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THE HORSESHOE FAULT

Evidence for Prehistoric Surface-Rupturing Earthquakes in Central Arizona

by Lucille A. Piety and Larry W. Anderson
Seismotectonics and Geophysics Section, U.S. Bureau of Reclamation,
Federal Center, Denver, CO 80225

Have earthquakes strong enough to rupture the ground surface occurred on faults in central Arizona during the recent geologic past? Could such earthquakes happen in the future? If so, where are they most likely to occur?

The Seismotectonics and Geophysics Section of the U.S. Bureau of Reclamation has, during the last 6 years, been working on answering these questions (Anderson and others, 1986, 1987; Anderson, 1990; Piety and Anderson, 1990). The Bureau of Reclamation is interested in earthquakes because it is responsible for the safety of eight major dams in central Arizona, including Horseshoe Dam on the Verde River (Figure 1). All but one of these dams were built between 1908 and 1946, long before anyone realized that strong earthquakes could occur in this region. The possibility of such earthquakes was not readily recognized, partly because earthquakes large enough to rupture the ground surface have not been observed historically within Arizona (DuBois and others, 1982; Stover and others, 1986).

Recognition of the potential for strong earthquakes in Arizona arose in the middle 1970's, when geologists began to search the State for evidence of prehistoric surface-rupturing events (Soule, 1978; Morrison and others, 1981; Menges and Pearthree, 1983; Pearthree and others, 1983; Pearthree and Scarborough, 1984). Interestingly, these studies revealed that such evidence is common in Arizona. The evidence chiefly consists of scarps, or abrupt breaks, on gently and evenly sloping surfaces of alluvial deposits. Because these scarps are associated with known faults and are similar in appearance, size, and length to scarps formed during historical earthquakes throughout the world, geologists infer that the scarps in Arizona formed during earthquakes that were strong enough to rupture the ground surface. Such earthquakes in the western United States are typically larger than about magnitude 6, which is large enough to cause significant damage to nearby, inadequately designed or poorly constructed structures. Because scarps

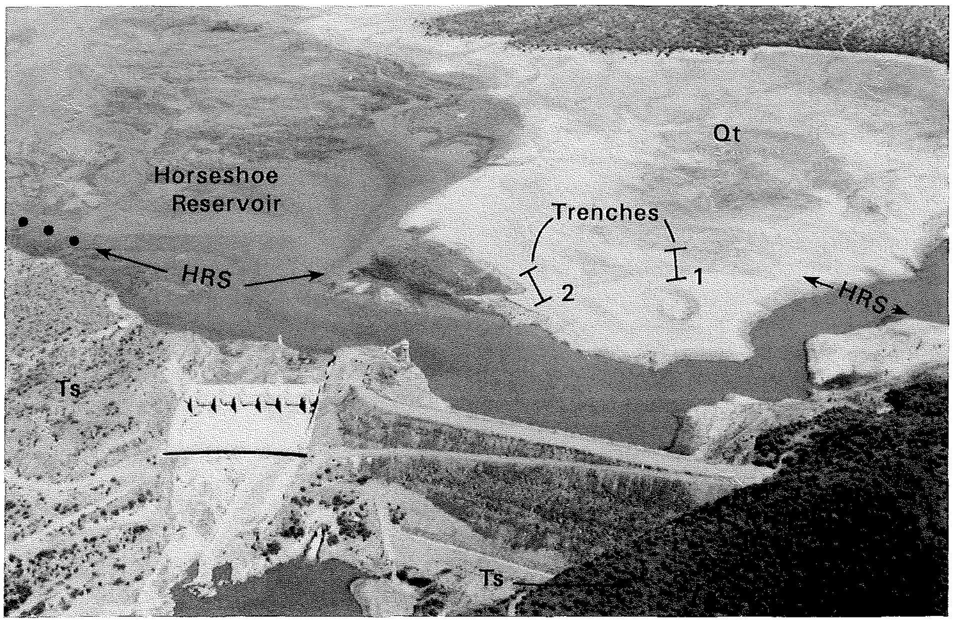

Figure 1. Aerial view of Horseshoe Dam (foreground). This view toward the north-northwest shows the curving north-facing scarp on the terrace surface (Qt) along the Horseshoe Reservoir segment (HRS) of the Horseshoe fault, a segment that was only recently identified. The approximate locations of two trenches excavated across this scarp are shown. (See section titled "Horseshoe Reservoir Segment.") Ts indicates tuffaceous sedimentary and volcanic rocks of late Tertiary age (Figure 3).

are eventually eroded from the landscape, those that formed during the last several hundred thousand years are easiest to recognize. Furthermore, scarps that indicate multiple ground-rupturing earthquakes along a fault during the last few hundred thousand years may be the most likely sites of future ground-rupturing earthquakes and, thus, are of greatest interest to those who assess the potential hazard to manmade structures.

Most faults in Arizona that display evidence of activity during the last 2 million years (m.y.; the Quaternary Period) lie within a diffuse band that trends diagonally across the State from the northwest to the southeast (Pearthree and others, 1983) and extends beyond its borders (e.g., the numerous faults in southwestern Utah and southern Nevada [Wallace, 1981] and the Pitaycachi fault in northern Sonora, Mexico [Pearthree, 1986; Pearthree and others, 1990]). This band of faults roughly coincides with a northwest-trending, poorly defined concentration of historical seismicity (Sumner, 1976; Pearthree and others, 1983) and the Transition Zone physiographic province (Peirce, 1984, 1985; Figure 2). The Horseshoe fault, which we investigated as part of a seismotectonic study of Horseshoe and Bartlett

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The Osgood File, CBS News Radio

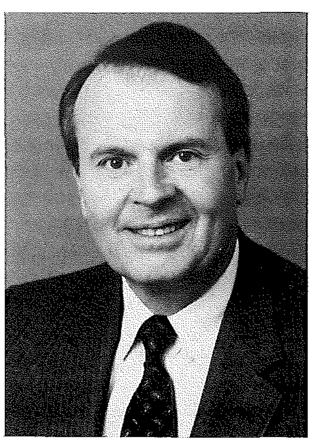
The Once and Future Past

In June 1991, Mount Pinatubo in the Philippines and Mount Unzen in Japan, two volcanoes that had been dormant for centuries, erupted. The multiple blasts of volcanic ash and subsequent mud flows caused by heavy rains killed more than 200 persons, left another 200,000 homeless, caused more than $400 million in damage, and instilled fear in nearby residents because of the apparent unpredictability of these geologic events. In a special segment broadcast on June 13, Charles Osgood of CBS News read the following essay, reprinted below with the network's permission. -- Editor

Figure 1. San Francisco Mountain, as viewed toward the southeast. Photo by Ken Matesich.

We know where the wars are likely to break out. The pressures and tensions build up over time in certain places, and suddenly there's a conflict. We know where the hurricanes, typhoons, cyclones, and tornadoes are likely to blow. The same places are hit again and again over the years. And we know where the Earth's faults are, where earthquakes have struck in the past and will again. Yet we seem not to learn. The latest examples are the volcanoes erupting in the Philippines and in Japan. We know what volcanoes do, but we're lulled into complacency by the fact that so much time passes between eruptions. It's difficult for us, whose lives are so short, to worry about something that only happens every few centuries or so.

One reason the news keeps surprising us so much is our own frame of reference. Even though we know the world is changing all the time, we take the present status quo for granted and act as if we expected it to go on indefinitely. We know that wars break out and that volcanoes erupt. We even know where they're likely to happen. We know where the stresses are, where the pressures build up. But because there hasn't been an eruption in a given place for awhile, we get to thinking, or at least to pretending, that it isn't going to happen. The place where Clark Air Base now stands was buried under lava the last time Mount Pinatubo erupted, but that was 600 years ago. You can't blame us for thinking that if something hasn't happened for 600 years, we don't have to worry about it anymore. Mount Unzen, the Japanese volcano that's now come to life, has killed 38 people already, mostly journalists and scientists who perhaps should have known better than to come so close. But there hadn't been an eruption since 1792. That one, by the way, set off a huge tsunami that killed 15,000 people. We go on taking our chances, building our cities, planning our futures, as if only the things that have happened lately were what we have to worry about. We want to think that peace is permanent, that markets won't crash, that the Earth itself won't play some terrible trick



Charles Osgood is the writer and anchor of four daily CBS News broadcasts on the CBS Radio Network that feature humorous pieces and news commentary titled "The Osgood File." On the CBS Television Network, Osgood coanchors the "CBS Morning News" and provides commentary for "CBS This Morning" three times a week; a television version of "The Osgood File" is featured during each Monday broadcast. Osgood also writes a nationally syndicated, twice-weekly newspaper column.

