FIELD GUIDE TO EARTH FISSURES AND OTHER LAND SUBSIDENCE FEATURES IN PICACHO BASIN

Arizona Geological Society
Arizona Hydrological Society
Fall 1999 Field Trip
November 13, 1999

Arizona Geological Survey
Open-File Report 99-26

Leader:
Raymond C. Harris
Arizona Geological Survey

EARTH FISSURES AND OTHER LAND SUBSIDENCE FEATURES IN PICACHO BASIN

Arizona Geological Society / Arizona Hydrological Society
Fall 1999 Field Trip

Leader:
Raymond C. Harris
Arizona Geological Survey

INTRODUCTION

This field trip focuses on subsidence features caused by removal of groundwater at rates greater than natural recharge in the Picacho basin. Land subsidence is common in Arizona's alluvial basins, where extensive groundwater withdrawal has lowered water tables by as much as six hundred feet. The water pressure (weight) of groundwater produces a subsurface buoyancy force. Removal of groundwater and the associated buoyancy force results in compaction of basin sediments, reduction of pore space, and subsidence at the Earth's surface. Subsidence has occurred in every basin in Arizona where use of groundwater has significantly lowered water levels. Earth fissures typically appear at the margins of subsiding basins and accommodate subsidence of the basin interior relative to basin margins and flanking bedrock.

Multiple, extensive earth fissures have developed around the Picacho basin, an agricultural area where groundwater is being depleted. This field trip includes a visit to an area where an earth fissure system has developed that is over one mile long. The fissure system displays most of the features typical of earth fissures around the state.

FIELD TRIP LOG

Distance/Mileage

0.0 **0.0** Ina Road at Interstate 10, Tucson. Proceed north.

7.0 **7.0** Arizona Portland Cement Company Rillito plant on left. In operation since 1949, the plant produces cement from Paleozoic limestone deposits four miles south, at the Twin Peaks quarry (Rains, 1987). Although not apparent anymore, there really were two peaks there before one was removed by quarrying. The remaining peak is composed of Precambrian schist and granite, and Cambrian Bolsa and Abrigo Formations (Lipman, 1993).

22.0 **29.0** Picacho Peak State Park, exit #219. Picacho Peak, on left, consists of Mid-Miocene volcanic rocks. Picacho Peak volcanic rocks are separated from the Picacho Mountains to the north by a mid-Tertiary low-angle detachment fault (Kerrich and Rehrig, 1987; Richard and others, 1999). Exposures of the fault can be seen on the SE flank of the Picacho Mountains, where a small, dark exposure of upper plate volcanic rocks contrasts with the underlying, light-colored lower plate mylonitic Precambrian crystalline rocks. Faulting has tilted the Picacho Peak rocks 30-60 degrees to the NE.

4.5 **33.5** Picacho earth fissure ("El Grande") crosses freeway, approximately milepost 215.3 (**Figure 1**). The fissure runs adjacent to the water tank on a small tower just north of the freeway. Where the fissure crosses the highway there is a noticeable dip in the road that marks the vertical offset of the fissure.

This fissure system, nearly 10 miles long, is the longest in Arizona. It forms a system of multiple, en echelon cracks with a surface expression up to 50 feet wide and 60 feet deep (Slaff, 1989). Opening in 1927, the fissure system has the distinction of being Arizona's first.

Maximum subsidence in Picacho Basin was measured at 15.4 feet between 1952 and 1985 (Slaff, 1993). Continued groundwater pumping has increased the amount of subsidence since then. Seismic, gravity, and drill-hole data (Pankratz and others, 1978; Holzer, 1978) indicate that the earth fissures here are coincident with Basin and Range bedrock fault scarps. The earth fissures are not tectonic faults themselves, but represent fracturing due to differential compaction and subsidence of de-watered sediments over the bedrock offsets. A detailed discussion (Holzer and others, 1979) of the mechanisms responsible for the formation of the Picacho earth fissure, and historical photographs (Robinson and Peterson, 1962) are included in Appendix A.

15.4 **48.9** Exit Freeway at exit #200, Sunland Gin Road. Turn south (left, and cross over freeway from Tucson, right from Phoenix) , turn right into the south end of Love's Truck stop. We will regroup and meet any participants coming from Phoenix here. Continue south on Sunland Gin Road.

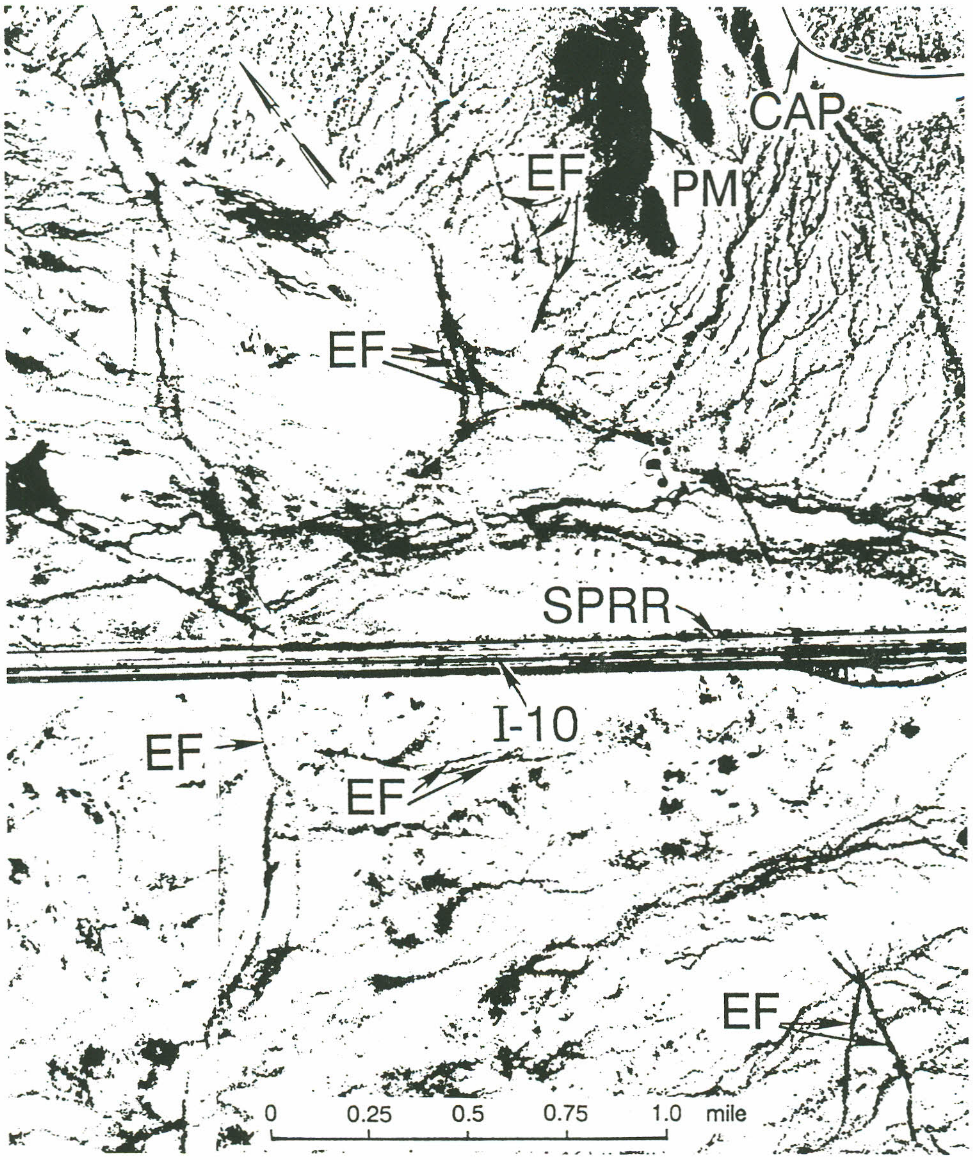


Figure 1. Earth fissure crossing Interstate 10. Earth fissures, marked 'EF' in the air photo, have formed in numerous areas in the eastern Picacho basin. The long earth fissure on the left side of the photo is known as "El Grande" and where it crosses Interstate 10 there is a noticeable drop-off. Symbols are as follows: EF = earth fissures; I-10 = Interstate 10; SPRR = Southern Pacific Railroad tracks; PM = Picacho Mountains; CAP = Central Arizona Project canal. Figure modified from Slaff (1989); Air photo by Arizona Department of Transportation, 1987.

For the next two miles, to Houser road, is an area of extensive fissuring between Sunland Gin Road and the Casa Grande Mountains. Two articles in Appendix A (Pashley, 1961; Jachens and Holzer, 1982) detail the history of development of these fissures over time. An aerial view of one of the larger fissures at the south end of the area appears as Figure 1 in the Fall 1999 issue of Arizona Geology (Fellows, 1999, Appendix A). Bedrock of the Casa Grande Mountains consists of Precambrian schist and granite with a few small mid-Tertiary granitic intrusives (Berquist and Blacet, 1978).

3.6 52.5 Entering Arizona City. Mostly a retirement community, with two large lakes and golf courses.

6.0 58.5 Harmon Road. Access to the north end of the Sawtooth Mountains via this road. The Sawtooth Mountains, to the southwest, are nearly flat-lying mid-Tertiary (25.9 Ma) volcanic rocks (Ferguson and others, 1999).

4.0 62.5 Greene Reservoir Road. Shortcut back to Tucson via this road, across the southern end of Picacho basin. Road eventually connects to Sasco Road and intersects freeway at Red Rock exit.

3.7 66.2 Main Road turns right - continue straight, going up and over drainage control birm. (Access southern Sawtooth Mountains by continuing west on main road.)

0.2 66.4 Small earth fissure crosses road from NE to SW in front of large mesquite tree on left and creosote on right. Trace of fissure marked by line of dense vegetation. Continue south.

0.1 66.5 Bear left at fork in road.

0.2 66.7 Bear right at fork in road, then left. Road continues through gap between two small hills at north end of Tator Hills. Volcanic rocks (trachyte) of the Tator Hills are the same as those in the Sawtooth Mountains (Ferguson and others, 1999).

0.4 68.1 Turn left at faint tracks.

0.1 68.2 Stop 1. Large earth fissure.

Along the western edge of the Picacho Basin are numerous zones of earth fissures resulting from lowering of groundwater levels, which causes the land to subside. This field trip looks at a group of fissures at the southwest corner of the valley. Earth fissures have developed along the flanks of the Tator Hills and other locations nearby **(Figures 2 and 3)**. The largest fissure system, on the east side of the hills, is over a mile long, and in most of the zone there are two or three parallel fissures **(Figure 4)**. Toward the northern end of the zone, eight separate fissures can be distinguished on the ground. The fissures here are typical of those found in Arizona in size and length. Most are several feet wide and 5 to 15 feet deep. In a few places, the fissure is so deep the bottom is hard to see.

One feature here that is very unusual for a large, active fissure is the presence of a wash crossing the fissure near where the cars are parked at Stop 1. Normally, earth fissures interrupt all drainage, but in this case there is enough sediment being brought in to fill this section of the crack and form a temporary bridge. At this point, a person could cross the fissure and easily mistake it for a wash.

When the fissures in this part of the basin first opened up is not known, but the large fissure on the east side of the Tator Hills and several others in the region are indicated on 1981 USGS topographic maps **(Figure 2)**. A comparison of the fissures present when the USGS map was field-checked in 1977 with fissures found in 1994 shows the addition of many new cracks and lengthening of older fissures **(Figure 5)**. The large fissure system now typically consists of two or three parallel cracks and toward the north end begins to form multiple, offset (en echelon) cracks.

Although the older fissures formed prior to 1977, they are still active, as indicated by their steep sides and highly variable depth **(Figure 6)**. In many places the fissure bottom drops out and is too deep to see. To the east of the main fissure(s) are younger cracks just beginning to open. These younger fissures are more discontinuous along their length and are not as deep. Some are not much more than alignments of small depressions or narrow cracks. Even these incipient cracks are usually marked by a line of vegetation, which is often the first sign of a developing fissure.

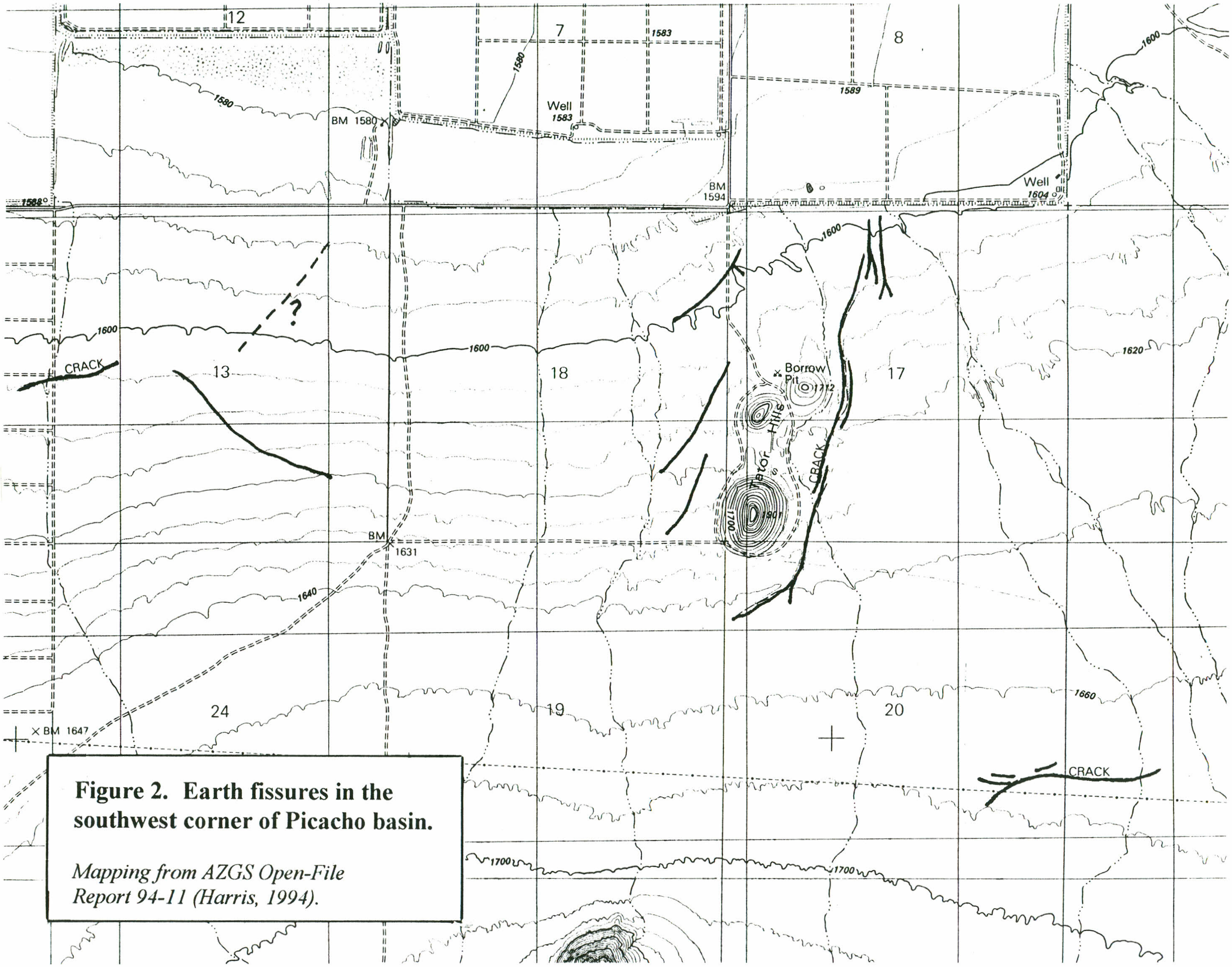


Figure 2. Earth fissures in the southwest corner of Picacho basin.

Mapping from AZGS Open-File Report 94-11 (Harris, 1994).

Figure 3. Aerial view of earth fissures around the Tator Hills, southwest Picacho Basin. Fissures have formed on both sides of the hills. The fissure zone to the east (right) of the hills is over a mile long. The fissure continues past the bottom of this aerial photo several hundred yards. Photo is about 1.1 miles from top to bottom. *(Aerial photo from Pinal County.)*

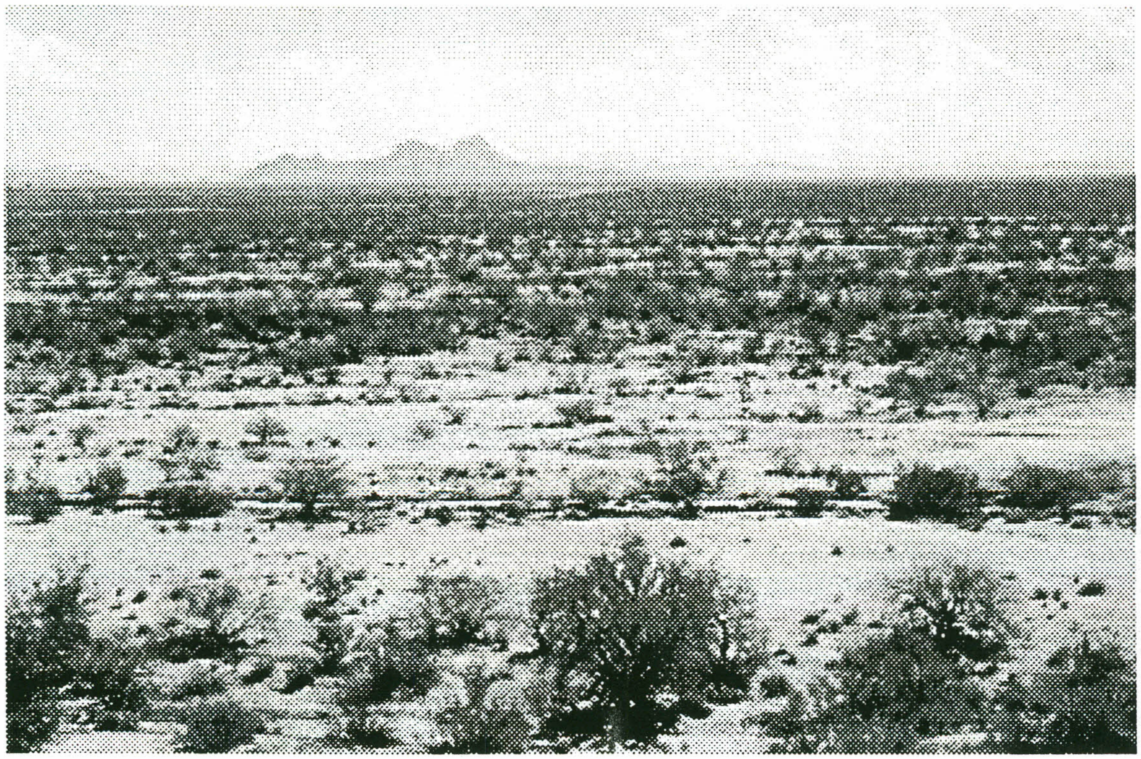


Figure 4. View of large earth fissure zone on east side of Tator Hills. Fissure zone here consists of two parallel cracks (horizontal lines about one-third up from bottom of photo). *(Photo by R.C. Harris.)*

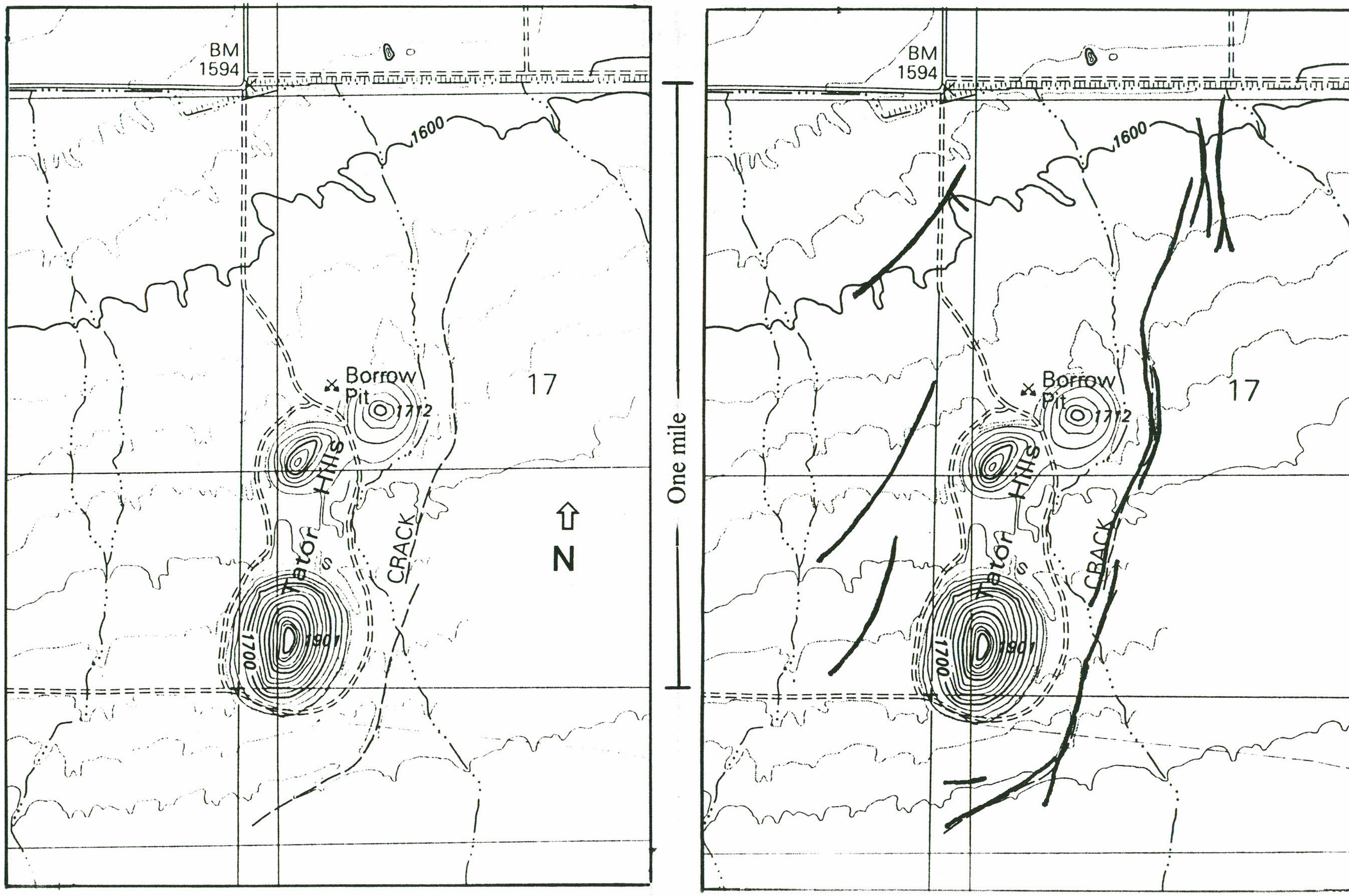


Figure 5. Development of earth fissures from 1977 to 1994. Map on left is from 1981 USGS Greene Reservoir topographic map, compiled from air photos taken in 1976 and field checked in 1977. Map on right shows fissures found in survey in 1994 (Harris, 1994). Fissures present in 1977 have increased in length and new fissures have formed.

Figure 6. Large earth fissure. Crack here is 3-4 feet wide, up to 15 feet deep. *(Photo by R.C. Harris.)*

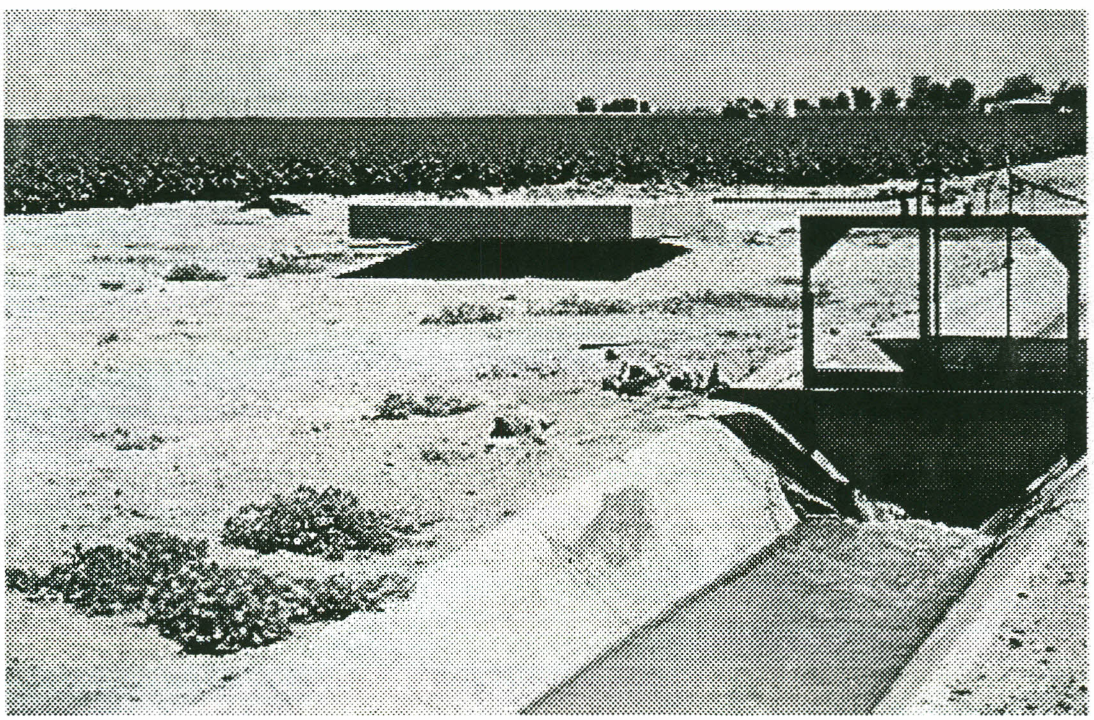
Retrace route north on Sunland Gin Road to Interstate 10.

18.1 **85.3** Interstate 10. Turn north onto freeway.

4.8 **90.1** Exit 194. Turn Right on Highway 287.

2.4 **92.5** **Stop 2.** Protruding well head.

Protrusion of this wellhead (**Figure** 7, below) has been attributed to regional subsidence. The bottom of the well casing was, at least at one time, anchored below the depth where compaction has occurred, so as the ground surface has subsided the well head has not subsided as much as the surrounding area. The concrete slab is attached to the top of the well casing and is supported only by the casing.



End of trip. Return to Tucson via I-10 or continue east on Hwy 287 to Hwy 84. Turn right (south) on Hwy 87 to intersection with I-10 between Picacho and Eloy.

REFERENCES

Berquist, J.R., and Blacet, P.M., 1978, Preliminary reconnaissance bedrock geologic map of the Casa Grande Mountains quadrangle, Pinal County, Arizona: US Geological Survey Open-File Report 78-547, scale 1:24,000.

Fellows, L.D., 1999, Ground-water pumping causes Arizona to sink: Arizona Geology, v. 29. no.3, Fall 1999, p. 1-4.

Ferguson, C.A., Gilbert, W.G., Klawon, J.E., and Pearthree, P.A., 1999, Geologic map of the Sawtooth Mountains and the north end of the West Silverbell Mountains, Pinal and Pima Counties, southern Arizona: Arizona Geological Survey Open-File Report 99-16, 25 p., scale 1:24,000.

Harris, R.C., 1994, A reconnaissance of earth fissures near Apache Junction, Chandler Heights, and southwestern Picacho Basin: Arizona Geological Survey Open-File Report 94-11, 5 p., 2 sheets.

