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Rock Varnish and Desert Pavement Provide Geological and Archaeological Records

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In the deserts of the southwestern United States, "rock art" in the form of petroglyphs and geoglyphs provides glimpses into the lives of early inhabitants (Figure 1). Rock varnish and desert pavement were the "paints" and "canvases" used for these artworks. These same materials hold clues to climates of the past and offer geologists another means of dating land surfaces and recent geologic events, such as floods and debris flows.

ROCK VARNISH

Rock varnish is the thin (commonly 10 to 30 microns thick), dark, hard, glossy coating that accumulates on rock surfaces after long exposure (Dorn and Oberlander, 1982). The commonly used term **desert varnish** is somewhat of a misnomer because the same type of glaze that coats rocks in desert environments also covers rocks in arctic, alpine, and other regions (Krinsley and Dorn, 1991). This term, however, may be more popular because rock varnish is best developed and most noticeable in desert regions, where rock exposures are numerous.

The color of the rock varnish reflects its composition. Black varnish, the focus of most studies of rock varnish, forms on surfaces exposed to air. The black color is due to the concentration of manganese oxides. Orange varnish, which is rich in iron but contains very little manganese, develops on the undersides of rocks in desert areas. The manganese concentration in black varnish is commonly 50 times that in orange varnish (Dorn and Oberlander, 1981b). Dusky-brown varnish is intermediate in both color and composition. As the varnish thickens with time, its color darkens: The upper surfaces of rocks graduate from brownish-black to ebony, and the undersides of rocks change from orange to red.

Scientists studying the rate of varnish accumulation have discovered differences based on the environment. In laboratory experiments in which limiting factors were controlled, varnishes formed in less than 6 months (Dorn and Oberlander, 1981a). Varnishes have formed within 40 years in arctic regions and in less than 100 years in riverine areas (Dorn and Oberlander, 1982). In deserts, however, varnishes form much more slowly. Most scientists believe that it takes thousands to tens of thousands of years for varnish to coat a rock completely in the desert (Krinsley and Dorn, 1991). The varnishes on many desert rocks have been accumulating since the Pleistocene.

Rock varnish is composed of clay minerals, such as illite, montmorillonite, and kaolinite, as well as manganese and iron oxides. Clay minerals compose up to 70 percent of black manganese-rich varnish and up to 90 percent of orange manganese-poor varnish (Potter and Rossman, 1977, 1979). Lesser amounts of silica, calcium carbonate, and trace elements (e.g., magnesium, potassium, phosphorus, calcium, and titanium) may also be present (Dohrenwend, 1987; Krinsley and Dorn, 1991).

Conflicting theories have been proposed for the formation of black rock varnish. Early theories suggested an internal source (the underlying rock) for varnish constituents and a chemical

(continued on page 4)

Figure 1. Petroglyphs etched on varnished rocks in Saguaro National Monument west of Tucson. Photo by Evelyn VandenDolder.

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Environmental Education in Arizona Becomes a Coordinated Effort

On January 7, 1992, the Governor's Task Force on Environmental Education presented its report, *Comprehensive Plan for Environmental Education*, to Governor Fife Symington (Figure 1). The Task Force was established by the Arizona Environmental Education Act of June 6, 1990 (HB 2675). It consists of 31 members with experience in environmental issues who represent private citizens and organizations, educational institutions, State and Federal agencies, the Legislature, and the Governor's Office. The *Comprehensive Plan for Environmental Education* presents 5 goals, 14 objectives, and 92 recommendations to accomplish the legislative intent of HB 2675: to develop an integrated environmental education program that provides students and the general public with an awareness that is "thorough, continuous and meaningful." The Task Force has specified the organizations that it believes should be responsible for enacting the recommendations, both formal educational institutions (e.g., the Arizona Department of Education, public and private schools, and universities) and informal educational groups (e.g., the Governor, Legislature, State agencies, media, and industry).

At that same meeting on January 7, Governor Symington and representatives from 16 State agencies signed a *Memorandum of Understanding* to encourage coordination of interagency activities in environmental education. The 16-member Arizona Interagency Committee on Environmental Education, established by the Arizona Environmental Education Act, includes the following agencies: Arizona Department of Transportation, Arizona Department of Water Resources, Arizona Department of Environmental Quality, Arizona State Land Department, Arizona State Parks, Arizona Geological Survey, Arizona Energy Office, Arizona Solar Energy Advisory Council, Arizona Game and Fish Department, Arizona Department of Agriculture, Arizona Office of Tourism, Arizona Department of Education, Commission on the Arizona Environment, Arizona State Mine Inspector, Arizona Department of Health Services, and Office of the Attorney General.

Excerpts from both of these documents are reprinted below.

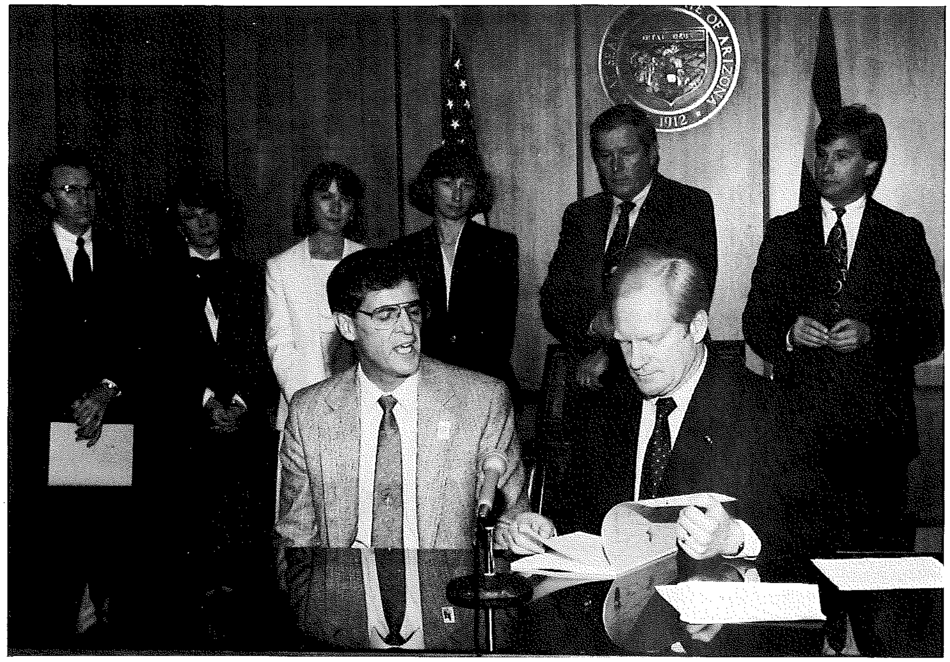


Figure 1. Chris Williams (left foreground) of the U.S. Soil Conservation Service and Chairman of the Governor's Task Force on Environmental Education, presents a copy of the Comprehensive Plan for Environmental Education *to Governor Fife Symington. Other government officials pictured in the background are, left to right, Dan McGovern (U.S. Environmental Protection Agency, Region IX), C. Diane Bishop (Superintendent of Public Instruction), Cynthia Krug (Arizona State Parks), Senator Karan English (Chairman of the Arizona Senate Environment Committee and primary sponsor of the Arizona Environmental Education Act), Jack Haenichen (Arizona Energy Office), and Representative Bill Mundell (Chairman of the Arizona House of Representatives Environment Committee).*

Comprehensive Plan for Environmental Education

"Environmental education is that component of education that may include one or more of the following: aesthetic appreciation of the natural world; basic scientific knowledge of how the natural world works; appreciation of the value of environmental quality; understanding of how humans affect their environment and how the environment affects humans, past and present; experience in how personal choices and actions affect the natural environment; and experience in methods of local-through-global community responsibility, in order to deal effectively with contemporary environmental issues....

"The primary goals of environmental education in Arizona are:

(1) Each individual should have a basic understanding of the environmental sciences.
(2) Each individual should understand the interrelationships between human actions and the environment.
(3) Environmental education should be integrated into all school curriculums.
(4) Diverse environmental education opportunities should be available to the general public.
(5) Environmental education in Arizona should be a cooperative venture, coordinated at all levels within the state and with national and international networks....