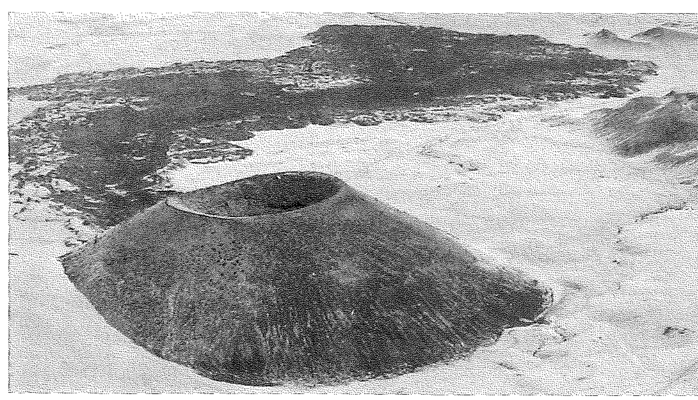


Figure 2. Aerial photograph of S P Crater and basalt flow. Photo by Dale Nations.

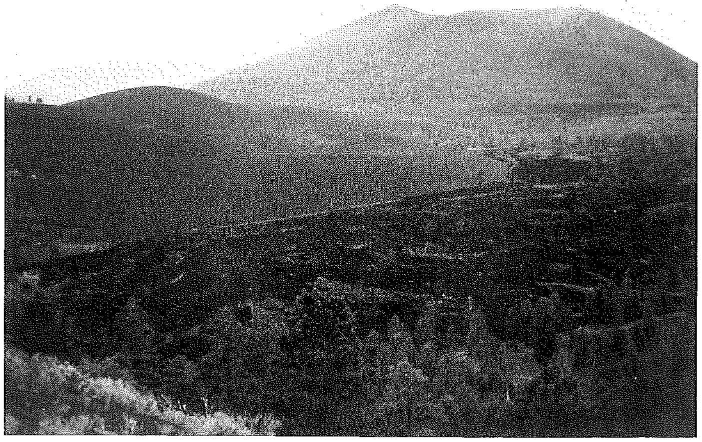


Figure 3. Sunset Crater, with associated basalt flow in foreground. Photo by Larry D. Fellows.

on us. The lesson of history is that, for better or for worse, just because something hasn't happened in a long time, doesn't mean it isn't going to happen now.

Although he used the Unzen and Pinatubo eruptions as examples, Charles Osgood's comments also apply to geologic events that have occurred and could recur within the borders of Arizona.

Volcanoes have erupted intermittently in the State since the Precambrian, 1.8 billion years ago. A more recent eruption occurred about 70 million years ago, when the Tucson Mountains were a volcano. This eruption exploded with 100 to 1,000 times the force of the Mount St. Helens' eruption in 1980. San Francisco Mountain (Figure 1), a composite volcano that is also Arizona's highest summit, was formed within the last 3 million years. The eruption that formed SP Crater (Figure 2), a cinder cone north of Flagstaff, occurred about 70,000 years ago. As recently as A.D. 1065, Sunset Crater (Figures 3 and 4) exploded, lighting up the night with glowing lava and darkening the day with airborne volcanic ash; eruptions continued for about 100 years. Basalt, tuff, and other volcanic rocks give testimony to the lava and ash flows that have blanketed the State throughout geologic time (Figure 5).

From 1980 to mid-August 1991, 33 earthquakes of magnitude 3.0 or greater occurred in Arizona. Although no large earthquakes (of magnitudes greater than 6.0) have occurred within the State during historic times, several large earthquakes in surrounding areas have affected Arizona residents. The 1887 earthquake that was centered in Sonora, Mexico had an estimated magnitude of 7.2 and damaged buildings as far away as Phoenix. The 1940 earthquake in Imperial Valley, California measured about 7.1 on the Richter scale. It caused at least $5 million in property damage in the United States, $50,000 of which was in Yuma County. Fault movement continues to generate earthquakes in Arizona and is a potential geologic hazard. (See article on page 1, this issue.)

"Just because something hasn't happened in a long time, doesn't mean it isn't going to happen now." The words of Charles Osgood are a reminder that even a deceptively quiescent area like Arizona could rumble one day, heralding the onset of yet another geologic, and possibly catastrophic, event. -- Editor

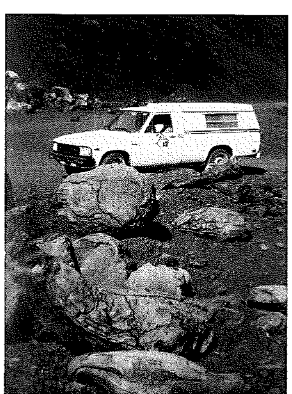
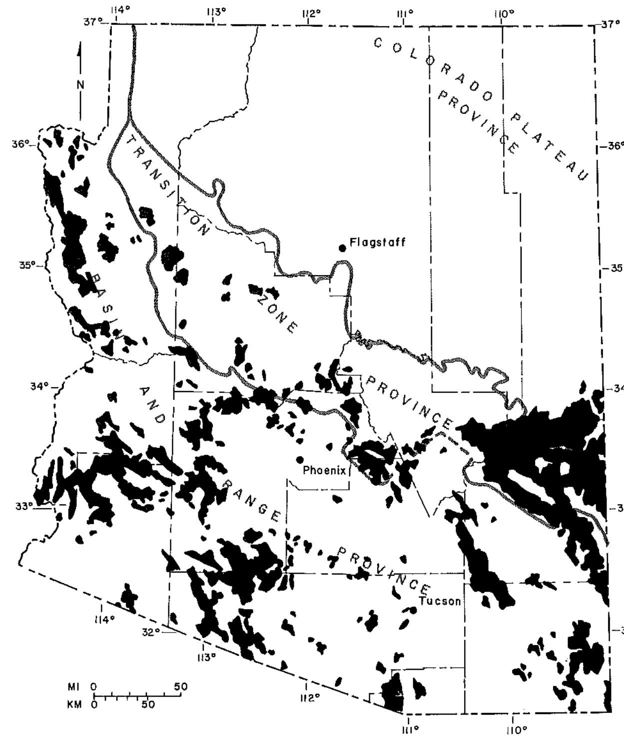
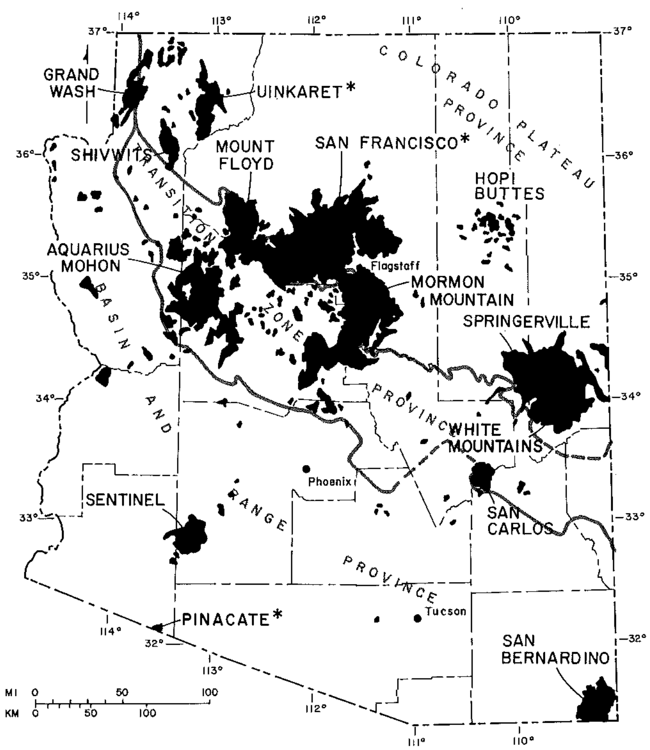


Figure 4 (left). Volcanic bombs solidified from airborne lava erupted from Sunset Crater. The hill of cinders (background) is being mined for cinder blocks, aggregate, and other uses. Photo by Larry D. Fellows.



DISTRIBUTION OF MID-TERTIARY (40-15 m.y.) VOLCANIC ROCKS



DISTRIBUTION OF UPPER CENOZOIC (15-0 m.y.) VOLCANIC ROCKS AND VOLCANIC FIELDS

***Figure 5 (a and b).** Distribution of volcanic rocks formed during the last 40 million years (m.y.). Young volcanic fields, or areas of volcanic rocks that were deposited at about the same time, are identified in the second map. Although these maps show that recent volcanism was widespread in Arizona, only the volcanic fields that have erupted within the past few thousand years (marked with asterisks in second map) are considered dormant and potentially hazardous. Both maps are from Reynolds, S.J., Welty, J.W., and Spencer, J.E., 1986, Volcanic history of Arizona: Fieldnotes [now called Arizona Geology], v. 16, no. 2, p. 1-5. See also Lynch, D.J., 1982, Volcanic processes in Arizona: Fieldnotes, v. 12, no. 3, p. 1-9.*

(continued from page 1)

Dams, lies within both the Transition Zone and the northwest-trending band of Quaternary faults (Figure 2).