Holzer, T.L., 1978, Results and interpretation of exploratory drilling near the Picacho Fault, south-central Arizona: US Geological Survey Open-File Report 78-1016, 38 p.

Holzer, T.L., Davis, S.N., and Lofgren, B.E., 1979, Faulting caused by groundwater extraction in southcentral Arizona: Journal of Geophysical Research, v. 84, no. B2, p. 603-612.

Jachens, R.C., and Holzer, T.L., 1982, Differential compaction mechanism for earth fissures near Casa Grande, Arizona: Geological Society of America Bulletin, v. 93, p. 998-1012.

Kerrich, R., and Rehrig, W., 1987, Fluid motion associated with Tertiary mylonitization and detachment faulting: $^{18}O/^{16}O$ evidence from the Picacho metamorphic core complex, Arizona: Geology, v. 15, no. 1, p. 58-62.

Lipman, P.W., 1993, Geologic map of the Tucson Mountains caldera, southern Arizona: US Geological Survey Miscellaneous Investigations Series Map I-2205, scale 1:24,000.

Oppenheimer, J.M., and Sumner, J.S., 1981, Gravity modeling of the basins in the Basin and Range Province, Arizona: Arizona Geological Society Digest 13, p. 111-115.

Pashley, E.F. Jr., 1961, Subsidence cracks in alluvium near Casa Grande, Arizona: Arizona geological Society Digest 4, p. 95-101.

Peirce, H.W., 1976, Tectonic significance of Basin and Range thick evaporite deposits: Arizona Geological Society Digest 10, p. 325-239.

Rains, J.W., 1987, Arizona Portland Cement Company's Rillito operation, in H.W. Peirce, editor, Proceedings of the 21st forum on the geology of industrial minerals: Arizona Bureau of Geology and Mineral Technology Special Paper 4, p. 134.

Richard, S.M., Spencer, J.E., Ferguson, C.A., and Pearthree, P.A., 1999, Geologic map of the Picacho Mountains and Picacho Peak, Pinal County, southern Arizona: Arizona Geological Survey Open-File Report 99-18, 43p., scale 1:24,000.

Robertson, G.M., and Peterson, D.E., 1962, Notes on earth fissures in southern Arizona: US Geological Survey Circular 466, 7 p.

Slaff, S., 1989, Patterns of earth-fissure development: Examples from Picacho Basin, Pinal County, Arizona: Arizona Geology [Arizona Geological Survey], v. 19, no. 3, p. 4-5.

Slaff, S., 1993, Land subsidence and earth fissures in Arizona: Arizona Geological Survey Down-to-Earth Series 3, 24 p.

APPENDIX A

ARTICLES ABOUT SUBSIDENCE AND EARTH FISSURES IN ARIZONA

Fellows, L.D., 1999, Ground-Water pumping causes Arizona to sink: Arizona Geology, v. 29. no.3, Fall 1999, p. 1-4.

Holzer, T.L., Davis, S.N., and Lofgren, B.E., 1979, Faulting caused by groundwater extraction in southcentral Arizona: Journal of Geophysical Research, v. 84, no. B2, p. 603-612.

Jachens, R.C., and Holzer, T.L., 1982, Differential compaction mechanism for earth fissures near Casa Grande, Arizona: Geological Society of America Bulletin, v. 93, p. 998-1012.

Pashley, E.F. Jr., 1961, Subsidence cracks in alluvium near Casa Grande, Arizona: Arizona Geological Society Digest 4, p. 95-101.

Robertson, G.M., and Peterson, D.E., 1962, Notes on earth fissures in southern Arizona: US Geological Survey Circular 466, 7 p.

Vol. 29, No. 3
Fall 1999

Arizona Geology

Published Quarterly by the Arizona Geological Survey

ARIZONA GEOLOGICAL SURVEY

The State agency for geologic information

MISSION

To inform the public about geologic processes, materials, and resources in Arizona and assist citizens, businesses, governmental agencies, and elected officials in making informed decisions about managing Arizona's land, water, mineral, and energy resources.

GOALS

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

Ground-Water Pumping Causes Arizona to Sink

Larry D. Fellows
Director and State Geologist

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

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

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

(continued on page 2)

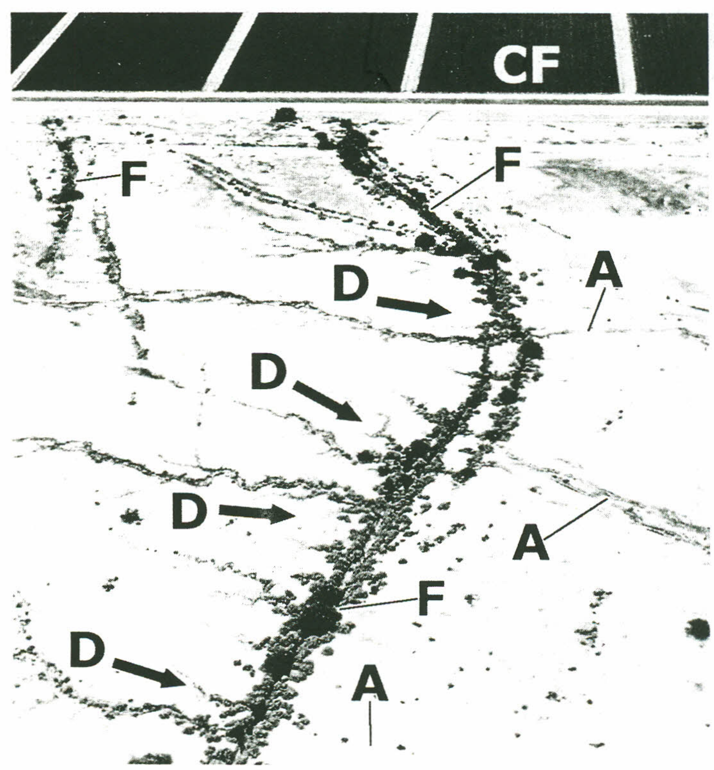


Figure 1. Fissures (F), which appear to stop at the edge of irrigated cotton fields (CF) southeast of Casa Grande in Pinal County, developed at right angles to existing stream channels. After heavy rainfall, runoff drains in the direction of the arrows (D) into the fissures. Channels on the right side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

GOVERNOR
JANE DEE HULL

ARIZONA GEOLOGICAL SURVEY

September 1999

OFFICE OF THE DIRECTOR
Larry D. Fellows, Ph.D.
Director and State Geologist

Rose Ellen McDonnell, B.S.
Assistant Director of Administration

INFORMATION AND PUBLICATIONS
Peter F. Corrao, B.S.
Nancy A. Duffin
Georgeanna L. Meeker
Cathy L. Moore, M.S.
Mary E. Redmon

LIBRARY AND DATABASES
Thomas G. McGarvin, B.A.
Richard A. Trapp, M.S.

MAPPING AND INVESTIGATIONS
Jon E. Spencer, Ph.D.
Senior Geologist
Philip A. Pearthree, Ph.D.
Stephen M. Richard, Ph.D.
Charles A. Ferguson, Ph.D.
Wyatt G. Gilbert, Ph.D.
Raymond C. Harris, M.S.
Tim R. Orr, M.S.
Steven J. Skotnicki, M.S.
Lee Amoroso, M.S.
Douglas B. Bausch, M.S.

OIL AND GAS
Steven L. Rauzi, M.S.

Arizona **Geology**

Arizona Geology is published quarterly by the Arizona Geological Survey (AZGS), an Executive Branch agency of the State of Arizona. The AZGS headquarters is at 416 West Congress Street, Suite 100, Tucson, AZ 85701; telephone (520) 770-3500.

Web address
http://www.azgs.state.az.us.

Design and layout by
Peter F. Corrao

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

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

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

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

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

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

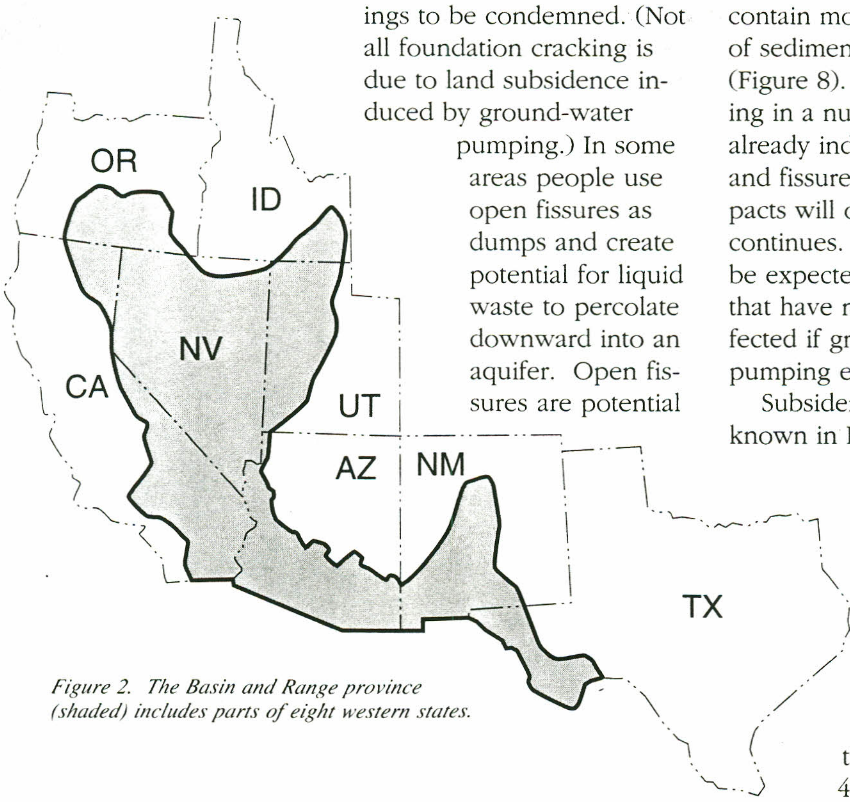


Figure 2. The Basin and Range province (shaded) includes parts of eight western states.

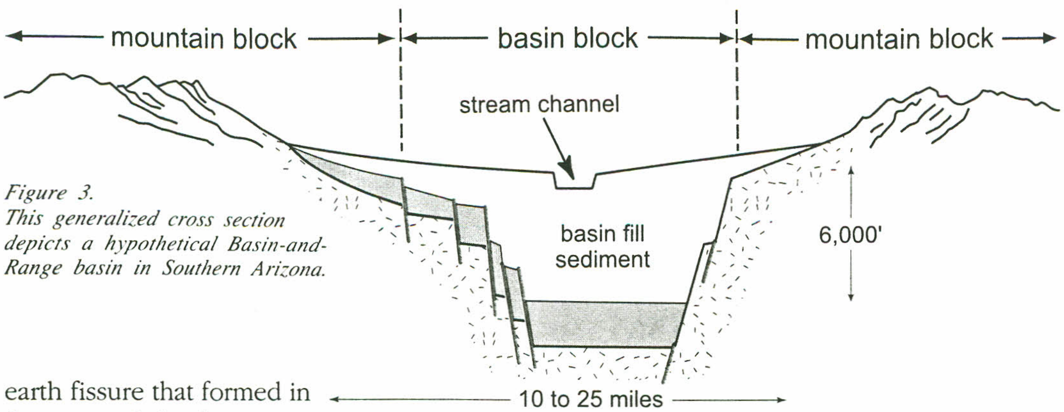


Figure 3. This generalized cross section depicts a hypothetical Basin-and-Range basin in Southern Arizona.

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

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

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

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

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

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

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

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

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

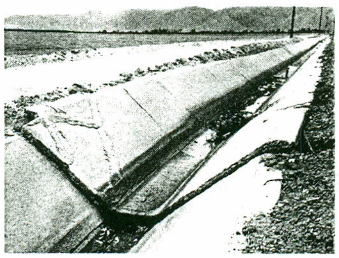
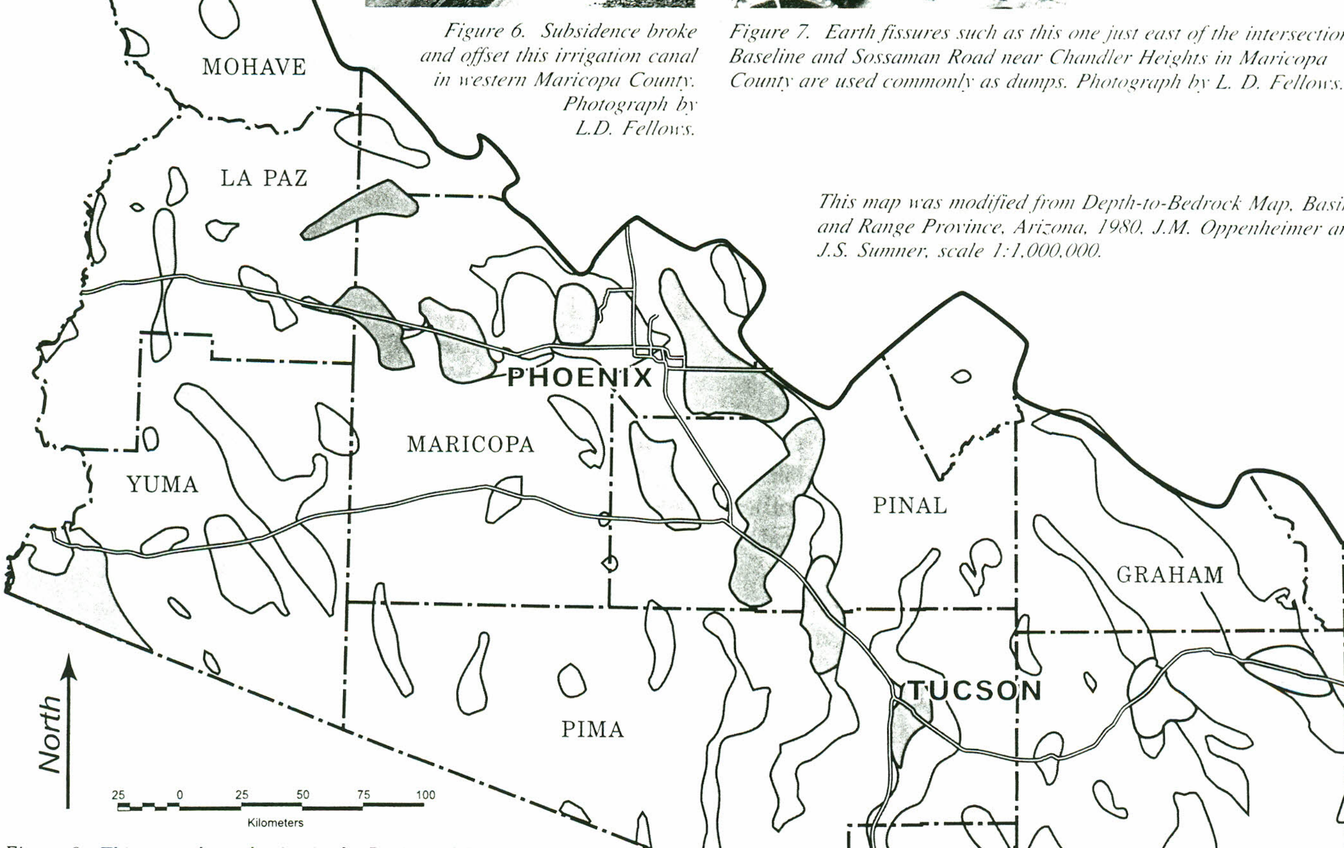


Figure 6. Subsidence broke and offset this irrigation canal in western Maricopa County. Photograph by L.D. Fellows.

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



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

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

Faulting Caused by Groundwater Extraction in Southcentral Arizona

THOMAS L. HOLZER

U.S. Geological Survey, Menlo Park, California 94025

STANLEY N. DAVIS

University of Arizona, Tucson, Arizona 85721

BEN E. LOFGREN

U.S. Geological Survey, Sacramento, California 95825

Modern surface faulting, 4.8 km southeast of Picacho, Arizona, has created a scarp ranging from 0.2 to 0.6 m high and approximately 15 km long. The scarp, which has been steadily increasing in height since it began to form in 1961, occurs along the eastern margin of the Eloy-Picacho subsidence bowl where more than 2.9 m of land subsidence, caused by declines of groundwater levels, occurred from 1934 to 1977. Faulting is concluded to be related to groundwater withdrawal. First, the scarp is restricted to an area underlain by alluvium in which groundwater levels have declined. Second, faulting postdates the beginning of water level declines and associated land subsidence. Third, observed vertical displacements associated with faulting are compatible with results from a model of subsurface faulting in which rupture does not extend beneath the zone affected by stresses related to declines of water levels. The model is based on elastic dislocation theory. And fourth, analysis of levelings of bench marks unaffected by man-induced subsidence indicates minor regional crustal movements that do not appear to be compatible with the magnitude of fault offset.

INTRODUCTION

Investigations of modern surface faulting associated with petroleum withdrawal demonstrate that fluid withdrawal in certain circumstances can cause fault offset [*Castle and Yerkes,* 1976; *Pratt and Johnson,* 1926]. The only mechanism for this faulting that has been seriously evaluated attributes the faulting to horizontal extensional strains caused by differential compaction [*Castle and Yerkes,* 1976]. Although it has not been demonstrated with field data that this mechanism may apply in areas of land subsidence caused by groundwater withdrawal, a relation between modern surface faulting and groundwater extraction has been suggested or implied by many investigators. Possible examples of such faulting occur in California [*Church et al.,* 1974; *Holzer,* 1977; *Rogers,* 1967], Mexico (G. E. Figueroa Vega, personal communication, 1977), and Texas [*Kreitler,* 1977; *Van Siclen,* 1967]. The principal evidence supporting such a relation is temporal and areal association of fault offset with the groundwater withdrawal [*Holzer,* 1977]. This association, of course, is not conclusive evidence unless the possibility of fault offset of tectonic origin contemporaneous with groundwater production is excluded. Such an analysis has never been performed, and published field relations permit a tectonic interpretation of all of the reported faulting.

This article documents a scarp that has formed since 1961 in southcentral Arizona in an area of land subsidence caused by groundwater level declines and attributes the scarp to faulting related to groundwater extraction. A tectonic origin of the faulting is argued to be unlikely based on analyses of geodetic data. First, the magnitude of the fault scarp appears to exceed the magnitude of regional crustal movements. And second, agreement between observed vertical surface displacements associated with faulting and those computed by modeling suggests that modern fault offset within the subsurface is restricted to the subsurface zone that is affected by water level declines. In addition to documenting faulting related to groundwater withdrawal, this article suggests an approach by which the origin of faulting in other areas of groundwater withdrawal might be determined. The approach is based on an estimation of depth of fault rupture by comparison of observed vertical displacements associated with faulting with displacements computed with models. In the example cited here, the model is based on elastic dislocation theory.

Heretofore, earth fissures or cracks were the only type of ground failure that has been conclusively attributed to groundwater withdrawal [*Holzer,* 1977]. These earth fissures can be distinguished from ordinary soil desiccation cracks by their long lengths and great depths. Movement of blocks perpendicular to the crack surface indicates that earth fissures are caused by tension and distinguish earth fissures from faults in which the relative displacements are predominantly parallel to the failure zone. Areas in which earth fissures are found include central and southeastern Arizona [*Eaton,* 1972; *Schumann,* 1974], Las Vegas, Nevada [*Mindling,* 1974], San Jacinto Valley, California [*Morton,* 1977], and the San Joaquin Valley, California [*Lofgren,* 1971].

GEOLOGY AND HYDROGEOLOGY

The surface fault to be described occurs on the eastern margin of a deep alluvial basin in southcentral Arizona (insert in Figure 1) which is in the southern part of the Basin and Range physiographic province. This province is characterized by fault-bounded alluvial basins and mountains. Faulting and uplift in southcentral Arizona occurred relatively early in Late Cenozoic time [*Eaton,* 1972], and the area is now seismically inactive, or nearly so [*Scott and Moore,* 1976; *Sturgal and Irwin,* 1971]. The only historic seismicity reported in the area of modern faulting occurred in the 1970's. Although *Yerkes and Castle* [1976] attributed the seismicity to extraction of groundwater, other investigators have concluded that the seis-

Paper number 8B1005.

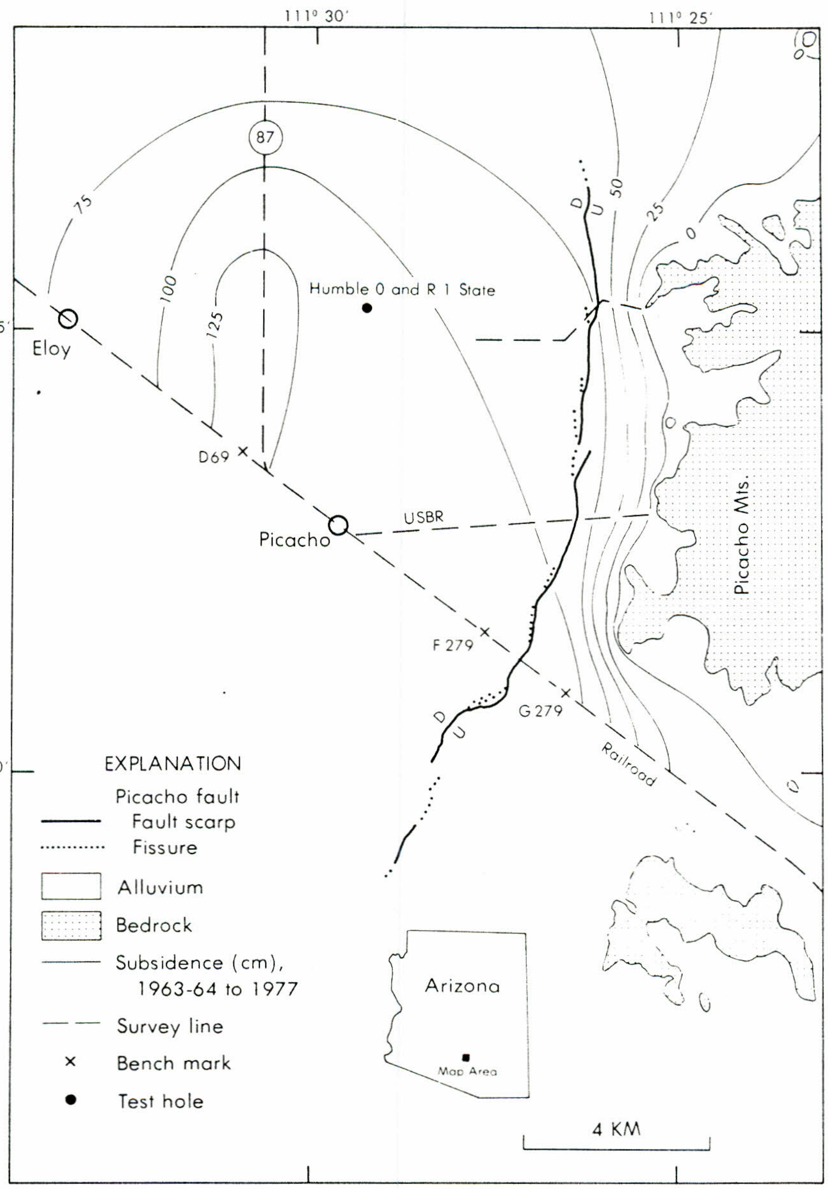


Fig. 1. Location map of the Eloy and Picacho, Arizona, area. The alignment of the Picacho fault is shown as of May 1976. Earth fissures contiguous with the fault scarp also are shown. Subsidence from 1963–1964 to 1977 is based on the survey lines shown on the map. Interstate Highway I-10 parallels and is essentially adjacent to the railroad survey line. Groundwater production wells are restricted to the western side of the Picacho fault.

mic events were related to supersonic flights of military aircraft [*Peirce,* 1975; *Shakel,* 1977]. Based on a microearthquake investigation conducted for 9 days north of Eloy, A. L. Lange (personal communication, 1977) concluded that no seismically active tectonic processes were present in the basin cut by the fault during the investigation. The investigation consisted of a 260-km² seismic network with a detection threshold for earthquakes within the network of less than Richter magnitude −1.

The depth of the alluvial basin in which the fault to be discussed occurs has been documented by a test hole (Humble 0 and R 1 State, Figure 1) that penetrated crystalline bedrock at a depth of 3011 m [*Peirce,* 1976]. Previous investigators [*Peirce,* 1976; *Peterson,* 1964; *Schumann and Poland,* 1971] have suggested, based on either regional gravity surveys or the Humble 0 and R 1 State test hole, that at least a portion of the eastern margin of the basin in the region of the modern fault is bounded by a tectonic fault offsetting the buried bedrock surface with the western side of the fault downthrown relative to the eastern side. Recently conducted detailed seismic refraction and gravity surveys (L. W. Pankratz et al., unpublished data, 1977), however, indicate that subsurface conditions beneath the modern fault are more complex than earlier interpretations of a major, localized change in elevation of the bedrock surface. The recent results suggest that the crystalline bedrock surface (velocity = 5.6 km/s) dips basinwide at approximately 25° and is offset approximately 100 m at a depth of 800 m beneath the modern fault. In addition, the seismic refraction survey identified a refracting layer at a depth of approximately 300 m that undergoes an abrupt lateral change of velocity from 3.1 to 3.7 km/s beneath the modern fault.

Three hydrogeologic units from which groundwater presently is extracted in the basin cut by the fault have been described [*Hardt and Cattany,* 1965]: an upper sand and gravel unit, attaining a thickness as great as 365 m, in which the groundwater is unconfined; an intermediate silt and clay unit that in places exceeds 244 m in thickness; and a lower heterogeneous sand and gravel unit in which groundwater occurs under confined conditions. Early groundwater developments were entirely from the upper unconfined unit. The maximum depth of existing production water wells is approximately 760 m. Thickness and properties of the hydrogeologic units near the modern fault scarp are poorly known. Electric logs from a test hole drilled by the U.S. Bureau of Reclamation approximately 4.2 km west of the fault at its north end indicate that approximately 183 m of fine-grained materials underlies 335 m of heterogeneous, coarse-grained material, which agrees with the stratigraphy delineated by *Hardt and Cattany* [1965]. However, driller's logs of wells nearer the fault are inadequate to clearly delineate hydrogeologic units in the vicinity of the fault. The water table near the fault prior to groundwater development was approximately 50 m from the land surface.

PICACHO FAULT

The alignment of the modern fault scarp shown in Figure 1, hereinafter referred to as the Picacho fault, is based on aerial photography flown in December 1975 and field reconnaissance in May 1976. Earth fissures contiguous with the fault scarp also were mapped and are shown in Figure 1. The fault scarp presently is approximately 15.8 km long. Vertical profiles of undisturbed desert surface based on surveys across the fault in May 1976 show the character of the scarp on the desert surface to vary from a sharp and well-defined feature with little modification by erosion to a visually detectable flexure. Vertical offset ranging from 0.2 to 0.6 m was observed to persist along the fault. Prior to the present investigation, vertical offset on the Picacho fault had been described [*Peterson,* 1962, 1964] only in the vicinity of the railroad survey line (see Figure 1). The lateral continuity of the vertical offset along the fault apparently was not recognized by previous investigators.

Evidence of prehistoric surface faulting along the trace of the Picacho fault was not revealed by field reconnaissance. In many places, a smooth desert floor was offset by historic fault movement, and little erosion had occurred on the upthrown side of the scarp. No abrupt changes in surficial materials across the fault were recognized in two shallow trenches dug across the fault. The only conspicuous feature revealed by examination of aerial photography taken in 1936 and 1949 prior to the occurrence of historic ground failure associated with the Picacho fault was an alignment of vegetation that coincided with a small portion of the trace of the future fault scarp near its south end. A map with a 1-foot contour interval prepared in 1931 for a railroad survey (C. C. Winikka, unpublished data, 1976) did not reveal a topographic manifestation of this feature.