"The ... objectives developed by the Task Force [are]:

(1) To coordinate environmental education efforts among all public and private agencies, organizations and educational institutions.
(2) To begin operation of a statewide network for environmental education.
(3) To develop policy documents recognizing the importance of environmental education and establish program guidelines to implement ARS 15-706.
(4) To coordinate research in environmental education among public and private agencies, organizations and educational institutions.
(5) To identify diverse funding sources and direct allocation of available funds for environmental education in Arizona.
(6) To create models of environmental responsibility at schools and other public facilities.

(7) To implement a comprehensive program integrating environmental education throughout the kindergarten through twelfth grade curriculum in support of ARS 15-706 by 1994.
(8) To provide training in environmental education as a part of preservice and graduate-level teachers' course work to implement ARS 15-1643 by 1993.
(9) To implement an integrated program of teacher in-service training in environmental education by 1993.
(10) To integrate environmental education into all post-secondary degree programs in Arizona by 1994.
(11) To assess Arizona's environmental education programs on a regular basis beginning in 1995.
(12) To improve communication between agencies, organizations and the media and expand coverage of environmental issues and environmental education.
(13) To create new and utilize existing recognition programs which support innovative or outstanding efforts in environmental education.
(14) To establish a body to pursue full implementation of this comprehensive environmental education plan for Arizona."

By passing the Arizona Environmental Education Act, Arizona became one of only a handful of States who have recognized the importance of creating a strong environmental education program. HB 2675 established three funds to support the activities described in the bill. The Arizona Department of Education's Environmental Education Fund may be subsidized by legislative appropriations or donations from interested individuals and organizations. The Environmental Number Plate Fund will be collected by the Arizona Department of Transportation through the sale of environmental number plates. The Arizona Environmental Education Task Force Fund will be financed by private individuals and organizations. By December 31, 1991, about $110,000 had been donated to the first and third funds. Most of this money came from the Arizona Game and Fish Heritage Fund.

The 66-page *Comprehensive Plan for Environmental Education* also includes the text of the Arizona Environmental Education Act of 1990, SB 1176 amending the 1990 Act, and the Tbilisi Declaration (adopted by delegates to the World's First Intergovernmental Conference on Environmental Education in October 1977), as well as a synopsis of the National Environmental Education Act of 1990. Single copies of the *Comprehensive Plan for Environmental Education* are free and available from Jeff Cohen, Arizona Dept. of Education, 1535 W. Jefferson, Phoenix, AZ 85007; tel: 1-602-542-5950.

> *"In the end, environmental education boils down to a simple yet profoundly important imperative: preparing ourselves for life and all its surprises in the next century. When the 21st century rolls around, it will not be enough for a few specialists to know what is going on while the rest of us wander around in ignorance."*
>
> -- William K. Reilly
> Administrator, U.S. Environmental Protection Agency

Memorandum of Understanding

"The objectives of this agreement are that the undersigned agencies ... have formed the Arizona Interagency Committee on Environmental Education ... to coordinate, improve and support education about Arizona's Natural and Cultural Environments past and present. The Committee shall encourage the coordination of interagency activities regarding environmental education to promote the efficient distribution of information, and to facilitate the planning and development of educational materials of state agencies. The Committee shall also act as a liaison between local, state and federal agencies relating to environmental education in Arizona.

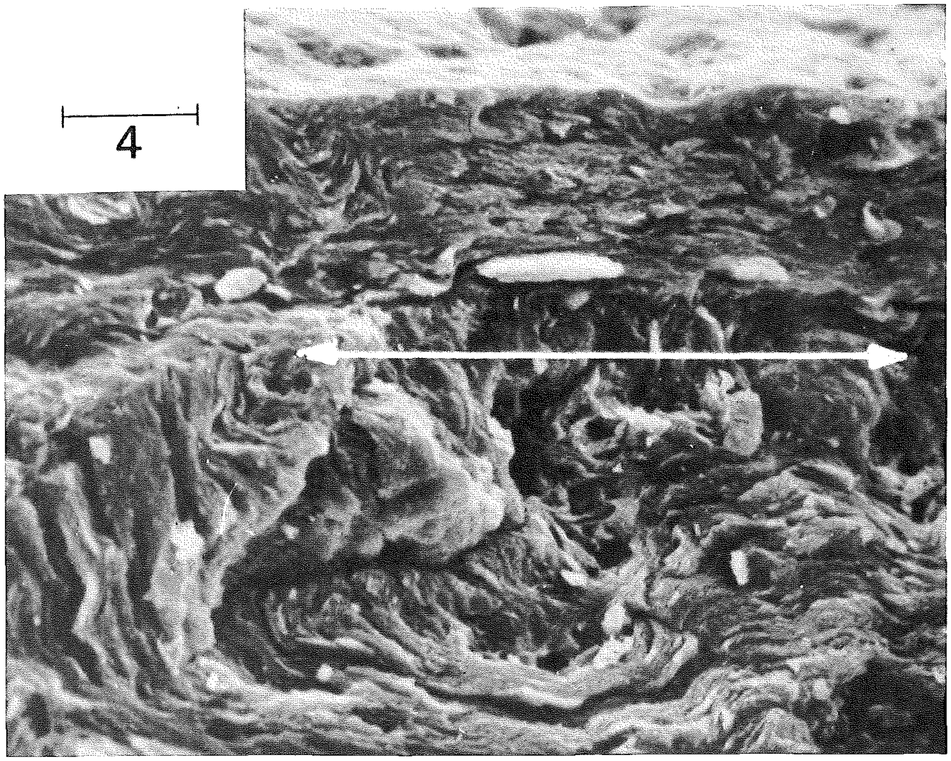
"The Committee shall achieve its purpose by:
(1) Coordinating agency services, programs and materials;
(2) Cooperatively developing educational materials and programs;
(3) Providing technical review for accuracy and validity of member agency educational materials;
(4) Implementing programs;
(5) Communicating between and among participating local, state and federal agencies;
(6) Providing professional development and training opportunities for member agencies and audiences;
(7) Assessing the characteristics and effectiveness of intra and interagency programs; and
(8) Providing recommendations for action by agencies to improve their environmental education programs.

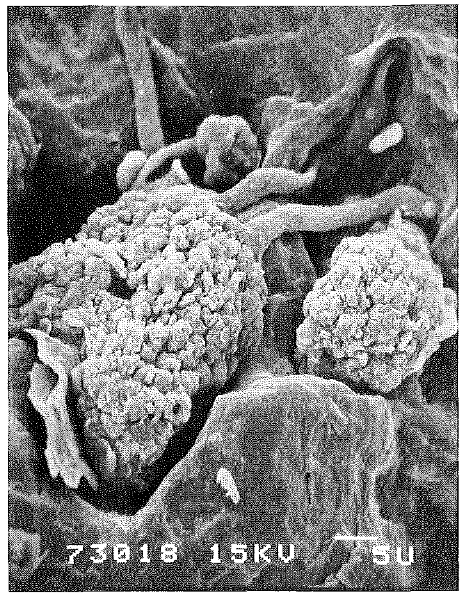
"The undersigned agencies agree:
(1) To direct their respective staffs to provide information and cooperate fully with the Committee.
(2) To submit to the Department of Education references of environmental educational materials used by the agency for inclusion in the Environmental Education Resource Information System.
(3) To provide available resources, at the discretion of the Agency, including funds, staff and technical information to the Committee to facilitate the Committee's statutory mandates.
(4) To establish a formal process for sharing environmental education materials for review by the Committee.
(5) To periodically provide information to the Committee regarding the agencies' environmental education programs and events.
(6) To develop interagency training opportunities to facilitate the development and coordination of environmental education."

PROFESSIONAL MEETINGS

Geologic Reason: A Basis for Decisions Affecting Society. Symposium at American Institute of Professional Geologists annual meeting, September 27-30, Lake Tahoe, Nev. Topics include modeling geologic phenomena, predicting earthquakes, cleaning up wastes, managing environmental hazards, and managing Federal lands. Abstracts due June 15. Contact Jonathan G. Price, Nevada Bureau of Mines and Geology, M.S. 178, University of Nevada, Reno, NV 89557-0088; tel: 1-702-784-6691.

Engineering Geology into the 21st Century. Association of Engineering Geologists, annual meeting, October 2-9, Long Beach, Calif. Papers due May 1. Contact Martin L. Stout, AEG Program Chair, Dept. of Geological Sciences, California State University, Los Angeles, CA 90032-8203; tel: 1-213-343-2409 or 1-213-343-2400.