HORSESHOE FAULT

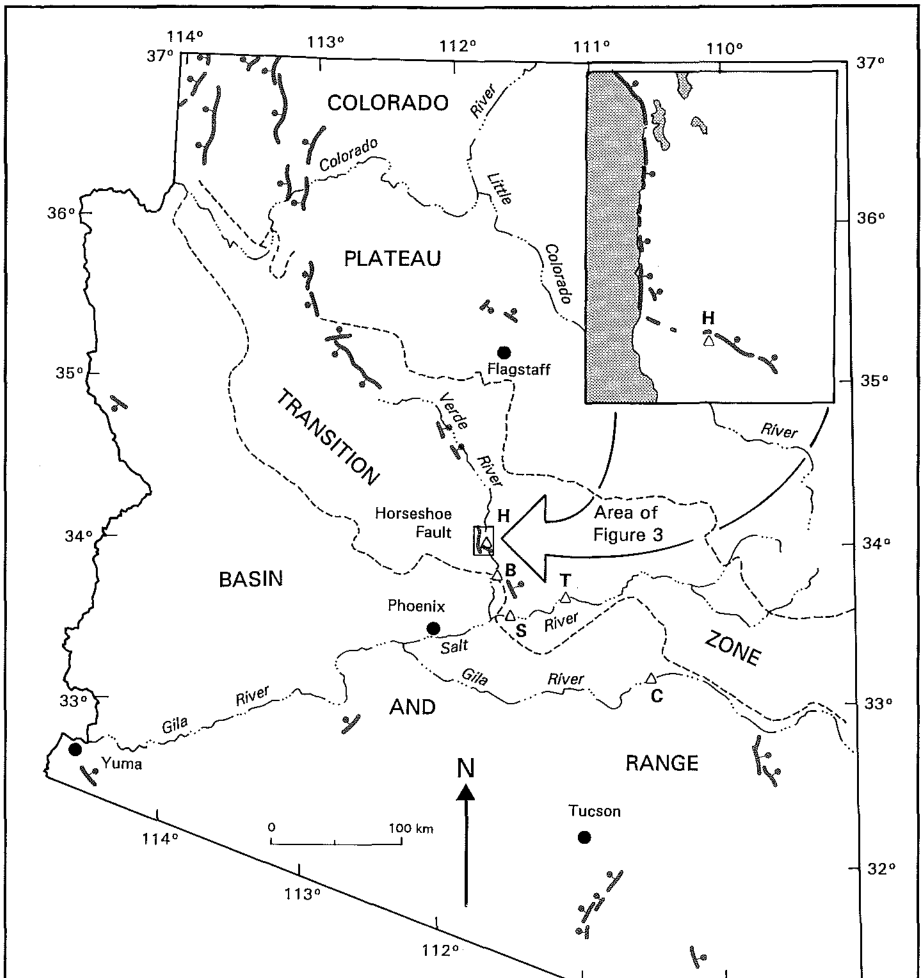
The Horseshoe fault is a north-trending normal fault that has characteristics similar to those of other faults within the Transition Zone that show evidence of Quaternary activity. Although our study focused on the Quaternary displacement along the Horseshoe fault, evidence for older displacement is also preserved. The basin east of and adjacent to the Horseshoe fault, which we informally call the Horseshoe basin, is filled with Tertiary sediments and volcanic rocks that consist of at least two distinct units: an older one containing abundant volcanic rocks (basalt, volcanic breccia, and tuffaceous sediment) and a younger, finer grained unit containing markedly fewer volcanic rocks (predominantly mudstone with some conglomerate and sandstone). The older unit dips steeply and contains numerous faults. An isotopic age on a basalt suggests that the older unit was deposited about 15 m.y. ago (Scarborough and Wilt, 1979). In contrast, the younger unit displays only minor deformation and may have been deposited between 10 m.y. and 5 m.y. ago (Scarborough and Wilt, 1979).

The lithologic characteristics and ages of these two units suggest that the timing of the main phase of activity along the Horseshoe fault may be similar to that along other basin-bounding faults in Arizona. This activity began between about 15 m.y. and 10 m.y. ago and may have diminished or ceased between about 8 m.y. and 6 m.y. ago (Scarborough and Peirce, 1978; Shafiqullah and others, 1980; Menges and McFadden, 1981; Menges and Pearthree, 1989). This period of late Tertiary activity, called the Basin and Range disturbance, affected many of the normal faults in the Transition Zone and adjacent Basin and Range Province in Arizona. This disturbance is thought to be primarily responsible for the alternating ranges and basins that now characterize large portions of these two physiographic provinces.

The Horseshoe fault is one of several faults in the central Transition Zone that were active during the late Tertiary and that either have been reactivated during the Quaternary or have continued to be active at lower rates (Pearthree and others, 1983). Compared to other possibly reactivated faults in the area (e.g., the Big Chino, Verde, and Sugarloaf faults; Figure 2), the Horseshoe fault is unusual because it is composed of two nearly perpendicular strands, only one of which is along a range front (Figures 2 and 3). One strand, which we informally call the Hell Canyon segment, trends almost due north, separating an unnamed mountain range to the west from Horseshoe basin. The other strand, which we informally call the Horseshoe Reservoir segment, trends west-northwest, slicing obliquely across Horseshoe basin. Both strands of the Horseshoe fault exhibit evidence for surface ruptures during about the last 300,000 years.

Hell Canyon Segment

The Hell Canyon segment separates Precambrian granitic rocks that form the unnamed mountain range west of the fault from the Tertiary sedimentary and volcanic rocks that fill Horseshoe basin (Figures 3 and 4). This fault segment, which is 11 to 12 kilometers long and dips eastward beneath the basin, was recognized by earlier workers (Ertec, 1981; Morrison and others, 1981; Menges and Pearthree, 1983; Pearthree and



EXPLANATION

Probable late Quaternary faults (displacement occurred during the last 150,000 years); bar and ball on downthrown side.

Approximate boundaries of the three physiographic provinces of Arizona.

Drainages.

Granitic rocks (Early Proterozoic; 1,650 m.y. to 1,750 m.y. old).

△ Dams for which U.S. Bureau of Reclamation seismotectonic reports have been completed:
B-Bartlett Dam (Piety and Anderson, 1990).
C-Coolidge Dam (Anderson, 1990).
H-Horseshoe Dam (Piety and Anderson, 1990).
S-Stewart Mountain Dam (Anderson and others, 1986).
T-Theodore Roosevelt Dam (Anderson and others, 1987).

Figure 2. Probable late Quaternary (active during the last 150,000 years) faults and their relationship to the three major physiographic provinces in Arizona. The faults have been modified from Menges and Pearthree (1983) and Scarborough and others (1986); the boundaries of the physiographic provinces are from Peirce (1984).

Scarborough, 1984). Its location is easily identified by lineaments created by differences in vegetation and by the abrupt contact between the Precambrian and Tertiary rocks (Figure 5). These features, however, are not necessarily indicative of Quaternary surface rupture along the fault.

Quaternary surface rupture is manifested by scarps on the relatively smooth surfaces of alluvial fans estimated to be of Pleistocene age (between 2 m.y. and 10,000 years old). These alluvial fans are composed of boulders, cobbles, and sand eroded from the adjacent range. Their surfaces slope 1° to 13° toward the Verde River away from the range front, except where the scarps abruptly steepen the slopes to 10° to 27°. The scarps, which are preserved discontinuously along some 9 kilometers of the Hell Canyon segment, displace the alluvial-fan surfaces from 2 to 5 meters (Figures 3 and 6). The scarps' alignment with the faulted contact between the Precambrian and Tertiary rocks and their roughly perpendicular orientation to drainages that issue from the range strongly indicate that the scarps were formed by surface-rupturing earthquakes along the fault rather than by erosion along the drainages that flow into the Verde River.

The scarps demonstrate that the Hell Canyon segment has experienced at least one, and possibly as many as three, strong earthquakes since the alluvial fans were deposited. Unfortunately, the ages of these alluvial fans could not be determined with any precision. Characteristics of the scarps themselves, however, suggest that at least one, and probably two, surface ruptures occurred during the late Quaternary (within about the last 150,000 years). The scarps are straight, relatively steep (maximum slope angles between 10° and 27°, with scarp heights of 2 to 7.5 meters), and not markedly dissected or modified by stream erosion. In other areas of the western United States, where scarps have been dated through the use of radiocarbon techniques or by the identification of volcanic ash layers, scarps with the above characteristics are thought to have formed during the last 30,000 to 15,000 years (Wallace, 1977; Bucknam and Anderson, 1979). Because scarp characteristics are influenced by many factors besides age, direct comparison of these characteristics among areas with different climates, rock types, or erosion rates is questionable. The straightness, steepness, and location of the scarps near the base of the range front, however, suggest that only limited erosion has occurred along this fault segment since the most recent surface-rupturing earthquake. From these characteristics, we infer that at least one, and probably two, surface ruptures took place on the Hell Canyon segment during the late Quaternary; the most recent rupture may have occurred during the last 30,000 to 15,000 years.

