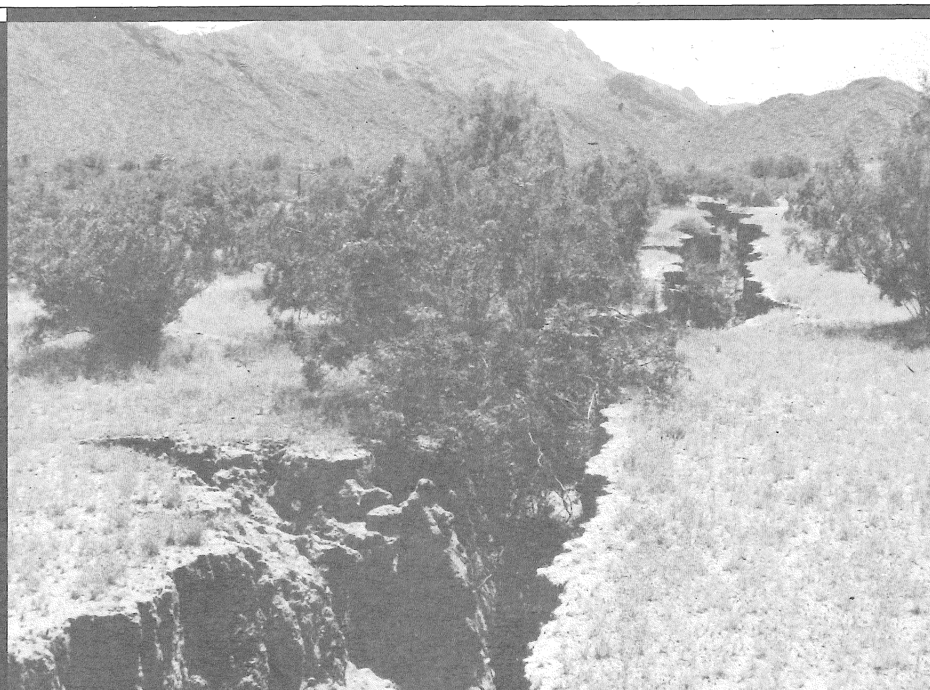
LAND SUBSIDENCE
AND
EARTH FISSURES
IN ARIZONA



Steven Slaff

Arizona Geological Survey
Down-to-Earth Series 3
1993

Arizona Geological Survey

The Arizona Geological Survey (AZGS) became a stand-alone State agency on July 1, 1988, in accordance with Senate Bill 1102, which was enacted in 1987. The purpose of the AZGS is to encourage and assist stewardship of lands and mineral resources in Arizona by conducting scientific and investigative research and providing geologic information. Responsibility for regulating the drilling and production of oil, gas, geothermal resources, and helium was assigned to the AZGS on July 1, 1991.

The Office of the Territorial Geologist was established by the Territorial Legislature in 1881. Its primary duties were to collect and provide information about mineral resources. From 1893 until statehood in 1912, Territorial Geologists were affiliated with the University of Arizona and its mineral-testing laboratory, known informally as the "Bureau of Mines." A 1915 statute created the Arizona Bureau of Mines as a State agency administered by the University of Arizona, continuing, essentially unchanged, the functions of the Territorial Geologist and "Bureau of Mines." Data collection and research activities continued to be concentrated on mineral resources. In 1977, the agency's enabling legislation was modernized and its name was changed to the Arizona Bureau of Geology and Mineral Technology. It continued to be administered by the University of Arizona. The agency was charged with investigating geologic hazards and limitations, as well as the geologic framework and mineral resources of Arizona, in anticipation of population growth and increased competition for and conflict over land, water, mineral, and energy resources.

AZGS geologists prepare geologic maps of Arizona; investigate the State's geologic framework; conduct research on Arizona's geologic hazards and limitations, as well as its mineral and energy resources; compile data; and maintain a geologic library and a repository of rock cuttings and cores. AZGS geologists regularly conduct cooperative projects with Federal, State, and local agencies and work closely with university faculty and graduate students on projects within Arizona. Advisory committees for environmental and engineering geology, mineral resources, and earth science education provide program guidance.

The Arizona Geologic Information System (AGIS) includes several databases: AZGS library holdings; AZMIN, which contains mining production data, mine names, and mineral-related references; AZAGE, a compilation of radiometric age determinations; and AZGEOBIB, a comprehensive bibliography of more than 11,000 references on Arizona geology. The AZGS publishes maps, reports, and *Arizona Geology*, a quarterly newsletter. A list of available publications may be obtained from the AZGS at the address listed below. The AZGS library is open to the public during normal working hours.

To obtain copies of this publication, contact the Arizona Geological Survey, 845 N. Park Ave., Suite 100, Tucson, AZ 85719-4816; phone: (602) 882-4795.

Land Subsidence and Earth Fissures in Arizona

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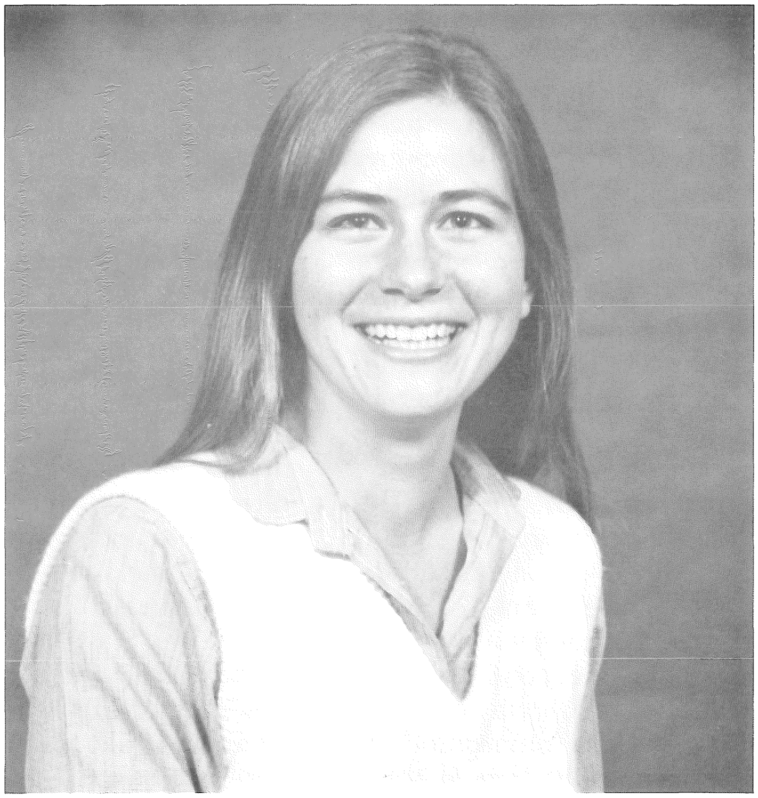
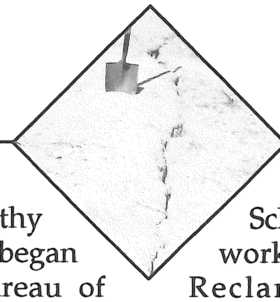


Dedicated to the memory of

CATHY SCHULTEN WELLENDORF

1956-1988

PREFACE



Land subsidence and earth fissuring have occurred in large portions of southern Arizona, where they have caused a variety of structural damage and land-management problems. As Arizona's population continues to increase, so will the demand for ground water. Subsidence and earth fissuring will continue, extend into new areas, and create additional problems. The purpose of this report is to describe, in terms that are understandable to persons who are not trained in geology, what land subsidence and earth fissures are, why they develop, where they occur, what kinds of problems they create, and what can be done about them.

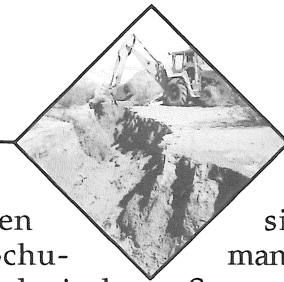
This report is dedicated to the memory of Cathy Schulten Wellendorf. Cathy developed a deep interest in applied geology while working on a bachelor's degree in geology at the University of Dayton. She continued her education in applied geology by completing a master's thesis, "Environmental Geology of the Tempe Quadrangle, Maricopa County, Arizona," at Arizona State University. Cathy subsequently was a coauthor of a report with the same title that was published by the Arizona Geological Survey as Geologic Investigation Folio GI-2.

In 1980, Cathy Schulten Wellendorf began working at the U.S. Bureau of Reclamation's Arizona Projects Office, where she planned and conducted numerous applied geologic investigations, including studies of earth fissures in the Apache Junction and Picacho areas. In addition, she served as lead geologist for the Stewart Mountain Dam Modification Project from 1984 until her death in 1988. In her memory, Cathy's family established the Cathy Wellendorf Memorial Fund with the Arizona Geological Survey. The fund is used to support engineering and environmental geology projects and activities. This report is dedicated to Cathy's memory because of her experience and strong interest in applied geology, including land subsidence and earth fissures.

Steven Slaff began working at the Arizona Geological Survey in 1988 to investigate earth fissures in south-central Arizona. I asked him to prepare this report because of the understanding of earth fissures that he has developed. The Cathy Wellendorf Memorial Fund provided part of the financial support that was needed to prepare and publish this report.

Larry D. Fellows
Director and State Geologist
April 1993

ACKNOWLEDGMENTS

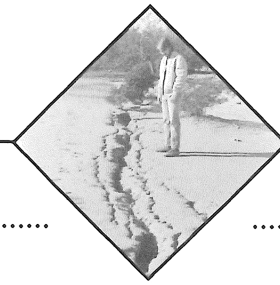


Preparation of this report was facilitated by a grant from the Cathy S. Wellendorf fund, administered by the Arizona Geological Survey. I am honored to be the first recipient of research support from this fund, which commemorates the work and interests of Ms. Wellendorf.

Assistance from several individuals enhanced this report. Discussions with Don Pool and Mike Carpenter of the U.S. Geological Survey and Don Helm of the Nevada Bureau of Mines and Geology clarified certain aspects of compaction, subsidence, and earth-fissure formation. Paul Lindberg, consulting geological engineer, provided a copy of his report on Devil's Kitchen sinkhole. Herb Schumann of the U.S. Geological Survey and Rob Genualdi of the Arizona Department of Water Resources provided photographs that were used as figures. Larry Fellows and Phil Pearthree of the Arizona Geological Survey critically reviewed the manuscript. Evelyn VandenDolder and Emily Creigh carefully edited the text; Evelyn also designed the layout. Pete Corrao skillfully drafted the figures and designed the cover. I sincerely appreciate the contributions of each individual.

