EARTH -FISSURE ACTIVITY NEAR BRADY AND PICACHO PUMPING PLANTS., TUCSON AQUEDUCT., CENTRAL ARIZONA PROJECT, PINAL COUNTY, ARIZONA

A Report to the U.S. Bureau of Reclamation

by
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INTRODUCTION

Earth fissures are one of the geologic hazards that have damaged the facilities of the Central Arizona Project (CAP). Earth fissures exist along at least two reaches of the Tucson aqueduct, and more are likely to develop in the future. Within the region investigated for this project, potential hazards resulting from earth-fissure development were recognized during the CAP-planning phase and the proposed route of the aqueduct was changed accordingly (Schumann and others, 1984). Where the aqueduct had to pass through a zone of existing or potential fissures, its lining was strengthened with reinforcing steel mats (Sandoval and Bartlett, 1991). The lining was tested when an earth fissure developed beneath the aqueduct in Avra Valley during 1988, in a previously identified hazard zone (Anderson, 1988). The steel mats successfully supported the aqueduct (while it was full of water) until repairs were completed. Through careful planning, construction, monitoring, maintenance, and repair, the U.S. Bureau of Reclamation (USBR) has been able to minimize the impact of fissures on the CAP.

Earth fissures are open surface and subsurface tension cracks that occur in unconsolidated and semi-consolidated sediments and that may display vertical displacement. Most earth fissures are a result of the following: 1) the quantity of ground water withdrawn from an unconsolidated-sediment aquifer grossly exceeds the quantity of recharge; 2) the resulting water-table- altitude decline causes compaction of aquifer sediments; 3) sediment compaction leads to land-surface subsidence; and, 4) stress results from differential subsidence, and fissures form where horizontal stress is great (Strange, 1983).

Most earth fissures result from human activities, but some probably are caused by natural processes that lead to sediment compaction, including long-term climatic change. Fissures also may result from other processes, including hydrocompaction, horizontal contraction, earthquake shaking, natural compaction of sediments, desiccation, and horizontal seepage forces. The features formed are not commonly called earth fissures, and they are not discussed in this report.

Hundreds of fissures exist west of the Picacho Mountains in Picacho basin (also known as Eloy basin or the lower Santa Cruz River basin, see Figure 1), and their spatial and temporal development patterns were described in Arizona Geological Survey (AZGS) Open-File Report 89-10 (Slaff and

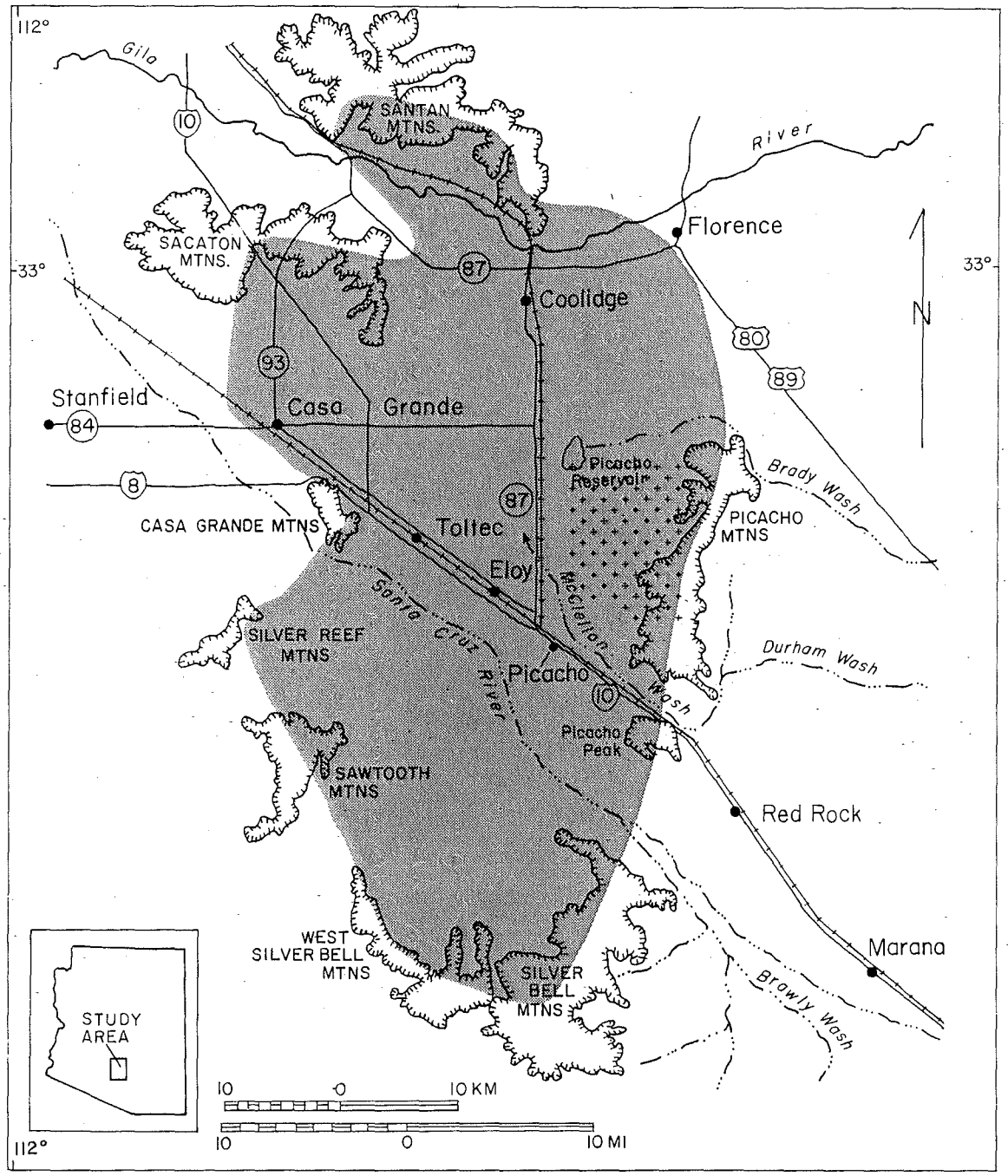


Figure 1. Location map showing approximate extent (shaded) of Picacho basin, south-central Arizona. The area included in the study is shown with the cross pattern.

others, 1989). This investigation focuses on a smaller portion of Picacho basin, which includes Brady and Picacho pumping plants and the adjacent portions of the Tucson aqueduct, Santa Rosa canal, and Central Arizona Irrigation and Drainage District (CAIDD) canal (Figure 1).

The objective of this project was to identify and map earth fissures in the study area, and to evaluate the potential for future fissure development to damage the CAP. Changes in the local water-table altitude were examined to see whether they provide a qualitative indication of present and future fissure-activity rates. Very large format aerial photographs were tested as a fissure-identification tool.

The results of the investigation, which are reported in detail in the Findings section, are summarized here. Approximately 50 fissures are located within 3.7 km (2.3 mi) of the CAP in the study area. Two of the fissures, and portions of eight others, are currently active. Five are expected to lengthen in known directions. The average length of an active fissure segment (381 m [1,250 ft]) is less than those of potentially active and inactive segments. At least one fissure may cross the Tucson aqueduct in the future. A fissure currently crosses the Santa Rosa canal, and has an active segment that is located 150 m (492 ft) from the canal. Another is located close to the canal, but appears to be lengthening in the opposite direction. A fissure that passes beneath the CAIDD canal may experience continuing activity, including gradual vertical displacement.

Localized collapse pits and piping were mapped in five areas. Four of the zones are near existing fissures. The fifth zone is not, but may be a precursor of fissure formation. It is located close to Santa Rosa canal. Water-table altitude data for 25 wells located in and near the western portion of the study area show long term water-level declines, with small rises in some wells during the past several years. The water-level records are not consistent with each other in terms of the periods that they span or the frequency of measurements. Without additional earth fissure activity data and water table altitude data, no correlation can be made between water-level decline and fissure-activity rates.

The physiography and surface-water hydrology of the Brady/Picacho area are changing in response to regional land subsidence, the presence of the CAP, and the development of piping, collapse pits, and earth fissures. The changes mostly affect drainage patterns, as old stream channels are abandoned and new ones are established. Rates and loci of erosion and deposition are being altered, and the distribution of plants and animals is changing. The central portion of Picacho basin now experiences

greater depth of inundation during flooding than it used to.

The usefulness of very large format aerial photographs for fissure mapping was evaluated. The photos show a lot of detail and allow fissure endpoints and short fissures to be identified accurately. The disadvantages are that they cannot be viewed stereoscopically, they are unwieldy, and other lineaments are easy to mistake as fissures. Each of these topics is discussed more thoroughly in the Findings section below.

PURPOSE

The major goal of the project is to gain a better understanding of earth fissures and the factors that control them so that the amount of damage and loss that they cause can be reduced. To date, most fissures have formed in rural portions of the state, where population and engineering structures are not concentrated. Even so, many types of structures have been damaged. The likelihood that more extensive damage will occur is increasing now that the CAP crosses zones of existing and potential hazard, and urban areas are encroaching onto subsiding agricultural land. Earth fissures have caused millions of dollars worth of damage in southern California; allegedly more than $50 million of damage occurred in one portion of southwestern Riverside County alone (Corwin and others, 1991). Perhaps by recognizing and responding to the hazard in Arizona prior to development, costly litigation can be avoided.

Other goals of the project include the following: 1) determine the current status of fissures near the reach of the Tucson aqueduct between Brady and Picacho pumping plants; 2) evaluate the changing water-table altitude and its possible effect on fissure-development patterns and rates in the Brady/Picacho pumping plant region; and, 3) determine the utility of using very large format aerial photographs to identify fissures, especially incipient fissures and those with weak ground-surface expression.

The portions of Picacho basin described above were chosen for the study because they have experienced considerable subsidence and fissure development, the CAP occupies part of the eastern portion, and previous work done there (Slaff and others, 1989) provides a data base on which to build. This is the second project that AZGS has completed in the area, and investigations are

expected to continue.

PHYSICAL SETTING

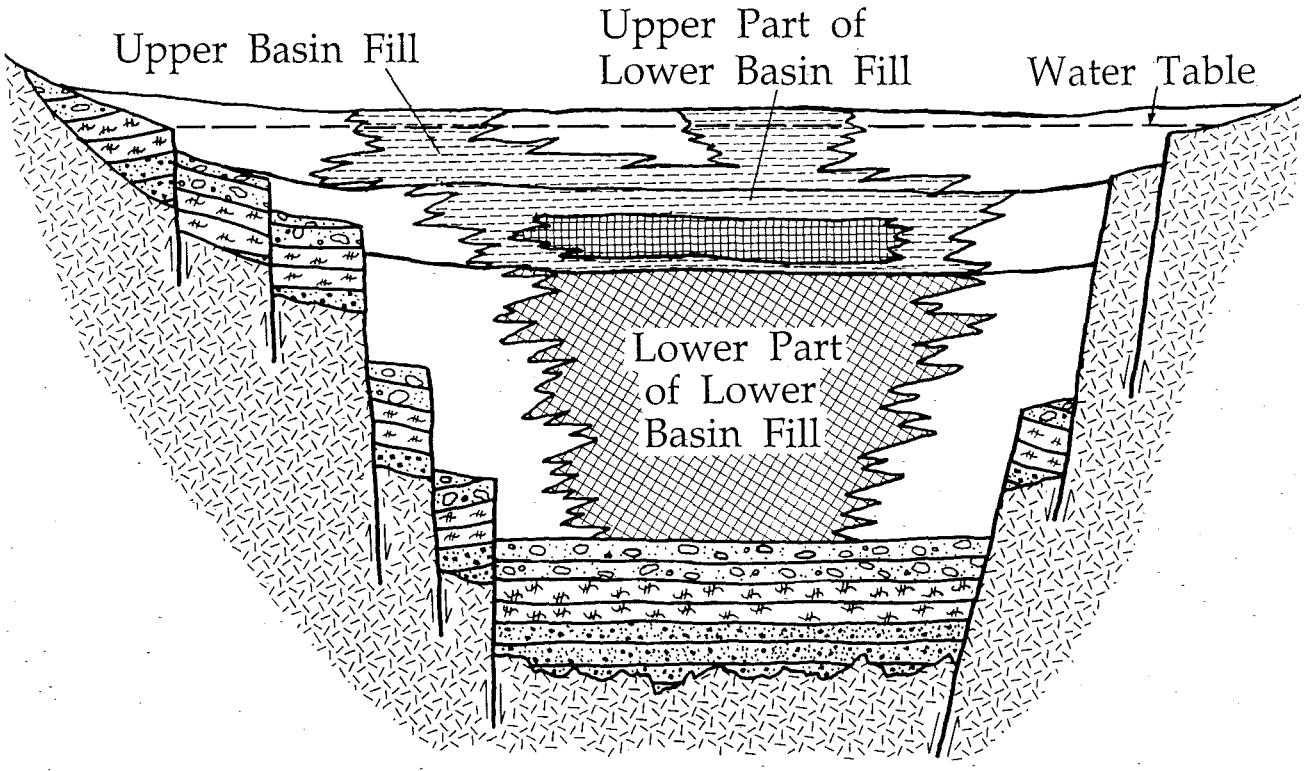
Geographic

Picacho basin is an alluviated expanse of relatively low relief located between approximately 32° 25' and 33° 7' north latitude and 111° 49' and 111° 24' west longitude in Pinal County, south-central Arizona. It comprises an area of approximately 1,165 km^2 (450 mi^2) bounded by eight short mountain ranges (Figure 1). The basin slopes gradually down to the northwest, and its altitude ranges from 665 m (2,180 ft) along the upper reaches of streams in the Picacho Mountains to 427 m (1,400 ft) at Casa Grande. It is drained by the Santa Cruz and Gila Rivers, and a number of smaller ephemeral streams. The area receives an average of 208 mm (8.2 in.) of precipitation per year (Sellers and Hill, 1984). Land use is predominantly agricultural. The principal towns are Casa Grande, Eloy, Picacho, and Toltec.

