DEVELOPMENT OF EARTH FISSURES IN PICACHO BASIN, PINAL COUNTY, ARIZONA FROM 1959 TO 1989

A Report to the U.S. Bureau of Reclamation and
the Arizona Department of Transportation

by
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INTRODUCTION

Earth fissures are open surficial tension cracks in unconsolidated and semi-consolidated sediments that may display vertical and/or horizontal displacement. Earth fissures have become increasingly common in the sediment-filled basins of southern Arizona where ground water is being removed at high rates. Water-table altitude decline resulting from withdrawal of large quantities of ground water causes compaction of aquifer sediments, and aquifer compaction leads to land-surface subsidence. Differential subsidence produces stresses in sediments, and fissures develop where horizontal stresses are relatively large (Strange, 1983).

Earth fissures have damaged a variety of facilities in southern Arizona during the past 60 years. The formation of fissures is one of several geologic hazards that must be recognized, understood, and overcome in order to construct and maintain reliable roads, buildings, utility systems, and other structures. Under contract to the U.S. Bureau of Reclamation (USBR), the Arizona Geological Survey (AZGS) conducted an evaluation of earth-fissure development in a portion of Picacho basin (also called Eloy basin or the lower Santa Cruz River basin) in order to determine development patterns and rates. The locations of Picacho basin and the portion of the basin studied are shown in Figure 1.

The area was chosen for this investigation because the Arizona Department of Transportation (ADOT) has obtained twelve sets of aerial photographs of it during the past 30 years and the USBR's Central Arizona Project (CAP) aqueduct extends through a nearby portion of Picacho basin. The aerial photographs allow detailed spatial and temporal patterns of earth-fissure development to be determined. These patterns are displayed graphically in Plates 1 through 6 and are discussed below in the Findings section. In general, the rates of formation of new fissures and lengthening of existing fissures were highest during the late 1960's, mid-1970's, and late 1980's. The rates were lowest during the late 1970's and early to mid-1980's. There is reasonably good correlation of the amount of intense precipitation in Picacho basin and the number of newly developed earth fissures. Generalized morphological characteristics have been identified which allow the relative age of a fissure to be estimated, but other variables, such as sediment grain size and regional slope direction, must also be taken into account. Most very young earth fissures cannot be identified on 1:24,000 or smaller-scale aerial photographs even if the interpreter knows exactly where to look.

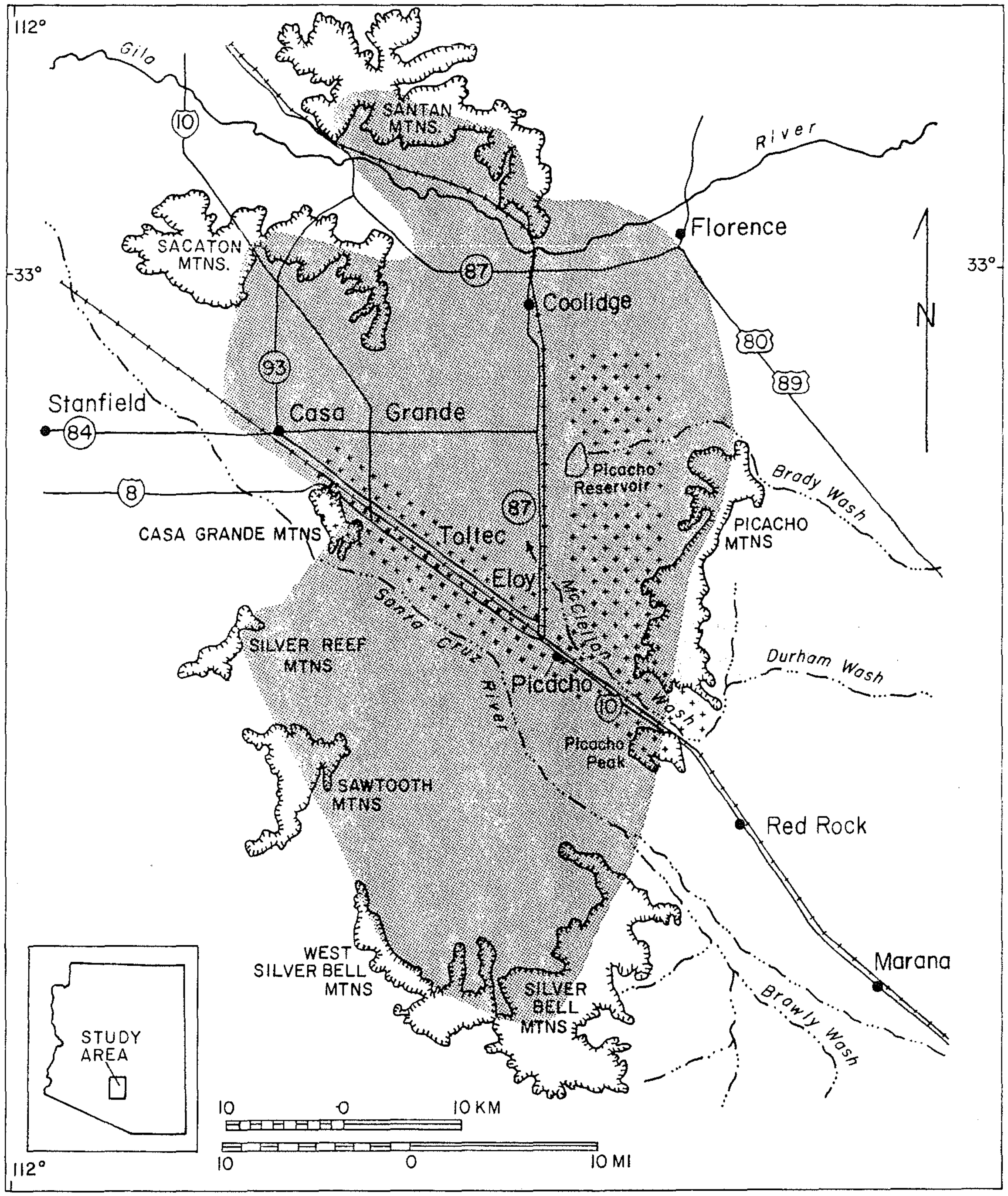

Figure 1. Location map showing approximate extent (shaded) of Picacho basin, south-central Arizona. The area included in the study is shown with the cross pattern.

Some earth fissures initially appear as linear or arcuate, narrow (up to 3 cm- [1.2 in.-] wide), discontinuous or en echelon cracks tens to hundreds of meters (tens to thousands of feet) long (Figure 2). Other fissures are first expressed as series of shallow (up to 30 cm- [1 ft-] deep) circular to elongate depressions. During intense rainstorms and large human-induced water discharges, fissures erode into so-called fissure gullies (Kam, 1965) as sediment erodes from the land surface and from the walls of the fissure and is deposited at depth. The maximum dimensions of a fissure gully are determined by the sediment storage capacity of the fissure, and have reached at least 10 m (33 ft) wide, 6 m (20 ft) deep, and 300 m (984 ft) long in Picacho basin. Some fissures apparently develop at depth and propagate upward, whereas others may open initially at the ground surface and then extend downward (Anderson, 1986).

Fissures in surficial sediments may be caused by a number of other processes in addition to the sequence of ground-water withdrawal, aquifer compaction, and land-surface subsidence. Other causative processes include: 1) earthquakes; 2) horizontal seepage forces; 3) natural compaction; 4) horizontal contraction; 5) dessication; and, 6) hydrocompaction (vertical collapse of low-density near-surface sediments in response to a large and/or sudden application of water) (Anderson, 1986). Fissures caused by dessication and hydrocompaction are common in southern Arizona basins, but their dimensions are considerably smaller than those caused by water-table altitude decline, aquifer compaction, and land subsidence. Only those features associated with water-table altitude decline are referred to as fissures or earth fissures in this paper.

The earliest detailed published report of an earth fissure occurring in Arizona is Leonard's (1929) description of a feature that formed 4.8 km (3 mi) southeast of the town of Picacho in September 1927. It was approximately 305 m (1000 ft) long, up to 0.9 m (3 ft) wide, and up to 4.6 m (15 ft) deep. Another fissure nearby is more than 15.8 km (9.8 mi) long at present, and is the longest earth fissure in Picacho basin (see Plates 1 and 2). Many other fissures have developed in the basin since the 1920's; the combined length of all fissures in the portion of the basin covered in this report is >100 km (62 mi) at present.