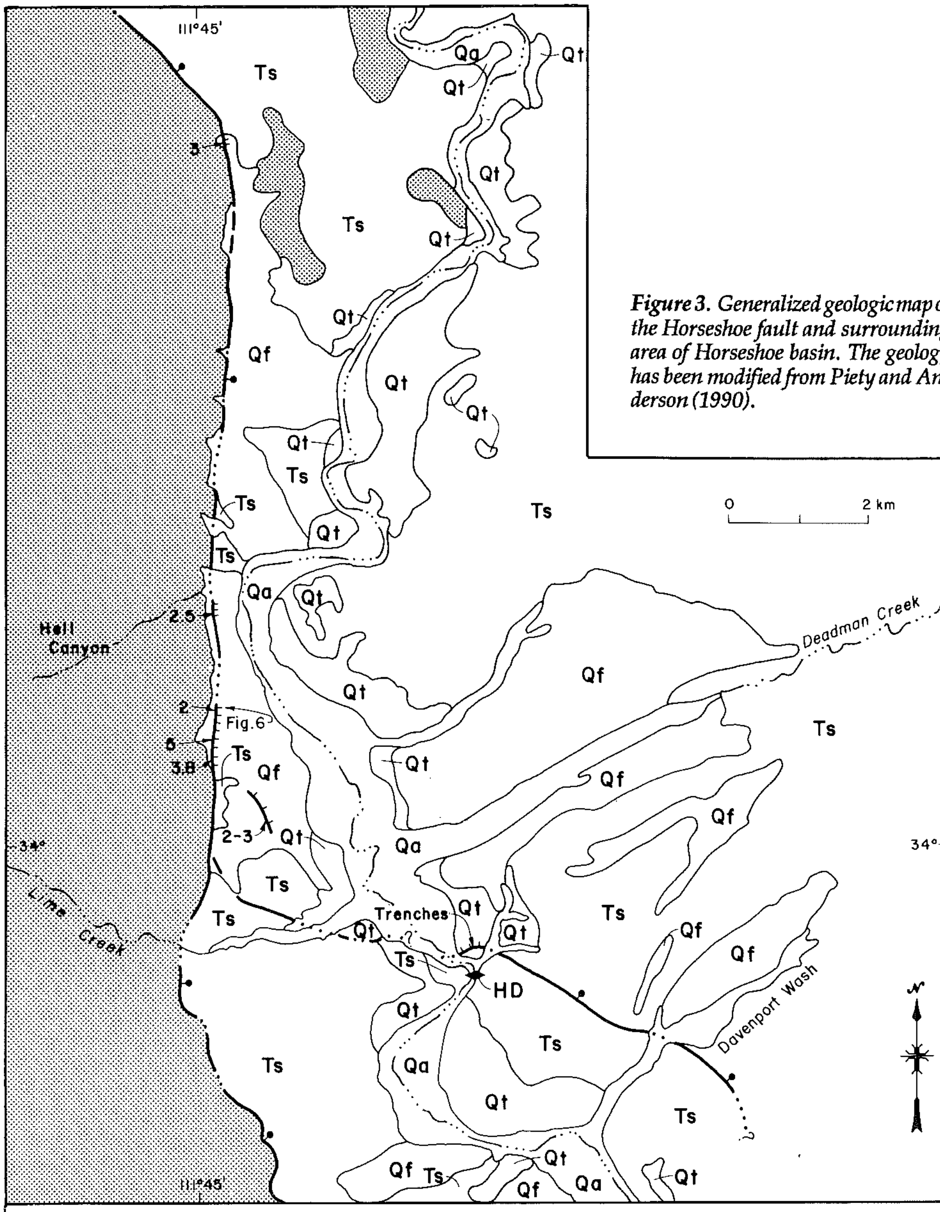


Figure 3. Generalized geologic map of the Horseshoe fault and surrounding area of Horseshoe basin. The geology has been modified from Piety and Anderson (1990).

Qa -- Floodplain deposits (Holocene)

Qf -- Alluvial-fan deposits (Pleistocene)

Qt -- Terrace deposits along the Verde River (Pleistocene and Pliocene?)

Ts -- Tuffaceous sediment, volcanic rock (chiefly basalt), volcanic breccia, conglomerate, sandstone, and mudstone (Pliocene? and Miocene)

Granitic rocks (Early Proterozoic, 1,650 m.y. to 1,750 m.y. old)

Horseshoe fault -- Solid where well located or approximately located, dotted where concealed; bar and ball on downthrown side. Hachures indicate scarps on Pleistocene alluvial fans. Numbers indicate vertical surface displacement (in meters) estimated from topographic profiles.

Drainages

HD -- Horseshoe Dam (Horseshoe Reservoir not shown)

Horseshoe Reservoir Segment

The Horseshoe Reservoir segment, which trends west-northwest across Horseshoe basin, separates south-southwest-dipping Tertiary basalt, basaltic breccia, and tuffaceous sandstone on the south from nearly horizontal Tertiary mudstone on the north. This segment, which is 9 to 10 kilometers long and dips northward (Figure 3), was not identified by previous workers, probably because much of this segment is usually concealed by Horseshoe Reservoir. The fault is marked by a lineament along the strike of a basaltic bed that is more resistant to erosion than the weakly cemented mudstone adjacent to it, and by a steeply dipping fault contact between volcanic breccia and

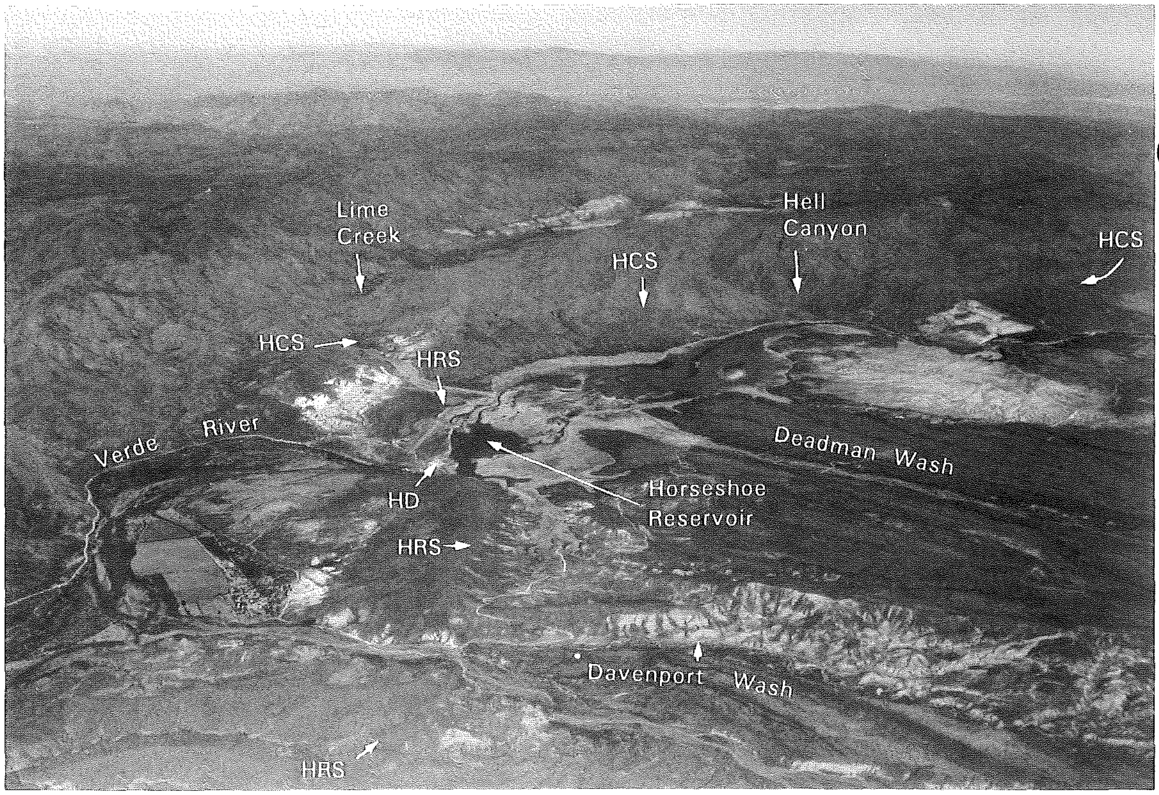


Figure 4. Aerial view toward the northwest of the two segments of the Horseshoe fault. The Hell Canyon segment (HCS) trends along the range in the middle ground. The Horseshoe Reservoir segment (HRS) trends away from the viewer toward the Hell Canyon segment. Horseshoe Dam (HD) is partially concealed in the middle ground.

mudstone exposed in Davenport Wash (Figure 3).

In contrast to the discontinuous scarps preserved along some 9 kilometers of the Hell Canyon segment, evidence for Quaternary surface rupture on the Horseshoe Reservoir segment is readily apparent at only one locality: on a terrace of the Verde River just north of Horseshoe Dam (Figure 3). A curving, north-facing scarp is preserved on this terrace surface, but is visible only when water levels in Horseshoe Reservoir are low (Figure 1). The displacement history of this segment was determined by excavating two trenches across this scarp (Figures 1 and 3). Detailed mapping of the fault and descriptions of the deposits exposed in the trenches clearly show that surface-rupturing earthquakes accompanied by about 1 meter of displacement occurred at least twice on the Horseshoe Reservoir segment since deposition of the Verde River terrace gravel. Evidence for surface rupture is indicated by a step in the surface of the fluvial gravel and by alignment of gravel clasts, which were rotated to a near-vertical orientation as the gravel deposits on adjacent sides of the fault slid past each other (Figure 7). After this step or scarp formed on the terrace surface, exposed gravel clasts fell from the scarp and accumulated at its base. Sand deposited by water flowing along the base of the scarp or by wind blowing down the Verde River Valley filled in and eventually covered the scarp. The gravel that accumulated at the base of the scarp and some of the sand that was deposited against the scarp have also been disrupted by fault displacement, indicating at least one additional surface rupture.