The portion of Picacho basin that was mapped in detail for this investigation is a 133 km^2 (52 mi^2) low-lying area on the east side of the basin just west of the Picacho Mountains. Altitudes range from 665 m (2,180 ft) in the highest alluviated drainage basins of the Picacho Mountains to 457 m (1,500 ft) at Picacho Reservoir. The ground surface slopes gradually down to the west-northwest. The region is drained by many small ephemeral streams, some with headwaters in the Picacho Mountains and others that begin on the alluvial fans. Most of the land is used for livestock grazing, some for irrigated agriculture.

Geologic

Picacho basin is in the Basin and Range physiographic province. The physiography of the region is principally a result of extensional tectonism that occurred primarily from 13 Ma (million years ago) to 5 Ma (Scarborough and Peirce, 1978; Eberly and Stanley, 1978; Shafiqullah and others, 1980). The tectonism involved block faulting, which down-dropped the basin (Figure 2) and left the surrounding mountains as high-standing horsts. Prior to 3 Ma to 5 Ma, the Picacho basin region was a closed basin (with internal drainage) where sediments accumulated. After that time, through-flowing streams



Sand and gravel (alluvium). Middle Miocene to Holocene age.

Claystone, minor gypsum and anhydrite. Late Miocene to Pleistocene age in Upper Basin Fill, middle Miocene to late Pliocene age in Lower Basin Fill.

Halite. Middle Miocene to late Pliocene age.

Bedded anhydrite, minor shale. Middle Miocene to late Pliocene age.

Volcanic-clast conglomerate. Eocene to middle Miocene age.

Dark colored volcanic flows. Eocene to middle Miocene age.

Gneissic pebble conglomerate. Eocene to middle Miocene age.

Crystalline bedrock. Precambrian to middle Tertiary.

Normal fault

Figure 2. Generalized stratigraphy and structure of Picacho basin. Modified from Pool, 1986; Scarborough and Peirce, 1978; Freethey and others, 1986.

were established and both sedimentation and erosion occurred. Pediments (gently sloping, shallowly buried bedrock surfaces) have been eroded along the margins of most of the mountain ranges. A pediment may exist along the western base of the northern Picacho Mountains, where numerous inselbergs protrude above the surficial sediments. (Inselbergs are exposed outlying bedrock bodies that are connected with the principal mountain mass at depth). The southern Picacho Mountains are bounded on the west by a system of buried inactive normal faults across which there is a large amount of displacement downward to the west (Pankratz and others, 1978).

Bedrock comprises the down-dropped floor and walls of the basin, most of the pediments, and the mountains. It includes Precambrian, Paleozoic and Mesozoic igneous, metamorphic, and sedimentary rocks, early to middle Tertiary igneous intrusive and metamorphic rocks, and middle Tertiary volcanic and sedimentary rocks.

Basin fill that is up to approximately 2,300 m (7,550 ft) thick overlies the basin floor (Scarborough and Peirce, 1978). Basin fill is divided into lower and upper parts, and each of those parts is further subdivided into lower and upper parts, based on structural and stratigraphic characteristics. Basin fill is made up of evaporites (anhydrite, gypsum, and halite), claystone, shale, gravel, sand, silt, and clay.

The western Picacho Mountains are composed primarily of granitic gneiss of early Miocene to Oligocene age (18 Ma to 38 Ma) (Reynolds, 1988). Surficial deposits consist of various facies of the upper basin fill, which are shown in detail on Plates 1 and 2 in Slaff and others, 1989. These deposits include alluvial fans of various ages (early to middle Holocene fans cover the largest areas), eolian features, deflated areas, and playa sediments (located mostly to the south of Picacho Reservoir), axial stream terraces (deposited by the Santa Cruz and Gila Rivers and their ancestral counterparts), and active stream channels and terraces.

Hydrologic

Although surface water is ephemeral in Picacho basin, a vast quantity of ground water is present. Most of it is within the basin fill. The aquifer system consists of many alluvial aquifers that are interconnected to various degrees. Ground water is unconfined in most of the aquifers; it is confined

or semi-confined in sand and gravel lenses within the fine-grained facies of the basin fill, and within deep portions of the fine-grained facies (Anderson, 1986).

Significant rates of ground-water withdrawal began in Arizona around 1910 (Schumann and Poland, 1970). The withdrawal rate has greatly exceeded the rates of natural and artificial recharge since the mid-1930's (Holzer, 1981). Between 1923 and 1977, water-table altitudes decreased by 30 m (100 ft) near Eloy and by 91 m (300 ft) near Picacho. The depth to the water table in 1977 ranged from 30 m to 61 m (100 to 200 ft) below ground surface near Casa Grande to 122 m to 152 m (400 ft to 500 ft) near Picacho (Konieczki and English, 1979). Rates of water-table altitude decline as high as 3 m (10 ft)/yr have been measured.

Decline in water-table altitude causes aquifer compaction, which in turn causes land-surface subsidence. Most of the basin has subsided, but not enough data are available to determine how much subsidence has occurred at each point. It is clear, however, that a 261 km^2 (101 mi^2) area that extends northward to a point 4 km (2.5 mi) south-southwest of Picacho Reservoir (Figure 1) subsided a minimum of 2.1 m (7 ft) between 1905 and 1977 (Laney and others, 1978).

APPROACH

Four principal tasks were undertaken during this investigation. Pertinent available literature was reviewed. Water-table altitude data were assembled and plotted. Aerial photographs, including a very large format set, were interpreted during both office and field work. Fissures and related features were mapped in the field. Each of these tasks is discussed in more detail below.

The literature reviewed for this investigation included, in addition to information about subsidence and earth fissures, measurements of historical water-surface altitudes in wells. The measurements were used to evaluate the amount of stress on the aquifers in the Brady and Picacho pumping plants area and its possible relationship with fissure-development rates and patterns.

Two sets of black and white 1:24,000-scale aerial photographs (one set taken in 1975, the other in 1989) were examined stereoscopically to identify and locate fissures and to document changes in fissure patterns over time. Then, a set of five very large format black and white air photos (taken in

1989) was studied in an attempt to locate additional fissures. A limited stereoscopic examination was made of 1:24,000-scale black and white air photos taken in 1981. This set only covers part of the study area.

Almost every fissure and potential fissure noted on the air photos was field checked between November 1990 and April 1991. The locations of fissure endpoints were verified, activity levels were estimated, and morphologic data were recorded.

FINDINGS

Results of the investigation are grouped into four major subsections, presented below. In the first subsection, specific fissures that may have an impact on the CAP are discussed, and predictions are made based on a hypothesis that explains the locations of some of the principal fissures in the study area. Another subsection presents data on changes of water-table altitudes. Substantial lowering of the water table provides the driving force for sediment compaction and land subsidence. The third subsection deals with ongoing changes in local geomorphology and surface-water hydrology that are resulting from human modification of the surface and subsurface systems. The final subsection addresses the advantages and disadvantages of using very large format aerial photographs to identify earth-fissure locations.

For the purposes of this report, "active" fissures are defined as those with very young or young morphology that are likely to lengthen, branch, and/or undergo considerable erosion in the future, and that are still under tensional stress. "Reactivated" fissures are preexisting ones that show signs of renewed activity or tension. Typically, a mature fissure gully develops a deeper, narrower crack in its floor or along the previously undisturbed ground next to it. A mature, old, or very old fissure thus develops one or more segments with young or very young morphology. "Potentially active" fissures are young, mature or old features that display evidence that they may still be under tensional stress. The evidence may be: 1) end segments that have younger morphology than the rest of the fissure; 2) one or more subparallel or *en echelon* cracks beside the main trace. (*En echelon* refers to a pattern in which a line is offset laterally, consistently to either the left or right, into two or more segments that parallel each other); 3) a localized zone of collapse pits and/or piping nearby; or, 4) a

history (documented by air-photo interpretation) of periodically renewed activity. "Inactive" fissures have, in decreasing order of abundance, old, very old, or mature morphology, and lack any indication of ongoing or potentially renewed activity. "Lengthening" fissures are those that appear to be currently increasing in length. Evidence of lengthening is presented below in the Lengthening Fissures subsection.

Caution must be exercised in the use and interpretation of the information presented herein because of the following conditions: 1) Fissures designated "inactive" may be reactivated at any time; 2) A few features that were identified on the air photos as possibly fissures could not be field checked because of time limitations. Such features were included or excluded from Plates 1 and 2 solely on the basis of air photo interpretation; 3) As Table 1 indicates, some fissures were discovered in the field and are invisible or nearly so on the air photos. Very young active fissures typically lack the width or vegetation concentration that allows young, mature, and old fissures to be identified on air photos. Thus, some of the potentially most damaging fissures can be mapped only by field examination. Obviously, every single point could not be visited in the field. Therefore, fissures may exist that are not shown on Plates 1 and 2; and, 4) Fissure traces are deflected as they pass upward through strata with various different compositions and properties. In some cases, reactivation opens fissures beside rather than within existing traces. The CAP could be damaged adjacent to a visible fissure trace, where a subsurface cavity exists and causes loss of support.

Earth-Fissure Distribution and Activity

Approximately 50 fissures exist within 3.7 km (2.3 mi) or less of the Tucson aqueduct, the CAIDD canal, or the Santa Rosa canal in the mapped area (Plates 1 and 2). One fissure crosses each of the canals, and three fissures are located within 100 m (328 ft) of the aqueduct. Two fissures and portions of eight others (20% of the fissures mapped) are active. All or portions of 30 fissures (60% of those mapped) are reactivated or potentially active, and all or portions of 23 (46% of those mapped) are inactive. (Percentages total > 100 because many fissures change from one activity level to another along their lengths [see Plates 1 and 2]).

A detailed discussion of fissure morphology and morphologic age groups appears in Slaff and others (1989). A brief review is presented here. Many fissures follow a predictable sequence of

morphological changes once they become visible at the ground surface. By considering a fissure's form, as well as other variables such as soil type, land-surface slope, precipitation patterns, and the fissure's geographic orientation, the age of the fissure can be estimated. Very young (morphologic age group 1) fissures are narrow discontinuous cracks or lines of pits with steep to vertical walls extending tens of meters (scores of feet) deep. Young (morphologic age group 2) fissures have been modified somewhat by erosion, sedimentation, and mass wasting. They are wider, more continuous, shallower, and in some cases longer than very young fissures. Mature (group 3) fissures are wider and shallower still, lined with vegetation, and may resemble arroyos. Small gullies, carved as they carried sediment from upslope into the fissures, intersect mature fissures at high angles. Most old (group 4) fissures are < 1 m (3.3 ft) deep, have moderately sloping walls and flat floors. Vegetation along them is dense, and gullies that formed in response to their presence are relatively long. Very old (group 5) fissures may be difficult to identify because they are "healed". Only a shallow depression remains because they are nearly or completely filled with sediment. Remnants of the vegetation that formerly lined them may be the strongest indication that they are actually fissures.

The data presented below include the lengths and relative abundances of each type of fissure segment within the 133 km^2 (52 mi^2) study area. Active fissure segments range in length from 73 m to 1.02 km (238 ft to 0.64 mi). The average length (from 15 active segments) is 381 m (1,250 ft) and the total length of all segments combined is 5.71 km (3.55 mi). Reactivated or potentially active segments' lengths range from 98 m to 2.5 km (322 ft to 1.6 mi). The average length (determined from 40 segments) is 506 m (1,660 ft), and the total length of all segments combined is 20.2 km (12.6 mi). The length range for inactive segments is from 98 m to 1.4 km (322 ft to 0.88 mi). Average inactive-segment length (calculated using 28 segments) is 423 m (1,388 ft), and the total length of all segments combined is 11.8 km (7.4 mi). The density of all types of fissure segments combined in the study area is 0.28 km/km^2 (0.45 mi/mi^2).

Details about each fissure segment that was field checked are provided in Table 1. Fissures that are located close to each other geographically are grouped together on the table. Fissures within each group are arranged from youngest to oldest morphologic age group (1 to 5). Activity level, morphologic age group, and probable lengthening direction were determined by examining the physical expression of the segment. Very young and young fissures (age groups 1 and 2) tend to be active and narrow. They display relatively uneroded pits and cracks where surface expression is

Reference number	Activity level	Age	Morphologic age group	Avg. width (m)	Max. width (m)	Avg. depth (m)	Max. depth (m)	Probable lengthening direction	First mapped by	Comments
PICACHO RESERVOIR ORTHOPHOTOQUAD										
131114	A	post-'82	1	0.3	0.6	0.3	0.7	NE	FW	- -
131115	A	post-'82	1	0.2	0.5	0.3	1.1	NE	FW	- -
131113	A	pre-'82	1	0.5	1.5	0.8	4.5	- -	AP	- -
12413	A	post-'89	1	0.1	0.3	0.2	0.4	SE	FW	- -
12412	A	post-'82 pre-'89	1	0.1	0.6	0.2	1.3	NNE	AP	- -
12411	A	post-'89	1	0.2	- -	0.2	- -	NNE	FW	1
17434	A, R	pre-'75	1	0.4	1.0	0.4	1.5	- -	AP	2
17433	A, R	pre-'75	2	2.0	4.0	1.0	1.8	- -	AP	2
11310	A, R	pre-75	1	0.2	0.3	0.3	0.5	- -	AP	2
11311	A, R	pre-'75	1	0.3	0.6	0.3	0.5	- -	AP	2
12311	A,	post-'75 pre-'89	1	0.1	0.25	0.1	0.25	S	FW	- -
21230	A,R	pre-'75	1	0.3	0.4	0.2	0.4	- -	AP	2
20321	A,R	pre-'75	1	0.1	1.2	0.3	1.6	- -	AP	2
20311	A	pre-'89	2	0.3	0.4	0.3	0.7	N	FW	- -
131111	PA	pre-'82	2	0.7	1.7	0.4	1.0	- -	AP	- -
19611	PA	pre-'82	2	0.5	1.1	0.3	1.4	- -	AP	3
19612	PA	pre-'82	2	0.6	1.2	0.4	1.2	- -	AP	3
131117	PA	post-'75 pre-'89	3	0.8	1.9	0.3	0.8	- -	AP	- -
131116	PA	post-'75 pre-'89	3	1.3	2.1	0.3	0.5	- -	AP	- -
5411	PA	pre-'82	2	0.9	1.6	0.6	1.0	- -	AP	4
17432	PA	pre-'75	2	0.6	1.2	0.6	1.2	- -	AP	5
17444	R	post-'75 pre-'82	3	1.5	2.1	0.3	1.0	- -	AP	- -
10423	PA	pre-'75	3	0.2	0.3	0.1	0.2	- -	AP	- -
12321	PA	pre-'75?	2	0.5	1.0	0.6	1.0	- -	FW	- -
26234	R	post-'75 pre-'89	2	0.8	1.2	0.4	0.6	- -	AP	- -

Table 1. Status of earth-fissure segments.

