LAND SUBSIDENCE IN CENTRAL ARIZONA

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Carl C. Winikka
Paul D. Wold

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Carl C. Winikka and Paul D. Wold
Administrator, Arizona Resources Information System, Phoenix, Arizona
Geologist, U.S. Bureau of Reclamation, Phoenix, Arizona

Abstract

Land subsidence and earth fissures occurring in parts of central Arizona are related to water-level declines caused by large-scale ground-water withdrawal. Differential land subsidence and earth fissures have damaged Picacho Reservoir, agricultural lands, water-distribution systems, water wells, buildings, interstate highways, county roads and streets, and have necessitated rerouting of a proposed major aqueduct. Earth fissures, probably associated with the land subsidence, were first reported in 1927, and land subsidence was first measured in 1948.

The maximum documented subsidence from 1948 to 1967 was 2.29 m near the town of Eloy. Since 1967, more than 0.9 m of subsidence has been measured along Interstate Highway 10 near Picacho.

Between 1948 and 1967, in the lower Santa Cruz Basin, about 570 square kilometers have subsided more than 0.15 m, and about 155 square kilometers have subsided more than 0.9 m in the Casa Grande-Eloy area. In the Stanfield-Maricopa area, approximately 200 square kilometers have subsided more than 0.3 m.

In the Salt River Valley, the land surface has subsided as much as 1.16 m near Queen Creek, 0.64 m west of Luke Air Force Base, and 1.13 m east of Mesa, between 1948 and 1967. Between 1971 and 1975, approximately 0.3 m of subsidence was measured southeast of Mesa.

By 1964, large-scale pumping, principally for irrigation, had lowered water levels more than 110 m in parts of the area, and numerous earth fissures were observed. Since 1964, water levels have declined more than 24 m in local areas. Compaction-recorder data indicate long-term water-level declines correspond with land subsidence. Seasonal water-level fluctuations correspond with seasonal sediment compaction and expansion; however, the amount of compaction greatly exceeds the expansion. Between April 1965 and April 1974, measured compaction in the upper 253 m of sediment in the Santa Cruz Basin near Eloy accounts for 0.41 m (63%) of the 0.65 m total surface subsidence at the compaction-recorder site.

Earth fissures, as much as 13.8 km long, occur in the alluvial sediments on the periphery of the subsiding areas, transect natural drainageways, and act as drains. The fissures intercept surface runoff in undeveloped areas, and capture irrigation water traversing cultivated lands. Downward and lateral water movement in the fissures causes rapid near-surface widening--partly by slumping but mainly by erosion of the sides.

In 1976, renewed fissuring near the Picacho and Santan Mountains and several areas of previously unmapped fissures were mapped on orthophoto quads using a helicopter. New and renewed fissuring, measured water-level declines and sediment compaction, together with the limited leveling data available indicate land subsidence continues to occur over large areas of central Arizona.

Acknowledgments

Data presented were collected by persons from several agencies. The following assisted in mapping: Robert L. Laney and Thomas L. Holzer of the U.S. Geological Survey; Edward A. Nemecek and Phillip C. Briggs of the Arizona Water Commission. Robert L. Laney and his staff prepared the water-level declines maps. Richard H. Raymond of the Bureau of Reclamation was of much assistance in all phases of gathering and interpreting data. Herbert H. Shcumann of the U.S. Geological Survey furnished valuable background information.

Introduction

Major dams constructed on rivers in central Arizona provide the water necessary for extensive agricultural and industrial development. This development coupled with a mild, dry, sunny climate have made Arizona an increasingly more desirable place to live and development has continued at a rapid pace. From 1970 to 1975, Arizona's increase in population was over 25 percent, the highest growth rate of any State in the Nation.

To meet water requirements of this growing area, ground water is being pumped in addition to that supplied through the reservoir system. The volume of ground water withdrawn now greatly exceeds the rate of recharge. Land subsidence and earth fissures occurring in parts of central Arizona are related to water level declines caused by large-scale ground-water withdrawal (Figure 1).

Ground-water withdrawal in Arizona now exceeds the recharge by 2,700 cubic hectometers per year. The Central Arizona Project is expected to lessen this overdraft by approximately 1,500 cubic hectometers of water per year beginning in the 1980's. In the meantime, substantial subsidence and the intensification of earth fissuring in subsiding central Arizona basins is continuing. The Central Arizona Project, new highway construction, and flood control projects will all be affected by this continuing subsidence process. Residential, industrial, and commercial expansion which follow will also be affected not only by the physical hazards involved but also by the depreciation effect earth fissures have on property when occurring in or near development (Figure 2) or irrigated farmland (Figure 3).

At present, the extent to which declining ground water levels, subsidence, and related earth fissures constitute environmental hazards is minimal. Subsidence effects are gradual and take place generally in agricultural or undeveloped desert areas.

While fissures normally occur in natural desert areas they have also occurred across interstate highways, in irrigated fields, across pipelines, and frequently across unpaved local roads. In two known instances, earth fissures are in residential areas. Subsidence has caused the collapse of well casings and in some places apparent extrusion of well casings from the ground surface. Subsidence has thus required well replacement or modification.

The subsidence process in Arizona transects both the scope and geographical extent of agency responsibilities. As a result, the total

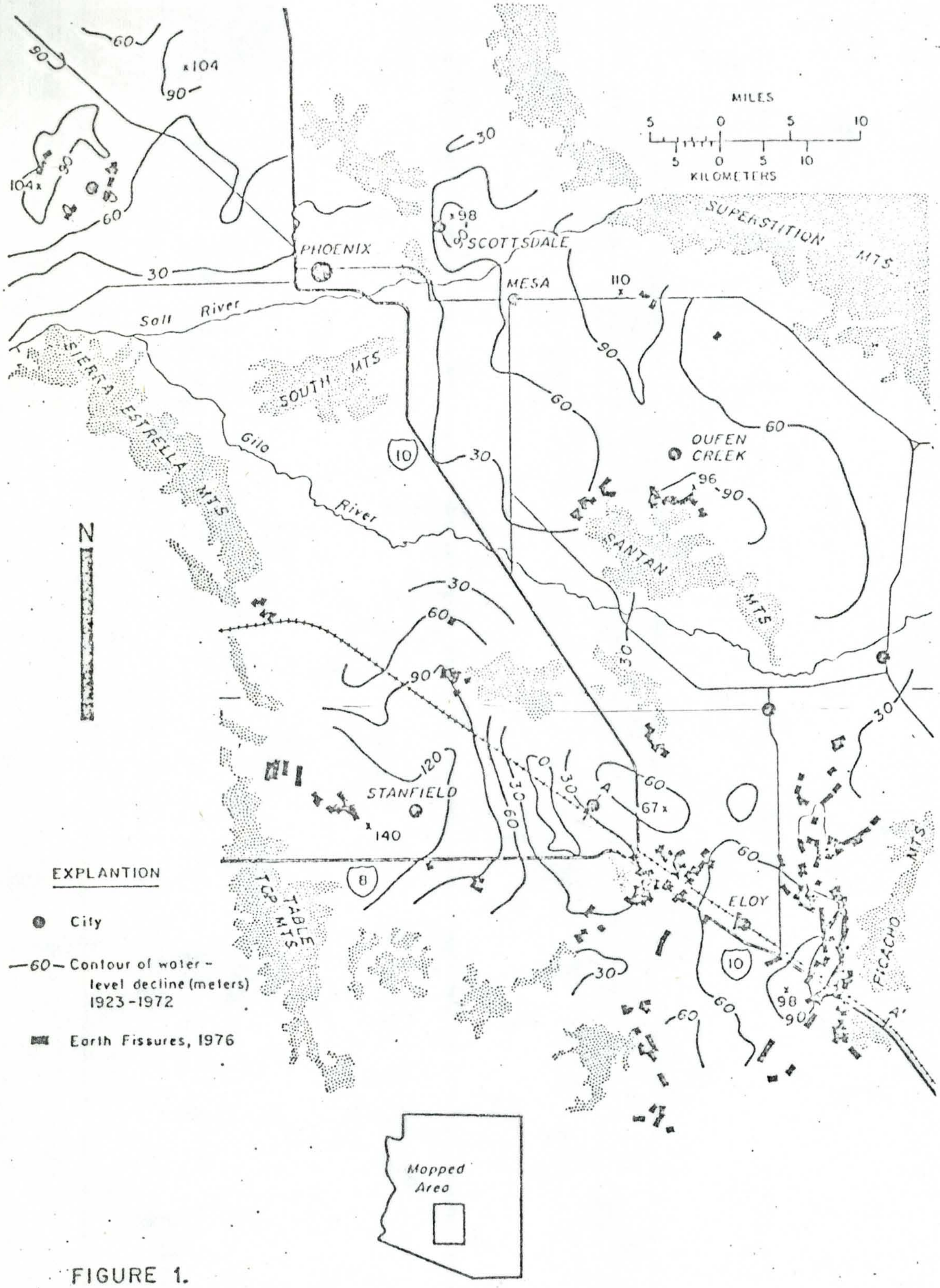


FIGURE 1.

LOCATION OF WATER-LEVEL DECLINES AND EARTH FISSURES IN CENTRAL ARIZONA.