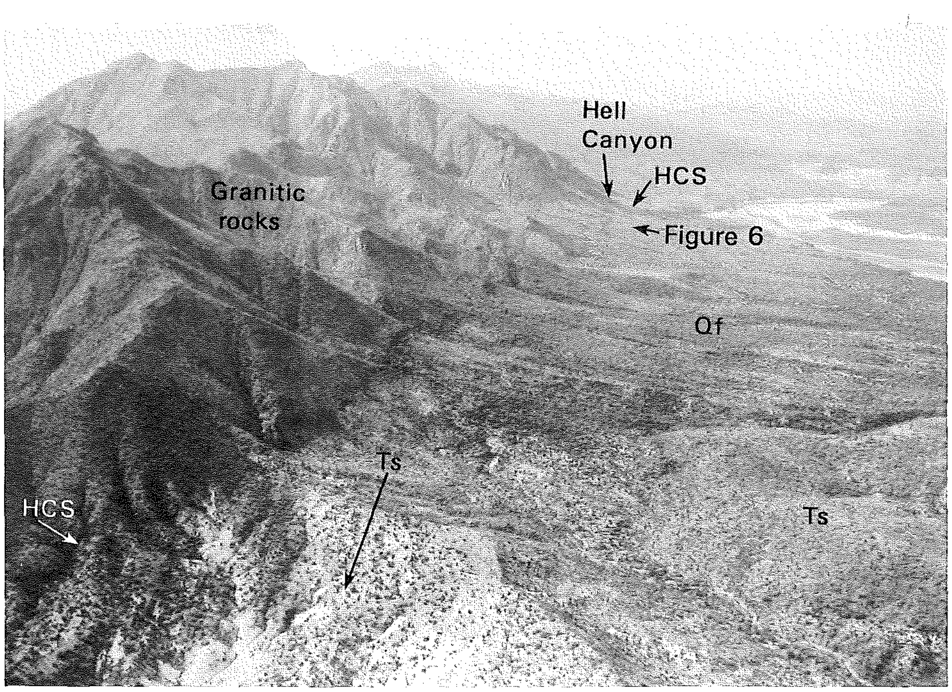


Figure 5. Aerial view toward the north-northwest along the Hell Canyon segment (HCS) of the Horseshoe fault. Lime Creek is just out of view in the foreground, and Hell Canyon is in the background. Tuffaceous sedimentary and volcanic rocks of late Tertiary age (Ts) and alluvial-fan deposits of Quaternary age (Qf) are juxtaposed against granitic rocks in the range (Figure 3).

Soils developed on the deposits exposed in the trench were used to estimate the time between surface ruptures and the time since the last rupture (for a description of methods, see Birkeland, 1984). Because of the height (18 meters) of the terrace surface above the present floodplain of the Verde River and the strong soil development on the fluvial gravel, we infer that the gravel was deposited at most about 300,000 years ago. Thus, the two or more surface ruptures exposed in the trench must be younger than this. The moderate to strong soil development during the interval between two of the surface ruptures indicates that about 50,000 to 100,000 years separated the two events. Furthermore, the relatively weak soil developed on the sand that overlies all deposits displaced by the fault suggests that the youngest rupture occurred before 10,000 to 20,000 years ago. Our best estimate for the timing of these surface ruptures on the Horseshoe Reservoir segment is about 15,000 years ago for the most recent event and about 100,000 years ago for the penultimate event. Based on empirical relationships between rupture length, apparent surface displacement, and earthquake magnitude developed by Bonilla and others (1984), we estimate that these earthquakes were about magnitude 6.5 to 7.

FUTURE SURFACE-RUPTURING EARTHQUAKES

Earthquakes strong enough to cause rupture of the ground surface have undoubtedly occurred on the Horseshoe fault during the last few hundred thousand years. Could such earthquakes happen in the future? Assuming that displacements took place simultaneously on both segments of the Horseshoe fault and that these displacements during the last few hundred thousand years have been approximately evenly spaced, we estimate that an interval of 50,000 to 100,000 years separates the surface-rupturing earthquakes. Because the youngest rupture occurred before 10,000 to 20,000 years ago, it is possible that several tens of thousands of years may pass before the next surface-rupturing earthquake on the Horseshoe fault. On the other hand, it is equally possible that surface ruptures are not evenly spaced. After several hundred thousand years of quiescence, the current phase of activity may be just beginning. Evidence from well-studied faults in other areas indicates that surface-rupturing earthquakes on some faults recur within a relatively short period that is followed by a relatively long period without such earthquakes (Schwartz, 1988). Such temporal clustering of surface-rupturing earthquakes along the Horseshoe fault cannot be ruled out. Because accurate earthquake prediction is not yet possible and because additional data that future studies might provide are needed to improve our understanding of fault behavior in Arizona, faults with evidence of Quaternary activity in central Arizona, including the Horseshoe fault, should be considered potential sites for future surface-rupturing earthquakes.

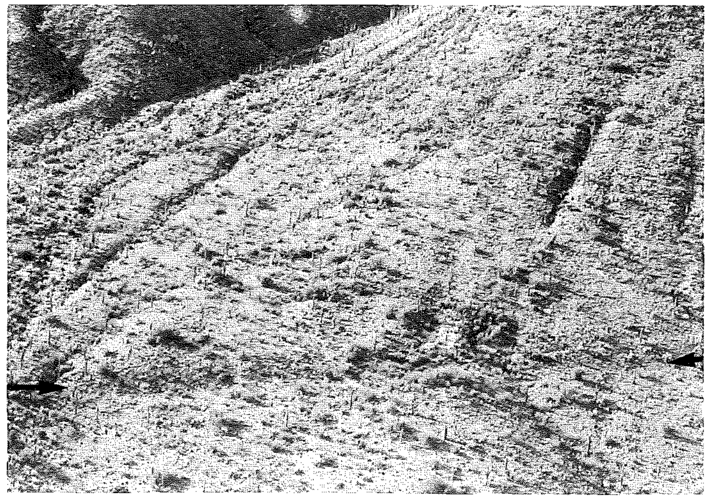


Figure 6. *Aerial view toward the west of a linear east-facing scarp (between arrows) along the Hell Canyon segment of the Horseshoe fault between Lime Creek and Hell Canyon (Figures 3 and 5). The displacement of the alluvial-fan surface across this scarp is about 2 meters. The slope of the alluvial-fan surface is 10° to 13°; the maximum slope of the scarp is about 27°.*

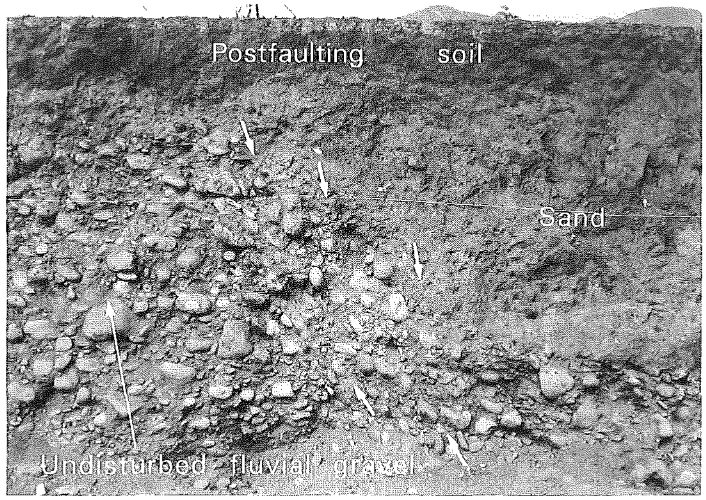


Figure 7. *The Horseshoe Reservoir segment (HRS) of the Horseshoe fault exposed in Trench 1 excavated into the terrace just north of Horseshoe Dam (Figure 1). The west wall of the trench is shown. The fault displaces fluvial gravel that was deposited by the Verde River and is now preserved as a terrace about 18 meters above the river. The fault is marked both by the step in the gravel surface and by the gravel clasts that have been rotated and aligned (sheared) by at least two ruptures. The arrows indicate zones along which the gravel clasts have been rotated by displacement on the fault. Sand deposited by water flowing along the base of the scarp or by wind blowing down the Verde River Valley has partially covered the scarp. A weak soil has developed in this sand (postfaulting soil) since the last displacement on the HRS.*

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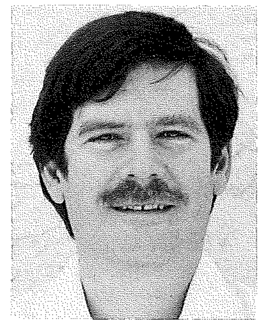
AZGS Takes on Oil and Gas Regulatory Responsibilities; Steve Rauzi Joins AZGS Staff

To reduce expenditure of General Revenue funds, the Arizona Legislature transferred regulatory responsibility for the drilling and production of oil, gas, geothermal, and helium resources to the Arizona Geological Survey (AZGS) in Tucson, effective July 1, 1991. The Oil and Gas Conservation Commission, a State agency in Phoenix, was eliminated. One position, Oil and Gas Program Administrator, filled by Steven L. Rauzi, was transferred to the AZGS to work under the direction of AZGS Director and State Geologist, Larry D. Fellows. Staff support for this position is provided by the AZGS.