Steven Slaff

CONTENTS



Introduction 1

What Is Subsidence? 1

Which Areas in Arizona Are Subsiding? 2

What Is Pumping Subsidence? 4

Where Does Pumping Subsidence Occur? 6

What Are the Effects of Pumping Subsidence? 8

Effects on Structures 8

Effects on Natural Systems 9

Can Pumping Subsidence Be Stopped? 10

What Is an Earth Fissure? 11

What Is the Life Cycle of Earth Fissures? 13

Where Do Earth Fissures Develop? 16

What Are the Effects of Earth Fissures? 17

Effects on Structures 17

Effects on Natural Systems 18

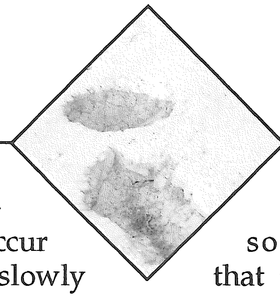
Can Earth-Fissure Formation Be Stopped? 19

How Can the Hazards of Subsidence and Earth Fissures Be Reduced? 20

Conclusion 22

Selected References 22

INTRODUCTION



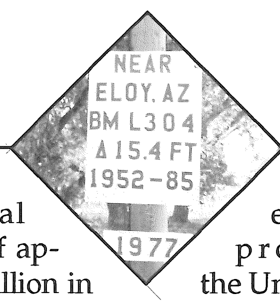
During a recent summer thunderstorm in a rural part of Pinal County, a man heard a loud rumbling that he could not identify. He walked in the direction of the sound, from his house to a small artificial pond nearby. The pond was usually dry, but that night it was full of water from previous storms. In the dim light the man saw a crack in the ground at the edge of the pond. The roar he had heard came from water pouring into the crack. As he watched, the crack grew, extending across the pond toward him and the back porch of his house. In less than a minute, more than 100,000 gallons of water disappeared into the crack, emptying the pond. At the same moment, the crack quickly lengthened and damaged the man's house and driveway.

This man was one of very few people to witness the formation of an earth fissure. Earth fissures, like the one pictured on the cover of this report, are related to land subsidence. Both phenomena are examined in the following pages.

The Earth's surface may seem stable and unchanging, but it is actually subject to many disturbances. Some occur so infrequently or slowly that they are easily ignored. Fortunately, most geologic conditions have minor impacts on people and property. Normal geologic processes, however, can become **geologic hazards**. The *Glossary of Geology* defines a geologic hazard as a "geologic condition or phenomenon that presents a risk or is a potential danger to life and property. Examples include landsliding, flooding, earthquakes, [and] ground subsidence" (Bates and Jackson, 1987, p. 271).* Monetary losses caused by geologic hazards amount to millions (and frequently billions) of dollars in the United States every year.

**A name(s) and date in parentheses identify the author(s) and publication date of a book, article, or report that is the source of the information just presented. It is a method of giving an abbreviated citation. Complete bibliographic information is included in the Selected References section beginning on page 22.*

WHAT IS SUBSIDENCE?



Subsidence is the downward movement or sinking of the Earth's surface caused by removal of underlying support. The movement may be slow or fast, and it may affect a large region (thousands of square miles), a medium-sized area, or a local area (smaller than 1 acre). Tens of thousands of square miles of the Earth's surface have subsided worldwide. The effects of this process are usually not as sudden and spectacular as those of an earthquake or volcanic eruption, but they are nonetheless significant. Subsidence causes annual economic losses of approximately $500 million in the United States, according to the National Research Council. Another $10 million per year is spent on studying subsidence. Some areas subside naturally, whereas others sink because of human activities. Dr. R.L. Ireland and his colleagues at the U.S. Geological Survey identified subsidence as one of the largest and most important changes of the Earth's surface ever caused by human beings.

Which Areas in Arizona Are Subsiding?

More than 3,000 square miles have subsided in Arizona. Slow, large-scale subsidence is occurring in several portions of the State (Figure 1). In Pinal County, between Phoenix and Tucson, an area of more than 100 square miles sank at least 7 feet between 1952 and 1977 (Figure 2). The region includes the town of Eloy, a 5-mile segment of Interstate Highway 10, more than 6 miles of State Highway 87, and more than 5 miles of the Southern Pacific Railroad. Dr. Donald R. Pool, a hydrogeologist with the U.S. Geological Survey, measured approximately 2 inches of subsidence that occurred between October 1988 and February 1989 at a site near Eloy. This is a very high rate, and the land is still sinking. Subsidence usually occurs so slowly that it is undetectable unless careful land surveys are made or until the cumulative effects become apparent.

Many natural processes and certain human activities cause subsidence. (See the box on page 5.) Most of the measurable subsidence currently taking place in Arizona occurs when more water is pumped out of wells than is returned to the natural underground water-storage area that the wells tap. In this report, this process is informally referred to as **pumping subsidence**. Although this report focuses on pumping subsidence and related processes, two of the other causes of subsidence in Arizona are briefly discussed below.

One cause is **sinkhole** formation. In some areas, underground water dissolves soluble rocks, such as limestone, and creates subterranean cavities. When loss of support becomes too great, the ground surface collapses and the cavities become sinkholes. (In some cases, the ground merely sags, creating small closed depressions.) There are many sinkholes in central and northern Arizona. A sinkhole in Flagstaff called the Bottomless Pits is about 50 feet in diameter and 25 feet deep. Devil's Kitchen is a sinkhole near Sedona that was studied by consulting geological engineer Mr. Paul A. Lindberg, at the request of the U.S. Forest Service. It is 80 to 160 feet wide at the ground surface and 40 to 60 feet deep. The cavity beneath Devil's Kitchen is much deeper, but most of it is filled with rubble. Cavities in Arizona's soluble rocks formed thousands and even millions of years ago, perhaps when wetter climates provided more underground water. Only a few of

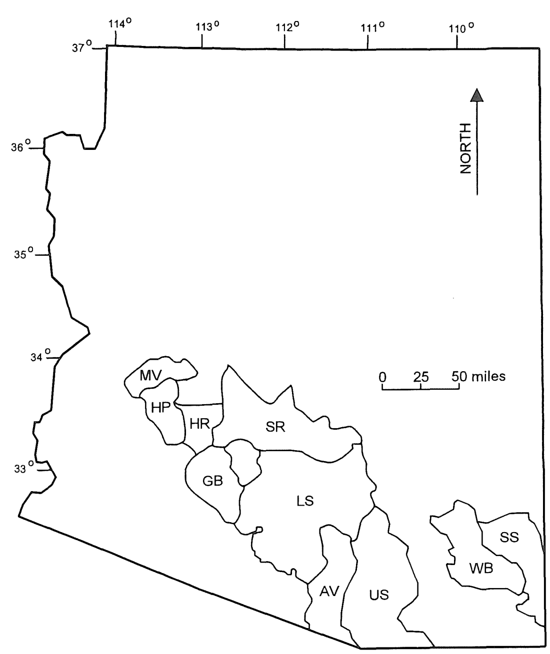


Figure 1. Regions of Arizona known to have undergone pumping subsidence. The regions shown are ground-water areas. Only a portion of each area has subsided. In McMullen Valley, subsidence has not been measured but has probably occurred. AV = Avra Valley; GB = Gila Bend Basin; HP = Harquahala Plain; HR = lower Hassayampa River valley; LS = lower Santa Cruz River basin; MV = McMullen Valley; SR = Salt River Valley; SS = San Simon Basin; US = upper Santa Cruz River basin; WB = Willcox Basin. Modified from Schumann and others (1986).

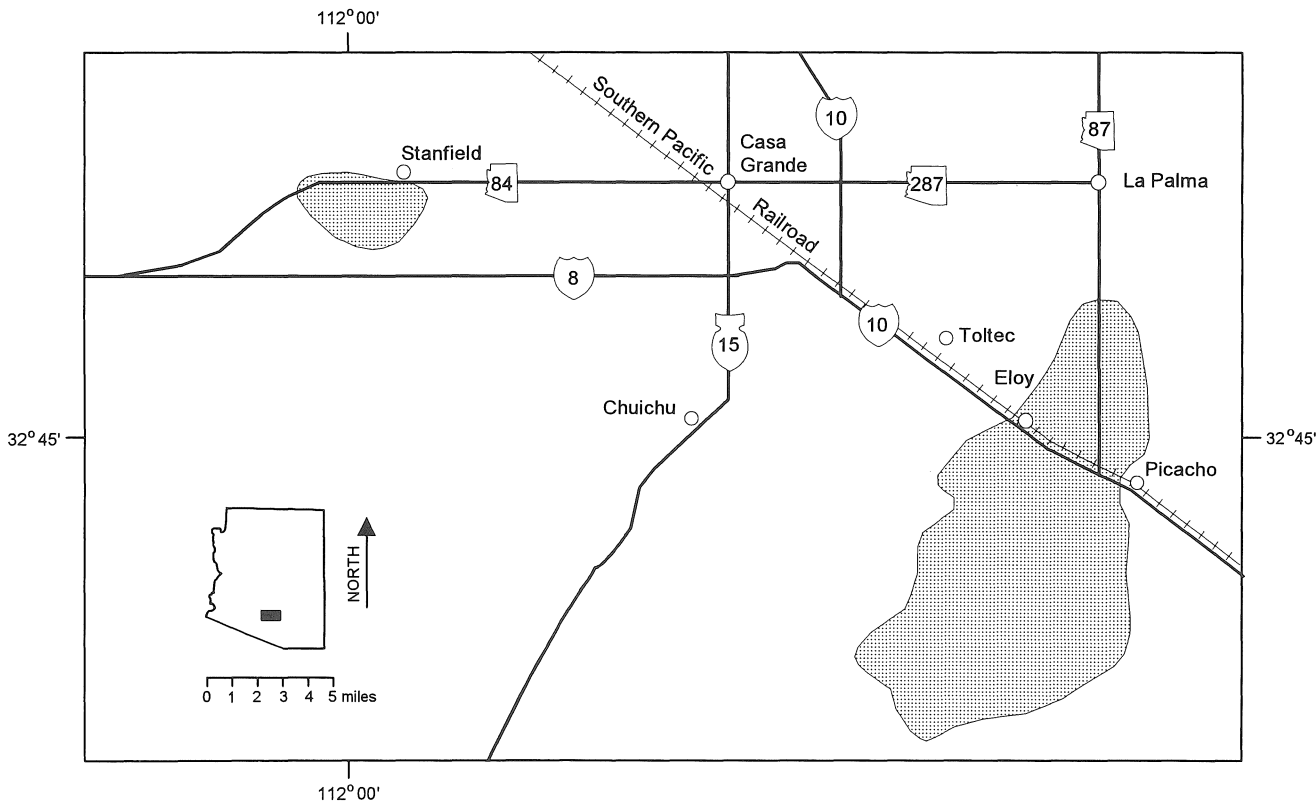


Figure 2. Areas in Pinal County known to have subsided 7 or more feet between 1952 and 1977. Shading shows approximate extent of areas. Adapted from Laney and others (1978).