PURPOSE

There are several goals of the project. The ultimate aim is to gain a better understanding of fissures and the processes that create and modify them so that they will be less hazardous to

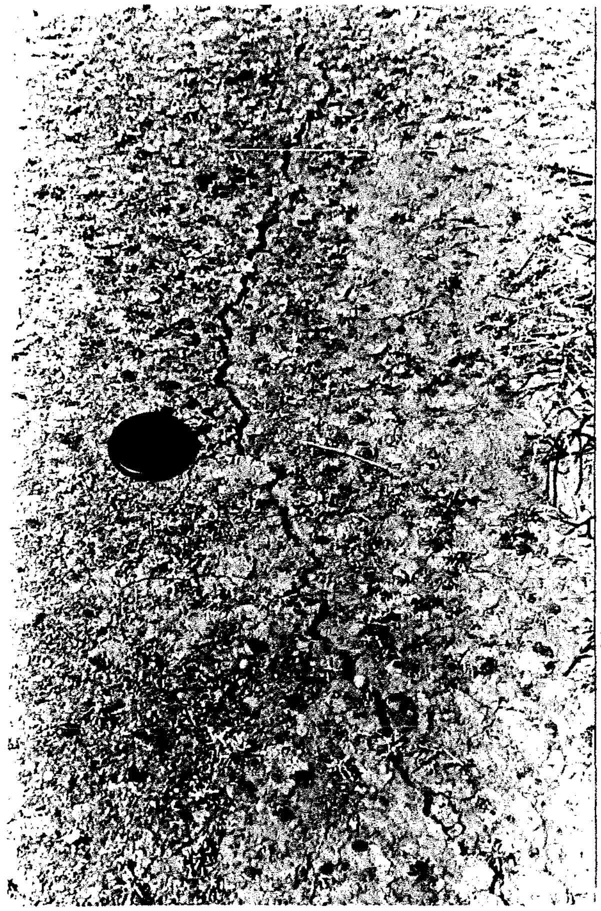

Figure 2. This very young fissure (16332b on Table 1) is a sinuous discontinuous crack less than 1 cm (0.4 in.) wide at this point. See Plate 6 for location.

people and property. Picacho basin was chosen because many sets of aerial photographs were taken along the same flight line between 1959 and 1989. (No fissures were identified on air photos taken in 1936 which cover two isolated parts of the basin). Picacho basin was also chosen because it has an abundance of fissures of various ages, it is readily accessible, considerable work has been done there previously, and because a portion of CAP aqueduct is located nearby.

Other goals of the study include the following: 1) determine whether incipient or very young fissures may be identified by inspecting air photos; 2) assess the roles of heavy precipitation and variations in annual climate in fissure formation and development; 3) determine if soil and sediment type affect fissure form and/or development; and, 4) attempt to develop a generalized set of time-dependent morphologies that fissures exhibit as they age. This is a pilot project. It is anticipated that related work will be done in the future to reduce the hazards presented by new fissure development and existing fissures in southern, central, and western Arizona.

GEOGRAPHIC SETTING

Picacho basin is a low-lying alluviated expanse of approximately 1165 square kilometers (450 sq mi) in Pinal County, south-central Arizona. Picacho basin is an informal name for a broad region that does not coincide with the boundaries of any single ground-water basin. It is a large physiographic basin bounded on the north by the Santan Mountains, on the east by the Picacho Mountains, on the south by the Silver Bell and West Silver Bell Mountains, on the west by the Sawtooth, Silver Reef, and Casa Grande Mountains, and on the northwest by the Sacaton Mountains (Figure 1). Basin altitudes range from 549 m (1800 ft) south of Picacho Peak to 427 m (1400 ft) at Casa Grande. Picacho basin slopes gently down to the northwest and is drained by the Santa Cruz River and a number of smaller ephemeral streams. The Gila River flows across the northernmost portion of the basin. The area receives an average of 208 mm (8.2 in.) of precipitation per year, based on data collected at five stations for periods of 16 to 41 years ending in 1972 (Sellers and Hill, 1984). Slightly more than one half of the annual precipitation arrives from the south and southeast with convective thunderstorms during the summer months. The remainder is brought mainly from the west by large-scale cyclonic (frontal) storms during the cooler half of the year.

Access is excellent to most of the parts of Picacho basin included in this study. The area is bisected by Interstate Highway 10, and State highways 87 and 287 pass through the eastern and northern portions of the area, respectively. Some secondary paved roads exist, as well as many graded and unimproved dirt roads. Land use is predominantly agricultural. The principal towns are Casa Grande, Eloy, Picacho, and Toltec.

GEOLOGIC SETTING

Picacho basin is in the Basin and Range physiographic province of Arizona. The physiography of the region resulted primarily from middle and late Cenozoic extensional tectonism. During the mid-Tertiary Orogeny from 32 Ma (million years ago) until 20 Ma, vast quantities of ash flows and other volcanic deposits were extruded. Large-scale normal faulting and detachment faulting occurred in southern and central Arizona during this interval (Reynolds, 1985; Dickinson and Shafiqullah, 1989). Regional subsidence probably occurred contemporaneously with detachment faulting. Magmatic and tectonic activity and normal faulting decreased between 20 Ma and 15 Ma and sediments began to accumulate in the ancestral Picacho basin. The Basin and Range disturbance began approximately 13 Ma (Scarborough and Peirce, 1978; Eberly and Stanley, 1978; Shafiqullah et al, 1980). From 13 Ma to 5 Ma the crust thinned and block faulting down-dropped the basins and left intervening mountains as high-standing horsts. Sediments continued to fill the basins. Internal drainage prevailed until approximately 3 to 5 Ma, when through-flowing streams were established. Tectonic activity has been relatively minor for the past 5 My (million years). Pediments formed as mountain fronts retreated, and sediments partially filled the valleys. While continental glaciation occurred to the north during much of the past 1.6 My, the climate of the American southwest was cooler and perhaps moister, but with a smaller proportion of the precipitation occurring during the summer (Van Devender et al., 1987).

Quaternary Geology and Geomorphology

Picacho basin is different than basins upstream along the Santa Cruz and Gila Rivers in that there is very little dissection of surficial deposits. Although the basin is externally drained, downcutting by through-going streams has been very modest during the Quaternary epoch (the past 1.6 My). This has resulted in a lack of relative altitude differences between terraces of different ages, and the deposition of playa-like and eolian sediments.

Three landform types are present in Picacho basin: piedmont terraces, alluvial fans, and eolian deposits (see Plates 1-6 for descriptions). Piedmont terraces occur at low altitudes and are associated with axial drainages. Relative ages of terraces were determined only by examining soil-profile development because of the lack of relative altitude differences between terraces of different ages and because agriculture has extensively modified many of the landforms. Climatically induced changes in stream power have produced a series of alluvial fans which emanate from the mountains on the periphery of the basin and have steeper gradients than the piedmont terraces. Eolian landforms include relict dunes and deflation pits. These deposits typically are found in low-lying areas. They are extensive near Picacho Reservoir, creating a gently undulating to hummocky surface with low drainage density. Relief between the dunes and deflation pits is up to 2 m (6.1 ft).

Like the piedmont terraces, alluvial fans of different ages do not show large or abrupt altitude differences: Although older fans tend to occur higher on the piedmont slopes, altitudes of adjacent fans of different ages are similar. Fan ages are estimated based on drainage patterns and the development of desert pavement, rock varnish, and soil profiles. Most piedmont terraces are composed of sediment that is too fine-grained to develop varnish or pavement.

Throughout the Quaternary, the areal drainage has been dominated by discontinuous ephemeral streams. The Santa Cruz River itself may be viewed as a large ephemeral stream that usually terminates in Picacho basin. Its fan has shifted across the basin since at least middle Pleistocene time (approximately 500,000 years ago). The general pattern of fan migration can be seen in the distribution of piedmont terraces of different ages (see Plates 1-6). T1 is commonly found in the northeast, T2 is most extensive in the central and north-central basin; T3 is found primarily in the south-central and southwest parts of the basin, and Y is most abundant in the southernmost part of the basin (much of this is not within the mapped area). Thus the locus of deposition seems to have moved from the north and northeast to the south and southwest. This migration resembles the depositional pattern of smaller alluvial fans, which migrate to maintain a gradient sufficient to transport their sediment loads. McClellan Wash seems to have behaved similarly.