The five-member Oil and Gas Commission, appointed by the Governor, will continue to function. Major responsibilities of the Commission include holding formal hearings, conducting regular meetings, and setting policy for the regulation of oil, gas, geothermal, and helium resources. Jan C. Wilt is chairman of the Commission. Other members are James E. Warne, Jr. (vice chairman), J. Dale Nations, Barbara H. Murphy, and Archie Roy Bennett. The activities of the Commission and the AZGS Oil and Gas Regulatory Program will be announced in future issues of *Arizona Geology*.

To obtain more information about the Oil and Gas Regulatory Program, contact Mr. Steven L. Rauzi, Oil and Gas Program Administrator, Arizona Geological Survey, 845 N. Park Ave., Suite 100, Tucson, AZ 85719; tel: (602) 882-4795.



Steve Rauzi grew up in Moab, Utah and received B.S. and M.S. degrees in geology from Utah State University in Logan. From 1980 to 1987, he worked for Texaco in Los Angeles as an exploration and development geologist. Since 1988, he worked as Oil and Gas Specialist for the Oil and Gas Conservation Commission in Phoenix until that agency was merged into the AZGS on July 1, 1991. He now serves as the Oil and Gas Program Administrator for the AZGS in Tucson.

Steve Reynolds Leaves AZGS for University

Arizona State University's (ASU) gain is our loss! Dr. Stephen J. Reynolds, who began working at the Arizona Geological Survey (AZGS) in February 1981, became an Associate Professor in the Department of Geology at ASU in August 1991. We congratulate him and wish him success, but will miss him tremendously.

Steve began working at the AZGS immediately after receiving a Ph.D. degree in geology from the University of Arizona. He conceived and initiated the AZGS open-file report series; initiated and supervised all aspects of computerization, including acquisition, installation, training, maintenance, and problem solving; and conceived the Arizona Geologic Information System, a centralized computerized data bank for geologic information on Arizona. Steve eagerly answered hundreds of inquiries from other professionals, governmental agency staff, and the public each year. He assisted more than 40 graduate students by serving on thesis or exam committees, reviewing drafts of theses, and accompanying students in the field.

Steve was principal investigator and supervisor of the Cooperative Geologic Mapping Program (COGEOMAP) in west-central Arizona since its inception in 1984. The U.S. Geological Survey provided more than $320,000 in Federal funds, which partially matched the funds provided by the AZGS for this cooperative effort.

In addition to these activities, Steve published more than 100 items on Arizona geology, including authoring or coauthoring AZGS Bulletins 195, 196, 197, and 198; Maps 24, 25, 26, and 30; Circular 26; 37 open-file reports; 13 articles in *Arizona Geology* (previously named *Fieldnotes*); and 30 articles that were published by other professional societies and groups. A complete list of his publications would have been included here had there been enough space.

It's easy to see why Steve will be missed. We expect to maintain a close working relationship with him, however, and will announce future collaborative projects in *Arizona Geology*.

Other Staff Farewells

Sherry F. Garner, AZGS Graphic Designer since 1987, has left the AZGS. Sherry received a B.A. degree in art and has almost completed an M.Ed. media degree. Her previous jobs included working as a book designer for the University Press of Kentucky and graphic designer for Agricultural Communications at the University of Arizona. Sherry designed the layouts and typeset the text for numerous AZGS publications, including *Arizona Geology*. She drafted maps and figures and, as the AZGS photographer, created slides for professional talks and illustrations for publications. Her marketing ideas and promotional efforts, including displays, brochures, and sales fliers, brought the accomplishments of the AZGS to the public.

Kevin C. Horstman, AZGS Research Assistant since 1987, has also left the AZGS. Kevin received B.S. and M.S. degrees in geology and is completing a Ph.D. dissertation. He has worked as a geologist for Occidental Oil and the U.S. Geological Survey. Kevin collected and verified thousands of references for the AZGS computerized bibliography on Arizona geology. He also coauthored an open-file report (OFR-88-13) on bibliographic conventions used by the AZGS.

Nancy Schmidt, AZGS Editorial and Research Assistant since 1988, has also left the AZGS. Nancy received B.A. and M.S. degrees in geology and has worked as an exploration geologist for Chevron U.S.A. and ASARCO and as an editor for the Office of Arid Lands Studies at the University of Arizona. Through her efforts, the AZGS computerized bibliography has grown to 12,000 references. She also edited scientific manuscripts, wrote articles and news items for *Arizona Geology*, and created brochures and other promotional materials. Nancy compiled the subject index to the AZGS publications list, as well as other indices, and was an invaluable source of information and willing tutor on the use of computer programs.

We will greatly miss the skills and talents of Sherry, Kevin, and Nancy. Their contributions have added much to our agency.

The Artillery Manganese District in West-Central Arizona

by Jon E. Spencer
Arizona Geological Survey

Pure manganese is a grayish-white metal that resembles iron, but is harder and very brittle. These two elements lie side-by-side in the periodic table of the chemical elements and have similar chemical behavior. Manganese is essential to modern industrial society. It is a strategic and critical mineral primarily required for the production of steel, but also used in other commodities, such as some types of batteries.

Manganese deposits are abundant in west-central Arizona and southeastern California, where they are scattered over an area of approximately 40,000 square kilometers, herein referred to as the western Arizona manganese province. Most of the deposits are vein deposits, which formed when mineralizing aqueous fluids filled fractures within host rocks and the minerals precipitated because of chemical or physical changes within the fluid. The greatest amount of manganese, however, is in the stratiform manganese deposits in the Artillery Mountains. Stratiform deposits are deposits that are parallel to the enclosing sedimentary beds. The origin of the stratiform manganese deposits in the Artillery Mountains is not well understood, but may be related to low-temperature, alkaline, saline water that flowed beneath playas or lakes, which were present in the area several million years ago. This same water may have caused potassium metasomatism, a chemical alteration during which the amount of potassium in the rock was greatly increased.

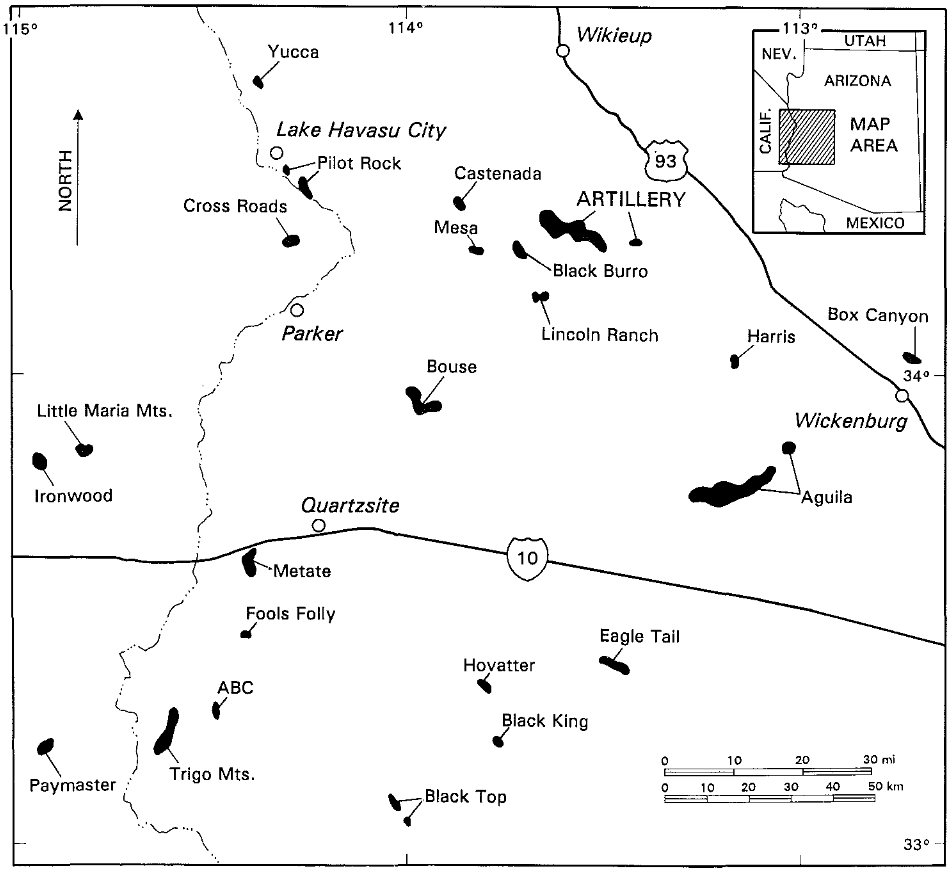


Figure 1. Mineral districts in the western Arizona manganese province that have recorded manganese production (see Table 1). Data from Davis (1957) and Keith and others (1983).

The manganese deposits of the Artillery manganese district are the largest and perhaps only significant group of manganese deposits in the United States. This technical article describes the uses and economics of manganese, as well as the geology and origin of manganese deposits within this district.