Arizona's sinkholes have formed or enlarged during historical times, probably because of the general lack of surface water and shallow underground water.

Hydrocompaction or **near-surface subsidence**, which is also common in Arizona, is caused when water is added to a certain type of soil at or near the ground surface. This soil is very lightweight because it has a lot of air space between the solid particles. The largest particles are called gravel. As particle size decreases, the materials are called sand, silt, and clay. Individual clay particles are visible only through a microscope. In soil that is susceptible to hydrocompaction, the clay and silt grains form "bridges" that prevent the sand grains from touching each other. These bridges are strong when dry, allowing the soil to support its own weight, along with that of a house or other structure that may be built on top of it. When the bridges are saturated, however, they collapse, allowing the sand grains to move closer together. The soil compacts, and the ground surface sinks. This type of subsidence usually affects small areas where large amounts of water accumulate. In some places, merely watering plants in the yard around a house causes localized subsidence. Hydrocompaction is most common in the wide valleys in the western and southern parts of Arizona. It has occurred in Phoenix, Scottsdale, Tucson, other parts of Maricopa and Pima Counties, and Yuma County.

What Is Pumping Subsidence?

Pumping subsidence has been documented in Arizona since 1948. To understand how pumping subsidence works, you need to know something about the land surface in Arizona and what lies beneath it.

Arizona may be divided into three major regions based on gross physical characteristics of the land (Figure 3). The southern, south-central, and western region, called the Basin and Range Province, is characterized by wide, gently sloping valleys (also called **basins**) separated by steep, narrow mountain ranges. Beneath the valleys are accumulations of sand, silt, gravel, and clay that are hundreds or thousands of feet thick. The sand, silt, gravel, and clay are called **sediment**, and between each sediment grain are tiny open spaces called **pores**. Some of the rain that falls on the valleys and mountains seeps into the ground and flows through the pores in the sediment. Below a certain depth, all of the pore spaces are full of water.

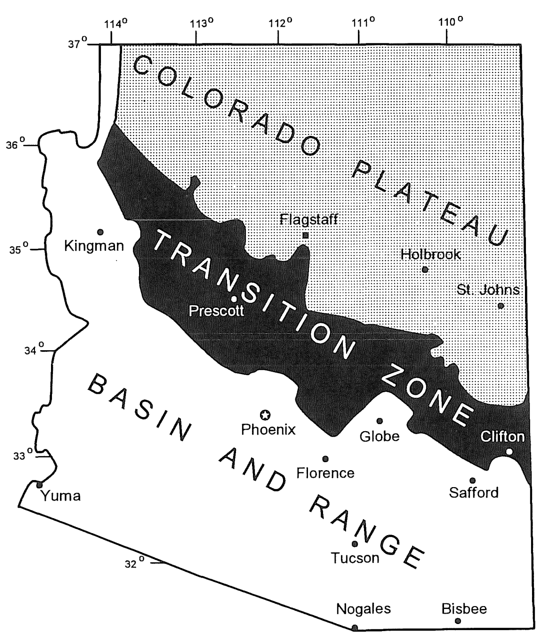


Figure 3. Arizona is divided into three regions based on physical characteristics of the land. The southwestern area (white) is called the Basin and Range Province. It consists of wide, gently sloping valleys (basins) and isolated, steep, narrow mountain ranges. The central region (black), the Transition Zone, includes rugged terrain and steep slopes where mountain ranges are separated by narrow, moderately sloping valleys. The Colorado Plateau is the northeastern area (gray). It is characterized by wide, gently sloping plateaus and mesas, deep canyons, and scattered mountain ranges.

You can simulate a sediment-filled valley by placing sand, silt, gravel, and clay in a glass bowl. Even though the bowl is full of sediment, it can still hold water. As you pour in water, it seeps downward until it reaches the bottom of the bowl; you can see it saturating the pores in the sediment from the bottom upward. When the water reaches $^1/_4$ inch or so from the top of the sediment, the bowl is a scale model of a valley in southern Arizona.

The top of the saturated sediment, typically tens to hundreds of feet below the ground surface, is called the **water table**. The water in the saturated sediment is called **ground water**. This ground water is tapped when a well is drilled into the sediment. Water flows from the pores into the well and is pumped to the land surface.

A tremendous quantity of water exists below most of southern and western Arizona's valleys. This water accumulated over thousands of years. It also takes a long time for new water to seep downward from the ground surface and outward from the mountains to the basins to replace what is pumped out. If a small amount is pumped out, it can be replaced by new water seeping in, thus maintaining equilibrium. When a lot of water is removed over a short period, however, the pores are drained and the water table drops.

Objects are more buoyant in water than they are in air. It is easier to lift a heavy object in a swimming pool than on the ground because the water supports part of the object's weight. In the same way, ground water supports part of the weight of sediment within and above it. Over thousands of years, as large amounts of sediment were eroded from surrounding mountains and deposited in the valleys of southern and western Arizona, ground water also accumulated in large quantities, helping to support the tremendous weight of the sediment.

When the water table moves deeper because of excessive withdrawal of ground water, the buoyant support that the water gives the sediment decreases. The overlying particles press down harder, causing the sediment in the newly drained zone to compact. **Compaction** occurs when sediment grains move closer to each other. The volume of space occupied by the sediment decreases, as does the size of the pores. Thus, there is less space in which to store water.

Imagine standing on top of an open aluminum can full of soda. If the soda were drained slowly, the can would crumple beneath your weight. The soda represents the ground water, and the can is like the sediment. Compaction of the coarser grained sediment, the sand and gravel, may be reversed in many cases if more water under sufficient pressure moves into the pores and expands them (e.g., see Lofgren and Klausing, 1969, p. 74-76). If you could force soda back into the crushed can under high enough pressure, the can would expand to its original shape. Intense compaction of most finer grained sediment (clay and silt), however, is irreversible. Even if additional water is available, it cannot reexpand the pores. The water-storage capacity of the material is permanently reduced. Using the above analogy, once the soda can is crushed, it remains crushed.

As the soda can collapses, you move down with it, and so it is with Arizona's valleys. Compacted sediment occupies a smaller volume at depth, and the ground surface subsides.

CAUSES OF SUBSIDENCE

Any one of several processes can cause the removal of underlying support that leads to subsidence. Some of these operate naturally, whereas others result from human activities. The list below is divided into natural and human causes of subsidence. Not all of these processes occur in Arizona.

Natural Processes

- Dissolving of soluble rocks and sediment, such as limestone
- Forces within the Earth that cause earthquakes and pull some areas downward
- Earthquake shaking that causes some deposits to compact and settle
- Decay of organic matter in organic-rich sediment and soils, such as peat
- Thawing of "permanently" frozen ground (permafrost)
- Certain types of volcanic activity
- Erosion and weathering that operate beneath the ground surface
- Accumulation of a heavy load on the ground surface, such as the filling of a lake, growth of a glacier, flowing of lava, or deposition of a thick mass of sediment
- Long-term climatic change, which may result in lowering of the water table, drying out of soil and sediment, growth of a glacier, or filling of a lake

Human Activities

- Withdrawing subsurface fluids, such as water, petroleum, natural gas, or brine
- Thawing "permanently" frozen ground (permafrost)
- Saturating near-surface, low-density, collapsible sediment
- Mining by certain methods
- Draining or reclaiming land that causes clay to dry out, peat or other organic-rich sediments to decompose, etc.
- Dissolving soluble rocks and sediment, such as limestone
- Placing a heavy load on the ground surface, such as forming a reservoir by damming a river
- Manipulating certain surface-water and ground-water systems on a large scale

Where Does Pumping Subsidence Occur?

Pumping subsidence can occur wherever a fluid is removed from a compactible deposit. The fluid does not have to be water. Significant land settlement has resulted from the extraction of petroleum, natural gas, or brine in Long Beach, California; along the Gulf Coast of Louisiana and Texas; and around Lake Maracaibo, Venezuela, to name a few places. This report, however, focuses on subsidence caused by ground-water withdrawal. Cities that have suffered damage from this type of subsidence include Houston, Texas; Las Vegas, Nevada; San Jose, California; Mexico City, Mexico; Venice, Italy; Bangkok, Thailand; and many more worldwide.

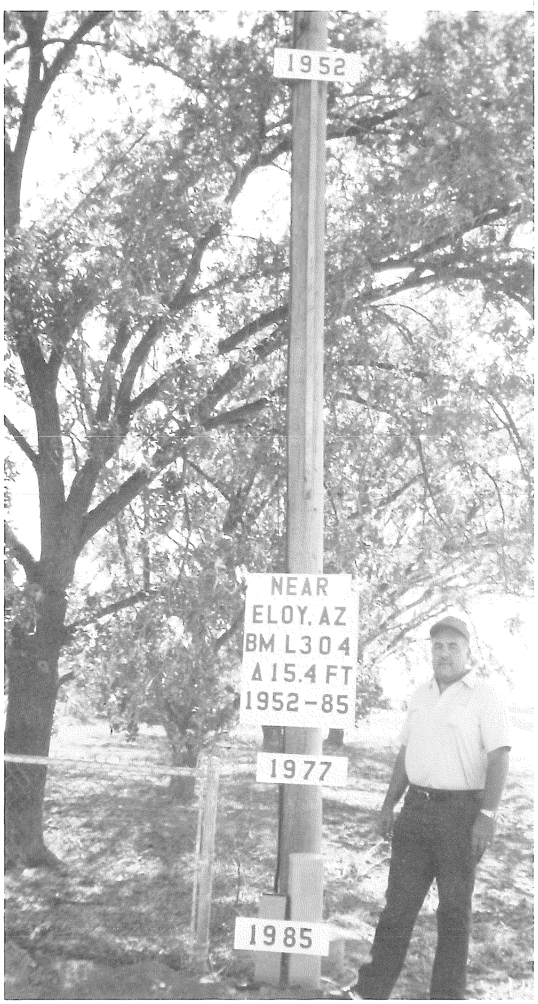


Figure 4. Dates on pole dramatize the amount of pumping subsidence that occurred at a site near Eloy between 1952 and 1985. In 1952 the ground surface was where the sign is now, high on the pole. By 1985 the land had sunk more than 15 feet. Herbert Schumann of the U.S. Geological Survey, who is 6'2" tall, is included for scale. Photo by the U.S. Geological Survey.

