Drop by drop, crystal by crystal, as calcium carbonate came out of solution, **stalactites** formed — thin "soda straws" at first, later thickening and building up from the outside. Sturdy, splatter-topped **stalagmites** below them grew as water dripped from the stalactites. Occasionally stalactite and stalagmite met, forming a **column**. Thin **draperies** built where flowing water trickled down the walls.

With increasing aridity at the end of the Pleistocene rainy spells, the cave dried up. No water drops or flows there now, and the ornaments bear a thin coating of dust.

As you leave the cave, look southward from the portico to the high, flat level between the distant mountains. This level, too, is Pleistocene — an old gravel and sand deposit that partly surrounds the Santa Rita, Empire, and Whetstone Mountains. It is discussed under AZ 82-83.

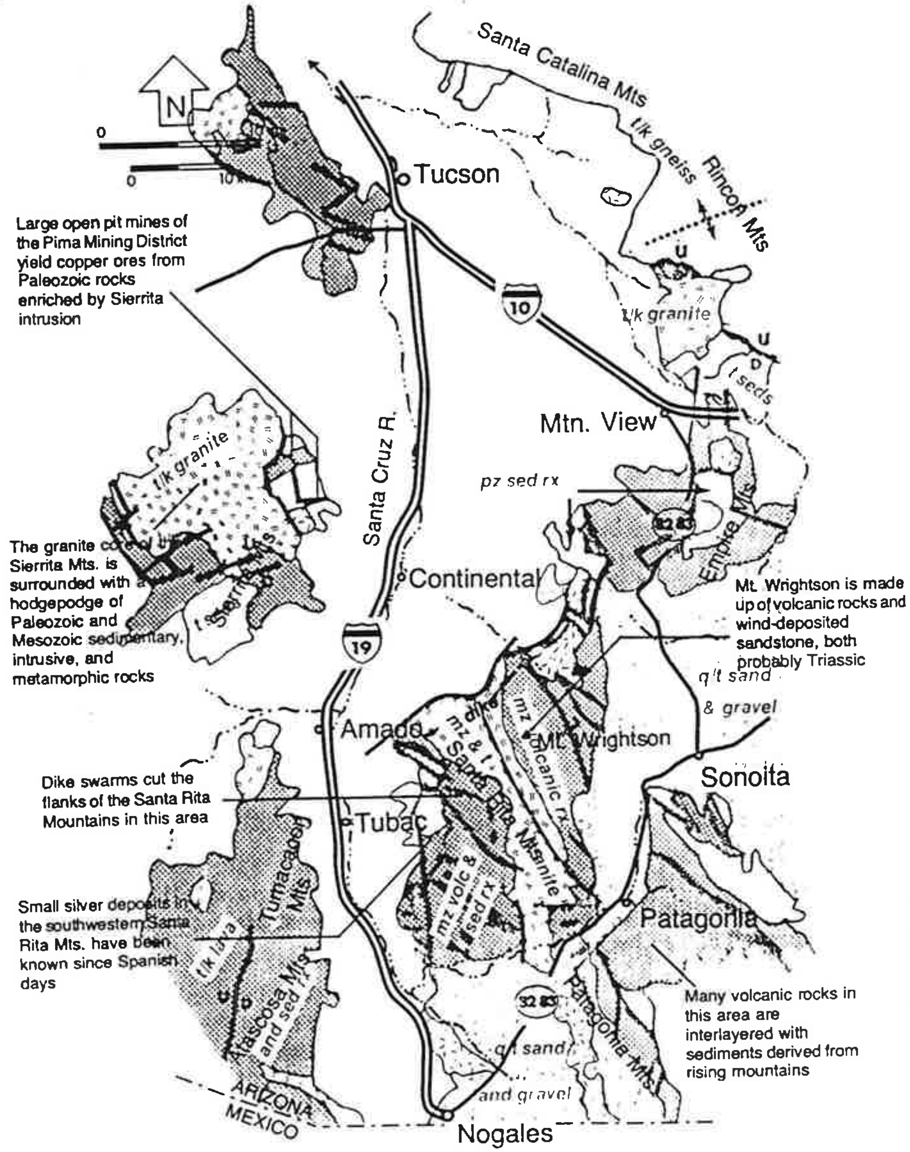
Picturesque San Xavier Mine produced copper ores from underground workings. Availability of heavy machinery and new processing techniques made large open pit mines more practical.
Tad Nichols photo

Interstate 19
Tucson — Nogales
106 kilometers (66 miles)

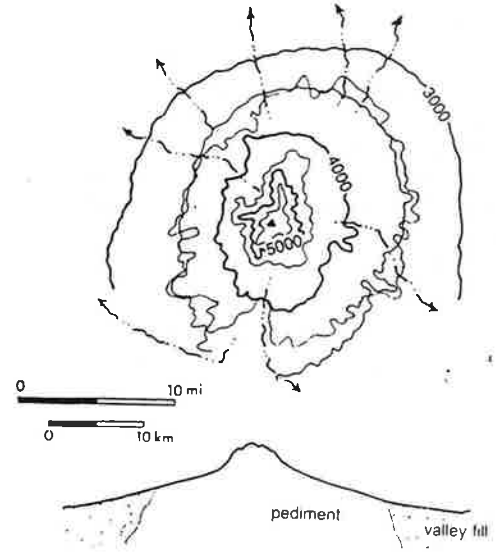
This highway is marked with metric units. One kilometer (km) equals 0.622 miles.

The southern end of the Tucson Mountains can be seen to advantage from this route. Here the range consists of faulted, tilted blocks of Cat Mountain Rhyolite, volcanic rock dated as less than 70 million years old. South of the intersection with Arizona 86, at kilometer 100, the hills near I-19 are composed of an odd, somewhat controversial rock unit named the Tucson Mountain Chaos — a plum pudding mixture of broken rock fragments and volcanic materials that may have resulted from explosive eruptions similar to the 1980 eruption of Mt. St. Helens.

From kilometer 92, San Xavier Mission shows up to the west against dark mid-Tertiary and younger volcanic rocks of Black



I-19
Tucson to Nogales
AZ 82/83
Nogales to I-10



The Sierrita Range is surrounded by a broad, evenly sloping pediment that blends with no change in angle with surrounding valley fill. Drainage is radial. Large mine tailings east of the range now interrupt the symmetry shown here.

Mountain. Built between 1783 and 1797, this mission succeeds an earlier one constructed around 1700 by Jesuit priest Father Kino, one of the first white men to explore and describe this area.

The Santa Cruz River west of the highway flows north and then northwest toward the Gila River. Its present channel, cutting through soft, fine floodplain deposits, postdates 1880, when a cycle of **arroyo** or gully cutting began in the southwestern deserts. Prior to that time the river meandered broadly on its floodplain; early reports say that it flowed all year. The downcutting, which may or may not have been triggered by overgrazing, continues to this day.

The area south and east of San Xavier overlies the deepest part of the Tucson Basin, with about 7000 feet of valley fill.

Southwest of kilometers 90 to 80, dumps of several large open pit copper mines mark the slopes below the Sierrita Mountains. The Sierrita region — the Pima Mining District — is endowed with some of the largest low-grade copper deposits in the world. From 1908 to 1975 this district produced, in order of abundance:

copper	2,842,498 tons
zinc	more than 100,000 tons
molybdenum	91,592 tons
lead	43,587 tons
silver	1,260 tons
gold	2 tons

Open pit copper mines south of Tucson penetrate copper deposits associated with a Tertiary intrusion. Both the Rincons (background, right) and the Santa Catalina Mountains (left) are metamorphic core complexes. Tad Nichols photo

The bulk of these metals came from great open pit mines that began operations in the 1960s near sites of earlier underground workings. The ore bodies fit into the pattern of **porphyry copper** deposits, where shallow Tertiary intrusions of granite porphyry penetrated, altered, and enriched Paleozoic limestone and quartzite. The principal ore mineral is chalcopyrite.

The granite intrusions, as well as the blocks of Precambrian, Paleozoic, and Mesozoic rocks, were lifted during Basin and Range faulting. Some of the sedimentary rocks may represent the upper slab of a broad thrust sheet now many miles northeast of its original position. The possibility of such thrusting leads as you might expect to a good deal of speculation as to the whereabouts of the original base of the intrusion and of the mineral deposits!

To see one of the big open pit mines, turn west on Duval Mine Road at exit 69, go west about 3 miles, and follow the signs to the visitor viewpoint. The depth of the pit can be calculated by counting the benches: each bench is 40 feet high. Trucks down in the pit have

wheels ten feet in diameter and carry 75 to 130 tons of rock. The ore is greenish, and was originally covered by several hundred feet of overburden. Ore is carried out of the pit and to a crushing mill by conveyor belt. Crushed and ground to powder, it is mixed with water and chemical frothing agents that bring copper-bearing particles to the top of the mixture, where they are skimmed off. One ton of ore yields about 40 pounds of the skimmed-off concentrate, a third of which is copper. Molybdenum is recovered from the concentrate by a similar process, and then the concentrate is shipped to smelters for further processing.

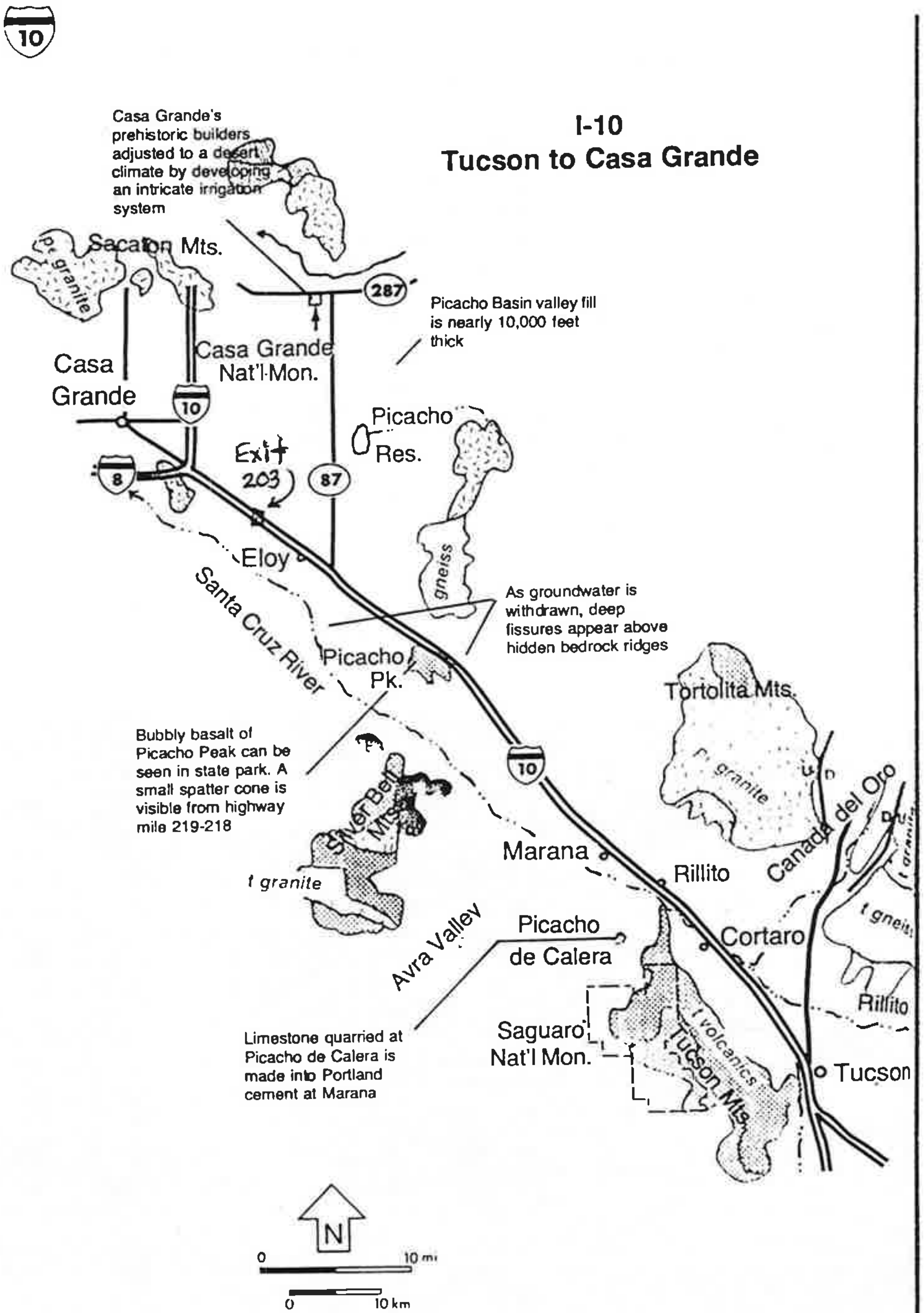
To the east across the highway from these mines are the Santa Rita Mountains, with Mt. Wrightson (9453 feet) as their high point. Here as in many southern Arizona mountains the geologic pattern includes enigmatic thrust faults with slices of Paleozoic sedimentary rocks sitting astride or leaning up against a Precambrian core. The overthrust school subscribes to broad movement of a thin sheet of rocks from as much as 100 miles to the southwest. Thrust faulting in the Santa Ritas occurred 75 to 80 million years ago. Because their sedimentary sequence is relatively complete and only slightly deformed, these mountains contain more clues than most to the geologic history of the region. Both Paleozoic sedimentary strata and Precambrian core are intruded by Tertiary porphyry associated with scattered copper deposits.

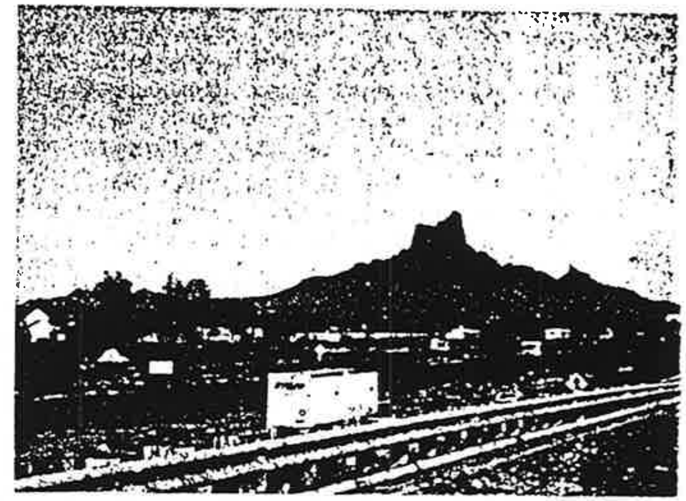
An especially large alluvial fan spreads out below the Santa Rita Mountains. It is grooved by stream-cut channels, many of them the work of post 1880 arroyo cutting. Near the west end of the Santa Ritas, Elephant Head is part of an intrusion that occurred 68 million years ago. There were at least four episodes of intrusion in the Santa Ritas, and many of the dikes that were formed are visible from the rest stop near kilometer 31, in tilting ridges at the base of the mountains.

South of Green Valley the highway cuts through another alluvial fan and exposes the layered fine and coarse sandstone and gravel of which it is made. The layers are channeled and refilled in places. Watch for reddish soil zones covered over by younger gravel.

South of the Santa Ritas, again in sight from the kilometer 31 rest stop, is another high gravel surface. Deposits below it fill a narrow valley created by faulting; they are about 600 feet thick. The Patagonia Range farther south extends on beyond the Mexican border; this range is almost entirely Precambrian and Cretaceous granite.

The Tumacacori Mountains west of Tubac contain volcanic rocks similar in composition and appearance to those of the Tucson Mountains. Tubac lies near the site of a fortified Spanish presidio estab-





Nourished by water from the Salt River, green fields supplant desert near Picacho Peak.

Interstate 10
Tucson — Casa Grande

(59 miles)

Northwest of Tucson I-10 follows fairly closely the course of the Santa Cruz River. Quite dry most of the time, or with a diminutive trickle across the sand, this desert wash "drains" the western part of the Tucson Basin. The eastern part is drained by Pantano Wash and the Rillito, the latter flowing into the Santa Cruz near mile 251. Another stream, Canada del Oro (Canyon of Gold!) drains the northwest side of the Santa Catalina Mountains. Gold *can* be washed from its sands, but adequate stream flow is infrequent. During or after heavy rains these streams may flow bank to bank; even so, the water is likely to sink into porous sands of the Tucson and Avra Valleys, rarely if ever reaching the Gila River.

Looking back at the Santa Catalina Mountains from about mile 248, you can see the sloping sides of the forerange anticline, fronting the great dome of granite that makes up the highest part of the range, the core of the metamorphic core complex. In the other direction are clustered small intrusions and lava flows of the Tucson Mountains. Both these ranges are described in the preceding section. The prominent peaks in this northern part of the Tucsons are small intrusions, probably the hardened contents of volcanic conduits.

North of the highway and northwest of the Catalinas rise the Tortolitas, geologically a single large mass of light-colored granite. In the Tortolitas as in most fault block ranges the edges of the upfaulted blocks have eroded back, creating a pediment flush with surrounding valley deposits. Looking between the Tortolitas and the Catalinas you can see a high platform of Tertiary sediments that fills much of the downfaulted graben between the two ranges.

An industrial complex at Rillito manufactures cement from Paleozoic limestone quarried from two small hills known as Twin Peaks or Picacho de Calera. One of several sets of Twin Peaks in Arizona, these are about 3 miles southwest of Rillito. Much farther south along the Avra Valley are the Baboquivari and Quinlan Mountains, their northernmost summit bearing the white observatory towers of Kitt Peak National Observatory.

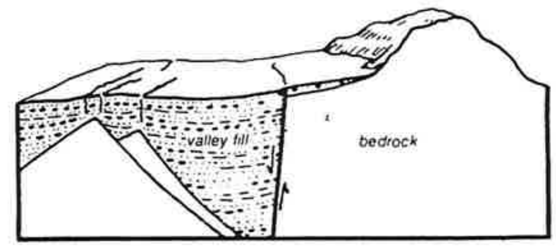
Silver Bell Mountains west of Marana draw their name from Silver Bell Mine, an old underground mine now reactivated as an open pit. The little range is an odd mixture of Tertiary and Quaternary volcanic rocks around both Precambrian and Tertiary granite cores.

Marana is an agricultural center; in every direction from it are cotton and alfalfa fields irrigated with well water drawn from deep **aquifers**, water-bearing layers of sand and gravel.

In the broad desert valleys of the Basin and Range Province, wind erosion is every bit as important as erosion by water. Blowing winds lift immense amounts of soil skyward, especially where the desert surface has been plowed for agricultural use. Dust devils, whirlwinds that create tall, slender columns of dust, scour the surface and transport sand and even gravel for sizeable distances. The soil here is tan, without the darkening vegetal matter that characterizes soils of wetter climates. In places the surface of plowed and planted soil is coated with white alkali salts from water used for irrigation. High mineral concentrations retard or prevent plant growth, and eventually soils may become too highly mineralized for further use.

Except for an enigmatic block of granite near its summit, Picacho Peak is composed of volcanic rock.
Courtesy of Picacho State Park

To the north now, projecting against the sky and looking very much like a volcanic neck, rises the prominent "Ship of the Desert," Picacho Peak. Recent studies show that it is not a volcanic neck at all, but the faulted, tilted and eroded remains of a sequence of lava flows. The rest of the sequence, faulted and separated from this part, lies under several thousand feet of valley fill. The summit of Picacho, however, contains a single large block of Precambrian granite that must have been ripped from the wall of a conduit and carried up toward the surface.



When withdrawal of groundwater causes subsidence, earth fissures *develop over buried ridges and the edges of pediments where, because the valley fill is thinner, total compaction is not so great.*

Light-colored hills directly across the highway from Picacho are the Picacho Mountains, their southern end gneiss, their northern end granite. Like that of the Tortolitas their granite is similar to that of the northwest dome of the Santa Catalinas.

In the Picacho area rapid increases in groundwater pumping during the last 30 years have caused severe lowering of the water table. The Santa Cruz Valley as a whole has been sinking as water is withdrawn, and near Picacho and the Picacho Mountains many deep, irregular cracks — a result of this sinking — cross the desert floor. Because the fissures have all developed since 1951, when deep irrigation wells began to appear, they are blamed on compaction of valley sediments as water is removed. The fissures develop above bedrock ridges (located by precise gravity measurements) because the degree of compaction is proportional to the thickness of the sediments. The cracked zone crosses both the railroad and the highway, necessitating frequent repairs.

Groundwater is now being pumped from southern Arizona valleys at rates far exceeding the rates of normal, natural recharge. Depletion in the Tucson and Phoenix Basins is four times as great as natural recharge. Geologists call this process — taking water out faster than it is replenished — "mining" the water, depleting the

Earth fissues such as this are caused by man-induced lowering of the groundwater surface.

T. L. Holzer photo, courtesy of USGS.

total remaining supply. Only a major climate change, for instance a **pluvial** (rainy) cycle like those in Ice Age time, could naturally reverse this process. Without such a climate change, conservation, water importation, and reduction of agricultural use are necessary alternates. As wells are drilled deeper and deeper the irrigation water becomes, of course, more and more expensive. It is getting to the point now where pumping water to farm the desert is no longer cost-effective. Some farms have already been abandoned.