Stratigraphy

Picacho basin is a deep structural trough filled with terrigenous deposits of middle and late Cenozoic age (Figure 3). Units that pre-date the Basin and Range disturbance include

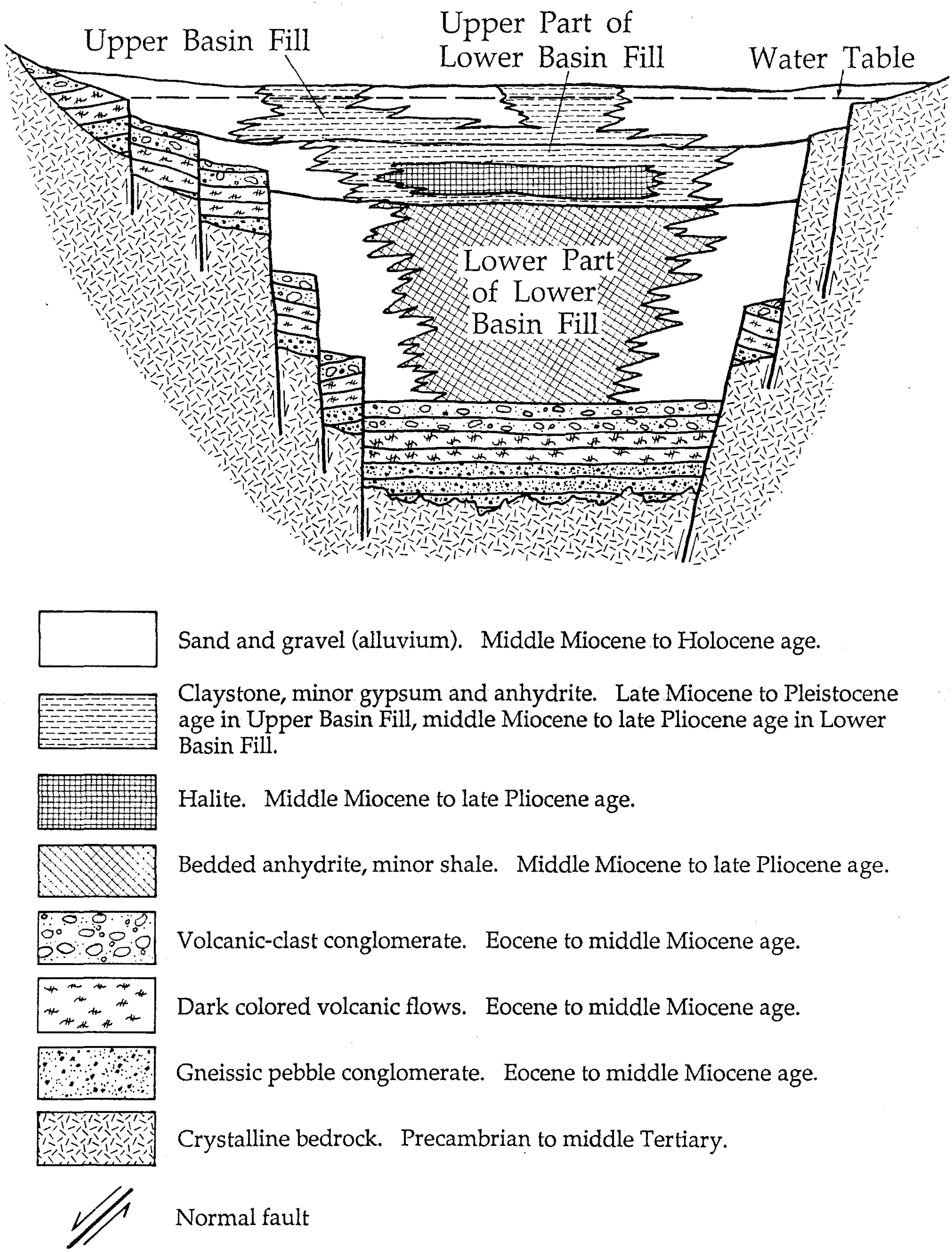

Figure 3. Generalized stratigraphy and structure of Picacho basin. Modified from Pool, 1986; Scarborough and Peirce, 1978; Freethey and others, 1986.

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. These units make up the down-dropped floor and walls of the basin, most of the pediments, and the mountains.

Overlying the basin floor is approximately 2335 m (7660 ft) of basin fill, which is divided into lower and upper units based on structural and stratigraphic characteristics (Scarborough and Peirce, 1978). Lower basin fill is subdivided into a lower part and an upper part. Based on information from a 3103 m-deep (10,180 ft-deep) borehole drilled in Picacho basin by Chevron USA Inc., the lower part of the lower basin fill is 1824 m (5985 ft) of bedded anhydrite with minor shale. The upper part is 219 m (720 ft) of claystone with minor gypsum and anhydrite overlying halite. Lower basin fill was deposited in an internally drained basin during the Basin and Range disturbance, between approximately 13 Ma and 7 Ma.

The lower part of the upper basin fill, deposited while tectonic activity waned and then ceased, consists of approximately 291 m (955 ft) of claystone with minor gypsum and anhydrite. These sediments are similar to the underlying upper part of the lower basin fill, and also probably were deposited in a closed basin. The distribution of the coarse- and fine-grained facies was strongly influenced by the locations of major sources of clastic material: The coarse-grained facies was deposited closer to principal sources of detritus. The upper part of the upper basin fill is made up of 201 m (660 ft) of gravel and sand which were deposited by a gradually aggrading, regionally integrated drainage system. Upper basin fill was deposited after approximately 7 Ma (Pool, 1986). Alluvium of the Santa Cruz River is up to 30 m (100 ft) thick and is found within 3.2 km (2 mi) of the present river channel (Pool, 1986).

HYDROLOGIC SETTING

Potentially water-bearing units of Picacho basin include alluvium, basin fill, and some of the older consolidated rocks (Precambrian, Paleozoic, and Mesozoic igneous, metamorphic, and sedimentary rocks). The older rocks owe their (secondary) permeability to fractures. The highest discharge rates are obtained from wells in saturated coarse-grained alluvium, but the enormous volume and widespread occurrence of basin fill make it the most important aquifer. Ground water is unconfined in most of the aquifers; it is confined or semiconfined in sand and gravel lenses within the fine-grained facies of the basin fill and within deep portions of the fine-grained facies.

The depth to the water table in 1977 ranged from 30 m to 61 m (100 ft 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). In general, depth to ground water increases from the basin center to the bounding mountains. Significant rates of ground-water withdrawal began in Arizona around 1910 (Schumann and Poland, 1970). The withdrawal rate has greatly exceeded the rate of natural and artificial recharge since the late 1930's (Strange, 1983). Between 1923 and 1977, water tables decreased in altitude by 30 m (100 ft) near Eloy, by 91 m (300 ft) near Picacho, and by almost 152 m (500 ft) near Stanfield, which is 19.3 km (12 mi) west of Casa Grande (Konieczki and English, 1979). Rates of water-table altitude decline as high as 3 m (10 ft) per year have been measured.

As water-table altitude decreases, hydrostatic pressure on dewatered sediments decreases and effective load increases. Hydrostatic pressure is transmitted to the base of the sediments through pore water, whereas effective load is transmitted through points of contact between sediment grains. Increased effective load causes compaction by reorienting grains in sediments that were not previously packed as tightly as possible. Compaction at depth causes subsidence of the ground surface. The entire study area subsided a minimum of 0.49 m (1.6 ft) between 1905 and 1977, and a site 4.8 km (3 mi) south of Eloy subsided 3.8 m (12.5 ft) during the same period (Laney and others, 1978).

RESEARCH APPROACH

The study began with a review of pertinent literature. Much is available, and the AZGS is presently compiling an exhaustive bibliography of references pertaining to earth fissures. The literature reviewed included climatic records that were used to determine the relationship between intense precipitation events, total annual precipitation, and the formation or elongation of fissures.

Eleven sets of black and white and one set of color aerial photographs were examined stereoscopically to identify and locate fissures and to monitor changes in the fissures over time. The nominal scale of the photos is 1:24,000; they were taken in 1959, 1963, 1967, 1969, 1971, May and December 1975, 1976, 1978, 1985, 1987, and 1989. The older photos were examined first, so that knowledge of the locations of more-recently formed fissures would not bias the interpretations. Then, after examining the more recent photos, the older photos were viewed again to see if incipient fissures could be recognized earlier in time once the interpreter had learned where to look for them.

Many of the mapped fissures were visited in the field between February and July 1989. The locations and lengths of the fissures were verified, photographs were taken, and morphologic data were collected (see Table 1). A few fissures were discovered during the field checking which do not appear on the aerial photographs because they are young, narrow, and lack vegetation concentrations. Surficial deposits were mapped on aerial photographs and verified in the field. Reconnaissance checking of soil profiles, desert pavement, rock varnish, grain-size distribution, and sediment composition were used to distinguish various deposits.

FINDINGS

The results of this study include: 1) the development of a morphologic framework with which to assess relative ages of fissures; 2) an evaluation of whether all existing fissures may be recognized on 1:24,000-scale aerial photographs; 3) the determination of rates of fissure development during the past 30 years; and, 4) the correlation of certain aspects of climate with fissure development.