Reference number	Activity level	Age	Morphologic age group	Avg. width (m)	Max. width (m)	Avg. depth (m)	Max. depth (m)	Probable lengthening direction	First mapped by	Comments
PICACHO RESERVOIR ORTHOPHOTOQUAD										
11323	R	pre-'75	3	1.8	3.2	1.1	2.3	- -	AP	- -
12332	R	post-'75 pre-'82	3	1.7	2.5	0.8	1.7	- -	AP	6
20332	PA	post-'75 pre-'89	3	0.7	1.2	0.2	0.7	- -	AP	- -
26211	R	post-'75 pre-'89	4	2.0	4.0	0.2	0.4	- -	AP	- -
21221	R	pre-'75	3	1.5	3.0	1.2	2.5	- -	AP	7
131112	I	pre-'82	4	0.8	1.4	0.2	0.4	- -	AP	- -
131118	I	post-'82 pre-'89	4	0.5	0.9	0.2	0.3	- -	AP	- -
5410	I	post-'75 pre-'89	4	0.4	0.7	0.2	0.3	- -	FW	- -
17411	I	pre-'89	4	0.7	1.8	0.2	0.6	- -	AP	- -
11321	I	pre-'75	3	0.4	0.8	0.3	0.5	- -	AP	- -
11322	I	pre-'75	3	1.3	2.4	0.7	1.3	- -	AP	- -
12323	I	post-'75 pre-'89	3	1.4	2.0	0.4	0.6	- -	AP	- -
12322	I	pre-'75	3	2.1	3.5	0.9	1.2	- -	AP	8
11312	I	pre-'75	4	0.7	1.2	0.3	0.5	- -	AP	- -
11313	I	post-'75 pre-'82	4	0.7	1.2	0.5	0.6	- -	AP	- -
12324	I	post-'75 pre-'89	4	0.7	1.1	0.2	0.3	- -	FW	- -
12331	I	pre-'75	5	0.6	1.1	0.1	0.3	- -	AP	- -
26221	I	post-'75 pre-'89	4	1.4	2.0	0.2	0.3	- -	AP	- -
26241	I	post-'75 pre-'89	4	0.4	0.5	0.3	0.4	- -	AP	9
26233	I	post-'75 pre-'89	5	0.7	1.1	0.1	0.2	- -	AP	9

Table 1. Status of earth-fissure segments, *continued.*

Reference number	Activity level	Age	Morphologic age group	Avg. width (m)	Max. width (m)	Avg. depth (m)	Max. depth (m)	Probable lengthening direction	First mapped by	Comments
PICACHO RESERVOIR ORTHOPHOTOQUAD										
26232	I	post-'75 pre-'89	5	1.5	3.0	0.1	0.3	- -	AP	- -
26231	I	post-'75 pre-'89	5	0.6	1.0	0.1	0.2	- -	AP	- -
12312	I	post-'75 pre-'89	3	0.8	1.2	0.4	0.7	- -	AP	10
21231	I	pre-'75	4	1.2	4.0	0.1	0.3	- -	AP	11
20312	I	pre-'75	5	2.6	4.0	0.1	0.2	- -	AP	- -
20322	I	pre-'75	5	1.8	2.1	0.1	0.1	- -	AP	- -
4111	I	post-'75 pre-'89	4	0.5	1.0	0.1	0.2	- -	AP	- -
17442	I	pre-'75	4	1.5	1.7	0.2	0.3	- -	AP	- -
17431	I	pre-'75	4	0.7	1.5	0.3	0.5	- -	AP	- -
RED ROCK NW ORTHOPHOTOQUAD										
10414	A,R	pre-'75	1	0.06	0.2	0.8	2.0	- -	AP	2
10413	A,R	pre-'75	2	0.6	2.0	0.3	0.9	- -	AP	2, 12
10412	R	pre-'75	3	2.0	3.0	1.5	3.0	- -	AP	13
5421	PA	pre-'75	2	0.4	0.7	0.3	1.0	- -	FW	14
5425	PA	post-'75 pre-'89?	2	0.7	1.1	0.8	1.7	- -	FW	15
5427	PA	post-'75 pre-'89	3	1.7	3.0	1.1	2.0	- -	AP	16
5424	PA	pre-'75	3	1.5	2.5	1.5	3.5	- -	AP	17
5423	PA	pre-'75	3	0.7	1.0	0.9	1.9	- -	FW	- -
5422	PA	pre-'75	3	1.5	2.5	1.5	3.5	- -	FW	- -
5426	PA	pre-'75	3	0.7	1.2	1.6	4.0	- -	AP	18
10411	I	post-'75 pre-'89	3	0.8	1.0	0.4	0.5	- -	AP	- -

Table 1. Status of earth-fissure segments, *continued.*

Table 1. Status of earth-fissure segments near Brady and Picacho pumping plants. Locations of fissure segments are shown (using identification numbers) on Plates 1 and 2. Fissures are listed in geographic groups, first those on the Picacho Reservoir 7.5' orthophotoquad (Plate 1), followed by those on the Red Rock NW orthophotoquad (Plate 2), to facilitate referring back and forth from the table to the maps. Activity level abbreviations are as follows: A = active; R = reactivated; PA = potentially active; I = inactive. Morphologic age-group designations are as follows: 1 = very young; 2 = young; 3 = mature; 4 = old; 5 = very old. Only very general age designations were made for this study. Probable lengthening direction was determined by examining morphology at existing fissure end-points and by evaluating direction of most recent lengthening. Methods used for the initial mapping of each feature are abbreviated as follows: FW = field work; AP = interpretation of aerial photographs. Status of areas of localized collapse pits and piping is discussed in the text.

Comments

1 Not a fissure *per se* - disconnected pits and pipes at this time.
2 Data (except age) pertain to reactivated part, not to older part of fissure.
3 Mostly disconnected pits. Longest continuous-crack reach is 6 m (20 ft) long.
4 Up to three subparallel to *en echelon* cracks in a zone 10 m (33 ft) wide. Possibly will lengthen to the west-southwest.
5 Disconnected pits and pipes occur 2 m to 3 m (7 ft to 10 ft) west of the fissure.
6 Up to three subparallel cracks in a zone 15 m (49 ft) wide. Age pertains to reactivated strand only.
7 North end first mapped by field work.
8 Some reaches marked by soil mounds up to 1 m (3 ft) in diameter and 0.4 m (1 ft) high.
9 Small collapse and piping features are present in this immediately area.
10 Up to three subparallel cracks in a zone 4 m (13 ft) wide.
11 *En echelon* pattern along some reaches.
12 Approximately 0.6 m (2 ft) of vertical displacement occurs across fissure.
13 Up to two subparallel cracks in a zone 2 m to 6 m (7 ft to 20 ft) wide.
14 Up to two subparallel cracks in a zone 8 m (26 ft) wide.
15 Up to two subparallel cracks in a zone 5 m (16 ft) wide.
16 Up to two subparallel cracks in a zone 4 m (13 ft) wide.
17 Approximately 0.3m to 0.4 m (1 ft to 1.3 ft) of vertical displacement occurs across fissure. Up to four subparallel cracks in a zone 10 m to 18 m (33 ft to 59 ft) wide.
18 Up to two subparallel to *en echelon* cracks in a zone 9 m (30 ft) wide.

Table 1. Status of earth fissure segments.

recent, and such features at the current endpoint of a fissure indicate that the fissure may lengthen in the same general direction. Of the ten mapped fissures that are active or have active segments, five appear to be lengthening (Plate 1). Many young and mature fissures (age groups 2 and 3) are potentially active or reactivated, but lack evidence of probable future lengthening. Mature, old, and very old fissures (age groups 3, 4, and 5) that are inactive are less likely to lengthen and damage CAP facilities, but until dewatering and compaction of underlying aquifers is complete, any fissure may lengthen and/or become reactivated along or near its existing trace.

Most of the fissures were first mapped on aerial photographs and then field checked. Thirteen segments and fissures, however, were discovered in the field. Later, some of them were observed as faint traces on the air photos, and others could not be seen at all. Thus, even very large format air photos are no substitute for periodic field checking, especially in known fissure areas and in the immediate vicinity of critical facilities.

Lengthening Fissures

As defined above, "lengthening" fissures are those that appear to be currently increasing in length. Two types of evidence indicate current lengthening: One indicator is the presence of very young morphology at existing endpoints (especially in the case of fissures that display more mature morphology along their central reaches). Another type of evidence is the presence of endpoints that have advanced measurably since the 1989 air photos were taken. Fissures that are lengthening toward the CAP clearly pose a threat. Those that are very close to the CAP and are lengthening away from it are not as dangerous but also should be monitored in case they begin to lengthen toward it. The following discussion focuses on each known lengthening fissure, assessing its possible future development with respect to the CAP. Lengthening fissures are unpredictable. They may propagate 0.5 km (0.3 mi) or more during a single rainstorm, or advance only a few meters (several feet) one year and 0.5 km (0.3 mi) the next year. They may advance in discontinuous patterns, leaving middle reaches unbroken at the ground surface.

The so-called Brady fissure (identification numbers 12411, 12412, and 12413 on Plate 1 and Table 1) is actively lengthening at both ends. Located less than 1 km (0.62 mi) west of the Tucson aqueduct between Brady and Picacho pumping plants, it is a spectacular fissure gully that is more than 1.6 km

(1 mi) long and up to 3 m (10 ft) wide and 3 m (10 ft) deep along its young (morphologic age group 2) middle reach (Figure 3). The width and depth of the "Brady" fissure near its endpoints, which are listed in Table 1, are substantially less than the current dimensions of its middle reach. Geophysical data that show depth to bedrock and the subsurface configuration of the basin fill/bedrock contact at this site were unavailable for this investigation. These conditions are thought to play an important role in determining the position of fissures located close to the western front of the Picacho Mountains (Pankratz and others, 1978). During the past few years, the southern end of the "Brady" fissure has lengthened to the southeast, in the direction of the aqueduct. If the fissure location is controlled by subsurface structural relationships and if a buried pediment is present that roughly parallels the existing mountain front, then the fissure would be expected to curve to the south and stop lengthening before reaching the aqueduct. Because the aqueduct is located very close to and on bedrock to the south of the existing fissure endpoint (and Picacho pumping plant is on bedrock), the potential for damage in that region is relatively low. However, if the fissure continues to propagate to the southeast, in the direction of an embayment in the mountains that may exist in the pediment as well, it could intersect the aqueduct. Obviously, this zone should be monitored very carefully. Runoff and infiltration should be diverted away from the area and an attempt should be made to prevent further subsidence by eliminating or at least reducing overdraft of ground water from wells located several kilometers (a few miles) to the west.

The north end of the "Brady" fissure is currently lengthening as well. During this investigation, a linear system of collapse pits was discovered 300 m to 540 m (984 ft to 1,772 ft) north of and on trend with the existing fissure endpoint. Thus, the fissure is expected to lengthen in this direction. This direction (north-northeast) is probably parallel to the edge of the (buried) pediment (if a pediment is present), which may roughly correspond to the strike of the range-bounding normal fault. The collapse pits were discovered in the field during April, 1991, and they are not apparent on the very large format aerial photographs. The pits were obscured when the site was visited again in October, 1991. Rainfall, runoff, and burrowing animals probably made the pits less obvious. An additional 1.8 km (1.1 mi) of lengthening beyond the northern-most existing pit would bring the fissure into contact with the aqueduct approximately 200 m to 300 m (656 ft to 984 ft) downstream of the point at which the water emerges from Brady pumping plant. Interpretation of aerial photographs indicates that between 1981 and 1989, the "Brady" fissure lengthened 0.56 km (0.35 mi) to the north. If this rate is maintained and the direction does not change, the fissure will not reach the aqueduct

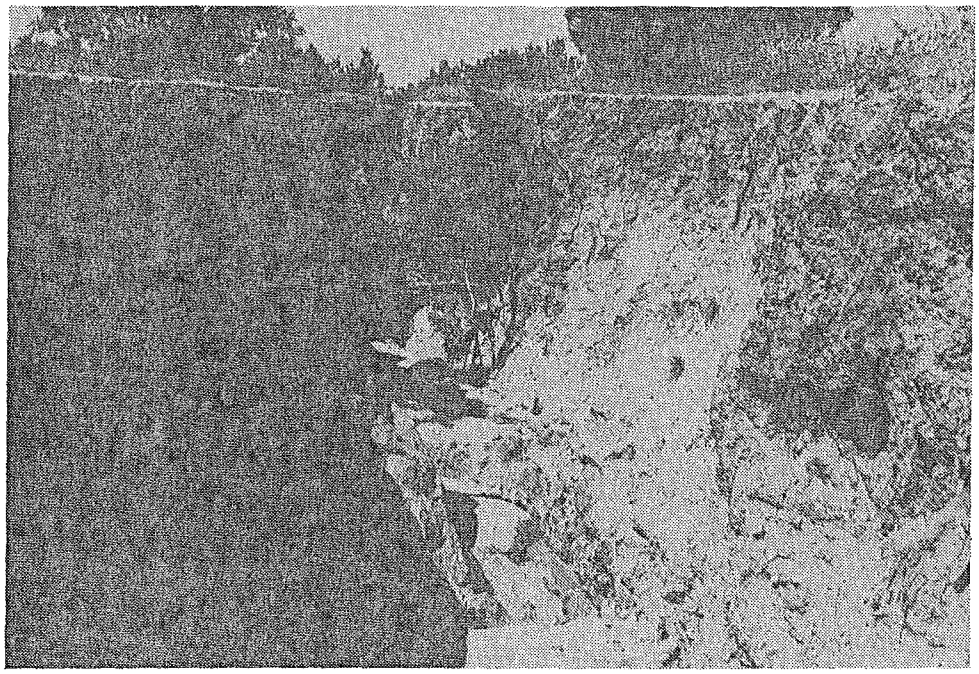


Figure 3. The young (age group 2) middle reach of the "Brady" fissure, between segments 12412 and 12413 on Plate 1. The gully is approximately 2 m (6.6 ft) wide and 2 m (6.6 ft) deep. View to the north.