USES AND ECONOMICS OF MANGANESE

Manganese is the fourth most widely used metal in the United States, following iron, aluminum, and copper. It is an essential ingredient in steel: When added to iron, manganese acts as a deoxidizer that impedes the formation of defects ("pinholes"); combines with residual sulfur and prevents the formation of iron sulfide, an impurity that detracts from the desired metallurgical properties of steel; and improves mechanical properties, such as hardness, strength, wear resistance, and rolling and forging qualities. Manganese is also used for dry-cell batteries, ceramics, bricks, agricultural fertilizers and fungicides, water and waste treatment, fuel additives, welding, and many other processes and products (Weiss, 1977).

Virtually all manganese used in the United States is imported (90 percent) or obtained from recycling (10 percent). More than 800,000 tons of manganese were imported in 1988 (the last year for which statistics are available), primarily as manganese ore, concentrated ore, and ferromanganese. Ferromanganese is a manganese-iron alloy that contains 78 percent manganese. In 1988, approximately 416,000 tons of manganese were imported in the form of ferromanganese at a cost of $340 to $550 per ton of manganese. Most of this was imported from France and South Africa. In addition, 250,000 tons of manganese in the form of ore or concentrate, which contained an average of 48 percent manganese, were imported from Gabon, Australia, Mexico, and Brazil at a cost of about $120 per ton of manganese (Jones, 1990).

Although manganese deposits in western Arizona are not of sufficient grade or tonnage to mine them economically today, minor production from several mines in this area occurred intermittently during much of this century. Most of the production occurred between 1953 and 1955, when the U.S. government purchased manganese at depots in Arizona and New Mexico (Farnham and Stewart, 1958). Much of the manganese mined during this brief period still sits in a large black pile at a U.S. Bureau of Mines storage facility next to the railroad tracks just east of the town of Wenden in west-central Arizona. It is part of the U.S. strategic- and critical-mineral stockpile that is intended to provide domestic manganese if foreign sources are suddenly cut off.

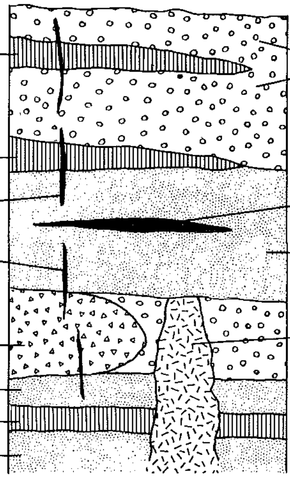


Figure 2. Schematic stratigraphic column of the upper Artillery Formation, overlying pre-Quaternary strata, and manganese deposits. Data from Lasky and Webber (1949), Spencer and others (1989a), and J.E. Spencer (unpublished data).

THE ARTILLERY MANGANESE DISTRICT

Numerous small to moderately sized, low- to medium-grade manganese deposits, many of which have recorded production (Keith and others, 1983), are present in western Arizona and southeasternmost California (Figure 1) and make up the western Arizona manganese province. Parts of the Artillery and adjacent Lincoln Ranch and Black Burro manganese districts contain stratiform manganese deposits. In contrast, virtually all other deposits in the province are vein and fracture-filling deposits that are typically associated with calcite and barite. Both types of deposits are known or suspected to be of Miocene age and probably formed during or shortly after an episode of volcanism, normal faulting, and basin formation that greatly modified the geology and landscape of western and southern Arizona (Spencer and Reynolds, 1989).

The Artillery manganese district (Figure 1) contains both stratiform and vein manganese deposits that are hosted in Tertiary strata (Figures 2 and 3). More than 95 million pounds of manganese have been produced from the district (Table 1; Keith and others, 1983).

Geologic Setting

The manganese deposits of the Artillery manganese district are within a thick sequence of sedimentary and volcanic rocks (Figure 2) that are estimated to range in age from about 8 to 25 million years (m.y.). The strata are tilted to the southwest, and the dip of the strata decreases stratigraphically upward. Strata at the base of the sequence dip approximately 30° to 40°, whereas dips at the top of the sequence are approximately 10° to 20° (Figure 3; Spencer and others, 1989a). The upward-decreasing dip of the sequence indicates that the strata were deposited during tilting.

The Artillery manganese district lies above a gently northeast-dipping, large-displacement normal fault known as the Buckskin-Rawhide detachment fault. This detachment fault is exposed along the southwestern side of the district (Figure 3). Granitic and gneissic rocks below the detachment fault were displaced out from beneath the Artillery Mountains and ranges to the east. Tilting of strata in the Artillery Mountains was related to movement on this underlying fault. Normal faulting, basin formation, sedimentation, volcanism, and formation of stratiform manganese deposits all occurred within an approximately 10-m.y. period.

The strata that make up the lower and middle part of the sequence were designated the Artillery Formation (Figure 2; Lasky and Webber, 1949). The Artillery megabreccia, an enormous, catastrophic debris-avalanche deposit that contains intact blocks of rock hundreds of meters across, forms the top unit of the Artillery Formation. The formation is overlain by the Chapin Wash Formation, a characteristically brick-red sandstone that is black where it contains stratiform manganese. The Artillery Formation is cut by an igneous intrusion at Santa Maria Peak that is, in turn, depositionally overlain by the Chapin Wash Formation. Biotite from the intrusion has been dated by the K-Ar method at 20.3 m.y. (R. Miller, oral commun., 1988). The Artillery Formation, therefore, is older than approximately 20 m.y., and the Chapin Wash Formation is younger. The Cobwebb Basalt, dated at 13.3 m.y. by the K-Ar method (Eberly and Stanley, 1978), overlies the Chapin Wash Formation, and is, in turn, overlain by the Sandtrap Conglomerate. The Manganese Mesa basalt is interbedded with the Sandtrap Conglomerate and has been dated by the K-Ar method at 9.5 m.y. (Shafiqullah and others, 1980).

Stratiform Manganese Deposits

The Chapin Wash Formation contains large, low-grade, stratiform manganese deposits that are exposed in two northwest-trending belts (Figure 3). The southwestern belt contains numerous lenses, up to several tens of meters thick, of manganiferous sandstone that are within and separated by nonmanganiferous sandstone. Little mining has occurred within this zone. The northeastern belt contains a 5-kilometer-long zone of stratiform manganiferous sandstone and siltstone that ranges in thickness from a few meters to many tens of meters. Most of the manganese is, by far, in the northeastern belt.

Lasky and Webber (1949) estimated that the Chapin Wash Formation contains a total of at least 200 million tons of material averaging 3 to 4 percent manganese, which includes about 2 to 3 million tons of material containing more than 10 percent manganese. Most of this manganese consists of very fine-grained oxides within pore spaces in sandstone and siltstone. Approximately 15 million tons of material described as "hard ore" averages 6.5 percent manganese. The hard ore is recrystallized, possibly because of interaction with ground water long after the deposit originally formed.

Table 1. Recorded manganese (Mn) production from mineral districts in the western Arizona manganese province. Data from Davis (1957) and Keith and others (1983).

MINERAL DISTRICT	COUNTY	MANGANESE PRODUCTION (LBS)
Artillery	Mohave	95,108,000
Aguila	Maricopa	42,457,000
Lincoln Ranch	La Paz	24,000,000
Paymaster	Imperial (Calif.)	24,000,000±8,000,000
Ironwood	Riverside (Calif.)	12,800,000±7,200,000
Little Maria Mts.	Riverside (Calif.)	10,000,000±6,000,000
Bouse	La Paz	9,659,000
Cross Roads	San Bernardino (Calif.)	2,800,000±1,200,000
Trigo Mts.	La Paz	2,096,500
Box Canyon	Yavapai	1,002,000
New Water*	La Paz	512,900
Black Burro	Mohave	331,000
ABC	La Paz	300,000
Planet*	La Paz	237,500
Black Top	Yuma	224,000
Yucca	Mohave	175,400
Kofa*	Yuma	148,000
Fools Folly	La Paz	105,700
Harris	Yavapai	100,500
Hovater	Yuma	93,000
Mesa	Mohave	60,000±20,000
Black King	Yuma	29,000
Eagle Tail	La Paz	19,000
Bonegas	Mohave	15,000
COMBINED TOTAL		226,273,500±22,420,000

*Most Mn production was as a byproduct of other metal production.

Vein Manganese Deposits

Many vein deposits of manganese oxides, calcite, and barite are within or near the northeastern belt of stratiform deposits (Figure 3). Vein deposits in the northwestern part of this belt, at the Shannon mine and along faults north of this mine, typically consist of fine-grained to microcrystalline manganese oxides and coarse white and black calcite. Manganese oxides form colloform (globular) encrustations up to 1 centimeter thick along fractures at the Shannon mine. These deposits are within the Sandtrap Conglomerate and interbedded 9.5-m.y.-old Manganese Mesa basalt (Spencer and others, 1989a).

The Priceless mine, which is near the southeastern part of the northeastern belt of stratiform manganese deposits, contains pervasive, fracture-filling, colloform manganese-oxide encrustations up to 1 centimeter thick that are composed of ramsdellite and cryptomelane. A several-meter-thick barite vein projects toward the mine from the north, but no barite is present at the mine. Near Black Diamond and Neeye mines, manganese oxides are within numerous subvertical veins of black, gray, and white calcite. Analysis of fluid inclusions within calcite, barite, and chalcedonic quartz associated with all of these vein deposits indicates that mineralizing fluids were of fairly low salinity (0 to 3 weight percent NaCl equivalent; Figure 4; Spencer and others, 1989a).