Picacho Basin north of the Picacho Mountains is, like other Basin and Range valleys, underlain by several thousand feet of sand and water is somewhat salty, and if it flows into undrained basins in a dry climate, such as that which has prevailed here off and on for several their collective name implies, such evaporites form by evaporation, here in saline lakes rather than from the sea. Almost all desert river water is somewhat salty, and if it flows into undrained basins in a dry climate, such as that which has prevailed here off and on for several million years, the basins become just so many giant evaporating pans. It's clear that this and a number of other basins once held briny lakes like Great Salt Lake in Utah and the many smaller saline lakes in Utah, Nevada, and the southern desert of California.

The history of irrigation in the Casa Grande Valley is a long one. The Hohokam people who lived here long before the coming of the white man — the people who built the Casa Grande, now a national monument — developed an intricate irrigation system to water their corn, beans and cotton. However, they developed no water storage dams and dug no wells. They lived with vagaries of weather and climate and eventually had to give up their desert home, probably because their agricultural lands became waterlogged and unproductive.

Exit 203

Turn left (south), cross over I-10 & turn right (west) on Houser Road.

Go west on Houser Road 4 miles to the near end of a concrete canal.

turn right on a dirt track and go north ½ mile to subsidence cracks in playa.

Geological Summary and Perspective of Porphyry Copper Deposits in Southwestern North America

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ABSTRACT

Porphyry copper deposits in the American southwest comprise a distinctive and important metal resource. Their exploration and exploitation during the past hundred years was accompanied by significant advances in geological knowledge and development of increasingly efficient mining and extraction methods. Cause and effect are indistinguishable because the necessity for increasing mining efficiency resulted in enhancement of extractive methods and because geological study of the ores resulted in recognition of broadly applicable geological and exploration concepts. The early view of linear tectonic-based regional controls was supplanted by integration of concepts of plate movements. Early views of the environment of formation of hydrothermal ores have been given rigor or modified by the results of studies based on modern methods of analysis and application of sophisticated chemical principles. Deposits have been sites of basic studies of hydrothermal systems, the results of which have been applicable across a wide spectrum of ore deposits. Most importantly, information and methods developed in the study of ores and their mining have served as bases from which the search for deposits in many regions of earth has proceeded successfully during the past half century.

INTRODUCTION

The American Southwest, comprising the southwestern half of Arizona and contiguous parts of New Mexico and Mexico ("the region") is the site of an extraordinary endowment of porphyry copper deposits. Most deposits are in southeastern Arizona where historic and recent copper production amounts to about two-thirds of newly mined copper in the United States. Significant quantities of by-product molybdenum, silver, gold, and platinum are also produced.

This paper presents a brief history of the technological evolution of southwest porphyry copper deposits as bulk low-grade deposits and the evolution of knowledge of their settings, habits, and genesis over the past century. This summary sets forth important parameters that may be contrasted and compared with other porphyry systems in other regions. The writer has selected significant characteristics described in an extensive literature developed during the past half century to serve as fundamental points from which to consider the environment and processes of formation of porphyry copper deposits as viewed in the 1990s.

Background

Following Daniel Jackling's innovations in mass mining at Bingham, Utah, during early years of the century, mines in the southwest gradually evolved from high-grade, mostly underground operations to bulk low-grade, mostly open-pit operations. These districts and mines included Miami, Inspiration, Ray, Chino, Morenci, and Bisbee. Under the impetus of material requirements for prosecution of the war, the search for copper ores by 1942 had focused almost solely on discovery of new disseminated orebodies and resulted in identification of 25 porphyry copper deposits by 1980. Among the first recognized as having porphyry copper potential by mid-century were the disseminated ores at Silver Bell, described by Richard and Courtright (1954). Much of the early history of these deposits has been recorded from economic and engineering perspectives by Parsons (1933, 1957).

In the early 1990s mining was proceeding at a dozen deposits in Arizona that had survived the economic downturn of the 1980s: Twin Buttes, Sierrita-Esperanza, San Xavier-Mission, San Manuel-Kalamazoo, Ray, Morenci, Pinto Valley and Inspiration, and Bagdad. Leaching of copper was taking place at Mineral Park, Lake Shore, and Silver Bell. Chino and Tyrone were operating in New Mexico, and Cananea and La Caridad were producing copper in Mexico. At this writing, ten more deposits have been explored but are undeveloped or unmined.

The porphyry copper deposits of the region have been not only sites of recovery of significant mineral wealth but also sites of detailed and extensive studies of process geology and development of mining and beneficiation technology. Geological studies of mining districts of the southwest reported mostly by geologists of the U.S. Geological Survey during the early part of the century developed a basis of regional stratigraphy and structural geology that is used to this day with only minor modifications. Basic concepts of ore occurrence and classification developed from studies of ores at Bisbee, Ray, Miami, and Morenci have been refined continuously since the beginning of the century with heightened study during the decades of the 60s, 70s, and 80s. Mines and districts of the region have been sites of development and testing of now widely used exploration technology that includes both geophysical (Brant, 1966) and geochemical (Bloom, 1966; Chaffee, 1982a, 1982b) methods. Arizona deposits have been sites of development of innovative technology in mineral extraction during the past half century and have served as field laboratories for development of methods and machinery.

Production and Grade

A tabulation of grade and tonnage of porphyry copper ores of the region has been published by Gilmour (1982) and summarized by Titley and Anthony (1989) and Titley (1994). Reserves in 1989 have been listed by Beard (1989). Production figures summarized for 45 porphyry copper deposits in the United States by Titley and Beane (1981) are 15.8 billion tons of copper ore production and reserves with a weighted copper grade of 0.68 percent. Fourteen deposits that reported molybdenum had a weighted grade of 0.0325 percent molybdenum.

Literature and the Growth of Knowledge

Literature of the first half of the century dealt largely with field observations and descriptions of known deposits. Much of this was in Monographs and Professional Papers of the U.S. Geological Survey, as Transactions of the American Institute of Mining and Metallurgical Engineering, and in serial publications such as Economic Geology. Viewed from the perspective of the evolution of ideas, papers of the 1940s were the first important reports treating alteration, mineral zoning, rock descriptions, and regional settings of these large systems. Collections of current reports focusing on the region and treating both deposits and topical information have been published by Titley and Hicks (1966) and Titley (1982a). Papers treating general properties of the deposits of the region as contrasted with deposits of other areas have been published by Jerome and Cook (1967), Lowell (1974), Hollister (1978), Titley and Beane (1981), and Titley (1992, 1994). Comparable treatment of porphyry deposits in western Canada has been published by Sutherland Brown (1976).

A surge of scientific interest has been marked by a comparable increase in the flux of papers treating different properties of porphyry copper systems. This increase began in the early 1960s, and the numbers of publications reached a peak during the late 1970s and early 1980s. The period was witness to application of increasingly widely available techniques of measurement and applications and testing of theory. Many concepts of hydrothermal ore genesis were refined. Porphyry systems were studied as examples of epicrustal intrusion-centered ores systems, of the evolution of hydrothermal processes in time and space, of the evolution of petrogenetic systems, of metal and alteration zoning, and of supergene enrichment and weathering processes. Many fundamental and now widely accepted notions of hydrothermal ore formation evolved from these studies.

GENERAL GEOLOGICAL HABITS AND GENESIS

Porphyry copper ores are phenomena of island arcs such as the western Pacific, of cratons in continental margin settings such as the western United States and contiguous Mexico, and of accreted, constructed continental margin settings such as western Canada. The character and complexity of deposits in these different settings vary in petrological and metallogenic detail, but notwithstanding such contrasts the deposits of all these regions share important features. The apparent association of ores with subaerial andesitic volcanic activity and the affinity of ores with felsic intrusive porphyry centers link porphyry copper deposits with specific geologic settings which have undergone the effects of plate convergence, most commonly along continental margins and island arcs.

Tectonic Settings and Geologic History

The history of modern knowledge and ideas concerning the regional association of ores with crust commences with Butler (1933), who noted the distribution of porphyry districts in a belt around the Colorado Plateaus. Under the influence of work by Billingsley and Locke (1935, 1941) and Mayo (1958), studies of the fabric of continents during the next two decades led to ideas of lineament control of ore districts. These workers showed districts to be localized at intersections of major regional structures or associated with major tectonic belts. Harrison Schmitt (1966) studied the location of porphyry districts from a global perspective and associated ore districts with major lineaments and zones of rifting. Even at this early time Schmitt invoked potential continental drift as a mechanism to explain continuation and offset of his major structures and proposed effects related to the influence of the East Pacific Rise. Using large numbers of potassium-argon radiometric dates, Jerome and Cook (1967) carried the notion of occurrence of districts in belts to a degree of sophistication and examined porphyry associations with characteristics of crustal geology. The idea that regional structures control the location of porphyry copper districts has withstood the advent of more recent notions concerning the evolutionary history of continental margins based on plate motions. Conflicting ideas of the importance of flaws in the crustal fabric of North America to district localization have been expressed by Lowell (1974) and Sillitoe (1975).

Areal and Structural Geology

Porphyry deposits of the region lie above the North American craton in Arizona, New Mexico, and contiguous Mexico. The geology of this region has been described in relevant parts by various workers including Anderson (1966, 1968) and Titley (1981, 1982b, 1992). The craton basement of the region comprises Proterozoic sedimentary and volcanic rocks at varying levels of metamorphism and batholithic scale plutons representative of at least three episodes of Proterozoic igneous activity. Most of the region's porphyry copper systems lie within or above a 1.68 to 1.72 Ga basement dominated by clastic metasedimentary rocks and included plutons; three deposits in northwestern Arizona lie within a possibly older (ca. 1.8 Ga) basement of metavolcanic rocks and older plutons. Figures 1A and 1B show the distribution of deposits and generalized basement ages of the region.

The Proterozoic basement is overlain by 2 to 4 kilometers of Phanerozoic cover consisting of Paleozoic platform strata and a variable thickness of Mesozoic clastic and volcanic rocks. In many districts mineralized basement is exposed in intrusive contact with porphyry intrusions and in fault contact with Phanerozoic strata, suggesting the existence of a still unresolved episode of Mesozoic tectonism that may have occurred in the Jurassic. Pre-Laramide Mesozoic rocks are represented by intrusions, by basin strata in the central part of the region, and by mixed volcanic and clastic strata in southern Arizona and contiguous Sonora, Mexico.

Courtright (1958) and Richard and Courtright (1960) were the first workers to report observations on volcanic rock successions that established the Laramide interval as manifesting a distinct geological style in contrast with that of the older Mesozoic. The Laramide interval is a 25 m.y. span of time marked by both volcanic and intrusive igneous activity. The interval followed a period of 90 m.y. of igneous quiescence and was succeeded by a further 25 m.y. period of similar quiescence in the region. Laramide lithologies of the region are dominated by igneous rocks ranging from extrusive flows and pyroclastic successions to intrusive batholiths, stocks, and dike-sill swarms. Magmas were emplaced in the shallow crust, and their first manifestation appears to have been development of andesitic stratovolcanoes. Remnants of subaerial flows are widely exposed through the region (fig. 2). The volcanic rocks are commonly altered or miner-

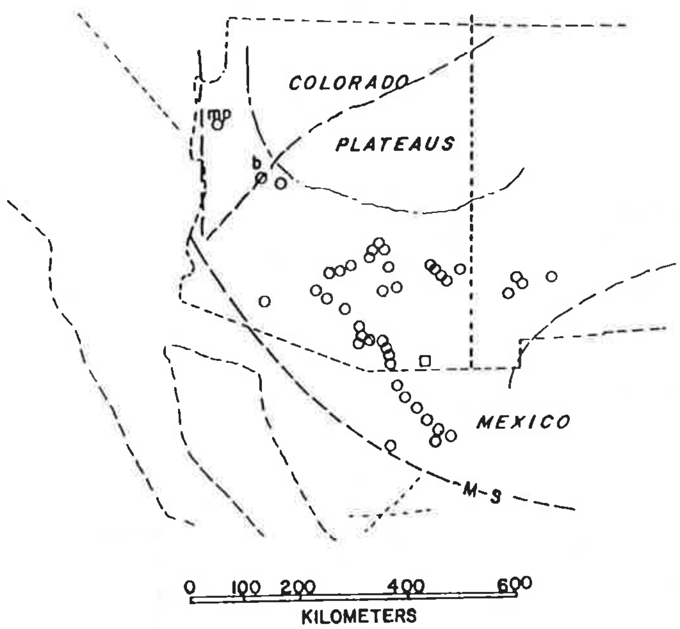

Figure 1B. Basement contrast map of Figure 1A with positions of significant porphyry copper deposits of the region shown as open circles. The deposits occur in the "copper quadrilateral" of Noble (1970) that is outlined by the Sonora Mohave megashear to the southwest and an uncertain northeast trending line across northwestern Arizona. This is the crustal block with a basement of assigned age of 1.7 to 1.8 Ga in figure 1A.

alized, and radiometric dating reveals close temporal correspondence with cross-cutting Laramide intrusions. An excellent example has been mapped by Dunn (1982) at Hillsboro, New Mexico (fig. 3). The widespread association of porphyry systems with these igneous suites coupled with observations of petrologic associations in island arcs and Andean-like margins has led to a general notion that the porphyry systems have evolved in the subvolcanic intrusive roots of andesitic stratovolcanoes. However, the evidence of evolution in such settings has not been successfully interfaced with interpretations of the existence of Laramide calderas in the region (Lipman and Sawyer, 1985).

Since Laramide time, oxidation, leaching, and episodes of erosion interrupted by younger episodes of volcanic activity and Basin and Range uplift have modified the original character of ores. Intermittent uplift and erosion has presently exposed porphyry deposits of the region at levels believed to be a few kilometers beneath their original tops.

Many modern ideas of the structural setting of the porphyry deposits had their roots in the application of lineament tectonics summarized by Schmitt (1966). More recent work concerning the structural style of the Laramide has been summarized by Krantz (1989). Mapping and interpretation in southeastern Arizona by Davis (1979) has demonstrated a Laramide structural style dominated by basement-cored uplift. This interpretation demonstrates the importance of an old northwest-oriented structural fabric parallel to the former continental margin which became rejuvenated during Laramide time (Titley, 1976). Despite this and other work, however, the structural controls of stock emplacement have remained elusive except at Bagdad, where Anderson and others (1955) mapped the intrusion center at the intersection of two orthogonal Laramide fault sets.

Time and Plate Tectonics

A link between porphyry ore genesis and tectonic events related to plate convergence was first suggested for the region by Sillitoe (1972, 1975). Two principal episodes of porphyry copper deposit formation are recognized in the region, one of Jurassic age as represented by the replacement and breccia complex at Bisbee and the other of Late Cretaceous to Early Tertiary (Laramide) age as represented by more than 40 mineralized centers in the region. Both the Jurassic and Laramide events represent short-lived episodes of near-normal convergence of the North American and Pacific Plates (Coney, 1978). The extensive dating of ore deposits in this region summarized in Reynolds and others (1985) leaves little doubt of the temporal correlation of ores with high rates of normal plate convergence during the Laramide. Moreover, Laramide stress directions inferred from plate convergence geometries are mimicked in fracture and dike patterns seen in Laramide intrusion centers (Heidrick and Titley, 1982). However, precise understanding of all elements of plate convergence phenomena that led to formation of the deposits of southwestern North America remains elusive.

The restoration of Baja California to a pre-rift fit along the Mexican mainland reveals that belts of deposits grossly parallel the old continental margin (fig 4), but the inference of a craton setting for deposits of coastal Mexico is subjective (Titley, 1992). Deposits of Arizona and contiguous Mexico represent ores of 58 to 65 Ma age, while those in a subparallel belt west of the volcanic cover of the Sierra Madre Occidental in Mexico are generally of about 55 Ma age (Damon and others, 1983).

Deposits of Mesozoic and younger age in the western hemisphere are along the western continental margin, while North American porphyry copper deposits of Paleozoic age are in parts of the old convergent margin now deeply eroded or hidden in the deformed parts of the Appalachian orogen along the eastern continental margin. The dense array of districts and deposits of the southwestern United States together with Cananea and La Caridad in Sonora have been considered a separate porphyry copper population. Concentration of study on this population by many workers including Noble (1970, 1976) has resulted in a provincial view of the cluster of deposits in the so-called "copper quadrilateral" and precluded a broader regional perspective and geologic synthesis. Data do exist: Sillitoe (1976) published results of a study of porphyry copper systems of Mexico, Coney and Campa (1987) have developed a regional view of Mexican geology based upon terrane analysis, and Anderson and Silver (1981) have presented results of a study of basement ages and distribution in northern Mexico. Based on these works a regional overview of porphyry copper distribution that extends beyond the border region of the United States and Mexico is shown in figure 4. In this figure the Gulf of California has been closed to approximate the inferred Laramide configuration of the continental margin. Basement ages and relationships as determined or suggested from the work of Anderson and Silver (1981) in Mexico and by Bennett and DePaolo (1987) in the contiguous United States are integrated with the terranes of northern Mexico to suggest a configuration of basement and tectonics at the time of Laramide ore formation.

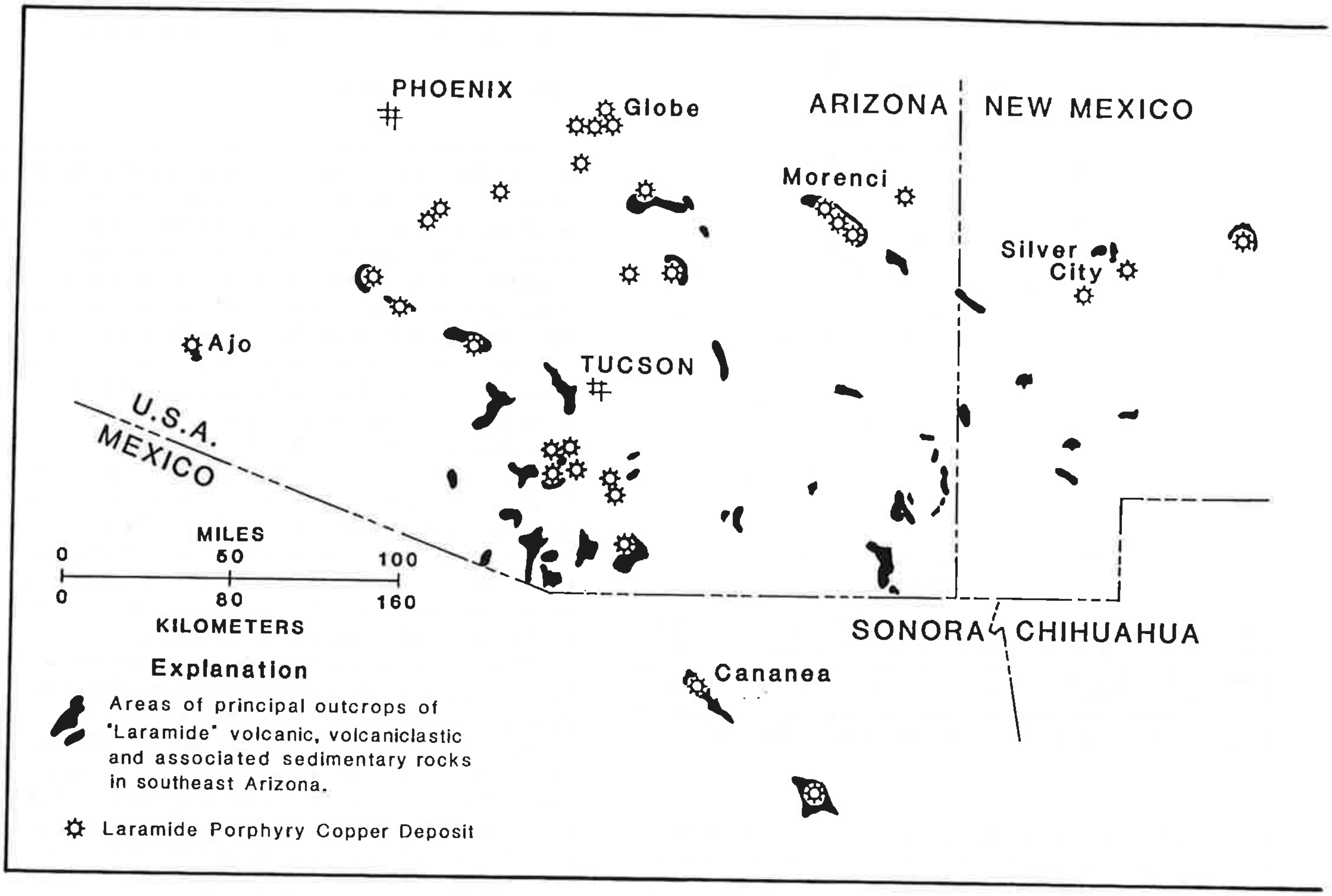

Figure 2. Map of southeastern Arizona, southwestern New Mexico, and northern Sonora showing distribution of Laramide porphyry copper deposits and outcrops of Laramide volcanic and volcaniclastic rocks. That these rocks and Laramide porphyry ores were regionally coextensive was recognized in the 1960s.