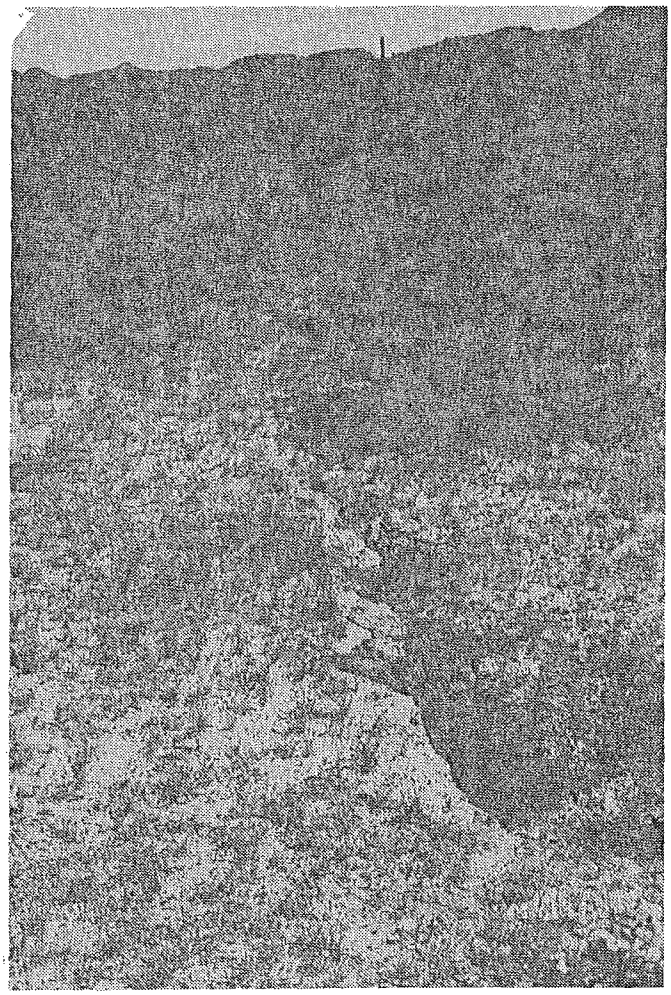


Figure 4. This very young (age group 1) fissure segment (131115 on Plate 1 and Table 1) is lengthening toward the northeast. Note Tucson aqueduct in background. View to the northeast.

until the year 2015. But as Slaff and others (1989) determined, single-fissure lengthening rates in Picacho basin vary considerably over time, and from one fissure to the next. Between 1959 and 1989, average rates ranged from approximately 20 m/yr (66 ft/yr) to 100 m/yr (328 ft/yr) and maximum rates ranged from approximately 65 m/yr (213 ft/yr) to 530 m/yr (1,739 ft/yr). The rate of lengthening to the north of the "Brady" fissure between September 1981 and March 1989 was 74.7 m/yr (245 ft/yr).

The "Brady" fissure may be the northern equivalent of the so-called Picacho fissure. The "Picacho" fissure is a 15.8 km- (9.8 mi)-long feature that displays up to 0.6 m (2 ft) of vertical displacement. Segments of it are identified as 17431 on Plate 1, and as 10414, 10413, 10412, and 10411 on Plate 2. It parallels the trend of the Picacho Mountains 1.5 km to 4 km (0.9 mi to 2.5 mi) west of the exposed bedrock, and is believed to overlie an inactive normal fault system (Pankratz and others, 1978). The existing northern end of surface expression of the "Picacho" fissure is located 2 km (1.2 mi) west of the existing southern end of the "Brady" fissure (see Plate 1). At this location, the exposed bedrock of the Picacho Mountains steps 3 km to 4 km (1.9 mi to 2.5 mi) to the east.

If the "Brady" fissure is the northern equivalent of the "Picacho" fissure and both are surface expressions of a buried inactive normal fault system that is downthrown on the west, then the following developments may be expected: 1) The "Picacho" fissure will not lengthen much farther to the north; 2) The "Brady" fissure will not lengthen much farther to the south; 3) The group of predominantly east-west trending fissures located 1 km (0.6 mi) north of Picacho pumping plant (Plate 1) are surface manifestations of a lateral step in the buried range-bounding fault system, and they will continue to lengthen and branch and perhaps develop minor vertical displacement (down to the north). It is also possible that these fissures overlie not a fault system but a positive gravity anomaly or buried bedrock knob. In this case too, they probably will continue to lengthen and branch, but they probably will not develop vertical displacement; 4) The "Brady" fissure will branch and will continue to lengthen to the north, perhaps by several kilometers; 5) The "Brady" fissure will gradually develop minor vertical displacement, downthrown on the west, through the process of aseismic creep. (Aseismic creep is the very slow process, without earthquakes, of accumulation of displacement across a fault); and, 6) Fissure 17411 (Plate 1) may become reactivated and incorporated into a "Brady" fissure system.

Fissures 131114 and 131115 (Plate 1) are active segments of the east-west trending group near Picacho pumping plant (mentioned in item 3 above). Both appear to be lengthening toward the northeast, and will cross the Tucson aqueduct if they continue for another 0.75 km (0.5 mi) in that direction (Figure 4). It is somewhat unlikely that they will reach the aqueduct, however, because of its proximity to bedrock along this reach. They may continue to curve to the north, eventually becoming part of a "Brady" fissure system. As with other fissures located close to the aqueduct, this group should be monitored regularly.

Segment 12311 appears to be likely to lengthen toward the south (Plate 1). It has lengthened a short distance (in this case, approximately 50 m [164 ft]) since the air photos were taken in 1989, as have most fissures with probable lengthening directions listed in Table 1. The Santa Rosa canal is located 1.25 km (0.8 mi) south of the existing southern endpoint of the fissure. The feature does not pose much of a hazard at present, but if the southward-lengthening trend continues, it will have to be reevaluated in the future.

Fissure 20311 (Plate 1) has been lengthening to the north, away from the Santa Rosa canal, which lies 200 m (656 ft) south of the fissure's south end. The danger of damage to the canal here is relatively low, but because of the feature's close proximity to the canal and the possibility of reactivation and a reversal of lengthening direction, periodic monitoring is advised.

Active Fissures

Five fissures have active segments but do not display strong evidence of current lengthening. All exhibit very young or young morphology. They are discussed individually below.

Segment 10414 is in contact with the CAIDD canal (Plate 2). Although it initially formed before 1975, this portion of the "Picacho fault" has been reactivated as a very young, narrow, deep crack beside a mature fissure gully. With the distinct possibility of continuing vertical displacement, this feature poses a significant hazard to the canal. Figure 5 shows a 0.5 m (1.6 ft)-deep depression occurring immediately upslope (southeast) of a wildlife crossing that is located approximately 110 m (360 ft) downstream from where the main branch of the "Picacho fault" crosses the canal. The depression, located in an area that is aggrading (undergoing an increase in surface altitude caused by

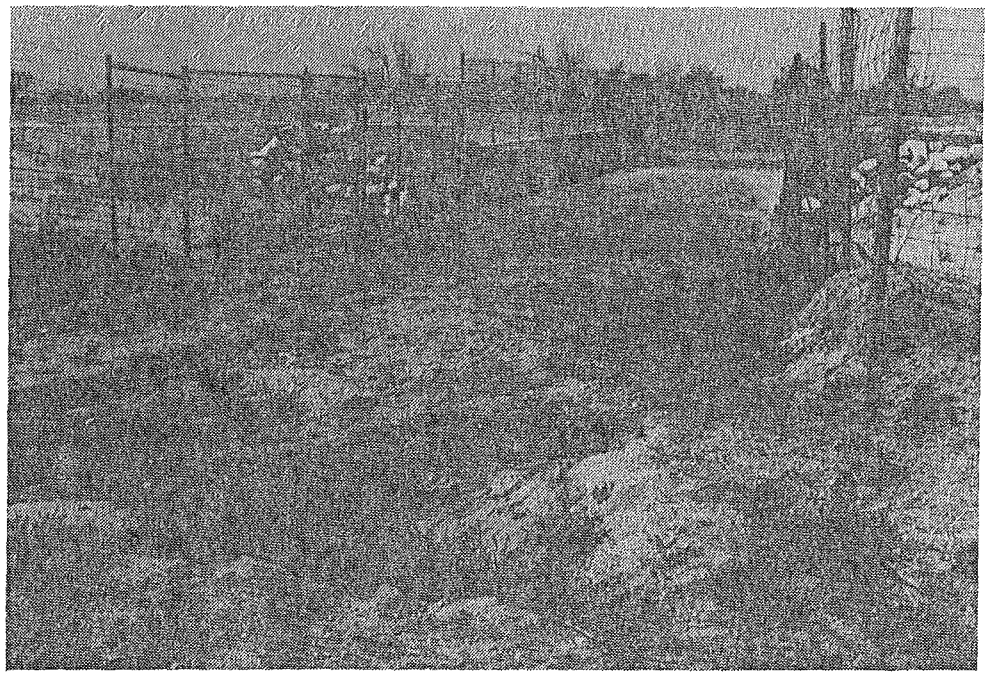


Figure 5. The 0.5 m (1.6 ft)-deep pit in the foreground is a sign of activity on "Picacho fault" segment 10414 close to where the fissure crosses the CAIDD canal (see Plate 2 for location). The depression, located on the upslope side of the canal, is in an area that is aggrading. A bridge that enables wildlife to cross the canal is in the background. View to the northwest.

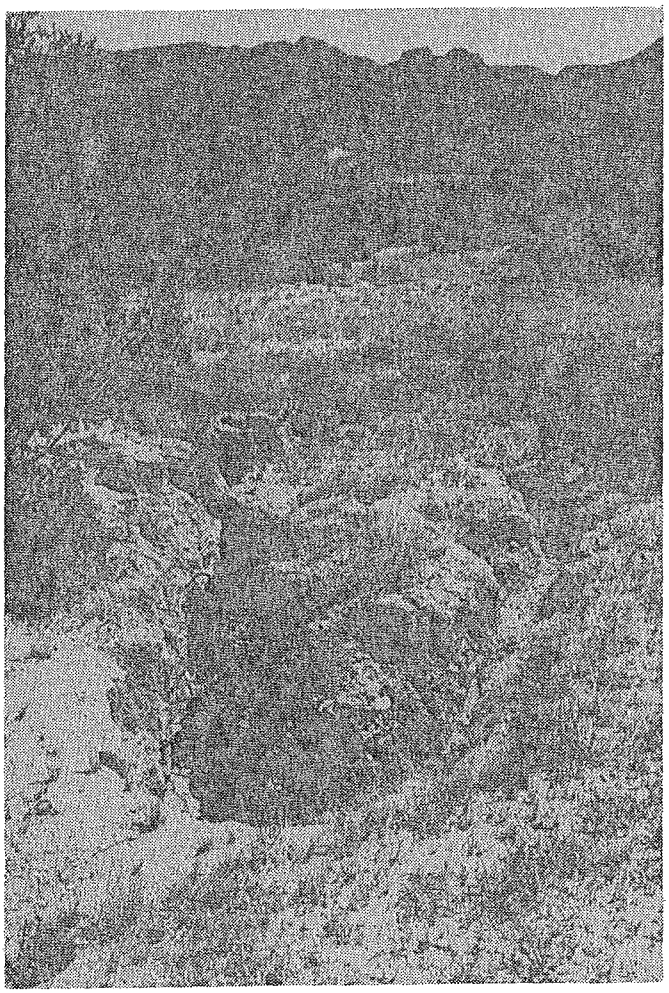


Figure 6. Young pit on active segment 10413 (see Plate 2) of the "Picacho fault". Approximately 0.6 m (2 ft) of vertical displacement is visible across the pit (down on the right [west] side), and motion may be still occurring slowly. Notice trace of Tucson aqueduct in background. View to the southeast.

deposition of sediment), is additional evidence of the active status of this segment.

To the south of the segment discussed above, the "Picacho" fissure is expressed as three subparallel linear features. The western splay dies out to the north as a series of pits. The central branch is a shallow, relatively narrow, morphologically old fissure gully. The eastern trace, segment 10413, is a series of relatively large, morphologically young pits across which approximately 0.6 m (2 ft) of vertical displacement has occurred (Figure 6). Displacement may be still occurring. Carpenter (1991) reports that the "Picacho" fissure was first observed in 1927. According to Holzer and Lluria (1987), it was first observed in 1949, and vertical displacement across it was first detected in 1961. Initially, the scarp increased its height at a rate of 6 cm/yr (2.4 in./yr), and later the rate decreased to 0.9 cm/yr (0.35 in./yr) between 1975 and 1980 (Holzer and Lluria, 1987). From 1980 to 1984, the rate of scarp-height increase decreased further to 0.5 cm/yr (0.2 in./yr) (Carpenter, 1988). Unfortunately, some of the survey stations that had been used to measure vertical and horizontal movement were destroyed during CAP construction, so future scarp-height growth-rate measurements will be based on fewer control points. (Carpenter, oral commun., 1990).