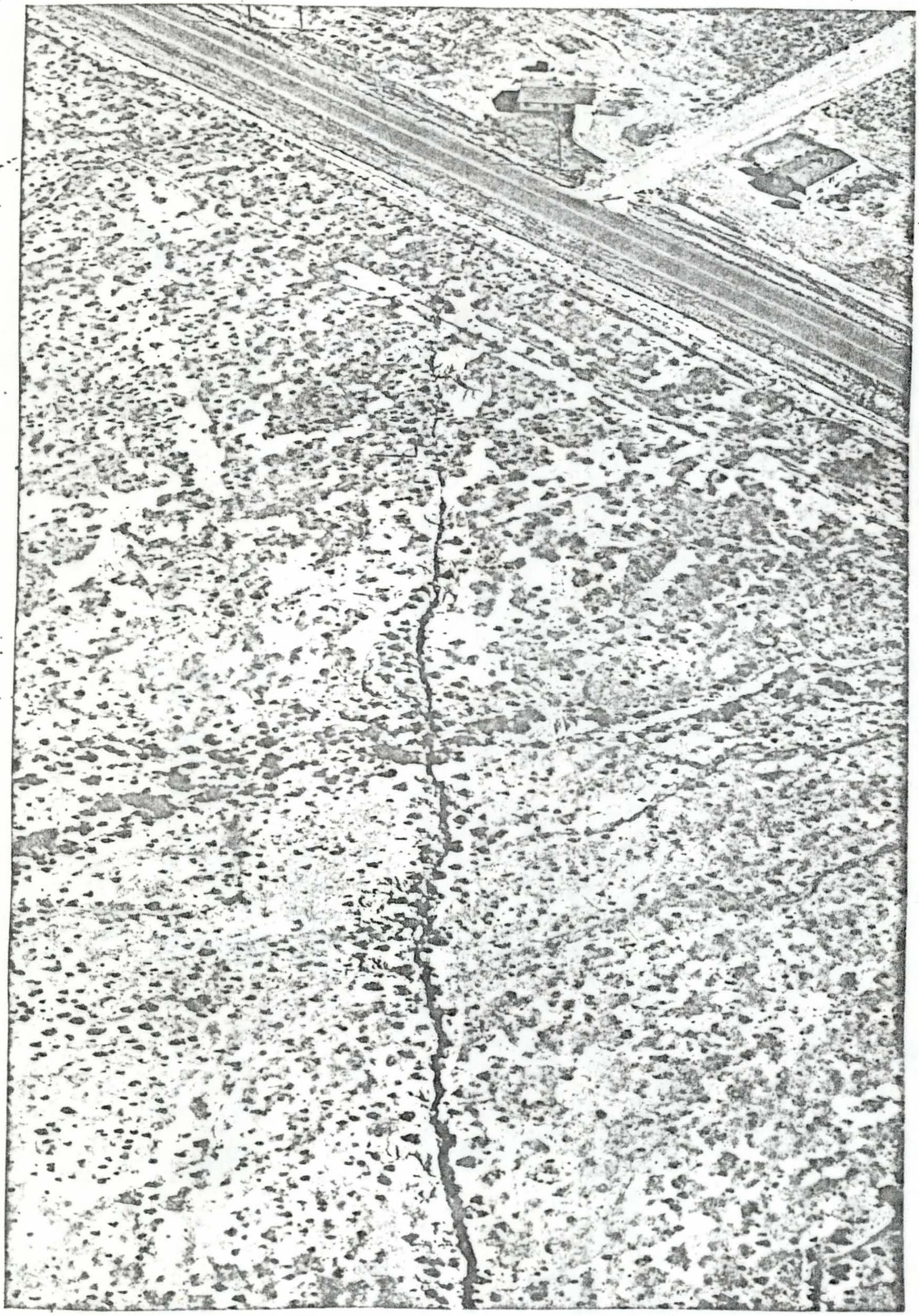
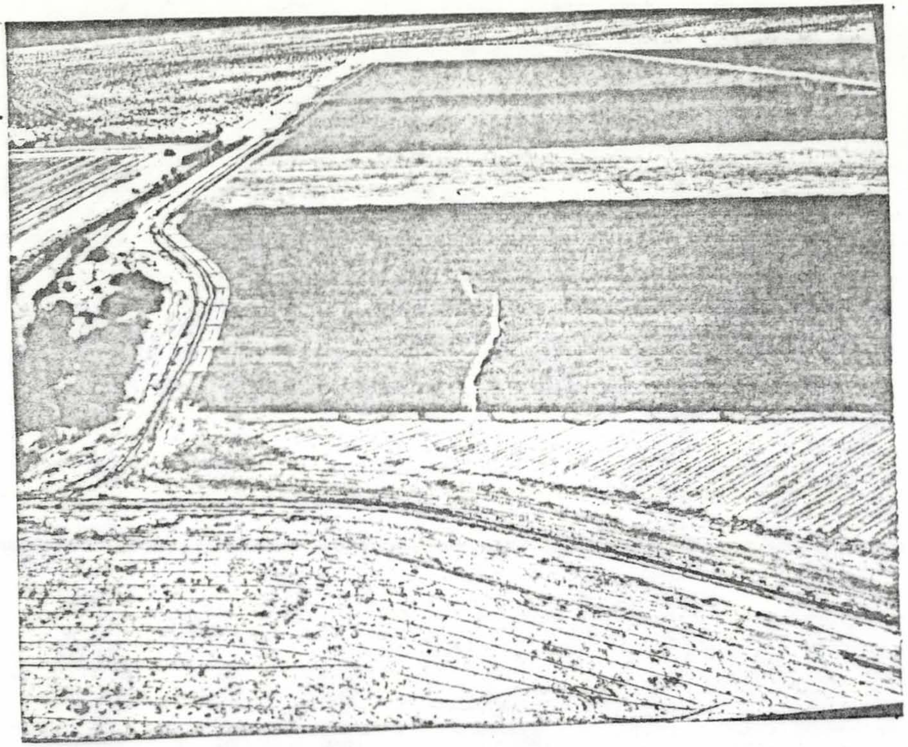


Figure 2 - New earth fissure heading toward housing development south of the Sacaton Mountains.



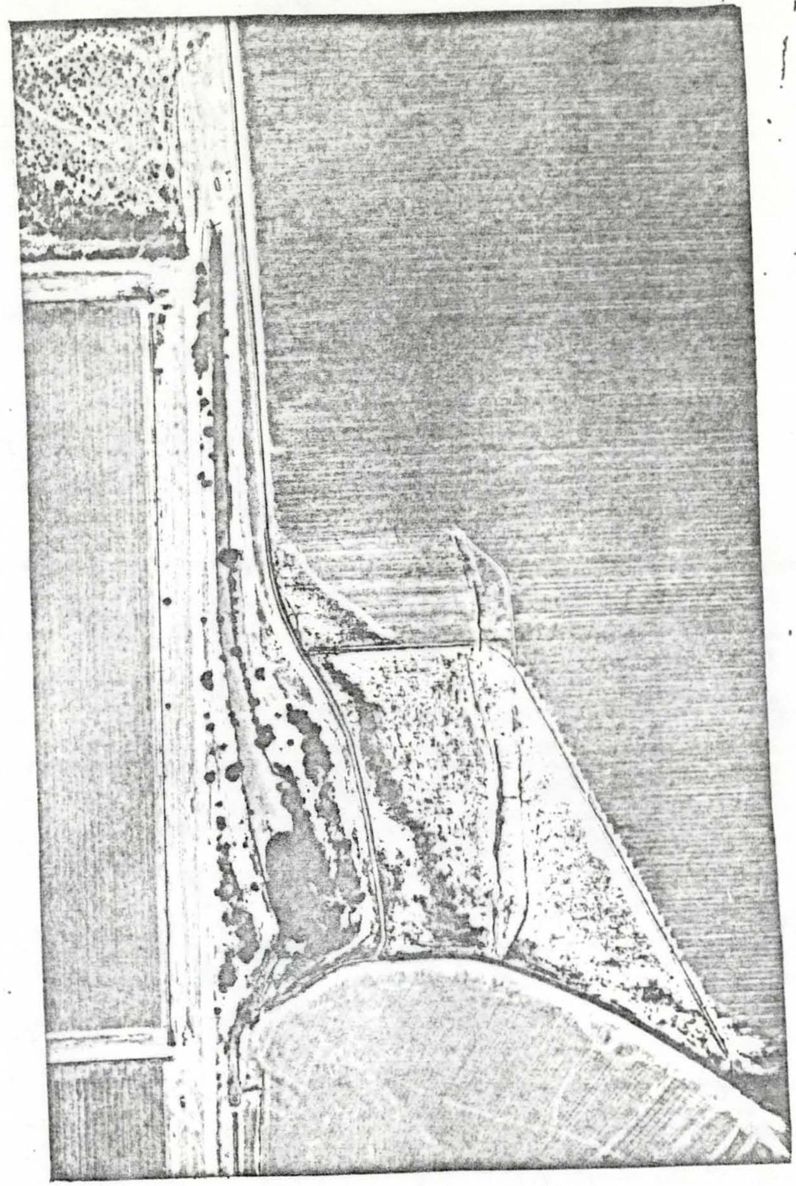


Figure 3 - Oblique aerial view (above) of earth fissure in agricultural land photographed in April 1970, 3 days after fissure appeared during irrigation. The same fissure (right) in a vertical aerial photograph taken in June 1974. Note land taken out of production and extension of fissure toward top of photograph.

effects are not known and any assessment of the effects on future projects requires a considerable data gathering effort. Records of subsidence are scarce and existing level lines must be carefully evaluated prior to use for subsidence measurements. A continuity of elevation change measurements is made increasingly difficult due to the destruction of bench marks and the rising cost of field surveys.

Earth fissures not shown on existing maps were discovered during studies for the Bureau of Reclamation's Central Arizona Project. Other interested Federal and State agencies, with a common need for this information, joined the Bureau of Reclamation in mapping all visible earth fissures in the 2,000 square kilometer area in three major basins south and east of Phoenix, Arizona (Figure 1).

This paper reports on a joint effort by several agencies to update and bring together information to better understand the interrelationship between ground-water declines, subsidence, and earth fissures.

Techniques

Mapping of the earth fissures was done in two stages. First, 1:24,000 and larger scale color infrared aerial photographs were taken of all known fissure areas. A total of 144 aerial photographs were obtained. The aircraft and camera were provided by Arizona Department of Transportation and the film by the U.S. Geological Survey. All identified fissures, as well as probable fissures, were transferred from this photography to 1:24,000 scale orthophotoquads (Winikka-Morse 1974) furnished by the Arizona Resources Information System.