WATER LEVEL DECLINES AND VERTICAL SURFACE DISPLACEMENTS

Smith [1940] noted that although pumping in the Eloy-Picacho area began before 1920, large groundwater withdrawals did not occur until the middle 1930's. In response to this increase of pumping, the rate of decline of groundwater levels increased significantly as demonstrated by a composite well hydrograph (Figure 2) based on wells in the upper aquifer near Eloy, the original center of the regional cone of depression. This increase in the rate of decline also is reflected in the water level declines mapped in the Eloy-Picacho area for four time periods, 1915–1940, 1949, 1963, and 1977 (Figure 3), which used a map of water levels observed in 1915 [*Smith,* 1938] as the reference datum. The maps also show the extent of faulting and fissuring associated with the Picacho fault during these periods.

Many investigators [*Peterson,* 1962; *Schumann and Poland,* 1971; *Winikka,* 1964] have concluded that the declining water levels have caused sediment compaction resulting in land subsidence in the Eloy-Picacho area. Repeated relevelings of two survey lines of the National Geodetic Survey near the Picacho fault give some of the history of this land subsidence. One line, first surveyed in 1934, runs due north from Picacho (Highway 87 survey line, Figure 1). The other line, first surveyed in 1905, runs northwest-southeast through Picacho along a Southern Pacific Railroad track which is adjacent to Interstate Highway I-10, formerly State Highway 84 (Railroad survey line, Figure 1). Maximum subsidence from 1948 to 1967, based on these two survey lines, was more than 2.2 m in the Eloy-Picacho area [*Schumann and Poland,* 1971]. Releveling of the railroad survey line in 1977 indicated that maximum subsidence since 1948 had exceeded 2.9 m along this line (Figure 4*a*). In addition to the subsidence profiles (Figure 4*a*), the areal distribution of subsidence northeast of the railroad survey line and in the vicinity of the Picacho fault for the time period 1963–1964 to 1977 is well documented by relevelings of survey lines (Figure 1).

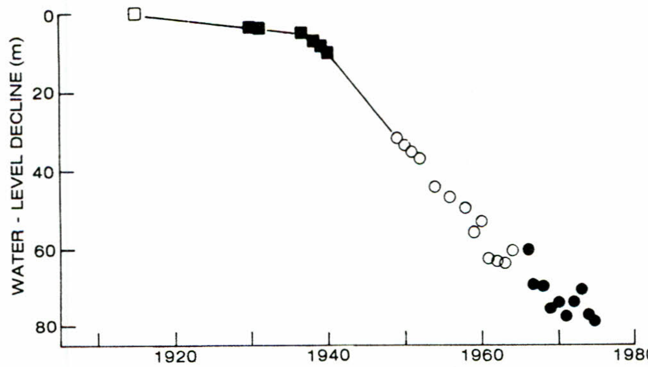


Fig. 2. Composite well hydrograph of springtime water level measurements in wells located approximately 1 km north of Eloy. The area is near the original center of the cone of depression within the alluvial basin. All wells used in the compilation, indicated by different symbols, were completed in the upper aquifer.

Comparison of unadjusted field survey data tying the two oldest bench marks on the railroad survey line, A279 and G279 (Figure 4*a*), suggests that subsidence in the alluvial basin in the Eloy-Picacho area essentially began during the period 1934–1948. These bench marks, orginally tied by first-order leveling in 1905, were tied by second-order leveling in 1934 and again by first-order leveling in 1948. Bench mark A279 subsided 0.012 m relative to G279 from 1905 to 1934 compared to 0.137 m from 1934 to 1948. This comparison, although based on only two bench marks, is informative because G279 appears to have been relatively unaffected by subsidence before 1952 (Figure 6*a*) and A279 appears to have been within the area affected by the earliest man-induced subsidence (Figure 4*a*). Although a small amount of subsidence from 1905 to 1934 may have occurred according to the level data, its magnitude is uncertain. One standard deviation for random error in the comparison of first- with second-order levelings tying the two bench marks, which are 17.6 km apart, is estimated to be 0.0062 m using the standards of accuracy cited by the *Federal Geodetic Control Committee* [1974]. For leveling of the vintage used here, this estimate of the standard deviation probably is low by a factor ranging from 2 to 3 (R. O. Castle, personal communication, 1977).

Man-induced compaction of sediments in the basin cut by the Picacho fault and in adjacent basins precludes determina-

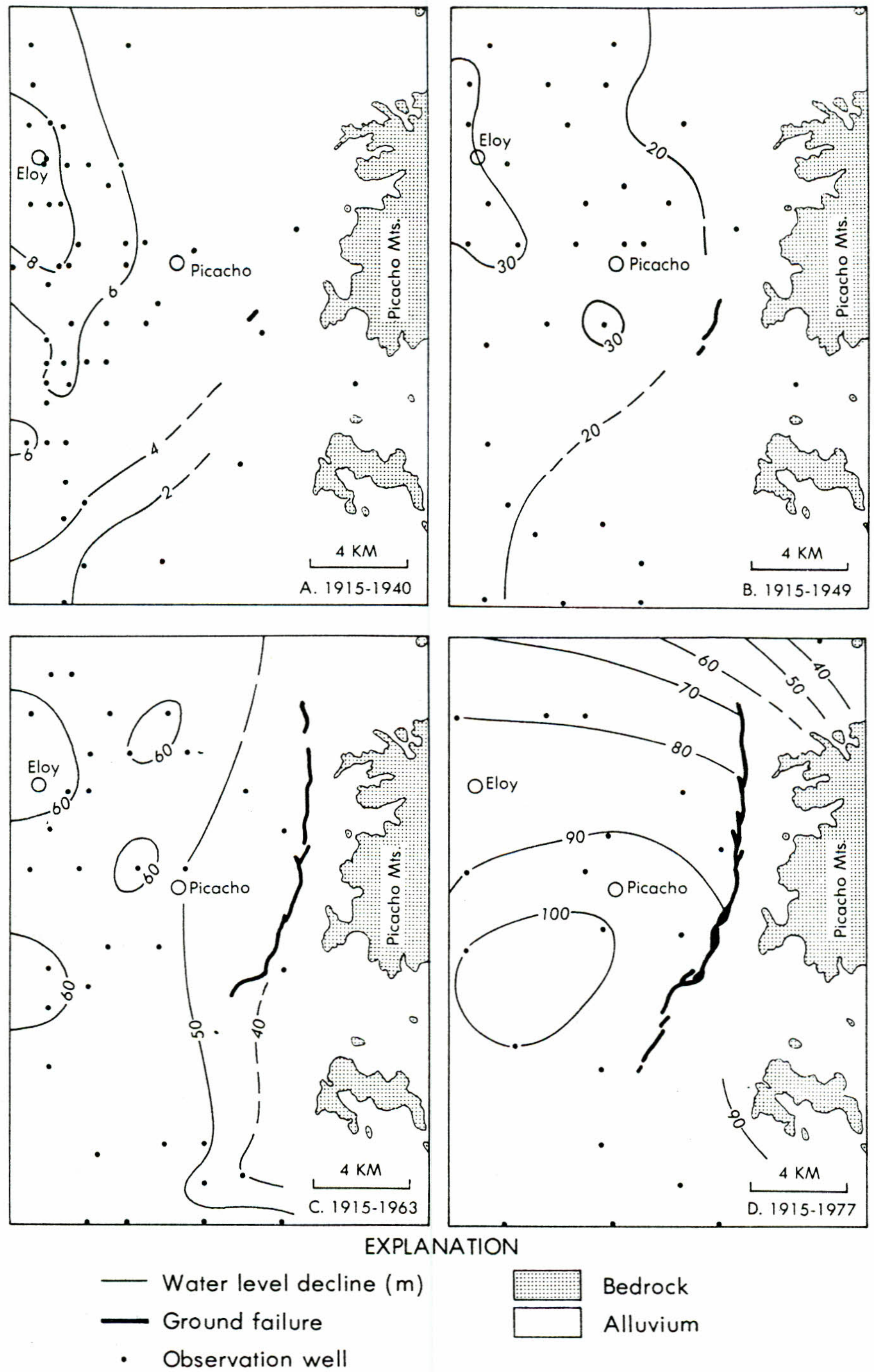


Fig. 3. Maps of groundwater level declines with associated ground failure during successive periods. Water levels are based on wells penetrating only the upper sand and gravel unit. (*a*) 1915–1940: 1927 fissure trace mapped by Southern Pacific Railroad (unpublished data); (*b*) 1915–1949: 1949 fissure traces mapped by *Heindl and Feth* [1955]; (*c*) 1915–1963: Trace of ground failure based on 1963 aerial photography; and (*d*) 1915–1977: Picacho fault from Figure 1.

tion of the magnitude of deep-seated vertical crustal displacements in the general area and in the immediate vicinity of the fault. However, analysis of unadjusted field survey data from releveling of bench marks on the railroad survey line established over shallowly buried crystalline bedrock at the margins of the basin cut by the fault reveal that the margins did not move significantly relative to each other from 1948–1949 to 1977 (Figure 5). In addition, from 1905 to 1948–1949, elevations of many bench marks established on alluvium within the basin cut by the fault and the basin to the southeast were not yet affected by man-induced sediment compaction, i.e., water level declines were minor, so that crustal movements within portions of the basins can be evaluated for this time period (Figure 5). With the exception of the movement of bench mark A279, which was previously discussed, bench marks leveled in both 1905 and 1948 indicated no movements along a 77-km profile across the fault. These data indicate that the magnitude of relative displacement of the margins of the basin from 1905 to 1977 was less than 5 cm. Analysis of vertical crustal displacements in southcentral Arizona, based on additional data and extending beyond the region considered in Figure 5, essentially corroborates the conclusion concerning bedrock stability (T. L. Holzer, unpublished manuscript, 1978). Relative movements of widely separated bench marks in areas unaffected by water level declines were minor from 1905 to 1977.

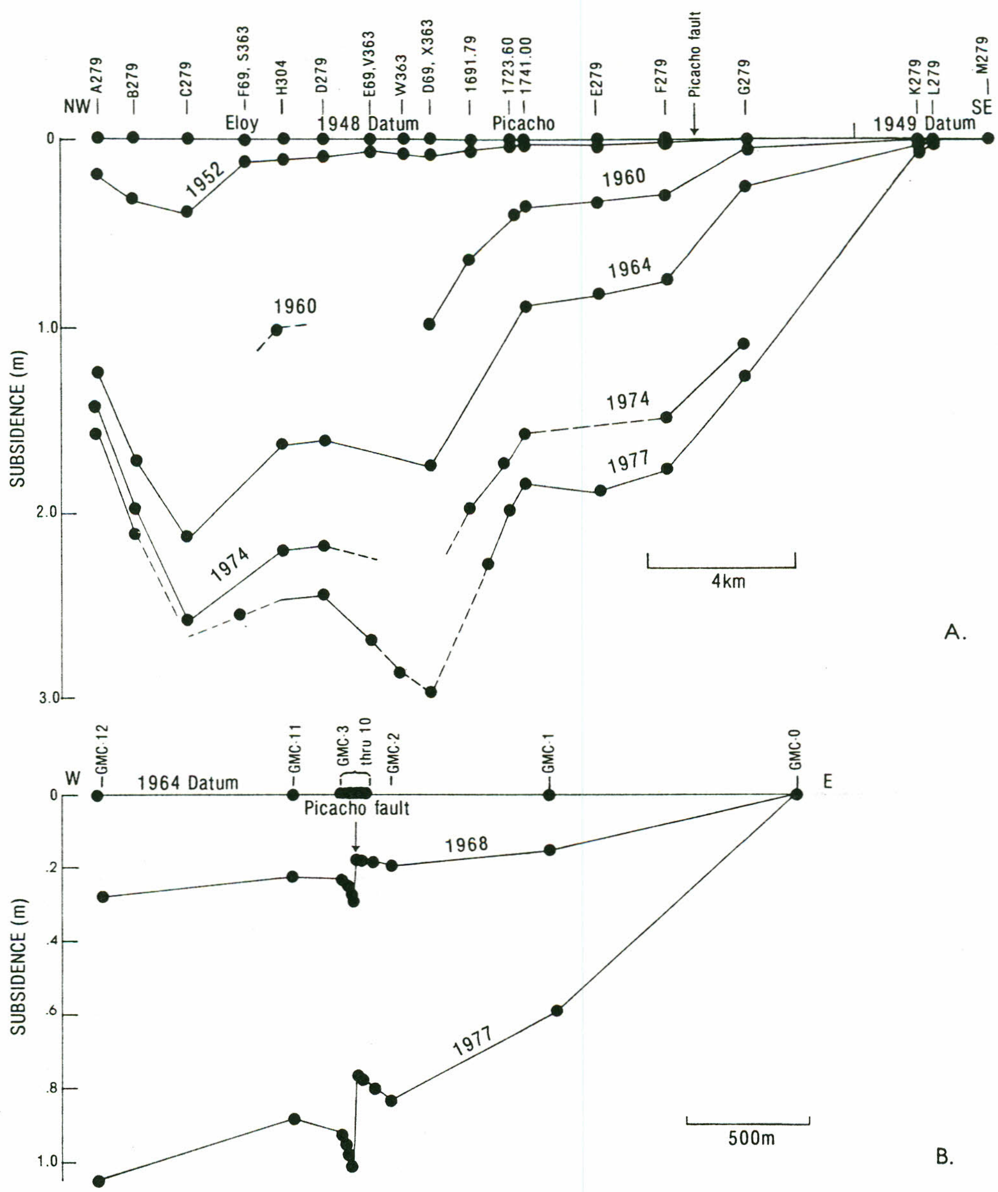


Fig. 4. Subsidence profiles. (*a*) Portion of railroad survey line, 1948 datum, based on published adjusted data. Subsidence is dashed where inferred. Profiles based on surveys in 1905, 1934, and 1967 are omitted for convenience. Subsidence prior to 1948 was very small compared with subsidence after 1948; (*b*) Eastern portion of USBR survey line, 1964 datum. Subsidence on USBR survey line is relative to bench mark GMC-0, established in crystalline bedrock. Note the close spacing of bench marks near the Picacho fault.

GROUND FAILURE AND VERTICAL DISPLACEMENTS AT THE FAULT

The earliest reported ground failure in the Eloy-Picacho area is that by *Leonard* [1929] of an earth fissure which opened 3.9 km southeast of Picacho on September 11, 1927 (Figure 3*a*); it was approximately 300 m long and had no vertical offset across it. Previous investigators [*Feth,* 1951; *Peterson,* 1964; *Schumann and Poland,* 1971; *Winikka,* 1964] have assumed that subsequent ground failure on the Picacho fault partially coincided with the 1927 fissure. However, we can demonstrate conclusively, based on historical records and photography, that the 1927 fissure was 0.87 km northwest of the modern fault scarp. The first occurrence of ground failure on the trace of what became the Picacho fault that can be documented was an earth fissure that occurred in 1949 [*Feth,* 1951; *Heindl and Feth,* 1955] (Figure 3*b*). No vertical offset of opposite sides of this fissure was observed in 1949 despite a careful search for such displacement (J. H. Feth, personal communication, 1976). As the fissure intersected both a paved highway and the railroad tracks, significant vertical offset would have been conspicuous. Moreover, the gently sloping desert floor provided a reference plane which would have displayed any vertical offset had it taken place.

The next episode of ground failure reported along the present-day fault trace was in 1961, when horizontal opening accompanied by vertical offset along the 1949 fissure was observed by *Peterson* [1962] in the vicinity of Interstate Highway I-10, adjacent to the railroad survey line. *Peterson* [1962] first inspected the fissure in 1959 and described it as an earth fissure having an 'inactive, weathered appearance.' He reported that hairline cracks began to appear during May 1961, and by July 1, 1961, a bump was noticeable on the interstate highway where the fissure intersected it. On August 20, 1961, *Peterson*

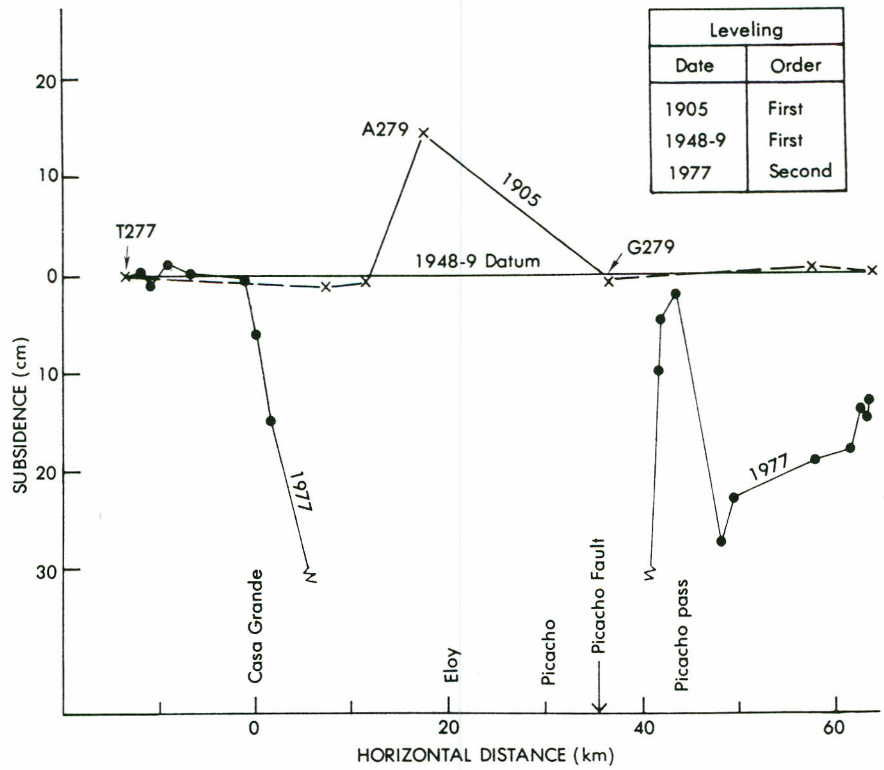


Fig. 5. Changes of elevation based on unadjusted field survey data from 1905 to 1977 on railroad survey line extending to and beyond margins of the Eloy-Picacho basin. Changes are referenced to bench mark T277 and a 1948 datum. The areas west of Casa Grande and in Picacho Pass define the margins of the Eloy-Picacho basin and are unaffected by water level declines.

[1964] measured an offset of 2.7 cm across the fault; by November 2, 1962, it had increased to 8.2 cm. Our examination of aerial photographs taken in 1954, 1956, and 1959, however, reveals that during the period from 1949 to 1961 the trace of ground failure was extending from the highway to the northeast and southwest. The nature of the ground failure during this period cannot be determined from the aerial photography, so one must rely on *Peterson*'s [1962, 1964] descriptions of ground failure in the vicinity of the highway for the early history of faulting.

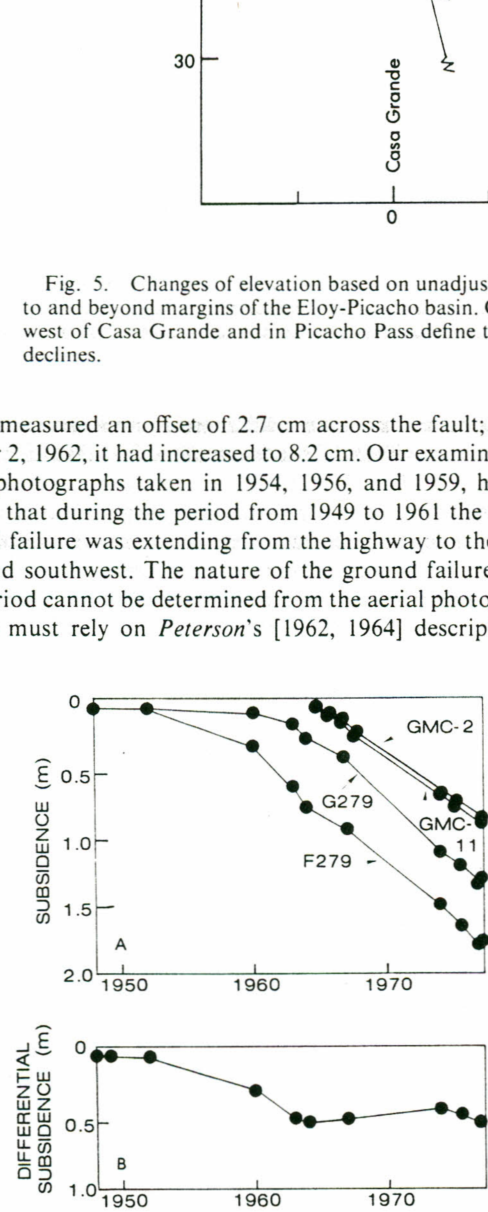


Fig. 6. (*a*) Subsidence histories of pairs of bench marks on the opposite sides of Picacho fault on railroad (F279 and G279, 1948 datum) and USBR (GMC-2 and GMC-11, 1964 datum) survey lines. Bench mark F279 is 2200 m west of G279, bench mark GMC-11 is 404 m west of GMC-2; and (*b*) differential subsidence of bench mark F279 relative to G279 from 1948 to 1977.

The history of relative land subsidence, as contrasted with fault offset near the Picacho fault is documented by relevelings of two level lines that cross the fault. The older line, the railroad survey line, was established in 1905 (Figures 1 and 4*a*). The other level line, the USBR survey line, was established by the U.S. Bureau of Reclamation in 1964 (Figure 1). It crosses the Picacho fault 3.7 km north of the location where the railroad survey line intersects the fault. Bench marks on this line are closely spaced near the Picacho fault (Figure 4*b*).

Subsidence on the railroad survey line from 1934 to 1948 of bench mark D69 relative to G279, which are 8.6 km apart and are on opposite sides of the fault (Figure 1), was 8.7 cm based on comparison of second- and first-order surveys. Differences of subsidence from 1948 to 1977 across the fault based on relevelings of bench marks F279 and G279 which are 2.2 km apart (Figure 1) are shown in Figure 6*b*. The leveling in 1948 was first order, and subsequent relevelings ranged from first-to third-order. Bench mark F279 subsided more than G279 from 1948 to 1964 when a reversal in the sense of differential movement occurred; that is, G279, on the upthrown side of the fault, began to subside slightly faster than F279 (Figure 6). The reversal in the sense of differential subsidence apparently was not accompanied by a cessation of faulting on the survey line because fault offset at the adjacent interstate highway continued to increase.

The lack of indication of faulting based on the relative subsidence after 1964 of bench marks on the railroad survey line near the fault also is suggested by relevelings of the USBR survey line. A 'ripple' in the subsidence profiles from 1964 to 1977 is associated with the fault (Figure 4*b*). Thus from 1964 to 1977, the land surface on the USBR survey line adjacent to but on the upthrown side of the fault moved upwards relative to the land surface further away from the fault on the upthrown side (and vice versa on the downthrown side). The results suggest that fault-associated vertical displacements from 1964 to 1977 were a localized phenomenon, being virtually undetectable at bench marks more than 150 m from the fault (GMC-2 and GMC-11, Figure 6*a*).

The complete history of the fault scarp at the interstate highway adjacent to the railroad survey line can be estimated if similar histories of growth of the scarps at the interstate highway and the USBR survey line from October 1964 to January 1977 are assumed (Figure 7*a*). If the growth in height of the scarp from 1964 to 1977 on the USBR survey line, based on bench marks GMC-6 and GMC-7 (14.3 m apart), is used to interpolate a value in May 1976, and this value is then subtracted from the total scarp height surveyed in May 1976 at the interstate highway, the difference is the magnitude of scarp growth from May 1961 to October 1964. The inferred pre-1964 rate of growth agrees with *Peterson*'s [1964] measurements at the interstate highway.

Seasonal periodicity of fault movement superimposed on the long-term fault creep is suggested by short-term (3–6 months) relevelings of bench marks GMC-6 and GMC-7 on the USBR survey line (Figure 7*b*). The period from October 1964 to October 1965 during which the bench marks were releveled approximately every 3 months is especially suggestive of seasonal periodicity. During the 1-year period, 67% of the fault movement occurred during the period from June to October. Biannual relevelings through April of 1968 also suggest a seasonal variation of fault movement. During this period, more annual movement occurred from April to October than from October to April.

INTERPRETATION OF VERTICAL DISPLACEMENTS

We interpret that surface faulting on the Picacho fault was preceded by a narrow zone of differential subsidence across the site of the future fault that caused a monoclinal flexure of the land surface and that the flexure began to transform into a fault scarp in 1961. This interpretation is shown schematically in Figure 8. According to this interpretation, the flexure essentially ceased growing in 1964 when the differential subsidence from 1948 to 1964 between bench marks F279 and G279 on the railroad survey line diminished. The ripple observed in the subsidence profiles on the USBR survey line is interpreted to be primarily a consequence of the flexure transforming into an abrupt fault scarp. We infer that if the bench marks on the USBR survey line had been established in 1948 rather than 1964, subsidence profiles qualitatively similar to those shown in Figure 8 would have been observed on the USBR survey line. The subsidence profiles on the USBR survey line from 1964 to 1977 with localized effects from faulting therefore are interpreted to have resulted from the establishment of bench marks in 1964 across a deformed surface.

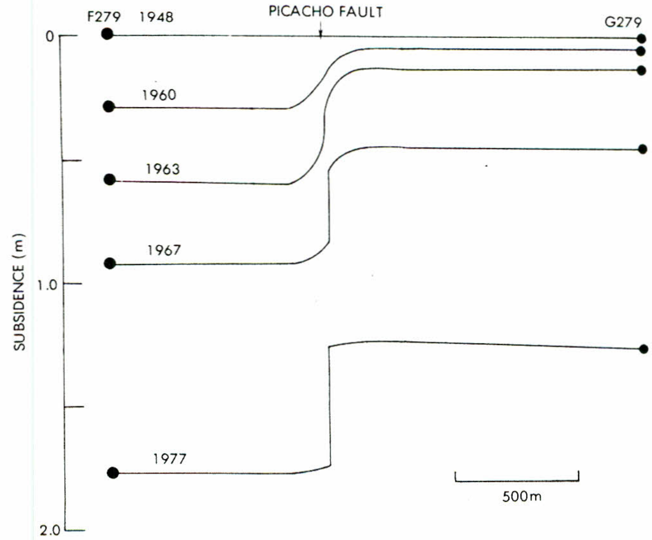


Fig. 8. Interpretive profiles of subsidence across the fault at the railroad survey line assuming differential subsidence measured by bench mark F279 relative to G279 occurred across a narrow zone prior to surface faulting. In the interpretation, the flexure transforms into a fault scarp from 1961 to 1977.

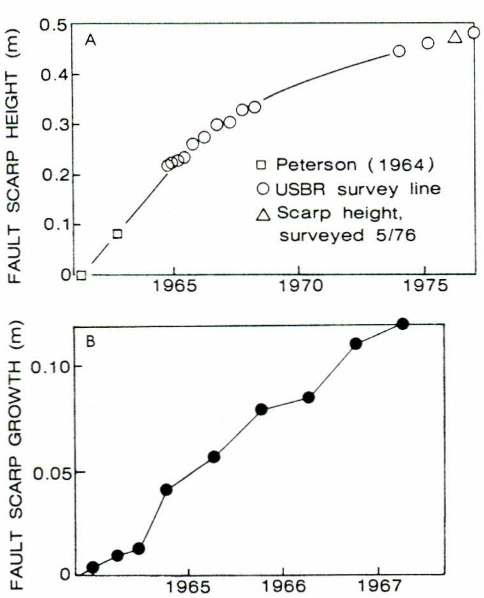


Fig. 7. Development of fault scarp. (*a*) Estimated height of fault scarp at interstate highway, adjacent to railroad survey line, from beginning of faulting in 1961 to 1977; and (*b*) measured increase from 1964 to 1968 of height of fault scarp at USBR survey line based on bench marks 14.3 m apart on opposite side of fault scarp. Seasonal variation of fault offset is suggested by greater offset from April to October than from October to April.