In the United States, more than 11,750 square miles of land had been affected by pumping subsidence by 1981, as reported by Dr. Joseph F. Poland of the U.S. Geological Survey. California had the largest area of subsidence, followed by Texas. Arizona was third, with more than 1,040 square miles affected by subsidence, including parts of Tucson and Phoenix (Figure 1). A much larger portion of Arizona, more than 3,000 square miles, had subsided by 1983, according to Dr. William E. Strange of the National Oceanic and Atmospheric Administration. Strange studied Arizona in detail and compiled all the subsidence information that was available at the time. Because land surveys and other means of verifying subsidence have not been undertaken in many parts of Arizona, additional areas may be affected and known areas may be larger than suspected. Subsidence had been documented in nine ground-water areas by 1983. In most of these localities, the land is probably still subsiding.

The maximum measured pumping subsidence in the United States by 1981 was 29.6 feet at a site in the San Joaquin Valley of central California. The maximum amount of subsidence measured in Arizona was approximately 15.4 feet at the time of this writing. It occurred about 3 miles south of Eloy between 1952 and 1985 (Figure 4). More subsidence has probably occurred there since the last measurement was made. Mr. Herbert H. Schumann, a hydrologist with the U.S. Geological Survey who has studied subsidence and earth fissures in Arizona for many years, suspects that a similarly

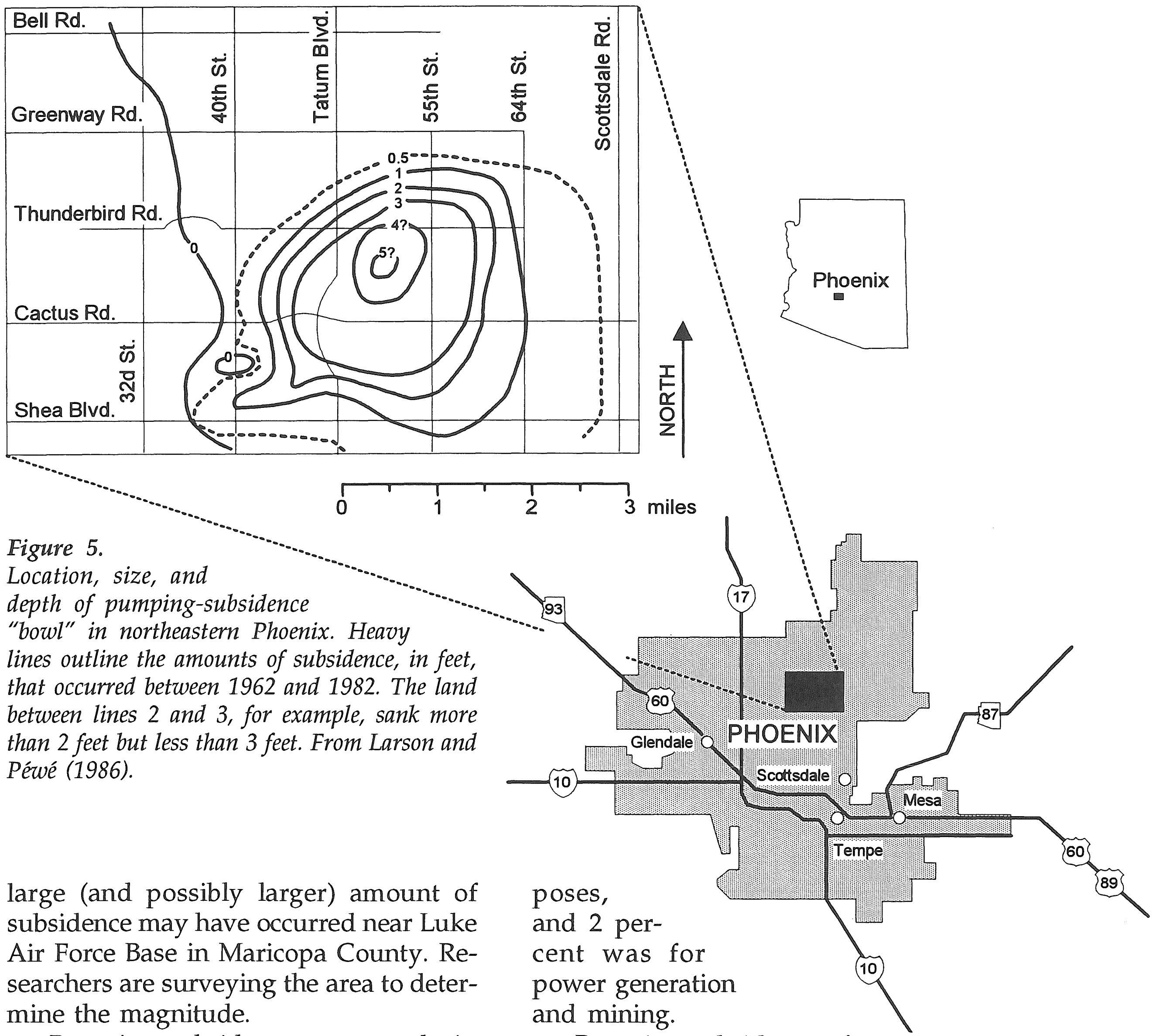


Figure 5.
Location, size, and depth of pumping-subsidence "bowl" in northeastern Phoenix. Heavy lines outline the amounts of subsidence, in feet, that occurred between 1962 and 1982. The land between lines 2 and 3, for example, sank more than 2 feet but less than 3 feet. From Larson and Péwé (1986).

large (and possibly larger) amount of subsidence may have occurred near Luke Air Force Base in Maricopa County. Researchers are surveying the area to determine the magnitude.

Pumping subsidence occurs only in areas where water-saturated unconsolidated or semiconsolidated sediment exists underground, and where much more water has been removed than replaced. As mentioned above, most places with these conditions are broad valleys in the western and southern parts of the State that are devoted to farming or urban use. According to Mr. Mason R. Bolitho of the Arizona Department of Water Resources, in 1990 (the most recent year for which preliminary figures are available), 79 percent of all the water used in Arizona was for agriculture, 19 percent was for municipal and industrial purposes, and 2 percent was for power generation and mining.

Pumping subsidence affects relatively large areas, and in most cases the greatest amount of settlement occurs approximately where the most ground water has been removed. The result is a large, bowl-shaped depression that can be represented on a map with a "bull's-eye" pattern of concentric "circles" (Figure 5). Monitoring programs designed to measure the amounts and rates of subsidence are being carried out in parts of Arizona, mostly in urban areas and where highways and expensive facilities are located.

What Are the Effects of Pumping Subsidence?

Lowering the land surface causes several things to happen; some occur immediately, whereas others take years to develop. The impact of subsidence on structures is discussed below, followed by its impact on natural systems.

Figure 6. Protruding wellhead near Stanfield, Arizona. Dark cylinder in center of photo is top of casing. Compaction of sediment at depth caused ground-surface subsidence that broke the concrete slab. Compaction also crushed the casing at depth. Photo by Robert B. Genualdi.

Effects on Structures

In most cases, pumping subsidence affects broad areas, decreasing in severity from the centers to the edges. This means that a structure such as a factory or house normally sinks uniformly with the ground and is not damaged. Harm is more likely to occur where **differential subsidence** lowers one side of a building more than another. The facilities that suffer most commonly from pumping subsidence are long ones, such as canals and pipelines, that cross all or a large part of a subsidence "bowl." Canals, aqueducts, sewers, and drains are built with very precise slopes so that the liquids flow under the force of gravity or are pumped at a fixed pressure. Subsidence, however, changes the slope and causes liquids to flow too slowly, too fast, or not at all, which may cause ponding, overflowing, or overloading of checkpoints and distribution systems. In extreme cases, subsidence can cause fluids to flow backward through force-of-gravity systems.

The Central Arizona Project (CAP) structures were located, designed, and built taking subsidence predictions into account. These measures resulted in higher costs, the use of more materials, and the need for an ongoing subsidence-monitoring program. Considerable money and time were probably saved in the long run, however, by addressing the hazard before rather than after the project was completed.

In northeastern Phoenix, pumping subsidence has decreased the slopes of sewers, thereby reducing their capacities. This could lead to the generation of excessive sewer gases, which would require treatment with chemicals or installation of pumps. Remedial action has not been required yet, but subsidence is still occurring in the area and is being closely monitored.

On some farms in Arizona, irrigation canals and drains had to be repaired after subsidence rendered them useless. Agricultural fields had to be regraded after subsidence interfered with irrigation and drainage in the Salt River Valley, the lower Santa Cruz River basin, and probably other areas.

Other facilities commonly damaged by subsidence are water wells. Most wells are cased; that is, after the hole is drilled, it is fitted with cylindrical steel or plastic pipe called **casing**. The casing is lowered into the hole in sections that are attached to each other end-to-end. The casing has holes or slits in its walls at the appropriate depths, allowing water to flow into the well while keeping sediment out. The tremendous compressional force of sinking land causes some well casings to bend, collapse, or break. Those wells must either be repaired or abandoned and replaced with new wells drilled nearby. Casing damage at depth indicates, in some cases, that subsidence is occurring where it has not been measured yet.

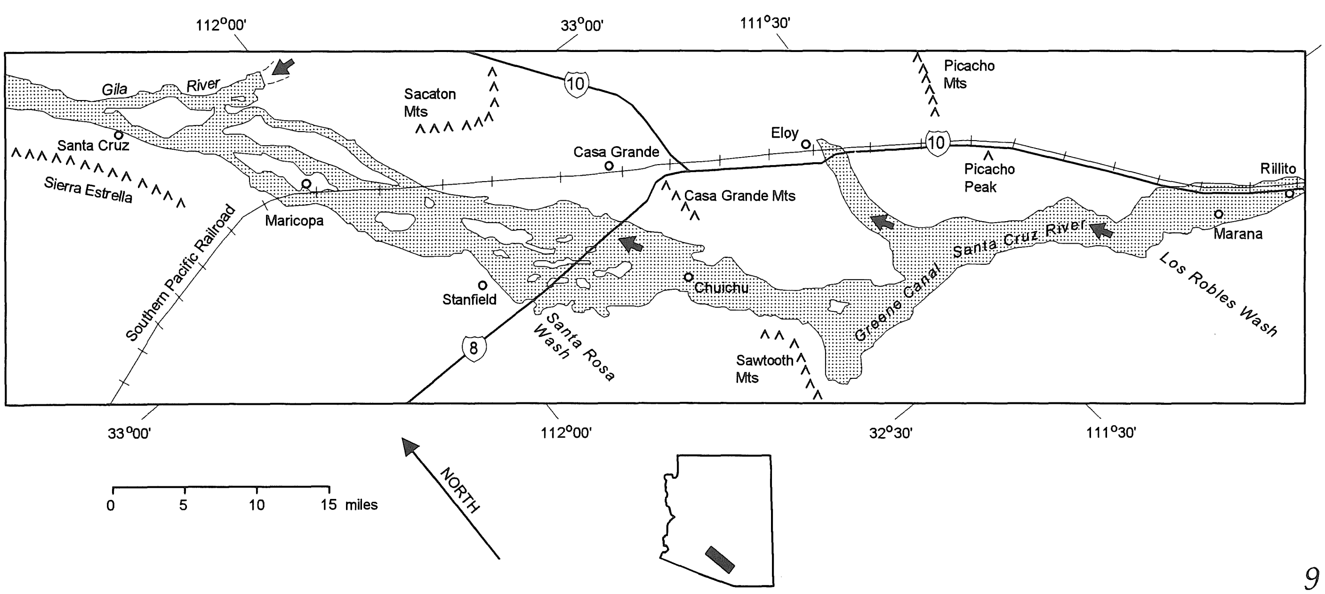
Wells used for municipal water supply and irrigation have been damaged by bent or broken casings and by wellhead protrusion. A **wellhead** is the uppermost portion of a well. A concrete slab is normally constructed at the ground surface at the top of a well and attached to the casing. The slab serves as a foundation for a pump and other hardware. In many wells, the casing extends all the way to the bottom of the hole, deep enough so that when the land subsides, most of the compaction occurs above the casing bottom. The ground surface sinks, but the wellhead does not. Because the wellhead is left protruding from the ground, the pump may become difficult or impossible to use (Figure 6).