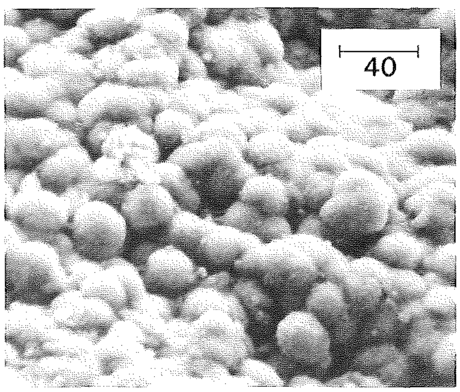


Figure 2 (top left). *Lamellate varnish layers on rock sample from the Mojave Desert in California. Two* ***unconformities*** *(gaps in the depositional sequence) are visible. The area beneath the double white arrow was eroded, probably by acid-secreting fungi or lichens. The depression was later refilled with more varnish. The slightly darker, horizontal line directly above the arrow marks another area of erosion, probably caused by wind abrasion. The bar scale is 4 microns long. Photo by Ronald Dorn.*

Figure 3 (top right). *Surface view of lamellate varnish on rock sample from the Florence area of Arizona. The varnish is being eroded by organic acids secreted by the octopuslike microcolonial fungi. Varnish covered with abundant fungi cannot be dated. The bar scale is 5 microns long. Photo by Ronald Dorn.*

Figure 4 (bottom left). *Botryoidal varnish on rock sample from the Three Sisters Wilderness in Oregon. The bar scale is 40 microns long. Photo by Ronald Dorn and David Krinsley.*

process for varnish formation. Soluble minerals from within were believed to accumulate on the rock surface through evaporation and precipitation. More recent studies, however, suggest an external source and a biotic process. Airborne materials, such as microorganisms (bacteria), clay minerals, magnesium, and iron, settle on the rock surface. The slow-growing bacteria oxidize and concentrate manganese and iron, cement the clay minerals to the rock surface, and adsorb other airborne and waterborne particulate matter. The clays shield the bacteria from climatic extremes and anchor the bacteria to the rock surface (Dorn and Oberlander, 1981a,b; Krinsley and Dorn, 1991). Highly magnified views of rock varnish look like **stromatolites,** which are layered, typically dome-shaped masses of limestone deposited by the metabolic activities of blue-green algae. Some scientists believe that these features are evidence that a biological process controls the formation of rock varnish.

Several factors may restrict the growth of black rock varnish: increased competition from faster growing microorganisms, lack of manganese, dramatic changes in oxidation potential (Eh), and a high pH. The manganese-oxidizing bacteria that form black varnish flourish in environments where the pH is near neutral, on surfaces exposed to air. Because the undersides of rocks are protected from rain, soluble salts accumulate, creating an alkaline (high pH) environment that is detrimental to manganese-oxidizing bacteria. Other factors enhance the growth of black varnish: an arid climate, which restricts the growth of faster growing microorganisms; more frequent wetting and drying cycles; more permanent rock surfaces; and limited organic material, which encourages bacterial oxidation of manganese (Dorn and Oberlander, 1981b).

The amount of airborne dust determines the amount of clay minerals that settles on rock surfaces and, thus, the composition and structure of the varnish formed by bacteria. Rock varnish records climatic changes in its **micromorphology,** i.e., its shape and structure as viewed under a high-powered electron microscope. When the climate is dusty (and presumably drier), the accumulation rate of clay exceeds that of oxides. Clay-rich varnish is **lamellate,** or layered, like the leaves of a book (Figures 2 and 3). When the climate is less dusty (and presumably wetter), the accumulation rate of oxides exceeds that of clay, and clay-poor varnish is formed. This type of varnish is **botryoidal,** or spherical in shape, like a bunch of grapes (Figure 4). Varnished rocks in the Mojave Desert of California record climatic changes that occurred from the late Pleistocene to the Holocene (approximately 10,000 years ago). Varnish on rocks from a late Pleistocene pavement surface is botryoidal, whereas rocks from a Holocene alluvial surface are coated with lamellate varnish. This difference indicates a change from less dusty to dustier conditions and, presumably, from a wetter to a drier climate (Dorn, 1984b). Similar climatic changes are recorded on varnished rocks near the Dead Sea in Israel (Figure 5).

Changes in the chemical composition of rock varnish may also mirror climatic changes. Alternating layers of manganese-

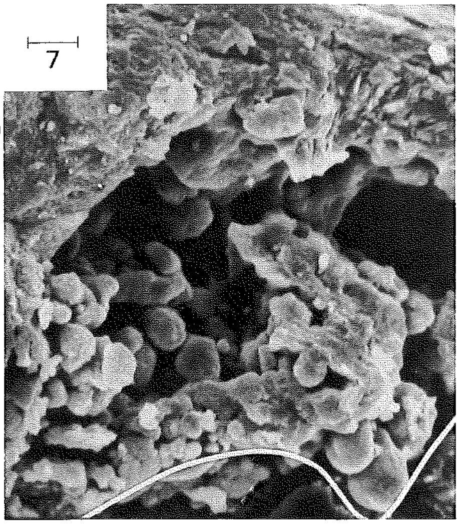


Figure 5. Lamellate varnish layers deposited on top of botryoidal varnish layers on rock sample from Israel. The sample was collected from an ancient shoreline of Lake Lisan (the precursor of the Dead Sea). This shoreline receded about 18,000 years ago. The climate in the area was still wet, however, and fostered the development of the botryoidal varnish. About 10,000 years ago, as the climate became drier, the lamellate varnish formed. The bar scale is 7 microns long. The white line indicates the boundary between the varnish and the rock. Photo by Ronald Dorn.

rich and manganese-poor varnish may indicate changes in the alkalinity of airborne (**eolian**) dust. Based on studies of rock varnish, scientists estimate that at least 13 fluctuations in eolian alkalinity have occurred during the last 1.1 million years. These fluctuations may reflect cycles of low moisture, sparse vegetation, and **playas** (dry lake basins) followed by high moisture, denser vegetation, and shallow lakes (Dorn, 1984a).

Both geologists and archaeologists have used rock varnish as a relative dating method. (See VandenDolder, 1990, 1991 for more information on relative and absolute dating techniques.) Geologists studying areas with potential flood and debris-flow hazards use the presence of rock varnish and the degree of its development as one measure of the time that has elapsed since an area was flooded or disturbed (Pearthree, 1991). Archaeologists have also used this method to determine the relative ages of petroglyphs and varnished artifacts.

Petroglyphs, or incised rock designs (Figures 1 and 6), were created by early inhabitants of the Southwest, who scraped away the dark varnish to expose the underlying light-colored rock. (**Pictographs**, by comparison, are designs that have been painted on rocks.) Archaeologists believe that petroglyphs are not a complex language, as are hieroglyphs, nor are they the idle doodles of prehistoric peoples. Petroglyphs with geometric designs that are similar to those used in prehistoric pottery may be just decorative elements. Anthropomorphic petroglyphs of figures that are dancing or wearing headdresses, however, may illustrate ceremonial aspects of a prehistoric culture (Figure 6). Some petroglyphs may depict shamans, mythical beings, or even gods. Petroglyphs that show successful hunting scenes may be a ceremonial way of capturing the magic of the hunt and controlling nature by invoking the help of the spirit world (White, 1965; Ferg, 1974). Galleries of petroglyphs adorn the rocks of the Southwest, including Arizona, which contains more petroglyphs than any other State (White, 1965). Hundreds of sites and thousands of designs have been discovered in the Picacho Mountains alone, midway between Tucson and Phoenix (Wallace and Holmlund, 1986). Petroglyphs discovered in the western section of Saguaro National Monument near Tucson were probably etched by the Hohokam from A.D. 900 to 1300 (White, 1965).

To obtain more quantitative, absolute dates for black rock varnish, scientists require rock samples on which the varnish has been continually deposited. By viewing thin sections of varnish samples under an electron microscope, scientists can determine which samples have never been eroded by wind abrasion, acid-secreting microorganisms, or other mechanisms and, thus, are more reliable for absolute dating (Figures 2 and 3; Krinsley and others, 1990).