Segments 17433 and 17434 are active reactivated fissures that originally formed before 1975 (Plate 1 and Table 1). They appear to be associated with the northern end of the existing "Picacho" fissure. Along with the nearby fissures 17444 and 17442 they form a pattern that is fairly common among Basin and Range-province range-bounding fault scarps. Near the ends of some faults or near their lateral steps, the scarps curve toward the basin and bifurcate into a group of relatively short subparallel scarps. The resemblance of the pattern formed by this group of fissures to the range-bounding fault-scarp pattern described above may be coincidental, but if segments 17433 and 17434 are controlled by this type of fault geometry at depth, they probably will not lengthen very much nor develop much vertical displacement. Segment 17433 (Figure 7) has young collapse pits in its floor as well as in lines a few meters beside (mostly to the west of) the morphologically mature fissure gully. A bench (former floor) above the existing floor is additional evidence of reactivation. The main trace of segment 17434 is a mature fissure gully that has intercepted a stream channel. It has been reactivated, and along its western edge is a morphologically very young to young narrow crack (Figure 8).

Active segments 20321 and 21230 are located on a 3.75 km (2.3 mi)-long fissure that formed before

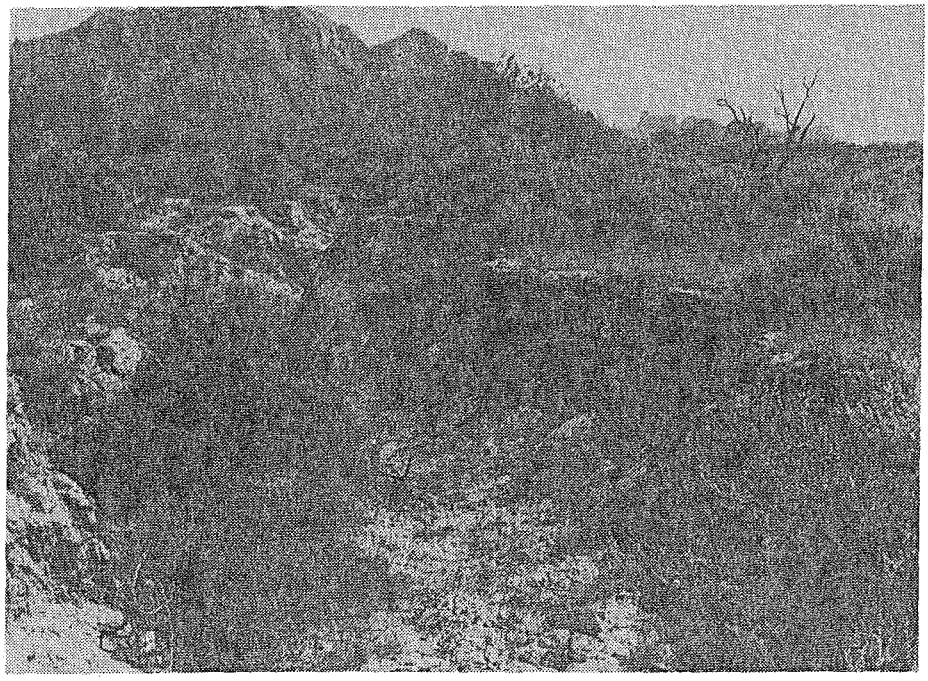


Figure 7. Active fissure segment 17433 (see Plate 1 for location) appears as a mature fissure gully here, but has young (age group 2) morphology elsewhere. Features not visible in the photo that indicate active/ reactivated status include young collapse pits in fissure floor as well as in lines beside fissure, and a bench (former floor) preserved above the existing floor. View to the south-southeast.

Figure 8. Active/reactivated fissure segment 17434 (see Plate 1 for location). Light-colored fissure floor (on left, under mesquite trees) has diverted a stream and shows mature (age group 3) morphology. Very young (age group 1) morphology is displayed by reactivation crack (dark area in left foreground). View to the south-southeast.

1975 (Plate 1 and Table 1). Where the fissure crosses Santa Rosa canal, and along most of its length, it is inactive and morphologically very old. However, approximately 150 m (492 ft) south of the canal, segment 20321 is a morphologically very young narrow crack and series of collapse pits. Although this reactivated reach does not appear to be propagating northward toward the canal, it is close enough to warrant periodic inspection. Segment 21230 displays lines of collapse pits parallel to and approximately 10 m (33 ft) from the main fissure trace. It is located more than 1 km (0.62 mi) from the canal and poses little danger to the CAP.

Segments 11310 and 11311 are located at the northeastern end of a prominent fissure that formed before 1975 (Plate 1 and Table 1). The morphology of this mature fissure becomes progressively younger to the northeast along segment 11311. Figure 9 shows reactivation of the feature. A trench has formed in the fissure floor, creating a fissure within a fissure. Segment 11310 is a morphologically very young narrow crack near the end of segment 11311 (Figure 10). It only extends approximately 40 m (131 ft) beyond the mature fissure-gully segment 11311. Even if it continues to lengthen to the northeast, it probably will not do so at a high rate because it has not lengthened measurably since 1975. The existing endpoint is 1 km (0.62 mi) from the Tucson aqueduct.

Localized Collapse Pits and Piping

A total of five areas shown on Plates 1 and 2 are characterized by localized collapse pits and piping. Four of the zones, identified as 26234, 26213, 131123, and 5428, are relatively small in area (approximately 7500 m^2 [80,500 ft^2] each), occur close to existing fissures, and are considered potentially active. These areas have scattered small pits and troughs (up to 0.4 m [1.3 ft] deep, 0.5 m [1.6 ft] wide, and 2 m [6.6 ft] long) that are not currently aligned in a curvilinear or *en echelon* pattern typical of a fissure. Whether these features will enlarge, contract, disappear, or develop into fissures remains to be seen. They should be examined when the nearby fissures are monitored.

The zone of piping and disrupted drainage identified as 131123 on Plate 1 (one of the four zones discussed above) occurs where a small group of fissures was modified during construction of power lines and an access road to Picacho pumping plant. This zone apparently was part of a fissure before construction (U.S. Department of the Interior, Bureau of Reclamation, 1982, sheet 344 330 3565A).

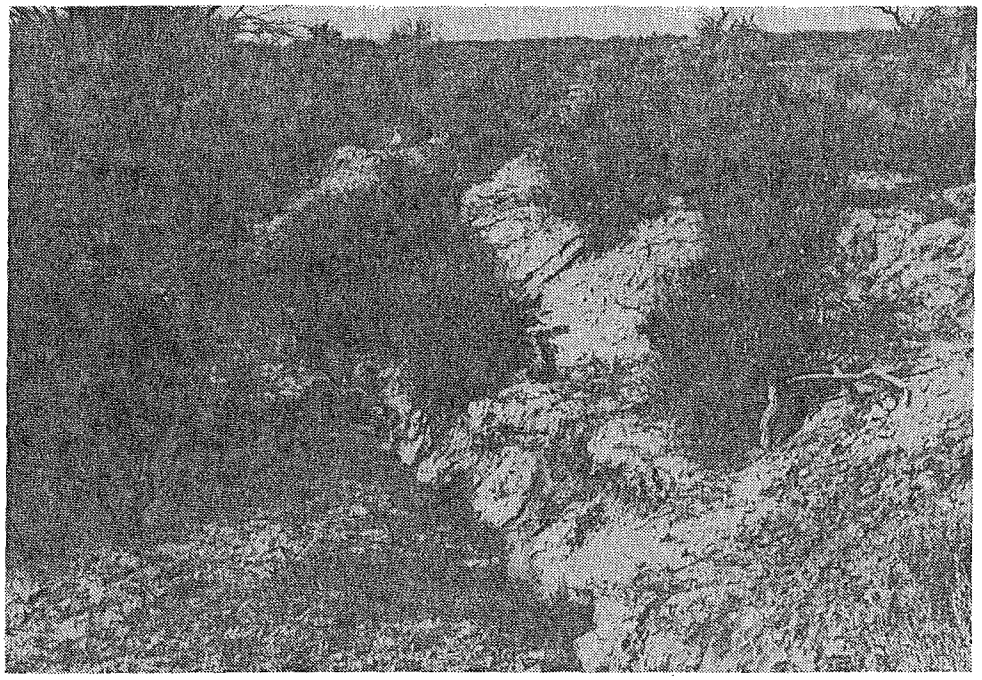


Figure 9. Reactivated fissure segment 11311. Smooth floor of mature (age group 3) fissure is on left. Very young (age group 1) crack, indicating reactivation, cuts the older fissure's floor in lower center of photo. The original ground surface is visible in the upper right. View to the west.

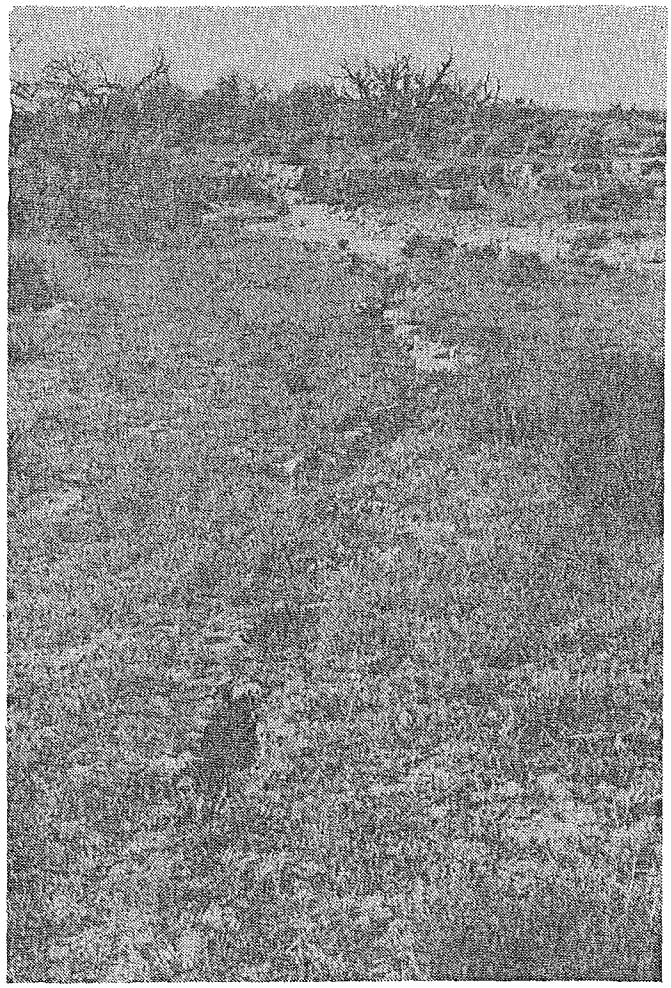


Figure 10. Very young (age group 1) fissure segment 11310 (see Plate 1 for location). Notice narrow width and vertical walls. View to the southwest.

It has shown little activity since it was backfilled and graded.

The fifth area of localized collapse pits and piping, 11343 on Plate 1, is active and is larger (approximately 0.37 km^2 [0.14 mi^2]) than the other four areas combined. Small pits with young morphology are isolated and widely scattered within the zone. Erosion and headcutting are active here because the Santa Rosa canal embankments act as a large dam on the upslope drainages. Regional subsidence of Picacho basin to the west has lowered the local base level, and this may be another cause of erosion and headcutting. This topic is discussed in more detail in the subsection Changes in Geomorphology and Surface-Water Hydrology on page 32. Figures 11 and 12 show one of the collapse pits and its position in relation to the Santa Rosa canal and the Picacho Mountains near Brady pumping plant, respectively. This area also should be examined when the fissure that crosses Santa Rosa canal 2.8 km (1.7 mi) west-southwest of here is inspected. Developments to watch for include serious erosion and headcutting at the canal embankment, pronounced subsidence of the area, or joining of collapse pits and pipes into an earth fissure. As with monitoring fissures, an effective way to document temporal changes is to establish identified locations where photographs are taken during each inspection.

Water-Table Altitude Change

Most investigators accept the premise that water-table altitude decline caused by excessive ground-water pumping leads to aquifer-sediment compaction, land-surface subsidence, and earth-fissure formation (e.g., Poland, 1981). In Picacho basin, the amount of compaction and subsidence per meter of water-level decline is relatively small (and partially reversible) as long as total cumulative water-table altitude decline is less than approximately 32 m (105 ft) (Holzer, 1981). Once the cumulative decline exceeds 32 m (105 ft), the amount of compaction and subsidence per meter of water-level decline is more than one order of magnitude greater, and most of the compaction is irreversible. The magnitude and rate of subsidence are well documented to the west and southwest of the study area, where bench marks along the Southern Pacific railroad track and Interstate Highway 10 have been releveled repeatedly. However, until the recent advent of the releveling program along subsidence-prone reaches of the CAP, no control points existed within the study area that could be used to calculate cumulative subsidence magnitudes.

Figure 11. One of the pits in the area of localized collapse pits and piping designated as 11343 on Plate 1. The pit is approximately 2 m (6.6 ft) in diameter and 0.75 m (2.4 ft) deep.

Figure 12. To facilitate future inspection of this site, the same pit shown in Figure 11 is in the foreground, with the Santa Rosa canal and Picacho Mountains in the background. View to the southeast.

Water-table altitude changes reported at wells in and adjacent to the study area are summarized in Table 2. Well locations are shown in Figure 13. The data are based on measurements reported by Arizona Department of Water Resources (ADWR, 1990). The 238 km^2 (92 mi^2) region for which well data are tabulated is slightly larger than the study area. Wells exist in the region depicted in Figure 13 that are not shown in the figure nor listed in Table 2. They are omitted because of the following: 1) they are not included in the ADWR data; 2) only a single water-table altitude measurement is available, so altitude change could not be calculated (25 wells); or, 3) all measurements made were affected by pumping of water from the well or from a nearby well (2 wells).

Of the 25 wells included in Table 2, seven had one or more measurement that was affected by pumping. Such measurements were discarded, so the calculations are based on true static water levels. Measurement dates range from 1942 (for one well only) to 1989 (four wells). The number of measurements reported for each well ranges from 2 to 28, and averages 5.7. The periods over which measurements are reported range from 1 to 40 years, with an average of 8.6 years. The frequency of reported measurements ranges from 10/yr to one every 5.3 years. The average is one measurement every 1.9 years.