Second, these fissures were checked and the entire area of approximately 2,000 square kilometers was searched by two observers and a recorder in a four place helicopter. Fissures were spotted from the air and checked on the ground. Locations were determined by using the orthophotoquads as base sheets. This procedure took three days for a total of about 15 hours flying time.

Ground-water decline and measured subsidence information was gathered from State and Federal agency records. Recent information was found to be available from the U.S. Geological Survey and the Arizona Department of Transportation.

Water-Level Declines

Substantial water-level declines are continuing in a number of ground-water dependent areas in central Arizona (Laney-in preparation). While these areas are predominantly agricultural, urban areas are not excluded (Figure 1). Maximum values of water-level decline are 140 meters near Stanfield, 110 meters east of Mesa, 98 meters southeast of Eloy, south of Queen Creek, and at Scottsdale. The decline at Scottsdale is recent, having occurred since 1952 (USBR-in preparation). In all of the above areas declines are increasing in magnitude and in total area affected.

Subsidence

Land subsidence in Arizona related to ground-water withdrawal (Poland-Schumann 1969) is continuing. Subsidence has a relationship to ground-water declines in the Casa Grande-Picacho section of Pinal County (Figure 4). When declines and subsidence are plotted against time, a strong linear relationship is found at Picacho (Figures 5 and 6).

Information available on four bench marks in the Toltec-Eloy area of Pinal County shows subsidence of these marks from 1960 to 1975 to range from 0.44 m to 0.69 m. In the Picacho area several marks have subsided more than 0.70 m from 1967 to 1975 with the result that the area of maximum measured subsidence has shifted approximately 6 kilometers southeasterly along the Casa Grande-Picacho Peak profile since 1967 (Figure 4). The maximum known subsidence measured in Arizona between 1967 and 1975 has occurred at Picacho where a 1967 National Geodetic Survey Bench Mark, X363, subsided 0.93 m. During that same time period, other marks in the area subsided by amounts exceeding 0.70 m, as illustrated in Figures 4 and 6.

The longest earth fissure in Arizona, 13.8 kilometers in length, which also has a vertical displacement (Figure 4), crosses Interstate Highway 10 between bench marks B and C. The southeastern side of this fissure is now subsiding at the same rate as the northwestern side, 0.09 m per year. An intensified fissure pattern is developing north and south of Interstate Highway 10 within 3 kilometers of the existing long fissure.

The subsiding areas of central Arizona are substantial as shown by Schumann 1974. In Pinal County within the lower Santa Cruz Basin from 1948 to 1967, an area of about 570 square kilometers subsided more than 0.15 m and about 155 square kilometers of this area has subsided more than 0.9 m. In the Stanfield-Maricopa area approximately 200 square kilometers has subsided more than 0.3 m.

Earth Fissures

Earth fissures have existed in parts of Arizona for many years (Schumann-Poland 1969) and (Schumann 1974). The new mapping of these fissures confirms the fact that they are continuing in or near areas of substantial subsidence (Figure 1). Three forms of intensification were noted during the mapping. First, fissures have occurred in new areas, second, fissures are developing en echelon with or parallel to older fissures, and third, older fissures have reopened. These forms of intensified fissuring are expected to continue unless stabilized ground-water levels are achieved.

Conclusions

The coincidence of areas of continued ground-water declines, continued subsidence, and increased earth fissuring support the view that there is a causal relationship begun by ground-water declines. These phenomena are having an adverse impact on habitation and agriculture.

The full significance of ground-water withdrawal, subsidence, and earth fissuring is relatively unknown at this time. Much additional information, primarily costly field surveying, is needed to adequately define this potentially severe problem.

The ground-water withdrawal, subsidence, and earth fissuring occurring in Arizona are broader in scope than existing agencies are able to address.

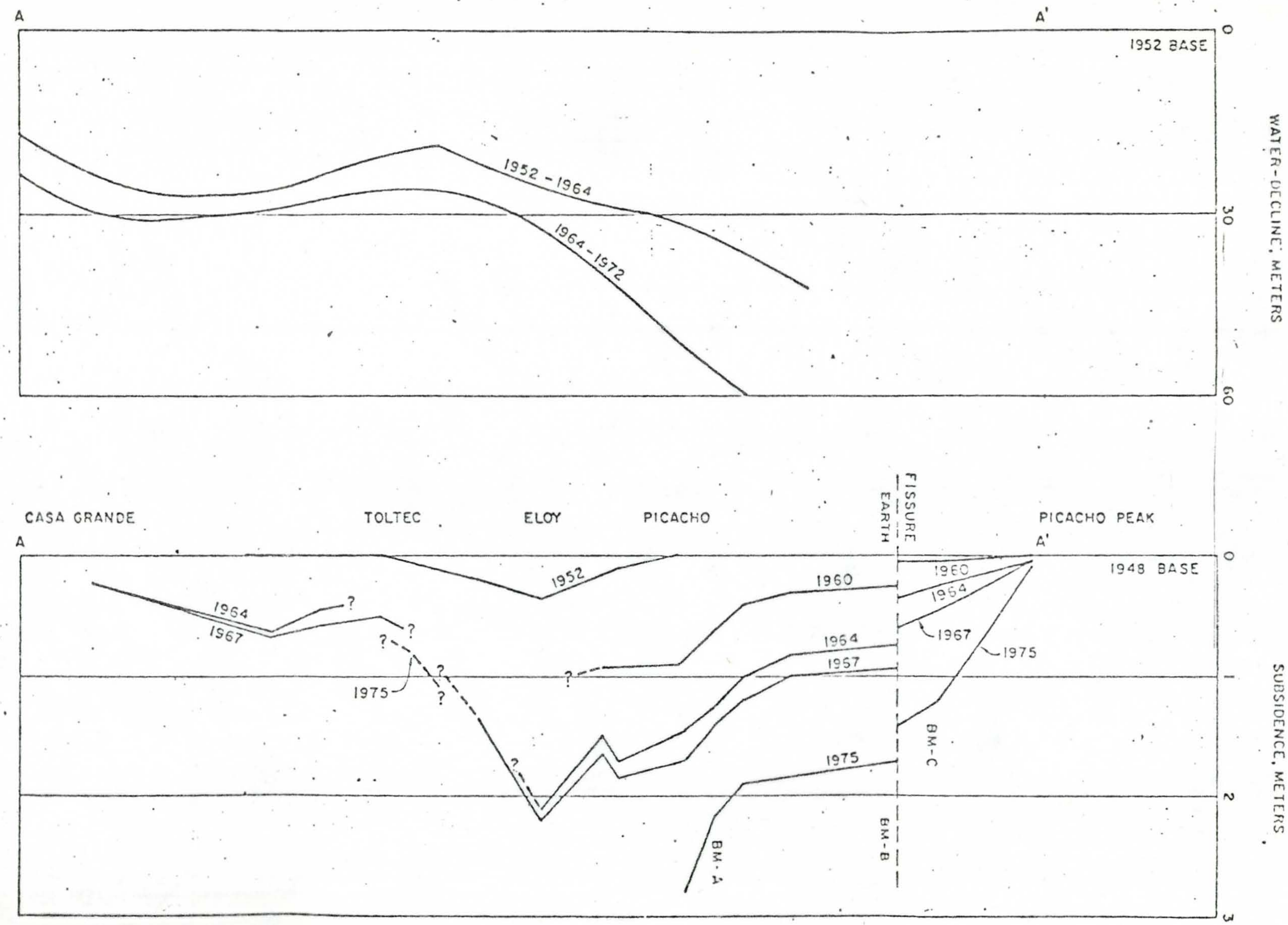


FIGURE 4. PROFILES OF WATER-LEVEL DECLINES AND SUBSIDENCE IN PINAL COUNTY.