Effects on Natural Systems

Streams are the primary natural features affected by subsidence. Most of Arizona's streams and rivers flow only after considerable rainfall or snowmelt, so it is not obvious that they can be just as effective in causing erosion and deposition as streams that flow year-round. In fact, most of Arizona's landscape has been produced or modified by streams.

The slope of a stream bed is called its **gradient**. Gradient is delicately adjusted to the amount of water flowing in the stream, the amount of sediment in the water, the grain size of the sediment, and other factors. The gradient of a stream that crosses a subsiding valley becomes steeper where the stream enters the sunken zone and gentler where the stream crosses the zone's center and where it leaves the zone. The steepening causes the stream to erode more sediment upstream from the subsidence zone, and the decrease in gradient causes more deposition of sediment in the subsidence zone. Increased erosion and gullying cause loss of topsoil and dissection of the land. Increased sediment deposition raises the land surface and buries preexisting features. These effects on natural

Figure 7. Approximate area inundated along part of the lower Santa Cruz River during the flood of October 2-4, 1983. Arrows show the direction of flow. Notice the 1-mile-wide band of water that left the main flood path and flowed north over subsided land near Eloy. Modified from Roeske and others (1989).



systems also have an impact on facilities that are built in subsiding areas.

Where subsidence forms a closed depression of the land surface, water that flows into the area is trapped. With nowhere lower to drain, the water stands in the depression until it soaks into the soil or evaporates. This problem is especially apparent where the sea has invaded sinking coasts, such as in parts of California and Texas.

The danger of flooding, which affects both natural systems and structures, also increases as land sinks. In 1983, after a week of abundant rainfall, flooding occurred on the Santa Cruz, San Francisco, San Pedro, and Gila Rivers and smaller streams in southern Arizona. Most of the floodwater carried by the Santa Cruz River followed the river's usual route through the southern and western portions of the lower Santa Cruz River basin to the Gila River (Figure 7). Because the basin had subsided, however, a 1.5-mile-wide band of water flowed northward along ditches, roads, and a remnant of an old Santa Cruz River channel, flooding the eastern part of Eloy. The water flowed into an area that had sunk more than 7 feet between 1952 and 1977 (Figures 2 and 4) and covered it to record depths. The flooding caused more than $50 million worth of damage in the Eloy area (Roeske and others, 1989).

Can Pumping Subsidence Be Stopped?

Pumping subsidence can be stopped either by suspending all withdrawal of ground water or by allowing only limited pumping. The first option is obviously unfeasible at present. Pumping can be limited, however. One way is for farmers to adopt irrigation techniques and select crops that consume less water. In urban areas, low-flow plumbing devices could be installed, native plants could be used for landscaping, and greater use could be made of treated effluent.

Hydrologists can estimate the amount of ground water that may be safely removed during a year without appreciably lowering the water table. They do this by calculating the average annual quantity of water that seeps downward and laterally to join the ground water beneath a valley. If more water than usual reaches the saturated sediment during a particular year, more is available for withdrawal. The additional water may come from unusually heavy precipitation or from human manipulation of natural systems. An example of the latter is Colorado River water diverted into the CAP system and then into washes or ponds, where it seeps downward to join the ground water at depth.

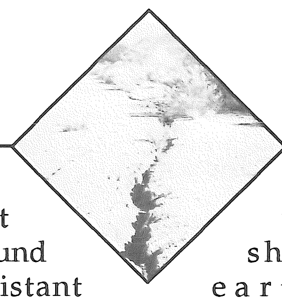
Many options are available to counteract the effects of pumping subsidence. Water-use programs may be tailored to each subsiding valley depending on local hydrologic, geologic, and economic conditions. In some areas it may be advantageous to distribute the pumping among more wells or to use some wells only during certain years. In other areas it may be feasible to pump water mostly from sediment of low compressibility. This procedure was tried in North Las Vegas, Nevada, and may have slowed or stopped subsidence there during the mid-1960's. Sediment of low compressibility is more likely to reexpand when additional water enters it, reversing compaction and preventing a permanent decrease in its water-storage capacity. In some parts of Arizona, Colorado River water supplied by the CAP system may be used instead of ground water.

Unfortunately, subsidence will not stop as soon as excessive pumping ceases, just as a bicycle will not stop rolling the instant its rider ceases pedaling. Excessive withdrawal of ground water removes the buoyant support that helps hold up the overlying sediment — remember the can of soda? The sediment presses down harder, squeezing more water out of the pores as it compacts. Fine-grained sediment (clay and silt) tenaciously holds water in its pores and contains little space for water movement. Thus, water drains slowly from this sediment, and compaction and subsidence occur gradually. Even if excessive pumping were to cease tomorrow, its effects might continue for months or even years. Subsidence will slow down and eventually stop, however, after excessive pumping is curtailed.

In some cases, subsidence may be reversed. As pumping air into a flat tire raises a car, pumping sufficient water down into wells and then out into the surrounding sediment may raise the ground surface. Merely curtailing removal of ground water and allowing surface water to seep down naturally can raise the land surface. This has been demonstrated in California's San Joaquin Valley (Lofgren and Klausing, 1969). The technique tends to work better where coarse-grained sediment (sand and gravel) has been compacted. In most cases, though, the land surface does not rise to its original elevation.

Obviously, water is a rare and valuable resource in most of the semiarid and arid Southwest. Its scarcity has traditionally limited plant and animal populations, including human habitation. Modern technology has allowed the discovery and rapid exploitation of vast amounts of water hidden beneath the desert soil. Current rates of use simply cannot be maintained unless alternate sources are discovered. In lieu of such discoveries, conservation and recycling are the simplest ways to ensure a prosperous and long-lasting human presence in the Southwest.

What Is an Earth Fissure?



A **fissure** is a crack or opening that is caused, in most cases, by something breaking or pulling apart. Most fissures are long, deep, and narrow. An **earth fissure** is a crack at or near the Earth's surface that is caused by subsidence. Many other processes can cause cracks to form at the Earth's surface, but the term "earth fissure" is usually reserved for cracks caused by pumping subsidence or subsidence due to natural lowering of the water table.

The first documented earth fissure in Arizona was discovered 3 miles northeast of Picacho on September 12, 1927, the morning after an intense rainstorm. The fissure was approximately 1,000 feet long, up to 15 feet deep, and up to 3 feet wide where eroded. It crossed the railroad and the Tucson-Casa Grande Highway (now Interstate Highway 10). The geologist who studied the fissure in the late 1920's believed that it was caused by ground shaking from a distant earthquake. Most geologists now think that it was caused by subsidence interacting with underground conditions at the site. In the 65 years following its discovery, the fissure has become filled with sediment and overgrown with plants, making it difficult to recognize.

As mentioned previously and shown in Figure 5, land does not sink uniformly within a subsidence zone. Sediment that has sunk more pulls adjacent sediment that has sunk less, and the latter pulls back. Where the pull is strong enough, the land splits open into a fissure. Imagine an apple pie that has just been taken out of the oven. As it cools, the filling in the center sinks more than the filling around the edges. The crust stretches until it breaks open between the center and the