A topographic profile based on the absolute elevations of bench marks on the USBR survey line in 1964 supports the interpretation that surface faulting on the Picacho fault was preceded by a flexure (Figure 9). Furthermore, comparison of topographic and subsidence profiles based on relevelings of the USBR survey line from 1964 to 1977 demonstrates that the flexure diminished as the height of the fault scarp increased (Figure 10).

This interpretation of the vertical displacements associated with faulting suggested to us an approach based on elastic dislocation theory by which the depth of fault rupture could be estimated. Using this approach, the fault-associated vertical displacements observed on the USBR survey line can be shown to be compatible with subsurface faulting restricted to the zone that is affected by stresses related to declines of groundwater level. Theoretically, once an elastic medium has been stressed to near rupture on a normal or reverse fault, the width of the zone of vertical displacements at the surface associated with subsequent rupture are determined in large part by the depth to which rupture extends [*Smylie and Mansinha,* 1971]. For example, surficial vertical displacements associated with a fault that has ruptured to a depth of 10 km are theoretically predicted to extend much further from the fault

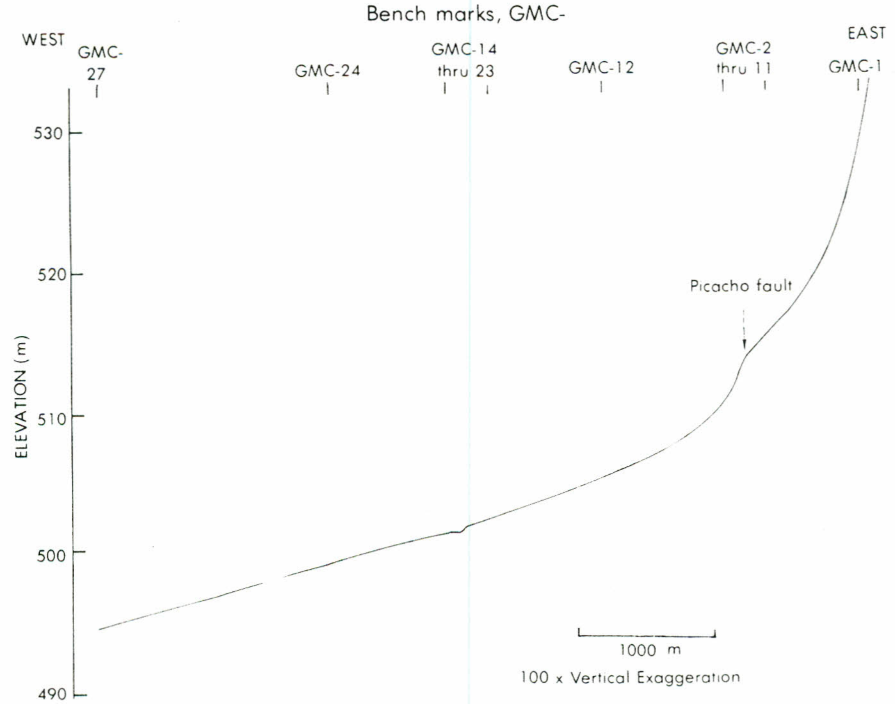


Fig. 9. Topographic profile along USBR survey line based on absolute elevations of bench marks in 1964. A flexure is associated with Picacho fault.

than are predicted surficial displacements associated with a fault that has ruptured to a depth of only 1 km. On this basis, one might anticipate that the width of the zone of vertical displacements associated with the transformation of the flexure near Picacho into a fault scarp would be directly related to the depth to which rupture extends. In order to estimate this

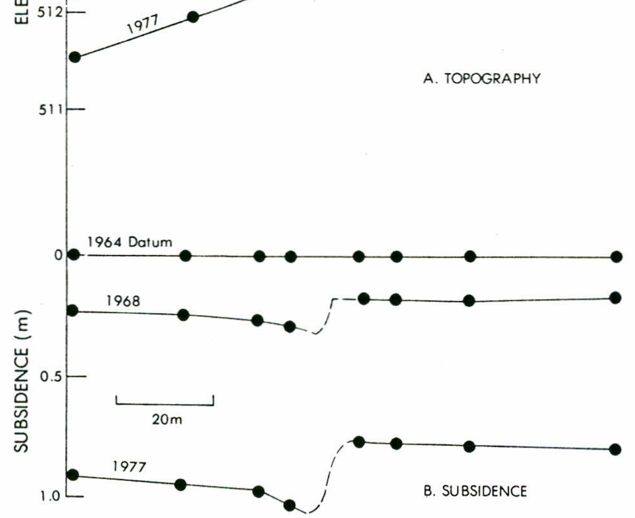


Fig. 10. Comparison of (*a*) concurrent topographic profiles with (*b*) measured subsidence on the USBR survey line near the Picacho fault.

depth, an analytical model formulated for analyses of tectonic faulting was used [e.g., *Savage and Church,* 1974; *Savage and Hastie,* 1966]. The model is based on solutions to elastic dislocation theory, and for a complete discussion of the theory the reader is referred to *Smylie and Mansinha* [1971]. For the present investigation, displacements computed from a variety of two-dimensional dip slip fault models in a homogeneous, linearly elastic half space were compared with the vertical displacements observed from 1964 to 1977 on the USBR survey line near the fault. The best agreement between observed and computed displacements for models assuming uniform offset from the surface to a given depth on the dislocation was obtained for a normal fault with a dip of 70° that extended to a depth of 190 m (Figure 11). Although the match between data and model is not exact, particularly to the west of the fault, the fit is considered satisfactory in light of the simplified nature of the model. More complex models, with, for example, slippage decreasing with depth, provide better fits. However, all of the successful models retain the same basic features and are characterized by shallow faulting on planes that dip steeply to the west. It is important to note that the dislocation models used here are not unique. Displacements related to faulting and subsidence were somewhat arbitrarily separated so that deeper-seated components of faulting are not excluded by the analysis. Nevertheless, the analysis suggests that observed surface displacements are compatible with fault rupture that does not extend beneath the zone that is affected by stresses related to groundwater level declines. It also is of interest here that relative horizontal and vertical displacement from 1964 to 1977 of bench marks close to the fault (not shown here) also indicate that faulting was high angle, normal.

CAUSE OF FAULTING

The principal question addressed by the present investigation is whether or not surface faulting beginning in 1961 near Picacho is related to groundwater extraction. Although the evidence presented here does not demand a relation between

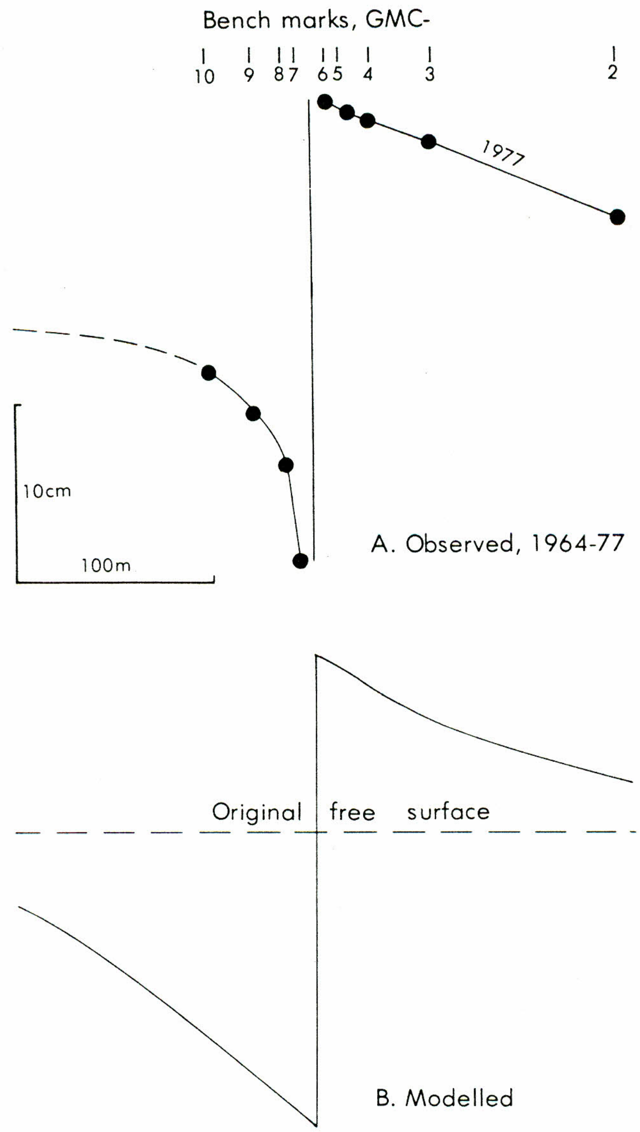


Fig. 11. Comparison of (*a*) observed fault-associated vertical displacements on the USBR survey line with (*b*) those computed based on elastic dislocation theory. Modeled displacement are for a dislocation extending from the surface to a depth of 190 m and with a dip in a normal sense of 70°.

faulting and groundwater extraction, we consider such a relation to be likely. First, modern faulting on the Picacho fault postdated the beginning of groundwater level declines and its associated subsidence and was restricted to the area with water level declines. In addition, the faulting has occurred along a zone for which there is no evidence at the land surface for faulting antedating water level declines. The significance of the 1927 earth fissure is uncertain, but it may be significant that it was 0.87 km away from the future scarp and features of similar appearance but of nontectonic origin in arid basins are known [*Neal et al.*, 1968]. Second level data indicate that changes of surface elevation as contrasted with fault offset within the Eloy-Picacho area were minor until groundwater levels began to decline. Moreover, preceding and during the surface faulting, relative vertical displacement of the margins of the basin in areas unaffected by declines of groundwater level were less than 5 cm. These observations require that if there were any crustal movements within the region near the fault, these movements were not only restricted to within the basin but also were restricted temporally and areally to those portions subjected to water level declines. Third, vertical displacements based on closely spaced bench marks near the fault are compatible with subsurface faulting restricted to the zone affected by water level declines. Fourth, the apparent seasonal periodicity of fault displacements suggests a seasonal variation in the stressing of the system. Seasonal variations of both water level and compaction are observed in the Eloy-Picacho area [*Schumann and Poland*, 1971]. And finally, if the modern faulting is of natural origin, it is somewhat unusual in the Basin and Range province in that it has occurred as aseismic creep. This assumes of course that the seismicity felt in the 1970's was related to supersonic flights. Only three other possible examples of aseismic dip slip fault creep in the Basin and Range province have been reported, and all of these either postdated or antedated earthquakes [*Myers and Hamilton*, 1964, p. 60; *Neumann*, 1934, p. 43; *Savage and Church*, 1974, p. 689].

DISCUSSION

This investigation gives credence to proposals by others that surface faulting in other areas may be related to groundwater withdrawal, but it may be particularly relevant to studies of faulting in the Texas Gulf Coast where three different causes of faulting are suspected to be acting contemporaneously—geologic forces, petroleum withdrawal, and groundwater withdrawal [*Reid*, 1973; *Van Siclen*, 1967]. At present the need exists for techniques to evaluate the cause of surface faulting on individual faults there. The inference of the depth of fault rupture on the Picacho fault, based on comparison of observed surface displacements with those computed by modeling, suggests the possibility of this approach for evaluating the cause of surface faulting in the Gulf Coast. However, a closer spacing of bench marks, particularly near fault scarps, than is presently available in the Texas Gulf Coast is required to determine the depth of fault rupture there. Some published observations indicate that a test of the applicability of the elastic dislocation model is warranted [*Van Siclen* 1967, p. 27; *Kreitler*, 1976, p. 16].

Acknowledgments. We thank J. K. Boling, Jr., M. C. Carpenter, R. O. Castle, R. H. Raymond, N. D. White, and C. C. Winikka for discussions and assistance; W. R. Thatcher for the model computations; and J. D. Bredehoeft and R. F. Yerkes, who critically reviewed the manuscript.

REFERENCES

Castle, R. O., and R. F. Yerkes, Recent surface movements in the Baldwin Hills, Los Angeles County, California, *U.S. Geol. Surv. Prof. Pap., 882,* 125, 1976.

Church, J. P., R. O. Castle, M. M. Clark, and D. M. Morton, Continuing crustal deformation in the western Mojave Desert (abstract), *Geol. Soc. Amer. Abstr. Programs, 6*(7), 687, 1974.

Eaton, G. P., Deformation of Quaternary deposits in two intermontane basins of Southern Arizona, USA, *Proc. Int. Geol. Congr.*, 24th, 607–616, 1972.

Federal Geodetic Control Committee, Classification, standards of accuracy, and general specifications of geodetic control surveys, 12 pp., Nat. Oceanic Atmos. Admin., U.S. Dep. Commer., Washington, D. C., 1974.

Feth, J. H., Structural reconnaissance of the Red Rock quadrangle, Arizona, open file report, 32 pp., U.S. Geol. Surv., Tucson, Ariz., 1951.

Hardt, W. F., and R. E. Cattany, Description and analysis of the geohydrologic system in western Pinal County, Arizona, open file report, pp. 1–92, U.S. Geol. Surv., Tucson, Ariz., 1965.

Heindl, L. A., and J. H. Feth, Discussion of symposium on land erosion, 'Piping,' by J. E. Fletcher, K. Harris, H. B. Peterson, and V. N. Chandler, *Eos Trans. AGU, 36*(2), 342, 1955.

Holzer, T. L., Ground failure in areas of subsidence due to groundwater decline in the United States, Land Subsidence Symposium,

edited by A. I. Johnson and S. Yamamoto, *Publ. 121*, pp. 423–433, Int. Ass. Sci. Hydrol., Washington, D. C., 1977.
Kreitler, C. W., Lineations and faults in the Texas coastal zone, *Invest. Rep. 85*, pp. 1–32, Bur. of Econ. Geol., Univ. of Tex., Austin, 1976.
Kreitler, C. W., Fault control of subsidence, Houston, Texas, *Ground Water, 15*(3), 203, 1977.
Leonard, R. J., An earth fissure in southern Arizona, *J. Geol., 37*(8), 765, 1929.
Lofgren, B. E., Field measurement of aquifer-system compaction, San Joaquin Valley, California, USA, Land Subsidence, vol. 1, edited by L. J. Tison, *Publ. 88*, pp. 272–284, Int. Ass. Sci. Hydrol., Washington, D. C., 1971.
Mindling, A. L., Effects of ground-water withdrawal on I-15 freeway and vicinity in North Las Vegas, Nevada, *Proj. Rep. Ser. 33*, 37 pp., Center Water Resour. Res., Desert Res. Inst., Reno, Nev., 1974.
Morton, D. M., Surface deformation in part of the San Jacinto Valley, Southern California, *U.S. Geol. Surv. J. Res., 5*(1), 117, 1977.
Myers, W. B., and W. Hamilton, Deformation accompanying the Hebgen Lake earthquake of August 17, 1959, *U.S. Geol. Surv. Prof. Pap., 435*, 55–98, 1964.
Neal, J. T., A. M. Langer, and P. F. Kerr, Giant dessication polygons of Great Basin playas, *Geol. Soc. Amer. Bull., 79*(1), 69, 1968.
Neumann, F., United States earthquakes 1934, *U.S. Coast Geod. Surv. 593*, 43, 1934.
Peirce, H. W., Rumbles and rattles, *Field Notes, 5*(2), 4, 1975.
Peirce, H. W., Tectonic significance of basin and range thick evaporite deposits, *Ariz. Geol. Soc. Dig., 10*, 325–339, 1976.
Peterson, D. E., Earth fissuring in the Picacho area, Pinal County, Arizona, Master's thesis, Univ. of Ariz., Tucson, 1962.
Peterson, D. E., Earth fissuring in Picacho area, Pinal County, Arizona, open file report, 52 pp., U.S. Geol. Surv., Tucson, 1964.
Pratt, W. E., and D. W. Johnson, Local subsidence of the Goose Creek oilfield, Texas, *J. Geol., 34*(7), 577, 1926.
Reid, W. M., Active faults in Houston, Texas, Ph.D. thesis, Univ. of Tex., Austin, 1973.
Rogers, T. H., Active extensional faulting north of Hollister near the Calaveras fault zone, *Bull. Seismol. Soc. Amer., 57*(4), 813, 1967.
Savage, J. C., and J. P. Church, Evidence for post-earthquake slip in the Fairview Peak, Dixie Valley, and Rainbow Mountain fault areas of Nevada, *Bull. Seismol. Soc. Amer., 64*(3), 687, 1974.
Savage, J. C., and L. M. Hastie, Surface deformation associated with dip slip faulting, *J. Geophys. Res., 71*, 4897, 1966.
Schumann, H. H., Land subsidence and earth fissures in alluvial deposits in the Phoenix area, Arizona, *Misc. Invest. Map I-845-H*, U.S. Geol. Surv., Washington, D. C., 1974.
Schumann, H. H., and J. F. Poland, Land subsidence, earth fissures, ground-water withdrawal in South-central Arizona, USA, Land Subsidence, vol. 1, edited by L. J. Tison, *Publ. 88*, pp. 295–302, Int. Ass. Sci. Hydrol., Washington, D. C., 1971.
Scott, J. D., and R. T. Moore, The Palo Verde nuclear power station, *Field Notes, Ariz. Bur. Mines, 6*(3, 4), 1, 1976.
Shakel, D. W., Long-range atmospherically induced ground shaking at Tucson, Arizona (abstract), *Geol. Soc. Amer. Abstr. Programs, 9*(4), 498, 1977.
Smith, G. E. P., The physiography of Arizona valleys and the occurrence of ground water, *Ariz. Agr. Exp. Sta. Tech. Bull., 77*, 91, 1938.
Smith, G. E. P., The ground water supply of the Eloy district in Pinal County, Arizona, *Ariz. Agr. Exp. Sta. Tech. Bull., 87*, 42, 1940.
Smylie, D. E., and L. Mansinha, The displacement fields of inclined faults, *Bull. Seismol. Soc. Amer., 61*(5), 1433, 1971.
Sturgal, J. R., and T. D. Irwin, Earthquake history of Arizona and New Mexico, 1850–1966, *Ariz. Geol. Soc. Dig., 9*, 1–39, 1971.
Van Siclen, D. C., The Houston fault problem, paper presented at 3rd Annual Meeting, Texas Section, Amer. Inst. of Prof. Geol., Dallas, 1967.
Winikka, C. C., Subsidence in the Eloy-Picacho area, paper presented at 11th Arizona Land Surveyors Conference, Ariz. Eng. Exp. Sta., Tucson, 1964.
Yerkes, R. F., and R. O. Castle, Seismicity and faulting attributable to fluid withdrawal, *Eng. Geol., 10*(2–4), 151, 1976.

(Received July 29, 1977;
revised September 14, 1978;
accepted September 25, 1978.)

Differential compaction mechanism for earth fissures near Casa Grande, Arizona

ROBERT C. JACHENS
THOMAS L. HOLZER
U.S. Geological Survey, 345 Middlefield Road, Menlo Park, California 94025

ABSTRACT

Precise gravity measurements indicate that earth fissures or tension cracks caused by ground-water withdrawal within a 10-km^2 area southeast of Casa Grande, Arizona, are associated with relief on the buried interface between the alluvial aquifer and underlying bedrock. All of the fissure zones, which have a cumulative length of >8.7 km, occur above either ridges or steps in the bedrock surface. Intersecting fissure zones overlie intersecting bedrock features, and the angle of intersection of the zones accurately reflects the angle between the bedrock features. These relations suggest that the fissures are forming in response to localized differential compaction caused by localized variations of aquifer-system thickness. Topographic profiles across fissures on undisturbed desert floor confirm differential compaction proportional to the variations in aquifer thickness. The occurrence of the fissures at points of maximum convex-upward curvature in profiles of both the topographic and buried bedrock surfaces indicates that the fissures result from tensile strains caused by bending of the strata above the buried bedrock features in response to the differential compaction. Tensile strains at failure are estimated to range from ~0.02% to 0.2% on the basis of modeling of the bending process.

INTRODUCTION

Earth fissures or long open tension cracks associated with land subsidence induced by ground-water withdrawal have been reported in many alluvial basins in the western United States (Fig. 1). These fissures typically occur both as isolated straight to arcuate cracks and in narrow zones (Morton, 1976; Laney and others, 1978; Patt and Maxey, 1978; Guacci, 1979). In three areas, however, cracks form complex polygonal patterns (Fife, 1977; Holzer, 1980). The greatest length reported for an earth fissure is 3.5 km (Holzer, 1980), but lengths measured in hectometres are more common. Although horizontal displacements across earth fissures are small (Holzer, 1977), enlargement of fissures by erosion into wide and deep gullies creates landforms that in places are spectacular. Gullies at least 1 m wide and 3 m deep are common. In fact, enlargement by erosion may be the principal hazard associated with the fissures because of the potential danger to both animals and people.

Despite the widespread occurrence of earth fissures, research on the specific mechanisms of their formation has been primarily qualitative and necessarily speculative. Several hypotheses have been proposed to explain the mechanism of their formation, including localized differential compaction (Feth, 1951), hydrocompaction (Pashley, 1961), horizontal seepage forces (Lofgren, 1971), regional differential compaction (Bouwer, 1977), and desiccation caused by water-table declines (Holzer and Davis, 1976). Several investigators (Anderson, 1973; Jennings, 1977; Pankratz and others, 1978b; R. Beruff, 1979, written commun.; Jachens and Holzer, 1979; Sumner and Christie, 1980) have identified localized variations in aquifer-system thickness beneath arcuate earth fissures in south-central Arizona that suggest localized differential compaction near these fissures. On the basis of numerical modeling, Jachens and Holzer (1979) concluded that tensile strains of sufficient magnitude to cause failure had been generated by bending of the overburden by localized differential compaction in the area they studied. Measurement of localized differential subsidence across arcuate earth fissures at four sites in Arizona, California, and Nevada suggests that localized differential compaction probably occurs in these other areas as well (Holzer and Pampeyan, 1981).

The present investigation focused on a 10-km^2 area of intense fissuring ~80 km south-southeast of Phoenix, Arizona, and east of the Casa Grande Mountains (Fig. 2). The study area is part of a large region in south-central Arizona undergoing subsidence and

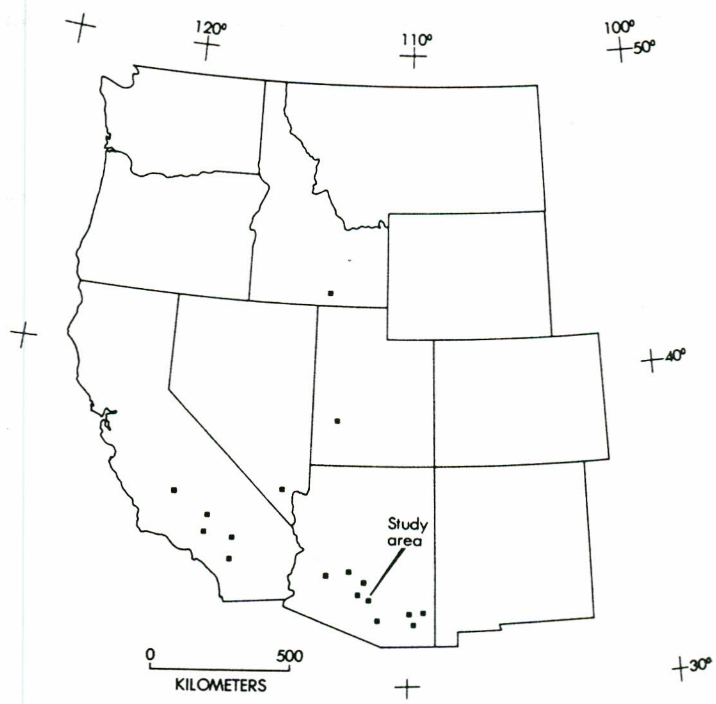


Figure 1. Locations of earth fissures associated with ground-water withdrawal in the western United States.

Geological Society of America Bulletin, v. 93, p. 998–1012, 13 figs., 1 table, October 1982.

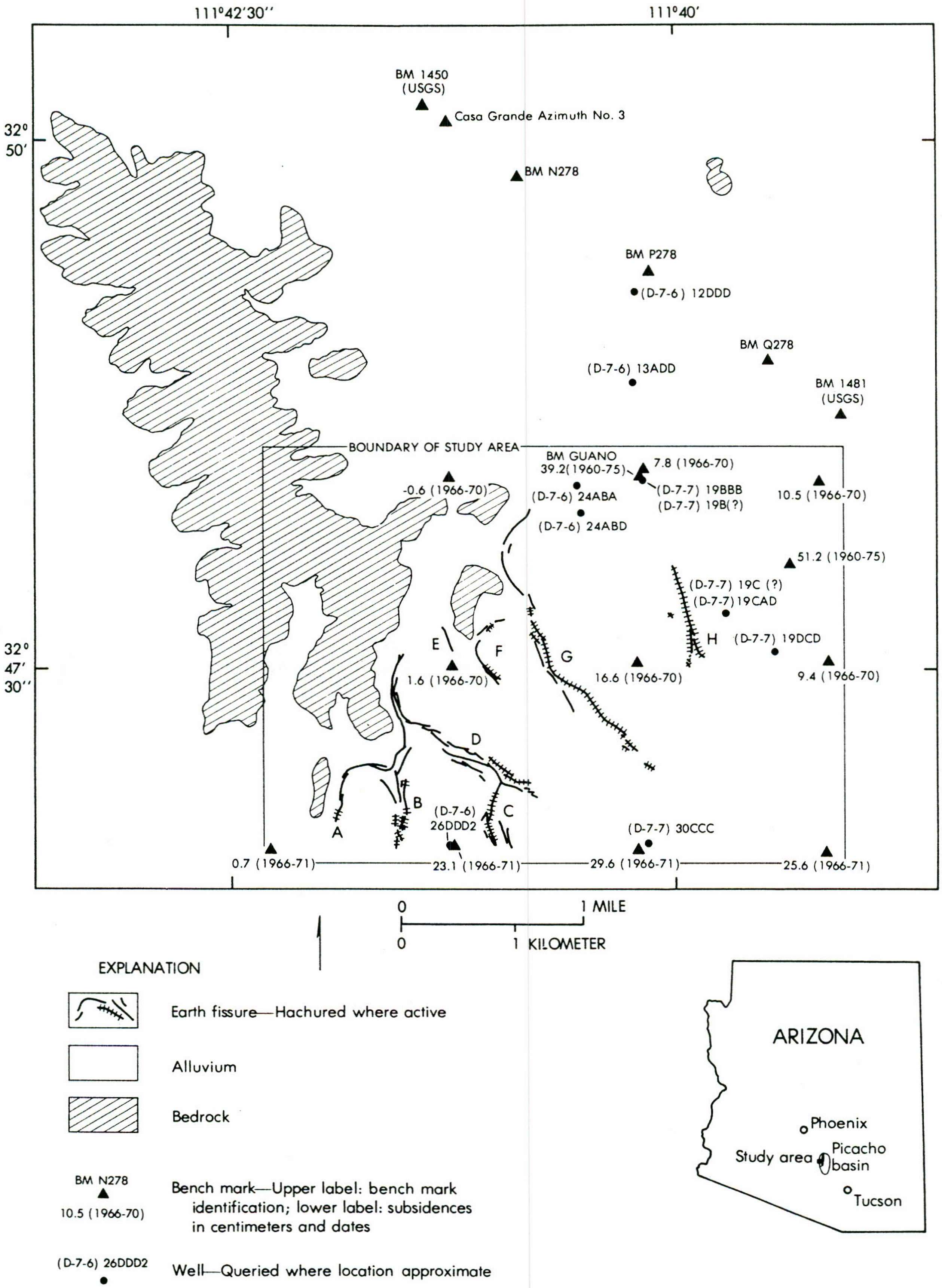


Figure 2. Map of study area (outline) and fissures as of April 11–19, 1980. Fissure zones are designated by letter. Fissures designated as active are those that formed after January 30, 1970, or showed field evidence of recent opening. Bedrock outcrop area modified from Bergquist and Blacet (1978).

fissuring (Laney and others, 1978). Within the study area, a complex system of straight to arcuate fissures has formed piecemeal since 1949 in response to ground-water withdrawal. Jachens and Holzer (1979, Fig. 8), as part of a regional study, measured and interpreted the gravity field in the study area along two east-west profiles that intersected several fissures. They concluded that the fissures were caused by localized differential compaction related to variations of aquifer-system thickness. In the present investigation, gravity measurements have been extended throughout the study area in order to determine areal variations of aquifer-system thickness. Our objectives were: (1) to determine whether the locations of fissures within the complex fissure system are systematically related to variations in aquifer-system thickness and whether localized differential compaction could explain their locations; (2) to determine whether the history of fissure formation could be explained in terms of localized differential compaction; and (3) to estimate the tensile strain at failure on the basis of theoretical modeling of the field conditions.