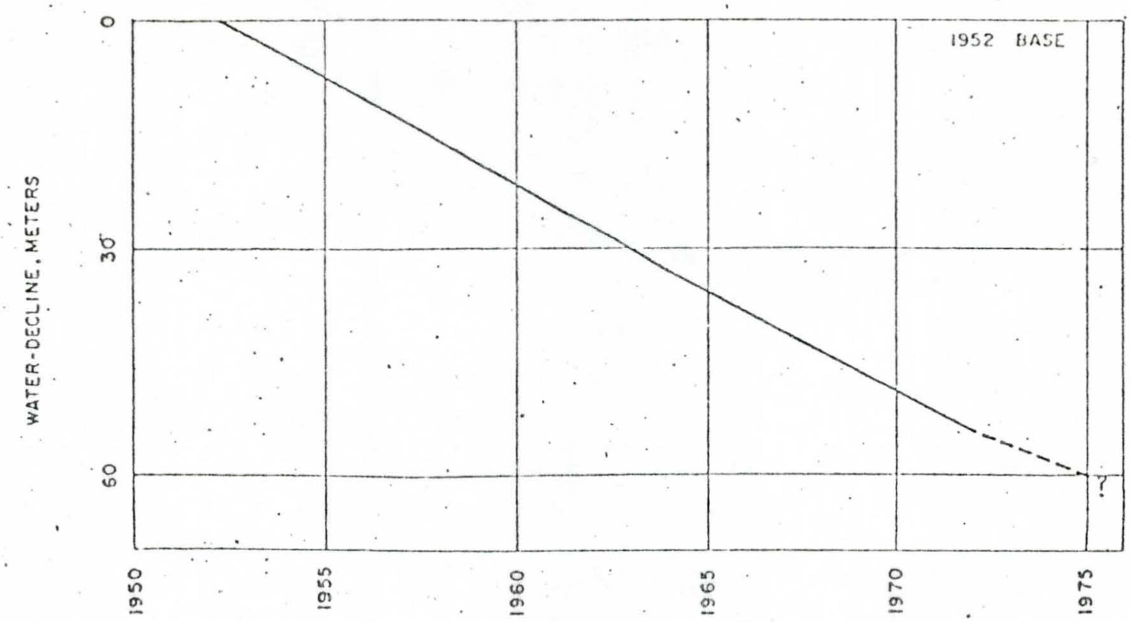


FIGURE 5. WATER-LEVEL DECLINE IN PICACHO VICINITY 1952-1972

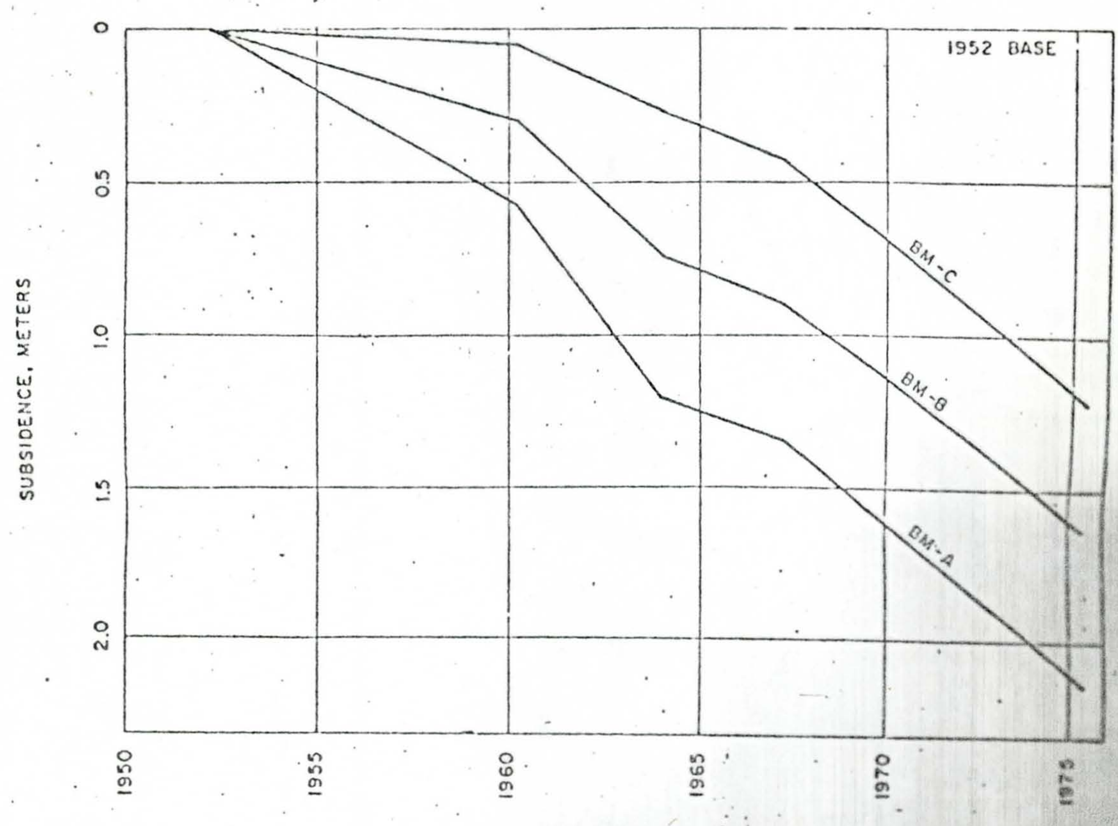


FIGURE 6. TOTAL SUBSIDENCE AT THREE BENCH MARKS IN PICACHO VICINITY. 1952-1975. (FOR LOCATION SEE FIGURE 4)

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FIELDNOTES

From The State Of Arizona
Bureau Of Geology And Mineral Technology

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SUBSIDENCE-FISSURES AND FAULTS
In Arizona

By H. Wesley Peirce

Introduction

Quietly, hundreds – perhaps thousands – of square miles of Arizona's land surface is being lowered by *subsidence.* Peripheral fracturing in the form of earth fissures and cracks is relatively widespread and common. These ongoing, somewhat insidious phenomena have an important influence not only on already-completed engineering structures but on planning for future land use. Implications for the future suggest an increasing entanglement between Arizona's population growth and areas susceptible to subsidence and related hazards.

The Picacho–Casa Grande region of Pinal County is the most intensively-investigated subsidence, fissure and "fault" area in Arizona. Laney, R. L. (U.S. Geological Survey), Raymond, R. H. (U.S. Bureau of Reclamation) and Winikka, C.C. (Arizona Department of Transportation) developed and compiled two important maps, with some text and survey profiles. These items, published in 1978 (see references), are available free of charge from the Arizona Water Commission*. This work impressively demonstrates the magnitude of the problem as evidenced in Maricopa, Pinal and Pima Counties (Figure 1).

The U.S. Geological Survey has undertaken special studies under the direction of geologist Tom L. Holzer. Tom is studying subsidence and fissuring throughout the southwest from Texas to California. He is especially interested in: (1) controls and causal factors that attend the nine-mile-long Picacho fissure zone which occurs between the Picacho Basin and the Picacho Mountains on the east, and (2) learning the extent to which the prediction of future fissuring in susceptible areas of the U.S. might be possible.

General Geologic Setting

The Basin and Range Province, constituting the southwestern half of Arizona, is characterized by broad–to–narrow valleys that alternate with large–to–small mountain ranges. It is the geologic setting of this province (where over 90% of Arizona's population resides) that is conducive to the processes of subsidence, fissuring and "faulting" (Figure 1).

Beneath the valleys are thick sequences of relatively–young, soft sedimentary materials capable of storing large amounts of groundwater within a thousand feet of the surface. This water, combined with rich soils and a long growing season, is supportive of extensive agricultural development (about 95% of Arizona's irrigated acreage is in the southwestern half of the State). However, the valleys or basins terminate laterally against the hard rock ranges. This interface between valley and range constitutes a major geologic and land-use discontinuity that cannot be overemphasized (Vuich and Peirce, 1973).

Arizona Water Commission, 222 N. Central Avenue, Phoenix, Arizona.

Water can be viewed as a geologic material, a part of the overall foundation inherited from the geologic continuum that predates the coming of technological man. Under the surface, it is called groundwater, and it occupies pore spaces in sediments – soft sediments in the case of southern Arizona basins. If the water is removed there is a natural tendency for the finer-grained, soft sediment to become more compact, to occupy less space. The amount of compaction or shrinkage is controlled largely by the volume of sediment dewatered by pumping.

Subsidence

Subsidence is a lowering of the earth's surface caused by processes acting below the land surface. Although subsidence is a result of the interaction of natural earth forces, it can also be man-induced by the large-scale removal of underground fluids, such as, petroleum or water.

Land level changes can be quantified only by repeated, high quality survey measurements at established points. Most likely much of the subsidence in Arizona remains undocumented due to the absence of a network of appropriately-placed survey stations that can be periodically monitored. Fortunately, there are a few adequately- surveyed and monitored regions in Arizona that can

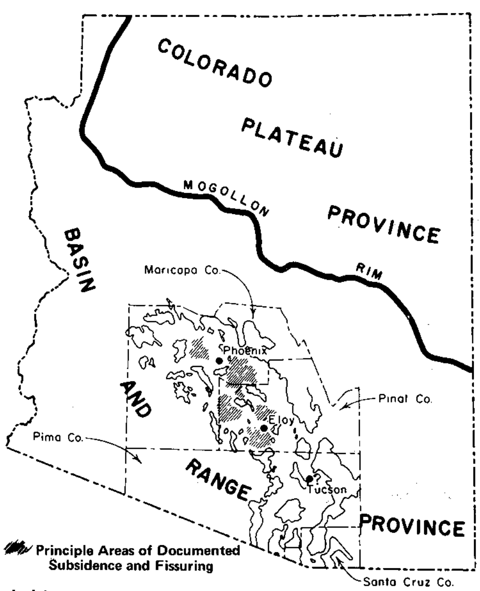


Figure 1, *Subsidence.*

serve as important 'case histories', illustrating subsidence.

In Arizona, in the Basin and Range country, large quantities of water are pumped from the ground. As an example, in 1977 alone, enough water was pumped to cover a football field with a water column over 1,000 miles in height. Groundwater is an integral part of the natural foundation of the earth; when it is removed in large quantities, dewatered earth materials may shrink or compact, thereby lowering the earth's surface (Fig. 2B). How large might this effect be?

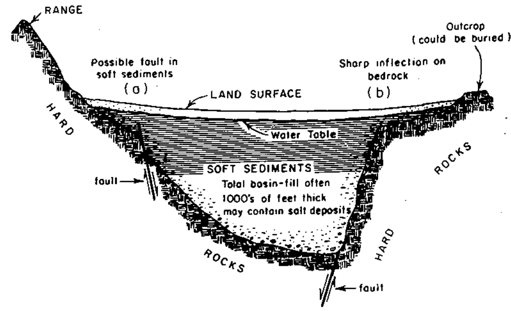
In the Picacho Basin, centered about the town of Eloy, an area of at least 120 square miles has subsided between 7.0 and 12.5 feet since 1952. The maximum average subsidence rate has been calculated at 0.5 feet per year. Importantly, the groundwater decline in this region ranges from about 200 to just over 300 feet for the period 1923-1977 (Laney and others, 1978). Near Stanfield, 12-15 miles west of Casa Grande, an area of about 7 square miles has subsided between 8.0 and 12.0 feet, with groundwater declines up to 450 feet.

These are the regions that represent the best *known* elevational lowering of the land surface in Arizona. Away from this area of relatively-intense monitoring, survey data rapidly decrease. Because there is a direct relationship between water decline and subsidence, decline data are essential for evaluating subsidence potential. Again, the actual demonstration of subsidence requires repeated land-level surveys.

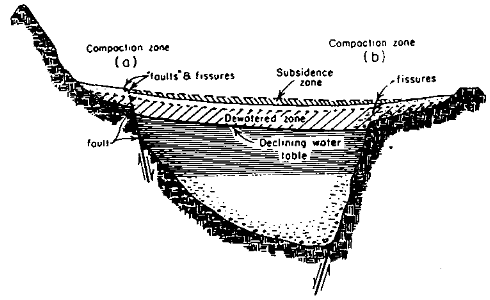
Information is skimpy for the larger Phoenix region. Schumann (1974) documents some subsidence and Laney and others (1978) show important water decline data and the positions of known fissures. Groundwater decline of up to 300 feet beneath portions of Scottsdale and the Arizona Canal suggest a subsidence potential for this region. A potential for fissuring also exists where the dewatered sediments are interrupted laterally along the east side of a north-south Camelback Mountain-Papago Buttes bedrock trend.