The oxidizing and alkaline environment of desert regions hinders the preservation of charcoal and other materials that could be dated by the ^{14}C (radiocarbon) method. Because rock varnish contains organic carbon, the radiocarbon method has been used to date samples scraped from the lowest (oldest) layers of the varnish. The dates represent minimum ages because they reflect when the lowest varnish layers were deposited, not necessarily when the object was first exposed to air (Dorn and others, 1989).

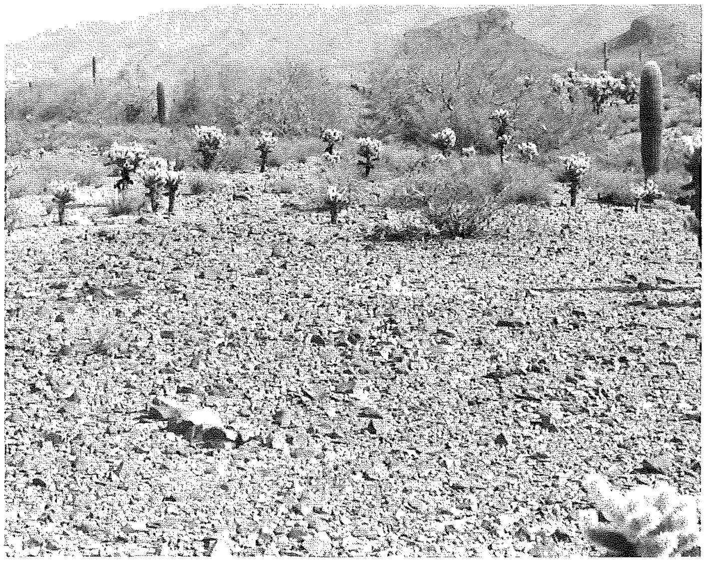
Another dating technique, bulk chemical analysis of varnish coats, has been used when the amount of carbon in a varnish sample is insufficient or the sample is too old for radiocarbon dating. The surface area of most petroglyphs, for example, is too small for radiocarbon dating (Dorn and others, 1989). Through chemical analysis, a researcher can determine the ratio of potassium and calcium **cations** (positively charged ions) to titanium cations ($K^+ + Ca^{2+} / Ti^{4+}$) in a varnish sample (Dorn and Oberlander, 1981b; Dorn and Krinsley, 1991). This technique assumes that potassium and calcium are more mobile than titanium and are leached from the varnish as it ages. The cation ratio of rock varnish, therefore, decreases with time (Dorn and Krinsley, 1991). Although the use of this dating method is controversial (Reneau and others, 1990), some tests of its validity have been favorable (e.g., Loendorf, 1991).

DESERT PAVEMENT

Desert pavement is a veneer of closely packed pebbles, cobbles, and boulders that mantles a desert surface and overlies deposits of sand, silt, and clay (Figure 7). It develops in relatively stable environments where the vegetation is sparse, such as abandoned alluvial-fan surfaces in arid regions (Dohrenwend, 1987).

Early theories suggested that desert pavement developed as the wind removed smaller particles, such as sand and dust, from the spaces between rock fragments. Recent studies, however, suggest a more

Figure 6 (a and b). Petroglyphs near Picture Rocks Retreat in northwestern Tucson reflect ceremonial aspects of a prehistoric culture. Photos by Evelyn VandenDolder.



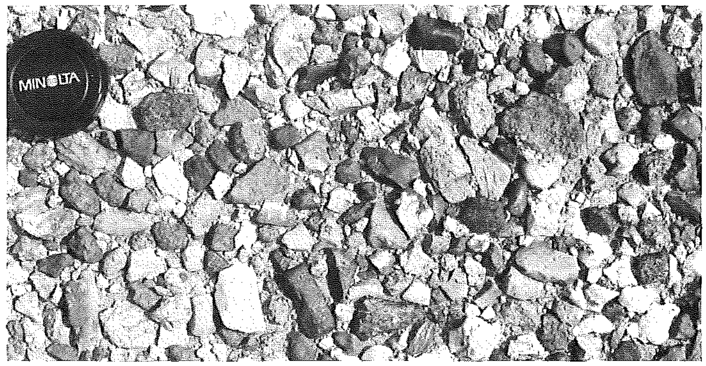


Figure 7 (a and b). Desert pavement on alluvial fan near the White Tank Mountains west of Phoenix. Note the mosaic of rock fragments and the paucity of fine-grained sediments. Photos by John Field.

complex series of processes. Repeated cycles of wetting and drying cause the soil to swell and shrink, respectively. When the soil swells, the larger rock fragments are lifted slightly; when the soil shrinks, it cracks, and finer grained material falls or is washed into the cracks. The rock fragments are gradually brought to the surface, and the finer grained material is gradually displaced downward. Desert pavements, therefore, are not formed because finer grained material is carried away by the wind; rather, they are produced by the accumulation of this fine-grained material and the lifting of larger rock fragments as this material expands and contracts in response to repeated cycles of wetting and drying (Dohrenwend, 1987).

Salts contained in desert soils cause the mechanical weathering (splitting) of rock fragments and the smoothing of desert pavements. Medium- to coarse-grained plutonic and metamorphic rocks are more susceptible to salt weathering, whereas many fine-grained sedimentary and volcanic rocks are relatively resistant. In areas that contain a variety of rocks, the composition of a desert pavement reflects the relative age of that pavement: Older pavements consist of fewer coarse-grained and more fine-grained rock fragments (Dohrenwend, 1987). Varnish is generally darker on finer grained rocks because these rocks are more stable.

Geologists studying the history of flooding in an area have used the extent of pavement development to help determine when the last flood occurred (Field and Pearthree, 1991; Pearthree, 1991). The physical characteristics of **alluvial surfaces** (areas covered by stream deposits) on piedmonts in the arid Southwest provide clues to their relative ages. The ages of these surfaces reflect the last time they were modified through deposition or abrasion by large streams. Older surfaces, i.e., those that have not been disturbed for thousands of years, are mantled by well-developed desert pavements. Geologic processes, such as floods and debris flows, may strip away desert pavements, leaving traces of their passage.

The rate of pavement development depends on the extent of development of the soil horizon closest to the land surface. (A **soil horizon** is a distinguishable layer of soil characterized by its structure, color, texture, content of organic matter, or degree of acidity or alkalinity. In the desert, the **A horizon**, the soil horizon closest to the land surface, is typically composed of silt, clay, sand, and organic matter.) The more the underlying soil horizon is developed, the faster is the development of the desert pavement. In areas where the desert pavement was artificially stripped but the underlying soil horizon was left intact, well-developed pavements re-formed in less than 25 years. On late Holocene (younger than 4,000-year-old) alluvial-fan surfaces, the uppermost soil horizons (and thus, the desert pavements) are commonly absent or very weakly developed. On older surfaces (middle Holocene to late Pleistocene), both horizons and pavements are progressively better developed (Dohrenwend, 1987).

Before desert pavement was studied by geologists, it was altered by early inhabitants of the Southwest to "draw" giant figures called **geoglyphs**. Geoglyphs were created by moving and stacking the black varnished rocks of the desert pavement to expose the lighter, underlying soil horizon. About 300 geoglyphs portraying humans, game animals, reptiles, and abstract designs (Figure 8) have been discovered in the deserts of the Southwest. Rock varnish on several geoglyphs along the Colorado River has been radiocarbon dated at about 1,000 years. These geoglyphs, therefore, are older than about A.D. 900 (Dorn and others, in press). Some archaeologists believe that the

Where to See Rock Varnish, Desert Pavement, Petroglyphs, and Geoglyphs

Rock varnish and desert pavement are especially well-developed in areas that have been relatively undisturbed, such as abandoned alluvial fans near mountain ranges. Varnish may also coat the rocks and pavement may mantle the desert surface along hiking trails.

Petroglyphs are etched in rocks throughout Arizona. Some of the most accessible sites are Painted Rocks State Park west of Gila Bend, Petrified Forest National Park east of Holbrook, Waterfall Canyon (Maricopa County Park) in the White Tank Mountains west of Phoenix, and Signal Hill in Saguaro National Monument west of Tucson. Archaeologists at the Pueblo Grande Museum and Cultural Park in Phoenix give tours to view petroglyphs in South Mountain Park. Call Tom Hulen at 1-602-495-0901 for more information. To learn about interpretive programs on petroglyphs at Saguaro National Monument--West, call 1-602-883-6366.