Igneous Petrology

Porphyry copper deposits and genetically comparable intrusion-centered deposits of molybdenum and tin are conventionally viewed as results of late stage events in the emplacement and cooling of felsic magmas that produce porphyritic rocks at shallow (less than 5 kilometers) depths during a volcanic cycle. That granite-associated ores may evolve in caldera rather than isolated volcanic systems and that some porphyry-related ores may have evolved as results of diatreme genesis are commonly recognized exceptions to this generalization: diatreme association may be represented at Ok Tedi in the New Guinea Highlands (about 1 Ma in age), which lacks associated volcanic strata. Notwithstanding such exceptions, the presence of closely contemporaneous andesitic volcanic strata with many systems in both cratons and island arcs lends credence to the conventional model. Rapid rise of magmas and their rapid cooling in a shallow environment is believed to result in porphyritic textures and profound thermal disequilibrium, which in turn results in the cracking of very large (cubic kilometers) volumes of wall rock conducive to the convective cooling processes that result in hydrothermal fluid flow (Burnham, 1981; Burnham and Ohmoto, 1980; Norton, 1979, 1982). Thus the petrology of igneous rocks and their cooling history is important to the understanding of porphyry copper systems. The focus of mineralization on centers of porphyry intrusion indicates a close genetic tie with cooling processes of magmas in the shallow crust, the effects of flow of hydrothermal solutions are temporally and spatially associated with certain plutons. Moreover, certain metal assemblages appear to be linked with specific igneous suites, which are also commonly regionally constrained.

Petrogenic studies treated the petrology of rock descent and differentiation and the questions of magma source, evolution, and ascent. Results of both of these approaches have been productive during the past several decades in advancing knowledge of how porphyry-centered metal systems evolve. No unanimous view among workers has yet developed, but there exists substantial field, experimental, and theoretical bases on which study continues to progress. Stringham (1966) summarized much petrographic data and outlined igneous associations in some copper districts. The first overview of petrologic compositional trends of Arizona deposits was offered by Creasey (1977) in a series of variation diagrams treating rocks from Ray. Cornwall (1982) further detailed chemical petrology at Ray, favoring a model that implies magmas and solutions from a probable source in the mantle. Igneous evolution of systems in the region commenced with outpouring of andesite-dacite volcanic materials followed by emplacement of intrusions which evolved to progressively more felsic phases. Sharp contacts and striking compositional contrasts in the intrusive suites of the region are the rule and have been interpreted as representing emplacement of successive magmatic phases rather than *in situ* differentiation of single magmatic progenitors.

Compositions of igneous rock series associated with deposits have been reported from Sierrita (Anthony and Titley, 1988a, 1988b), Christmas (Koski and Cook, 1982), Ajo (Wadsworth, 1968), and numerous additional Laramide districts (Lang, 1991). In terms of long accepted rock names, evolutionary trends of intrusions of the Laramide districts run from quartz diorite through granodiorite to a preponderance of porphyries of quartz monzonite. This range corresponds roughly with the I.U.G.S. (Streckheisen, 1973) nomenclature of monzodiorite through granodiorite to granite.

Burnham (1967, 1979) has traced magmatic evolution of porphyry-deposit related systems through the stage of formation of hydrothermal fluids by in situ differentiation. The role of water is addressed in detail because of its importance to magmatic processes and ground preparation through stages of solidification of igneous carapaces and their subsequent rupture as the pressure of confined volatiles increases during magma cooling. This results in the jointing of rocks, typically creating a stockwork. Wyllie (1981) reported studies of the origin of calc-alkaline melts in a subduction-related environment. Farmer and DePaolo (1983, 1984) have attributed the source of many Great Basin magmas including those related to porphyry metal systems to the crust. Anthony and Titley (1988a, 1988b) and Lang (1991) have reported results of studies of the evolution of major and trace element chemistry and neodymium and strontium isotopes in Laramide igneous suites of the region that reveal apparent deep crustal sources of porphyry magma progenitors to the mineralization. A plot of neodymium-strontium data is shown in figure 5, where Laramide suites are compared with island arc and Chilean intrusions and with the mid-Tertiary volcanic episode of the Sierra Madre Occidental of Mexico. One significant property of the Laramide intrusive centers in the Arizona region is that their isotopic properties reveal continuous evolution and change from magmas of perhaps 50 percent mantle component to magmas dominated by crustal components. The youngest intrusions are most evolved, and Anthony and Titley (1988a, 1988b) have interpreted a lower crustal amphibolite magma source on the basis of rare earth element patterns. An additional property of the intrusive suites is their evolution along specific trend lines as revealed by the isotopic habits in figure 5; changes in rock isotopic compositions are transitional, indicating gradually evolving magmas rather than abrupt contributions of different magmas from changing sources. Chemical and isotopic analyses of these rocks reveal that no single rock may be considered as representative of a porphyry copper intrusion and that interpretations of magma genesis and evolution must be premised upon the composite signature of the suite as a whole, petrogenic interpretations of porphyries must be made in the context of the properties of magma suites rather than the properties of single samples of igneous rocks.

The Style of Alteration and Mineralization

The style of hydrothermal modification in deposits has been described in general terms by Titley (1982c). The most common habit of porphyry copper mineralization is as hydrothermally altered, copper-mineralized stockworks. The stockworks comprise tens of cubic kilometers of fractured rock many tens of square kilometers in area either centered on porphyry intrusion cores or (more commonly) distributed asymmetrically across intrusion wall-rock contacts. Vertical exposures and measurements of paleopressures suggest mineralization and alteration originally extended over many kilometers vertically; most Laramide deposits of Arizona are exposed at a weathered level 1 to 3 kilometers below the original surface. The deposits ubiquitously reveal zoning of metals and alteration in patterns and cross-cutting habits that indicate a complex sequence of origin. Significant mineralization and the more commonly recognized alteration types are restricted to relatively small volumes in the hearts of stockworks. Where altered fractures of the stockworks have been mapped as at Sierrita (fig. 6) (Haynes and Titley, 1980; Titley and others, 1986), Silver Bell (Kanbergs, 1980; Norris, 1981), and Red Mountain (Kistner, 1984), mineralized centers defined by copper grades are revealed to be located in a few cubic kilometers of volume of closely spaced (centimeter) joints within a larger volume of less abundant fractures composing the stockwork.

The mineralogical, chemical, and physical conditions of alteration have been subjects of significant interest during the last half-century. The habits and environment of alteration have been important both in the search for ore and in the advancement of important elements of hydrothermal theory. Significant data on alteration including specific information treating porphyry metal systems have been published by many authors. Papers of the 1940s were among the first to describe the physical habits of alteration of deposits in Arizona. Much of this was the work of Peterson and others (1946) at Castle Dome and Anderson (1950) at Bagdad. Nearly 30 years of intense study of the chemistry of the alteration process in the region, much of it receiving impetus from the classic work of Sales and Meyer at Butte (1948), developed a fundamental base of knowledge of hydrothermal processes. By the early 1960s a generalized view of the essential nature of alteration had been developed and many of the habits of alteration of porphyry systems had been elucidated by Jerome (1966). Fundamental mineral associations and specifications of alteration stages had been outlined by Creasey (1966); and Beane and Titley (1981) outlined the alteration mineral chemistry in porphyry systems.

The minerals of alteration suites differ fundamentally with differences in their host rocks. Host rocks are varied, and their proximity to intrusions is controlled solely by geological coincidence. Porphyry copper deposits commonly manifest varied styles and compositions of alteration influenced in the main by the contrasts between and among mafic, carbonate, and potassium silicate dominated hosts: Conversion of volumes of rock to garnetite is a phenomenon seen in carbonate rather than potassium-aluminum silicate host rocks, while conversion of volumes of rock to orthoclase is a phenomenon seen in potassium-aluminum silicate rather than carbonate host rocks. These seemingly simple contrasts form an important basis for consideration of the

The Geology of the Mineral Hill Area, Mission Mine, Pima County, Arizona

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ABSTRACT

The Mission Mine, 32 kilometers southwest of Tucson, Arizona, is developed on a porphyry copper skarn with ore hosted in the Permian Epitaph, Scherrer, and Concha Formations and the Triassic Rodolfo Formation. The western portion of the orebody in the Mineral Hill area has distinct geologic and structural differences from the Mission Pit sequence. Cross-sections constructed from recent drill-hole data reveal that three major faults are responsible for these differences. Two of these faults have brought carbonate rocks of uncertain formation identity into the project area. Identification of these carbonate formations has been attempted by comparison of their normative mineral compositions with those of known formations and by using neural networks, a computer algorithm that has been successful in classifying complex patterns. Normative mineral compositions were too similar to be useful, but a combination of neural networks and stratigraphic data was moderately successful in correlating the carbonate rocks to sections of the Cambrian Abrigo, Devonian Martin, and Permian Rain Valley Formations, the presence of which was previously unconfirmed at Mission.

INTRODUCTION

The Mission Mine is located approximately 32 kilometers southwest of Tucson, Arizona, on the eastern pediment of the Sierrita Mountains. The mine is developed in a sequence of east-northeast-striking and southeast-dipping Permian and Triassic sediments that have been intruded by a Tertiary (Laramide) quartz monzonite porphyry. Upper Permian limestones, dolomites, and sandstones have been altered to marble, calc-silicate skarn, and quartzite. Overlying Triassic clastic sediments have undergone recrystallization and some hydrothermal alteration. The porphyry stock has undergone potassium-silicate and sericitic alteration. The general geology and stratigraphy of the Mission-Pima Orebody have been studied by a series of authors (for example, Jansen, 1982) and are well known.

The western portion of the orebody, informally known as the Mineral Hill Area (figs. 1 and 2) does not appear to involve the same stratigraphic succession found in the Mission Pit. This discrepancy is a result of two things: (1) disruption caused by intrusion of Laramide quartz monzonite porphyry into the Paleozoic sequence and (2) transport of the orebody ten kilometers northward along the Tertiary San Xavier Fault (Cooper, 1960) and other post-intrusive movements on several northwest-trending high-angle faults. Non-carbonate rocks are generally distinctive enough to be recognizable from drill core within the project area, but the identity of some of the Paleozoic carbonate units west of the high-angle faults has been uncertain to past workers due to lack of surface outcrop and drill-hole data and the effects of metamorphism.

The major ore-bearing units east of the Daisy Fault (the Concha, Scherrer, and Epitaph Formations) are not present on the west side as a result of faulting. Past workers have suggested that the Daisy Fault, a northwest-striking, northeast-dipping high-angle fault located in the western portion of the study area, may be the upsection continuation of the Twin Buttes Fault which cuts the Paleozoic section in the western portion of the Twin Buttes Mine ten kilometers to the south. Barter and Kelly (1982) estimate a minimum displacement of 1,067 meters (3,500 feet) along the Twin Buttes Fault. Identification of units to the west of the Daisy Fault may allow an estimate of that fault's displacement and thereby strengthen or refute the suggestion of its correlation with the Twin Buttes Fault.

The problem of identification and delineation of Paleozoic meta-carbonate units west of the high-angle faults has been addressed: (1) using recent extensive drill-hole data to construct cross-sections and level maps and (2) by using whole-rock geochemistry to attempt correlation with known stratigraphic units.

In an effort to delineate ore reserves and assist in mine planning, the ASARCO Mission Unit has drilled many vertical holes in the Mineral Hill area. Considered in conjunction with approximately 3,000 meters of older drill hole logs by previous workers, logging by R.L. Williamson of approximately 4,300 meters of reverse-circulation chips and 2,000 meters of diamond-drill core allowed construction of an extensive series of north-south and east-west cross sections set 61 meters (200 feet) apart (fig. 2).

Geochemical analyses were conducted on 80 samples from outcrops of 9 carbonate units known in the area (the Abrigo, Martin, Escabrosa, Horquilla, Colina, Epitaph, Scherrer, Concha, and Rain Valley Formations; fig. 3), from within the Mission Pit, and from drill core within the project area. Samples were analyzed by induced neutron activation analysis (INAA) and

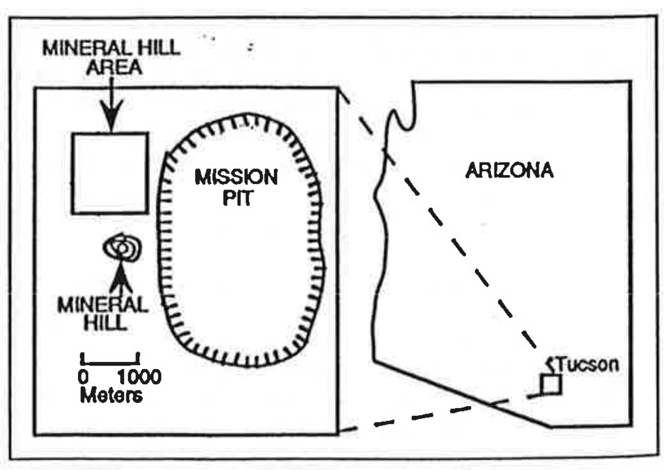

Figure 1. Map showing location of the Mineral Hill area and Mission Mine, Pima County, Arizona.

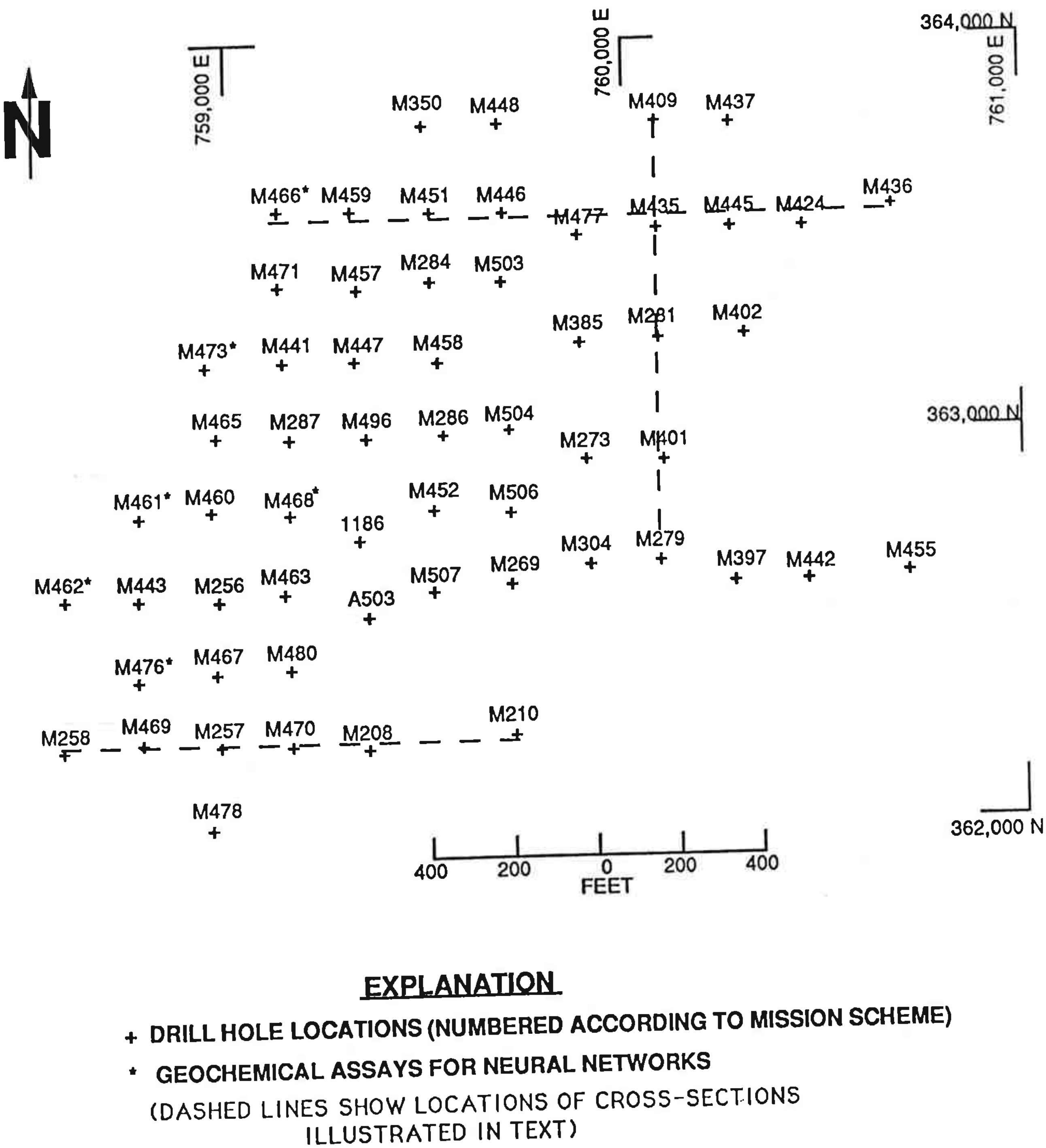

Figure 2. Map showing locations of cross sections and drill holes, Mineral Hill area, Mission Mine.

induction-coupled plasma mass spectrometry (ICP) by XRAL Activation Services, Inc., and two independent XRF analyses, one by Arizona Portland Cement and the other by the Mission Unit assay lab. Eighty-one analyses for 51 elements were run on the 80 samples, 30 of these analyses were replicates. Geochemical classification by formation was then attempted by two means: The first used SEDNORM, a program to calculate normative mineralogy for sedimentary rocks based on chemical analyses (Cohen and Ward, 1991), and the second used neural networks, a category of computer algorithms that has successfully classified complex patterns elsewhere. The classification that the neural network gave to the unknowns was then used in conjunction

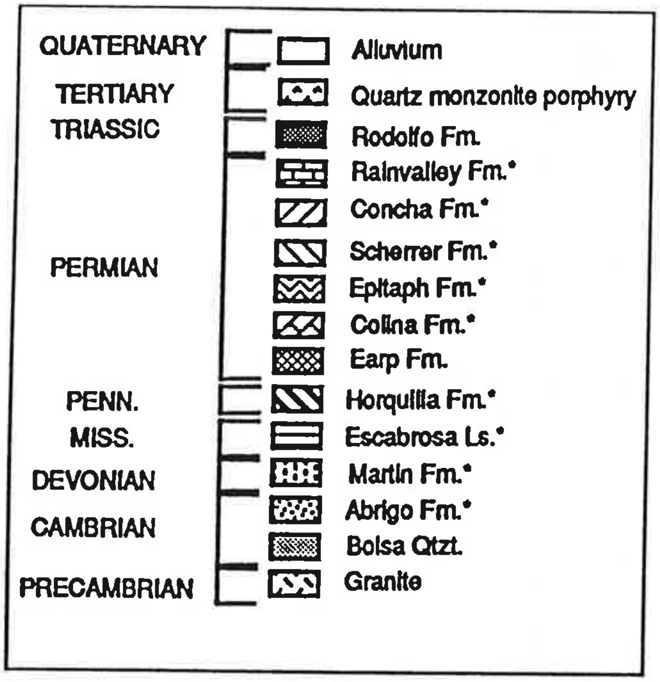

Figure 3. Stratigraphic column of rocks in the Mission Hill area, * indicates formations sampled for geochemical study.

with stratigraphic data to determine the identity of specific units and to determine the validity of the neural network classifications, particularly for samples where other clues to identity existed.

History and Production

The Pima Mining District has a long history of production which began in the late 1700s when the Spaniards operated several small mines there. Intermittent production from several small underground mines continued through the 1940s. Geophysical work conducted by R.E. Thurmond and W.E. Heinrichs, Jr. of the United Geophysical Company led to the discovery of the Pima Orebody in 1950. Subsequent geologic analysis by Kenyon Richard and J. Harold Courtright of American Smelting and Refining Co. (ASARCO) led to the discovery of the Mission Orebody in the late 1950s. The Pima Mining Company (Cyprus Mines, Union Oil, and Utah Construction and Mining Company) commenced open pit mining on the Pima Orebody in 1955, and ASARCO began mining operations on the Mission Orebody in 1959. By the early 1960s it had become apparent that the Pima and Mission Mines were operating on one continuous orebody. Four organizationally separate mines (Pima, Mission, Palo Verde, and San Xavier South) formerly operated on this orebody, but since the mid-1980s they have been acquired by ASARCO Inc. and integrated into one large open pit operation, the Mission Complex.