Recently, a lady from Pennsylvania, with a retirement house under construction in Arizona, contacted State officials about an item that was printed in a Pennsylvania newspaper. The emphasis of the article was that Arizona was "sinking". Quite naturally she wrote to learn more about what was going on that might affect her future here. Her new home is being constructed in the Sun City area of Phoenix. Utilizing the available data, we note that groundwater decline beneath Sun City and environs is between 200 and 300 feet. This alone is enough to invoke a probability of some subsidence. A close look at data suggestive of the subsurface condition indicates a major northwest-trending irregularity, probably a change from thick valley fill on the southwest to thin valley fill and shallow bedrock on the northeast. This change takes place approximately beneath State Highway 93 from south of Glendale northward to Sun City and beyond. A conservative interpretation would suggest that there is some potential for surface fissuring. Whether subsidence and/or fissuring will ever become a serious problem in the Sun City region cannot be presently determined.

Tucson's water supply is exclusively from groundwater, much of which is pumped from within the same valley as the city is located. Groundwater decline has passed 100 feet in some areas and is increasing with time. Officials concerned with this problem consider that the City may be on the threshold of subsidence. A cooperative program between the City of Tucson and the U.S. Geological Survey is being initiated. Emphasis will be placed on: (1) measuring water level trends, (2) placing compaction recorders in selected wells, (3) remeasuring points of elevation that were accurately established in the past, and (4) adding new leveling stations. Here is a chance to study the effects of groundwater removal in a basin before it has undergone the readjustment process. It has been suggested elsewhere that the potential longer-range subsidence problem in Tucson could be reduced by taking a larger percentage of water from an undeveloped basin to the west.



A. Predevelopment setting with theoretical subsurface marginal conditions (a) & (b).



B. Post-development response to groundwater withdrawal & decline showing dewatering, subsidence & local differential compaction of soft sediments near basin margins (a) & (b).

Figure 2, ***Subsidence.***

Fissures and "Faults"

Earth fissures, as used here refers to relatively-lengthy cracks that develop at the surface in soft soils or sediments. An initial crack, inconspicuous one day, may become a gaping fissure the next. It is reported that the first fissure in the Picacho region was observed on Sept. 12, 1927, after a heavy thunderstorm the previous night (Leonard, 1929). Initially, this fissure (not a part of the present Picacho fissure zone) was about 1,200 feet in length. At the time, this new phenomenon stimulated much discussion and speculation as to its origin.

Fissures, thought to be related to water withdrawal, occur in Cochise, Pinal and Maricopa counties. There are at least 15-fissure areas in the latter two counties, involving over 100 individual fissures.

The Picacho fissure zone, about 9 miles in length, has received the most attention and publicity. Holzer and others (1979) suggest that this zone is unique in Arizona because it consistently reflects vertical offset ranging up to 1.5 feet. The west or valley side is down relative to the east or mountain side. The sharp step or scarp reflects a different kind of failure than the more common pull-apart, or tension fissure. As a consequence of its fault-like appearance, they refer to this feature as the *Picacho fault.* However, Holzer and colleagues are quick to point out that this is not the kind of fault that produces earthquakes. Rather, the "fault" occurred after 1961, as a result of groundwater extraction combined with poorly-understood subsurface controls. The lack of documented earthquakes in this region since 1961 supports their contention. Any claims to local seismicity are believed to stem from mistaking atmospherically-induced shocks (Peirce, 1975; Shakel, 1977; see Dubois, this issue) for earth-generated vibrations (Yerkes and Castle, 1976).

A recent newspaper article, entitled, "Earthquake Fault Line at Picacho," included the statement: "Geologists have discovered a possibly-active *earthquake fault line* (italics ours) caused by groundwater pumping north of Tucson" (Tucson Citizen, Nov. 16, 1969). This terminology, while unfortunate, exemplifies the difficulty of conveying scientific ideas to the public.

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Symposium Offers New Insights Into Porphyry Copper Genesis

By Stanley B. Keith

On April 3 through 6, 1979, the Society of Economic Geologists held a major field conference on Tucson-area porphyry copper deposits, attended by 198 people. The participants heard numerous talks, examined rocks at two operating mines, and inspected surface exposures of one potential mine. The conference was well timed with respect to increased interest in prophyry copper deposits (and in increased copper and molybdenum prices). Three days of the conference were spent in the field examining prophyry copper geology in outcrop, and debating to what extent various models of porphyry copper genesis explained the field observations. A second symposium followed on April 9-10, entitled, "Exploration Geochemistry in the Basin and Range Province", sponsored by the Association of Exploration Geochemists.

John Guilbert, one of the principle organizers of the conference, delivered the opening remarks. Problems addressed included zoning, fluid mechanisms and sources, metal sources and distributions, solution geochemistry, geothermometry, and geobarometry, structure and structural control and areal-regional distribution and occurrence. Denis Norton of the University of Arizona next discussed principles of the convective fluid flow model, and its role in porphyry copper genesis. The model, outlined in Figure 1, involves the following: 1) emplacement of a thermal energy source (magma) into cold brittle host rocks, 2) transport of thermal and mechanical energy away from the pluton heat source into the surrounding countryrock, 3) deformation of the cooling pluton or magma and surrounding countryrocks in the form of fractures that increase rock permeability, 4) flow of hydrothermal fluids, which contain ore-forming components, from source regions some distance away from the pluton heat source, to depositional sites along recently-made fractures near the pluton heat source, and 5) reactions between mineralized fluids and those in the fracture walls to form hydrous-silicate alteration phases which are accompanied by deposition of copper-lead-zinc-bearing sulfide minerals. In Figure 1, the fluid-paths are envisioned as large sub-circular cells which initiate in the wall rocks, flow toward, through and out the top of the pluton heat source. Various combinations of alteration assemblages form, and base metal-bearing sulfide minerals deposit along the path.

Spencer R. Titley of the University of Arizona next examined the complex interplay in space and time of various alteration types and styles which accompanied porphyry copper mineralization. Titley pointed out the increasing importance and role of time in alteration processes which have traditionally relied on space-related zoning concepts, (the now classic Lowell-Guilbert "light bulb" zoning concept, Figure 2). For example, propylitic alteration, which was traditionally regarded as peripheral in the Lowell-Guilbert model, may in fact be superimposed on a former system-wide, early-biotitic alteration event. Similarly, the familiar phyllic or quartz-sericite-pyrite assemblage, traditionally regarded as an envelope around the mineralized core of a porphyry system, also appears to be a consistently-late phenomena, and is not universally present in all porphyry copper sulfide systems. The original, symmetrical alteration shells of the Lowell-Guilbert concept may be severely distorted or modified by rock composition, solution composition and changes in rock permeability which are time-related as well as space-related.

Dick Beane, also from the University of Arizona, summarized the latest results of fluid inclusion studies (mostly on quartz) from various cross-cutting vein types at the Red Mountain, Copper Creek, Santa Rita and Sierrita deposits, which are strategically located at various elevations within the profile of an idealized porphyry system (Figure 1). Results of fluid inclusion data at Santa Rita, Sierrita and Copper Creek indicate systematic changes in salinity and temperature of the hydrothermal fluid. Specifically, early fluids containing higher-dissolved salts, circulated through cracks at high temperatures (800-400° C). Sulfide deposition was not accompanied by formation of the hydrous silicate alteration phases which enveloped these cracks. Later cross-cutting fractures were generally filled by a low-salinity, intermediate-temperature solution, from which copper-bearing sulfides were precipitated. At the Red Mountain deposit, high in the idealized sulfide system on Figure 1, sulfides are associated with later, lower temperature, hypersaline fluids which postdate earlier, higher temperature, low- salinity inclusions. All available temperature data from Red Mt. indicate the fluids were cooler than 450° C. Interestingly, sodium-potassium ratios in the more saline fluid inclusions are similar to sodium-potassium ratios of nearby igneous rock types.

The scale of observation shifted to a more regional flavor in the next talk given by Tom L. Heidrick of Gulf Mineral Resources Company. Heidrick detailed recent developments in his ongoing, structural analysis (much of which was in cooperation with William Rehrig of CONOCO Minerals) of fracture systems in 75 to 50 m.y. plutons, fault-veins and vein and dike swarms. The overwhelming structural theme which emerges from 24 of the 26 districts Heidrick studied is that dikes, veins and mineralized dikes persistently occupy steeply-dipping fractures which strike EW to NE. Non-mineralized fractures consistently strike NW. Because fractures of the same orientation are found regionally in 75 to 50 m.y. rocks, they reflect a stress-field that has persisted for at least 25 m.y. If the dikes and veins fill tensional cracks, the prophyry province either was pervaded by wrench tectonics or by differential vertical uplift and normal faulting at various times within the 25 m.y. interval. Compressively-induced thrust faulting is subordinate to the above two processes.

Fracture systems in "productive" plutons have a definite tendency to "box-the-compass" more so than fractures in "non productive" plutons.