It is apparent that many fissures progress through a sequence of morphologic stages as they develop. However, evidence indicating reactivation of fissures was discovered at more than one-third of the sites examined in the field. Many fissures exhibit variations in morphology along their lengths. Although this may be related to characteristics of different surficial deposits through which the fissures extend, many fissures actually <u>are</u> different ages at different points. Field studies indicate that it is difficult to detect incipient fissures on 1:24,000-scale air photos, since a few very young fissures were found in the field that are not detectable on the photos. The rates of development of new fissures and propagation of existing fissures varied by more than an order of magnitude during the 30-year study period. Rates of formation of new fissures appear to correlate positively with the frequency of intense precipitation events. There also may be an inverse relationship between the rate of fissure development and the amount of annual precipitation. In some cases, surficial deposits exert a strong influence on fissure form. Each of these topics is discussed in more detail below.

Refer. No.	Width (m) Min	Width (m) Max	Width (m) Avg	Depth (m) Min	Depth (m) Max	Depth (m) Avg	Wall Slope	Floor Topo-graphy	Head-Cut Length	React-ivation Features	Bench Above Floor	Vert. Dsplce-mnt	Predom. Grain Size	Stand-ing Water	Morpho-logic Age
16332b	--	0.1	0.01	1.0	--	--	vt	e ir	0	N	N	N	si sa	N	1
26721b	--	0.2	0.01	0.6	--	--	vt	e ir	0	N	N	N	si sa	N	1
26721a	0.1	3.0	0.3	0.3	3.3+	1.6	vt-vt+	e ir	3	Y	N	N	si sa	N	2
26712	0.1	2.5	0.7	0.1	1.3	0.8	st	fl	7	Y	N	N	si sa	N	2
26711	0.2	1.8	0.7	0.1	0.8	0.4	st	fl-hm	8	N	N	N	si sa	N	2
14421	0.1	2.0	0.8	0.2	2.1	1.0	vt-gn	ir-fl	4	--	--		si f sa	N	2
832	--	--	0.5	--	--	0.7	vt	v ir	1	--	--	N	si f sa	N	2
1522	--	1.0	--	--	1.5	--	vt	ir	--	Y	N	Y?	--	N	2
16332a	0.5	1.0	--	--	--	1.5	vt	ir	0	N	N	N	si sa	N	2
332	0.5	1.8	--	0.1	6.1	--	e st	ir	--	--	--	N	gr	N	2
14411	--	2.1	1.5	--	2.1	0.8	vt-v st	hm	3	--	--	N	sa si	N	2
9311b	--	--	2.0	--	3.5	--	vt	v ir	--	Y	N	N	si sa	N	2
28351	0.5	4.0	3.0	0.5	4.5	2.2	--	--	--	N	N	N	si sa	N	2
833	--	9.0	--	--	4.0	--	vt	fl, hm	--	--	--	N	si cl sa	N	3
16321	1.0	2.5	--	0.2	3.7	--	vt-gn	sm-hm	8	N	N	N	sa si	--	3
3451	0.5	3.5	1.7	0.2	2.5	1.2	st-vt	hm	27	N	Y	N	sa si	N	3
10321	--	4.0	3.0	--	2.2	1.3	gn-vt	fl-hm	75	N	Y	N	si f sa	Y	3
834	3.0	10.0	--	--	2.0	--	vt-vt+	sm-ir	--	Y	Y	N	sa si	N	3
23322	0.1	4.0	--	0.2	2.0	--	gn-vt	sm-ir	--	Y	Y	N	si sa	N	3
9311a	--	>1.4	1.0	--	>1.7	0.6	vt-gn	ir	10	N	Y	0.7	sa si	N	3
28341	2.5	5.0	3.9	0.8	1.7	1.3	st	fl-s ir	25	--	--	N	cl si	Y	3

Table 1. Morphologic data from selected earth fissures in Picacho basin. Abbreviations are explained at the end of the table. All measurements are reported in meters.

REFER. NO.	WIDTH (m) Min	Max	Avg	DEPTH (m) Min	Max	Avg	Wall Slope	Floor Topo-	Head-Cut	React-ivation	Bench Above	Vert. Dsplce-	Predom. Grain	Stand-ing	Morpho-logic
14412	--	--	1.7	--	--	1.0	vt	fl-s ir	8	Y	N	N	sa si	N	3
1526	--	1.2	--	--	1.0	--	st	s ir	--	N	N	N	si	N	3
1527	--	1.0	--	--	1.0	--	st	s ir-sm	--	N	N	N	si	Y	3
26751	1.0	3.2	2.0	0.1	0.7	0.4	gn	fl-sm	8	N	N	N	sa si	N	3
11711	0.7	2.8	1.6	0.1	0.7	0.3	gn-md	fl-s ir	9	N	N	N	si sa	N	3
14413	--	3.0	1.5	--	0.4	0.3	vt-st	ir-hm	22	Y	Y	N	sa si	N	3
28331	1.0	4.0	2.0	0.2	2.5	0.7	gn-vt+	fl-ir	44	Y	N	N	si sa	Y	4
8311a	--	4.0	2.0	--	2.0	1.0	md	fl-hm	30	Y	N	0.5	sa	N	4
23321	0.7	5.0	--	0.5	1.5	--	gn-vt	sm-ir	7	Y	Y	N	si sa	N	4
3441	1.0	4.0	2.0	0.2	1.0	0.5	st	ir-hm	2	Y	Y	N	si cl	N	4
8311b	--	3.6	2.2	--	0.6	0.3	gn	sm-ir	--	--	--	0.8	pe sa si	N	4
9331	--	--	2.0	--	--	0.6	gn-vt	fl-hm	--	N	Y	--	si cl	N	4
23341	--	3.0	2.0	--	0.5	0.3	v gn	fl-sm	15	--	--	N	sa gr	N	4
6442	0.3	>3.0	1.7	0.01	0.5	0.2	gn-st	fl-sm	--	N	N	N	si cl	N	4
331	--	3.5	--	--	0.5	--	gn	sm-fl	--	Y	N	0.3	--	N	4
6411	0.3	3.3	2.0	0.02	0.4	0.1	st	fl-sm	--	Y	N	N	sa si	N	4
6412	0.2	2.0	0.8	0.1	0.4	0.2	st	fl-sm	--	N	N	N	sa si	N	4
1521	--	--	2.2	--	--	0.3	gn-md	sm-fl	23	Y	N	Y(?)	--	Y	4
1524	0.4	2.2	1.0	0.1	0.3	0.2	gn	sm-fl	--	N	N	N	si f sa	N	4
3451a	--	--	0.6	--	--	0.2	gn	fl-sm	12	Y	N	N	sa si	N	4
26741	0.5	3.0	0.7	0.1	0.4	0.2	gn-v gn	fl	--	N	N	N	sa si	N	5

Table 1. Morphologic data from selected earth fissures in Picacho basin. Abbreviations are explained at the end of the table. All measurements are reported in meters.

REFER. NO.	WIDTH (m) Min	Max	Avg	DEPTH (m) Min	Max	Avg	Wall Slope	Floor Topo-graphy	Head-Cut Length	React-ivation Features	Bench Above Floor	Vert. Dsplce-mnt	Predom. Grain Size	Stand-ing Water	Morpho-logic Age
23331	1.0	2.0	--	0.1	0.2	--	v gn	fl	--	--	--	N	sa gr	N	5
28311	0.3	2.0	--	0.0	0.2	--	v gn	fl	--	--	--	N	--	N	5
16311	--	--	1.3	--	--	0.1	e gn	fl-ir	--	N	N	N	si sa	N	5
1525	--	--	1.6	--	--	0.12	e gn	fl	--	N	N	N	si f sa	N	5
3431	--	2.0	1.0	0.0	0.25	0.10	gn-md	fl-sm	--	N	N	N	sa cl si	Y	5
3432	--	--	1.3	0.0	0.20	0.10	gn	sm-fl	--	N	N	N	sa cl si	N	5
3421	0.5	2.0	0.8	0.0	0.15	0.07	e gn	fl	7	N	N	N	sa si	N	5
6431	--	2.7	--	--	0.08	--	v gn	fl	--	N	N	N	si sa	N	5
16331	--	--	--	--	--	--	e gn	fl	--	N	N	N	si sa	N	5

Key to Abbreviations:

vt+ = overhanging
vt = vertical
st = steep
md = moderate
gn = gentle

ir = irregular
hm = hummocky
sm = smooth
fl = flat

f = fine
cl = clay
si = silt
sa = sand
pe = pebbly
gr = gravel

e = extremely
v = very
s = slightly

Y = yes
N = no

Table 1. Morphologic data from selected earth fissures in Picacho basin. Abbreviations are explained at the end of the table. All measurements are reported in meters.

Spatial Distribution of Earth Fissures

Many earth fissures form where alluvium thickness changes abruptly. This includes the following settings: 1) buried faults; 2) sites where bedrock is locally relatively shallowly buried (such as inselbergs, which are outlying bedrock bodies that are connected with the principal mountain mass at depth); 3) buried pediment edges; and, 4) convex-topped positive gravity anomalies (Christie, 1978). Comparing Plates 1 through 6 with gravity maps of the region (for example, Oppenheimer, 1980) shows that many Picacho basin fissures are located at sites of marked changes in alluvium thickness. Most of these sites occur close to the mountains near the perimeter of the basin, and the fissures trend subparallel to the basin boundary.