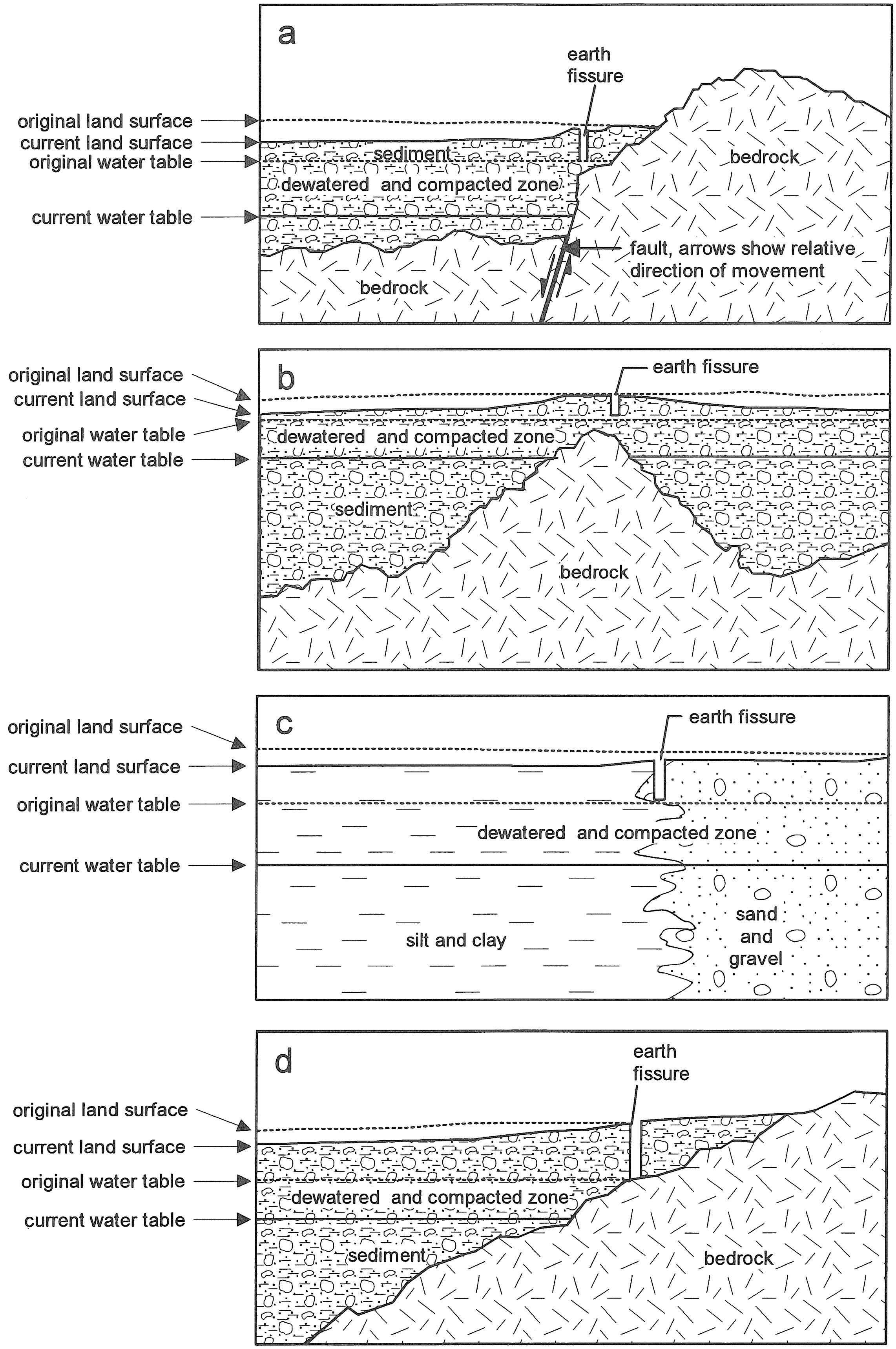

a
earth fissure
original land surface
current land surface
original water table
current water table
sediment
dewatered and compacted zone
bedrock
fault, arrows show relative direction of movement
bedrock
b
earth fissure
original land surface
current land surface
original water table
current water table
dewatered and compacted zone
sediment
bedrock
c
earth fissure
original land surface
current land surface
original water table
current water table
dewatered and compacted zone
silt and clay
sand and gravel
d
earth fissure
original land surface
current land surface
original water table
current water table
dewatered and compacted zone
sediment
bedrock

Figure 8 (opposite page). Underground conditions that influence where earth fissures form. (a) Fissure over buried inactive fault. Thicker sediment accumulation to the left of the fault allows more compaction there as the water table drops. (b) Fissure over buried bedrock ridge. Thicker sediment accumulation on either side of the ridge allows more subsidence there. (c) Fissure at boundary between coarse- and fine-grained sediment. The silt and clay compact and subside more than the sand and gravel as the water table drops. (d) Fissure at edge of subsiding area. The region to the right of the fissure is stable because the original water table was deeper than the top of the bedrock. The region to the left of the fissure subsides as the water table drops, exerting the strongest lateral pull on sediment near the fissure. (b) and (d) modified from Larson (1982).

edges. The cracks form curved lines parallel to the edge of the pie. Similarly, earth fissures often develop close to mountains that border valleys, and they parallel the trends of the mountain ranges.

Certain underground conditions influence where earth fissures form and increase the force of the pull. Some of these conditions are shown in Figure 8. If geologists can determine where such subsurface conditions exist, they can identify general areas in which fissures are likely to form. The precise location of a future fissure cannot be predicted, but areas where fissures are likely to form may be identified if sophisticated instruments that measure extremely small changes in pulling force are installed in the right places.

Along some of Arizona's earth fissures, the ground on one side is higher than on the other, which resembles the appearance of some earthquake faults. (Fissures cannot, however, generate earthquakes.) A height difference across some fissures is present when the cracks form. For example, one that formed south of Marana in 1988 and damaged the CAP aqueduct (see Figure 17) was 2 inches higher on one side when the crack first appeared. In contrast, both sides of some fissures are the same height when the cracks form, but a height difference develops slowly over time. The ground was the same height on both sides of a fissure east of Picacho when the crack formed. Thirty-four years later, one side was 1 to 2 inches higher than the other side. During the next 20 or so years, the height difference increased by 22 inches. This is the largest known height difference across an Arizona fissure.

What Is the Life Cycle of Earth Fissures?

When a fissure first forms at the ground surface, it is a thin crack 3 inches or less wide (Figure 9). Many are less than 1 inch wide, and some are not cracks but a line of small pits or depressions in the soil. These young fissures may be more than 1,500 feet long and hundreds of feet deep. (It is difficult to measure depths when fissures are narrow.) Their walls are steep or vertical.

Some geologists believe that certain fissures may initially extend from the ground surface to the original water table that was present before it was lowered by excessive pumping from wells. The huge quantities of water and sediment that can move into fissures suggest that some of the cracks are

Figure 9. Narrow crack at the ground surface; its appearance is typical of that of many earth fissures when they first become visible. The lens cap is 2 $^{1}/_{8}$ inches in diameter. Photo by Steven Slaff.

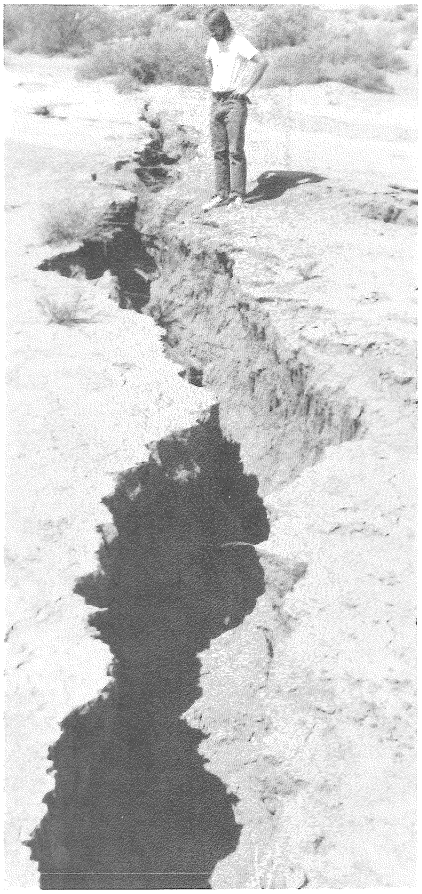


Figure 10. Erosion has widened this earth fissure into a more hazardous size than that of the crack shown in Figure 9. This fissure rendered a road impassable. Photo by Steven Slaff.

quite deep. The depths of some fissures have been estimated by making a simple calculation. If a fissure's length and width are known and if the volume of water and sediment needed to fill it are measured, then its approximate depth can be calculated. (The assumptions required to make such an estimate are that the shape of a fissure is regular along its height and that no large cavities exist at depth.) Using this method, University of Arizona hydrologists calculated depths of 175 to 1,500 feet for some of Arizona's fissures!

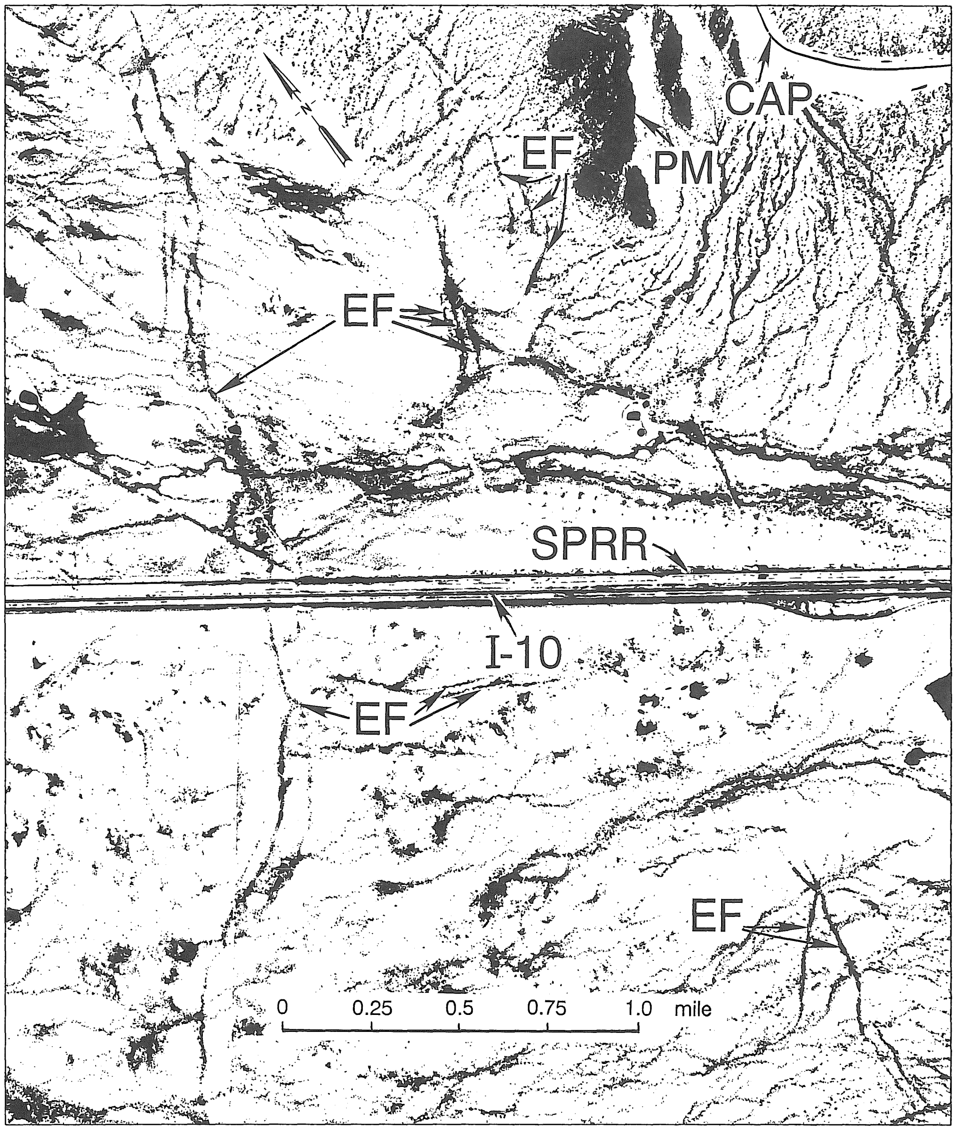
The processes that change the shapes and sizes of earth fissures are the same ones that change the shapes of mountains and valleys: erosion and deposition. Many fissures cut across gullies and washes. When enough rain falls, the washes fill with water carrying sediment. As the water and sediment flow into the fissures, more sediment is eroded from the fissure walls. The wall erosion widens the cracks (Figure 10), and the deposition of sediment at the bottom of the fissures makes them shallower. Erosion also connects lines of surface pits into continuous cracks as sediment caves into open spaces underground. Plants grow larger and closer together along fissures because fissures receive more water and retain it longer than the adjacent desert.