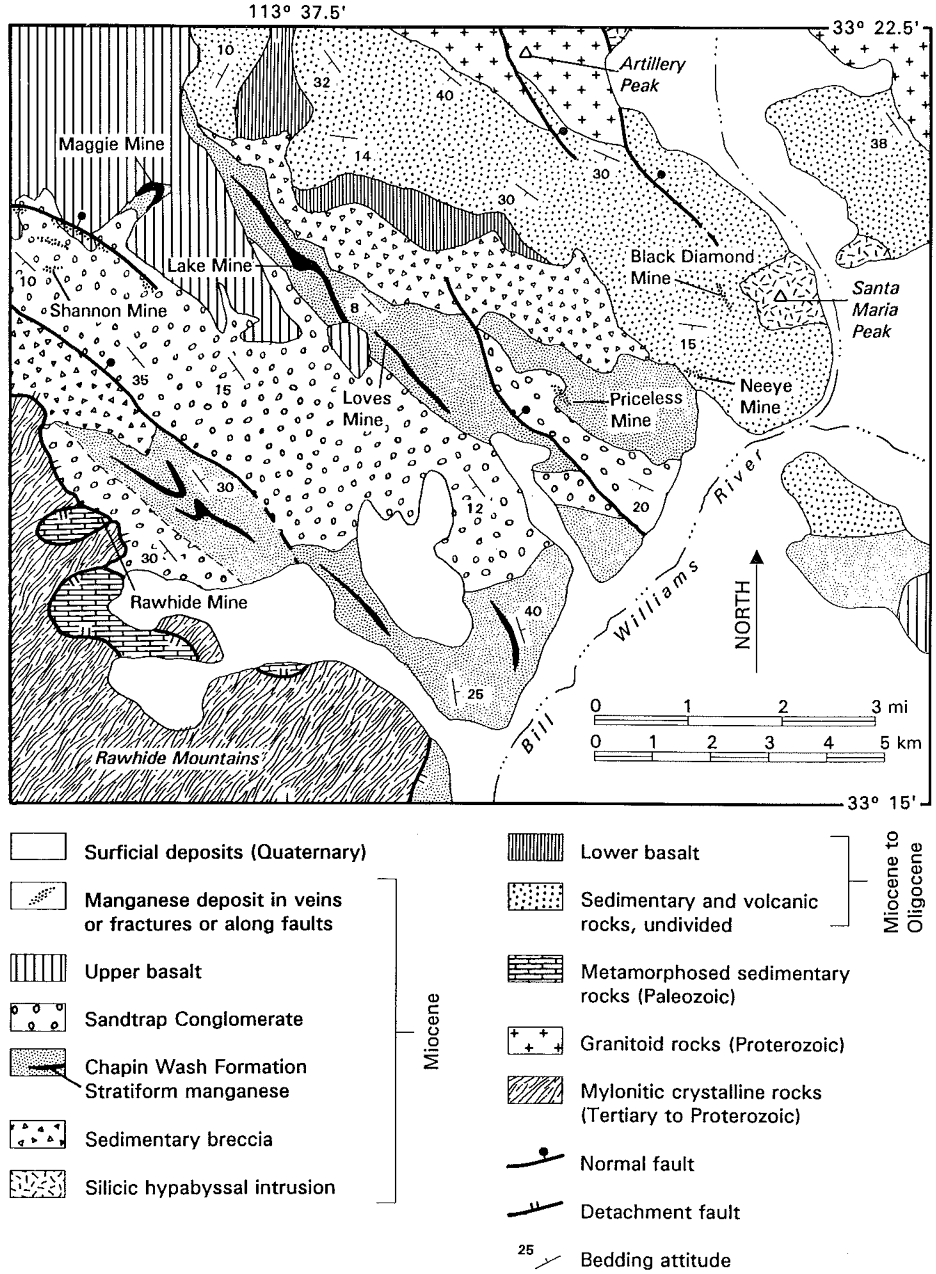


Figure 3. Simplified geologic map of the southern Artillery Mountains and adjacent areas. Data from Lasky and Webber (1949), Shackelford (1989), Spencer and others (1989a), B. Bryant (unpublished data), and J.E. Spencer (unpublished data).

Origin of Deposits

The origin of the stratiform deposits is unclear. Earlier studies (Lasky and Webber, 1949; Mouat, 1962) indicated that manganese mineralization occurred at or near the Earth's surface and that surface water eroded sandy and silty manganiferous sediments and redeposited them within less manganiferous or nonmanganiferous sediments. This indicates that manganese either was detrital (Lasky and Webber, 1949; Mouat, 1962) or was deposited by chemical processes so near the surface that manganiferous sediments were locally reworked by sedimentary processes.

The brick-red sandstone that hosts the manganese deposits in most of the Artillery Mountains is strongly altered by potassium (K) metasomatism (R. Koski, oral commun., 1991). K metasomatism is thought to occur under low-temperature conditions in the presence of saline alkaline water beneath or near lakes or playas and occurred over large areas in west-central Arizona during the Miocene (e.g., Roddy and others, 1988; Spencer and others, 1989b). In some areas, K metasomatism has completely converted rocks to an assemblage of potassium feldspar, quartz, and hematite. Because K metasomatism can chemically modify large volumes of rock and apparently removes manganese, it seems feasible that chemical and hydrological conditions associated with this type of alteration could liberate, transport, and reconcentrate manganese (Roddy and others, 1988).

The vein deposits are several million years younger than the stratiform deposits; thus, the two types are not obviously related. The spatial association of the two deposits, however, suggests that manganese in the vein deposits was derived from the stratiform deposits. This movement of manganese could be due to hydrothermal circulation associated with basaltic magmatism or to ground-water movement unrelated to magmatism. Four fluid inclusions in chalcedonic quartz from the Priceless mine formed at a minimum temperature of approximately 165°C, which is consistent with either mineralizing process. Mineralization, however, was not related to movement of basin brines (10 to 25 weight percent NaCl equivalent), such as those that caused detachment-fault-related mineralization (e.g., Roddy and others, 1988).

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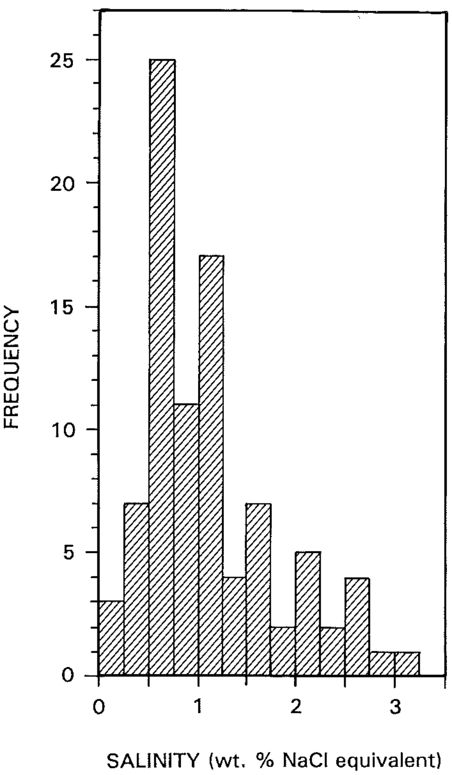

Figure 4. Histogram of fluid-inclusion salinities from vein deposits in the Artillery manganese district. Samples are from the Shannon mine area (33 inclusions in calcite), Priceless mine area (43 inclusions in barite and 4 in chalcedonic quartz), and Black Diamond mine (9 inclusions in calcite). Analyses by J.T. Duncan (unpublished data) and Spencer and others (1989a).

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Thesis Discusses Oil and Gas Potential

A new M.S. thesis by David A. Cook contains detailed information on the depositional environments and oil and gas potential of a hydrocarbon source rock in Arizona. The 800-foot-thick Walcott Member of the Kwagunt Formation (Chuar Group) was deposited in a northwest-trending rift basin on a carbonate ramp that was probably connected to the sea. Eustatic or tectonic changes in base level created alternating deposits of carbonates and organic-rich black shale. This 158-page thesis includes section descriptions from Nankoweap Butte and Sixtymile Canyon in the Grand Canyon, Rock-Eval TOC data, Van Krevlen diagrams, burial-temperature indicators, outcrop maps, and clay-mineralogy data used to predict oil potential. To purchase a copy of *Sedimentology and Shale Petrology of the Upper Proterozoic Walcott Member, Kwagunt Formation, Chuar Group, Grand Canyon, Arizona,* with color plates and vellum cover, contact David A. Cook, Dept. of Geology, Northern Arizona University, Flagstaff, AZ 86011; tel: (602) 774-3577.

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Director & State Geologist: Larry D. Fellows
Editor & Layout Designer: Evelyn M. VandenDolder
Illustrator: Peter F. Corrao

Arizona Geological Survey
845 N. Park Ave., Suite 100
Tucson, AZ 85719
Tel: (602) 882-4795