These data give a biased and very general picture of water-table altitudes for the following reasons: 1) natural (pre-pumping) water-table altitudes and fluctuations are unknown; 2) data are not available for some wells within the area; 3) the number of measurements, frequency of measurements, and period duration during which measurements were made varies considerably from well to well; 4) the average period during which measurements were made is less than ten years long; 5) the local sedimentology, stratigraphy, and hydrology at each well are not considered; 6) short- and long-range climatic conditions are not taken into account; and, 7) details regarding well completion and pumping history are not considered.

Fourteen of the 25 wells listed in Table 2 experienced water-table altitude declines. In general, those showing the largest declines have been measured for the longest periods. The wells with longer measurement periods (> 10 years) are more useful than those with shorter measurement periods (10 or fewer years) as indicators of water-level change patterns. Therefore, the two groups are discussed separately below. For the six wells that were measured for more than ten years, measurement

WELL	PERIOD OF MEASURE-MENTS	DURATION OF PERIOD (YEARS)	INTERVAL OF MAXIMUM CHANGE	DURATION OF MAX. CHANGE INTERVAL	W.T.A.C. DURING MAX. CHANGE INTERVAL	W.T.A.C. DURING WHOLE PERIOD
68-35ABB	'42-'49	7	'46-'48	2	-10	-14
68-35CCD	'84-'88	4	'84-'88	4	+4	+4
78-1DCC	'53-'56	3	'53-'54	1	-7	-9
78-1DDD	'51-'56	5	'52-'54	2	-9	-10
78-12AAC1	'84-'88	4	'84-'88	4	+5	+5
78-12AAC2	'84-'88	4	'84-'88	4	+16	+16
78-25CCC1	'71-'72	1	3/72-9/72	0.5	-15	-15
78-25CCC2	'71-'72	1	1/72-9/72	0.75	-16	-16
78-26CDD1	'84-'88	4	'84-'88	4	+10	+10
78-26CDD3	'84-'88	4	'84-'88	4	+10	+10
78-35CDA	'84-'88	4	'84-'88	4	+3	+3
78-35CDC	'84-'89	5	'88-'89	1	+6	+10
78-35CDD2	'84-'88	4	'84-'88	4	+10	+10
88-1DDD	'52-'89	37	'52-'71	19	-60	-66
88-11BDD	'84-'88	4	'84-'88	4	-2	-2
88-12DCC	'84-'88	4	'84-'88	4	+1	+1
88-12DCD	'84-'88	4	'84-'88	4	+6	+6
88-12DDD	'72-'88	16	'72-'84	12	-25	-28
88-13CDD	'83-'84	5	'83-'84	1	-7	-7
88-14BBB	'72-'88	16	'81-'84	3	-12	-14
88-14CDD	'84-'88	4	'84-'88	4	+6	+6
88-14DDD	'49-'89	40	'49-'75	26	-74	-84
89-7ADD	'81-'89	8	'83-'84	1	-9	-9
89-7DDD	'77-'84	11	'77-'84	7	-13	-13
89-18ADD	'71-'84	17	'75-'84	9	-14	-17

Table 2. Water-table altitude changes at wells in and adjacent to the study area. WTA = water-table altitude. WTAC = water-table altitude change. "+" indicates that WTA rose. "-" indicates that WTA fell. Measurements are in meters. Well-numbering system is as follows: First number is township; second number is range; third number (one or two digits) is section; first letter is 160-acre quarter of section; second letter is 40-acre quarter of first quarter; third letter is 10-acre quarter of second quarter. Letters are from A to D, moving counterclockwise from the upper-right quarter. Last number, if present, differentiates the well from others located in the same 10-acre plot. Example: 78-35CDA is located in T.7S., R.8E., the northeast quarter of the southeast quarter of the southwest quarter of section 35.

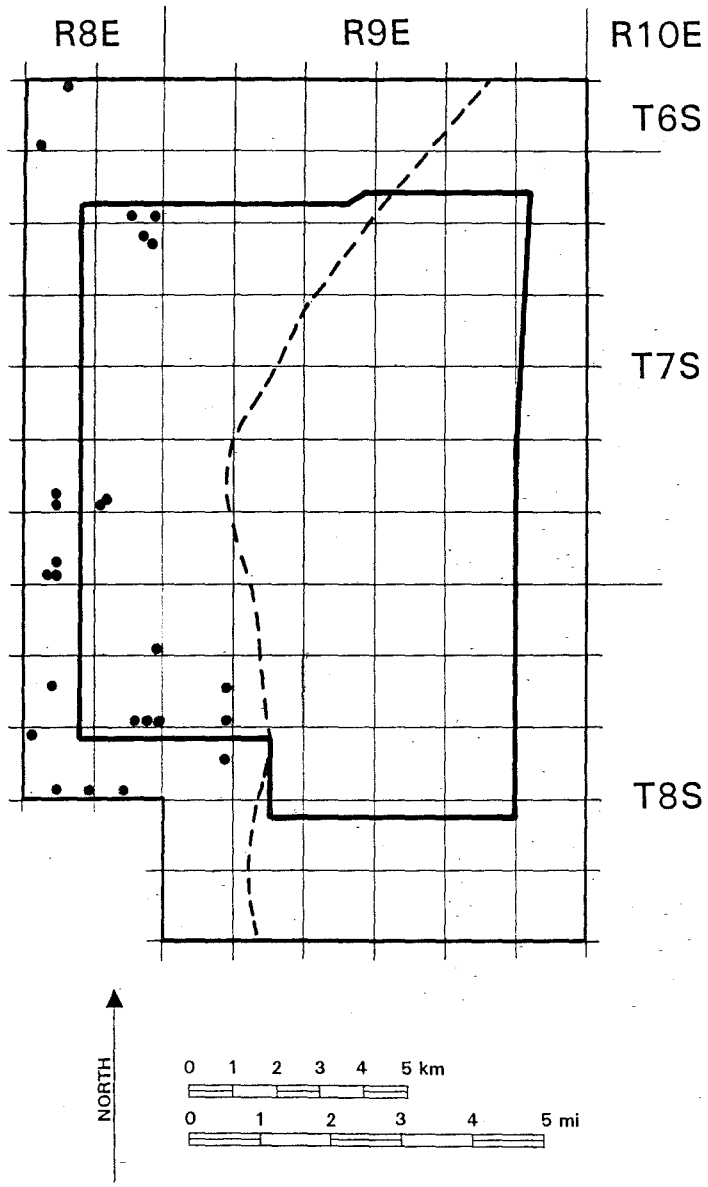


Figure 13. Locations of wells for which water-level data are listed in Table 2. Well locations are shown with small solid circles. Heavy line is border of study area in which fissures are mapped on Plates 1 and 2. Medium-weight line is edge of area in which water-well data were analyzed. Thin lines represent section boundaries. Dashed line is approximate boundary between aquifer (to the west) and nonaquifer areas (east of line). (Aquifer boundary from Laney and others, 1978).

periods range from 11 to 40 years, and average 23 years. Water-table altitude declines range from 13 m to 84 m (43 ft to 276 ft), and average 37 m (121 ft). All six of the wells are located in the southwestern portion of the area in which water-table measurements were analyzed (Figure 13). Subsidence and fissures (including the "Picacho" fissure) also occur in this area. The intervals during which the maximum rate of water-table altitude decline occurred are different for each well. This probably reflects different pumping rates at each of the three wells at different times, and different pumping rates of other wells in the region that tap the same aquifer(s). In two of the wells, water levels rose slightly recently, but only enough to reduce the overall decline by a small amount.

For the eight wells that were measured for ten or fewer years, measurement periods range from one to eight years, and average four years. Water-table altitude declines range from 2 m to 16 m (7 ft to 52 ft), and average 10 m (33 ft). The wells are scattered within the western portion of the area shown in Figure 13. As with the wells with longer measurement periods, the intervals during which the maximum rate of water-level decline occurred are different for each well, which probably results from different pumping rates at each well at different times.

Water levels rose during the period of record in 11 of the 25 wells (Table 2). The maximum water-table altitude increase in a single well was 16 m (51 ft), the average was 7 m (24 ft). All of these wells were measured only two or three times between 1984 and 1988 or 1989, inclusive. Thus, all of these wells have short measurement periods. They are probably old high-production wells that have not been used much recently, and were measured during large monitoring programs that were carried out in 1984 and 1988 to provide data with which to construct the Pinal County ground-water flow model (E.F. Corkhill, oral commun., 1991). If measurements had been made earlier, they probably would show substantial long-term water-level declines. The recent rises may be attributed to two situations: Water budgets and ground-water models suggest that the volume of water in storage is decreasing as the aquifers compact, and floods on the Santa Cruz and Gila Rivers in 1983 (and on the Gila again in 1985) raised water-table altitudes by contributing above-average quantities of recharge to the aquifers.

Amount of water-table altitude decline provides a clue to the amount of land subsidence expected, if the ratio between the two variables is known. Aquifer-sediment compactibility depends on a host of geologic and hydrologic factors, as well as on the amount of compaction that has already occurred.

A key factor is the thickness of clay- and silt-rich units in the aquifer. The range of the ratio of hydraulic-head altitude decline to land subsidence is from approximately 5:1 to 100:1 worldwide, for loosely consolidated clay-rich sediments of Tertiary and Quaternary age (Poland and Davis, 1969). In Las Vegas valley, Nevada, typical ratios are 20:1 for fine-grained sediments and from 40:1 to 60:1 for coarse-grained sediments (Bell, 1981). In the mostly unconfined aquifer system of Picacho basin, the average ratio of water-table altitude decline to land subsidence is 23:1 after the water-table altitude has dropped an initial 32 m (105 ft), and 666:1 before the water level has dropped by the initial amount. These ratios were obtained by averaging and taking the inverse of six values calculated by Holzer (1981).

The maximum reported water-table altitude decline at well 88-14DDD (the well-numbering system used in this report is explained in the caption of Table 2), located 1.3 km (0.8 mi) south of the southwestern corner of the study-area boundary, is 84 m (276 ft) (Arizona Department of Water Resources, 1990). Measurements were made at this well from 1949 to 1989. The total water-table altitude decline from *circa* 1900 to winter 1984-1985 at this location was 107 m (350 ft) (Corkhill and Hill, 1990, figure 3). The 666:1 ratio applies to the initial 32 m (105 ft) of decline, giving a calculated magnitude of land subsidence of 0.05 m (0.16 ft). The 23:1 ratio is used for the subsequent 75 m (245 ft) of water-level decline, giving a calculated magnitude of 3.3 m (10.6 ft) of subsidence. The total calculated subsidence is 3.35 m (10.8 ft). At the intersection of Milligan Road and the Southern Pacific railroad track, which is 3.1 km (1.9 mi) northwest of well 88-14DDD, 2.7 m (9 ft) of subsidence occurred between 1952 and 1977 (Laney and others, 1978).

The calculated amount of subsidence near the well agrees very well with the measured amount. The calculated amount is greater, as expected, since it is based on the approximately 89-year-long period from *circa* 1900 to 1989, while the measured amount occurred in just 25 years. However, the calculated magnitude of subsidence between 1949 and 1975, when the water level declined 74 m (242 ft), is 3.2 m (10.5 ft). This 26-year-long period is almost the same as the 25-year-long period when the measured subsidence was 2.7 m (9 ft). The calculated subsidence appears to be slightly too great. The two values actually agree well, considering all the variables involved and that the ratios of water-level decline to land subsidence were derived using "typical" basin sediment characteristics and other basin-wide average values.

It would be instructive to determine how strong the correlation is between periods of rapid water-table altitude decline and periods of intense earth-fissure activity. (As used here, the term "activity" means the new appearance of fissures at the ground surface, or the branching or reactivation of existing fissures). The length of the time lag between aquifer-sediment dewatering and earth-fissure activity could also be calculated. These determinations would require reliable long-term water-table altitude measurements from many wells, and several sets of air photos (or fissure maps) produced during the same long-term period. Neither data set was available for the Brady/Picacho pumping plants study area, but findings from Slaff and others (1989) pertaining to the east side of Picacho basin lying within the southern portion of the Brady/Picacho area and immediately to the south and west of it provide some clues. Those findings are based on interpretation of 12 sets of air photos taken between 1959 and 1989, and on limited field checking. The periods during which the greatest number of fissures were active was from 1987 to 1989, followed by the period from 1975 to 1976. Existing fissures lengthened the most from 1975 to 1976 and from 1987 to 1989. All indicators of fissure development show that the interval from 1977 to 1985 was the period of least activity. If these findings are true for the Brady/Picacho area, they suggest that current levels of fissure activity there are probably still high. Each period of high activity may be preceded by and overlap with a period of rapid water-table altitude decline.

Changes in Geomorphology and Surface-Water Hydrology

The physical form of the land, especially with respect to drainage patterns, is changing in the study area and in other parts of Picacho basin. The changes addressed here are caused by three human-induced factors, which are discussed separately below: 1) regional land subsidence; 2) earth fissures and localized collapse pits and piping; and, 3) the CAP aqueduct, canals, and appurtenant structures.

Regional Land Subsidence

Land subsidence is presumably affecting a large portion of Picacho basin. A lack of level lines, extensometers, and Global Positioning System bench marks makes documentation of the magnitudes and rates of subsidence difficult except at a few points in the basin (such as along Interstate Highway 10). However, the geomorphic and hydrologic manifestations of subsidence are becoming progressively more evident. The central portion of the basin, which is subsiding the most, has

become a center of fluvial deposition, in some places receiving slightly coarser-grained sediments than it had been under natural conditions. It is gradually being filled in.

Another result of subsidence in the basin center is more extensive and deeper inundation from flooding. During the October 1983 flood on the Santa Cruz River, most of the water flowed northwestward through the southwestern part of Picacho basin along the east sides of the Sawtooth and Silver Reef Mountains (Figure 1) to the Gila River near the towns of Maricopa and Santa Cruz. However, a 2.5 km (1.5 mi)-wide arm of water flowed northward along ditches, roads, and a remnant of an old Santa Cruz River channel and inundated the eastern portion of Eloy (Roeske and others, 1989). The floodwater traversed an area that had undergone more than 2.1 m (7 ft) of subsidence between 1952 and 1977, and flowed over the bench mark located approximately 5.6 km (3.5 mi) south of Eloy, where the greatest amount of subsidence (3.8 m [12.5 ft]) documented to have occurred in Picacho basin between 1952 and 1977 occurred (Laney and others, 1978).