As erosion and deposition of sediment continue, fissures mature, becoming even wider and shallower. They may become 50 feet wide and 16 feet deep or even larger (Figure 11). At this stage they look like gullies, except that most of their floors are uneven and do not slope steadily downward in one direction. Plants grow along them in such profusion that these cracks appear as distinct dark lines on photographs taken from airplanes (Figure 12). The fissure on the left side of Figure 12 that extends along the entire photograph is almost 10 miles long. It is the longest known fissure in Arizona.

With continued filling by sediment, fissures become shallower (approximately 1 to 2 feet deep) and have smoother floors and more gently sloping walls (Figure 13). Some of the preexisting stream channels that were cut off by the fissures reestab-

Figure 11. This earth fissure is 20 to 30 feet wide and 10 to 13 feet deep. Erosion and deposition have made the fissure resemble a gully. Note the person standing in the fissure. Photo by Steven Slaff.

Figure 12. Aerial photograph taken in August 1987 of area southeast of Picacho in Pinal County. Dense vegetation growing along earth fissures makes them appear as dark lines. EF = earth fissure; PM = southern end of Picacho Mountains; CAP = Central Arizona Project aqueduct; SPRR = Southern Pacific Railroad; I-10 = Interstate Highway 10. Photo by Arizona Department of Transportation.



lish their courses right across the cracks. Ultimately, fissures become very difficult to recognize because they are completely or nearly filled with sediment (Figure 14). If no vague furrow or linear strip of plants remains, old fissures are invisible.

Some earth fissures may be split open again after they first formed because of a continuation or renewal of the pulling force that opened them initially. In some cases, a fresh crack forms in the floor of a fissure (Figure 15). At other sites, a new crack opens beside an existing fissure. Either change slightly modifies the pattern of erosion and filling that the feature undergoes.

Researchers do not know precisely how long it takes from the time a fissure first appears until it is completely filled and invisible, but it probably ranges from a few years for some fissures to more than 50 years for others. Many factors influence the rate of fissure development, including soil type, climate, and location. Some fissures may undergo a different development pattern from the one shown in Figures 9 through 14.

Figure 13. As sediment continues to fill a fissure, it becomes shallower and more rounded. Photo by Steven Slaff.

Figure 14. Earth fissure (bare "trail" through center of photo) nearly completely filled with sediment. Eventually, no surface trace of the feature will remain. Note the shovel for scale. Photo by Steven Slaff.

Figure 15. Reactivated earth fissure. The original ground surface is near the top of the photo on the right and left. The fissure formed and then filled with sediment up to the original floor level shown by the light-colored, smooth surface to the left of the shovel. Renewed pulling split the floor open, forming the cleft in which the shovel rests. Photo by Steven Slaff.

Where Do Earth Fissures Develop?

Since the 1950's, the number of fissures in Arizona has increased dramatically. Hundreds have been identified in the valleys of northwestern Cochise, western Pima, western Pinal, and southern Maricopa Counties (Figure 16). Some may have formed from natural causes, but most are related to excessive withdrawal of ground water. Earth fissures have also been noted in New Mexico, Nevada, California, Utah, Idaho, Wyoming, Mexico, China, and Japan. They have probably formed in other locations as well, but Arizona appears to have more than any other region of comparable size in the United States.

Earth fissures form in sediment, not bedrock, so they are found in valleys, not mountains. They form in areas that are

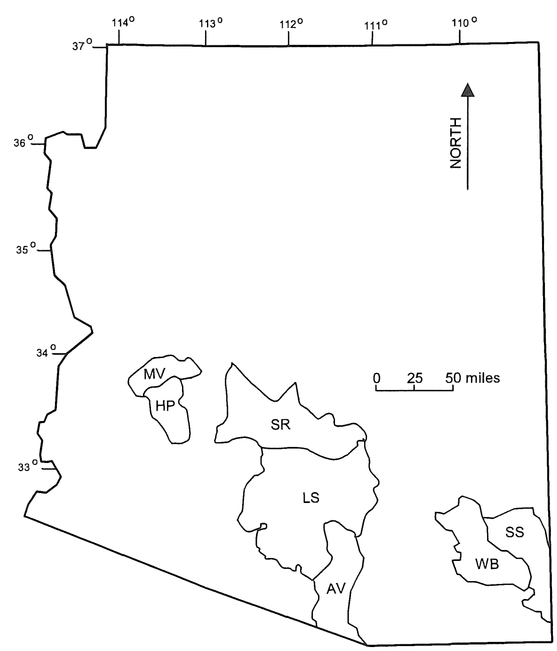


Figure 16. Regions of Arizona where earth fissures exist. Excessive use of ground water has caused moderate to large increases in the depth of the water table in each of these areas. The largest concentration of fissures is in the lower Santa Cruz River basin, where the most land subsidence and deepening of the water table have occurred. The regions shown are ground-water areas. Earth fissures have formed in only a portion of each region. AV = Avra Valley; HP = Harquahala Plain; LS = lower Santa Cruz River basin; MV = McMullen Valley; SR = Salt River Valley; SS = San Simon Basin; WB = Willcox Basin. Modified from Schumann and Genualdi (1986b) and Schumann and others (1986).

subsiding or have subsided, where the pull on sediment is strong. This happens where sediment thickness changes abruptly, because a thick layer of sediment can compact more than a thin layer. Sediment layers are much thinner next to mountains and over buried bedrock hills, so fissures form where these areas flank the thicker layers of valley sediment (Figures 8a and 8b). Clay-rich sediment can compact more than sand or gravel, so fissures may form where layers change laterally from clay to sand (Figure 8c). Another factor that localizes earth fissures near the edge of a subsidence zone is the lack of subsidence outside the zone (Figure 8d). This situation creates a strong pulling force on the sediment. A subsidence zone may end close to the edge of an overused well field or close to the boundary between a ground-water area and a dry area.

What Are the Effects of Earth Fissures?

Fissures have a significant impact on the areas where they develop. As with subsidence, some effects occur immediately, and some occur long after the fissures have formed. In certain cases, it is difficult to separate the effects of fissures from those of subsidence because both phenomena occur in the same areas and alter some systems in similar ways. Fissures are likely to have an even greater impact as ground water is more rapidly depleted and more facilities are developed in high-risk areas. Ways to lessen some of these damaging effects are discussed on pages 20 and 21.

Effects on Structures

Fissures that develop beneath structures cause a fundamental loss of support, which results in cracking, separation, or weakening of the foundation and overlying framework. In Arizona, facilities that have been damaged by fissures include highways, roads, railroads, recreational facilities, houses, other buildings, sewage-disposal facilities, irrigation canals, water-storage systems, agricultural fields, buried pipelines, and water-distribution systems, including the CAP.

Unlined canals, ditches, and drains may be broken and completely emptied by fissures. Once a break occurs, the water from the canal will quickly erode the fissure into a wider (and, in some cases, longer) crack, which may damage structures nearby. Isolated poles and towers, which have very narrow bases of support, may lean or fall. Poles that hold utility lines, however, such as electric transmission wires, may be prevented from falling or leaning too far by the support of adjacent poles and lines.

The CAP was damaged by a fissure in 1988 (Figure 17). The fissure developed where the aqueduct was already reinforced because the area had been identified as a potential fissure-hazard zone

Figure 17. *Earth fissure that formed in 1988 and damaged the CAP aqueduct in Pima County. The aqueduct (behind the embankment in the background) was cracked but not emptied. The white area on the embankment is plastic placed there to keep rain from eroding the crack caused by the fissure. Photo by Steven Slaff.*

before the aqueduct was built. This planning probably prevented the aqueduct from breaking, but repairs were still required. According to Mr. Gary A. Ditty, a civil engineer with the U.S. Bureau of Reclamation, the repairs cost approximately $50,000. Before certain other portions of the CAP were constructed, their proposed locations were changed because the hazard posed by existing and potential earth fissures was considered too great. This delayed the project and added to its cost. U.S. Bureau of Reclamation geologist Mr. John P. Sandoval estimated that by 1989, $120,000 had been spent to monitor subsidence and earth fissures along the CAP. Since then, approximately $30,000 per year has been spent on monitoring.

Interstate Highway 10 has been repaired several times where a fissure crosses it near Picacho. The same fissure damaged a railroad and natural-gas pipeline, necessitating costly repairs. A train derailment is believed to have resulted from misalignment of the track caused by another fissure. Fissures have also severely cracked house foundations and walls, undermined and exposed buried utility lines, and made dirt roads impassable. At least one person was injured when a motor vehicle was accidentally driven into an open fissure.

The impact of fissures on land use is substantial. The damage they cause is not covered by some insurance policies. The presence of one or more earth fissures has driven down property values dramatically in some areas. A fissure in an undeveloped area near Mesa affected land use when the city would not issue building permits sought by developers.

Other fissure-related problems occurred in Paradise Valley, an area in northeastern Phoenix. Since approximately 1950, large amounts of ground water have been pumped from wells in the area. The depth to the water table increased by as much as 550 feet between the mid-1950's and 1980. During the 1960's and 1970's, the land surface in southern Paradise Valley sank at least 3 feet. A 425-foot-long earth fissure formed there in 1980, in a housing subdivision that was under construction. Dr. Troy L. Péwé, a faculty member in the Geology Department at Arizona State University, reported that this was the first fissure known to have occurred in an Arizona city. (As Figure 16 shows, most fissures have formed in rural parts of the State.) The developer of the subdivision estimates that the cost of the project was increased by approximately $500,000 because of the fissure. Construction was delayed, consultants were hired, and plans were modified to reposition all buildings away from the crack.

Effects on Natural Systems

As mentioned above, many fissures cut across washes and stream courses. When the streams flow, they end abruptly by depositing all of their water and sediment into the fissures. Not only does this interfere with the normal patterns of erosion and sedimentation, but it also allows for potentially serious ground-water pollution.

Fissures trap sediment and cause new gullies to form nearby. Their great depths make them the lowest places in an area, so water flows into them, carrying with it sediment eroded from the surrounding land. The upslope sides of fissures are especially susceptible to gullying and loss of topsoil. As fissures gradually fill with sediment, "tributary" gullies, which may be 12 or more feet deep, also fill. Open fissures and deep gullies are dangerous to people and livestock. Domestic animals have died after falling into or getting trapped in fissures or gullies.

Streams intercepted by fissures markedly deepen their channels just upslope from the cracks. As new drainage patterns form, erosion can chisel away the soil that supports crops and structures, thereby changing the slope of the land surface. Farming may become impossible in the affected areas, and structures may be damaged.