HYDROGEOLOGY

Geology

The study area is on the western margin of Picacho basin, a deep alluvial basin in south-central Arizona (Fig. 2). Although the geologic history of the basin began at least as early as late Miocene, only the uppermost unconsolidated alluvial deposits that constitute the aquifer system are of interest here. These deposits typically are poorly sorted, consisting of fine- to coarse-grained alluvial sediments (Hardt and Cattany, 1965). Thicknesses of these deposits are poorly known but probably exceed 700 m near the center of the basin. Around the margin of the basin, these deposits rest on either crystalline bedrock or consolidated alluvium (Hardt and Cattany, 1965).

The stratigraphy within the study area is partly known from logs of four wells drilled near the boundary of the study area. All four wells initially penetrated unconsolidated coarse-grained sediments. Wells (D-7-7) 19BBB and (D-7-6) 24ABD, drilled near the northern boundary (Fig. 2), penetrated a clay unit at a depth of ~75 m. The clay stratum is ~70 m thick and rests on either crystalline bedrock or consolidated alluvium at these sites. Wells (D-7-6) 26DDD and (D-7-7) 30CCC, drilled on the southern boundary (Fig. 2), also penetrated a clay unit, but at a slightly greater depth, 100 m. These wells are 245 m and 183 m deep, respectively, and do not completely penetrate the unit. Presumably, the crystalline bedrock beneath the study area consists of schists and gneisses similar to those exposed in the Casa Grande Mountains. Many logs of wells just outside the study area and toward the center of the basin, however, reveal that an indurated conglomerate, hereafter referred to as consolidated alluvium, overlies the crystalline bedrock. Hence, the precise lithology of material beneath the unconsolidated alluvium in the study area is unknown.

Water Levels

Major ground-water withdrawals in Picacho basin began abruptly in the mid-1930s, when economic conditions became favorable for intensive agricultural development dependent on ground water (Smith, 1940). The principal aquifer developed since that time has responded to withdrawals as an unconfined aquifer. The history of water-level decline in the study area is illustrated by a composite well hydrograph (Fig. 3A) based on 11 wells located around the margin of the study area. The composite hydrograph is based on water levels measured in the spring, when water levels should be at their annual high. Seasonal measurements were not reported for any of the 11 wells, but, elsewhere within the basin, annual fluctuations exceeding 25 m are caused by seasonal pumping related to agricultural activities. Water levels measured in (D-7-6) 24ABA, (D-7-6) 26DDD, and (D-7-7) 30CCC, in April and September 1980, corresponding approximately to the beginning and end of the pumping season, indicated that no seasonal fluctuation occurred in 1980 within the study area.

The hydrographs suggest that the magnitudes and histories of water-level decline are similar throughout the study area. According to the hydrograph, water levels began to drop in about 1940. Before dropping, water levels were ~18 m below the land surface. The rate of decline was constant until 1962, when water levels stabilized at a depth of ~58 m, equivalent to a decline of ~40 m. The stabilization recorded in the composite hydrograph is compatible with that recorded in hydrographs of other wells in the area southeast of the Casa Grande Mountains. It is also compatible with a map of water-level changes from 1964 to 1972 prepared by the Bureau of Reclamation (1977, Fig. 344-314-1282).

SUBSIDENCE AND EARTH FISSURES

Subsidence

Extensive land subsidence due to compaction of unconsolidated sediments has accompanied man-induced water-level declines in Picacho basin (Winikka, 1964; Schumann and Poland, 1969; Holzer and others, 1979). Jachens and Holzer (1979) estimated that ~1,200 km^2 of land within the basin subsided 0.30 m or more from 1934 to 1977. The maximum documented subsidence was 3.8 m from 1952 to 1977 in the east-central part of the basin (Laney and others, 1978). The vertical distribution of compaction in the unconsolidated alluvium is poorly known.

Subsidence probably began in the study area after 1948 (Fig. 3B). Rates of subsidence were not constant during the period of record but decreased in the early 1960s (Fig. 3B). Despite changes in rates of subsidence, the similar trends exhibited by the subsidence histories of the bench marks shown in Figure 3B suggest that the history of subsidence near the margins of the study area can be represented by a single normalized curve. Such a series of curves are shown in Figure 4. Each curve in Figure 4 was constructed by dividing measured subsidence of the respective bench mark by its subsidence in April 1980. The latter value was determined by extrapolition of subsidence history of the relevant bench mark. The coincidence of the resulting curves (Fig. 4) is striking.

In addition to changes of rates of subsidence through time, areal variations of the magnitude of subsidence are significant. Such variations of magnitude can be demonstrated within the study area by comparing subsidence measured at bench marks during specific time periods (Fig. 2). Areal variations can also be documented north of the study area by comparing subsidence histories of bench marks (Fig. 3B). These areal variations of the magnitude of subsidence appear to be related to areal changes in the thickness of the unconsolidated alluvium in the subsurface. This can be documented by comparing the net subsidence measured during the period from 1967 to 1977 with measurements of complete Bouguer gravity field at bench marks north of the study area (Fig. 5). Low values of subsidence correspond to high values of gravity. Presum-

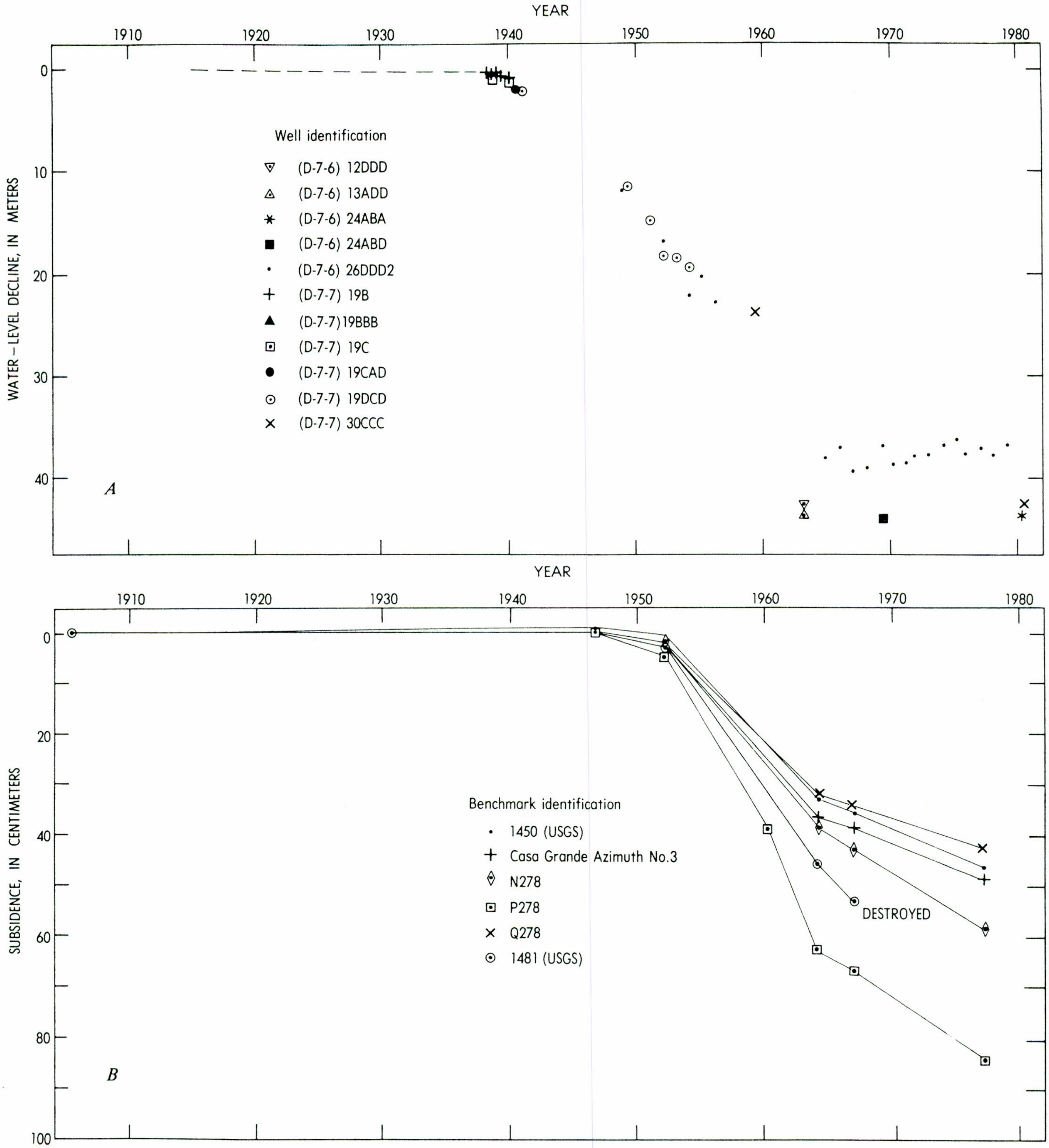


Figure 3. A. Composite well hydrograph based on wells in and near study area (Fig. 2) and datum from Smith (1938, Plate 3). B. Subsidence histories at six bench marks north of study area. Locations of wells and bench marks shown in Figure 2.

ably, values of gravity are highest where underlying bedrock is shallowest and unconsolidated alluvium is thinnest.

The ratio of compaction as of 1980 to saturated thickness can be inferred at bench mark Guano near the north edge of the study area (Fig. 2). At Guano, a subsidence of 0.39 m was measured from 1960 to 1975. According to the normalized subsidence curves, 49% of the total subsidence occurred from 1960 to 1975. Hence, total subsidence at the Guano site was approximately 0.79 m. By dividing the 0.79-m subsidence at Guano by the saturated thickness at nearby well (D-7-7) 19BBB, a ratio of compaction per metre of

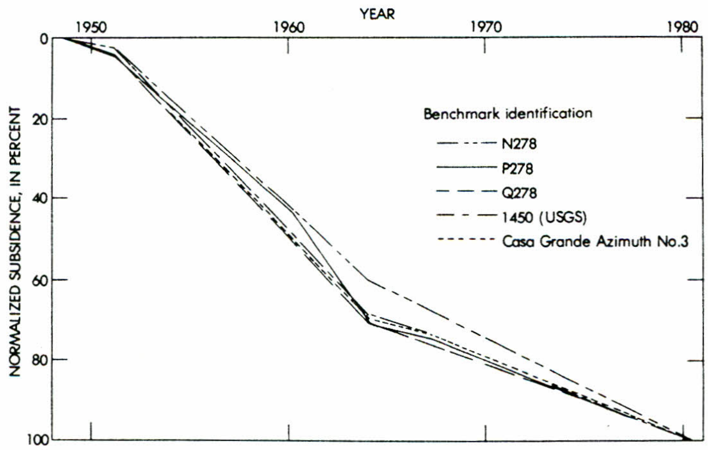


Figure 4. Normalized subsidence histories of five bench marks north of study area. See Figure 2 for location. Histories were normalized by dividing measured subsidence by subsidence in 1980 determined by extrapolation.

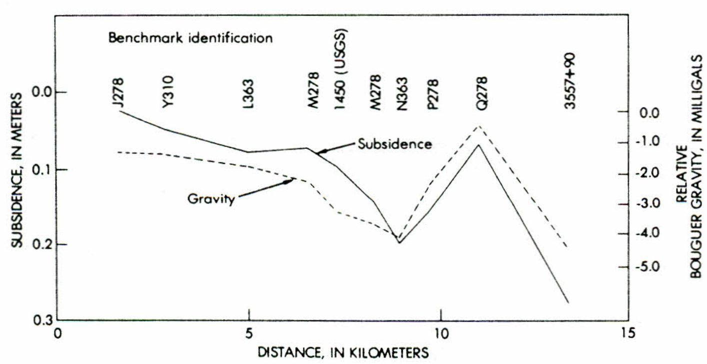


Figure 5. Comparison of relative Bouguer gravity with 1967 to 1977 subsidence at bench marks along a level line north of the study area.

saturated thickness of 0.0083 m is indicated. To compute the ratio, the 75-m saturated thickness observed in 1980 at (D-7-7) 19BBB was corrected to allow for compaction which occurred as of 1980 in the interval between the original and 1980 water tables, an interval approximately 40 m thick. It can be shown that the compaction caused by a water table dropping from the top to the bottom of a 40-m-thick interval is approximately equal to the compaction of a 20-m-thick confined interval subjected to a 40-m drop of water level. Accordingly, 20 m were added to the observed saturated thickness before computing the ratio.

Continued subsidence after springtime water levels ceased to decline at bench marks shown in Figure 3 can also be documented within the study area on the basis of bench marks that were releveled during parts of the 1962–1980 time period (Fig. 2). This behavior might be explained by either (1) slow dissipation of excess pore pressures in fine-grained beds or (2) by large seasonal water-level fluctuations that caused no net water-level decline but stressed the compacting interval for part of each year (see Riley, 1969). The first explanation appears more likely, because thick, fine-grained strata were reported in wells drilled in the unconsolidated alluvium and a significant seasonal fluctuation was not observed in 1980.

Earth Fissures

Complex fissure zones and isolated straight to arcuate fissures occur in alluvium within the study area (Fig. 2). Cross-sectional form and dimensions of fissures vary greatly along individual fissures and between different fissures as well. Differences in shape and size are due primarily to modification by erosion and deposition and to the amount of tensile strain relieved by each fissure. The largest fissure examined during the time of the study was approximately 3 m wide at the surface and open to a depth of >4 m. The smallest fissures were simply hairline cracks which had not yet been modified by erosion. The activity, that is, continued horizontal movement of opposing sides by displacement, of fissures also varied from fissure to fissure and sometimes systematically along the trace of fissure zones. A few fissures appeared to be inactive, being completely or partially filled in by sediment and displaying no cracking or collapse of the sediment fill (Fig. 2). Along parts of some fissure zones studied in 1980, the presence of cracked and collapsing sediment fill in individual fissures indicated that failure is still ongoing. One of these still active fissure zones (zone C in Fig. 2) formed originally between January 1954 and February 1956, as determined by analysis of aerial photographs.

The chronology of fissure formation is shown in Figure 6. Each map, except that for April 11–19, 1980, is based on aerial photographs. The 1980 map is based on ground traverses, using an April 22, 1979, aerial photograph as a guide. Photographs taken on February 18, 1949, February 6, 1956, and in May 1972, provide additional resolution of dates of fissuring. The first fissure formed in the study area some time between February 18, 1949, and February 6, 1954. The only large-scale mapping of fissures previous to our mapping was that by Pashley (1961), who mapped fissures in part of the study area in February 1960.

GRAVITY DATA

Gravity measurements were made at 369 locations in an area of ~ 10 km^2. Most measurements were made along profiles oriented nearly perpendicular to the trend of individual fissure zones. The spacing of measurements along the profiles was generally 100 m, except in areas where alluvial thickness was anticipated to be < 100 m or where elevation control was closely spaced.

Gravity measurements were made in closed loops with LaCoste-Romberg model G gravimeters equipped with electronic readout. Base-station measurements were repeated every 1 to 4 hr. Earth-tide effects were removed according to the formulation of Longman (1959), with a compliance factor of 1.160, and gravimeter drift was approximated by a linear or parabolic function of time. Gravimeters used in this study were calibrated by measurements over the U.S. Geological Survey's Mount Hamilton calibration range (Barnes and others, 1969). Surveys conducted with these instruments and following the procedures outlined above typically yield gravity differences with standard deviations of 0.010 to 0.015 mGal (Jachens, 1979).

Observed gravity data were reduced to complete Bouguer anomalies according to standard reduction formulas (Dobrin, 1960) with a reduction density of 2.60 g/cm^3. Terrain corrections were computed for all topography within 12 km of each measurement site. More than 90% of the terrain corrections are < 0.10 mGal, and those at sites near fissures are typically < 0.06 mGal. These terrain corrections have an uncertainty of about ± 10%.

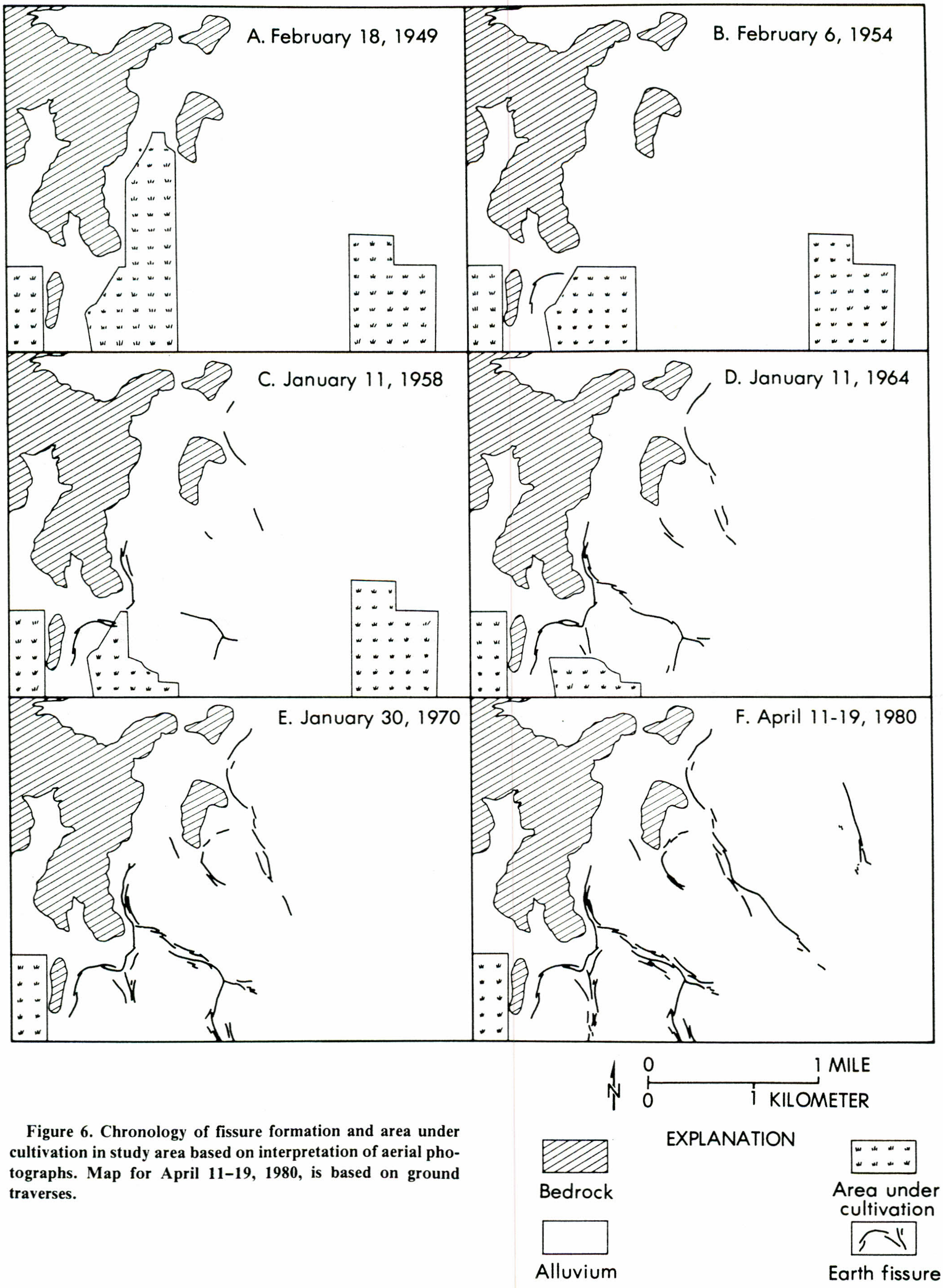


Figure 6. Chronology of fissure formation and area under cultivation in study area based on interpretation of aerial photographs. Map for April 11–19, 1980, is based on ground traverses.

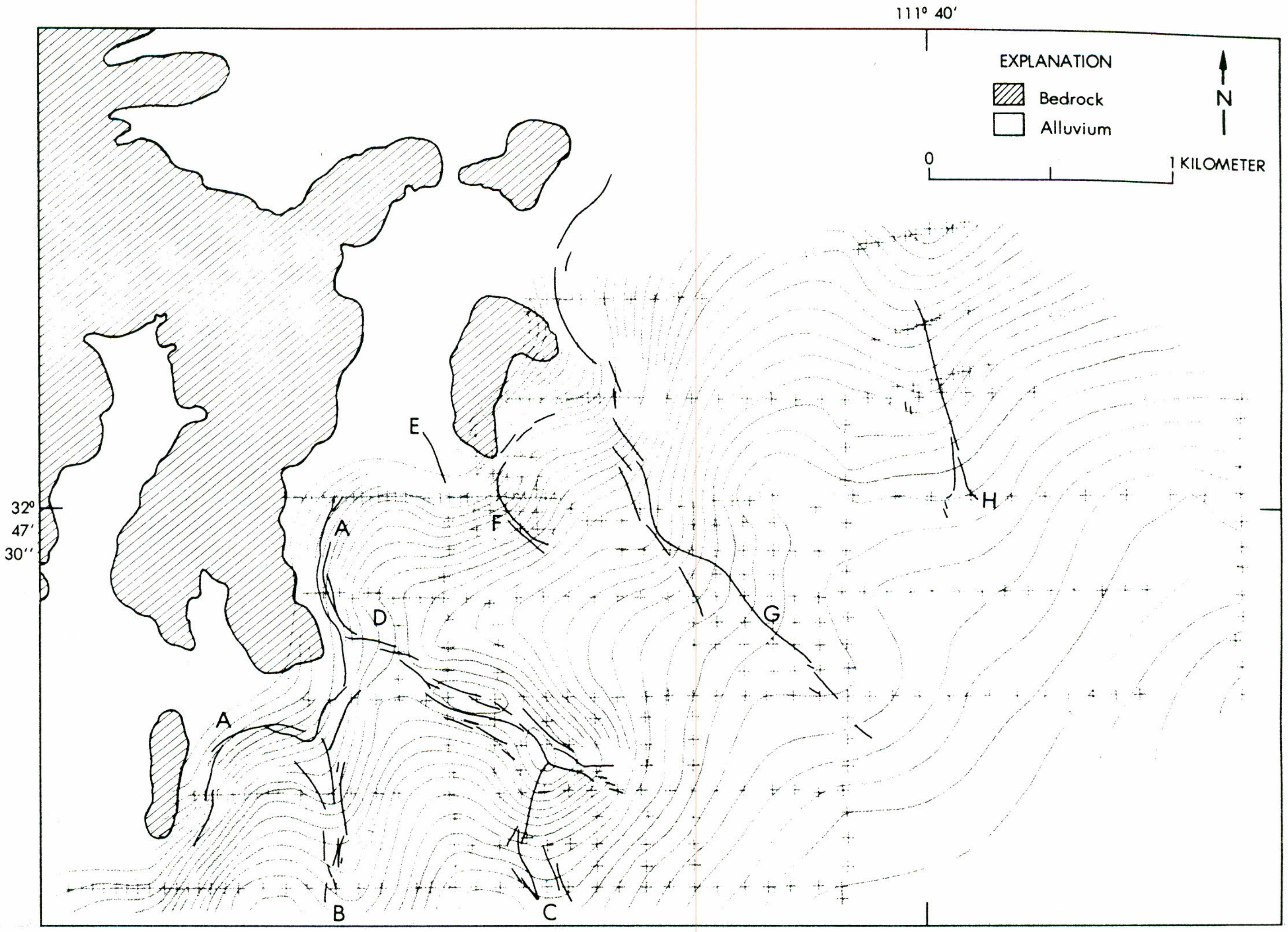


Figure 7. Relative Bouguer gravity field over the study area (Fig. 2). Contour interval is 0.2 mGal. All values have been referenced to zero at a bedrock gravity station. Crosses indicate locations of gravity measurements. Heavy lines and letters indicate fissure zones (Fig. 2). Fissures mapped during April 1980.

Elevation control for the gravity data was obtained from leveling surveys. Examination of loop closures and repeated measurements indicate that uncertainties in elevations probably are less than ± 0.1 m, equivalent to a gravity uncertainty of ± 0.02 mGal.

RESULTS

The Bouguer gravity field over the study area (Fig. 7) is highest near the bedrock exposures in the northwestern part and generally slopes down toward the southeast. The total range of gravity values over the study area is about 7 mGal. Southeast of the study area, the gravity field falls off smoothly by an additional 20 mGal and reaches its lowest values near the center of Picacho basin (Peterson, 1968). In the study area, numerous local gravity anomalies are superimposed on the general southeastward decline. These take the form of ridges, troughs, and abrupt changes of slope of the gravity field.

As discovered in the preliminary study of this area (Jachens and Holzer, 1979) and in investigations of other areas in southern Arizona (Anderson, 1973; Jennings, 1977; Pankratz and others,

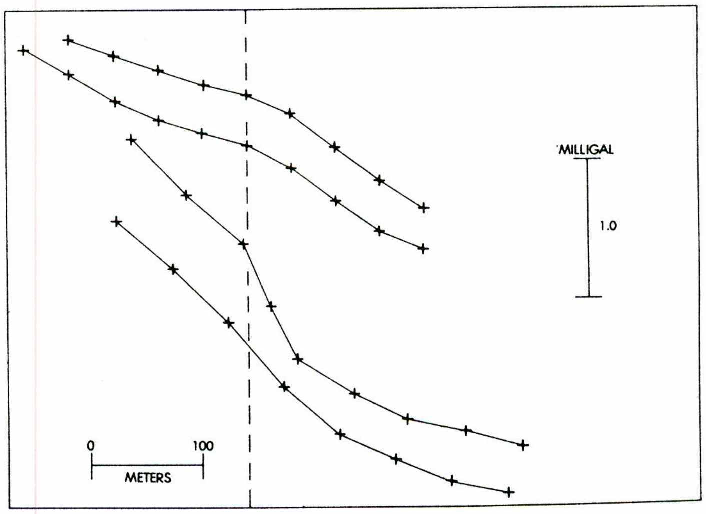


Figure 8. Local gravity anomalies along four east-west profiles that cross fissure zone A (Figs. 2, 7). Dashed line indicates location of fissure.