Differential subsidence and earth fissures also occur in the central parts of the basin, away from areas of abrupt alluvium-thickness change. These fissures are probably related to sedimentological and/or hydrologic changes in the basin fill along relatively short horizontal distances (Anderson, 1986). Such conditions may include changes in grain size, quantity and composition of matrix or cement, and aquifer thickness, water content, or water depth. Aquifer sediments containing a large percentage of silt and clay are particularly susceptible to compaction.

Morphological Indicators of Relative Earth-Fissure Age

Earth fissures, once formed, may follow one or more of a number of paths of development and modification. Changes in fissure morpholgy over time depend on factors such as bedrock/alluvium basin geometry, sedimentology of alluvium, orientation of the fissure with respect to surficial drainage pattern, regional and local slope, size of watershed, weather patterns, and magnitude and rate of local and regional subsidence. The path of fissure development that appears to be the most common in Picacho basin consists of the five stages described below. Characteristics which typify each morphologic age group (1 through 5) are summarized in Table 1.

1) Very Young Fissures. Narrow (up to 12 cm- [4.7 in.-] wide) discontinuous cracks, pits, and depressions form at the ground surface either preceding or following fissure formation at depth. Portions of the initial fissure may be up to 1 m (3.3 ft) wide. The overall length is up to 500 m (1640 ft) or more. Fissure walls are very steeply sloping or vertical (Figures 4 and 5), and fissures may be several meters (tens of feet) to tens of meters (scores of feet) deep (Strange, 1983). It has been postulated that some fissures may extend from the ground surface to the original water table that was present before excessive ground water extraction drained the aquifer (Holzer and Davis, 1976). Very young fissures interrupt drainage channels that cross them and display no "tributary" drainageways (headcuts) that feed into the fissures. They have no concentrations of vegetation along them, but there may be disrupted plants which have fallen or shifted. Some display series of en echelon cracks. The bottoms of very young fissures (where observable) are steeply sloping, irregular, and V-shaped. In other cases, coherent down-dropped "graben" blocks occur.

2) **Young Fissures.** Fissures that have existed for some time have been modified by the processes of erosion, sedimentation, and mass wasting. They are wider (approximately 1 m [3.3 ft] to 3 m [9.8 ft] wide), more continuous, and in some cases longer than very young fissures. The widening is accomplished by mass wasting and erosion, which also reduce wall slope angles slightly as fissure gullies begin to form (Figure 6). Deposition of sediment smooths out irregularities of floors and begins to change V-shaped cross sections to U-shaped profiles (Figure 7). Earth-fissure formation causes a local lowering of base level for streams that formerly flowed across an undisturbed surface. That tends to cause channel down-cutting (erosion) by the stream upslope from the fissure, and deposition of sediment in the fissure. During runoff events, headcuts form at the fissure and advance upslope. Some headcuts form on the downslope sides of fissures and advance downslope by reversing the local drainage-slope direction. Since fissures catch and retain runoff, vegetation begins to concentrate in and along them. As they age, fissures may lengthen and/or become reactivated and develop systems of subparallel cracks and pits (discussed below).

3) **Mature Fissures.** Older fissures express the continued operation of the processes described above. Widths increase to the 2 m to 4 m (6.6 ft to 13.1 ft) range as gullies are fully expressed. Most mature fissures are continuous features, and their walls slope less steeply than before unless the sediment is cohesive. They are shallower, with flatter, less hummocky floors because deposition has partially filled the gullies. Their cross sections are U-shaped and more regular (Figure 8). Headcuts extend small "tributary" drainage channels farther from the fissures. Preexisting streams that originally crossed the area are disrupted and locally steepened in response to the fissure-imposed base-level fall. Dense vegetation, which makes older fissures appear striking on aerial photographs, lines the features (Figure 9). Individual

Figure 4. Very young fissure (16332b on Table 1) with vertical walls, irregular floor, and no vegetation concentrated along it. This fissure rendered a dirt road impassable. See Plate 6 for location.

Figure 5. Another example of a very young portion of a fissure (14413 on Table 1), showing a discontinuous crack up to 19 cm (7.5 in.) wide with vertical walls and little disturbance of surroundings. See Plate 1 for location.

Figure 6. Young fissure (9311b on Table 1), which has undergone erosion and mass wasting, is wider and has less steeply sloping walls than a very young fissure. See Plate 2 for location.

Figure 7. Young fissure (1522 on Table 1) is becoming a fissure gully. See Plate 1 for location.

Figure 8. Flat floor and U-shaped cross section typical of mature morphology. This fissure (332 on Table 1) is classified as young based on a consideration of all of its morphologic parameters. See Plate 1 for location.

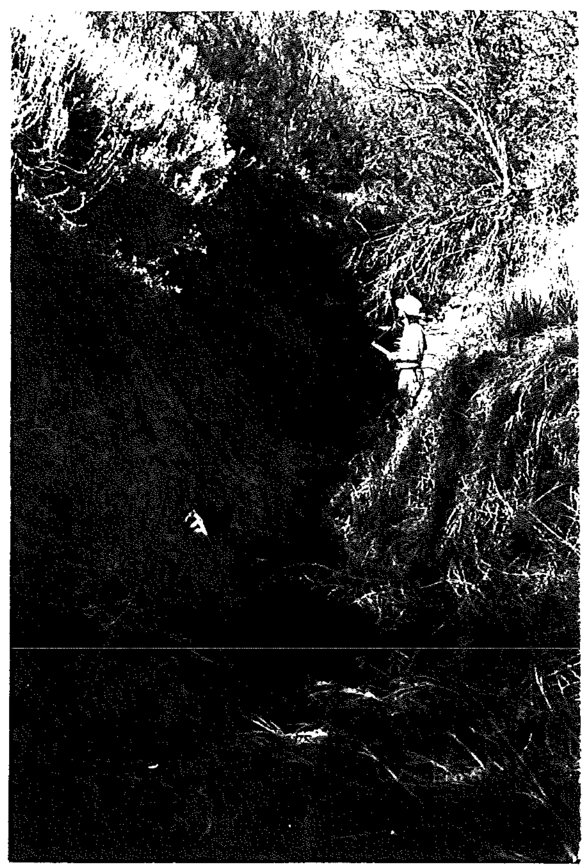

Figure 9. Mature fissure (833 on Table 1) showing large width, U-shaped cross section, and abundant vegetation. Good example of a fissure gully. See Plate 1 for location.

plants are larger and more luxuriant than those farther away from the fissure, and they grow closer to eachother. Some of the plant species in and along fissures are not found elsewhere in the region.

4) Old Fissures. Fissures that are still older may be even wider (3 m [9.8 ft] to 6 m [19.7 ft]), but in most cases the widening process has slowed or stopped by this time. Wall slopes are moderate and floors are flat, forming a U- or open-rectangle-shaped profile (Figures 10 and 11). "Tributary" drainage channels are relatively long: Their headcuts have extended farther from the fissures. Piping is well developed adjacent to the features. Preexisting stream channels once again cross the rifts with minimal disruption, having deposited enough material in the cracks to bring their beds back up to grade. Vegetation is dense (in some cases impenetrable) right along some old fissures, but near others plants are noticibly less concentrated than they are in the adjacent desert. This is probably because of surface water hydrology perturbations caused by fissures. Upslope from a fissure, precipitation that formerly infiltrated the fan or piedmont surface (allowing plant growth) now is concentrated into headcuts and "tributary" streams that empty into the fissure. The areas around the streams receive less infiltration, so plants suffer. Immediately downslope from a fissure, sheetflow runoff is cut off by the presence of the fissure, leaving little water available for plants.

5) Very Old Fissures. Very old fissures, and those that occur in rapidly subsiding sub-basins or in areas with high sedimentation rates, may be difficult to recognize. They appear as faint discontinuous lineaments on aerial photographs and some are nearly invisible in the field. Fissure gullies are completely or almost completely filled with sediment, so walls are nonexistent or very low (up to 15 cm [6 in.] high) and gently sloping (Figure 12). Floors are flat and smooth, although some display mudcracks that are larger, thicker, and better developed than mudcracks on adjacent ground. Cross sections are so subdued and regular along some very old fissures' entire lengths that the possibility must be considered that the features are actually abandoned streambeds, wagon trails, canals, or other types of man-made furrows. "Tributary" drainageways are long and in many cases are filled with sediment. Vegetation is not as concentrated as it is along some fissures that are not quite as old, but it may still be the most compelling indication that the feature actually is a very old fissure that retains water longer than the surrounding land (Figure 13).