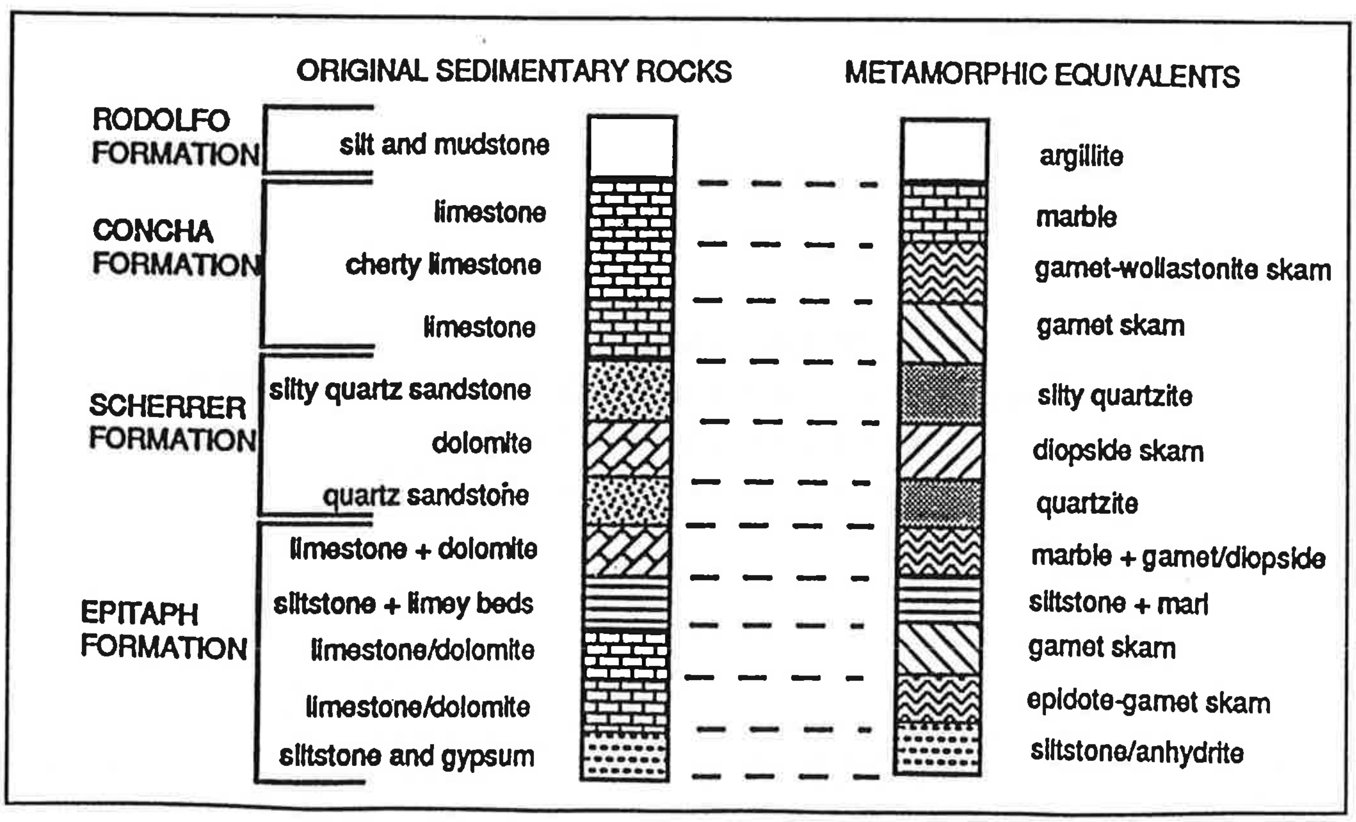

Figure 4. Stratigraphic column of original sedimentary rocks and their metamorphic equivalents at Mission, shown in their original stratigraphic position.

Combined production to date has been approximately 514 million tons at an average grade of 0.62 percent copper. Currently ASARCO is producing approximately 60,000 tons per day at an average grade of 0.65 percent copper.

SUMMARY OF THE GENERAL GEOLOGY OF THE MISSION-PIMA OREBODY

The general geology and stratigraphy of the Mission Orebody have been studied many times since its discovery in the mid-1950s, and the following is only a brief summary. Readers desiring a more detailed description of mine stratigraphy and structure are directed to Jansen (1982).

The Mission Orebody has been displaced and moved 10 kilometers northward by low-angle faulting (Cooper, 1960). The orebody is in an overturned sequence of Permian metasedimentary strata that lie in fault contact with granitoid rocks presumed to be Laramide (early Tertiary) in age. The Paleozoic strata are in turn overlain across an angular unconformity by Triassic clastic rocks assigned to the Rodolfo Formation by Himes (1973). The Paleozoic sequence has been deformed into broad, gentle, northwest-trending folds. There is a sill-like intrusion of quartz monzonite porphyry of Laramide age (c.a. 58 m.y.) on the western side of the Mission Orebody (Shafiqullah and Langlois, 1978).

Figure 4 shows a stratigraphic column of the original sedimentary rocks at Mission and their generalized metamorphic equivalents.

The vast majority (90 to 95 percent) of mineralization is hosted in altered sediments rather than in quartz monzonite porphyry. The mineralization is hypogene sulfide, primarily chalcopyrite with minor bornite. Minor amounts of "oxide" ores, primarily chrysocolla with minor malachite, azurite, and tenorite, are present in the upper 60 to 70 meters of the orebody directly below alluvium, but this "oxide" ore is not being processed by ASARCO at this time.

Epitaph Formation

Approximately 75 meters of the Epitaph Formation is present in the overturned Mission Mine sequence, compared to 225 meters in the type section in central Cochise County, Arizona (Cooper, 1971). Due to lateral variation in the composition of the formation and the effects of metamorphism, the section at Mission bears little resemblance to the type section. The principal basis of correlation is the presence in the unit at Mission of beds of anhydrite which are unique to the Epitaph Formation in the upper Paleozoic (Jansen, 1982).

The youngest but topographically lowest unit in the Mission Mine area consists of 15 to 20 meters of anhydrite interbedded with siltstone above which lies 7 to 10 meters of older green-brown epidote-garnet skarn. The next higher and older unit consists of 5 to 11 meters of light brown garnet skarn, which is in turn overlain by about 22 meters of still older light to dark green siltstone and marl within which carbonates are locally silicated to light brown garnet. The oldest and topographically highest unit of this overturned section consists of 11 to 22 meters of brown garnet skarn mixed with marble. Dolomitic beds are altered to light- to dark-green diopside rather than the grossularite-andradite series garnet that has replaced limestone (Gale, 1965). Altered carbonate units generally contain ore-grade sulfides.

Scherrer Formation

Within the Mission Mine the Scherrer Formation is overturned and consists of an upper (older), light-colored orthoquartzite unit up to 50 meters thick, a 10- to 20-meter-thick middle dolomite unit altered to light- to dark-green fine-grained diopside, and a lower (younger) 10- to 20-meter-thick unit of gray to brown quartzite. The lower quartzite is sometimes absent. The upper contact with the older Epitaph Formation is commonly faulted, but exposures in the east-central part of the mine show stratigraphic contacts (Jansen, 1982). The diopside commonly contains ore-grade disseminated chalcopyrite.

Concha Formation

The Concha Formation at Mission (fig. 4) is 150 to 170 meters thick, about the same as has been measured at the type locality in Cochise County. Mesozoic erosion and thinning that affected both the Epitaph and Scherrer Formations did not affect the Concha due to its topographically lower position. The upper 25 to 50 meters of the Concha is green garnet of grossularite-andradite composition (Gale, 1965); the lower part of the formation is variously altered thick-bedded marble with zones of wollastonite-garnet which probably represent original chert beds within the limestone. The Concha Formation is an important ore-bearing formation at Mission, where it contains zones of disseminated to massive chalcopyrite-bornite in its garnet and garnet-wollastonite skarns.

Rodolfo Formation

Himes (1973) proposed that the siliceous argillites, arkose, and local basal pebble conglomerates which lie above the Paleozoic metasediments across an angular unconformity belong to the middle siltstone member of the Triassic Rodolfo Formation described by Cooper (1971). This formation is also an important host to sulfide ore (usually fracture-controlled chalcopyrite), which is generally at a lower ore grade than that of the Paleozoic rocks. Notable within the Rodolfo Formation at Mission are pods of hydrothermally altered epidote skarn which usually contain higher-grade ore than the surrounding argillite.

Quartz Monzonite Porphyry

Gale (1965) described the quartz monzonite at Mission as being typical of porphyry copper plutons. It consists of subhedral phenocrysts of plagioclase, orthoclase, biotite, and quartz in a sub-graphic fine-grained potassium feldspar-quartz groundmass. The porphyry stock is potassically altered and weakly sericitized with no apparent alteration zoning. Weak silicification is also present, particularly in areas where extensive quartz veining exists.

Barter and Kelly (1982) described xenolithic, aphanitic, and aplitic quartz monzonite porphyry at Twin Buttes 10 kilometers south of Mission. Published descriptions are somewhat sketchy, but the porphyry at Mission appears to resemble the aplitic type most closely. Plagioclase phenocrysts have been pervasively replaced by sericite, but visible remnant texture generally remains. Potassium feldspar phenocrysts remain fresh. Biotite phenocrysts may be either unaltered, weakly sericitized, or chloritized. Fresh biotite commonly shows chlorite alteration rims. Biotite phenocrysts are generally either sericitized or chloritized within a single sample, but fresh and altered biotite phenocrysts do occur within some samples. Quartz veinlets may be barren or contain pyrite-chalcopyrite and average 1 to 2 volume percent of the rock. Potassic alteration haloes commonly exist around veinlets. Secondary potassium feldspar is much more abundant than secondary biotite in these haloes, and silicification is most common in areas where veinlets are greater than 5 to 10 millimeters wide. Thin gypsum veinlets less than 5 millimeters wide occur randomly and make up 1 or 2 percent of the rock. Gale (1965) estimated pyrite-chalcopyrite ratios at 3:2 to 3:1. Only rarely does chalcopyrite concentration exceed 1.0 volume percent, and copper usually averages 0.15 to 0.30 percent. Molybdenite is seemingly present in random minor concentrations associated with quartz veinlets or as "paint" on fractures; the average concentration is less than 0.15 percent molybdenum .

Rock type, alteration, copper grade, and sulfide ratios at Mission are similar to the porphyry stock complex at Twin Buttes (Einaudi, 1982).

GEOCHEMISTRY

SEDNORM Computer Program

Differences in normative mineral compositions of carbonate protolith units in the Paleozoic sequence at Mission were considered as a possible means of identifying formations where sight-recognition criteria fail. If this method proved successful for known units, it could then be applied to unknowns from the project area. In order to calculate the normative mineral compositions, a computer program entitled SEDNORM, a program to calculate a normative mineralogy for sedimentary rocks based on chemical analyses (Cohen and Ward, 1991) and written in standard FORTRAN 77 was used. Normative mineral distributions for 80 samples together with averages for each formation were individually calculated. Unfortunately, the SEDNORM program proved to be of minimal value in identifying the Paleozoic carbonates: Although the program worked well, there was not enough variation in the major mineral and element compositions of the knowns to be useful in identifying the unknowns.

Neural Network Classification of Lithologic Units

Artificial neural network processing includes a broad spectrum of computer algorithms that solve several types of problems including classification, parameter estimation, parameter prediction, pattern recognition, completion, association, filtering, and optimization. A neural network is a computer simulation of the way animals use neurons to process and store information. Neural networks can be simulated with sequential software, electronic circuits, or optical circuits. We used a software realization of the networks.

An intriguing aspect of neural networks is their ability to perform certain tasks well, such as pattern recognition, that humans traditionally have performed well. Neural networks have not solved problems that have remained previously intractable to humans; rather they have in some cases provided faster, more accurate, and more flexible solutions to problems for which methods of solution are known. Like humans, whose brain structure they were built to imitate, artificial neural networks retain a degree of unpredictability. Unless every possible option is input, there is no way to be certain of the precise output. A related complication lies in the inability of artificial neural networks to "explain" how they solve problems. The internal representations that result from training are frequently so complex as to defy analysis; this is understandable given our inability to explain how we ourselves recognize visual patterns despite differences in distance, illumination, angle, and time. Another limitation of neural networks is their inability to classify inputs as unknown. Where there is no answer to a problem, the network will assign the output that is the closest approximation.

Neural networks are not programmed; they solve problems by learning from other solutions. Typically a neural network is given a "training set" consisting of a group of examples from which it can learn. The most commonly used training scenarios utilize "supervised learning" during which the network is presented with an input pattern together with the desired pattern of the output, that is, the correct answer or correct classification of the input data. If training is successful, internal parameters are then adjusted such that the network can produce correct classifications in response to new input data patterns. Once trained, a network's response is insensitive to minor variations in its input. This ability to see through noise and distortion to the inherent pattern is vital to pattern recognition in a real-world environment. Sets of training examples are usually presented repeatedly during training to allow the network to adjust its internal parameters gradually. The computer software responds to each example by randomly activating its circuits in a particular configuration. Any connections that produce a correct answer are reinforced, while connections that produce an incorrect answer are weakened. After several thousand trials, the network activates only those circuits that produce the correct answer.

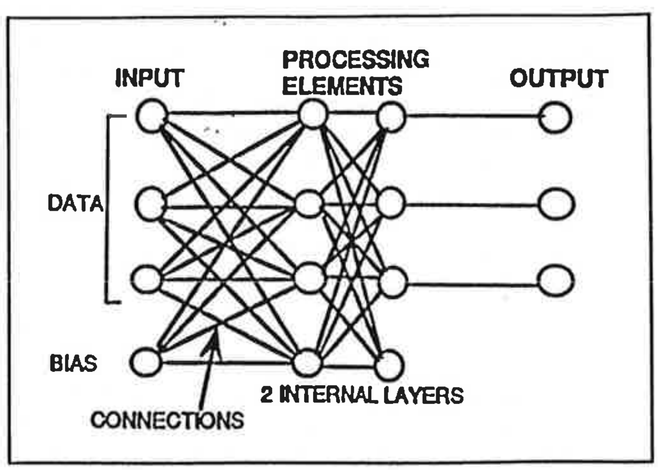

Figure 5. Flowchart of a neural network system.

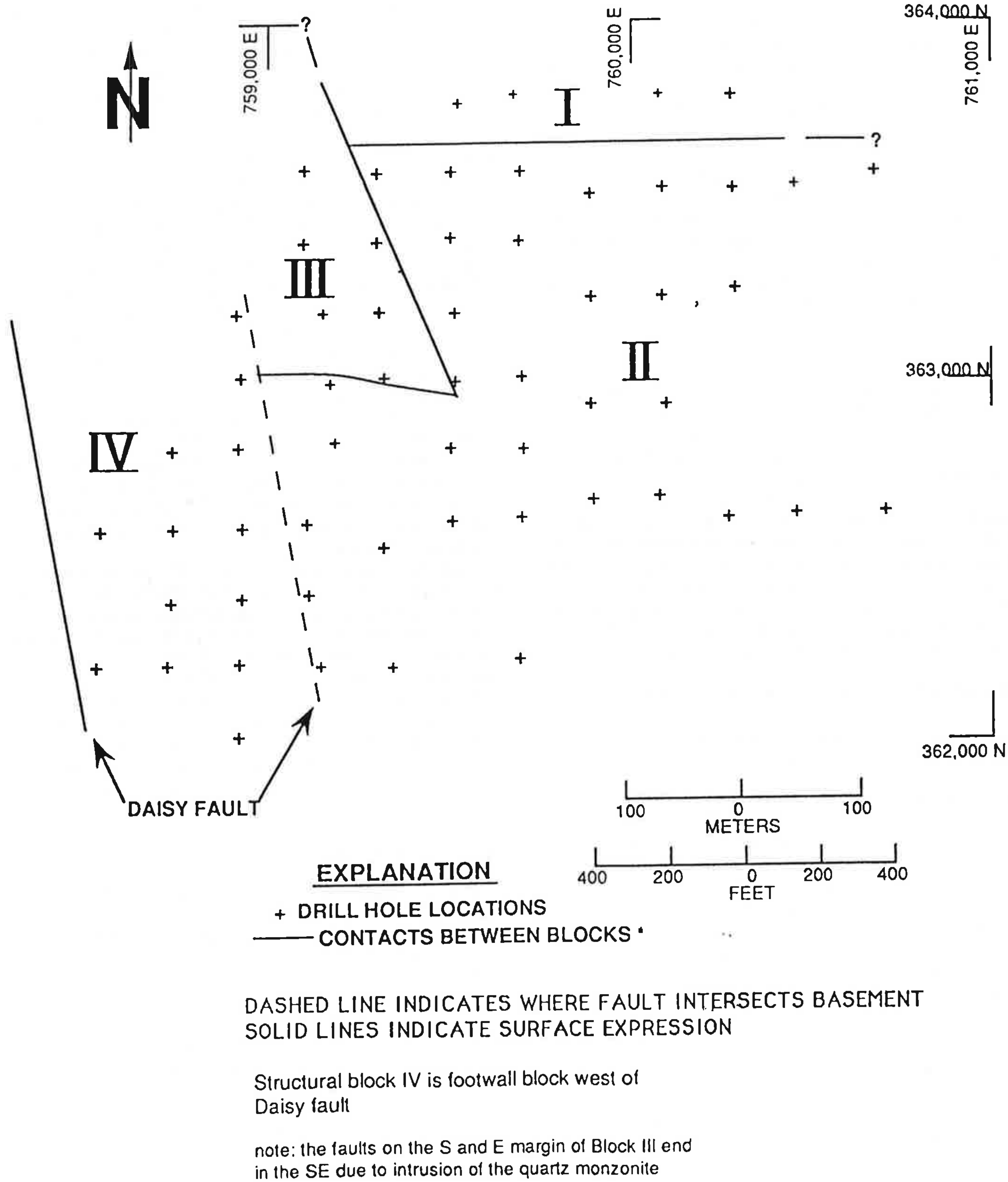

Figure 6. Map showing location of structural blocks in the Mineral Hill area, Mission Mine.

The foci of this part of the study were (1) to determine if neural networks could "learn" large, complex whole rock and major element geochemical profiles (patterns) of several Paleozoic carbonate formations and classify from them carbonate rocks whose geochemistry was known but whose formation identity was unclear and (2) to determine if neural networks could discover which major rock-forming elements were most important in identifying lithologic units, especially in the structurally complex silicated carbonate Upper Paleozoic stratigraphic section of southern Arizona.

Artificial neural networks consist of three key components: (1) processing elements (PEs), (2) layers, and (3) connections (fig. 5). They borrow the basic operating procedures of their biological counterparts, the mammalian brain. A "neuron" or PE in a first layer receives some external stimulation that is weighted and passed through to the next layer of PEs. In our implementation of neural networks each PE received one element of the input pattern, that is, one elemental assay from one sample. The signals coming into the PEs in the second layer were multiplied by the connection weights between the two layers and summed over all the connection weights; this sum is commonly referred to as the "activation" of the PE. The activation of the PE is modified by a transfer or activation function and sent to the next layer of PEs. The exact forms of the summation processes, transfer functions, and interconnection scheme vary according to the type of network. The memory of an artificial neural network consists of the values of the connection weights between PEs, that is, how they process new data in the context of the learning set. The reader is referred to material by Rumelhart and others (1986), Caudill (1988), Anderson and Rosenfeld (1989), Dayhoff (1989), and Wasserman (1989) for more details.

GEOLOGY OF THE MINERAL HILL AREA

There are four major structural blocks within the project area (fig. 6), and the geology of each will be discussed separately.

Structural Block I

Structural Block I contains the upper portion of the section found within the Mission Pit. The section is covered by approximately 60 meters (200 feet) of Quaternary(?) alluvium. Directly beneath the alluvium is very fine-grained, chocolate-brown argillite of the Rodolfo Formation (Himes, 1973) which varies from 70 meters thick in drill hole M-350 (fig. 2), the westernmost of the drill holes in which the argillite occurs, to 40 meters thick in M-437, the easternmost of the drill holes in which it occurs. This argillite is similar to that in the Mission Pit. The argillite lies atop a disconformity, which is probably a fault contact as indicated by drill logs and the steepness of the contact when seen in north-south cross-section (fig. 7). The upper 5 to 15 meters of the argillite is oxidized, with fracture-controlled sulfides altered to limonite and jarosite and copper mineralization occurring as chrysocolla with minor malachite and azurite. In the Mineral Hill area the argillite rarely contains intercepts of ore-grade material. Its copper content generally averages between 0.10 and 0.20 percent.

Beneath the argillite lies the green-brown siltstone and interbedded siltstone-anhydrite of the Epitaph Formation. The upper portion of the Epitaph, which is approximately 60 meters thick to the west in drill hole M-350, thins eastward to 15 meters in drill hole M-409 where an increase in limy and dolomitic beds causes the unit to become dominated by diopside and garnet skarn interbedded with anhydrite. In this structural block the Epitaph Formation strikes north-northwestward and dips 5 to 10° to the northeast. Further east the upper portion of the unit pinches out entirely, and the base of the argillite is in contact with quartz monzonite porphyry in drill hole M-437. The intrusion of the quartz monzonite porphyry is entirely within the Epitaph Formation in Structural Block I. Several "fingers" of the quartz monzonite intrude the Epitaph Formation in this section, with sections of garnet-diopside skarn-anhydrite and siltstone-anhydrite present above, within, and below these sill-like intrusions of quartz monzonite porphyry (fig. 7). The major quartz monzonite "sill" appears to be continuous from its outcrop in the western portion of the Mission Pit. It dips approximately 15° northwestward in this block and varies from 30 meters thick in the west to 125 meters thick in the east.