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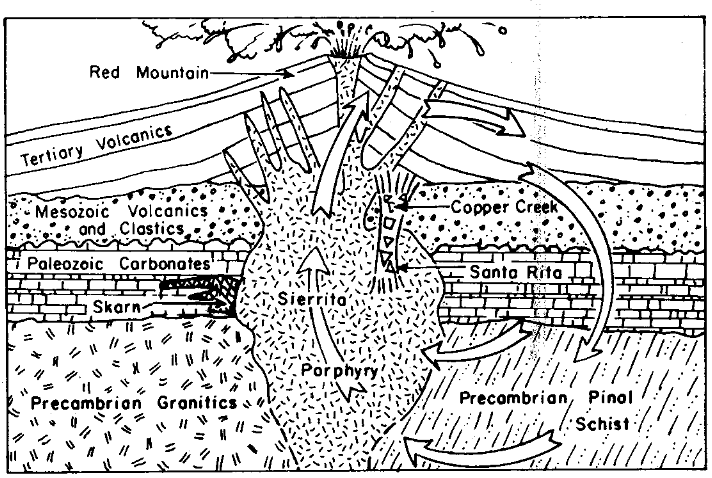


Figure 1, *Symposium.* Schematic cross section of pluton-volcanic complex in host rock analogous to Arizona-New Mexico porphyry copper province. Arrows represent hydrothermal circulation characteristic of permeable pluton and host rock environment, modified after Bodnar (1978).

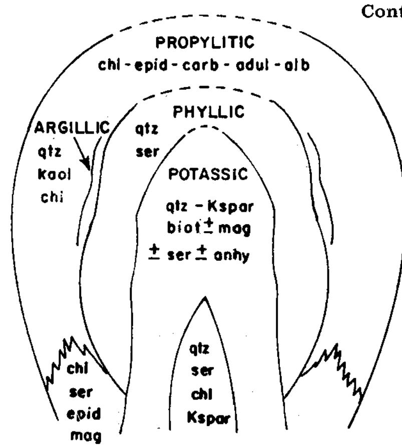


Figure 2, *Symposium.* Schematic drawing of alteration zoning in a typical porphyry ore deposit (from Lowell and Guilbert, 1970). Abbreviations are as follows: biot=biotite; kspar=potassium feldspar; mag=magnetite; anhy=anhydrite; kaol=kaolinite; chl=chlorite; epid =epidote; carb= carbonate; adul=adularia; alb=albite; ser=sericite; qtz=quartz.

SONIC BOOMS

By Susan M. DuBois

Rattling windows, low, rumbling noises and sharp jolts were reported to various government agencies, and to local news media, between January and May, 1979. Over the past few years, similar occurrences have been observed in Tucson, and less frequently, in Casa Grande, Phoenix, Green Valley and Tubac, Arizona (Richard Wood, pers. comm.). Investigation has revealed that *sonic booms,* generated west of Tucson by high-speed military aircraft have caused the shaking and noise.

Medium	Velocity (Ft/Sec)	Remarks	Reference
Air	1,116	at sea level, 59°F	Wiggins, 1969
Air	1,097	at 5,000 ft elev, 41°F	Wiggins, 1969
Air	968	at 65,000 ft elev, 70°F	Wiggins, 1969
Earth	19,690-21,980	Crust	Geology Today, 1973
Earth	26,250-27,890	Upper Mantle	Geology Today, 1973

TABLE 1 *Sonic Booms:* Compressional Shock Wave Velocities

Seismograph Evidence

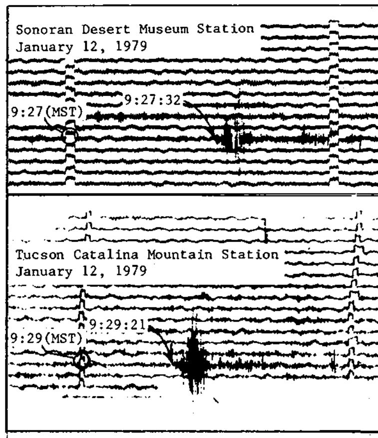
Shock waves travel at different speeds in different media: Generally speaking, the denser the material, the faster the waves travel. The earth (primarily solid) is much denser than the atmosphere (a mixture of gases). Thus shock wave speed is greater in the ground than it is in air (see Table 1).

When the first report of trembling was received at the Geological Survey Branch this year, a check of seismograph records was made at the two local earthquake recording stations 23 miles apart: the Santa Catalina Mountains and the Arizona-Sonora Desert Museum. Both stations had recorded a shock wave. However, the wave arrived at the Desert Museum 109 seconds before it reached the Catalina station. Simple calculations (Figure 1) demonstrate that the wave traveled through air, eliminating the possibility of earthquakes and mine blasts which are both generated in the earth. Thus, an explanation of air shock waves from the west was needed.

A likely cause for the airborne wave was formulated by Richard Wood, Official-in-Charge at the U. S. Weather Service Office, Tucson. In 1975, he had noticed a strong correlation between dates of "rattling and rumbling" calls and unusual occurrences of the jet stream over southeast Arizona. Combined evidence collected independently by Shakel (1976), Peirce (1975), local newspapers and military personnel supported Wood's theory. Supersonic flights occur Monday-Friday between 0700 and 1600 over the Luke AFB gunnery range between Sells, Ajo and Gila Bend (Wood, 1975; Shakel, 1976). Evidently, sonic boom shock waves may travel unusually great distances due to a rare set of circumstances related to atmospheric phenomena.

What is a Sonic Boom?

A sonic boom is a sudden pressure disturbance in the air created when an airplane exceeds the speed of sound. A *supersonic* aircraft cuts through the atmosphere so fast that the air molecules in front of the jet do not have time to move out of its path smoothly. Rather, the air is forcefully displaced, causing extreme local compression and heating of the air molecules (Shurcliff, 1970). Two jolting shock waves are produced, close together in the shape of nested cones; a compression wave (outer cone) originates first at the nose of the plane and a collapse shock



Arrival Time Difference= 109 sec

Distance Between Stations= 23 mi x 5,280 ft/mi= 121,440 ft

Velocity of shock wave= 121,440 ft/109 sec= 1,114 ft/sec

Figure 1, *Sonic Booms:* Seismograms illustrating sonic boom wave arrivals in Tucson vicinity on January 12, 1979. Shock wave velocity of 1,114 ft/sec was calculated. Comparison with Table 1 indicates that this value falls within the range of soundwave air travel.

(inner cone) forms second at the tail (Shurcliff, 1970; Wiggins, 1969). These 'waves' spread in all directions at a rate equaling the speed of sound – 760 mph at sea level, ranging to 650 mph at 65,000 ft where the air is less dense. The intensity of the sonic boom and the distance over which it dissipates depends on several parameters: altitude, weight, length, shape and speed of the airplane; maneuvers such as climbing and diving; and atmospheric conditions. Despite a common misconception, the wave front, or boom, is continuously produced along the flight path, as long as the aircraft is exceeding the speed of sound. Therefore, a 30 to 40 mile-wide strip of land is usually subject to boom vibration along the entire supersonic path. Generally, a sonic boom cannot be heard or felt more than 30 or 40 miles from its source (40-60 miles for a Concorde jet). The intersection of the conical shock wave front with the ground surface at any given instant forms a parabola, along which the sonic boom is *heard* and *felt* simultaneously. Only people situated along this parabola experience a loud bang accompanied by building vibration. However, under special circumstances, the *vibrations* may be felt beyond the usual distance of 30-40 miles from the aircraft source.

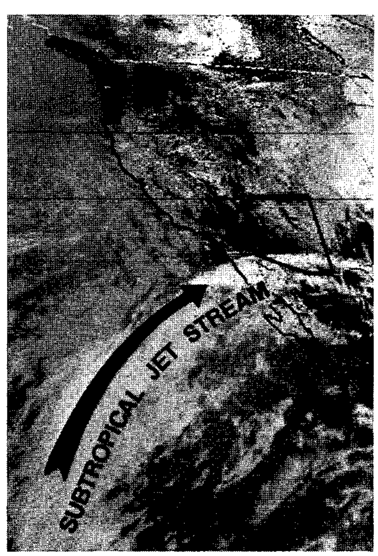


Figure 2, *Sonic Booms:* March 22, 1979 infrared image taken by the Geostationary Operational Environmental Satellite (GOES) approximately 22,000 miles. Jet stream winds reached 200 knots (230 mph) over the Tucson area, resulting in widespread, jolting sonic booms generated by jet activity in the vicinity of Sells, Arizona (55 mi SW of Tucson). Photo courtesy of Richard Wood.

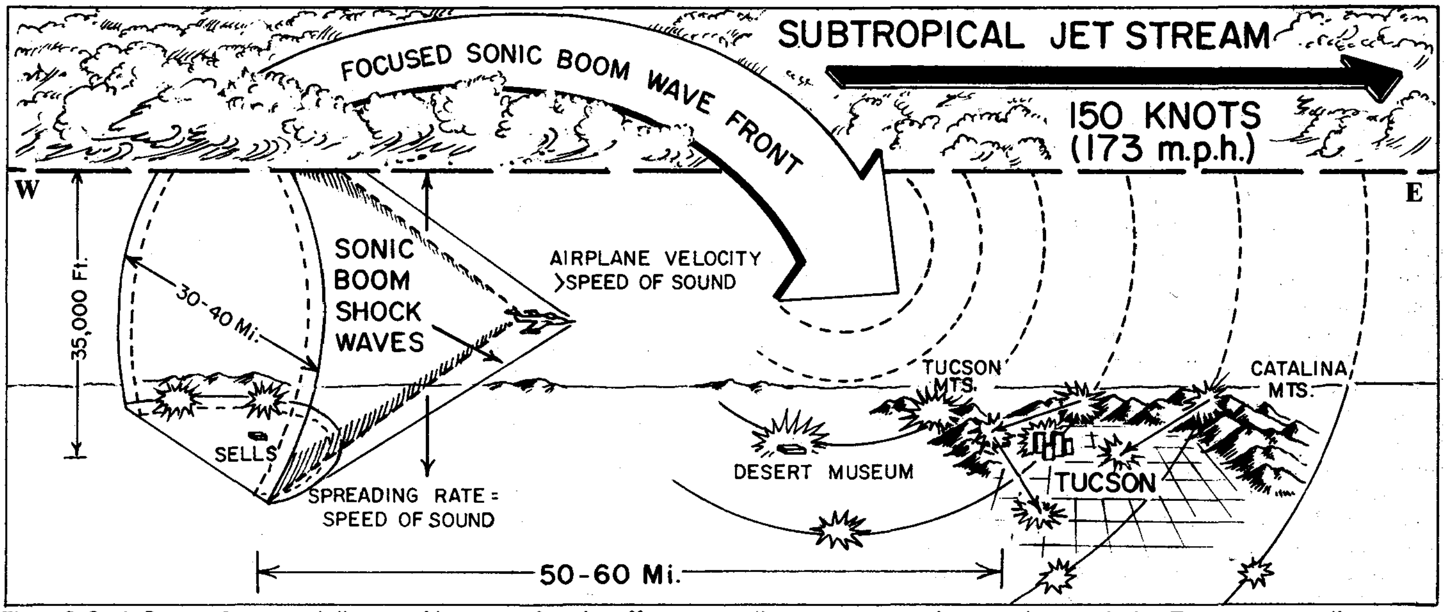


Figure 3, *Sonic Booms:* Conceptual diagram of jet stream focusing effect on sonic booms in the Tucson area. Boom activity in Tucson requires that 1) Supersonic flights occur (generally, weekdays between 0700 and 1600 over Luke AFB gunnery range – see Woods, 1975), 2) Jet stream lies over supersonic operations and the Tucson metropolitan area (generally possible between December and May), and 3) Jet stream wind speeds exceed 100 knots (115 mph).