Numerous geoglyphs have been discovered along the Colorado River. The most accessible site is just north of Blythe, California. Drive about 10 miles north on U.S. Highway 95 just past the agricultural area. Watch for the turnoff and sign for the "Desert Intaglios."

Archaeologists and park officials request that all visitors treat these and other cultural sites with respect, leaving all petroglyphs, geoglyphs, and artifacts untouched.

geoglyphs were created by shamans as entreaties to the spirits to bring back the rivers, lakes, and wildlife that flourished during an earlier, wetter climate (Bassett, 1989). The early artists who created the 297-foot-long human figure 75 miles west of Phoenix were among the few to add petroglyphs (on the tips of its hands) to a geoglyph (Bassett, 1989).

Geoglyphs have also been discovered in other parts of the world, most notably on a high desert plain near Nazca, Peru. This 35-mile-long "canvas" attracts thousands of tourists each year. The geoglyphs include straight lines that range up to 5 miles in length, as well as animal figures and abstract designs that range from 12 to 900 feet in length (Hayes, 1991). Interpretations of these 1,000-year-old geoglyphs have ranged from the agricultural to the extraterrestrial. Current theory suggests that the geoglyphs are a giant calendar that is keyed to the movements of the sun, moon, and constellations. By following this calendar, early inhabitants knew when to plant and irrigate their crops (Hayes, 1991). An earlier, more colorful theory proposed that these designs were landing strips for flying saucers (von Däniken, 1970). This other-worldly theory adds a touch of science fiction to the study of rock varnish and desert pavement.

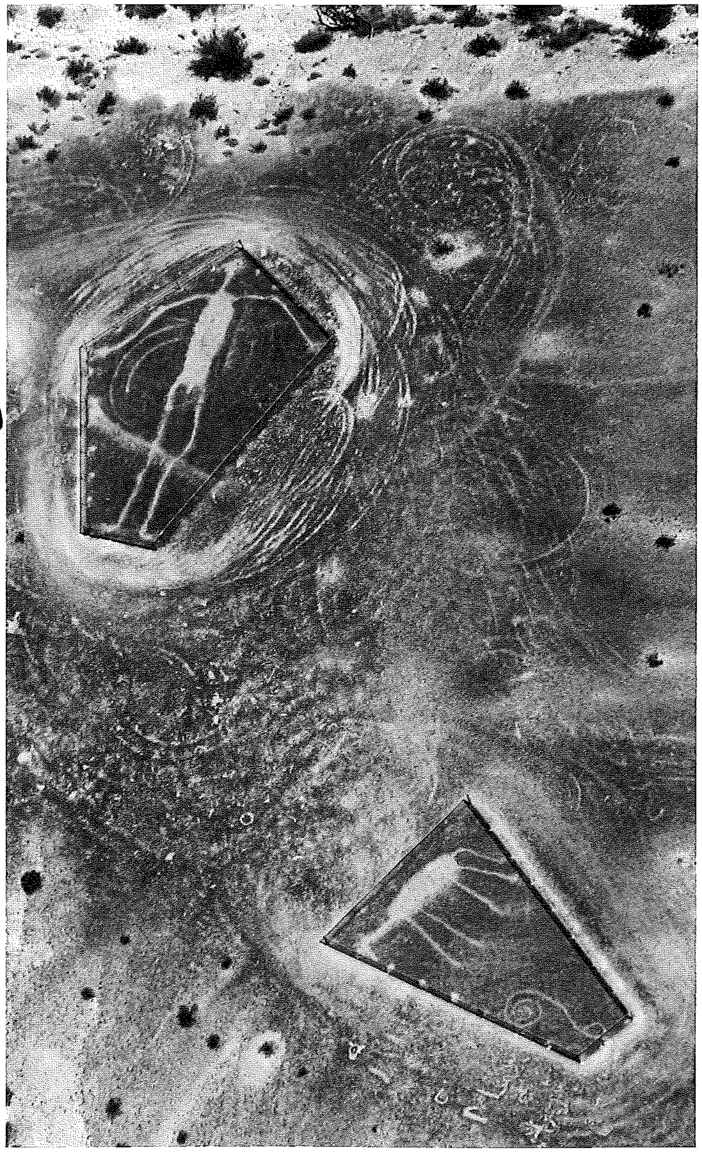


Figure 8. Aerial view of geoglyphs surrounded by protective fences near the Colorado River and Blythe, California. The varnish on rock samples from the animal figure has been radiocarbon dated at about 1,000 years, which indicates that the geoglyph was made before A.D. 900 (Dorn and others, in press). The curved lines near the geoglyphs were formed by off-road vehicles. These tire tracks, like the geoglyphs, will be visible for thousands of years. Photo by Harry Casey.

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Tertiary Extension in West-Central Arizona

by Jon E. Spencer
Arizona Geological Survey

Arizona contains some of the world's best known and most well-exposed areas of extreme crustal extension. Hundreds of mineral deposits containing gold, copper, manganese, and less abundant uranium, lead, zinc, and silver formed during extension and associated igneous activity. Studies of the geology of west-central Arizona over the past 10 years have greatly increased geologists' understanding of how large-magnitude extension occurs and how mineral deposits formed during extension. This article outlines the processes associated with crustal extension and briefly describes the middle Tertiary geology and tectonic history of west-central Arizona. It does not, however, discuss the origin of mineral deposits. (See Spencer and others [1988] and Spencer and Welty [1989] for information on mineral deposits related to crustal extension.)

CRUSTAL EXTENSION

Southern and western Arizona are within the Basin and Range physiographic province of North America. This area is characterized by largely isolated mountain ranges separated by Cenozoic basins. The Phoenix and Tucson metropolitan areas are almost entirely within such basins, flanked by mountain ranges of older resistant bedrock. The Basin and Range physiography of Arizona is mainly the result of geologic processes that greatly modified the Earth's surface from 30 to 10 million years ago. The primary geologic process was **crustal extension**. During extension, the Earth's crust is stretched horizontally and becomes thinner. In the traditional view of extension (e.g., Stewart, 1971), mountain ranges are bounded by faults that dip moderately to steeply beneath flanking basins. Fault movement causes uplift of the ranges, downdrop of the basins, and horizontal extension of the crust. These **normal faults** displace overlying rocks downward relative to underlying rocks. **High-angle normal faults**, which dip steeply (generally 40° to 70°), typically have displacements of a few hundred meters to several kilometers.

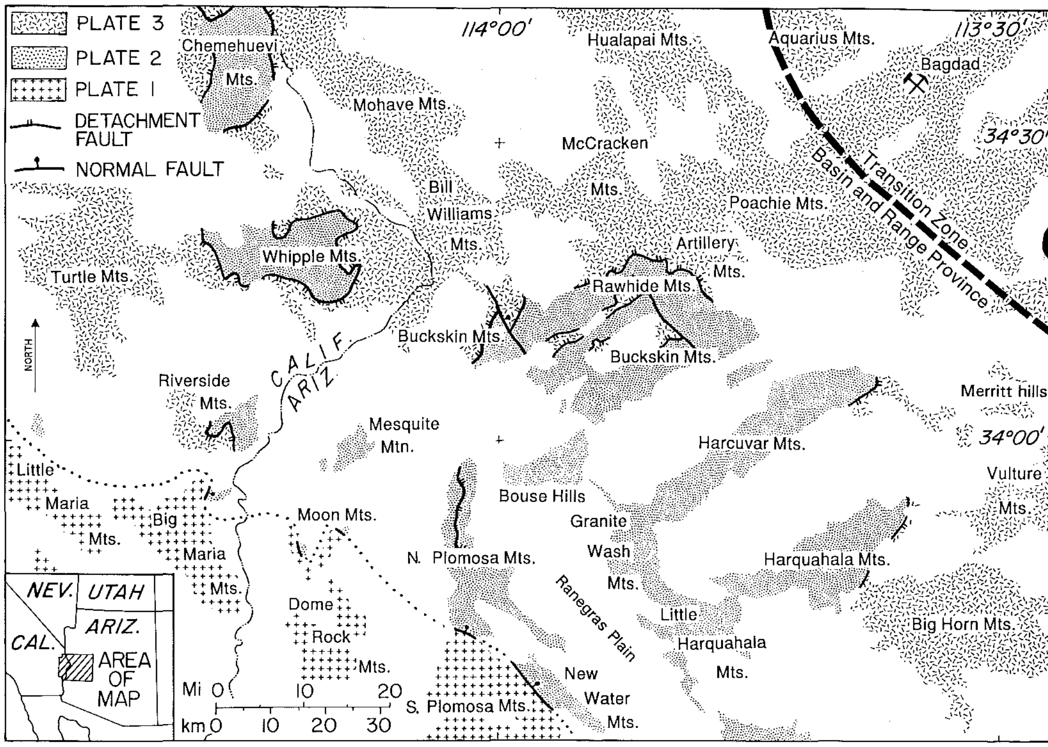


Figure 1. Mountain ranges and regional structural plates in west-central Arizona and southeastern California. Plate 1 consists of rocks that are structurally below the three large normal faults in the area. Plate 2 consists of rocks that are structurally above the lowest fault but below the highest and largest fault in the region (the Buckskin-Rawhide detachment fault). Rocks that are structurally above the three normal faults compose Plate 3 and extend northeastward to the Transition Zone and Colorado Plateau physiographic provinces (e.g., Peirce, 1984). Some correlations are speculative: Rocks shown as Plate 2 in California may actually be Plate 1 (Frost and Okaya, 1986).