Subsidence of the central basin lowers the local base level and leaves the peripheral areas, which consist mostly of alluvial fan deposits, relatively higher in altitude. This results in increased stream power, and when the streams flow (in response to heavy precipitation) they downcut into and erode the alluvial fans more deeply and quickly. A considerable amount of recently active gullying is visible in the Brady/Picacho area. The material eroded from the fans is deposited on the distal ends of the fans and on the basin terraces and other deposits that lie closer to the basin center.

Earth Fissures and Localized Collapse Pits and Piping

Many fissures, notably ones with structurally controlled locations at a basin's edge, trend normal or at high angles to stream axes. This orientation allows fissures to intercept stream flow and to lower local base level. Streams respond by dramatically deepening their channels upslope from the fissure, abandoning their channels downslope, and depositing their entire sediment loads in the fissures. This is occurring at many fissure-intercepted streams in the Brady/Picacho area. Some streams take a sharp turn and flow within the fissure for a distance. As the fissure fills with sediment, the stream aggrades (raises its channel altitude) back to its earlier position. When the fissure is full, in some cases, the stream once again crosses the area undisturbed, and reoccupies its old channel downslope from the fissure.

Open fissures, by lowering base level locally, cause the formation of headcuts and small channels that advance laterally from the fissures. Most of the headcuts form and lengthen farthest on the upslope sides of fissures, but some form on the downslope sides. The lengths of the channels are a function of their age, the type of material in which they form, the slope of the ground surface, and patterns of precipitation and runoff. Some of the headcuts form single, relatively narrow channels that may be up to tens of meters (scores of feet) long. Others are shaped like amphitheaters, with several small "tributaries" that coalesce into one or two main channels before reaching the fissure. Most of these form relatively rapidly in fine-grained sediments on gentle slopes.

Localized collapse pits and piping are small features that are associated with earth fissures in some places (for example, see location 131123 on Plate 1). In other places (11343 on Plate 1), where no fissure is known to be nearby, collapse pits and piping may be fissure precursors. In order for pipes and pits to form, there must be preexisting voids as low as or lower in altitude than the pipes and pits. Fissures that exist only in the subsurface could stimulate piping and the formation of collapse pits. These features may have local effects on drainage patterns and land-surface morphology, but they do not have the potential to alter geomorphology and surface-water hydrology on the scale of the other factors discussed in this section.

The CAP Aqueduct, Canals, and Appurtenant Structures

Placement of a long structure (such as the CAP) on the land surface causes predictable changes in surficial systems. The aqueduct acts as a long dam across the alluvial fans on which it rests. Runoff ponds on the upslope side of the aqueduct, causing sedimentation, abnormally deep water accumulation in and beside preexisting drainage channels, and unusually long periods of sediment saturation. The standing water may trigger piping, sediment collapse, and surface expression of voids and earth fissures that previously were only subsurface features. Water percolates into the alluvial fans and, if there is a slope parallel to the aqueduct, flows along the berm on the upslope side of the aqueduct until it reaches an overchute or other structure that conveys it down-fan. Drainage channels downslope from the CAP are cut off from their upstream catchment areas, so they no longer carry their natural volumes of water and sediments. When they receive runoff (from heavy precipitation), they downcut (erode) their channels, because the water is free of most sediment and thereby has more power to erode. Where overchutes and other drainage-conveyance structures empty downslope from

the aqueduct or canal, large quantities of runoff are introduced in locations where preexisting channels are not present or are adjusted to carry much smaller discharges. Rapid erosion ensues, as new channels are carved, and sediment is deposited downslope where channel gradients diminish and discharge decreases as water percolates into the soil.

Usefulness of Very Large Format Aerial Photographs

One of the purposes of this investigation was to evaluate the value of using very large format air photos to identify earth fissures, especially incipient fissures and those with little ground-surface expression. For this purpose, five 1:4,800-scale black and white 103 cm x 113 cm (40.5 in. x 44.5 in.) air photos taken in March 1989 were used. They are enlargements of standard 1:24,000-scale, 23 cm x 23 cm (9 in. x 9 in.) contact prints produced by Arizona Department of Transportation. The prints provided coverage of the entire study area. The advantages and disadvantages of the enlargements for fissure identification are summarized below.

Advantages

1) They show considerable detail, allowing the viewer to actually peer into some fissures. Branches, changes in width, and discontinuous reaches of fissures are readily observed.
2) Short fissures are easier to recognize on enlargements than on standard-format photos.
3) Fissure locations and endpoints and other geographic features can be accurately located. The user's field location also can be identified accurately.
4) Fissures with faint traces and those without vegetation concentrations along them are more readily identified on photo enlargements.

Disadvantages

1) They cannot be viewed stereoscopically.
2) They are unwieldy for field use.
3) They are only suitable for investigations of relatively small areas.
4) They are expensive.
5) They are not widely available.

6) Lineaments other than fissures (drainage patterns, vegetation alignments, man-made furrows and berms, etc.) are more striking, and are more easily interpreted as possible fissures on photo enlargements.

The very large format air photos were useful but not indispensable for this investigation. They were valuable in allowing the exact locations of fissures to be pinpointed, but they also drew attention to a large number of lineaments of uncertain origin that are not actually fissures.

SUMMARY

Many earth fissures occur within 4 km (2.5 mi) of the CAP facilities between Brady and Picacho pumping plants. Although the proposed route of this portion of the aqueduct was changed during the planning phase of the Central Arizona Project in an attempt to avoid fissures, this investigation suggests that lengthening of existing fissures and/or the formation of new fissures may damage the facilities. The "Brady" fissure is cause for concern, because over the years it may lengthen considerably and cross the aqueduct. It may also branch and develop vertical displacement (downthrown to the west) by the process of aseismic creep if it is the surficial expression of an inactive buried bedrock fault with large vertical displacement. Several other lengthening, active, and/or potentially active fissures and one zone of localized collapse pits and piping cross or are close to the Tucson aqueduct, the Santa Rosa canal, or the CAIDD canal. Periodic monitoring of these features (especially during periods of intense precipitation and runoff) will insure that changes in their status are discovered promptly, and that measures to protect the facilities are taken early so that damage is avoided or minimized.

The rate of ground-water withdrawal has greatly exceeded the rate of natural and artificial recharge in Picacho basin since the mid-1930's (Holzer, 1981). Measurements made at wells in and adjacent to the southwestern portion of the study area for periods spanning 11 to 40 years show water-table altitude declines of as much as 84 m (276 ft). Declines of this magnitude lead to aquifer-sediment compaction, land-surface subsidence, and earth-fissure formation. Some of the wells show modest water-level rises over the past several years. Without these partially offsetting rises, the overall declines would be even greater. Other wells, at which measurements were made only during the past several years, show similar modest water-level rises of 1 m to 6 m (4 ft to 20 ft). The rises probably

result from aquifer compaction that causes a decrease in the volume of water in storage, and/or from greater than normal recharge supplied by recent floods on the Santa Cruz and Gila Rivers.

The shape of the land surface in the study area is changing because of the effects of subsidence, earth fissures and localized collapse pits and piping, and the presence of the CAP. Gullying and channel downcutting are occurring on the upslope sides of fissures, on the downslope sides of the aqueduct and canals, and on some of the alluvial fans. Aggradation is occurring upslope from the aqueduct and canals, within the fissures, and in the central portion of the subsidence bowl. These geomorphic adjustments will continue to occur as the system responds to the human-induced changes it is undergoing.

The main advantages of using very large format air photos for this investigation are that they allow fissure endpoints and locations to be identified accurately. The drawbacks are that they are awkward to use and other types of lineaments easily can be mistaken as fissures.

The findings of this study suggest three lines of investigation that would be valuable for future work: 1) Geophysical exploration is needed to delineate basement structure and depth to bedrock in detail. This would help to resolve whether the "Brady" fissure is a northern continuation of the "Picacho" fissure, and if they are separated from each other to the north of Picacho pumping plant by an east-west trending step in the range-front fault. It would also provide better understanding of the relationship between fissure location and bedrock structure, and allow predictions to be made with more confidence; 2) Additional studies of this type are needed at other fissure-prone reaches of the aqueduct. Reaches both north and south of the Brady/Picacho area are suitable sites; and, 3) Further analysis of the ground-water hydrology as it relates to spatial and temporal earth-fissure development patterns would be useful. It would allow locations of some fissures to be explained and those of others to be predicted. In addition, present and future rates of fissure development could be understood in the context of aquifer sedimentology and aquifer stress.

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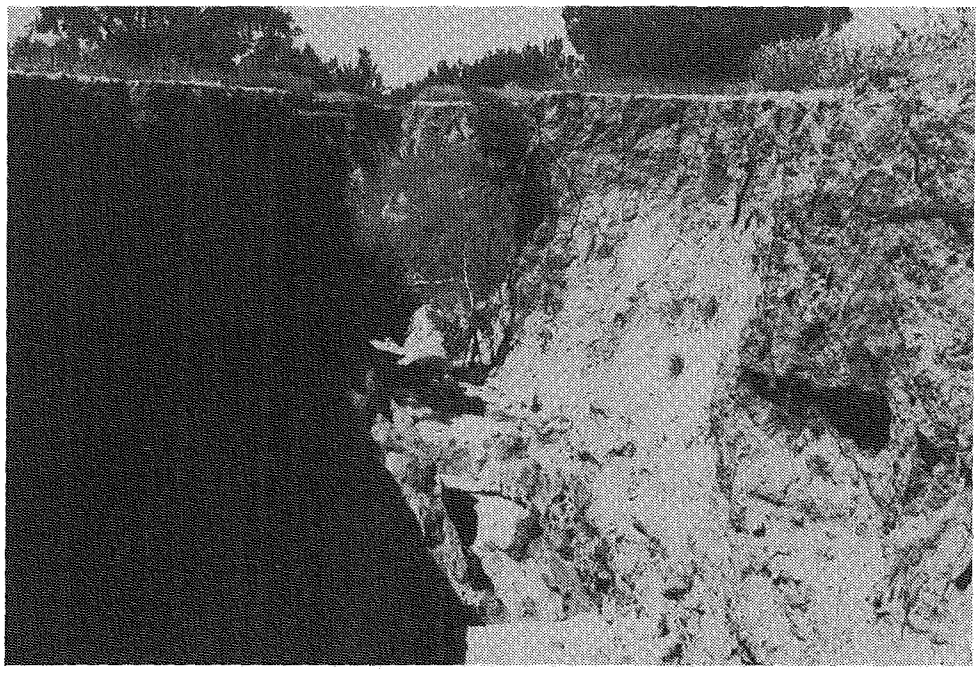

Figure 3. The young (age group 2) middle reach of the "Brady" fissure, between segments 12412 and 12413 on Plate 1. The gully is approximately 2 m (6.6 ft) wide and 2 m (6.6 ft) deep. View to the north.

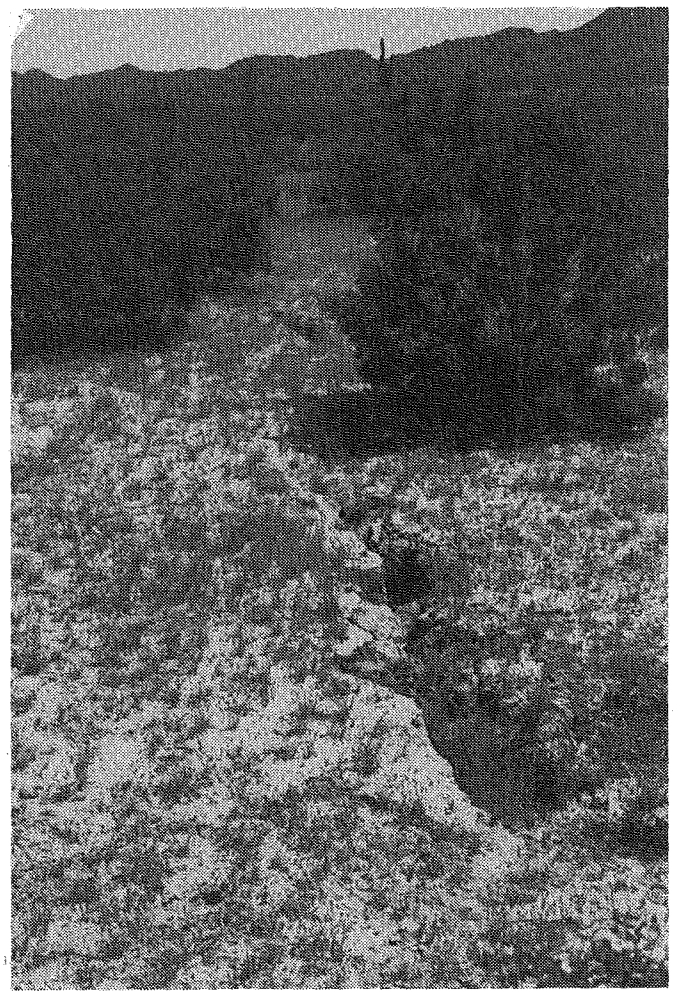

Figure 4. This very young (age group 1) fissure segment (131115 on Plate 1 and Table 1) is lengthening toward the northeast. Note Tucson aqueduct in background. View to the northeast.