As mentioned above, many fissures may initially be very deep, possibly extending to or close to the original water table. Surface water flows rapidly down the crack instead of seeping slowly through the thick layers of sediment that normally help purify it before it joins the ground water. Some of the water entering earth fissures may have flowed over agricultural fields or cattle feedlots, picking up chemical fertilizers, pesticides, herbicides, or animal wastes. Water draining from roads and highways may contain petroleum products, antifreeze, brake fluid, or other toxic compounds.

Fissures are popular sites for illegal dumping of garbage (Figure 18). Because most landfills are excavations in the ground, many people believe that a preexisting trench, such as an earth fissure, is the perfect place to dump garbage. They do not realize that the next rainstorm may carry pollutants straight down to their own (or someone else's) water supply.

Despite the dangers that fissures present, they do have some beneficial effects. They may provide paths along which unpolluted surface water can descend rapidly to join the ground water, instead of flowing away or evaporating. Wildlife concentrates in and along the cracks because fissures are cool, shady, protected places with abundant vegetation. After rainstorms, water remains in some fissures for up to several weeks after it has evaporated from the ground nearby. Fissures appear to be a desirable habitat for a variety of birds, reptiles, and mammals.

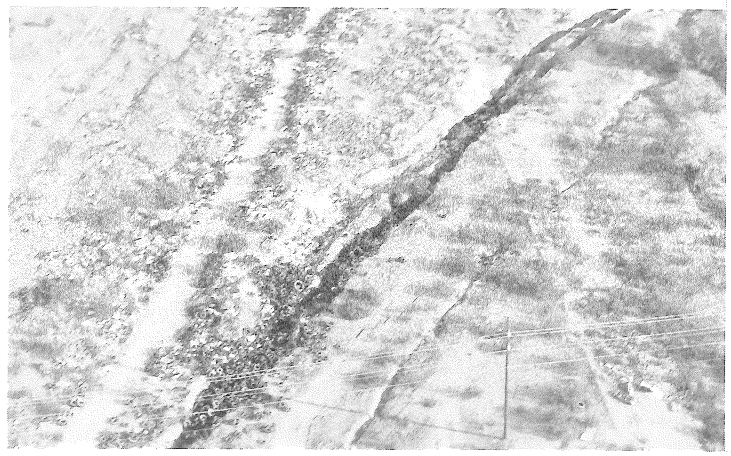


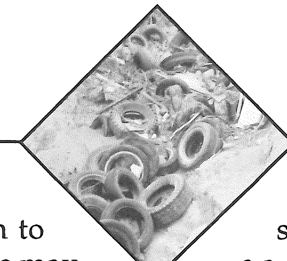
Figure 18. *Aerial view of tires and other garbage illegally dumped in an earth fissure near the town of Queen Creek in Maricopa County. The fissure extends from the lower left to the upper right of the photo. Note the narrower fissure to the right of the main crack. Photo by Herbert Schumann.*

Can Earth-Fissure Formation Be Stopped?

As already stated, most fissures in Arizona are caused by excessive withdrawal of ground water. Reducing this depletion — at least to an amount that equals the amount of ground water replenished each year by natural and artificial sources — will stop or delay the formation of most new fissures. It will also slow or stop the reopening, lengthening, and branching of existing fissures. Fissure formation, however, will not end the instant pumping is reduced to a sustainable level. There is a delayed reaction, as with subsidence; fissures may continue to form or grow for months or years after pumping is reduced. Because fissures go hand-in-hand with pumping subsidence, the techniques listed above for stopping subsidence will also reduce or eliminate fissure development. Methods for reducing the hazards of existing fissures are discussed in the next section.

Some fissures may not be caused by excessive pumping but may be related to natural lowering of the water table or drying of soil and sediment. These conditions could be brought about by natural, long-term changes in climate. Fissures related to natural causes probably make up a small fraction of the fissures that have formed in Arizona during this century.

How Can the Hazards of Subsidence and Earth Fissures Be Reduced?



As with other geologic hazards, there are three principal ways to deal with subsidence and earth fissures: (1) avoid living or building in the affected areas; (2) plan ahead and construct facilities that can withstand the damaging effects; or (3) repair and replace facilities as necessary, and abandon them if the damage becomes too extensive. The first option is the safest; the third involves the most risk. Each option is discussed in more detail below.

To avoid living or building in a problem area (option 1), the hazard must be identified and its extent determined. Although not every zone of subsidence and earth fissures in Arizona has been identified and mapped, most of the areas are probably known or suspected. The Arizona Geological Survey can provide information about locations and specifics of hazardous areas. Many publications are available that describe these hazards in more detail than is possible here. (Consult the list at the end of this report.)

Option 2 is to plan ahead and construct facilities that are expendable or that can withstand the effects of subsidence and earth fissures. Materials and designs are available to strengthen and improve almost every structure, but most of them increase the cost or time required for construction. A property owner must determine the appropriate level of safety based on an assessment of the expected useful lifetime of the structure, the available budget, the effect that damage would have on the structure's intended use, and other factors. For example, a school must be safer than a storage shed; a homeowner may be willing to risk having cracks in the garage, but not in the living room.

In addition to sinking, subsidence may cause the ground to tilt, stretch, and compress. In a structure such as a house, these conditions may result in cracking or separation of the foundation, floors, walls, or ceilings; sloping or buckling of the foundation or floors; broken utility lines; doors and windows that will not move properly; and nerve-racking sounds of groaning or tearing as the house moves. Subsidence can also sever utility lines where they attach to the trunk line or where they enter a building. Flexible lines with built-in slack usually solve this problem. Flexible lines are especially important for potentially dangerous utilities, such as electricity and natural gas.

Effective designs and materials are available for each part of a building to make it more resistant to damage from movement, but the foundation is probably the most important component. Many problems may be avoided by using specially reinforced foundations. These concrete slabs are similar to conventional foundations, but they are thicker and contain more reinforcing steel bars. They do not crack, even when one end is lowered 1 to 2 feet below the other.

Sometimes subsidence begins or worsens markedly after facilities are in place. In these cases, only the third option remains. Known subsidence and fissure zones may be chosen for development anyway because of certain advantages, such as proximity to existing facilities. Option 3 is to repair, replace, or abandon facilities that are damaged by subsidence or fissures. This is the option that most people choose or are left with because they were not aware of the problem in the first place, or they decided to ignore it and hope for the best. If damage does not occur or is not extensive, this approach may be the least expensive. If considerable damage does occur, however, repairs may be costly, and the property owner may suffer proportionately.

Earth fissures present additional dangers that may be divided into two major groups: (1) hazards of the open cracks themselves, and (2) hazards associated with fissure-caused changes in stream-drainage patterns that result in erosion and sedimentation.

One problem with open fissures is that people and livestock may fall into or become trapped in those that are large and steep sided. This danger may be reduced by keeping people and animals out of the general area or by fencing off the fissures. More fence may have to be added as fissures lengthen or branch. This approach may not be practical for large tracts of land.

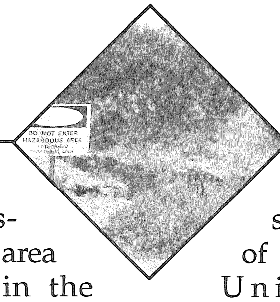
Another problem is that open fissures, especially deep, narrow ones, may provide paths for pollutants to reach the ground water. To prevent possible contamination, trash should never be placed in or near a fissure. If polluted water flowing over the land surface could reach an open fissure, the crack should be filled with sediment. Clay-rich sediment is ideal because of its low permeability. Packing sediment tightly into a narrow and deep fissure is difficult, however, so the seal may not be completely impermeable. The ground water may be further protected by constructing a **berm** (a long, low mound of soil) immediately upslope from the filled crack, which would reroute surface water away from the fissure. Vegetation planted along the fissure may also protect the ground water by drawing moisture out of the soil and into its roots. The site and any protective devices should be inspected regularly in case the fissure widens or lengthens.

Open cracks reduce the support of any structure under which they pass. Many structures can be designed and built to withstand some loss of support, but most are more expensive than equivalent unreinforced structures. The higher cost, however, is well spent when a reinforced structure is damaged very little or not at all by an earth fissure.

The same remedial measures recommended for open fissures may be used to slow or stop erosion and sedimentation caused by fissures. Flowing water must be kept from entering fissures. Streams that have been intercepted by fissures cannot reoccupy their channels downslope from the cracks until the fissures have been filled with sediment. As long as streams flow outside their channels, the natural balance between erosion and deposition is upset.

For any hazard-reduction program to be successful, the current status of fissures (and of any modifications made to them) must be known. Periodic inspection is important, especially after intense rainstorms, when changes are most likely to occur. Young, active fissures should be examined every 2 months. One inspection per year is probably sufficient for most old, less active fissures, unless new cracks have formed nearby or heavy rain has fallen. It is useful to place markers, such as stakes pounded into the ground, and to take photographs from known vantage points to record changes over time. Property owners can make measurements and keep written records if they desire a high degree of accuracy in monitoring fissure development.

Conclusion



Significant rates of ground-water withdrawal began in Arizona in approximately 1910. Since the late 1930's, these rates have greatly exceeded the replenishment rates in some areas. The highest withdrawal rates occurred mostly during the 1950's, 1960's, and 1970's. Excessive ground-water pumping causes unconsolidated and semiconsolidated water-bearing sediment to compact at depth and leads to land subsidence and earth-fissure formation. Compaction of some of this sediment is irreversible and permanently reduces its water-storage capacity.

Subsidence and earth fissures are significant geologic hazards in Arizona. Approximately 9 percent of the area affected by pumping subsidence in the United States is in Arizona (Poland, 1981). Hundreds of earth fissures have formed within the State just during the second half of the 20th century. Arizona may have more fissures than any other area of comparable size in the United States. As urban areas expand, especially at the expense of adjacent agricultural land, subsidence and fissures will have an increasing impact on residents and facilities.

Although earthquakes, volcanoes, and most other geologic hazards cannot be controlled, humans can stop or at least reduce most pumping subsidence and earth-fissure formation. The key is ground-water conservation. In some areas of Arizona, using water supplied by the CAP aqueduct instead of ground water may help. Solving the problem will require not only wise application of geologic and hydrologic knowledge, but also tough decisions based on economic, social, and political factors.

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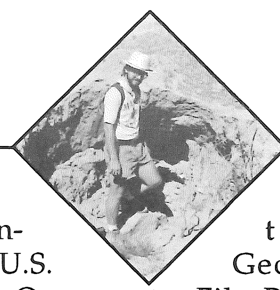

The following reports, some of which were used to prepare this booklet, contain additional information about subsidence and earth fissures. Those marked with an asterisk (*) are published by and available from the Arizona Geological Survey (formerly called the Arizona Bureau of Geology and Mineral Technology). Other useful publications that are not mentioned here contain more technical information and details about specific site conditions. Most of these are identified in the comprehensive bibliography compiled by Slaff (1990), which is listed below.

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