Below the porphyry the Epitaph Formation consists of interbedded siltstone-anhydrite, garnet-diopside skarn, and fine-grained gray marble with thin bands of serpentine. Where this banding effect is present within limestone, calc-silicate alteration has resulted in garnet bands; where it occurs within dolomite or high-magnesium limestone, calc-silicate alteration has resulted in serpentine.

The lower contact of the Epitaph Formation in Structural Block I is the Tertiary San Xavier Fault. This fault is at an elevation of 2,530 feet in the west and dips approximately 10° eastward to an elevation of 2,380 feet in the east. In drill core the San Xavier Fault generally shows less than one meter of broken or brecciated upper unit followed by less than one meter of fault gouge, which is followed in turn by broken or brecciated lower-plate Tertiary granodiorite believed to be the Ruby Star Granodiorite of Cooper (1960). The granodiorite becomes progressively less broken downward, and micas in the granodiorite are intensely chloritized near the fault but become less altered downward.

Structural Block II

Structural Block II contains the same overturned Paleozoic metasedimentary sequence as is present in the Mission Pit: the Epitaph, Scherrer, and Concha Formations intruded by the Tertiary quartz monzonite porphyry. The section is overlain by 10 to 60 meters of Quaternary(?) alluvium. The upper portion of the sequence in the Mission Pit consists of the Triassic Rodolfo Formation argillite, which does not occur in Structural Block II, where the Permian metasedimentary units strike north-northwest and dip 5 to 10° to the northeast or southwest. The quartz monzonite porphyry sill that intrudes the sequence dips generally to the north and west at a shallow angle (fig. 8). The porphyry sill is thickest to the east with a maximum thickness of 120 meters in drill hole M-436 and thins westward to 45 meters in drill hole M-466 (fig. 8).

The Paleozoic sequence above the quartz monzonite porphyry sill consists of up to 90 meters of siltstone, carbonates, and minor interbedded garnet and diopside skarn of the Epitaph Formation (figs. 8, 9). Below the porphyry sill orthoquartzite of

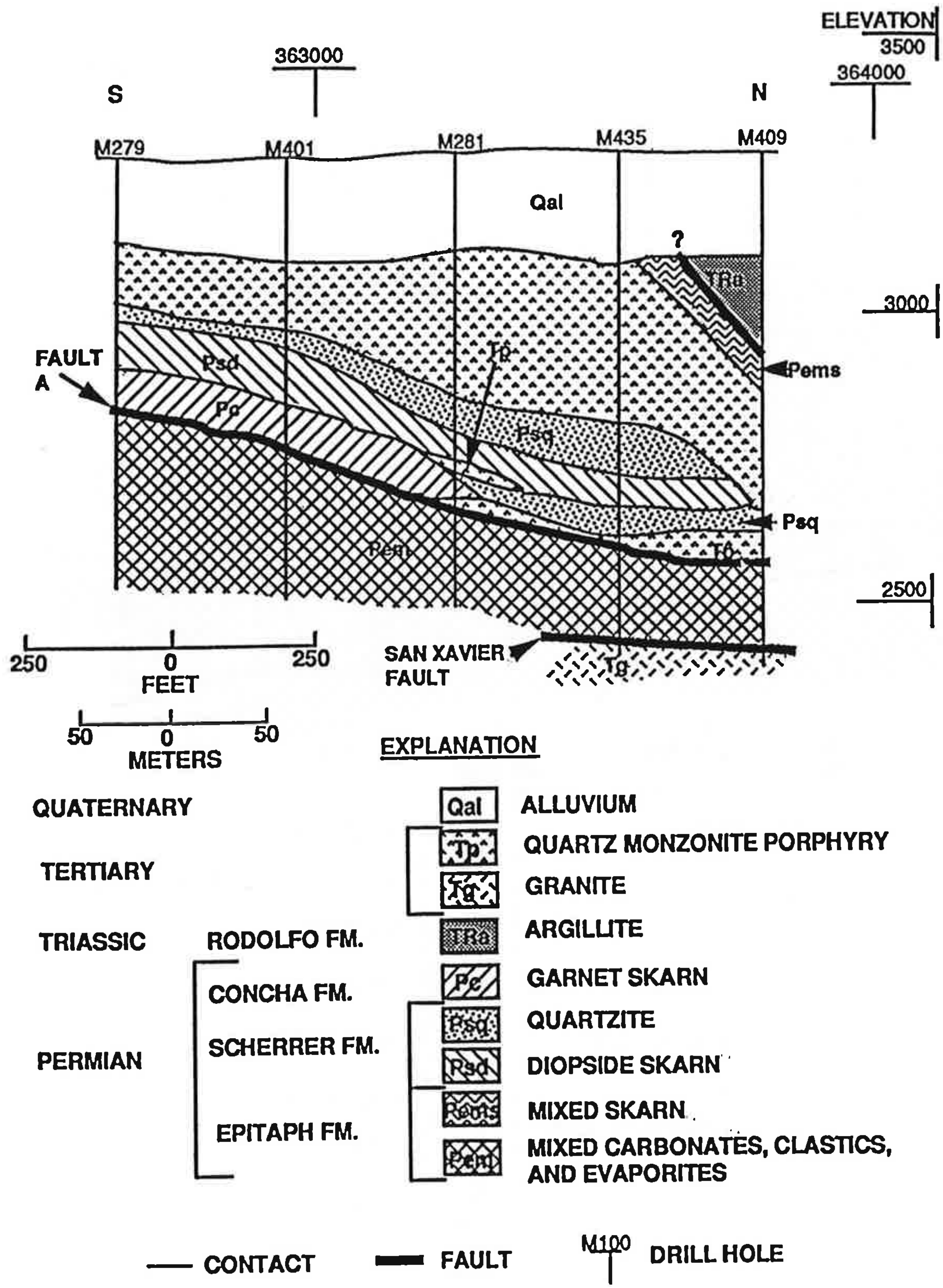

Figure 7. North–south vertical cross section through 760,100E.

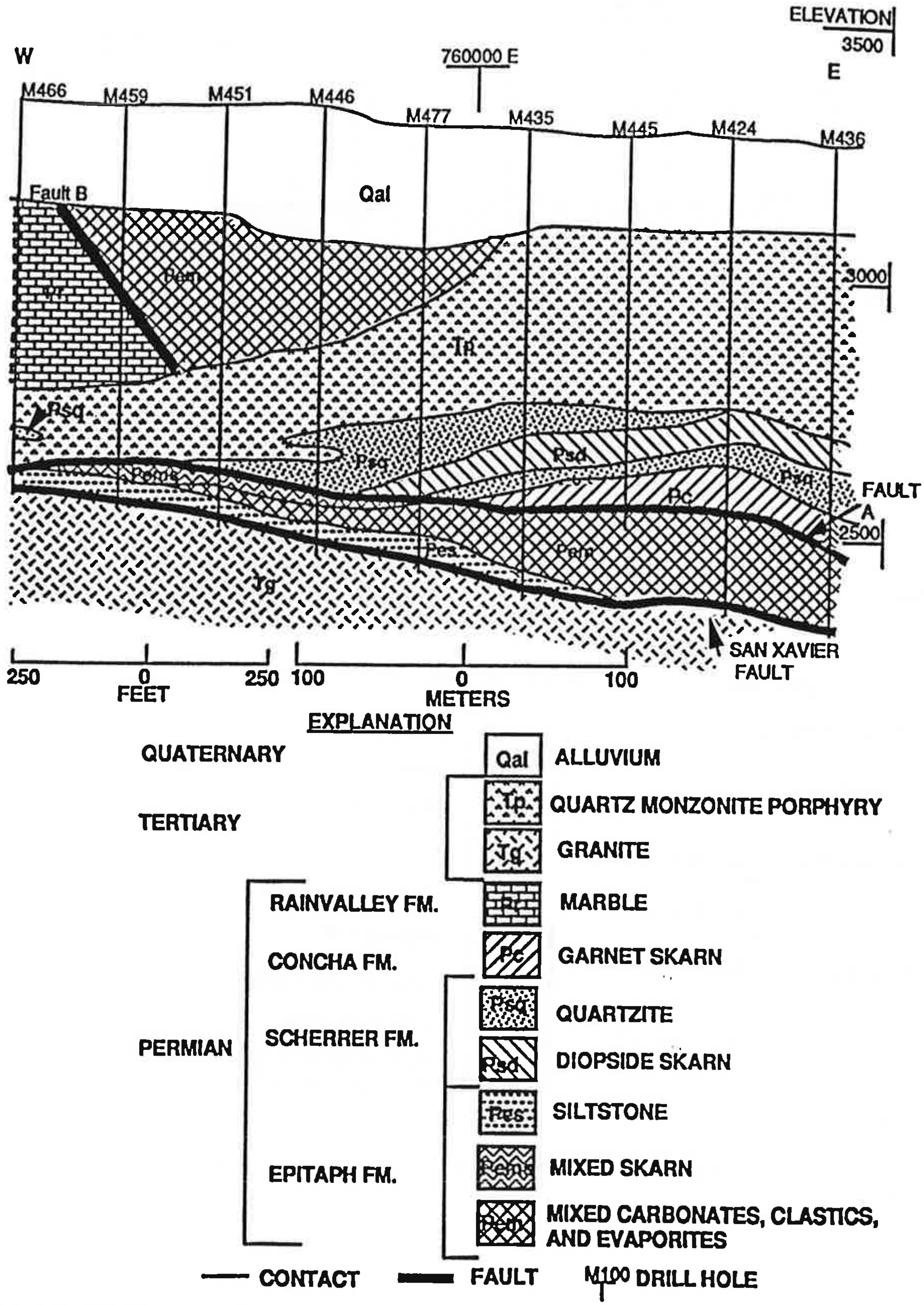

Figure 8. East–west vertical cross section through 363,600N.

the Scherrer Formation reaches a maximum thickness of 45 meters in drill hole M-385, from which it thins to both the east and west. Below the quartzite is the stratigraphically higher middle Scherrer diopside skarn, which is approximately 18 meters thick at its thickest point. Underlying the diopside skarn is up to 40 meters of Concha Formation garnet skarn and marble, which is thickest to the east and either pinches out against the porphyry intrusive or is cut off by a low-angle fault to the west. This fault is labeled Fault A in figures 7 through 9. It is most likely a splice or drag fault associated with the San Xavier faulting event, but it may be a thrust or detachment fault (pre-existing or contemporaneous with the San Xavier Fault) that causes the Scherrer and Concha Formation sequences to be emplaced atop the Epitaph Formation. The Epitaph Formation below Fault A is a sequence of siltstone, siltstone-anhydrite, and altered carbonates. Evidence from outside the project area suggests that rocks in the footwall of Fault A are in normal stratigraphic sequence. This sequence has a maximum thickness of approximately 45 meters and is underlain at an elevation of 2,300 to 2,600 feet by the San Xavier Fault, which dips shallowly to the east (fig. 8). Below the San Xavier Fault is Tertiary granodiorite as previously described.

Structural Block III

In Structural Block III the sequence of Paleozoic rock units is different than in Structural Blocks I and II and in the Mission Pit. Below 30 to 60 meters of Quaternary(?) alluvium which thins to the south is a dense black marble unit approximately 100 meters thick. This black marble is thermally altered with little or no visual evidence of hydrothermal alteration.

Black marble which appears to be from the same unit as that in Structural Block III is also present in the southern portion of the Mission Complex Pit (the old Pima Pit) in small fault-bounded blocks ranging in elevation from approximately 2,400 to 2,200 feet. Unpublished studies commissioned by ASARCO in the mid-1980s found no index fossils or other features that would allow identification of this unit, and up until now ASARCO geologists have had nothing upon which to base a unit classification. Our neural networks study included samples from two drill holes which intersect this unit (M466 and M473, fig. 2) and three samples from blocks from in the old Pima Pit. The neural networks classified samples from both of the drill holes and from the Pima Pit as belonging to the Rain Valley Formation, and this classification is tentatively accepted as correct.

The Rain Valley Formation in Structural Block III is fault-bounded to the east, west, and below. To the east is a high-angle normal fault, labeled Fault B in figure 8, which dips approximately 55° east and brings carbonates, altered carbonates, and siltstone of the Epitaph Formation against black marble. To the west this block of Rain Valley Formation is bounded by the Daisy Fault. The marble is underlain across an apparent fault contact by Epitaph Formation mixed skarn and siltstone or by quartz monzonite porphyry intrusive.

Fault B has brought Epitaph Formation rocks to the east against Rain Valley Formation rocks to the west and must predate the underlying quartz monzonite porphyry intrusion which is not cut by the fault. The intrusion apparently caused an unknown amount of lateral movement in the overlying block, because the fault does not continue in the meta-sediments below the porphyry (fig. 8).

In Structural Block III, as in Structural Blocks I and II, the quartz monzonite porphyry intrusion has a sill-like configuration, thickening and thinning irregularly and dipping at low angles to the north. Its average thickness is 50 to 60 meters (fig. 8). Rocks below the porphyry sill consist of mixed garnet-diopside skarn, siltstone and siltstone-anhydrite, and carbonates of the Epitaph Formation. The porphyry appears to be in contact with the Epitaph Formation across Fault A. The Epitaph Formation sequence varies from approximately 100 meters thick in the south of the Structural Block III to only 15 meters thick in the north. This thinning is due to the shallow northward dip of the quartz monzonite intrusion and the nearly flat aspect of the San Xavier Fault, which cuts off the Epitaph Formation sequence at between 2,610 and 2,650 feet elevation. Below the San Xavier Fault is Tertiary (Ruby Star?) granodiorite or granite.

Structural Block IV

Structural Block IV is in the far west of the project area beneath and to the west of the Daisy Fault (fig. 9). The Paleozoic sequence in this block is different than that of the other structural blocks and the Mission sequence and consists of carbonate and altered carbonate units which consist of marble, silty marble, and altered marble underlain by micaceous quartzite in drill hole M258 (fig. 9). These lithologies indicate that the Abrigo Formation is the predominant unit to the west and beneath the fault: Within the Paleozoic section such sequences occur only in the Abrigo and Epitaph Formations, and the Epitaph is not known to contain any quartzite beds but does contain abundant evaporites not found in the drill core. Moreover, thin bands of garnet occur marginal to thin siltstone beds within metamorphosed carbonate. This feature is informally referred to by Mission geologists as "banded gar-marble" and can also be seen in hills south of the project area where the Abrigo Formation, including a micaceous quartzite unit, crops out. That the sequence of rocks in drill holes to the west and below the Daisy Fault is the Abrigo Formation is supported by neural network analysis. The sequence of carbonates and altered carbonates is from the middle Abrigo siliciclastic-carbonate unit, and underlying micaceous quartzite is from the lower Abrigo siliciclastic mudstone. An upper plate granite 15 meters thick is present below micaceous quartzite in drill hole M258 (fig. 9). Granite and overlying micaceous quartzite units do not occur in holes to the east (M469 and M257) and north (M462), leading to the conclusion that a previously unrecognized fault must exist. This fault is labeled Fault C in figure 9. The exact attitude of this fault is unknown because it is cut off by the Daisy Fault and does not intersect any drill holes or the surface. Below the granite in M258 and lower-middle Abrigo Formation elsewhere is the San Xavier Fault at an elevation of between 2,700 and 2,500 feet (fig. 9). Below the San Xavier Fault (which dips approximately 10° to the east) is the previously described Tertiary granite or granodiorite. Drill hole M461 (fig. 2) contains a sequence of carbonate and altered carbonate below the Daisy Fault and above Abrigo Formation rocks which was identified by neural network analysis as belonging to the Devonian Martin Formation.

Drill hole data indicate that the Daisy Fault strikes approxi-

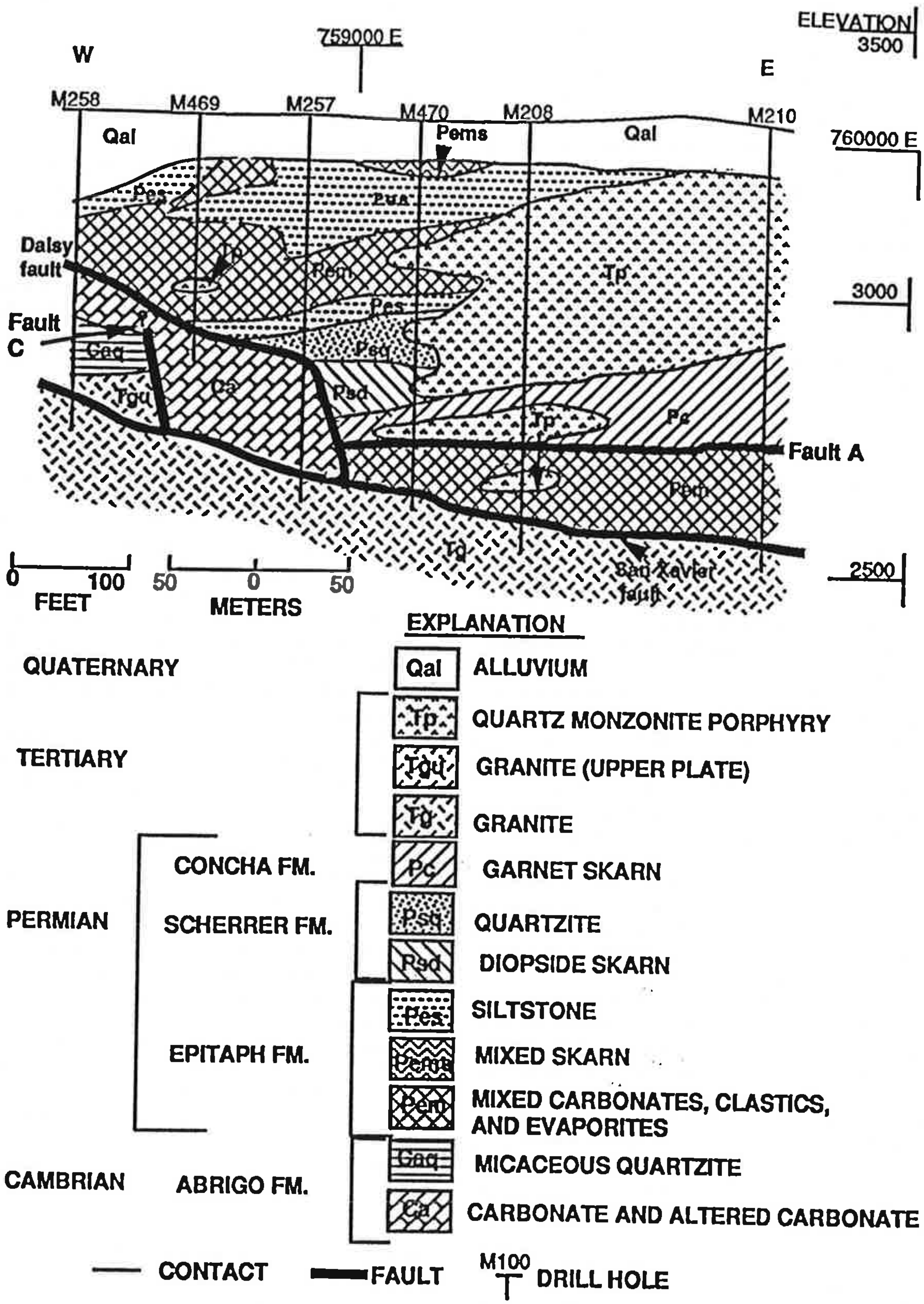

Figure 9. East–west vertical cross section through 362,200N.

mately N10°W and dips between 30 and 70° northeastward in this area.

RESULTS

Neural Networks

Although neural network classifications for some unknowns can be accepted with a high degree of confidence, overall success was far below what we had hoped for. Neural networks correctly classified 40 of 44 knowns (91 percent) and 15 of 32 unknowns (56 percent) whose formation classification can be confidently ascertained by geologic means. We believe this was because funding constraints severely limited the size of the training set available, making it much smaller than previous neural network researchers have deemed appropriate. Since all samples were carbonate rocks, many assay values overlapped in the different formations; a larger training set might have defined typical elemental value ranges more precisely and given better results. Another important cause for mis-classification of unknowns was probably the condition of the samples themselves: All of these rocks had undergone metamorphism. Care was taken to select samples that appeared to have undergone only thermal alteration, but the possibility of hydrothermal alteration with addition or subtraction of mobile elements was a possibility and would almost certainly have caused severe difficulty in classification for the neural networks.

Based on cross-section and lithologic data, many of the unknowns from the Mineral Hill Project area can be classified with a high degree of certainty as belonging to a particular formation. Using this data, 18 of 32 neural network classifications were deemed to be correct. Readers seeking a more detailed description of individual sample classifications and mis-classifications are directed to Williamson (1993).