In the 1970's, geologists began to recognize the importance of gently dipping (generally 0° to 40°) normal faults known as **low-angle normal faults** (e.g., Anderson, 1971). Total displacement on these faults may be as much as several tens of kilometers. Low-angle normal faults with large displacements are commonly known as **detachment faults**. Rocks exposed beneath detachment faults may be **plastically deformed** (deformed without fracturing) because they were deformed at high temperatures before being brought to the surface. Plastically deformed rocks, called **mylonites**, are exposed along the southern flank of the Santa Catalina Mountains and the western flank of the Rincon Mountains near Tucson (Davis, 1980; Spencer and Reynolds, 1989a; Dickinson, 1991) and in the eastern part of the South Mountains near Phoenix (Reynolds, 1985). Areas of detachment faults and associated mylonites are called **metamorphic core complexes**.

The upper crust (top 15 kilometers) of the Earth is generally brittle and, thus, is the area where most continental earthquakes originate. At greater depths, the temperatures are so high that rocks deform plastically and do not often build up the great stresses that cause earthquakes. If temperatures in the lower crust are high enough, such as during periods of **magmatism** (intrusion of great volumes of molten rock), the brittle upper crust floats on the easily deformed lower crust. Under such conditions, fault movement cannot significantly raise the mountain ranges because they will sink into the hot, plastically deformed lower crust, nor can it significantly deepen the basins because the lower crustal material will flow into and fill the areas beneath them. The concept of a strong upper layer floating on a deeper, fluidlike lower layer is known as **isostasy**; vertical movements in the upper crust that occur in response to buoyancy forces are known as **isostatic adjustments**.

Isostatic uplift can tilt a high-angle normal fault so that it dips at a low angle and warp a low-angle normal fault so that it has a subhorizontal undulating form. A specific type of fault, known

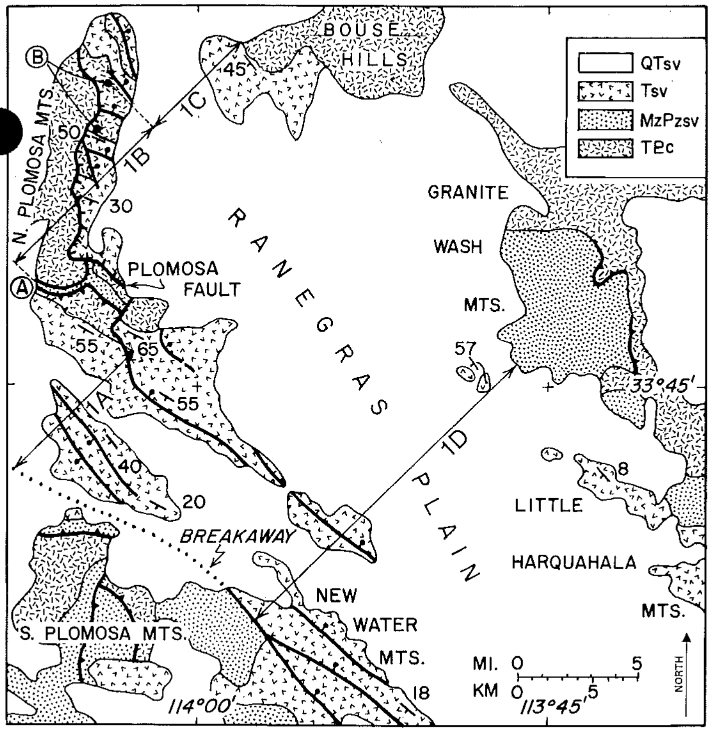


Figure 2. Simplified geologic map of the Ranegras Plain area showing locations of four transects for which magnitudes of extension have been estimated (Table 1). Abbreviations are as follows: QTsv, undeformed Quaternary and upper Tertiary sedimentary and volcanic deposits; Tsv, middle Tertiary sedimentary and volcanic rocks; MzPzsv, Mesozoic and Paleozoic sedimentary and volcanic rocks; and TPc, Tertiary to Proterozoic crystalline rocks.

as a **listric normal fault,** is a high-angle normal fault that flattens and becomes a low-angle normal fault at greater depths (e.g., Proffett, 1977). Consider a listric normal fault that undergoes several tens of kilometers of displacement. Rocks directly below the fault and initially many kilometers below the Earth's surface are uncovered by fault movement. If these rocks remained at this depth, they would be overlain by a very deep basin. Because of isostasy, however, they float up to the approximate prefaulting level of the Earth's surface.

WEST-CENTRAL ARIZONA

In west-central Arizona, three low-angle normal faults dip regionally to the northeast and separate shinglelike fault blocks. The easternmost and structurally highest fault, the Buckskin-Rawhide detachment fault, has by far the largest displacement. Two structurally lower faults with less displacement are exposed in the Plomosa and Moon Mountains. Some mountain ranges in west-central Arizona lie structurally below all three faults; some lie above all three faults; some lie above the lowest fault and below the highest fault (Figure 1). The structurally mid-positioned fault, the Plomosa fault, is exposed in the northern Plomosa Mountains. Its location beneath adjacent basins and its relationship to nearby mountain ranges are uncertain.

The structurally lowest of the three faults is exposed in the New Water and Plomosa Mountains. Rocks to the northeast of this fault (designated **breakaway** in Figure 2) are broken by normal faults and tilted to the southwest; they appear to have "broken away" from the less faulted rocks southwest of the breakaway fault. The steep tilt of some of the rocks above this fault indicates that the fault flattens with depth and is therefore listric. The Plomosa (middle) fault has been tilted by movement on the breakaway fault and is now gently dipping. It is thus a tilted high-angle fault or a tilted and warped, listric normal fault.

Total displacement, or extension, along three transect segments of the Plomosa fault is estimated at 23 ± 8 kilometers (Figure 2, transects 1A, 1B, and 1C; Table 1). Extension along a fourth transect across the Ranegras Plain (Figure 2, transect 1D) is approximately 25 kilometers (Table 1). Detailed analysis of each segment is beyond the scope of this article but is presented in another recent article (Spencer and Reynolds, 1991). An example of this analysis follows. At location "A" in the northern Plomosa Mountains (Figure 2), which is structurally below the Plomosa fault, Paleozoic and Mesozoic metasedimentary rocks form fault slices along a Mesozoic thrust fault. Similar rocks at location "B" above the Plomosa fault are thought to be the offset equivalents of the rocks at "A." Displacement along this part of the Plomosa fault is estimated at 13 ± 2 kilometers (Table 1, segment 1B).