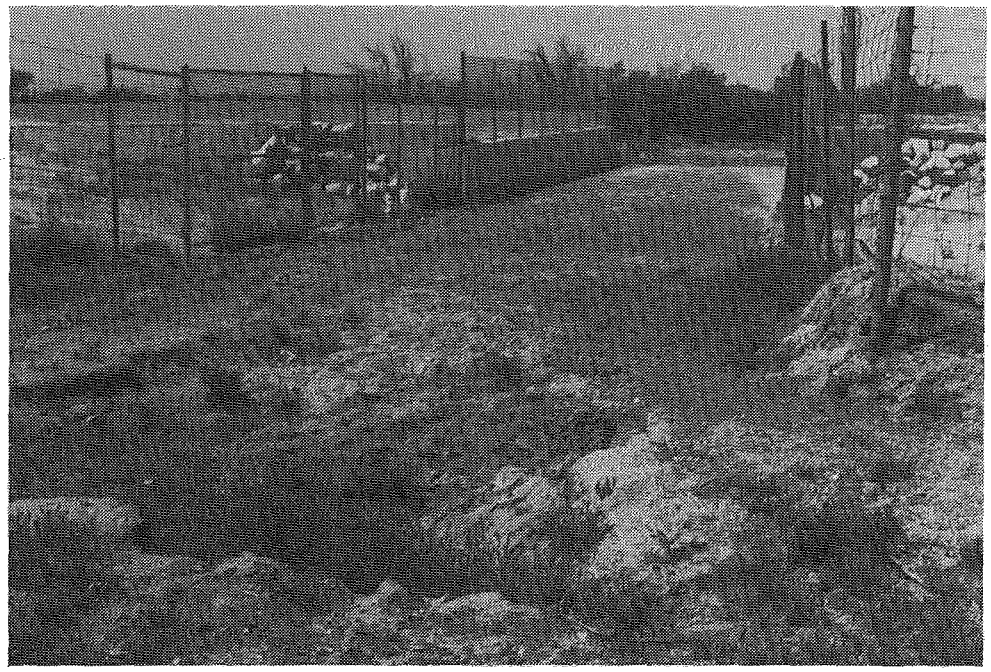

Figure 5. The 0.5 m (1.6 ft)-deep pit in the foreground is a sign of activity on "Picacho fault" segment 10414 close to where the fissure crosses the CAIDD canal (see Plate 2 for location). The depression, located on the upslope side of the canal, is in an area that is aggrading. A bridge that enables wildlife to cross the canal is in the background. View to the northwest.

Figure 6. Young pit on active segment 10413 (see Plate 2) of the "Picacho fault". Approximately 0.6 m (2 ft) of vertical displacement is visible across the pit (down on the right [west] side), and motion may be still occurring slowly. Notice trace of Tucson aqueduct in background. View to the southeast.

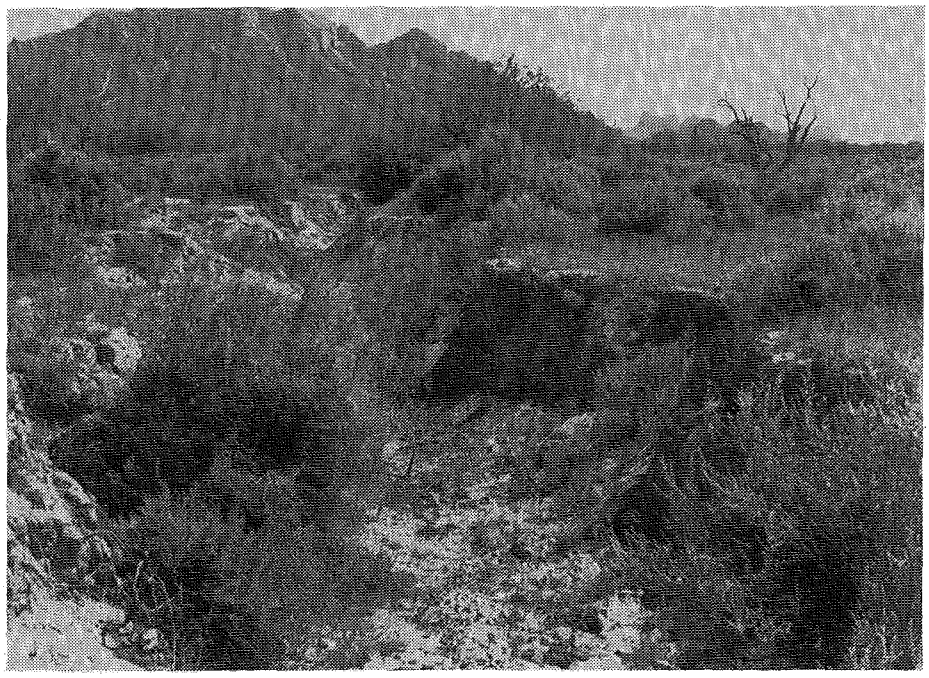

Figure 7. Active fissure segment 17433 (see Plate 1 for location) appears as a mature fissure gully here, but has young (age group 2) morphology elsewhere. Features not visible in the photo that indicate active/ reactivated status include young collapse pits in fissure floor as well as in lines beside fissure, and a bench (former floor) preserved above the existing floor. View to the south-southeast.

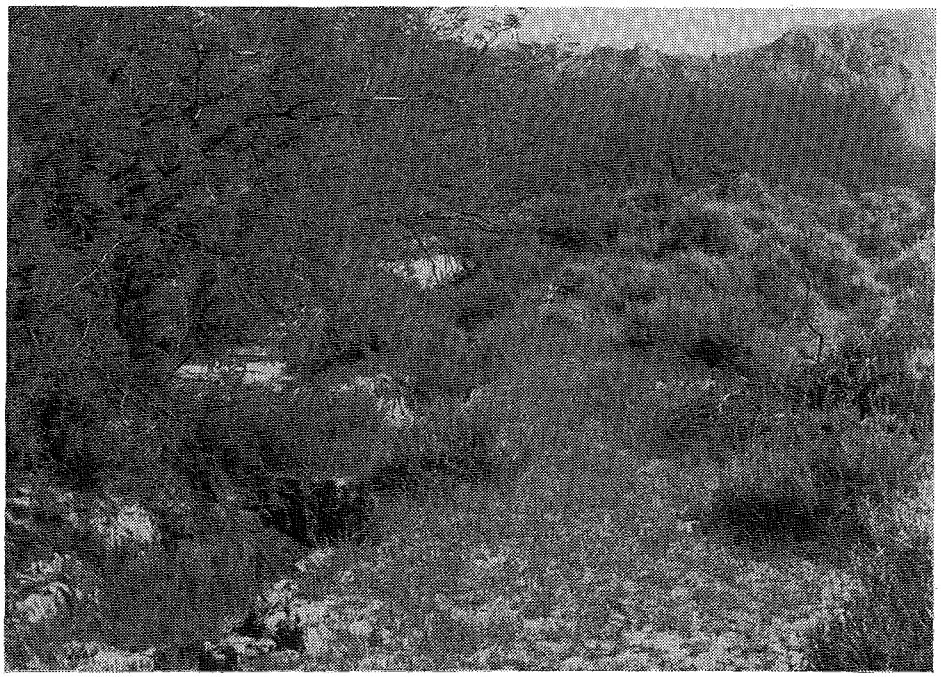

Figure 8. Active/reactivated fissure segment 17434 (see Plate 1 for location). Light-colored fissure floor (on left, under mesquite trees) has diverted a stream and shows mature (age group 3) morphology. Very young (age group 1) morphology is displayed by reactivation crack (dark area in left foreground). View to the south-southeast.

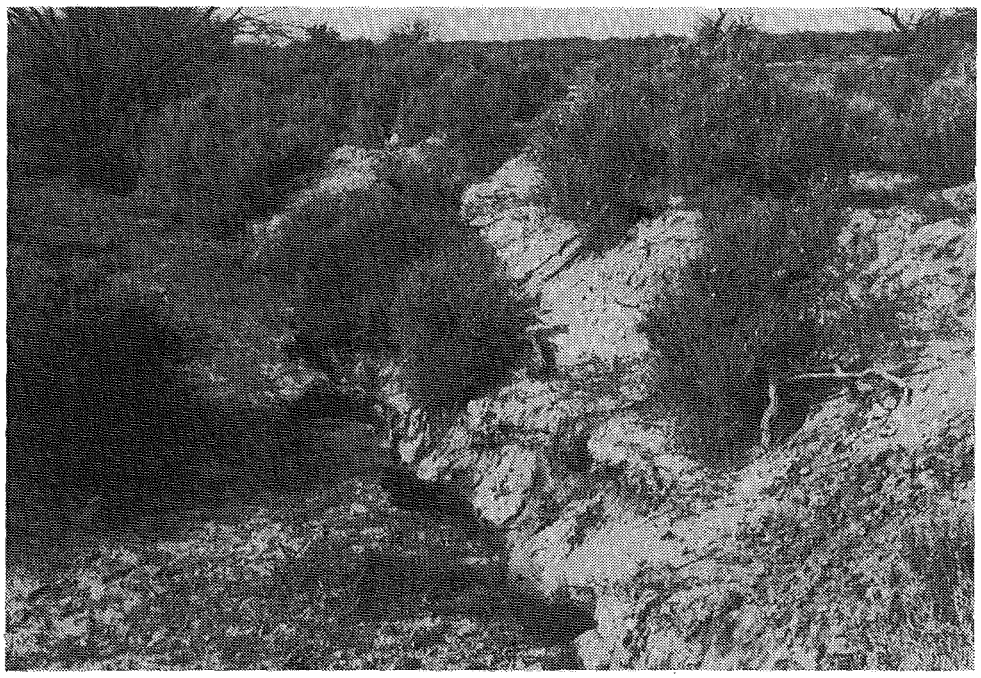

Figure 9. Reactivated fissure segment 11311. Smooth floor of mature (age group 3) fissure is on left. Very young (age group 1) crack, indicating reactivation, cuts the older fissure's floor in lower center of photo. The original ground surface is visible in the upper right. View to the west.

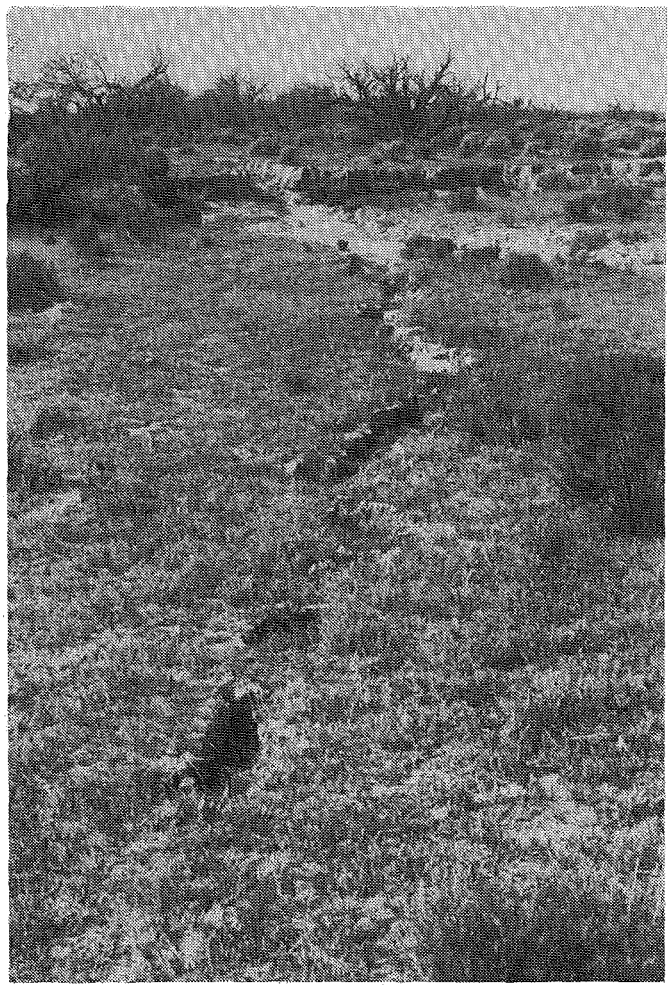

Figure 10. Very young (age group 1) fissure segment 11310 (see Plate 1 for location). Notice narrow width and vertical walls. View to the southwest.

Figure 11. One of the pits in the area of localized collapse pits and piping designated as 11343 on Plate 1. The pit is approximately 2 m (6.6 ft) in diameter and 0.75 m (2.4 ft) deep.

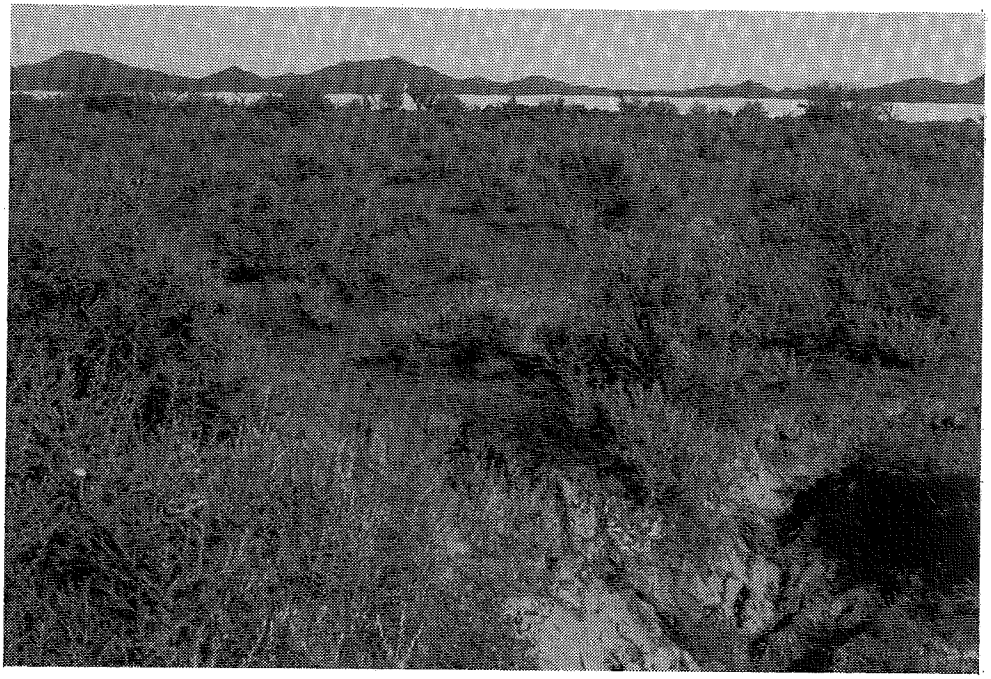

Figure 12. To facilitate future inspection of this site, the same pit shown in Figure 11 is in the foreground, with the Santa Rosa canal and Picacho Mountains in the background. View to the southeast.