Geology of the Mineral Hill Area

The major geologic and stratigraphic differences that exist between the Mission Pit and the Mineral Hill area are the result of three major faults. These are Fault B (fig. 8), which brought Rain Valley Formation rocks into contact with Epitaph Formation rocks in Structural Block III; Fault A (figs. 7 through 9), which brought Epitaph Formation rocks into contact with Scherrer and Concha Formation rocks in Structural Blocks I, II, and III; and the Daisy Fault, which brought Abrigo Formation rocks into contact with Epitaph Formation rocks. Of these, Fault A appears to be contemporaneous with the San Xavier Fault, and to have caused a small block to detach and overturn during the movement of the allocthonous upper plate of the San Xavier Fault. Timing of the other two faulting episodes in the Mineral Hill Project area is unknown, but post-mineralization movement along the Daisy Fault is probable.

The Paleozoic section is thinner in the Mineral Hill area than to the east because of the dip of the San Xavier Fault. This and the offset of Paleozoic strata along the Daisy Fault and Fault A which removes a portion of the Concha Formation and replaces it with Epitaph Formation rocks, cause the stratigraphically lower ore-bearing Concha and Scherrer Formations in the Mission Pit to be much less important ore hosts in the Mineral Hill area. Conversely, a much greater thickness of the Epitaph Formation exists in the Mineral Hill area than to the east, thus a much larger percentage of ore is in the Epitaph Formation than in the other formations in the Mineral Hill area.

Two major faults in the project area, Fault B which is the eastern boundary of Structural Block III and the Daisy Fault, both bring rock units not present in significant volume in the Mission Pit to the Mineral Hill area. Fault B brings Upper Permian rocks of the Rain Valley Formation into contact with rocks of the Epitaph Formation, a vertical displacement of at least 425 meters. The Daisy Fault brings rocks of the Cambrian Abrigo Formation and Devonian Martin Formation into contact with the Epitaph Formation, a displacement of at least 1,000 meters.

Another major difference between the Mineral Hill area and the Mission Pit may or may not have been caused by faulting. One of the major hosts to ore at the Mission Complex, the Triassic Rodolfo Formation argillite, is missing in the Mineral Hill area except for a small fault(?) wedge in Structural Block I (fig. 7). Whether this omission is due to erosion predating deposition of the Quaternary alluvium or by an unrecognized faulting episode that removed the section is unknown.

The question of whether the Daisy Fault may be correlated with the Twin Buttes Fault 10 kilometers to the south is complex. The Paleozoic strata at Twin Buttes are vertical, while at Mission they are overturned and deformed into broad, gentle, northwest-trending folds. The folding and overturning of the units at Mission is believed to have occurred before the major faulting episodes. The strike of the Daisy Fault is approximately 90° different from that of the Twin Buttes Fault, which strikes north 60 to 70° east while the Daisy Fault strikes north 10 to 20° west, and the dip is also much different on these two faults: The Twin Buttes Fault is vertical, while the Daisy Fault dips between 30 and 70° northeastward. Change in attitude of bedding due to folding may in large part account for these differences, or the differences could be due to movement of the San Xavier Fault. Despite these differences, however, the fact that vertical displacement along these two faults is virtually identical and their similar locations in the west of their respective orebodies make strong arguments for the correlation of the Daisy Fault as the upsection continuation of the Twin Buttes Fault.

ACKNOWLEDGMENTS

We wish to thank the management and staff of ASARCO Mission Unit for their funding and support. We especially thank Bob Cummings, without whose support this study would not have been possible, and Bill Williams and Bob Smith for their help and excellent suggestions. Mac MacCauley and Heath Howe provided computer support. We are grateful to the employees of the sample preparation lab for their careful and precise work in preparing the samples for analysis. We also thank Dr. John Guilbert for his excellent advice and editing.

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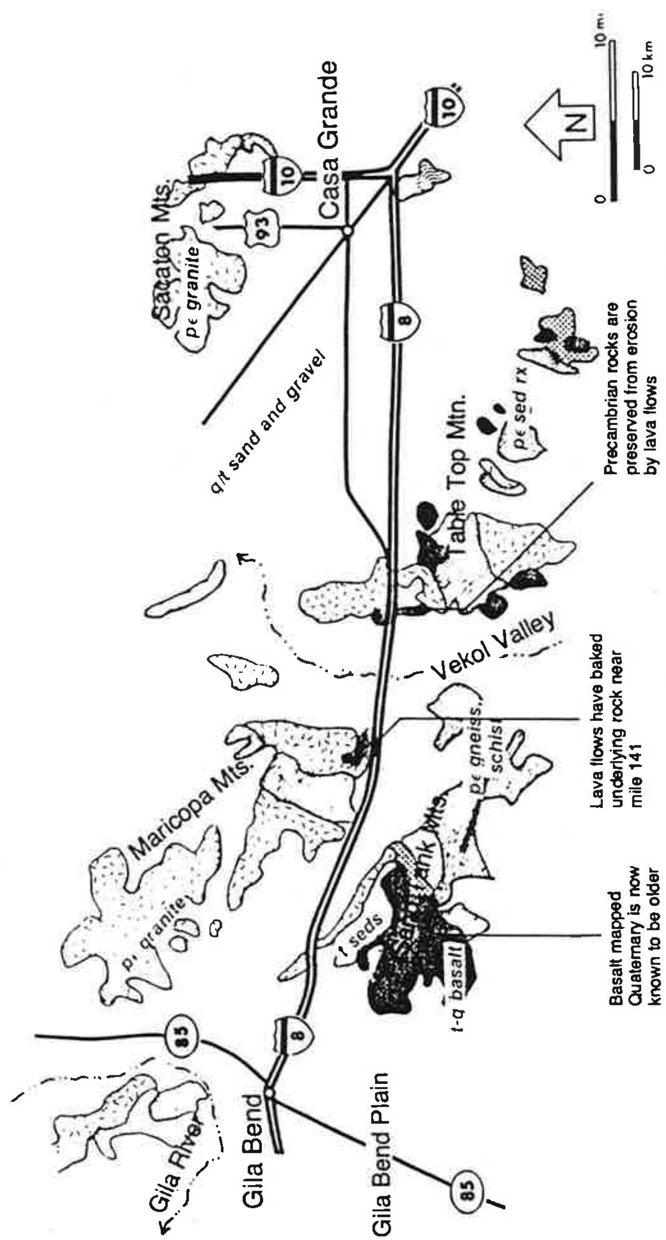
I-8
Casa Grande to Gila Bend



Abandoned mine buildings gaze empty-eyed across the Vekol Valley south of Interstate 8. Alkaline playa deposits mark low spots in the valley. Tad Nichols photo.

Interstate 8
Casa Grande — Gila Bend
(60 miles)

West of its junction with I-10, this highway crosses Quaternary sediments that floor the broad north end of the Santa Rosa Valley, heading toward the dark mass of Table Top Mountain. Although surface gravels in this and many other southern Arizona valleys are predominantly Pleistocene, exploratory drilling has revealed that they are underlain by thousands of feet of Tertiary stream and lake deposits, as well as by lava and volcanic ash layers by which these can be accurately dated.

Still farther west, beyond the irrigated farms of Casa Grande Valley, you may have a chance to observe wind as a major geologic force. In these open stretches, winds gain velocity and can pick up and carry sand and silt, sometimes as "dust devils" or whirlwinds and sometimes as billowing clouds. Loss of visibility is of course the great highway hazard. Health hazards are involved too — respiratory diseases like valley fever, carried by fungus spores. Sand grains and even gravel may blast structures and vehicles in the first few feet above the ground. Very fine dust is sometimes swirled quite high and picked up by high-altitude winds that transport it across the continent and even out over the Atlantic.

Desert washes in the area west of Casa Grande "flow" north toward the Gila River, about 20 miles away. The washes *do* occasionally flow, but their waters rarely reach the Gila; they sink instead into the loose gravel and sand of the valley floor, partly replenishing the groundwater supply. Par for the course in the southern deserts.

The upper part of the long, very gentle rise to Table Top Mountain is a pediment cut on granite bedrock, lightly covered with sand and silt. As its name might suggest, parts of Table Top Mountain are capped with lava flows that have not been bent or tilted but still lie in their original horizontal positions. The main parts of the range, however, are much older Precambrian granite and metamorphic rocks. Where the highway crosses these mountains, **outcrops** of weathered granite are preserved beneath the young basalts — the beginning and end of close to 1400 million years of geologic time. The granite is so deeply weathered and decomposed that mineral grains are no longer tightly joined; what once was granite is now just coarse, packed sand.

A few miles beyond, contrastingly dark lava, scarcely weathered at all, appears near the road. Though mapped as Quaternary, these flows may be older. Watch for reddish baked zones beneath the basalt flows.

The highway crosses Vekol Wash at milepost 151. Beyond Vekol Valley it slips between the Maricopa and Sand Tank Mountains, again composed of Precambrian gneiss and granite capped by Tertiary-Quaternary lava flows. In parts of the Sand Tank Mountains there are tilted and faulted Tertiary sedimentary rocks that were deposited before the last phases of Basin and Range faulting took place, and were caught up in the activity. Some of these sediments — hardly well enough consolidated to call rocks — can be seen as foothills at the north end of the range.

In general, you have been passing through a region where the overall grain or fabric of the land is NW-SE—sharply defined, ridge-like mountain ranges paralleling long, open valleys. Near Gila Bend we find evidence of a change of scene. For most of its journey from Phoenix to the Colorado River, the Gila River flows along a northeast-southwest trough that seems boldly to ignore the "lay of the land." **Seismic studies**, which analyze hidden subsurface features by bouncing man-made shock waves off underground reflective layers, show a **graben** 100 miles long and 10 miles wide, a down-dropped trough edged on each side by nearly vertical faults. The lava flows of the Gila Bend Mountains deflected the Gila River from this southwestward route, so that it bends south around both lava flows and Precambrian rock, then northwest to rejoin its former channel.

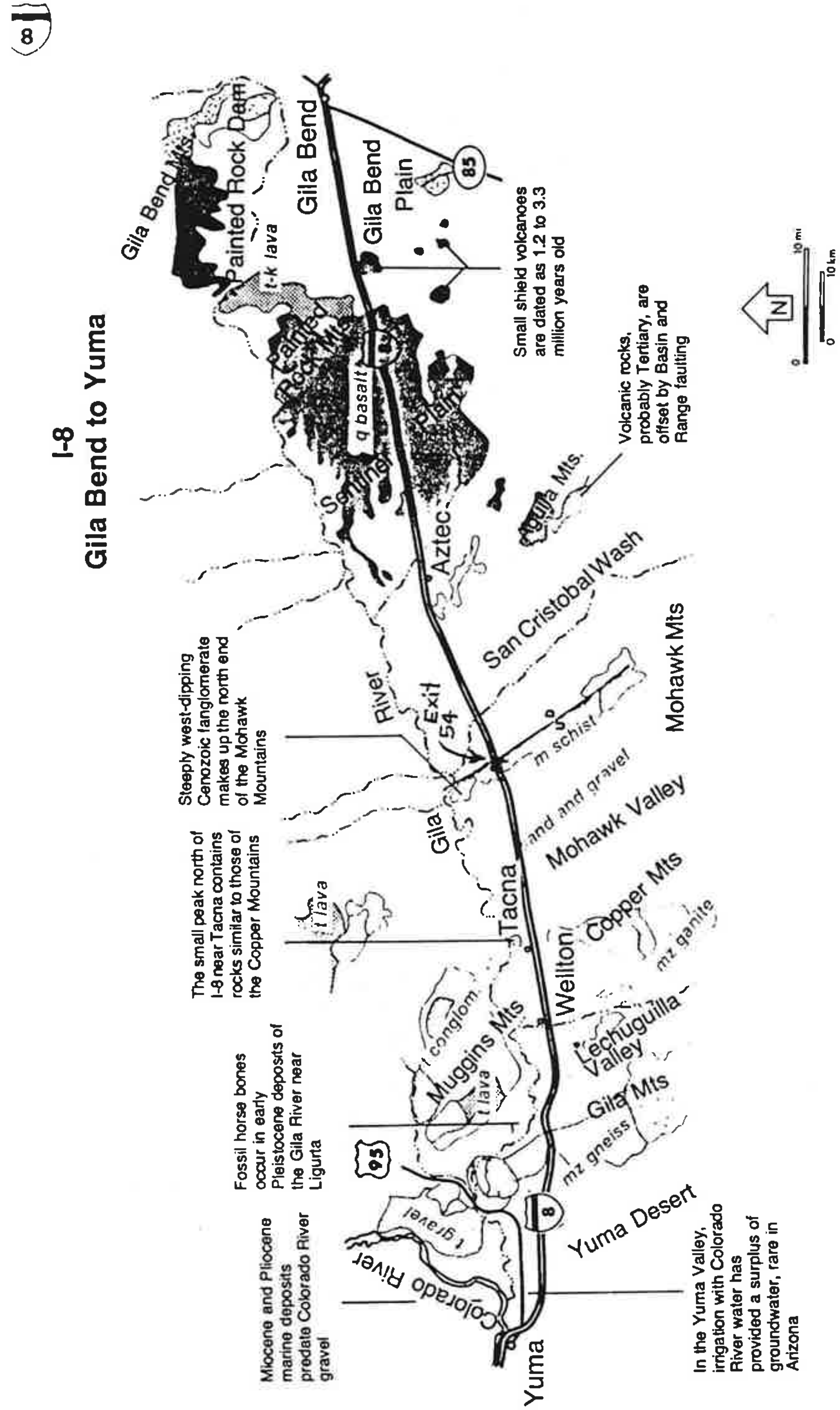
In the Gila Bend Mountains, Tertiary and Quaternary volcanic rocks overlie Precambrian granite and metamorphic rocks. Both are deeply eroded and darkened with desert varnish. New research on the dark brown varnish suggests that it forms from clay minerals in wind-blown desert dust deposited on rocks and then wetted by the rain that often follows dust storms. Over a few thousand years, rocks exposed to the dust and rain and to the alkaline desert environment, a necessary catalyst, gradually acquire this hard, shiny, iron-manganese coating.

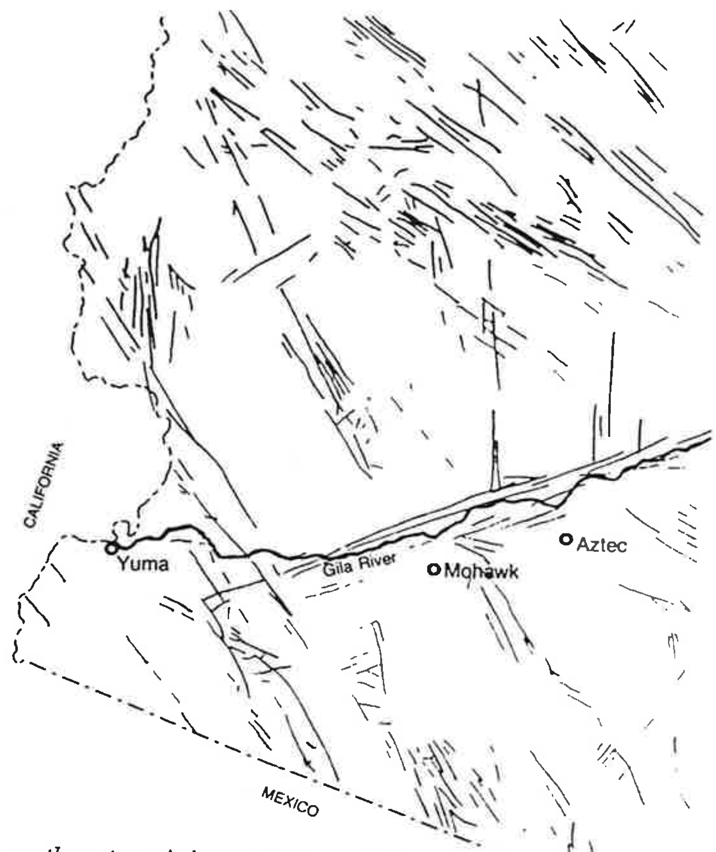
Interstate 8
Gila Bend — Yuma
(120 miles)

Northwest of Gila Bend, the Gila River bends northward through a narrow channel between the Painted Rocks and Gila Bend Mountains and into the graben described above, the Gila Trough. The almost horizontal floor of Gila Bend Plain is now heavily cultivated; the main crops are cotton and cattle feed. Ranges surrounding the plain are almost all volcanic; lava flows make up all but the easternmost part of the Gila Bend Mountains. Don't confuse this range with the Gila Mountains near Yuma or with other Gila Mountains on the east side of the state near Safford. Flows of the Painted Rock Mountains are older — Cretaceous to early Tertiary.

About three miles south of the highway near milepost 102, a small shield volcano is an outlier of the Sentinel volcanic field. The highway soon rises onto the basalt flows of this field. Here, in one of the youngest displays of volcanism in Arizona, individual flows are thin; the basalt lava was fluid and erupted quietly, spreading in sheets and shallow lava ponds. Because of the ease with which it flowed and the apparent low gas content of the lava, there is little buildup around the **volcanic vents**, and they are hard to identify. Sentinel Peak — one of the vents — is hardly a peak at all. The lava can be seen in more detail at the rest stop at milepost 85. All these flows are less than 2 million years old, having erupted early in Pleistocene time. The

I-8
Gila Bend to Yuma





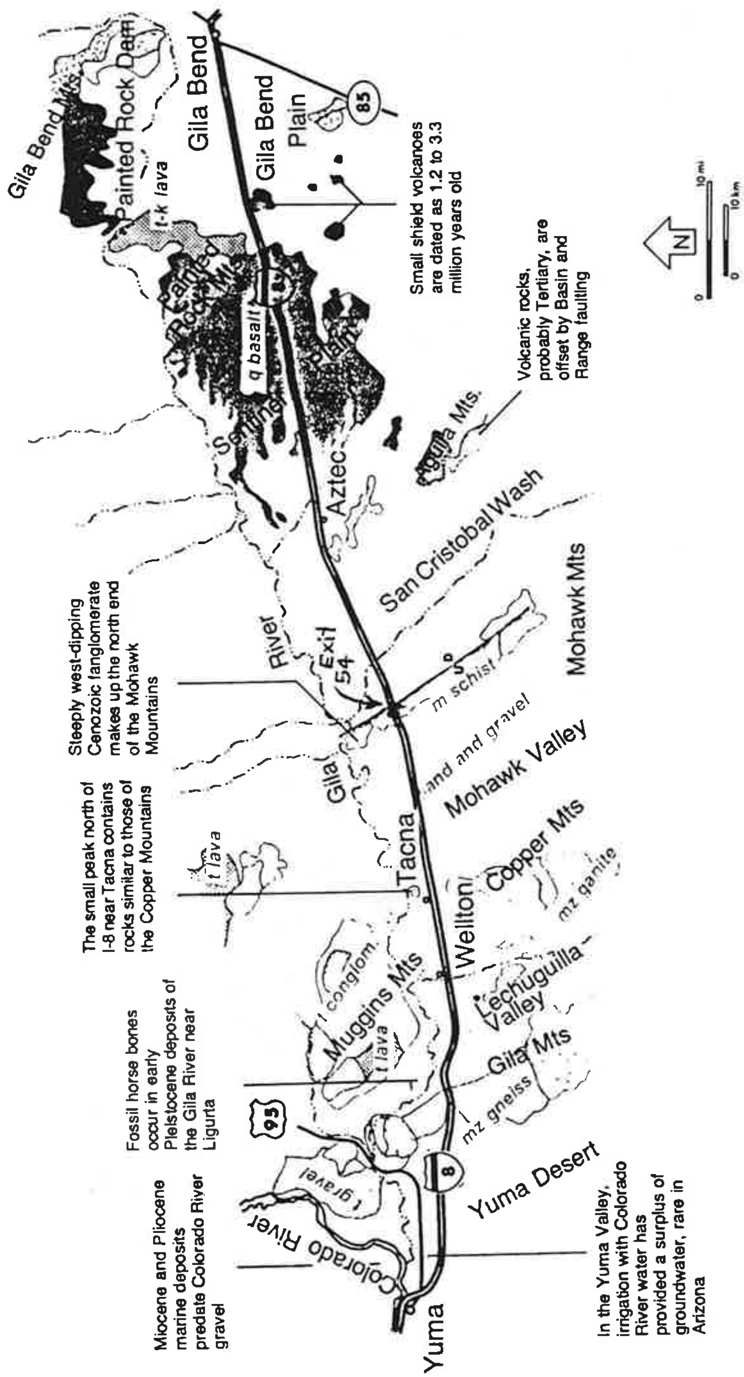
In southwestern Arizona, lineaments traced from satellite photographs give tantalizing clues to Basin and Range structure. Most lineaments run NW to SE. Often obscure at the surface, the lines may be faults, joints, folds, or contacts between different kinds of rocks.
Adapted from L. K. Lepley

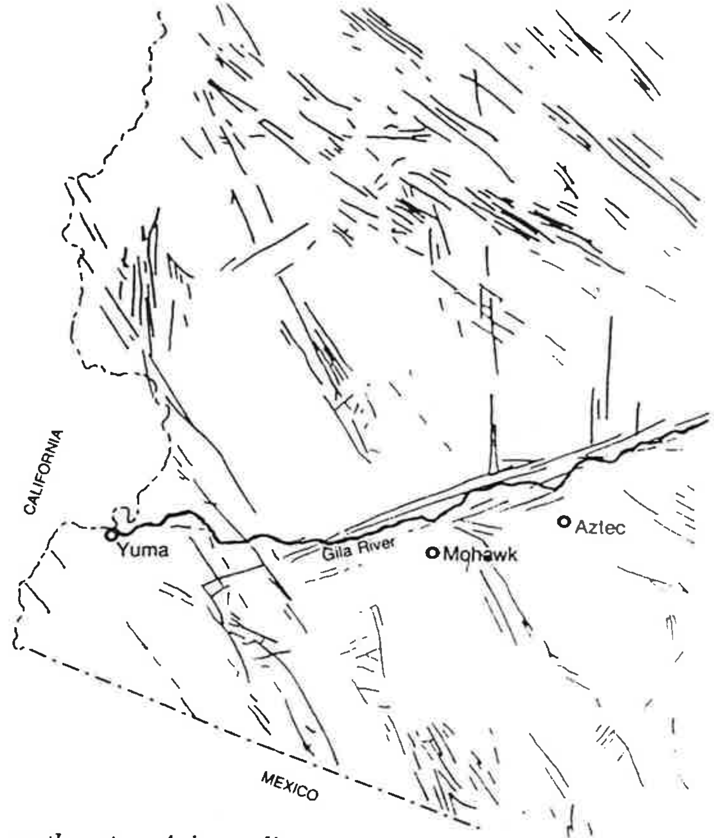
original surface of the uppermost flow has had time to weather and break up, leaving scattered blocks of basalt strewn about on the surface.