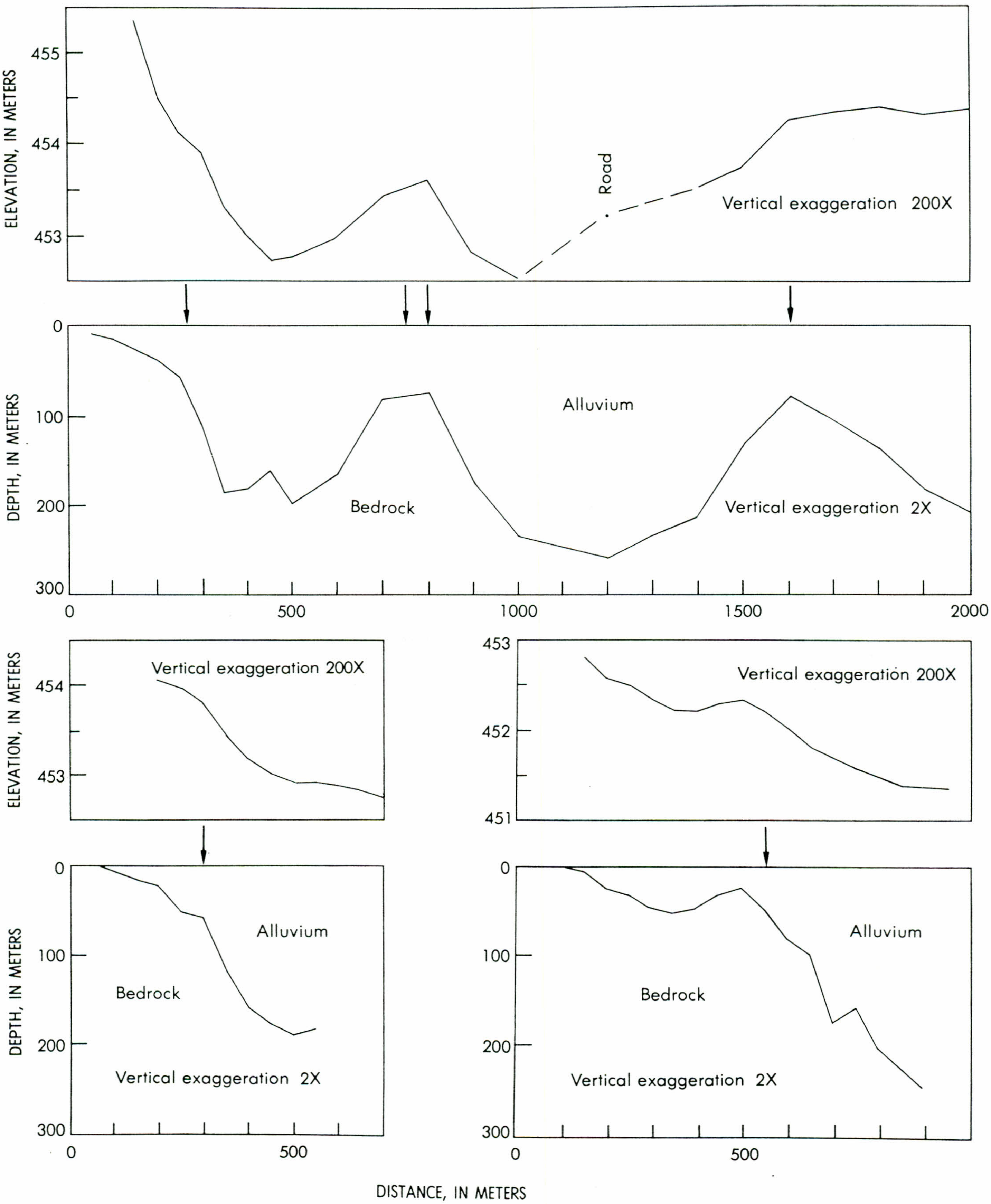


Figure 9. Surface topography in April 1980 and inferred configuration of buried bedrock surface along three profiles in study area. Arrows indicate locations of fissures.

1978b), a striking spatial correlation exists between many local gravity anomalies and the distribution of fissures (Figs. 7 and 8). Some fissures occur along the crests of ridges in the gravity field (B, C, D, H, and parts of F and G), whereas others occur where the slope of the gravity field changes abruptly and is convex upward (A, E, and parts of F and G). For fissures in the latter category, the correlation is not obvious from the map (Fig. 7) but is readily apparent from an examination of profiles (Fig. 8), even though the change of slope is subtle at some locations (for example, lower profile in Fig. 8). The spatial correlation between convex-upward gravity anomalies and fissures can be seen along every one of the more than 20 profiles that cross fissures. No fissures occur in areas where the gravity anomalies are concave upward.

Elevation data, collected in April 1980 for use in the gravity reductions, provided additional information relating directly to the fissures. In areas away from the steep topographic slopes associated with the mountain fronts, elevation profiles across fissures consistently show that fissures occur on local topographic highs or abrupt convex-upward breaks in slope. Several representative profiles which show this relationship are given in Figure 9.

INTERPRETATION

The thickness of unconsolidated alluvium throughout the study area (Figs. 9, 10, and 11) was inferred from gravity data by quantitative modeling of a simple two-layer structure: unconsolidated alluvium underlain by bedrock. The assumptions on which the modeling was based are as follows: (1) the gravity data, modified slightly to correct for the gravity low centered over Picacho basin (Peterson, 1968), reflect variations in thickness of the alluvium rather than density variations within the alluvium or bedrock, and (2) the density contrast between the alluvium and bedrock is 0.5 g/cm^3.

Densities

Support for the assumption that the local gravity anomalies primarily reflect variations in the thickness of alluvium can be found both within the study area and at nearby locations where fissuring has occurred. Within the study area, two highs in the gravity field, one associated with fissure zone B and another

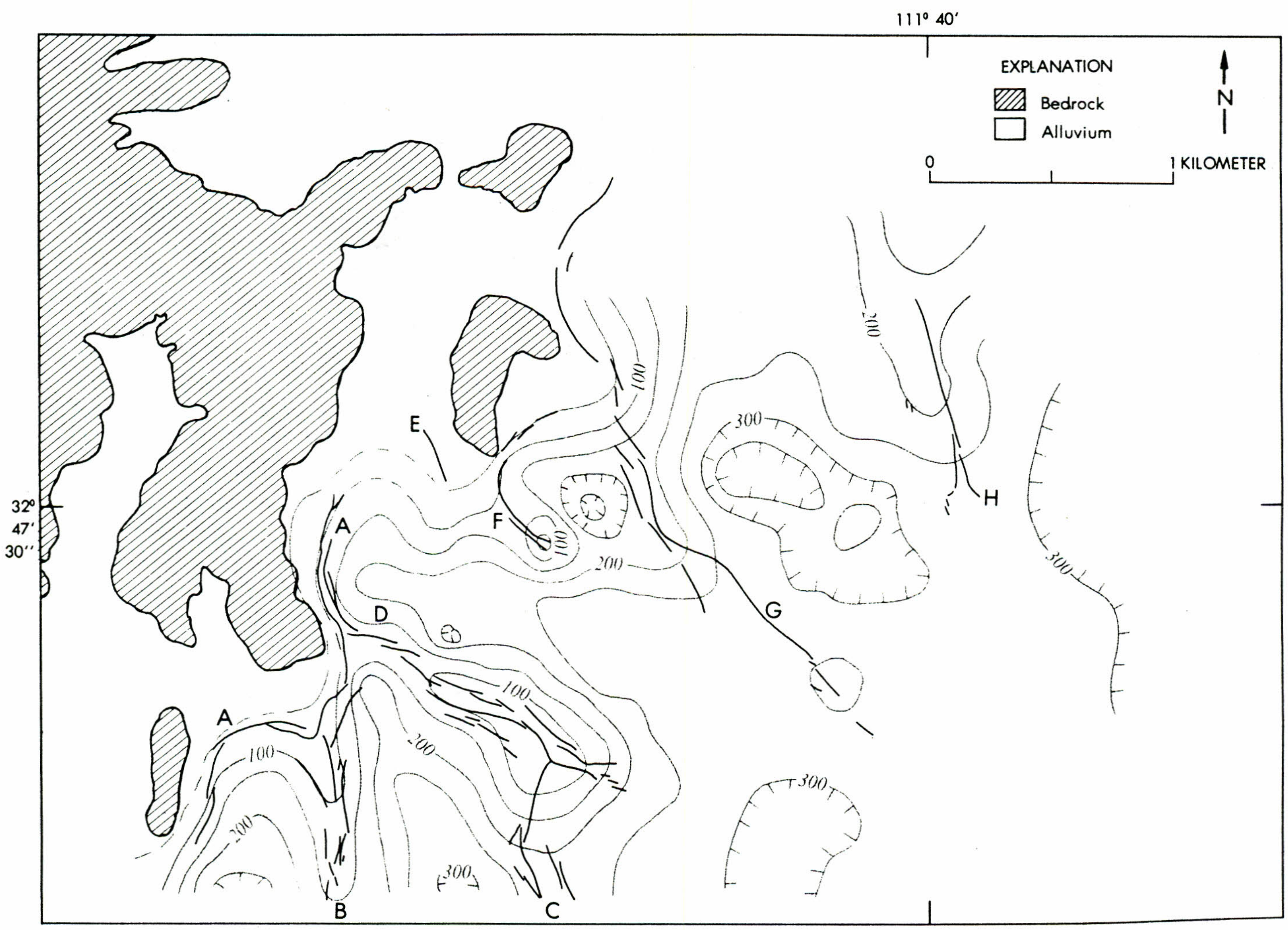
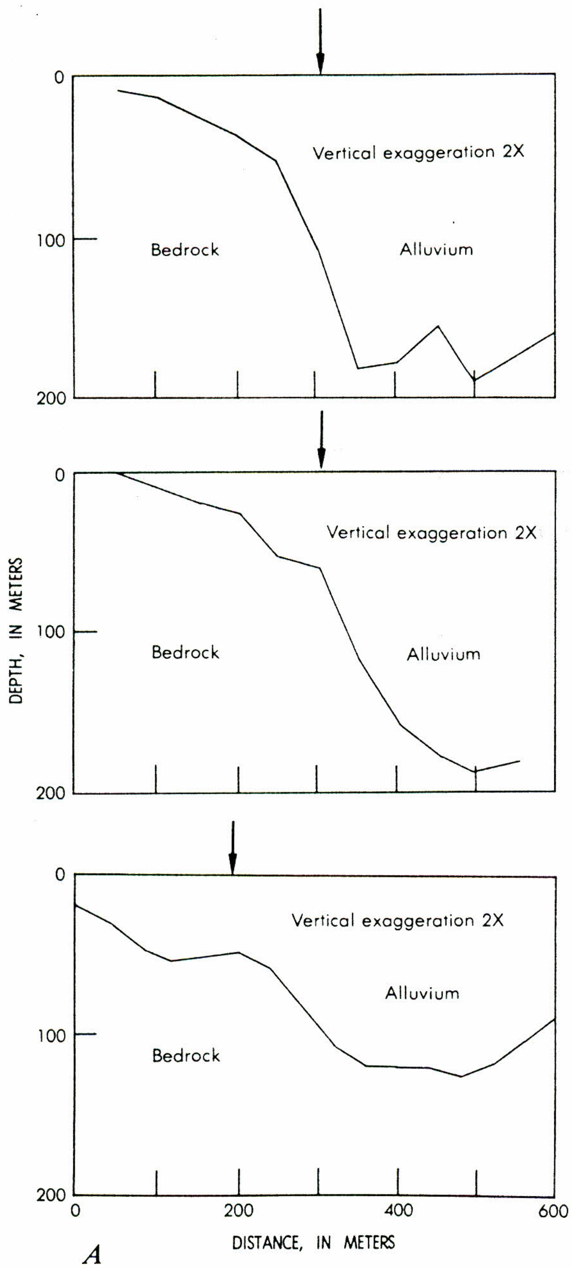


Figure 10. Map of inferred depth in metres to bedrock beneath land surface. Contour interval is 50 m. Fissures mapped during April 1980; see Figure 2 for location. Hachures on contours point in direction of increasing depth.

between fissure E and the southern part of zone F (Fig. 7), are located just south of and on the projections of exposed, north-south bedrock ridges. The bedrock configuration inferred from the gravity data under the assumptions stated above (Fig. 10) indicates that both exposed ridges continue to the south as buried ridges. Similarly, north of the study area, local gravity highs associated with two fissures occur above local basement highs inferred from seismic refraction measurements (Pankratz and others, 1978b).

Assumption of a uniform density for the bedrock beneath the study area is supported by the uniform density of hand samples of bedrock exposed around the margins of the basin. Measured densities of 15 hand samples of crystalline bedrock averaged 2.60 ± 0.06 (1σ) g/cm^3. Measured dry densities of six hand samples of consolidated alluvium from outcrops 16 km northwest of the study area averaged 2.53 ± 0.04 (1σ) g/cm^3, a value close to the average density of the crystalline bedrock samples.

Some confidence that variations of density within the alluvium are small and not a significant source of the gravity anomalies can be gained both from direct measurements of alluvial density and from indirect evidence based on other geophysical data. Saturated densities of cores from a 250-m-deep borehole near the center of Picacho basin (U.S. Bureau of Reclamation, 1965, unpub. report) and from three other boreholes in south-central Arizona (R. L. Laney, 1980, written commun.) averaged 2.0 g/cm^3. Saturated densities determined from gamma-gamma logs of boreholes near the eastern margin of the basin averaged between 2.1 and 2.2 g/cm^3 to a depth of 250 m. Indirect evidence for the uniformity of alluvial density comes from a site near the eastern margin of Picacho basin (Jachens and Holzer, 1979, site 2), where the observed magnetic data agreed with the magnetic anomaly computed for a bedrock surface inferred from gravity data. This agreement indicates that the gravity and magnetic anomalies arise from the same source. Because density variations within the alluvium are unlikely to be accompanied by proportional variations in magnetization, the source of the gravity anomaly most likely is not in the alluvium. At another site, along an 8-km seismic refraction profile near the eastern margin of Picacho basin, agreement of observed and computed gravity anomalies (Pankratz and others, 1978a) indicates that gravity anomalies resulting from density variations within the alluvium are smaller than ~0.1 mGal.



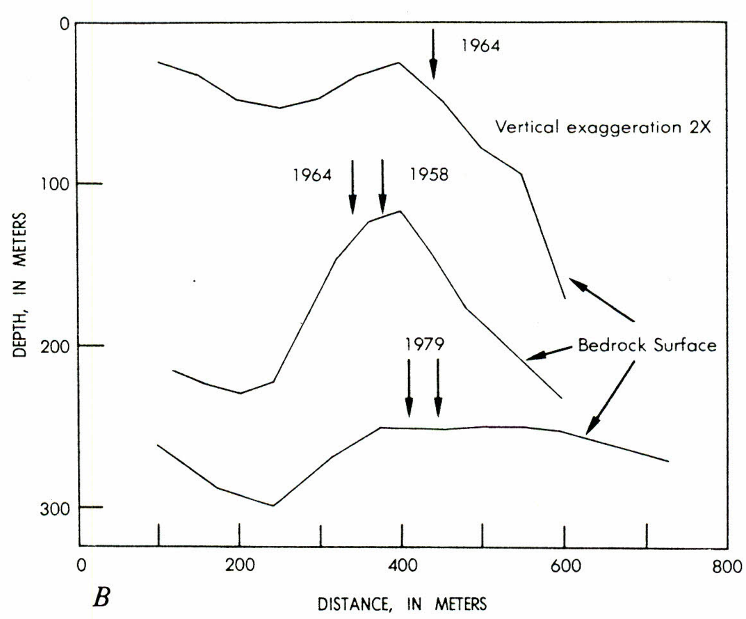


Figure 11. A. Inferred configuration of buried bedrock surface in three profiles across fissure zone A (Fig. 2). Arrows indicate locations of fissures.

B. Inferred configuration of buried bedrock surface in three profiles across fissure zone G (Fig. 2). Arrows indicate locations of fissures. Dates adjacent to the arrows indicate the earliest aerial photographs on which the fissures are recognized.

In summary, density measurements on bedrock hand samples discussed above suggest that a value of 2.6 g/cm^3 is representative of the crystalline bedrock density and that a slightly lower value is appropriate for consolidated alluvium. Measured average densities for unconsolidated alluvium range from 2.0 to 2.2 g/cm^3. These data indicate that the density contrast between the unconsolidated alluvium and the bedrock lies in the range of 0.4 to 0.6 g/cm^3. Therefore, the density contrast of 0.5 g/cm^3 assumed for the purposes of modeling is uncertain by about ± 0.1 g/cm^3.

Gravity Modeling

A three-dimensional configuration of the bedrock surface (Fig. 10) beneath the entire area was computed by the technique of Cordell and Henderson (1968). In this calculation, an initial model of the bedrock surface geometry was modified during successive iterations until the computed and observed gravity agreed closely. Because the computation is time-consuming and expensive, and because the gravity data are scattered somewhat unevenly over the area, a relatively coarse computational grid with cell width of 300 m was chosen. The solution was permitted to progress through four iterations, which was sufficient to yield a generalized representation of the bedrock surface geometry. More detailed two-dimensional computations were performed for profiles along which quantitative portrayals of the bedrock surface configurations were essential (see Figs. 9 and 11 for examples). A two-dimensional technique (Bott, 1960) that is similar to the three-dimensional technique described above was used for the profile computations.

Bedrock Control

Comparison of the distribution of fissures with the inferred configuration of the bedrock surface (Fig. 10) reveals that earth fissures in the study area are associated with relief on the interface between the bedrock and the alluvium. Fissure zones B, C, D, E, F (south half), G, and H all occur almost directly over the crests of buried bedrock ridges. Three crossings of the other fissure zone, A, show that it occurs above an abrupt, convex-upward change of slope of the bedrock surface (Fig. 11A). The bedrock control is particularly striking at junctions between fissure zones such as occur in the southwestern part of the study area. There, the angles of intersection of fissure zones B and D with A accurately reflect the angles at which their respective underlying bedrock ridges intersect. Another example occurs near the southeast end of fissure zone D, where the bedrock ridge buried beneath this system bifurcates into north-south– and east-west–trending ridges. Bifurcation of fissure zone D into two fissure zones (C and D) is coincident with the bifurcation of the underlying bedrock ridge.

Locations of the ends of fissure zones also are controlled by the form of the underlying bedrock. The southeast ends of zones D, F, G, and H are each located near the southeast ends of bedrock ridges. Bedrock control probably applies at the south end of E and at the northeast end of F, but at these locations the data are inadequate to establish precisely the end of the bedrock feature. The only documented exception occurs at the northwest end of H, where the bedrock ridge extends at least 200 m northwest of the end of the zone. Subsurface conditions beneath the ends of other fissure zones cannot be determined, either because there are no data in the appropriate area or because the locations of the ends of the zones are not precisely known because parts of the zones have been obliterated by cultivation, as along the south edge of the study area.

More precise estimates of the configuration of the bedrock surface beneath selected earth fissures, based on two-dimensional modeling of gravity profiles, indicate that, in general, fissures in the study area occur above points of maximum convex-upward curvature of the bedrock surface (Figs. 9 and 11). Horizontal distances between points of maximum curvature and locations of fissures were generally within the limits of resolution determined by the spacing between gravity measurements.

Topographic profiles across many of these fissure zones suggest that the buried bedrock irregularities have caused localized differential subsidence because the topographic and bedrock surface profiles are similar in shape (Fig. 9). Although we have no topographic maps that show sufficient resolution for us to assess detailed pre-1948 topography, comparison of the buried local relief across specific bedrock features with the relief on the corresponding topographic profiles suggests that the origin of the topographic relief is related to ground-water withdrawal. The average ratio of differential subsidence, assumed to be equal to the local topographic relief, to differential thickness, equal to bedrock relief, determined from six profiles, was 0.0092 (Table 1). This ratio agrees well with the compaction per saturated thickness of 0.0083 determined at bench mark Guano using borehole and leveling data. In addition, the small range of values of the ratio, 0.0081 to 0.0108, and the

TABLE 1. BOUNDS OF TENSILE STRAINS AT FAILURE

Fissure zone	Date of formation	Tensile strain (%)		Ratio of differential subsidence in 1980 to differential thickness
		Finite element	Equation 1	
A, Location 1	1949–1954	0 to 0.021	0 to 0.050	
A, Location 2	1958–1960	0.057 to 0.078		
A, Location 3	1954–1956	0.016 to 0.036	0.012 to 0.027	0.0081
B	? –1964	? to 0.169	? to 0.347	0.0091
C	1954–1956	0.015 to 0.034	0.022 to 0.051	0.0053(?)
D	1954–1956	0.021 to 0.048		0.0082
E	1964–1970	0.111 to 0.131	0.143 to 0.168	0.0108
F	1958–1960	0.043 to 0.059	0.099 to 0.135	0.0091
G, Location 1	1958–1964	0.022 to 0.050	0.048 to 0.108	0.0098
G, Location 2	1954–1956	0.021 to 0.048		
H, Location 1	1964–1970	0.144 to 0.169	0.197 to 0.232	
H, Location 2	1975–1979	0.120 to 0.131		
H, Location 3	>1980	0.191 to ?		

**Note:* Upper and lower bounds of tensile strain at failure correspond to indicated bounding dates of failure on the basis of aerial photographs.

uniform water-level decline suggest that the compressibility of the unconsolidated alluvium is approximately constant throughout the study area.

DISCUSSION

Mechanism

The association of earth fissures in the study area with variations in alluvial thickness and with man-induced changes in topographic relief indicates that the earth fissures have formed along zones of differential compaction. The specific mechanism by which differential compaction at depth may cause horizontal strain and tensile failure has been demonstrated in both experimental and analytical investigations by Sanford (1959) and Lee and Shen (1969). Both studies demonstrated that differential vertical displacements applied along the base of a horizontal layer cause differential horizontal displacements and horizontal strains at the land surface. The sense of the horizontal strain according to Lee and Shen (1969) is related to the curvature of the resulting subsidence profile. Horizontal strains are tensile where the profile is convex-upward, and compressive where it is concave-upward. This mechanism, which we propose to be the dominant cause of tensile failure in the study area, is illustrated schematically in Figure 12. We propose that as water levels declined in the study area, variations of aquifer thickness related to relief on the bedrock surface caused differential compaction to occur. This compaction was manifested to a first approximation as differential vertical displacements along the base of a layer which touches the highest point on the bedock surface (Fig. 12). The layer is so defined because we assume that compaction within the layer itself is inconsequential, that is, it causes only uniform vertical lowering of the land surface and no horizontal displacement. In a qualitative sense, this mechanism can be viewed as either a draping of the alluvium over the buried bedrock feature or a bending of the layer. By this mechanism, differential horizontal displacements and horizontal strains continue to increase as long as differential compaction continues.

The strongest evidence supporting this mechanism of fissure formation is the location of earth fissures in the study area at and above points of maximum convex-upward curvature in the topographic profiles and buried bedrock surface, respectively. According to Lee and Shen (1969), horizontal strains caused by differential compaction are tensile where subsidence profiles are convex-upward, and tension is greatest at points of maximum convex-upward curvature in the profiles (Fig. 12). Tensile failure, of course, would be most likely at points of maximum tension.

This mechanism is also supported by the chronology of fissure formation. For example, consider fissure zone G, which is associated with an irregularly shaped, buried bedrock ridge. The zone developed in a spatially and temporally discontinuous manner for more than 20 yr (Fig. 6); the earliest ground failure (1954–1958) occurred above the sharpest section of the ridge, whereas the latest ground failure (1975–1979) occurred above the most subdued parts of the ridge. Throughout the rest of the area, fissures tended to form first above the sharpest bedrock features. The relation is far from perfect, however, and other factors also may have influenced the time of cracking. These factors might include the magnitude of buried relief across the bedrock feature, pre-existing flaws in the alluvium, lateral variations of mechanical properties of the alluvium, and strain-rate-dependent tensile strength. Some of the discrepancies also might be attributed to lags between the time cracking occurred and the time it was recorded on aerial photographs.

Positions of now (1980) active earth fissures are also compatible with a differential compaction mechanism. As noted previously, some earth fissures appear to have had a long history of activity, whereas others appear to have become inactive. Active fissures typically occur where the water table is above the bedrock surface and differential compaction presumably is still occurring. Inactive fissure zones occur where the inferred bedrock surface is above the present water table and differential compaction should have ceased. Relations between fissure activity and bedrock depth and water-table depth are not simple, however. Active and inactive fissures lie adjacent to each other in some zones (C, southeast part of D, and central part of G, Fig. 2), and the inactive northwest strand of D lies above a bedrock ridge whose crest is 100–150 m below the ground surface.

Tensile Strain at Failure

The conclusion that earth fissures within the study area were caused by localized differential compaction suggests that the locations of potential earth fissures caused by differential compaction in other areas can be predicted if subsurface conditions conducive to this mechanism are identified. Evaluating the magnitude of water-level decline required to cause failure and accurate prediction of the time of failure, however, require data on the tensile strength of the surface soils and a method for estimating the field-generated horizontal strain. To address this problem, we have relied on research by Lee and Shen (1969), who examined in both analytical and experimental investigations the generation of surficial horizontal displacements by differential compaction at depth. For their two-dimensional analysis, they studied displacements in the plane of a vertical section. In essence, they examined the displacements at the top of a layer of constant thickness subjected to

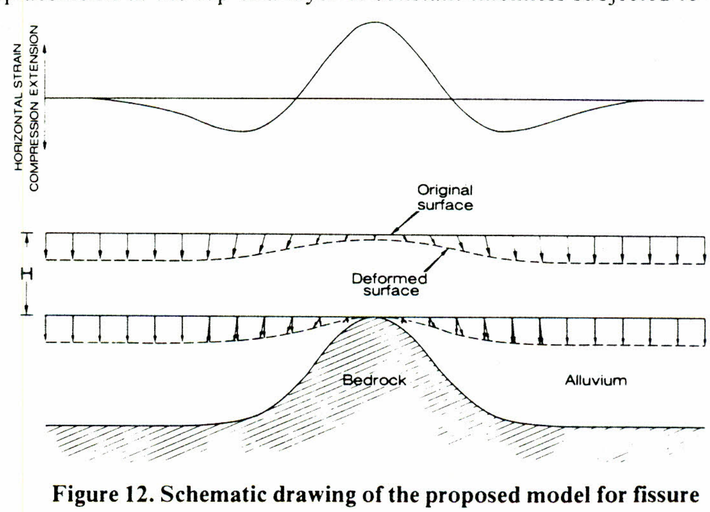


Figure 12. Schematic drawing of the proposed model for fissure formation in study area. Differential vertical displacements acting on base of layer (heavy arrows) are caused by differential compaction caused by variations of alluvial thickness. Light arrows indicate displacements resulting from vertical displacements imposed at base of layer. Thickness, H, of layer is equal to depth from land surface to highest point on buried bedrock features. Horizontal strains at land surface caused by displacements at base of layer are shown at top of figure.

differential vertical displacements applied along its base (Fig. 12). Of particular pertinence to our research is their conclusion that the thickness of the layer and the distribution of vertical displacements along its base were the most important factors controlling the horizontal displacements. All other refinements, including material properties of the layer, were of secondary importance. They used two approaches to compute surficial horizontal displacements. In the more rigorous approach, the layer was replaced with a finite element model to which vertical displacements were applied along its base. In the less rigorous approach, they calculated the horizontal displacement, m, at a point at the surface, using the empirical formula

$$m = k H\alpha \quad (1)$$

in which k is a factor to correct for the effect of shear and a variable modulus, H is the thickness of the layer, and α is the slope of the subsidence profile at the point. The constant, k, is empirical, but Lee and Shen (1969) found that a value of 2/3 reasonably reproduced observed displacements and those calculated by the more rigorous approach.