Fissure Evolution and Reactivation. The five stages of development suggest that the relative age of a fissure is indicated by its morphology. This is true in many cases, but factors other

Figure 10. Old fissure (28331 on Table 1) is shallow because of infilling by sediment. Notice flat floor, gently sloping wall on right, and presence of vegetation. See Plate 1 for location.

Figure 11. Old fissure (8311b on Table 1) is characterized by smooth slopes, large width, shallow depth, and rounded profile. Large plants line the fissure. See Plate 1 for location.

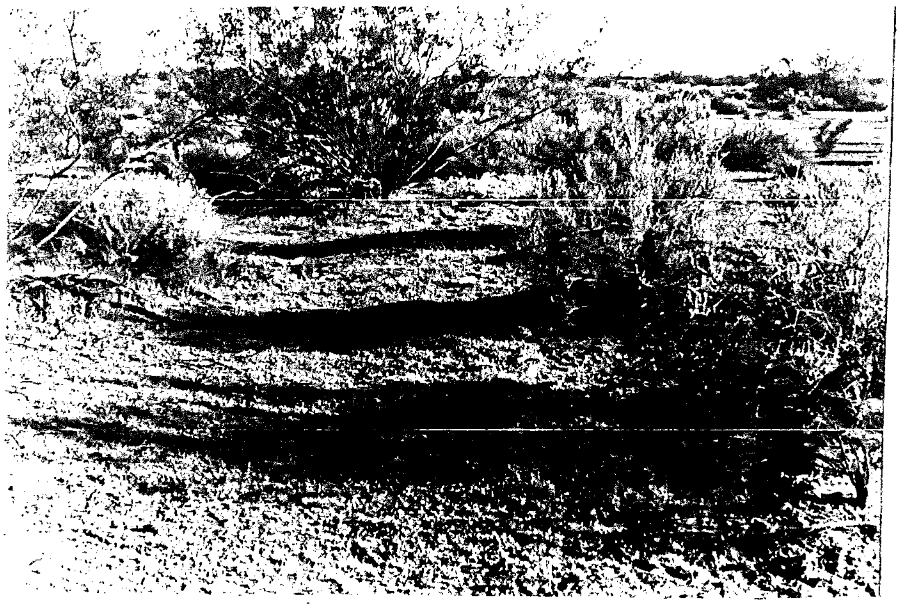

Figure 12. Very old fissure (6431 on Table 1) appears as a barely discernible swale lined with widely scattered creosotebush. See Plate 6 for location.

Figure 13. Very old portion of an old fissure (6411 on Table 1) is subtle and almost completely filled with sediment. A band of concentrated vegetation is the most striking indication of the feature's presence. See Plate 6 for location.

than time also help to determine the shapes of fissures. Many appear to have proceeded through the five stages of development (for example, the long fissure that formed before August 1959, extends to the northwest, and is located 0.8 km [0.5 mi] south of the I-10/I-8 interchange on Plate 6). Others have developed differently. Fissures such as portions of the one portrayed on Plate 5 at 32 deg. 49' north latitude and 111 deg. 22' west longitude have retained nearly the same appearance on the air photos over the past 30 years. Some have continued to lengthen and have developed subsidiary, intersecting cracks that make them more, rather than less, prominent on air photos as time goes on. An example ot this type of feature, called a reactivated fissure, is shown on Plate 1 at 32 deg. 41' north latitude and 111 deg. 27' west longitude. The 30-year time span for which aerial photographs of Picacho basin were available for this study is too short a period in which to document the patterns of development of those earth fissures that were already well established in 1959.

Evidence of reactivation of earth fissures was discovered at 20 of the 51 field sites visited. Reactivation is manifested in two ways: 1) Younger cracks, pits, and/or depressions occur adjacent and subparallel to a fissure. Such features found along very young fissures merely indicate on-going development, but along subdued older fissures they demonstrate reactivation (Figure 14). Subparallel surficial cracks may represent only a single fissure at depth. 2) One or more benches exist above the bottom of the main fissure gully (Figure 15). Such benches may show the location of a previously formed fissure floor which has been broken by renewed tension (indicating reactivation). Alternatively, they may be simply bridges that formed as the fissure filled with sediment which was subsequently partially removed by erosion, or they may result from delayed compaction of fill sediment (not related to reactivation). Benches above the floors of "tributary" stream channels emptying into fissure gullies, however, do indicate possible reactivation.

Recognition of Incipient Earth Fissures on Aerial Photographs

One of the purposes of this investigation was to determine if incipient or very young fissures may be identified by inspecting air photos. Unfortunately, in most cases they cannot be identified even when hindsight dictates exactly where to look. The small widths and lack of concentrated vegetation along these fissures render them invisible on 1:24,000-scale air photos. The young fissure at 47 deg. 30' north latitude and 111 deg. 39' 45" west longitude on Plate 6 was discovered unexpectedly in the field during March 1989. It may be faintly visible on the 1987 air photos (knowing where to look), but if it had not been mapped in the field it

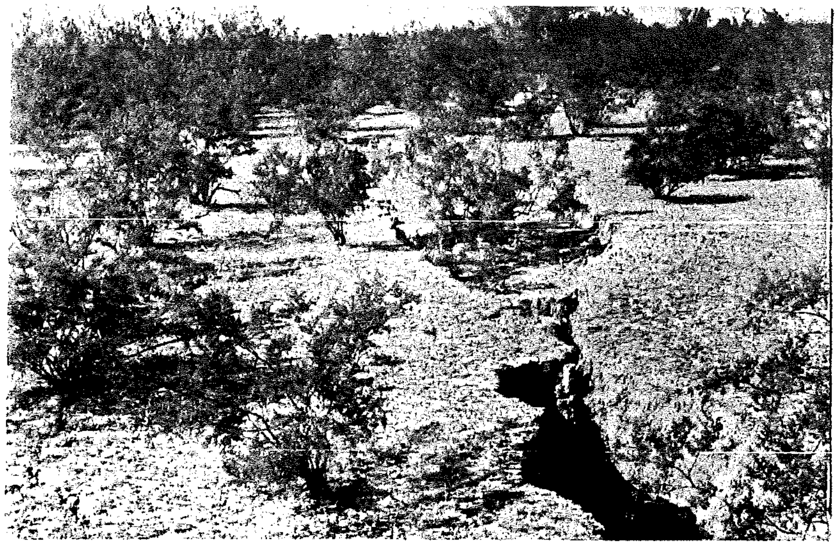

Figure 14. Young and very young cracks (9311b on Table 1) indicate that the old fissure located outside of the field of view to the left has been reactivated recently. See Plate 2 for location.

Figure 15. Crack in foreground resulted from reactivation of this fissure (834 on Table 1). The bench on either side of the crack is the former fissure floor, and the top of the wall in the background is the original ground surface. See Plate 1 for location.

certainly would not have been shown on Plate 6.

Larger-scale air photos are of some use in locating very young or incipient fissures. Good quality enlargements up to 10X the scale of the original photograph (1:2,400 for 1:24,000-scale photos) may be made from some negatives, but are difficult to view stereoscopically. ADOT personnel have enlarged photos taken at a scale of 1:1,920 to a scale of 1:192 (1 cm = 1.9 m or 1 in. = 16 ft) for site-specific inspection of a mature fissure in Maricopa County. ADOT supplied 5X and 10X enlargements of selected 1:24,000-scale air photos of Picacho basin. The enlargements show exceptional detail, allowing the interpreter to pinpoint sites of active fissure development. Many young fissures that lack vegetation concentrations can be identified and, in some cases, incipient fissures can be recognized. Future studies may involve detailed analyses of these enlarged photos and field checking in an attempt to locate all fissures in the critical area near Brady and Picacho Pump Stations on the CAP aqueduct (Plate 2).

It is impractical to use enlarged air photos for fissure identification in regional investigations. For such studies, the approach taken by Anderson (1986) is useful. By evaluating the distributions of conditions known to promote formation of earth fissures, he predicted areas where fissures are likely to form in the future. Those areas may be photographed at large scales and field checked regularly.

Recognition of Earth Fissures on Radar Imagery

Side-looking airborne radar imagery was evaluated as a potential tool for identifying fissures (Litton Aero Service and Goodyear Aerospace, 1972). It proved not to be useful at the largest scale (1:62,500) at which coverage of Picacho basin is available. Land-surface features appear grainy and fuzzy, and only the longest, heavily vegetated, and best-established fissures are visible.

Rates and Patterns of Earth-Fissure Development

Repeated aerial photographic surveys flown along the path of Interstate Highway 10 through Picacho basin from 1959 to 1989 provide a data base with which to explore some facets of earth- fissure development with time. As described above, fissures recognizable on air photos were mapped for each moment in time represented by the photographs. This process documented the formation and lengthening of individual fissures, which provided data with which to evaluate temporal variations in fissure development rate. The magnitudes of average and extreme fissure-development rates are now known. These data were compared with climatic records to see if correlations exist.