Sentinel lavas lie over Gila River sediments — fine, well sorted sand and silt — suggesting that the river, after being deflected southward around the Gila Bend Mountains, for some time flowed south of its present course. The Sentinel lava flows may have been the deciding factor in its return to the Gila Trough. West of these lavas the river and the trough gradually converge with the highway.

West of the Sentinel lavas watch for several small **cinder cones.** The Aguila Mountains, visible farther south, are capped by thin

I-8
Gila Bend to Yuma





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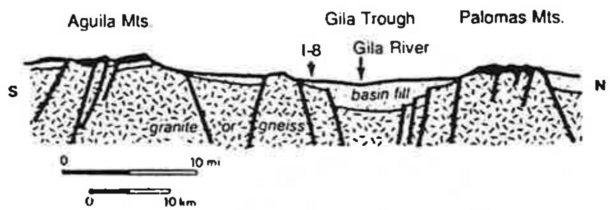

Section across I-8 and the Gila Trough near Aztec

basalt flows. Unlike those of the Sentinel Plain, these are slightly tilted and broken by faults, and are thought to date back to sometime before Basin and Range mountain-building.

Beyond Aztec the route crosses San Cristobal Valley and then approaches the Mohawk Mountains. A long, narrow backbone of a range, reminiscent of a "mohawk" haircut, these mountains are composed of Tertiary granite and metamorphic rocks, products of both Laramide and Basin and Range mountain-building.Gneiss and schist are well exposed near the highway. Looking along the fairly straight eastern flank of the mountains, you can well get a feeling for the approximate line of their bordering fault.

Dust devils — whirling columns of dust and sand — are frequent along this stretch of highway.

The next two ranges south of the highway, the Copper and Gila Mountains, are structurally similar to the Mohawks — slim, long, upward faulted slivers of Mesozoic granite and gneiss.

Muggins Mountains, to the north, consist largely of Miocene river and lake sediments, as do the light-colored foothills that edge the Copper Mountains. These sediments may once have sheeted across this entire area, but if so they wore away in Pliocene and Pleistocene time as the new-routed Colorado River cut rapidly downward, steepening the gradient and therefore the erosive strength of all the streams draining into it. Muggins Mountains contain some Tertiary volcanic rocks, too. Some of the Tertiary sediments contain uranium, and gravels at the mountain bases contain **placer gold**.

Not far upstream from Yuma, old Colorado River deposits appear as terraces, the highest 70 to 80 feet above the present river floodplain.

F. H. Olmstead photo, courtesy of USGS

Exit 54
Proceed west on Old 80 2 miles to roadcut.
Get out and ooh and ahh at the rocks.
Continue west on Old 80 12 miles to rejoin I-80 at Tacna.

The Lechuguilla Desert between the Copper and Gila Mountains is now in part irrigated farm land. Desert soil, however parched and poor it may look, is quite fertile where it is irrigated, and orange and other citrus trees thrive in the frost-free climate.

I-8 cuts right through the Gila Mountains, though they deflect the Gila River northward. Spectacular roadcuts reveal the finely fractured black and white banded gneiss of which these mountains — yet another fault block — are made. Elsewhere, dark brown desert varnish hides their wiggling, taffy-like patterns.

The Yuma Desert between the Gila Mountains and the Colorado is desert indeed, especially farther south where it is not used for agriculture. Barren, less than 200 feet above sea level, it is almost lifeless in the shimmering heat of a long summer. Blowing sand and whirling dust erode the faces of the mountains, as well a man-made objects near the highway.

The town of Yuma lies on a slight rise, Yuma Mesa, overlooking the Colorado River. This once mighty river used to be navigable well north of Yuma. It also used to flood severely. A large proportion of its waters are now held back for flood prevention, irrigation, power generation, recreation, and the myriad other uses to which water can be put in a desert land. Water that returns to the river along natural aquifers is higher in dissolved minerals than it was before removal, and can no longer serve the domestic and agricultural needs of the strip of Mexico that lies between here and the Gulf of California — a bone of contention between nations. Water for Mexico is now desalted in a large Bureau of Reclamation plant just east of Yuma, and put back into the river to complete its southward journey.

Yuma is very near the eastern margin of the Salton Trough, a northward extension of the rift that creates the Gulf of California. Formerly part of a mid-ocean ridge, this rift is here overridden by the continent. However, it keeps its character as the site of crustal spreading. In the last 20 million years it has opened up the gulf and the pronounced graben that extends northwest from Yuma, now partly occupied by the Salton Sea. In the Yuma area the trough is filled to a depth of several miles with marine limestone, Colorado River sediments, and interlayered volcanic rocks. The fault that forms the northeast edge of the trough cuts diagonally across the southwestern corner of Arizona between I-8 and the Mexican border. Northwestward it is virtually continuous with the San Andreas fault of California, and movement along it is related to the largely horizontal, shearing movement of the San Andreas fault.

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ARIZONA GEOLOGICAL SURVEY

The State agency for geologic information

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- Map and describe the bedrock and surficial geology of Arizona.
- Investigate and document geologic processes and materials that might be hazardous to the public or have adverse impact on land use and resource management.
- Administer the rules, regulations, and policies established by the Arizona Oil and Gas Conservation Commission.

Ground-Water Pumping Causes Arizona to Sink

Larry D. Fellows
Director and State Geologist

The land has subsided in several parts of southern Arizona since 1950 and is still subsiding. Two dish-shaped areas in Maricopa and Pinal Counties, as much as 6 miles wide, have subsided more than 15 feet at their centers. Gigantic open cracks (*fissures*), commonly 5-10 feet wide and 10-20 feet deep, have developed along their margins (Figure 1). Subsidence and related features have already caused serious problems and have the potential to cause even more. Around Phoenix, urban development is moving into subsiding areas that were once predominantly rural. Subsidence is taking place within the City of Tucson.

What causes the land to subside? Subsidence is taking place in southern Arizona because ground water has been pumped over an extended period of time faster than recharge has occurred. Subsidence does not happen in northern Arizona because the geologic setting is different. Southern Arizona is susceptible to subsidence because it's in what geologists call the "Basin and Range" province, which consists of alternating linear mountain areas and structural basins.

The Basin and Range, which extends northwestward from western Texas and northern Mexico into southern Oregon and Idaho (Figure 2), developed from about 15 to 5 million years ago in response to crustal stretching. Rocks cracked and broke into large blocks,

(continued on page 2)

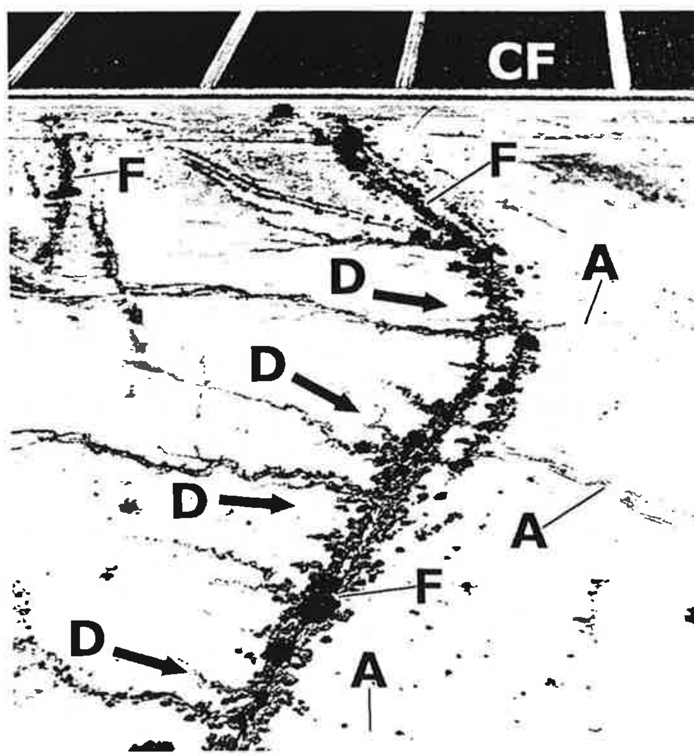

Figure 1. Fissures (F), which appear to stop at the edge of irrigated cotton fields (CF) southeast of Casa Grande in Pinal County, developed at right angles to existing stream channels. After heavy rainfall, runoff drains in the direction of the arrows (D) into the fissures. Channels on the right side of the fissures have been abandoned (A). Photograph by L. D. Fellows.

Ground-Water Pumping *(continued)*

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some of which moved downward with respect to others and formed basins (Figure 3). Most of the blocks are bounded by fault zones, along which the fracturing and movement took place. Gravel, sand, silt, and clay particles, the weathering products of rocks in the adjacent mountain blocks, were transported by streams and deposited in the basins. The process took place so long that 5,000-10,000 feet or more of sediment filled some of the basins.

Basin-bounding fault zones may be more than a mile away from the present-day mountain fronts and buried beneath several hundred feet of sand and gravel. Basin-margin areas underlain by relatively thin sediment deposits are highly susceptible to overpumping.

Sediment in the basins became saturated with water, which occupies the spaces between the individual particles of rock. Ground water can be pumped readily from layers known as aquifers. Subsidence occurs when an aquifer is dewatered and the sand and gravel particles within it get squeezed together more closely. Compaction reduces the porosity of the aquifer and, if enough water is removed, the overlying land surface slowly sinks.

What kinds of problems are caused by land subsidence? Subsidence and earth fissures cause varied problems (Figures 1, 4-7). Fissures have cut highways, roads, airports, canals, building foundations, swimming pools, and ponds. Fissures have caused buildings to be condemned. (Not all foundation cracking is due to land subsidence induced by ground-water pumping.) In some areas people use open fissures as dumps and create potential for liquid waste to percolate downward into an aquifer. Open fissures are potential hazards to people who are unaware of their presence. Subsidence can cause the land slope to change. This disrupts irrigation and sewage systems, which depend on gravity flow. Farmers who irrigate crops have had to abandon fields or have them releveled so that the irrigation water flows in the right direction. One of the first indicators of subsidence is the collapse of water well casings. Streams or washes that once drained in a certain direction may now channel water into other areas, causing water to stand or flooding to occur where it never did before. Land surveyors have difficulty closing traverses if any of the benchmarks in the traverse have subsided.

What parts of Arizona are subsiding? Many basins in southern Arizona contain more than 1,600 feet of sedimentary deposits (Figure 8). Excessive pumping in a number of them has already induced subsidence and fissures. Additional impacts will occur if pumping continues. Subsidence can be expected even in basins that have not yet been affected if ground-water pumping exceeds recharge.

Subsidence has been known in Pinal County since 1927 and in the Phoenix and Tucson areas since the 1950s. The lead article in the Spring 1998 issue of *Arizona Geology* is a description of a 4,400-foot-long

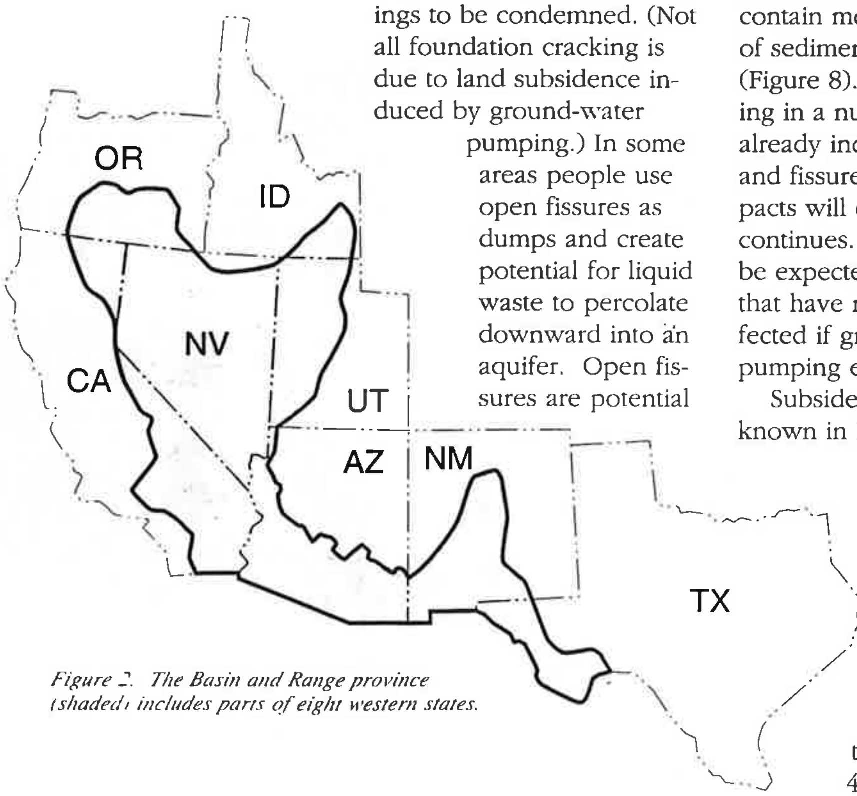

Figure 2. The Basin and Range province (shaded) includes parts of eight western states.

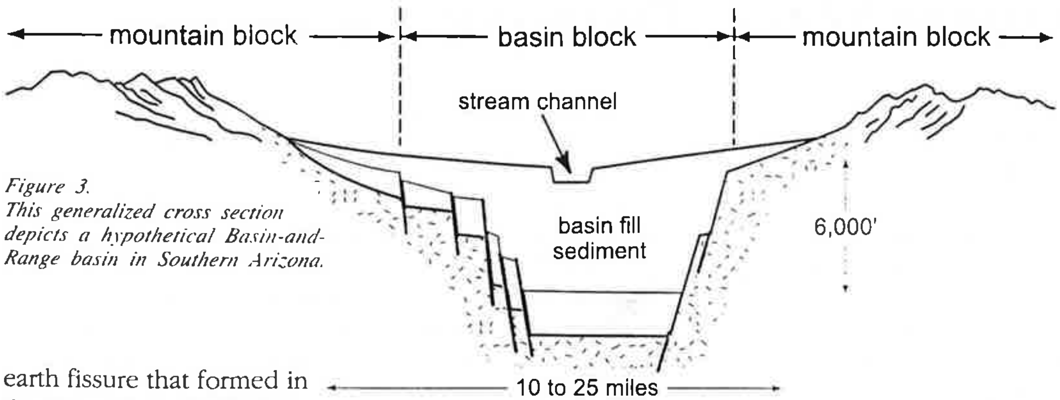

Figure 3. This generalized cross section depicts a hypothetical Basin-and-Range basin in Southern Arizona.

earth fissure that formed in the Harquahala Plain west of Phoenix after a heavy rain associated with Hurricane Nora in September 1997. Subsidence is suspected in other basins, but has not yet been measured.

The Basin and Range part of Arizona is not the only place where subsidence due to ground-water pumping is a known or potential problem. Las Vegas has been experiencing serious subsidence and related problems for several years. Subsidence has been recorded also near Deming, New Mexico. Potential exists for subsidence and related problems to occur in other basins within the Basin and Range province outside of Arizona.

How does one know that the land is subsiding? Subsidence takes place so gradually that it's hardly noticeable. It makes no noise and doesn't cause the ground to shake. Until a few years ago, subsidence could be confirmed only by conducting a land survey across the suspected area. A new method involves making repeat satellite-radar images. By this method, called *radar interferometry*, minute changes in the altitude of the land surface can be detected. Using this technique, the NPA Group, Edenbridge, United Kingdom, measured subsidence in western Maricopa County and the central Tucson basin. According to Ren Capes, Manager of Applications Development, the NPA Group determined that the central Tucson area subsided a maximum of 9 cm (3.5 in) between June 1993 and March 1997. This study, in combination with a previously generated result using a one-year temporal separation, indicated that the rate of subsidence was between 1.5 and 2.0 cm (0.6-0.8 in) per year for that period. A smaller area 5 mi southwest of the central area subsided about 6 cm (2.4 in) from June 1993 to March 1997.

Can subsidence be stopped? Subsidence can be stopped by slowing the rate of ground-water pumping so that recharge takes place as fast as or faster than pumping. If water is pumped back into the ground, however, subsidence will not be reversed. Once done, it's permanent.

Where can I get more information? The Arizona Geological Survey (AZGS), in cooperation with the Arizona Department of Water Resources (ADWR) and a dozen other governmental agencies, established the Center for Land-Subsidence and Earth-Fissure Information (CLASEFI). The purpose of CLASEFI is to serve as a central source of information about subsidence and related problems. Raymond C. Harris (AZGS) is the coordinator of CLASEFI activities.

Much information has been published about the cause and impacts of land subsidence. The AZGS published "Land Subsidence and Earth Fissures in Arizona," (Down-to-Earth 3) and bibliographies of published and unpublished maps and reports on subsidence (Open-File Reports 95-8 and 95-11). In addition, the AZGS maintains a web site that includes subsidence information. The ADWR, which periodically measures water levels in wells to determine changes, is now measuring land subsidence with Global Positioning System equipment. The U.S. Geological Survey, Water Resources Division, has released reports that describe land subsidence. The Water Resources Research Center and the Department of Geosciences at the University of Arizona also have information about subsidence on their web pages.

Visit the AZGS web page (**www.azgs.state.az.us**) for more information and links to other web sites.

Figure 4. An earth fissure cut this road in Pinal County several miles east of Chandler Heights. Photograph by R. C. Harris.

Figure 5. The land subsided more than 15 feet in Pinal County south of Eloy from 1950 to 1985. The marker on the pole shows where the land surface was in 1952. More subsidence has undoubtedly taken place since 1985. Photograph provided by H.H. Schumann.

Figure 6. Subsidence broke and offset this irrigation canal in western Maricopa County. Photograph by L.D. Fellows.

Figure 7. Earth fissures such as this one just east of the intersection of Baseline and Sossaman Road near Chandler Heights in Maricopa County are used commonly as dumps. Photograph by L. D. Fellows.

This map was modified from Depth-to-Bedrock Map, Basin and Range Province, Arizona, 1980, J.M. Oppenheimer and J.S. Sumner, scale 1:1,000,000.