In order to estimate horizontal strains at failure, horizontal displacements were computed in the present investigation by both approaches for a series of cross sections oriented perpendicular to the fissure zones. The thickness of the layer used in each cross section was the depth from the land surface to the highest point on the bedrock feature beneath the relevant fissure. Layer thickness, therefore, is different for each cross section. This choice of layer thickness was based on our assumption that the differential vertical displacements of interest result from compaction of only that part of the alluvium beneath a horizontal surface touching the highest point on the bedrock surface (see Fig. 12). Vertical displacements from compaction within the layer presumably cause only uniform lowering of the land surface. In our earlier research (Jachens and Holzer, 1979), the pertinent layer was assumed to be the zone above the final water table. This assumption unnecessarily ignored the effect of the propagation of differential vertical displacements through the part of the aquifer system between the final water table and the high point of the bedrock surface when the final water table was above the bedrock surface.

On the basis of equation 1, profiles of horizontal strain at failure were computed across eight fissures. Profiles were calculated where the original slope of the ground surface probably had been nearly uniform and had not been modified by recent cultural activity. Values of horizontal strain were calculated by taking the first horizontal derivative of equation 1. Accordingly, strains depend on k and H, which are constants for a given profile, and on the second horizontal derivative of the subsidence profile at the time of failure. The last parameter was determined from the topographic profile across each fissure corrected to the time of failure. Because each topographic profile was assumed to consist of a subsidence profile superimposed on an initially uniform topographic slope, the second derivatives of the subsidence and topographic profiles at a given point are equal. To correct 1980 topographic profiles to profiles at the time of failure, the date of formation of each fissure was bounded on the basis of aerial photographs. These dates were then used to derive, from the normalized subsidence curve of bench mark P278, the percentage of the 1980 subsidence that had occurred at the time of failure. Multiplying the topographic profile measured in 1980 by this percentage yielded the topography at the time of failure. The bounding values of the tensile strain at each of the eight fissures at the time of failure are given in Table 1.

Horizontal strains also were computed by the finite element method by considering a layer with differential vertical displacements applied along its base. The vertical displacement at a point on the base of the layer was set equal to the estimated compaction (as of 1980) per unit saturated thickness multiplied by saturated thickness beneath the point. In order to obtain the strain at failure, vertical displacements applied along the base of the layer were further multiplied by the percentage of subsidence that had occurred at the date of failure based on the normalized subsidence history of bench mark P278. An example of the computed horizontal strain along a profile across fissure zones A, B, and C is shown in Figure 13. Results for 13 sites are shown in Table 1. The compaction (as of 1980) per unit saturated thickness used in Table 1 was 0.0092.

The calculated strains at failure given in Table 1 are all tensile and range approximately from 0.02% to 0.2%, with most falling in the range 0.02% to 0.06%. The strains computed by equation 1 are slightly larger and show more scatter than those computed by the finite-element approach. However, considering the limitations of both approaches, the comparison is favorable. The strains based on equation 1 probably are more susceptible to challenge because the selection of k was empirical. Further examination of Table 1 also shows that fissures that formed latest seem to have failed at higher strains than earlier-forming ones, a pattern suggesting that the tensile strains at failure may be strain-rate dependent.

The strains computed by both methods are susceptible to uncertainties in the alluvial thicknesses inferred from the gravity data. As previously noted, the assumed density contrast of 0.5 g/cm^3 between the alluvium and bedrock has an uncertainty of about ± 0.1 g/cm^3. The uncertainty of the density contrast results in an uncertainty of about ± 15% in the calculated horizontal strains. The gravity technique introduces further uncertainty to the finite element approach because it is unable to resolve the sharpness of deeply buried bedrock features. Because sharp bedrock features would concentrate horizontal strains more efficiently than more subdued ones, the gravity technique might be expected to yield lower estimates of the horizontal strain than actually occur.

The small estimated magnitude of horizontal strain at failure is supported by modest field and laboratory investigations. Average annual horizontal strains measured over 1- to 4-yr periods across

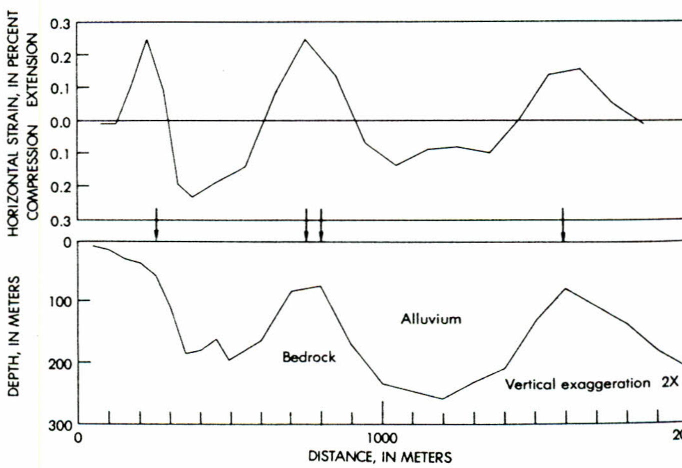


Figure 13. Computed horizontal surface strain (1980) and inferred configuration of buried bedrock surface beneath an east-west profile across fissure zones A, B, and C (Fig. 2). Arrows indicate locations of fissures.

four fissures in Arizona, California, and Nevada ranged from 0.01% to 0.03% (Holzer and Pampeyan, 1981). The representativeness of these values as long-term averages is uncertain, but subsidence at each site had been occurring for less than 25 years prior to failure. Accordingly, strains ranging from 0.2% to 0.7% are suggested. These magnitudes of tensile failure strains also are compatible with values determined in the laboratory, principally for compacted clays. Failure at less than 1% strain typically is reported for soils at low saturations, the condition typical of materials in the study area (Leonards and Narain, 1963; Hasegawa and Ikeuti, 1964; Ajaz and Parry, 1975).

Prediction

The present investigation supports the conclusion reached earlier by Jachens and Holzer (1979) that earth fissures caused by localized differential compaction can, in general, be predicted when subsurface conditions are known. Near the Casa Grande Mountains, the principal subsurface control is convex-upward irregularities of the bedrock surface forming the base of the aquifer system. Where similar subsurface conditions pertain in other areas, locations of potential earth fissures can probably be predicted with considerable precision. If sufficient data on tensile strength and compressibility of the subsurface materials are available, the finite element method provides a satisfactory tool for prediction of the magnitude of water-level decline at which fissuring could occur.

CONCLUSIONS

Earth fissures in unconsolidated alluvium on the east side of the Casa Grande Mountains in south-central Arizona are associated with zones of local minima in or abrupt changes of aquifer-system thickness. The variations in thickness, which were inferred from gravity measurements, are caused by relief on the bedrock surface defining the base of the aquifer system. This relief ranges from ridges to breaks in slope on the buried bedrock surface. In particular, fissures are above loci of points of maximum convex-upward curvature on the bedrock surface. In general, individual fissure systems formed piecemeal and slowly over these irregularities, in some cases evolving for more than 20 yr. Along a given bedrock irregularity, fissures tended to form earliest over the shallowest and sharpest segments. Later-forming fissures occurred over deeper and more subdued segments of the bedrock irregularity. Topographic profiles of undisturbed desert floor across the earth fissures indicate that the fissures also are coincident with zones of man-induced differential subsidence that have a geometry similar to the relief on the bedrock surface. Fissures occur along the loci of points of maximum convex-upward curvature.

On the basis of the preceding observations and theoretical considerations, we conclude that earth fissures in the study area were caused by bending of the unconsolidated material overlying the bedrock irregularities. The bending was caused by differential compaction related to local variations of aquifer-system thickness. Where the bedrock surface is convex upward, horizontal strains are tensile. Strains are at a maximum tension above the points where curvature is a maximum. Strains at failure were estimated, on the basis of modeling, to range approximately from 0.02% to 0.2%.

These results and the results of earlier studies suggest that locations of earth fissures caused by differential compaction can be predicted from a knowledge of subsurface conditions. In addition, if material properties are known, then the magnitude of water-level decline at which fissuring could occur also can be predicted.

ACKNOWLEDGMENTS

We are grateful to Lindrith E. Cordell, George H. Davis, Stanley N. Davis, and T. Leslie Youd for their careful and thoughtful reviews of preliminary drafts of the manuscript. William P. Elder assisted in the field work and with reduction of gravity data.

REFERENCES CITED

Ajaz, A., and Parry, R.H.G., 1975, Stress-strain behavior of two compacted clays in tension and compression: Geotechnique, v. 25, no. 3, p. 495–512.

Barnes, D. F., Oliver, H. W., and Robbins, S. L., 1969, Standardization of gravimeter calibrations in the Geological Survey: American Geophysical Union Transactions, v. 50, no. 10, p. 526–527.

Bergquist, J. R., and Blacet, P. M., 1978, Preliminary reconnaissance bedrock geologic map of part of the Casa Grande Mountains quadrangle, Pinal County, Arizona: U.S. Geological Survey Open-File Report 78-547, scale 1:24,000.

Bott, M.P.H., 1960, The use of digital computing methods for direct gravity interpretation of sedimentary basins: Astronomical Society Geophysical Journal, v. 3, no. 1, p. 63–67.

Bouwer, H., 1977, Land subsidence and cracking due to ground-water depletion: Ground Water, v. 15, no. 5, p. 358–364.

Bureau of Reclamation, 1977, Geology and ground-water resources report, Maricopa and Pinal Counties, Arizona, Volume 1: Phoenix, Arizona, U.S. Department of Interior, Bureau of Reclamation, Arizona Projects Office.

Cordell, L., and Henderson, R. G., 1968, Iterative three-dimensional solution of gravity anomaly data using a digital computer: Geophysics, v. 33, p. 596–601.

Dobrin, M. B., 1960, Introduction to geophysical prospecting (2nd edition): New York, McGraw-Hill, 446 p.

Feth, J. H., 1951, Structural reconnaissance of the Red Rock quadrangle, Arizona: U.S. Geological Survey Open-File Report, Tucson, Arizona, 32 p.

Fife, D. L., 1977, Engineering geologic significance of giant desiccation polygons, Lucerne Valley playa, San Bernardino, California: Geological Society of America Abstracts with Programs, v. 9, p. 419.

Guacci, G., 1979, The Pixley fissure, San Joaquin Valley, California, *in* Saxena, S. K., ed., Evaluation and prediction of subsidence: American Society of Civil Engineers, p. 303–319.

Hardt, W. F., and Cattany, R. E., 1965, Description and analysis of the geohydrologic system in western Pinal County, Arizona: U.S. Geological Survey Open-File Report, Tucson, Arizona, 92 p.

Hasegawa, H., and Ikeuti, M., 1964, On the tensile strength test of disturbed soils, *in* International Symposium on Rheology and Soil Mechanics, Grenoble, p. 405–412.

Holzer, T. L., 1977, Ground failure in areas of subsidence due to ground-water decline in the United States, *in* International Association of Hydrological Sciences Publication no. 121, p. 423–433.

—— 1980, Reconnaissance maps of earth fissures and land subsidence, Bowie and Willcox areas, Arizona: U.S. Geological Survey Miscellaneous Field Studies Map MF-1156, scale 1:24,000.

Holzer, T. L., and Davis, S. N., 1976, Earth fissures associated with water-table declines: Geological Society of America Abstracts with Programs, v. 8, p. 923–924.

Holzer, T. L., Davis, S. N., and Lofgren, B. E., 1979, Faulting caused by groundwater extraction in south-central Arizona: Journal of Geophysical Research, v. 84, no. B2, p. 603–612.

Holzer, T. L., and Pampeyan, E. H., 1981, Earth fissures and localized differential subsidence: Water Resources Research, v. 17, no. 1, p. 223–227.

Jachens, R. C., 1979, Temporal gravity changes as applied to studies of crustal deformation: U.S. Geological Survey Open-File Report 79-370, p. 222–243.

Jachens, R. C., and Holzer, T. L., 1979, Geophysical investigations of ground failure related to ground-water withdrawal—Picacho basin, Arizona: Ground Water, v. 17, no. 6, p. 574–585.

Jennings, M., 1977, Geophysical investigations near subsidence fissures in northern Pinal and southern Maricopa Counties, Arizona [M.S. thesis]: Tempe, Arizona, Arizona State University, 102 p.

Laney, R. L., Raymond, R. H., and Winikka, C. C., 1978, Maps showing water-level declines, land subsidence, and earth fissures in south-central Arizona: U.S. Geological Survey Water Resources Investigations 78-83, 2 sheets, scale 1:125,000.

Lee, K. L., and Shen, C. K., 1969, Horizontal movements related to subsidence: American Society of Civil Engineers Journal of the Soil Mechanics and Foundations Division, v. 95, no. SM1, p. 139–166.

Leonards, G. A., and Narain, J., 1963, Flexibility of clay and cracking of earth dams: American Society of Civil Engineers Journal of the Soil Mechanics and Foundations Division, v. 89, no. SM2, part 1, p. 47–98.

Lofgren, B. E., 1971, Significant role of seepage stresses in compressible aquifer systems [abs.]: American Geophysical Union Transactions, v. 52, no. 11, p. 832.

Longman, I. M., 1959, Formulas for computing the tidal acceleration due to the moon and sun: Journal of Geophysical Research, v. 64, no. 12, p. 2351–2355.

Morton, D. M., 1976, Surface deformation in part of the San Jacinto Valley, Southern California: U.S. Geological Survey Journal of Geological Research, v. 5, no. 1, p. 117–124.

Pankratz, L. W., Ackermann, H. D., and Jachens, R. C., 1978a, Results and interpretation of geophysical studies near the Picacho fault, south-central Arizona: U.S. Geological Survey Open-File Report 78-1106, 17 p.

Pankratz, L. W., Hassemer, J. H., and Ackermann, H. D., 1978b, Geophysical studies relating to earth fissures in central Arizona [abs.]: Geophysics, v. 44, no. 3, p. 367.

Pashley, E. F., Jr., 1961, Subsidence cracks in alluvium near Casa Grande, Arizona: Arizona Geological Society Digest, v. 4, p. 95–101.

Patt, R. O., and Maxey, G. B., 1978, Mapping of earth fissures in Las Vegas Valley, Nevada: University of Nevada Water Resources Center Publication no. 41051, 19 p.

Peterson, D. L., 1968, Bouguer gravity map of parts of Maricopa, Pima, Pinal, and Yuma Counties, Arizona: U.S. Geological Survey Geophysical Investigations Map GP-615, scale 1:250,000.

Riley, F. S., 1969, Analysis of borehole extensometer data from central California, *in* International Association of Hydrological Sciences Publication no. 89, p. 423–431.

Sanford, A. R., 1959, Analytical and experimental study of simple geologic structures: Geological Society of America Bulletin, v. 70, p. 19–52.

Schumann, H. H., and Poland, J. F., 1969, Land subsidence, earth fissures and ground-water withdrawal on south-central Arizona, U.S.A., *in* International Association of Hydrological Sciences Publication no. 88, p. 295–302.

Smith, G.E.P., 1938, The physiography of Arizona valleys and the occurrence of ground water: University of Arizona Agricultural Experiment Station Technical Bulletin No. 77, 91 p.

—— 1940, The groundwater supply of the Eloy district in Pinal County, Arizona: University of Arizona Agricultural Experiment Station Technical Bulletin No. 87, 42 p.

Summer, J. S., and Christie, F. I., 1980, Geophysical and hydrologic prediction of fissuring and land subsidence, south-central Arizona: National Technical Information Service Accession No. PB 80-159 908, 5 p.

Winikka, C. C., 1964, Subsidence in the Eloy-Picacho area: Arizona Land Surveyors Conference, Proceedings, 11th, Arizona Engineering Experiment Station, p. 39–43.

Manuscript Received by the Society May 26, 1981
Revised Manuscript Received October 30, 1981
Manuscript Accepted November 16, 1981

Printed in U.S.A.

Arizona Geological Society Digest, Volume IV, November 1961

SUBSIDENCE CRACKS IN ALLUVIUM NEAR CASA GRANDE, ARIZONA

By

E. F. Pashley, Jr.

U. S. Geological Survey, Tucson, Arizona

INTRODUCTION

Large cracks have appeared in the alluvium of the valleys of southern Arizona at various times but few have been located, described, or studied in detail. New occurrences of these cracks, popularly termed "earth cracks," are being reported continually. The purposes of this paper are (1) to review the few published accounts of these cracks, (2) to describe earth cracks observed by the writer near Casa Grande, Ariz., and (3) to suggest an explanation for the origin of these cracks by comparison to cracks formed under similar conditions in California (Inter-Agency Committee on Land Subsidence in the San Joaquin Valley, 1958).

REVIEW OF LITERATURE ON ARIZONA EARTH CRACKS

The first earth crack recorded in southern Arizona occurred at a point about 3 miles southeast of the town of Picacho. According to Leonard (1929, p. 765), the crack was discovered on the morning of September 12, 1927 after a severe rain and windstorm. In his discussion of the possible origin of the crack Leonard does not dismiss completely the possibility that the torrential rainstorm may have been a contributing factor; however, he prefers to attribute the cause of the crack to seismic vibrations presumably originating about 200 miles to the south at the same time as the crack appeared.

Fletcher and others (1954, p. 259-260), in a discussion of a tunnel-forming type of erosion known as piping, mention earth cracks at Picacho which appeared in 1949, 1951, and 1952. The appearance of all the cracks was preceded immediately by violent rain and windstorms, but seismic shocks were absent. They concluded that the cracks were erosional features called piping.

The Picacho earth cracks were examined independently by Heindl and Feth (1955, p. 343-345) who stated that the clean walls and sharp edges suggest tensional breaks. These may have been the result of differential settling along the edge of a concealed pediment marking a fault line or a buried fault-line scarp. They suggest that the heavy summer storms may have resulted in differential loading of sediments on either side of the possibly concealed pediment edge, or in the reduction of bearing strength of the surficial materials, or both.

The Casa Grande Dispatch (August 15, 1957) described a big crack that opened in the alluvium 3 miles north of Bon Station between Maricopa and Casa Grande. The break was reported to have occurred during a violent electrical storm on the morning of July 19, 1957.

DESCRIPTION OF SOME CASA GRANDE EARTH CRACKS

During 1958-60 the writer had the opportunity to observe the development of several earth cracks along the southeast edge of the Casa Grande Mountains about 3 miles southeast of the town of Casa Grande. The earth cracks were partly or completely filled by sediments when first observed in December 1958. Frequent visits to the area revealed no change until February 1960. In early February, heavy rains in the area had collected in two natural shallow basins, about 40 and 10 acres in extent. At this time, 5 or 6 new earth cracks had formed and some of the old, filled earth cracks had reopened. Some of the old cracks had been extended to several hundred feet in length. Many of the cracks paralleled the edge of one of the ponds near the foot of the mountains, much like a contour line on a topographic map (Fig. 1). The general trends of the pattern formed by the cracks and their apparent relationships to the edge of the bedrock are shown in Figure 2. Other cracks seemed to show no obvious relationship to the ponds or the bedrock outcrops. In all instances the cracks were confined to the alluvium and did not continue into the metamorphic and igneous bedrock complex of the Casa Grande Mountains.

The longest zone of cracks, consisting of several long cracks and a number of parallel short cracks, is continuous for slightly more than half a mile. The cracks range in depth from a few inches to as much as 8 feet, and in width from several inches to about 3 feet (Figs. 3 and 4). The depth seems to vary inversely with the width; the deepest cracks were usually the narrowest. Also, the depth of individual cracks varies greatly along their courses, and is roughly proportional to the amount of slumping. Widening of the cracks seems to have resulted from the slumping from the sides and the slumped material partly fills or bridges the deep parts of the cracks. No cracks showed evidence of horizontal movement.

[45]

Although the cracks appear to have received and acted as drains for large amounts of water, in most places the water did not flow laterally in the crack as it would in a graded arroyo; instead it either moved downward through outlets in the bottom of the cracks, possibly recharging the ground-water reservoir, or was absorbed by the dry permeable alluvium. None of the cracks is associated or connected with arroyos, as in piping, and in general the cracks show no relationship to the surface drainage of the area (Fig. 1). The outlets at the bottoms of some cracks apparently had become plugged and water was standing in them; other adjacent cracks were dry, indicating that the water in the cracks did not represent the level to which the underlying alluvium was saturated. In several places the cracks opened up into circular sinklike depressions as much as 4 feet in diameter (Figs. 5 and 6). These "sinkholes" occurred where lesser cracks joined a main crack and the lesser cracks may have been a contributing factor in the formation of the sinkholes.

At one place, a line of small depressions as much as a foot in diameter continued the trace of a crack after the crack itself had died out. The alined depressions suggest that the crack is present in the subsurface (Fig. 7).

A firsthand account of the formation of an earth crack was related to the writer by Mr. Ted Brown, an employee of Eloy Farms which controls the land immediately adjacent to, and partly including the area of this report. Brown had recently finished the construction of a new irrigation ditch across land which had never been farmed or irrigated. The new ditch crossed the faint trace of an old earth crack. On March 15, 1960, water was released into

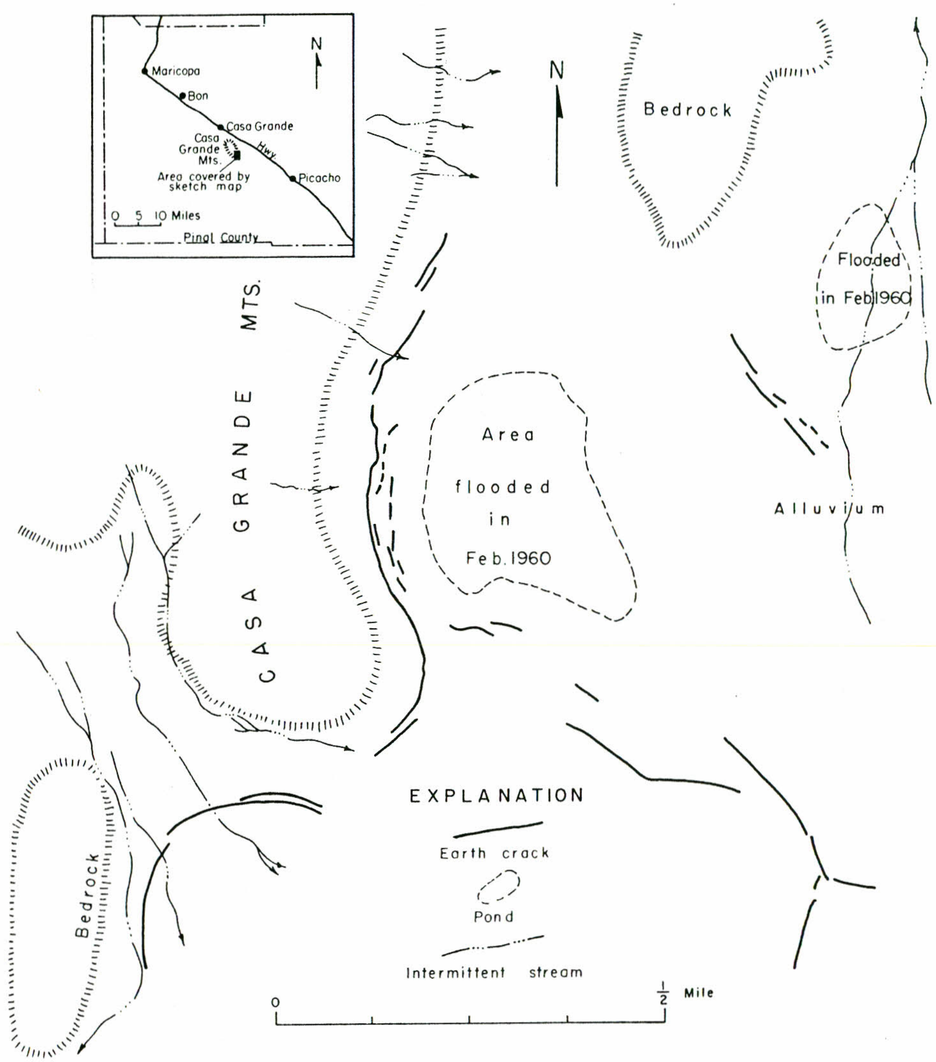


Figure 1. —Sketch map showing pattern of earth cracks at the southeast corner of the Casa Grande Mountains, February 1960.

the ditch for the first time to irrigate the new farmland. An estimated 300 gpm (gallons per minute) had been running through the ditch for about 3 hours, when suddenly the old crack opened up and diverted the entire flow of the ditch. This diversion continued for about 18 hours before the crack filled and began to overflow. In the meantime, several yards of dirt was pushed into the crack by a bulldozer without noticeably filling it. The crack was 6 inches wide when it first opened, but eventually widened to 14 inches by a process of spreading apart rather than by caving in of the walls. Brown stated that he was "unable to touch bottom of the crack with a 14-foot pole." Brown also described how subsidence in one of the adjacent fields had destroyed the grade of an irrigation ditch so that it had to be built up in order to get water through the sinking area.

SUBSIDENCE STUDIES IN CALIFORNIA

Some of the results of subsidence studies in California (Inter-Agency Committee on Land Subsidence in the San Joaquin Valley, 1958) will be reviewed here, because the work was done in an area geologically and geographically similar to southern Arizona. The investigation in California has led to recognition of two types of subsidence: (1) shallow subsidence of soil and near-surface deposits above the water table that occurs after initial application of irrigation water; and (2) deep subsidence that results from compaction of deposits below the water table, chiefly due to the withdrawal of ground water from confined deposits and the resulting decline in head. Earth cracks seem to be associated only with shallow subsidence and occur in deposits that compact appreciably on wetting. These deposits are restricted generally to the alluvial fans formed at the toe of small drainage areas with steep gradients. The deposits are composed of loose, loamy soils and sediments which have a large percentage of air-filled voids. Poor sorting and other features suggestive of mudflows also are characteristic of these deposits. Invariably the shallow subsidence occurs in the unsaturated deposits above the water table and is related closely to changes that take place in the deposits when wetting occurs. The rate and, undoubtedly the amount, of subsidence seem to be dependent on the quantity of water applied.

In California, compaction of the deposits above the water table occurred after the first application of irrigation water to the land surface, and, locally, has caused shallow subsidence of more than 10 feet. Extensive shrinkage and soil cracking commonly occurred along ditches or where water accumulated in ponds. Irregular, undulating surfaces developed in fields when irrigation was attempted. At one test plot, which was flooded in order to measure the rate of subsidence, the surface of the land settled more than 9 feet within about a year and concentric cracks encircled the plot to a radial distance of more than 150 feet. In one place a crack was reported to be 20 feet deep.

CONCLUSIONS

Wherever earth cracks have been described in southern Arizona, their sudden appearance has been associated closely with a heavy rainstorm or the sudden application of water to deposits that are normally dry. In California the earth cracks and shallow subsidence have occurred under similar conditions involving low-density, dry deposits soon after the initial application of irrigation water or ponding of rainwater.