Methodology. Field work conducted in 1989 indicates that interpretation of air photos faithfully reveals young, mature, and old fissures (age groups 2, 3, and 4) because they tend to be fairly continuous and have distinctive vegetation associated with them. Very young (age group 1) and very old (age group 5) fissures may not be evident on aerial photographs. Fissures were mapped on each set of air photos and then were compared with those mapped on older sets of photos of the same area; newly developed fissures were noted and transferred to 1:24,000-scale orthophotoquads. Lengths of fissures developed between aerial photo surveys were then measured on orthophotoquads on the east and west sides of Picacho basin (portions of the Newman Peak [Red Rock NW orthophotoquad] and Casa Grande Mts. quadrangles). The number of active fissures and their lengths were summed, respectively, for each of the ten intervals between air photo surveys. "Active" fissures refers to both lengthened and previously undetected ones. Intervals between photo surveys vary substantially; both the numbers of active fissures and their amounts of lengthening were normalized to rates per year in order to evaluate temporal variations in development.

Propagation Rates. Rates of lengthening (or gap-filling) vary substantially from air photo survey interval to interval. The average propagation rate of individual fissures over the entire 29.5-year period of record is approximately 76 m/yr (249 ft/yr). This rate was calculated by dividing the total length of fissures that developed during each interval between air photo surveys by the number of fissures that lengthened during each interval; fissures that were not active were not included in the calculations. Average rates range from approximately 100 m/yr (330 ft/yr) during the past two years to approximately 20 m/yr (66 ft/yr) between 1978 and 1985 (Figure 16). The maximum propagation rate of any fissure in the study area is 529 m/yr (1736 ft/yr). During the interval from 1976 to 1985, no fissure lengthened more rapidly than 70 m/yr (230 ft/yr). Clearly, fissures may propagate rapidly, and apparently they tend to lengthen most rapidly during intervals when many fissures are active (see below for further discussion).

Activity Rates. The number of active fissures (that is, newly detected or newly lengthened) during each interval between air photo surveys is another measure of temporal variation in

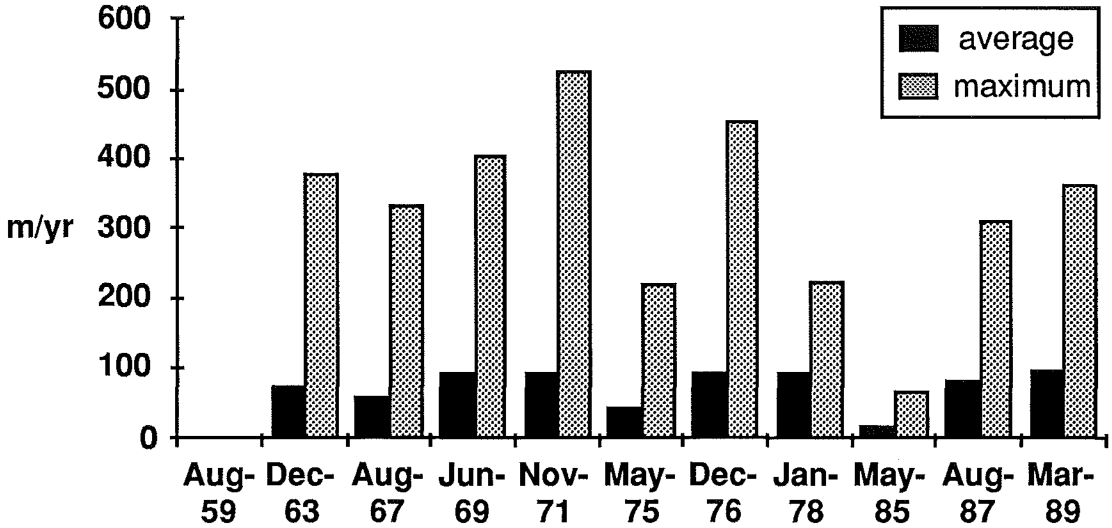

Figure 16. Propagation rates of individual fissures in the portions of Picacho basin covered by repeated aerial photo surveys. "Average "values represent the average rate of lengthening of those fissures that were active during any given interval; "maximum" values are the maximum rate of lengthening observed for any fissure during the same interval. The average rate of lengthening for all fissures active between 1959 and 1989 is 76 m/yr.

fissure development in Picacho basin. The number of active fissures per year has varied substantially during the past 30 years. Fissure activity reached its highest rate in the past one-and-a-half years (from Aug. 1987 to Mar. 1989). Similar activity rates were common during the mid- and late 1960's and the mid-1970's (Figure 17; Table 2). The period from 1978 to 1985 was one of very low levels of fissure activity. The early 1960's and early 1970's were times of intermediate rates. Minimum and maximum rates of activity per year differ by more than an order of magnitude, and this variation has occurred within the past 12 years.

Patterns of fissure activity are more complex if the east and west sides of Picacho basin are considered separately. The mid- and late 1960's was the period of maximum activity in the Casa Grande Mts. quadrangle, on the west side of the basin. During this interval the Newman Peak quadrangle (Red Rock NW orthophotoquad), on the east side of the basin, experienced moderate to low levels of fissure activity. In the early to mid-1970's the situation was reversed, with high rates of activity in the Newman Peak quadrangle and low to moderate rates in the Casa Grande Mts. quadrangle. Thus, the east and west sides alternately experienced moderate to high rates during these intervals. There has been little difference in rates of fissure activity on either side of the basin since 1976.

Total Propagation Rates. The most quantitative measure of activity is the total length of fissures that developed between air photo surveys. This measure, also normalized to rate of lengthening per year, reveals the same general patterns as the number of active fissures per year discussed above. The highest rate of fissure-lengthening occurred during the 1963-1967 interval, but the rate during the 1987-1989 interval is almost as high (Table 2; Figures 17 and 18). In the 1960's, primarily the west side of Picacho basin experienced high rates of activity, and the east side was more active during the early to mid-1970's. The east and west sides exhibited nearly identical rates from 1977 to the present, with very little lengthening occurring between 1977 and 1985, and increasing rates since 1985.

Substantial numbers of fissures existed on both sides of Picacho basin prior to 1959. In the area covered by repeated air photo surveys on the east side of the basin, approximately 46 km (29 mi) of fissures were recorded on the 1989 photographs; about 32% of these (15 km [9 mi]) existed in 1959. On the west side, approximately 70 km (44 mi) of fissures were observed on the 1989 photographs, and about 39% of these (27 km [17 mi]) existed by 1959. Thus, each side has undergone a similar pattern of development, but the west side has had consistently greater cumulative fissure length (Figure 18).