What is a Jet Stream?

A jet stream is a ribbon of fast-moving winds, commonly composed of cirrus clouds at an altitude of 30,000-35,000 ft in winter and 35,000-40,000 ft in summer. In our hemisphere, there are two jet streams: one in the mid-latitudes (30-50° N) and one in the subtropics. Both jet streams vary in their orientation and exact location throughout the year, although their airflow is always eastward. Between December and May, weather conditions occasionally cause the mid-latitude stream to dip down into northern Arizona. Likewise, the subtropical jet stream sometimes swoops up from the south Pacific, across Baja, California and into southern Arizona (Figure 2). On extremely rare occasions, both jet streams merge over Arizona.

Jet Stream Influence on Sonic Booms

Current theory (Richard Woods, pers. comm.) predicts that the presence of the subtropical or combination jet stream over the southern portion of Arizona serves to channel, or focus sonic booms eastward over great distances. Most commonly, supersonic flights over Luke AFB gunnery range (near Sells, Arizona) produce booms felt in Tucson, when an east-west jet stream orientation exists (Figure 2). If the airflow trends more northeasterly, south Phoenix might possibly experience a few booms, although the greater distance from the gunnery range decreases this likelihood. An east-west orientation further south may cause boom effects in Green Valley and Tubac, if transcontinental supersonic flights from a California AFB to Texas coincidentally occur (Woods, pers. comm.).

Figure 3 is a schematic diagram of the peculiar effects of sonic booms in the Tucson area, governed by jet stream activity. When the conical shock wave front, generated below the warmer jet stream air, intersects the jet stream interface, Wood believes that the boom waves are channeled into the Tucson area. Jet-stream wind speed and stratified temperatures within the air masses affect the path and intensity of the booms hitting Tucson buildings. Most likely, a series of simple reflection and refraction interactions combine to form a more complex arched pathway for the booms which reach Tucson (Richard Seebass, pers. comm.). Geographical features surrounding the city enhance sonic boom activity because waves ricochet from mountain faces into town and vice versa. Wind speeds must reach 100 knots (115 mph) for western and southern portions of Tucson to feel sonic boom effects. When jet stream air exceeds 150 knots (173 mph), the whole city experiences vibrations. Heavy jolts are felt above 175 knots (203 mph). Supersonic activity occurs over specific intervals only (Shakel, 1976; Wood, 1975). Thus, a rare set of circumstances must exist to produce sonic boom effects at a distance of 100 miles from the aircraft source.

Assuming that detection and recording instruments are functioning properly at both local seismograph stations, quick distinction between air shocks and earth shocks is possible through the coordinated efforts of Peter Kresan (Desert Museum Geologist), Marc Sbar (U of A Seismologist) and his seismology graduate students, and Susan DuBois (Geological Survey Branch Geologist). The Catalina station seismographs are housed at the Bureau of Geology and at the Department of Geosciences (U of A). Further cooperation with Dick Wood (Tucson Weather Service Office) will enable local scientists to advise the public and the military when atmospheric conditions make sonic boom effects probable in the metropolitan area.

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Subsidence continued

An interesting debate emerges: Because the Picacho feature looks like a fault, but is not a source of earthquakes, should it be called a fault? In this case it is the Bureau's intention to refrain from the unqualified use of *fault.* To the extent possible, we will not consider as faults the various land slippages that might leave scarps or steps attributed to processes not accompanied by earthquakes. In the case of the Picacho phenomena, it is very important to recognize the fact of vertical offset. It is important because the damage potential to man-made structures is greater than that associated with the more commonly-observed, "simple" tension or pull-apart fissures. Consequently, we will refer to the *Picacho fault* of Holzer and others as the *Picacho "fault".* The Picacho fissure or "fault" zone passes across I-10 and beneath the bed of the Southern Pacific Railroad. Because of this, periodic repairs are made to both transportation arteries. Recent resurfacing has, at least temporarily, subdued the visible (down-to-the-west) offset.

Additional work by Holzer (1978, subsequent to Holzer and others, 1979) was designed to investigate the nature of the subsurface controls. Holzer speculated that a buried fault might be cutting an older portion of the soft sediments – a fault that does not reach the surface. Holzer's model suggests that this preexistent fault influences groundwater–dewatering patterns, which in turn permit the stress build-up that is responsible for the Picacho surface "fault". This concept is depicted in Figure 2 B(a).

Fissures, in general, are believed to form above certain buried hardrock irregularities that control soft sediment thicknesses along basin margins (Fig 2 A(a). These irregularities frequently can be delineated by appropriate geophysical techniques. Various studies are underway in connection with alternative aqueduct alignments for the delivery of Central Arizona Project (CAP) water to the Tucson area.

Subsidence and related phenomena are examples of cause and effect in that an act of unbalancing begets an act of readjustment. In this case a great deal of geologic time was involved in establishing the original condition of balance, whereas the unbalancing and readjustment processes occurred in less than one generation of humankind. The act of unbalancing continues unabated; therefore a logical conclusion is that readjustment must follow.

Through FIELDNOTES, we will attempt to provide pertinent new information about subsidence-related matters in Arizona as it arises.

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Symposium continued

Heidrick suggested this phenomena implied fracture systems of local derivation which were radially or concentrically superimposed on those of more regional extent. The greater fracture abundance may represent the dynamic consequence of hydraulic fracturing in the vicinity of fluid-saturated plutons, where fluid pressure in the pluton exceeded the pressure exerted on the system by overlying rocks above the fluid-saturated pluton. The higher fracture density would correspondingly increase permeability and allow greater amounts of base metal deposition per unit volume.

The last talk by Stan Keith, of the Bureau of Geology and Mineral Technology, was perhaps the broadest in scope. In his view, porphyry copper deposits are part of a metallogenic spectrum that is sensitive to chemistry of time-related igneous rocks. This is supported by systematic variations of metal ratios in economic sulfide systems with alkalinity (sodium and potassium content) of time-related igneous rocks. Sulfide systems associated with time-related calcic magmas are zinc and copper-rich while those associated with more alkalic rocks (particularly potassic alkalic rocks) are more lead, molybdenum and gold rich (see Fieldnotes, v. 8, no. 1–2, p. 12, Figure 6). Similar variation of metal ratios in igneous rocks at trace metal concentration levels with the alkalinity of those igneous rocks also supports the above idea. Because alkalinity (specifically potassium content) of an igneous rock suite can be systematically related to subduction zone geometries, it follows that metals may be similarly related to subduction-derived magmas.

The occurrence of the porphyry copper cluster in southeast Arizona, according to Keith, was a fortunate coincidence involving a number of phenomena. The phenomena included: 1) pre-existing WNW to EW-trending, deep-seated basement flaws of the Texas zone, 2) subduction, 3) increased convergence rates nearly 80 m.y. ago which induced flattening of the underthrusting oceanic slab, 4) the shallowing slab produced calc-alkalic copper-bearing magmatism under the region from 70 to 50 m.y. ago, 5) the increased strain rates and a changing stress-field caused the Texas Zone flaws to move in left shear (see Fieldnotes vol. 8, no. 1–2, p. 12, Figure 5B), and 6) the left shear movement created deep-seated ENE-trending tensional zones that reached deep into the earth's upper crust and facilitated upward passage of magmas and volatiles, ultimately forming the porphyry copper deposits (Figure 4). Alone, each of the above phenomena were necessary but not sufficient for the occurrence of the prophyry copper cluster; in combination, however, they were sufficient. And, as a result, the region's inhabitants find themselves with a vital copper resource, the largest in the world.

Each of the introductory speakers emphasized different sets of working hypotheses to explain areas highlighted in John Guilbert's introduction. With respect to zoning, virtually all of the speakers stressed the emerging role of time in the alteration process. It is increasingly apparent that phyllic alteration (quartz-sericite-pyrite) consistently postdates earlier

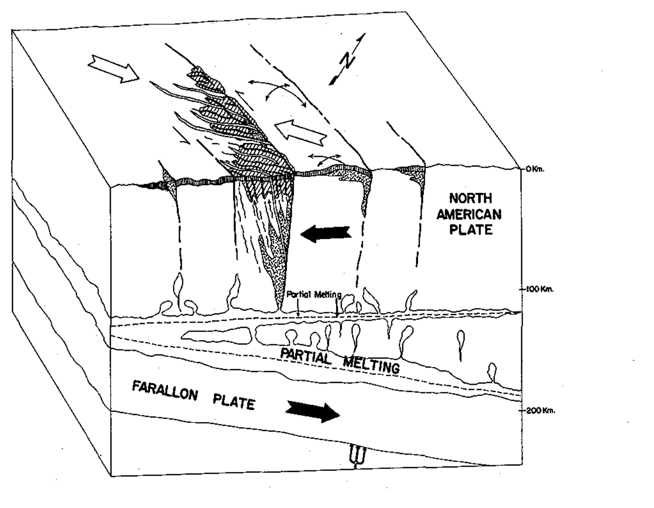

Figure 3, *Symposium.* Plate tectonic setting of SE Arizona prophyry copper deposits (75-50 m.y. ago).

potassic-propylitic assemblages of the landmark Lowell-Guilbert model (Figure 2). Norton and Beane would suggest that the phyllic alteration occurs late in the cooling history of the sulfide system when fluids containing near surface groundwaters flooded the sulfide system. Keith, on the other hand, would argue that the common, irregular distribution and occasional absence of phyllic alteration may imply it is not necessarily a consequence of porphyry copper mineralization, whereas potassic or propylitic types are.