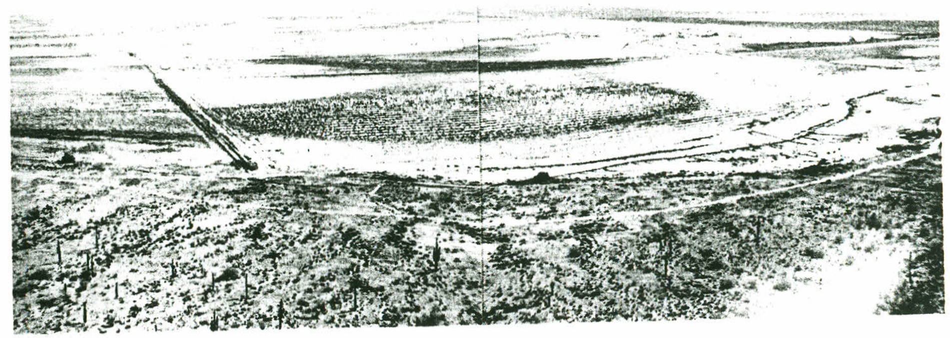


Figure 2.--View looking southeast from the Casa Grande Mountains across large pond in center of Figure 1, showing ponded rainwater in center of furrowed field and earth cracks bordering the pond.

Figure 3.--Typical earth crack, showing some modification by erosion but little slumping of sides.

Figure 4.--Earth crack which has become wider and shallower by slumping of the sides.

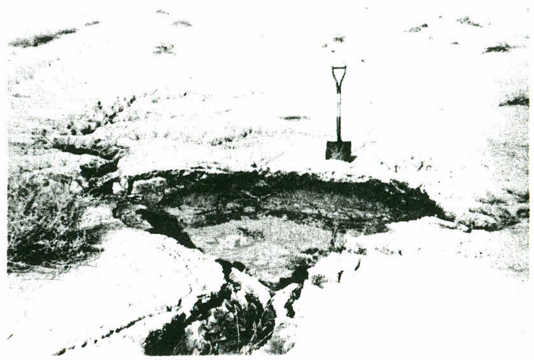


Figure 5. --Sinklike depression along an earth crack.

Figure 6. --Sinklike depression where three earth cracks meet.

In the area adjacent to the Casa Grande Mountains the trend of the cracks parallel to the edges of the ponds and the edge of the mountains supports the idea that the earth cracks are the result of shallow subsidence caused by the ponding of rainwater. Also, the ponds themselves probably occupy subsidence depressions.

No information is available regarding possible ponding of water in the Picacho and Bon areas, but the cracks formed during or following heavy rainstorms during which ponding may have occurred. Although the sudden application of water may not be the sole cause of the cracks at Picacho and Bon, the evidence suggests that it at least played a part in triggering their formation.

REFERENCES

Fletcher, J. E., Harris, Karl, Peterson, H. B., and Chandler, V. N., 1954, Symposium of land erosion "piping": Am. Geophys. Union Trans., v. 35, p. 258-262.

Heindl, L. A., and Feth, J. H., 1955, Piping and earthcracks—a discussion: Am. Geophys. Union Trans., v. 36, no. 2, p. 342-345.

Inter-Agency Committee on Land Subsidence in the San Joaquin Valley, 1958, Progress report on land-subsidence investigations in the San Joaquin Valley, California, through 1957: multilithed report, 160 p.

Leonard, R. J., 1929, An earth fissure in southern Arizona: Jour. Geology, v. 37, no. 8, p. 765-774.

Notes on Earth Fissures in Southern Arizona

By G. M. Robinson and D. E. Peterson

Geological Survey Circular 466

Washington 1962

Notes on Earth Fissures in Southern Arizona

By G. M. Robinson and D. E. Peterson

ABSTRACT

This report describes earth fissures at six sites in southern Arizona. These notes are preliminary to a more extensive study and detailed analysis being prepared by hydrologists in the Water Resources Division. Earth fissures were first recorded in Arizona in 1927, and have been noticed with increasing frequency since 1949. Fissures at Black Canyon, Bowie, Chandler Heights, Luke Air Force Base, Picacho, and Sells are discussed and illustrated with photographs.

INTRODUCTION

A recent short paper by Pashley (1961) called attention to large cracks or fissures that have appeared from time to time in valley alluvium in southern Arizona. Pashley's discussion was confined, however, to a brief review of several earlier accounts of earth fissures in the Picacho area, to his own observations during 1958-60 on fissures near Casa Grande, and to his hypothesis for their origin. No comprehensive paper has yet appeared that discusses the occurrence and formation of fissures throughout the State.

Although certain local residents are well aware that earth fissures have been developing for many years in several areas in the southern part of the State, earth scientists may not have been generally aware of the specific areas in which these phenomena have been, and still are, forming. Data are being collected by hydrologists in the Water Resources Division but the collection, interpretation, and analysis are not yet complete. Nevertheless it seems timely to present these notes on earth-fissuring activity in six distinct local areas, so that patterns and orientation may be viewed regionally as well as in local reference to the exposed rock masses and the general geologic environment. Subsequent reports will present more data and the conclusions that may be drawn therefrom.

The first earth fissure recorded in Arizona was discovered in September 1927, about 3 miles southeast of Picacho (pl. 1), and was described in some detail by Leonard (1929). Similar cracks recurred in that area in 1935 and 1949. Since 1949 reports of earth fissuring have been made with increasing frequency from widely separated areas throughout the southern part of the State.

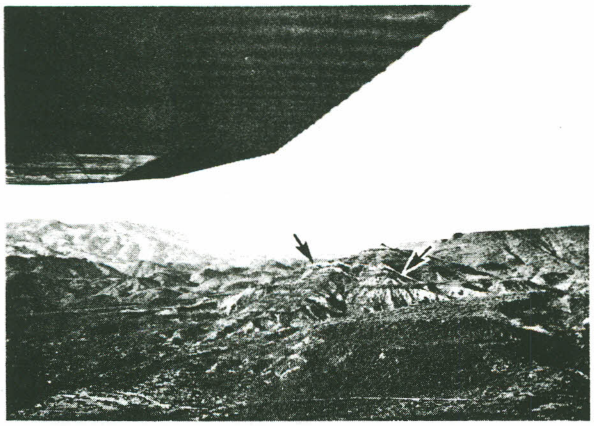
Of special interest is the fact that until February 1962 all reports concerned fissuring in valley alluvium. On February 1, 1962, however, local residents in the Black Canyon area north of Phoenix (pl. 1) reported new earth cracks or fissures; these occurred in a basalt and semiconsolidated sedimentary rock section exposed on a relatively steep dissected slope. Local investigation revealed that similar fissuring and slumping of the earth materials in this area had obviously taken place on previously unrecorded occasions.

Presented in the following paragraphs are a few details on earth fissuring in the selected areas, arranged in alphabetical order. Fissure locations, patterns, and orientation may be observed on plate 1 and in the photographs and subsidence profile included in figures 1 through 8.

BLACK CANYON

Earth fissures have formed in a volcanic rock area about 45 miles north of Phoenix on the east side of Arizona Highway 69, approximately 2 miles northeast of the junction of Squaw Creek with the Aqua Fria River. The fissures traverse a section of volcanic and semiconsolidated sedimentary rocks near the north edge of a small valley. Virtually no ground water is developed in the valley.

The sequence, in time, of the fissure development is not known. Aerial photographs of the general area, taken from an altitude of about 11,000 feet in 1936, clearly show the east-west traces of earlier fissures developed in conjunctión with faulting. On February 1, 1962, however, Phoenix newspapers reported the discovery by local residents of new earth movement in the fissure area. The exact time of occurrence seems to have gone unnoticed but air and ground inspection confirmed that the movement was indeed new and that it had been substantial. A photograph (fig. 1A) taken on February 1, 1962, from a



A

B

Figure 1. —Aerial views looking north at fissures near Black Canyon; A, distant view; B, closer view. Light-colored areas indicate the recent exposures. Photographed on February 1, 1962, by H. T. Chapman and A. E. Robinson.

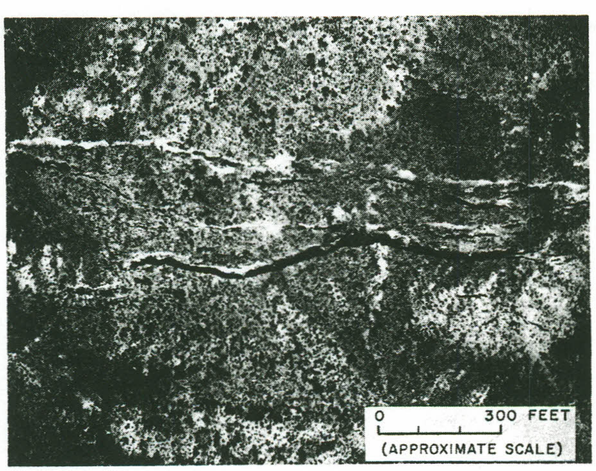
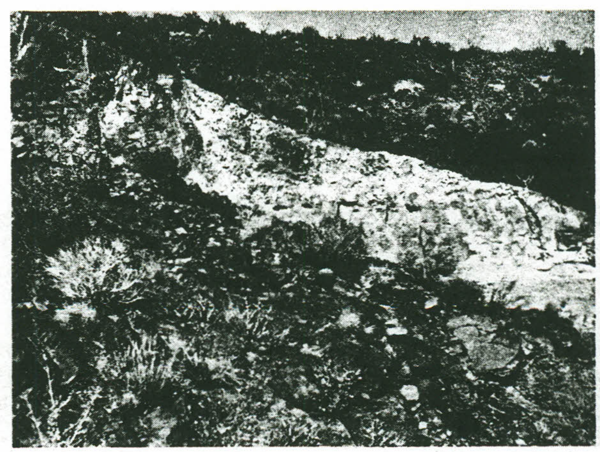
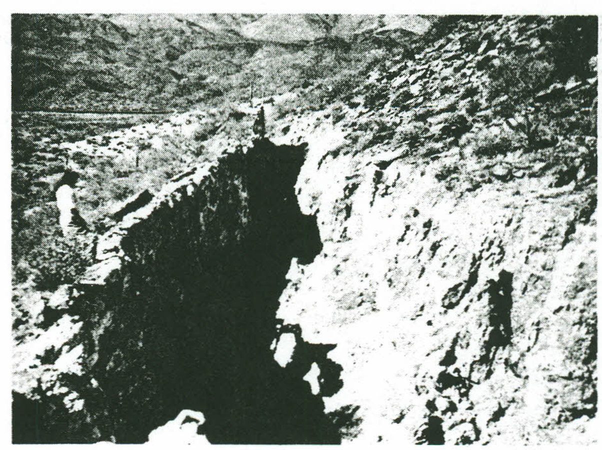


Figure 2. —Aerial photograph from altitude of 4, 000 feet showing principal fissures near Black Canyon. Photographed on March 26, 1962, by H. T. Chapman.



A



B

Figure 3. —Ground views of uppermost and lowermost principal fissures near Black Canyon. A, View looking north at vertical displacement near east end of slippage fault produced by upper fissure. B, View looking west at size of opening near western end of lower fissure. Photographs taken on February 3, 1962, by H. T. Chapman.

low-flying light plane, shows (white trace between arrows) freshly exposed areas on the face of the uppermost fissure or fault in relation to the local relief. The vertical interval from the valley floor (approximate elevation 2,100 feet, mean sea level) to the small cone-shaped hill that rises to the distant skyline (right of center) is between 600 and 700 feet. A similar photograph (fig. 1B) on the same date gives a closer aerial view of this and adjoining major fissures. The cone-shaped hill is again a convenient reference marker. A vertical aerial photograph (fig. 2) taken from an altitude of about 4,000 feet (mean sea level) identifies the major fissure pattern. The fresher and lighter appearing areas, along the northernmost fissure in the photograph, identify the new exposures associated with the most recent earth movement. The duller and darker areas denote exposures dating back to earlier movements. These details, as well as the vertical movement (about 10 to 15 feet) at this particular fissure, show to advantage in figure 3A, as photographed on February 3, 1962. The black band (fig. 2) along the lower or southernmost principal fissure is the shadow that the sharply defined southern rim casts into the opening. The opening size can be judged from figure 3B, photographed on February 3, 1962, from a ground vantage point on the fissure rim at about the western quarter point with respect to its length as indicated in figure 2.

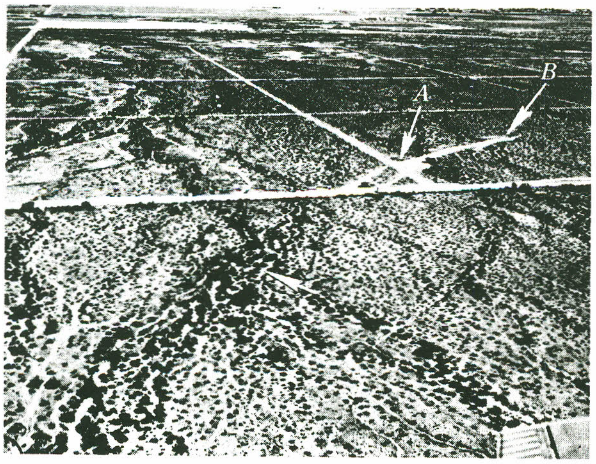
Figure 2 is one of a series of six overlapping aerial photographs which when viewed stereoscopically give dramatic evidence of the substantial earth movement. At each opening the earth or rock material appears to have failed in tension or to have been literally pulled apart. The photographs show no significant differential horizontal movement along the fissures. Elongate islands or blocks of material, created when fissures intersected one another, in some instances settled or slumped as grabens. Examples are found by carefully studying stereoscopically various pairs of fissures.

BOWIE

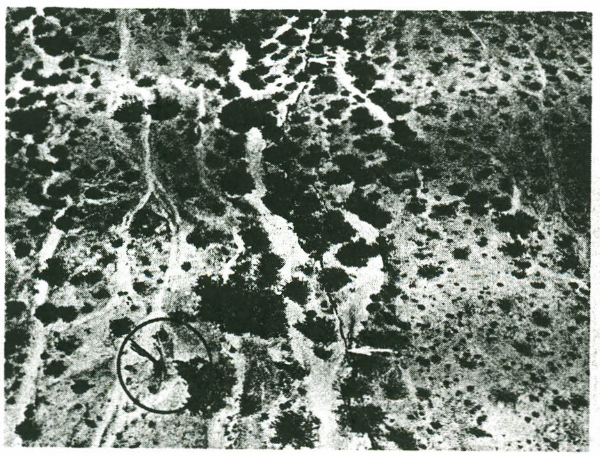
Approximately 6 miles east of Bowie on State Highway 86 an earth fissure crosses both the highway and the Southern Pacific Railroad. The fissure is in the center of a broad alluvial valley, north of the Dos Cabezas Mountains, and extends about 1 mile northward and about 1 mile south-southeastward from the highway (pl. 1). The use of ground water for irrigation has lowered water levels in the Bowie area more than 100 feet since 1950 (U.S. Geological Survey, 1940-61). The fissure site is near the common perimeter between two centers of heavy pumping, namely, the Bowie and San Simon areas. Compaction of the sediments in these two areas, accompanying the water-table decline, could gradually have built up tensile stresses in the peripheral area common to the two centers of pumping, leading to ultimate rupture of the earth material in the form of the observed fissure.

CHANDLER HEIGHTS

Close to the northernmost flank of Santan Mountain, approximately 30 miles southeast of Phoenix and 12 miles southeast of Chandler, local residents report that earth fissures have occurred on several occasions. The fissures are oriented roughly parallel to the nearest exposed segment of the mountain mass (pl. 1). The trace of a spectacular opening that formed in 1961 is marked on photographs (figs. 4A and B), which were taken from the air on February 10, 1962, to show the fissure site and part of the surrounding area. The lower left part of figure 4A is viewed closer up in figure 4B to show more clearly some details of the fissure trace. The circled saguaro cactus, about 30 feet tall, is also partly circled in the lower left corner of figure 4A. Irrigated land is visible to the north (fig. 4A) of the fissure site but the principal irrigated acreage and area of ground-water withdrawal lies to the northwest. The white scar bracketed by arrows A and B marks the interval in which the fissure terminated. The area was reworked by earth-moving equipment to fill the fissure. The magnitude of the fissure opening is graphically revealed in figure 5, as photographed on September 16, 1961, from a ground site near arrow A (fig. 4A). These photographs suggest that again the earth material has simply pulled apart. No differential horizontal movement can be seen along the fissure and no differential vertical movement is apparent. Where islands or blocks of material have been left standing in the larger openings some crumbling and slumping have occurred.



A



B

Figure 4.—Aerial views looking north at fissure near Chandler Heights. A, General view of the area with arrows denoting fissure trace. B, Closer view of fissure trace with same saguaro cactus circled. Photographs taken on February 10, 1962, by H. T. Chapman and A. E. Robinson.

LUKE AIR FORCE BASE

Earth fissures were first observed in the fall of 1959 in a 300-acre well-field area 1¼ miles east of Luke Air Force Base which is about 15 miles northwest of Phoenix (pl. 1). The well field has yielded substantial quantities of water for irrigation since 1936, with annual pumpage ranging between 4,000 and 8,000 acre-feet. The well-field area itself, in which the fissures occur, has never been in cultivation. To shallow depths, at least, the soil consists of caliche. Surrounding the well field are cultivated fields and additional wells for irrigation. The longest fissure extends for a distance of about 1 mile in a northwest-southeast direction.

Figure 5.—Magnitude of fissure opening near Chandler Heights, viewed from site marked by arrow A in figure 4A. Photographed on September 16, 1961, by D. E. Peterson.

PICACHO

Heretofore the limited notes and observations on earth fissures in Arizona, published in technical journals, have focused attention principally on the Picacho portion of the general Picacho-Eloy-Casa Grande area (pl. 1). The valley or basin floor is characterized by a northwesterly sloping plane that ranges in elevation from 1,750 feet (mean sea-level datum) near Picacho Peak and the Picacho Mountains to 1,400 feet near the Casa Grande Mountains. These mountains rise abruptly from the basin floor, effectively bounding it on the east and west. Agricultural development in the basin has been extensive.

Ground-water production for irrigation began near Eloy in 1936 because of the favorable market for cotton. A steady increase in irrigated acreage continued until after the war, at which time a sharp rise was noted. The following data on ground-water pumpage furnish a partial index to the agricultural development:

Year	Pumpage (acre-feet)	Data source
1937---	64,000	Smith, 1940, p. 26.
1940---	172,000	U.S. Geol. Survey, 1940-61.
1948---	360,000	Do.
1952---	300,000	Do.
1960---	330,000	Do.

The ground-water production has been accompanied by a steady water-table decline throughout the area. Present water levels range from 100 to nearly 200 feet below an assumed static level for 1930. Until the late 1940's the center of the cone of depression in the water table remained slightly west of Eloy. Subsequently the cone center has migrated steadily eastward in consort with the development of new irrigated acreage and the consequent production from new irrigation wells.

First-order leveling and subsequent checks, by the U.S. Coast and Geodetic Survey, of bench marks along Arizona Highway 84 yield extremely valuable subsidence data. The surveys span the 55-year period from 1905 to 1960 and show (fig. 6) how markedly subsidence rates have increased in the valley alluvium, especially in the Eloy-Picacho region. Of particular interest is the fact that the data show some land-surface subsidence centered around Eloy over the period from 1905 to 1934, before extensive ground-water development. However, the process seems to have been greatly accelerated, probably beginning in 1936, by the effects of persistently increasing ground-water pumpage and application of the water to the steadily increased acreage placed under cultivation. The correlation between subsidence rate and ground-water development is strengthened by noting (fig. 6) how the point of maximum subsidence migrated southeastward with time. This roughly correlates with the similar shift in the deepest part of the cone of depression in the water table. Maximum subsidence along the profile is now approaching 4 feet.

Also shown in figure 6 are the points at which several observed earth fissures intersect the profile along Arizona Highway 84. As might be expected, the fissures are near the outer limits of the subsidence profiles where the earth material could have been subjected to tensile stresses.

The fissure shown at the extreme right in figure 6, at a point on Highway 84 about 3 miles southeast of Picacho, is the one described by Leonard (1929) as having first opened in September 1927. Subsequent filling and reopening of this and other fissures in the general area are described by Heindl and Feth (1955). Leonard's description mentions the fissure length as one-fourth mile; it is now at least 8 miles long. Part of the fissure appears in a photograph (fig. 7A) taken on August 6, 1961, looking northeast across

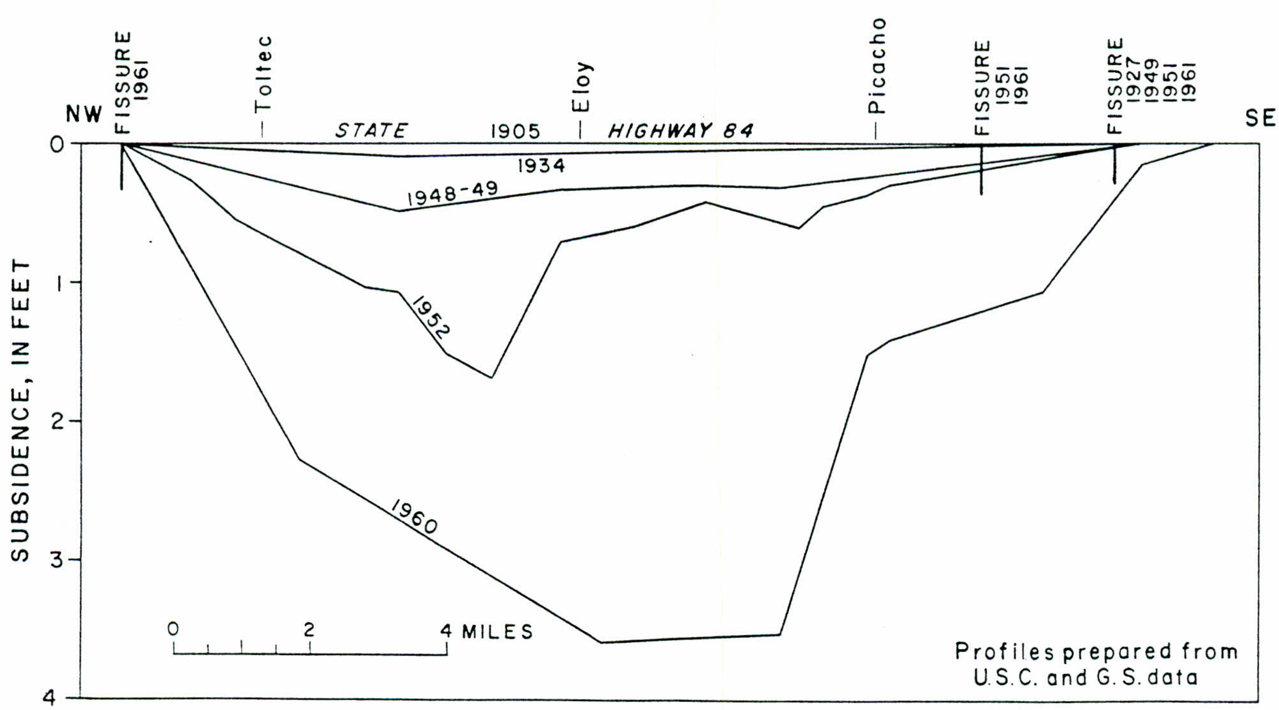


Figure 6.—Changes in land-surface elevation in the Eloy-Picacho area, Pinal County, Arizona.

A

B

Figure 7.—Views looking northeast at fissures crossing Arizona Highway 84 near Picacho Mountains. A, Fissure 3 miles southeast of town of Picacho; 2 days previous width appeared less than half an inch; torrential rain on previous day revealed this opening; note vegetal growth along fissure. B, Fissure 1 mile southeast of Picacho. Photographs taken on August 6, 1961, by D.E. Peterson.

Arizona Highway 84 at the distant Picacho Mountains. A second photograph (fig. 7B) shows a similar fissure about 1 mile southeast of Picacho. Again the view is northeastward across Highway 84 with the Picacho Mountains in the distance. Note the absence (figs. 7A and B) of differential vertical or horizontal movement along the two fissures. The openings are characterized by clean breaks and near-vertical walls.

Numerous other earth fissures have been observed from time to time in the general area of Picacho. Those examined as recently as 1961 are shown in the large circled area on plate 1. Some fissures intersect Picacho Reservoir (pl. 1) and in 1961 a retaining embankment overlying a fissure failed. Although the reservoir is only occasionally used to collect surplus water, the Bureau of Indian Affairs, responsible for its operation, is debating whether or not to discontinue its maintenance.

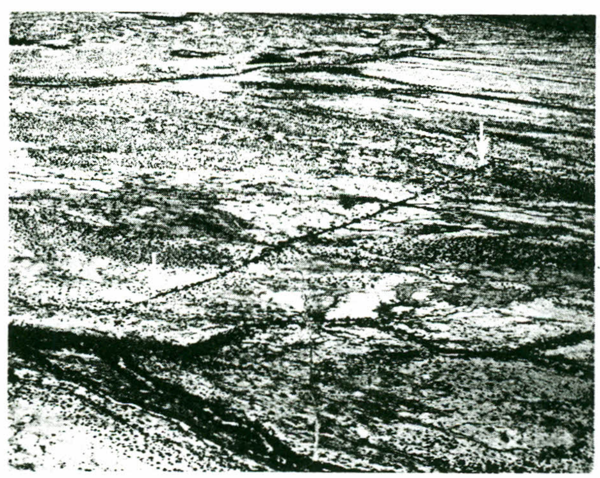


Figure 8.—Aerial view looking northeast at east-west trending fissure near Sells. Fissure intersects, nearly at right angles, a wash that is tributary to Chukut'Kuk Wash. Photographed on February 8, 1962, by H.T. Chapman and A.E. Robinson.

During the summer of 1961 the junior author surveyed the general area of Picacho by gravity meter and certain Bouguer gravity anomaly highs were observed. These are apparent highs but they can be related to the amount of rock mass present between the meter station and the mean sea level datum. Significantly, the location and trends of the earth fissures in the Picacho-Eloy basin are in general linear conformity with the gravity anomaly highs. This would appear to support the hypothesis advanced by Heindl and Feth (1955) that some fissures are tensional breaks that may result from differential settlement along the edge of a concealed (buried) pediment.

SELLS

An earth fissure 1/2 to 3/4 mile long was first observed in the early 1950's by personnel of the Bureau of Indian Affairs. The fissure is about 12 miles southwest of Sells near (east of) the Indian settlement of Chukut Kuk (pl. 1), in an area where irrigation farming, using ground water, has not been extensively practiced. A photograph (fig. 8) taken on February 8, 1962, from a low-flying light plane shows the straight east-west fissure trace intersecting at right angles with a wash tributary to Chukut Kuk Wash.

CONCLUSION

Observing the development, with respect to time, of earth fissures like those described in these brief notes affords an excellent opportunity to document the rates of certain geomorphic processes. In the Black Canyon area, for example, periodic detailed mapping of the local fissure area, using photogrammetric techniques, will reveal the rates and manner in which the landform changes and talus or debris accumulates. In valley-floor areas the occurrence of fissures in alluvial materials may present another useful key in the continuing search for improved understanding of the natural and man-induced mechanisms of sediment compaction and earth subsidence. Corollary thereto are changes in the landform, the surface drainage pattern, and the movement of sediment to streams.

REFERENCES CITED

Heindl, L. A., and Feth, J. H., 1955, Symposium on land erosion--"Piping"--a discussion: Am Geophys. Union Trans., v. 36, no. 2, p. 342-345.

Leonard, R. J., 1929, An earth fissure in southern Arizona: Jour. Geology, v. 37, no. 8, p. 765-774.

Pashley, E. F., Jr., 1961, Subsidence cracks in alluvium near Casa Grande, Arizona: Arizona Geol. Soc. Digest, v. 4, p. 95-101.

Smith, G. E. P., 1940, The ground-water supply of the Eloy District in Pinal County, Arizona: Arizona Univ. Agr. Expt. Sta. Tech. Bull. 87.

U.S. Geological Survey, 1940-61, Annual report on ground water in Arizona: U.S. Geol. Survey open-file reports, issued annually.

INT.DUP.,D.C.62-15268