Analysis of geologic relationships along three parallel transects that cross the Buckskin-Rawhide detachment fault and correlative detachment faults in the Harcuvar and Whipple Moun-

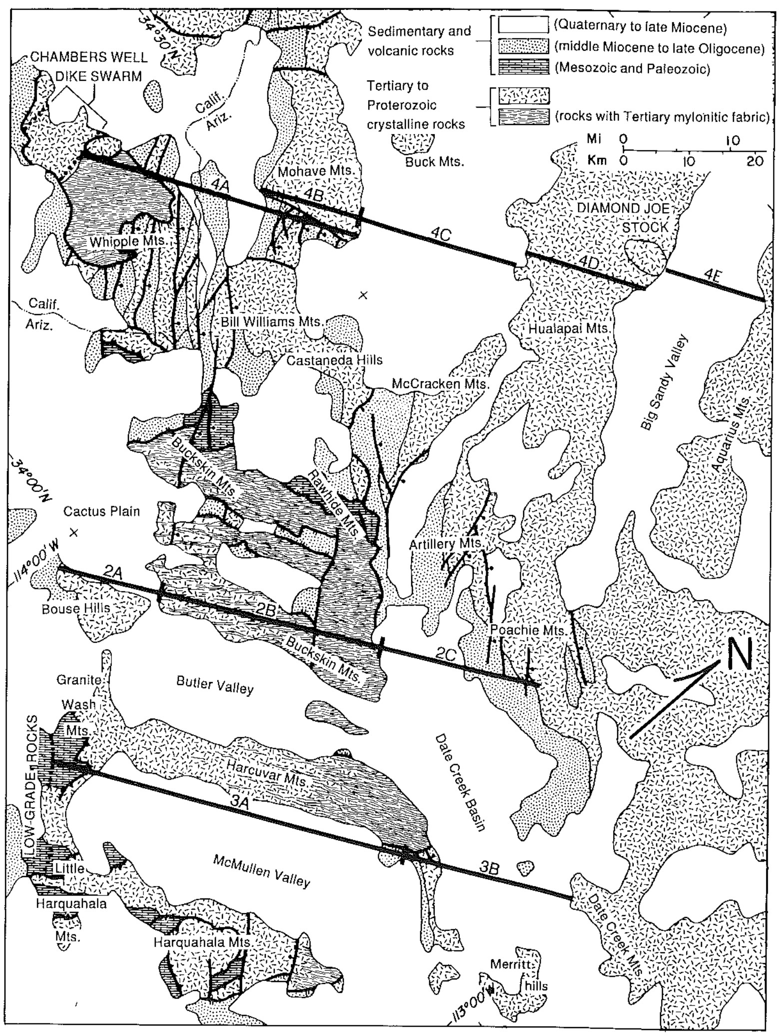
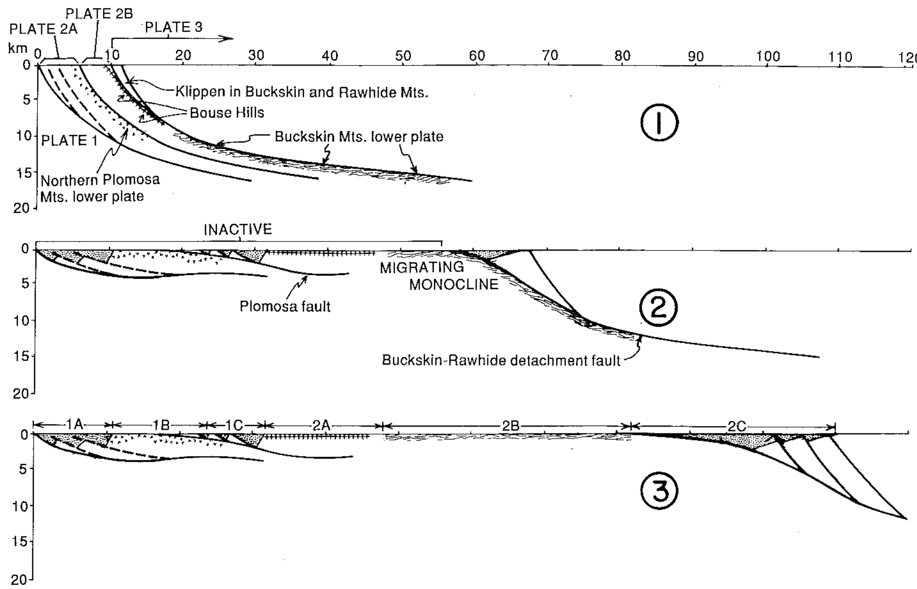


Figure 3. Simplified geologic map of west-central Arizona and southeastern California, showing locations of transects for which magnitudes of extension have been estimated (Table 1).

Figure 4. Cross-section evolution diagram along transects 1A, 1B, and 1C (Figure 2) and transects 2A, 2B, and 2C (Figure 3). ***Klippen*** *(cross-section 1) are erosional remnants of an originally sheetlike rock mass above a gently dipping fault.*



tains (Figure 3) shows that displacement along these faults was large. Along transect segments 2A and 2B, for example, the rocks below the Buckskin-Rawhide detachment fault have been almost completely uncovered by fault movement. Total fault displacement was at least as great as the width of the area of exposed rocks along the transect (Spencer and Reynolds, 1989b). Total displacement on the Buckskin-Rawhide detachment fault and correlative faults has been estimated at 66 $\pm$ 8 kilometers (Table 1; Spencer and Reynolds, 1991).

CONCLUSION

Based on geologic data, researchers (Spencer and Reynolds, 1991) have determined the approximate structure that the three major normal faults in west-central Arizona had when they formed and became active. The faults were initially listric (Figure 4, cross-section 1). The listric form of the underside of the fault block above the Buckskin-Rawhide detachment fault did not change much during fault movement (Figure 4, cross-sections 2 and 3). As they were uncovered, rocks below this fault must have warped to conform to the curved underside of the fault block above the detachment fault. Uplift and warping were caused by isostatic adjustment during uncovering. The flexibility of the rocks that form the fault block below the detachment fault, as revealed by recent analyses (Spencer, 1984; Wernicke and Axen, 1988; Spencer and Reynolds, 1991), is a newly discovered and rather astonishing aspect of this type of crustal extension. Earlier researchers (e.g., Stewart, 1971) believed that the rocks in the fault blocks remained rigid during extension. The more recent analyses have helped to explain how the processes of plastic deformation and isostatic uplift were associated with large-magnitude crustal extension in west-central Arizona.

Table 1. *Magnitudes of extension (in kilometers) along several transects in west-central Arizona (Figures 2 and 3).*

Transect	Segment	Segment Length (km)	Magnitude of Extension (km)
1 (Plomosa)	A (S. Plomosa Mts.)	11	6 $\pm$ 4
	B (Central Plomosa Mts.)	13	13 $\pm$ 2
	C (N. Plomosa Mts.)	8	4 $\pm$ 2
	TOTAL	32	23 $\pm$ 8
	D (Ranegras Plain)	25	< 25
2 (Buckskin)	A (Bouse Hills)	16	15 $\pm$ 1
	B (Buckskin Mts.)	34	33 $\pm$ 1
	C (Date Creek Basin)	24	18 $\pm$ 6
	TOTAL	74	66 $\pm$ 8
3 (Harcuvar)	A (Harcuvar Mts.)	55	55 $\pm$ 10
	B (Date Creek Basin)	25	12 $\pm$ 7
	TOTAL	80	67 $\pm$ 17
4 (Whipple)	A (Whipple Mts.)	45	45 $\pm$ 5
	B (Crossman Peak)	15	8 $\pm$ 3
	C (Sacramento Valley)	25	12 $\pm$ 8
	D (Hualapai Mts.)	22	0 $\pm$ 0
	E (Big Sandy Valley)	14	6 $\pm$ 3
	TOTAL	105 *	71 $\pm$ 19

* Represents distance between endpoints of transect.

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Resource Materials for Earth Science Teachers

Compiled by Emily Creigh DiSante, Arizona Geological Survey
with contributions from Julie Jackson, American Geological Institute

Earthquakes is a hands-on, introductory curriculum unit for grades 4-7 that helps students organize their thinking about the physical aspects and dynamic nature of the Earth. Developed by JoAnne Wolf, the 13 activities give students practice in making both direct and indirect observations, gathering and interpreting data, and forming their own hypotheses. The 37-page book may be ordered for $17.25 (includes shipping) from Science/Social Science Resource Center, Mesa Public Schools, 143 S. Alma School Rd., Mesa, AZ 85210-1103.

Earth Revealed: Introductory Geology is a new, 26-part television course and public television series that is suitable for advanced high-school earth-science classes. The course is divided into six topic areas: an introduction, plate tectonics, geologic time and life, the rock cycle, carving the landscape, and living with Earth. On February 6, the program began airing on KAET (Phoenix) on Thursday mornings at 2:30 and 3:00 a.m. (two consecutive, half-hour programs) and will run through April 30. For information on buying videocasettes or off-air, duplication, or statewide rights, write to Kimberly A. Smith, The Annenberg/CPB Projects, 901 E Street, NW, Washington, DC 20004; tel: 1-202-879-9657.