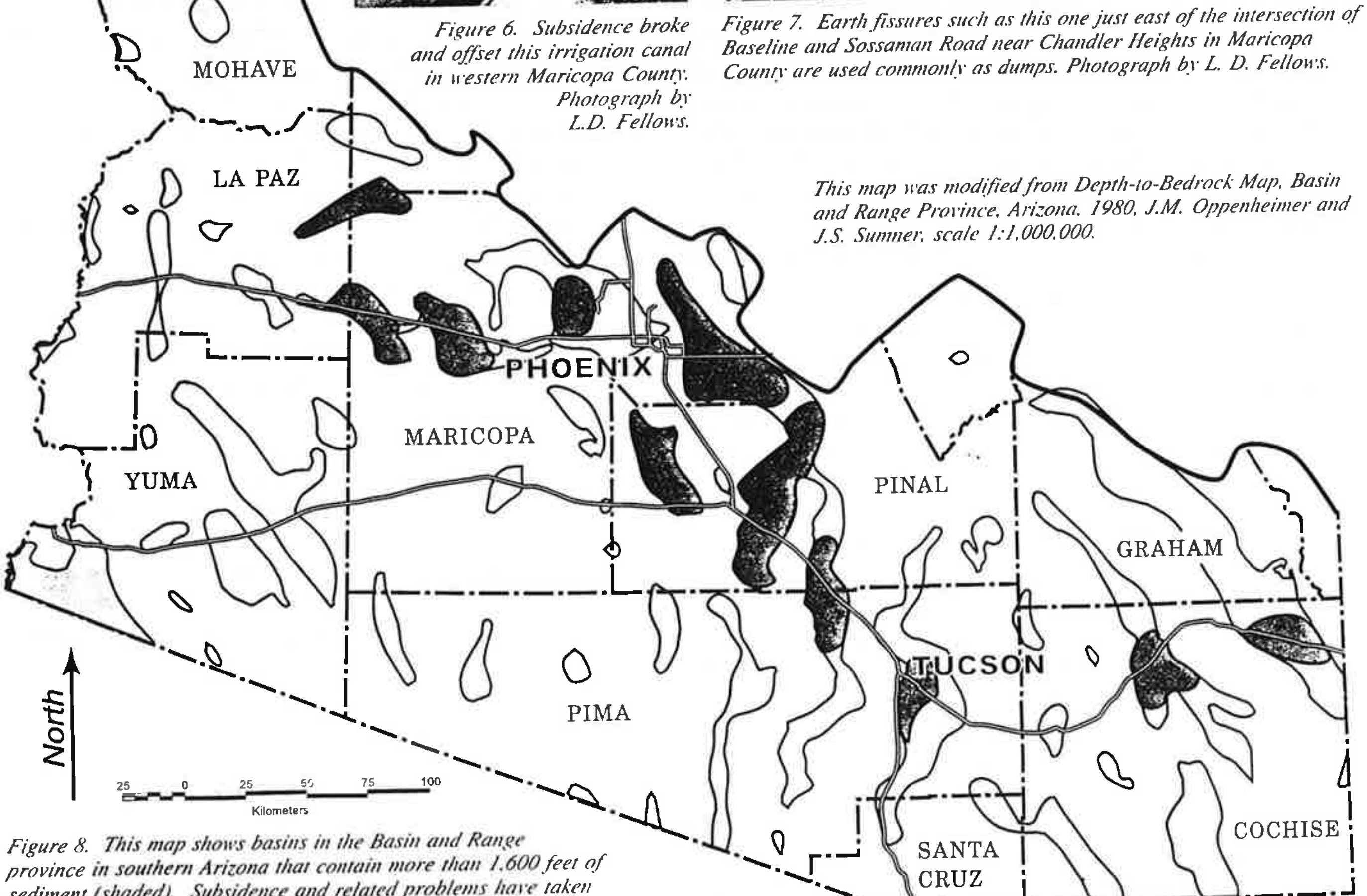

Figure 8. This map shows basins in the Basin and Range province in southern Arizona that contain more than 1,600 feet of sediment (shaded). Subsidence and related problems have taken place within those areas shown in red.

application of geologic principles for public welfare. These basic principles or earth science considerations must be presented clearly to planners and decision makers so that they can take efforts to reduce losses due to geologic hazards.

Millions of dollars and hundreds of lives have been lost in Arizona from the neglect and misunderstanding of catastrophic geologic hazards such as floods and earthquakes; less spectacular but far more costly in terms of property damage are geologic hazards such as landslides, expansive soils, land subsidence, and blowing dust.

LAND SUBSIDENCE AND EARTH FISSURES

Land subsidence in south-central Arizona

Known land-subsidence areas in Arizona comprise more than 7,800 km^2 and lie in the Basin and Range Physiographic Province of the south-central part of the state. It is here that most of the state's population and agricultural and urban development is located. About 1.9605 x 10^5 km^3 (157 million acre feet) of groundwater have been withdrawn in this area since 1900 (Babcock, 1977). For example, in 1975, about 6.78 x 10^3 hm^3 (5.5 million acre-feet) of groundwater were pumped from the permeable alluvial deposits (Babcock, 1977). These withdrawals of groundwater have greatly exceeded the amount of natural recharge. Subsidence in south-central Arizona was first detected near Eloy in the Picacho Basin in 1930-31 (Smith, 1940, table and plate III) (fig. 1). Repeated leveling since 1952 indicates as much as 3.8 m of subsidence near Eloy by 1977 (Laney and others, 1978), and subsidence is continuing. An area of 625 km^2 is affected. Maximum average subsidence rate near Eloy has been about 15 cm per year (Peirce, 1979).

In the lower Salt River valley, there are three areas at the present time where the groundwater table has dropped more than 100 m and land subsidence has been recorded: (1) Queen Creek-Apache Junction area, (2) southern Paradise Valley, and (3) western Salt River valley (Luke Air Force Base) (fig. 1). Just west of Apache Junction, the maximum measured subsidence between 1948 and 1981 of a benchmark near U.S. Highway 60 and the Bush Highway is 1.6 m (fig. 1) (Arizona Department of Transportation, 1981). During the same interval, probably 1.9 m of subsidence has occurred at two benchmarks near the intersection of Williams Field and Power Road, 6.4 km east of Chandler (Hoyos-Patiño and others, 1985). The Central Arizona Project aqueduct near Apache Junction required special design and construction to accommodate land subsidence in the area. More than 0.7 m of land subsidence has been measured since 1971 along the aqueduct route south of Apache Junction (Schumann and others, 1983).

Subsidence of the land in the southern part of Paradise Valley was brought to local and state attention with the reporting of the formation of a 130-m-long earth fissure in a new housing area in northeast Phoenix in 1980 (Péwé, 1980; Larson, 1983; Péwé and Larson, 1982; Larson and Péwé, 1983). Paradise Valley (fig. 1) is an elongate alluvial basin lying between the Phoenix Mountains on the southwest and the McDowell Mountains on the east.

Groundwater levels remained nearly constant in the valley until about 1950, generally within 75 m of the surface. However, since then there has been a tremendous amount of groundwater withdrawal, up to 25 x 10^6 m^3 annually. The groundwater level has declined as much as 90 m from its original level in 1950 in at least two areas, to as much as 165 m from the surface. Several wells have become dry, and land subsidence is active.

A detailed study of land subsidence has been made (Péwé and Larson, 1982; Larson and Péwé, 1983, 1986) of northeast Phoenix on the west side of Paradise Valley near Shea Blvd. The onset of land subsidence in northeast Phoenix probably began in the late 1960s or early 1970s in response to falling groundwater levels. A "subsidence bowl" formed and increased in size at an average rate of 5 km^2 per year, until the land has now subsided about 1.5 m and the bowl covers an area of at least 20 km^2. The 1980-82 rate of subsidence was 13 cm per yr.

Earth fissures

The most spectacular result of land subsidence due to groundwater withdrawal in Arizona is the formation of earth fissures (fig. 2). These are long, narrow, eroded tension cracks that occur in unconsolidated sediments, typically near the margins of mountains or outlying bedrock outcrops where groundwater levels have declined from 60 m to more than 135 m.

The first fissure reported in Arizona was observed near Picacho in 1927 (Leonard, 1929). During the last 60 years, accelerated groundwater withdrawal has caused intense fissuring of several alluvial basins in south-central Arizona (Feth, 1951; Heindl and Feth, 1955; Schumann, 1974; Laney and others, 1978; Peirce, 1979; Jachens and Holzer, 1982; Strange, 1983). Until recently, the fissure hazard has been confined to outlying agricultural areas, but in January 1980, a 130-m-long fissure opened in Paradise Valley at a residential construction site in northeast Phoenix. The Paradise Valley fissure is the first known occurrence in a densely populated, nonagricultural part of the state and the first in the City of Phoenix (Péwé, 1980). Early ideas on the origin of earth fissures did not relate to groundwater withdrawal; however, earth fissures in southern Arizona are now thought to be directly related to the lowering of the water table with subsequent compaction of the dewatered sediments and subsidence of the land surface (Schumann and Poland, 1969). Recent work utilizing geophysical and geodetic surveying techniques supports the hypothesis that many fissures are caused by differential subsidence and compaction over buried bedrock hills, ridges, or fault scarps (Schumann and Poland, 1969; Sauck, 1971, 1975; Jennings,

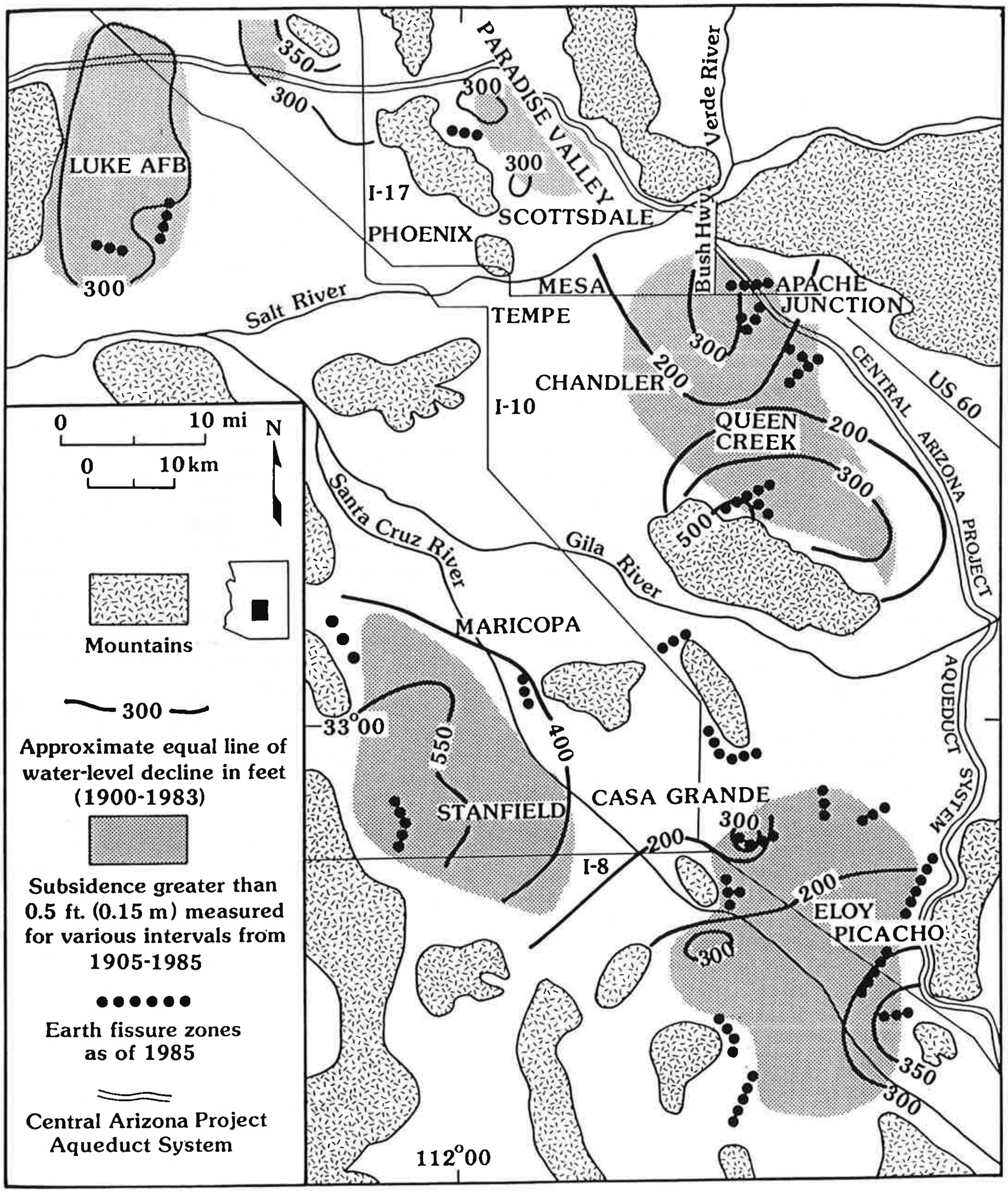

Figure 1. Water-level declines, land subsidence, and earth fissures in south-central Arizona (from Péwé, n. d.)

1977; Christie, 1978; Pankratz and others, 1978; Jachens and Holzer, 1979, 1982; Péwé and Larson, 1982; Raymond, 1985; Péwé and others, 1987; Péwé, in press).

The number of fissures has multiplied enormously since the 1950s, and now hundreds of fissures are known in the alluvial basins of southern Maricopa, western Pinal, western Pima, and northwestern Cochise Counties. Today, most are concentrated in Pinal and Maricopa Counties (fig. 1) (Schumann, 1974; Laney and others, 1978; Schumann and Genualdi, 1986).

Investigations of fissures indicate that many, if not most, occur (1) in the alluvial basin near the fronts of mountains, (2) where the depth to bedrock is 60 m to 300 m, and (3) where the alluvium is dewatered to a depth of 100 m or more. This distribution suggests, in a broad way, areas where new or additional fissures could be predicted to form as the water table declines (Schumann, 1974; Welsch and Péwé, 1979; Cordy and others, 1977). Later work indicated that many fissure locations occurred where there was dewatering and subsequent differential compaction of sediments over a convex bedrock irregularity such as a buried knoll, ridge, or erosional or fault scarp, or where abrupt changes in texture or thickness of the overlying alluvial sediments occur (Jachens and Holzer, 1982; Péwé and Larson, 1982; Larson and Péwé, 1983; Schumann and Tosline, 1983). This work permitted more accurate predictions of fissure locations.

In northeast Phoenix, detailed gravity traverses, geologic mapping, and well-data interpretation permitted the construction of a topographic map of the buried bedrock surface. This information by Péwé and Larson (1982) and calculated horizontal strain data by Ragan (1986) allow prediction of future fissures subparallel to the existing fissure at 40th Street and Lupine. Also, because differential subsidence over a buried bedrock knoll is the most positive hypothesis for the origin of the existing fissure of northeast Phoenix, nearby similar buried topography detected by gravity measures may be considered sites of possible future fissuring. For example, the presence of a buried hill 1.0 km north of the existing fissure suggests that a fissure may occur in the future near 40th Street and Cactus Road. Larson and Péwé (1986, fig. 1) outlined areas of potential fissuring in northeast Phoenix. Although localities of potential fissuring may be roughly outlined, the exact date of future fissure formation cannot be predicted.

SLOPE INSTABILITY

The most widespread evidence of landslides in Arizona occurs on the Colorado Plateau in the many precipitous canyons and on the steep, or formerly steep, bounding cliffs of the widespread mesas and buttes. The relatively flat lying formations of resistant sandstones, limestones, and basalts interbedded with shale and weak sandstones produce ideal conditions for landslides, especially rotational landslides (Dodge, 1901; Watson and Wright, 1963; Reiche, 1937; Péwé, 1983; Strahler, 1940; Schumm and Chorley, 1966). Although most of the steep slopes are stabilized, some are not, and a slide potential still exists, especially when the slopes are disturbed by man.

In the northeast part of the state, (as well as in the contiguous area east to the Rio Grande in New Mexico) and extending south to the White Mountains, there are flat-topped basalt- or sandstone-capped mountains flanked on the sides by aprons of hummocky landslide debris extending as much as 10 to 12 km from the present mountain scarp. The formation of discrete ridges and troughs in landslide masses close to the mountains is due to the back tilting of the rotational slide slices, but progressively farther from the mountains the older landslide debris forms a subdued irregular topography. The landslide forms, which are very evident from aerial photographs and large-scale topographic maps, are well displayed on the east side of the Chuska Mountains on the state line in northeast Arizona (Gregory, 1917; Watson and Wright, 1963); also south of the St. Johns area, especially near Lyman Lake and Lyman Lake State Park; and on the north side of the White Mountains along the Little Colorado River southwest of Springerville. Most of these slides are now inactive, but they could be reactivated by oversteepening due to river cutting or by road or other construction activities. Near Greer, on the Little Colorado River on the north side of the White Mountains in Apache County, landslide slump blocks are widespread. Some are up to 3 Ma old, but others are active today (Péwé, 1975) and present a geologic hazard.

In the Basin and Range Province of the southern part of the state, most landslides are rock slides, rock falls, boulder rolling, and toppling of rocks on steep slopes of the fault-block mountains (Melton, 1965), although locally rotational slides, debris slides, and other types of downslope movement occur (Robinson and Peterson, 1963, figs. 1-3). The downslope movement of unstable rock masses is generally the result of extensive rainfall with increase of pore pressure, triggering of rock masses by seismic shaking, or either of the above aided by blasting or undercutting by man (Hamel, 1970). Recent heavy precipitation in the Phoenix area has caused rock sliding and debris flows on Camelback Mountain (fig. 3) (Péwé, 1978) and elsewhere. Because of increased construction and excavation of all types in this part of the state, as well as nearness to earthquake epicenter, southern Arizona has the highest potential for damaging landslides in the state.

Characteristic of arid regions is the formation of large granite boulders perched on the tops and slopes of steep mountains (fig. 4) (Christensen and Péwé, 1980; Burt and Péwé, 1978, p. 60, 130; Ferry, 1984). Unstable boulders large enough to crush houses have moved downslope on the hills in the southern part of the state and will do so in the future. This is a common geologic phenomenon and is an ever-continuing process; boulders may crash down the hillside at any time. In many localities, houses are built at

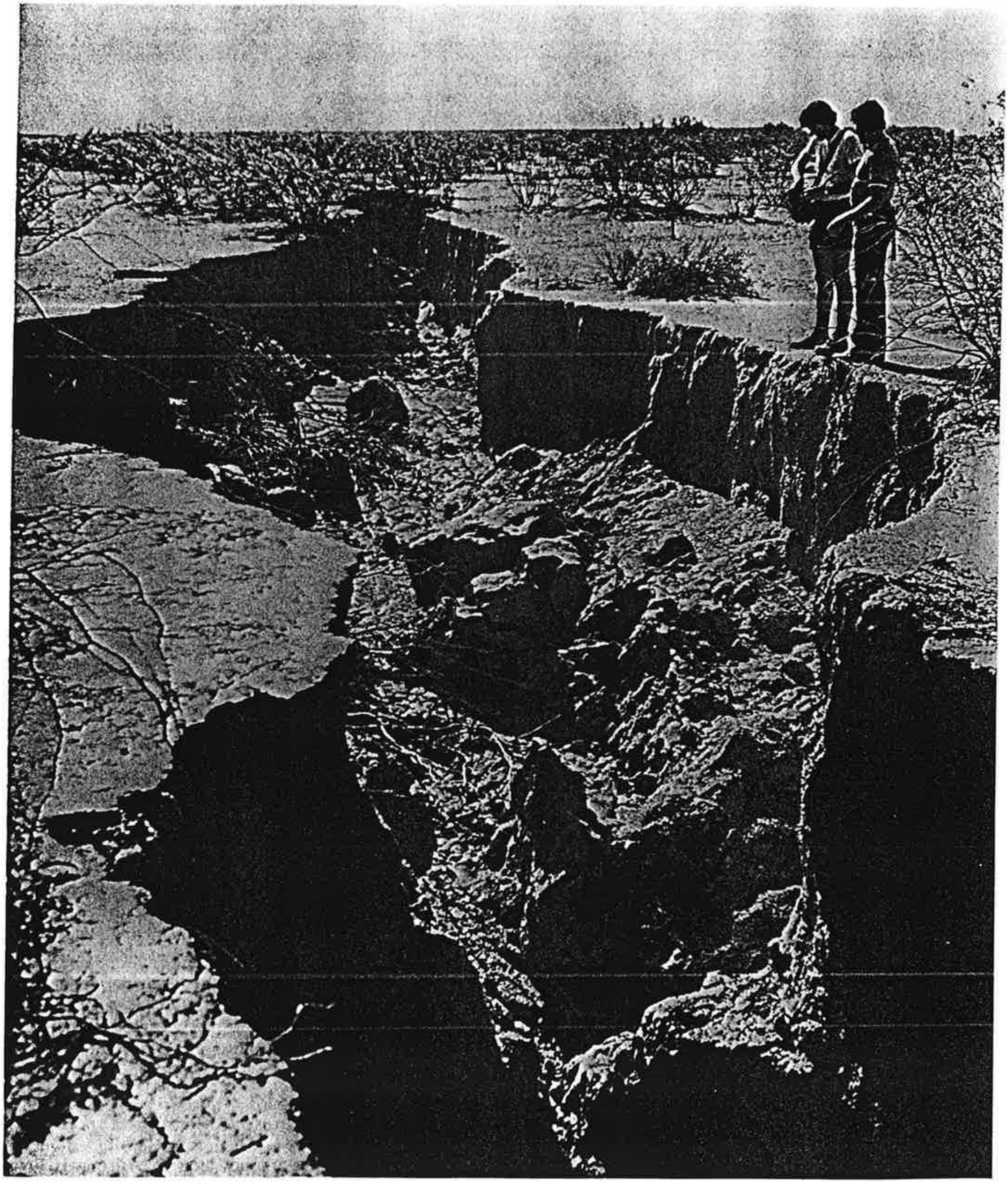

Figure 2. New earth fissure extending southeast in Apache Junction, Maricopa County, Arizona, near Central Arizona Project Aqueduct and Ironwood. This large fissure was formed July 18, 1984, in a matter of minutes when thousands of gallons of discharge water from a stock pond found egress into an underlying earth fissure in alluvium. The eroded fissure was about 200 m long. To the northwest the fissure severed electrical lines and an access road and intersected the concrete patio of a house. (Photograph no. 4815 by Troy L. Péwé, August 25, 1984.)

NAGT

Help Afterter talk.