With respect to fluid sources and transport, all speakers agreed that fracturing and permeability were of prime importance in localizing economic amounts of sulfide mineralization. This stems from the observation made by all of the field trip participants – that over 90% of the sulfide mineralization occurs in cracks. Norton, Beane, Titley and Heidrick, emphasized the vital role plutons have to play as agents of fracturing. Keith and Heidrick stressed the role that regional fracturing has to play, and would agree with Norton and Beane that in the vicinity of prophyry copper deposits, plutons and/or regional fracture intersections enhance fracture density, increase permeability, and thereby, increase the chance of a porphyry occurrence. Norton and Beane suggest fluid circulation is the inevitable consequence of pluton emplacement, which provides a heat source to convect fluids from the intruded wallrocks laterally toward the pluton. For Norton 95% of the fluids and an undetermined but large amount of metal ore are probably derived from the surrounding wallrocks. Consequently, the hydrothermal fluid which deposited the metals was presumed to be largely derived from groundwaters of meteoric affinity. Keith would counter that much of the fluid and metal is evolved from large calc-alkalic plutons at depth, and hence has a magmatic character. Overprint by meteorically-derived waters at metal depository sites high in the crust would obscure the former magmatic character of the fluid.

The barren-verses-productive sulfide system problem – the problem of why some sulfide systems are large copper producers and why other superficially-similar ones are not also has different solutions. Norton and Beane would submit that productivity may be related to permeability. That is, productive systems presumably have a greater fracture density than those in non-productive systems. If permeability is high, fluid circulation and perhaps fluid scavanging ability of metals from the fractured countryrock is increased. Permeability is heavily influenced by the ability of a pluton or regional tectonics to fracture rocks at the crucial time of mineralization – the time of intrusion of a pluton heat source. Keith debated that while fractures are crucial to provide open spaces for sulfides to fill, the fluid which fills them contains a chemistry that is controlled by chemical conditions in the source region of the fluid. Because of the similarity of metal ratios in time-equivalent sulfide systems and igneous rocks, Keith infers a pluton source region. Porphyry copper deposits are all associated with calc-alkalic plutons while the so-called barren systems are associated with more alkalic rocks and are distinctly more lead-zinc rich relative to copper. For Keith the bulk metal content of the more alkalic magmas precluded porphyry copper development because the more alkalic magmas simply did not contain enough copper.

These contrasting ideas permeated the field conference and indicated that prophyry coppers still defy a completely-rational explanation. It is interesting to see how much theory has evolved from the now classic Lowell and Guilbert porphyry copper model of 1970. Undoubtedly, we will have even more hindsight ten years from now. Certainly the next decade will introduce other significant discoveries and hypotheses that will force us to revise our current concepts of porphyry copper genesis.

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NOTICE

All unpatented mining claims located *before* October 21, 1976 must be recorded with the U.S. Bureau of Land Management by October 22, 1979 (Section 314 of P.L. 94-579: Federal Land Policy and Management Act). Claims located *after* October 21,1976 must be recorded 90 days from date of location. BLM address: Valley Center-Van Buren St. & Central, Phoenix, Az. 85073 (261-3706).

Geothermal Energy In Arizona

By Alice Campbell

The word "geothermal" is from two Greek words, "ge(o)" meaning earth, and "therme" meaning heat; geothermal energy is simply the natural heat from the deep interior of the earth. Arizona lacks such blatant examples of geothermal energy as geysers, active volcanoes or natural vents belching steam. Instead, Arizona has a rather modest collection of moderately – hot springs and wells, with abundant physical and chemical evidence of enormous amounts of near-surface usable heat energy. About 14 million years ago, southern Arizona started to break up, and areas like the Tucson and Phoenix basins began to sink. The end result of this crustal breakup is high heat flow.

The Geothermal Group of the Bureau of Geology & Mineral Technology has published a preliminary map of geothermal resources of Arizona, and is now collecting detailed information on how this heat is distributed in specific areas. Some of the areas under investigation include the Safford – San Simon basin, the Willcox, Tonopah, Hyder, Tucson and Phoenix basins, the Yuma area, the Kingman area, and the Springerville–St. Johns area (Although the Springerville–St. Johns area is on the Colorado Plateau, volcanism in the area has been repetitive for the past several million years, suggesting that the area has a long-standing association with a very deep-seated heat source). The Geothermal Group has been collecting data including detailed measurements of well temperatures to help establish the rate of heat flow in these different areas, water samples to find chemical clues to the temperature and movement of water within the basins, and existing data as background for these studies. Upon recommendation of the Geothermal Group, the Bureau of Reclamation is drilling heat-flow holes in selected geothermal anomalies, beginning in Springerville.

The results obtained so far from the various investigations indicate that large volumes of moderately–hot water (90 - 300°F) may be found at great depth in practically all of the deep basins in Arizona. Such waters could be used for heating and cooling communities or large buildings, for agriculture or food processing and for some industrial processes such as pulp and paper processing. A high-temperature reservoir possibly suitable for electric power generation has been identified at Clifton. Others may exist about 10,000 feet beneath most of the deep basins. Right now, these resources are unused, but existing technology could be used to develop them.

Mining and Mineral Resources Research Institute

By William H. Dresher

The Surface Mining Control and Reclamation Act of 1977, a bill originally authored by Congressman Morris K. Udall, authorized the federal government to select qualified states, to implement Mining and Mineral Resources Research Institutes. The State of Arizona was one of 22 states recently chosen to establish such an institute. This selection was based on the present mineral resources educational and research programs in both the College of Mines and the Bureau of Geology and Mineral Technology at the University of Arizona. The Bureau is a state agency and a Division of the University.

The federal program is administered by the United States Department of the Interior and, by the choice of the Secretary of the Interior, is assigned to the Office of Surface Mine Reclamation and Enforcement (OSM), a new agency also created by PL 95-87.

The purpose of the Mining and Mineral Resources Research Institute (MMRRI) program, as prescribed by Title III of the Act, is to enable the state institutes to conduct research, investigations, demonstrations and experiments on mining and mineral resources within the Institute's authorized regions. In addition, the Institute is responsible for the training of mineral engineers and scientists through the formal educational programs of the College and the research conducted under the auspices of the Institute.

The initial appropriation to the Arizona MMRRI was $270,000, of which $160,000 has been designated for use as scholarships, graduate fellowships and post doctoral fellowships. In addition, $110,000 was designated for institutional support. The Arizona MMRRI is currently competing with the other twenty-one institutes for $3 million in federal funds which have been made available for fiscal year 1979 to implement research projects in the following areas: mineral; exploration; extraction; processing; development; technology; supply and demand; conservation and best use of available supply; economic, legal and social aspects; reclamation; and mineral research and demonstration projects of industry-wide application. The Arizona MMRRI has submitted twenty-one proposals totalling $977,907 to OSM.

The Arizona MMRRI is directed by Dr. William H. Dresher who is also Dean of the College of Mines and Director of the Bureau of Geology and Mineral Technology. The formalized administrative units under the Arizona MMRRI are the following: the Geological Survey Branch and the Mineral Technology Branch of the Bureau; the Department of Mining and Geological Engineering, the Department of Metallurgical Engineering, the Department of Chemical Engineering of the College; and the Mine Reclamation Center.

The Mine Reclamation Center is a newly-formed group established under the Arizona MMRRI to plan, coordinate and implement interdisciplinary research in the area of mineral land reclamation. The University of Arizona units presently cooperating in the operation of the Center are: The College of Agriculture, the College of Architecture, the College of Mines and the Office of Arid Lands Studies. Each of these groups currently has projects underway in the area of the technology of mined land reclamation. Dr. Fred S. Matter, of the College of Architecture, is the chairman of the interdisciplinary management committee for the Center.

McDowell Map Series

The latest in a series of maps on the McDowell Mountains Area is now available from the Bureau of Geology. *Ground Water* designates water reserves (well data and ground water conditions) in a 50-square mile area northwest of Scottsdale. *Material Resources* includes an evaluation of selected consolidated and unconsolidated rocks and their possible uses. Other maps already completed are *Geology, Landforms, Land Slopes* and *Caliche.* Four additional maps *(Geologic Hazards, Excavation Conditions, Waste Disposal* and *Construction Conditions)* are currently being prepared. The entire folio of 10 maps, scaled at 1:24,000, is expected to be completed by the end of the year.

"Environmental Geology of the McDowell Mountains Area, Maricopa County, Arizona" is a study conceived and prepared by Arizona State University in cooperation with the City of Scottsdale, with drafting, editorial and publication assistance from the Bureau of Geology and Mineral Technology.

Maps are available for purchase from the Bureau of Geology for $1.25 per map, plus handling charge. The *Geology* and *Landforms* Maps are being sold as a unit for $2.50. The complete set of maps will sell for $10.00. Payment by check or money order must accompany each request; cash will be accepted for over-the-counter orders.

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FIELDNOTES
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Bureau of Geology and Mineral Technology
Director .... William H. Dresher
State Geologist....... Larry D. Fellows
Editor.............. Anne M. Candea

State of Arizona
Bureau of Geology and Mineral Technology
845 N. Park Ave.
Tucson, AZ 85719
(602) 626-2733

1084

MARICOPA COUNTY
FLOOD CONTROL OFFICE
3325 WEST DURANGO
PHOENIX AZ 85009