Science for Children: Resources for Teachers describes some of the best materials for hands-on, elementary science teaching that are available from publishers, distributors, and libraries. The 177-page guide lists activity books, curriculum materials, museums, and other sources of information. It was prepared by the National Science Resources Center, a joint effort of the National Academy of Sciences and the Smithsonian Institution, and is available from the National Academy Press, P.O. Box 285, Washington, DC 20055; tel: 1-800-624-6242. Single copies are $9.95; 2 to 9 copies are $8.50 each; 10 or more copies are $7.95 each.

Earth Science Education for the 21st Century: A Planning Guide provides a rationale and strategies for expanding earth-science education programs. Developed by the American Geological Institute (AGI) in conjunction with school administrators, teachers, curriculum planners, and scientists, the guide is intended to assist efforts to improve earth science teaching in grades K-12. It is divided into four sections that provide a framework for planning and implementing programs: goals for developing curricula; concepts essential to understanding the Earth and its interacting systems; recommendations for teaching earth-science subject matter; and recommendations for implementing new curricula in the schools. Written primarily for individuals with little or no background in earth science, the 34-page guide is available for $12.00 (includes shipping), with discounts for bulk orders, from the AGI Publications Center, P.O. Box 2010, Annapolis Junction, MD 20701; tel: 1-301-953-1744.

Earth Science Content Guidelines: Grades K-12 is a guide for incorporating earth science content into the precollege curriculum. Based on the goals, concepts, and recommendations outlined in *Earth Science Education for the 21st Century: A Planning Guide* (described above), this 76-page guide lists questions organized according to the interacting systems that characterize the Earth and its relationship to the Solar System. Each of the six content areas -- Solid Earth, Air, Water, Ice, Life, and Earth in Space -- divides the questions into grade levels K-3, 3-6, 6-9, and 9-12. Another section outlines ideas that students should understand while investigating the questions and includes suggestions for activities to help students acquire that understanding. The guide may be purchased for $19.00 (includes shipping), with discounts for bulk orders, from the AGI Publications Center (see above).

N.E.E.T. (News of Energy Education for Teachers) is a 12-page newsletter published three times a year for teachers of upper elementary to high school science. Covering issues of interest to Arizona, California, and Nevada, the newsletter features informative articles, local news, book reviews, announcements, proposal requests, and student worksheets that may be photocopied and used in the classroom. The free newsletter may be ordered from Robert C. Bird, Editor, N.E.E.T., Arizona Energy Office, Dept. of Commerce, 3800 N. Central, Suite 1200, Phoenix, AZ 85012; tel: 1-602-280-1430.

Free Materials for Schools and Libraries is a 16-page booklet that provides teachers and librarians with a regular list of free materials in science, social studies, computers, business, and other areas. It is published by Dyad Services five times a year; subscriptions are available at $17.00 per year prepaid ($20.00 if billed) from Free Materials for Schools and Libraries, Dept. 284, Box C34069, Seattle, WA 98124-1069; tel: 1-604-734-0255.

Teachers Clearinghouse for Science and Society Education newsletter is a 36-page, densely packed resource for science and social studies teachers of all grade levels. Sponsored by the Association of Teachers in Independent Schools, the newsletter contains articles about science education, editorials, announcements, updates on current events (such as recycling), reviews, activity pages, and more. In addition to the newsletter, the association publishes single-topic supplements and provides networking services for teachers. The free newsletter may be ordered from the Teachers Clearinghouse for Science and Society Education, 1 W. 88th St., New York, NY 10024.

The Catalyst Collection: Outstanding Earth/Space Science Activities is a collection of hands-on class projects developed by earth science teachers in southern California who participated in a 3-year, Earth/space-science enhancement program called "Project Catalyst," which was funded by the National Science Foundation. Most activities are aimed at middle to high school students, although some may be used with fourth graders. Chapters include Geology, Space Science, Oceanography, Meteorology, and Miscellaneous and contain activities that may be photocopied. For information on how to order the 390-page book, contact Dr. Gaylen R. Carlson, Dept. of Geological Sciences and Science Education, McCarthy Hall, Rm. 263, California State University, Fullerton, CA 92634; tel: 1-714-772-3942.

Earth Science Research Activities, by James Scannell, is one of four books in the series "Explorations in Science." The book contains 50 individual- and group-enrichment activities for grades 8-12. Each has been tested and includes a teacher's guide and answer key. The 273-page, spiral-bound book may be ordered for $38.50 (includes shipping) from Alpha Publishing Co., 1910 Hidden Point Rd., Annapolis, MD 21401; tel: 1-301-757-5404.

(continued on next page)

Resources for Earth Science Teachers 1991 lists 43 sources of earth-science reference and enrichment materials, including catalogs, publication lists, teacher packets, books, and journals. A copy may be obtained from the American Geological Institute, National Center for Earth Science Education, 4220 King St., Alexandria, VA 22302; tel: 1-703-379-2480.

Earthquakes: A Teacher's Package for K-6 was developed by the National Science Teachers Association (NSTA) with a grant from the Federal Emergency Management Agency (FEMA). This six-unit book contains a complete earthquake curriculum, with activities, lesson plans, line masters, and background information. FEMA is offering one free copy to schools while supplies last; contact FEMA, Earthquake Program, Attn: Marilyn MacCabe, 500 C St., SW, Washington, DC 20472. Additional copies may be ordered for $17.50 (includes shipping) from NSTA, 1742 Connecticut Ave., NW, Washington, DC 20009; tel: 1-202-328-5800.

Earth: The Water Planet, a book of readings and activities for middle-grade students and teachers, resulted from a joint project of Horizon Research, Inc., and the American Geological Institute. It is available for $19.00 (includes shipping) from NSTA (see above).

How to Construct a Paper Model Showing the Motion That Occurred on the San Andreas Fault During the Loma Prieta, California, Earthquake of October 17, 1989 (USGS Open-File Report 89-640A) is available for $1.50 paper copy, $4.50 microfiche, from the U.S. Geological Survey, Books and Open-File Reports Section, Box 25425, Denver, CO 80225; tel: 1-303-236-7476.

ADEQ Denies Cholla Landfill Permit

In December 1991, the Arizona Department of Environmental Quality (ADEQ) denied an Aquifer Protection Permit application to Browning-Ferris Industries (BFI) for the Cholla landfill in El Mirage near Phoenix. ADEQ denied the application because the proposed site was geologically inappropriate for a regional solid-waste landfill. The landfill would have been built near the Agua Fria River channel, which has flooded significantly in the past. The landfill would also have been directly over an aquifer that supplies drinking water to surrounding communities, and next to an area that is prone to land subsidence and earth fissures.

In 1990 the Arizona Legislature prohibited the location of landfills within 0.5 mile of a 100-year floodplain. Because of a grandfather clause, existing applications, including that of the Cholla landfill, were exempted from this prohibition. ADEQ's denial of BFI's application corrected "the unfortunate public policy created by the exemption," Governor Fife Symington said.

The 230-acre Cholla landfill site would have operated for 15 to 30 years and was expected to accept 2,000 to 4,000 tons of municipal solid waste per day from central and western Maricopa County and metropolitan Phoenix. ADEQ Director Edward Z. Fox said, "The risks of aquifer contamination posed by the geologic and hydrologic conditions of the proposed landfill site would require perpetual maintenance.... This site will always be here, but we can't guarantee that BFI will be." BFI announced that it would not appeal the ADEQ decision.

New AZGS Employee

Dr. Stephen M. Richard has joined the staff of the Arizona Geological Survey (AZGS) as a Research Geologist. Steve holds B.S. degrees in electrical engineering and earth and planetary science and M.S. and Ph.D. degrees in geology. He has extensive geologic-mapping experience in Arizona, California, Colorado, Montana, and Antarctica. He has worked for several mineral exploration companies and most recently for the Institute for Crustal Studies at the University of California in Santa Barbara. Steve is the author or coauthor of more than 25 publications. His research at the AZGS will focus on the bedrock geology and mineral deposits of Arizona.

Geologic Mapping Bill Still in Senate

As of March 1, 1992, the full Senate had not voted on S. 1179, the Geologic Mapping Act of 1991. (See *Arizona Geology*, v. 21, no. 4, p. 7-8 for description of bill.)

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