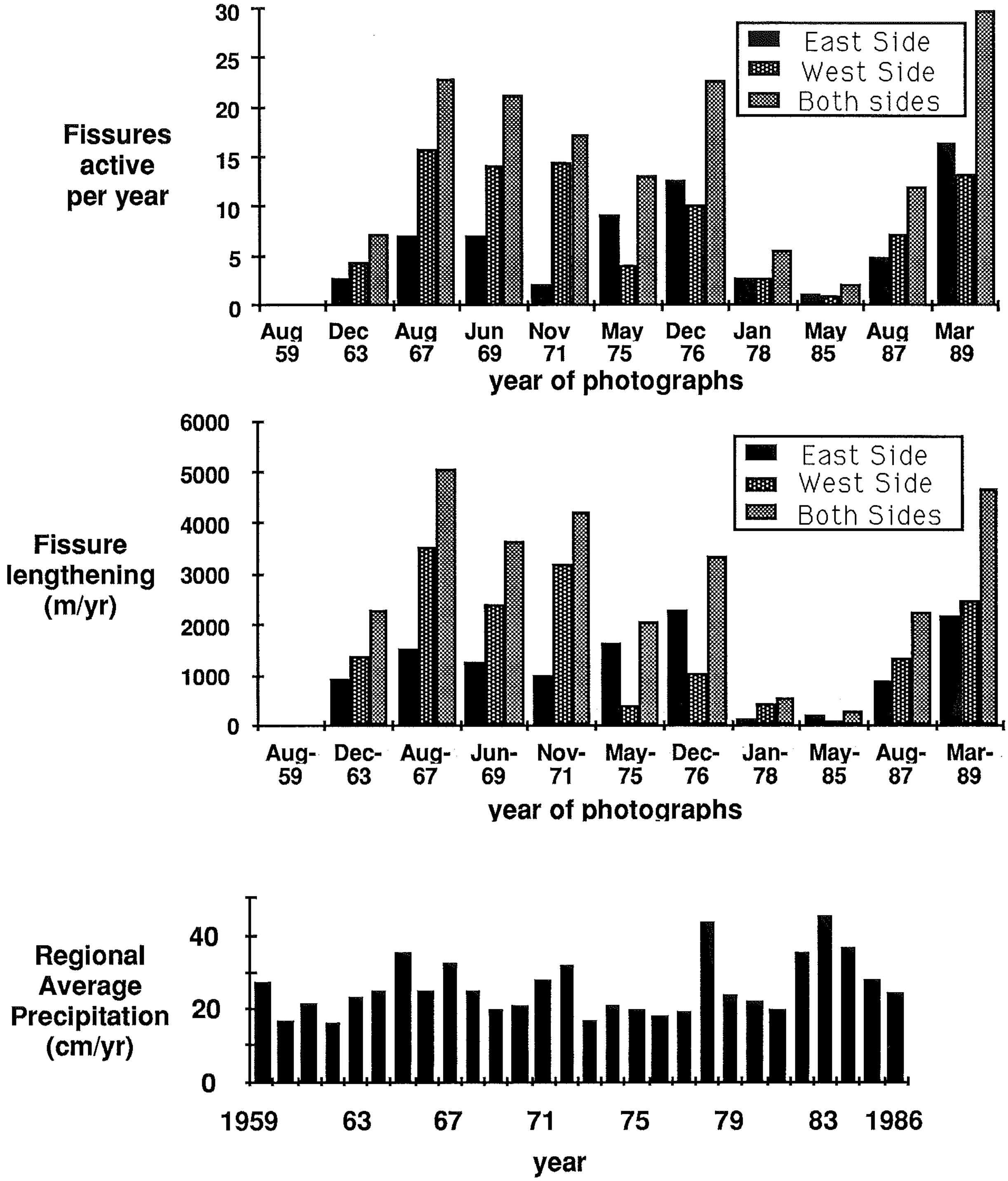

Figure 17. Active fissures and lengths of fissures developed on the east and west sides of Picacho basin, and regional trends in annual precipitation for the years since 1959. Rates are normalized to an annual basis because of the different intervals between aerial photo surveys.

PHOTO DATE		Aug 59	Dec 63	Aug 67	Jun 69	Nov 71	May 75	Dec 76	Jan 78	May 85	Aug 87	Mar 89
TOTAL LENGTH	(E)	14.8	4.0	5.6	2.3	2.5	5.8	3.6	0.1	1.4	2.0	3.5
PER INTERVAL	(W)	27.6	5.9	13.0	4.4	7.8	1.1	1.7	0.5	0.7	3.0	3.9
(km)	(Total)	**42.4**	**9.9**	**18.6**	**6.7**	**10.3**	**6.9**	**5.3**	**0.6**	**2.1**	**5.0**	**7.4**
CUMULATIVE		14.8	18.8	24.4	26.7	29.2	35.0	38.6	38.7	40.1	42.1	45.6
LENGTH (km)		27.6	33.5	46.5	50.9	58.7	59.8	61.5	62.0	62.7	65.7	69.6
		42.4	**52.3**	**70.9**	**77.6**	**87.9**	**94.8**	**100.1**	**100.7**	**102.8**	**107.8**	**115.2**
RATE	(E)		0.9	1.5	1.3	1.0	1.7	2.3	0.1	0.2	0.9	2.2
OF LENGTHENING	(W)		1.4	3.5	2.4	3.2	0.4	1.0	0.4	0.1	1.3	2.5
(km/yr)	(Total)		**2.3**	**5.0**	**3.7**	**4.2**	**2.1**	**3.3**	**0.5**	**0.3**	**2.2**	**4.7**
NO. OF	(E)		12	26	13	10	32	20	3	8	11	26
ACTIVE	(W)		19	58	26	35	14	16	3	7	16	21
FISSURES	(Total)		**31**	**84**	**39**	**45**	**46**	**36**	**6**	**15**	**27**	**47**
FISSURES			2.77	7.09	7.09	2.15	9.14	12.63	2.77	1.09	4.89	16.42
ACTIVE			4.38	15.82	14.18	14.48	4.00	10.11	2.77	0.95	7.11	13.26
PER YEAR			**7.15**	**22.91**	**21.27**	**16.63**	**13.14**	**22.74**	**5.54**	**2.05**	**12.00**	**29.68**

Table 2. Variations in fissure activity with time on the east **(E)** and west **(W)** sides of Picacho basin. Activity is represented by length of fissures developed and numbers of fissures active between aerial photo surveys. Rates of fissure development normalized to an annual basis were calculated to evaluate temporal patterns of fissure activity. All measures of fissure activity indicate that the period from about 1977 to 1985 was one of very low fissure activity.

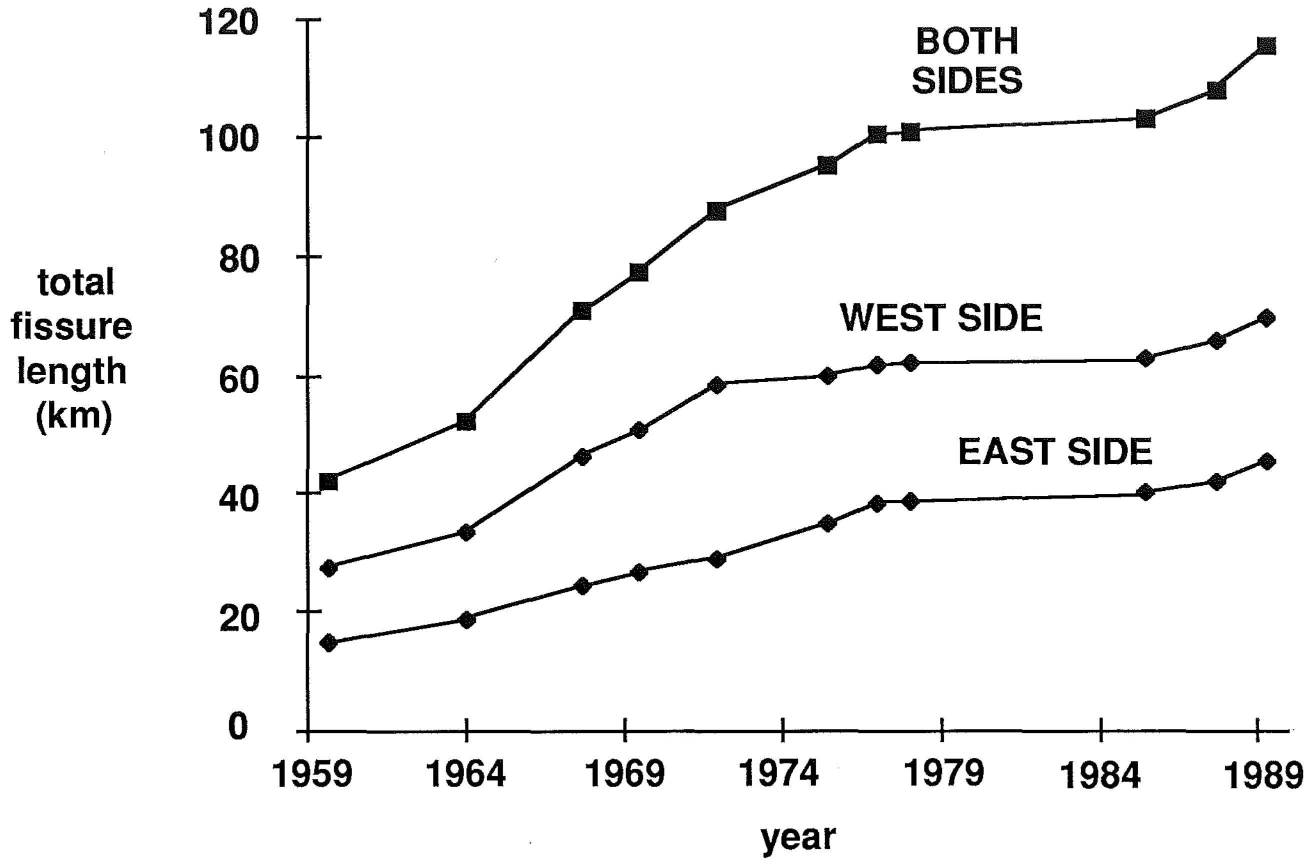

Figure 18. Cumulative lengths of earth fissures measured from repeated aerial photo surveys, Newman Peak and Casa Grande Mountains 7 1/2' quadrangles on the east and west sides of the basin, respectively. The slopes of the curves are the rates of fissure lengthening. There are some differences in the rates of fissure development on the east and west sides of the Picacho basin in the 1960's; both sides of the basin had very low rates of fissure development in the late 1970's and early 1980's, and rates of fissure development have increased on both sides in the late 1980's.

Activity Rates and Variations in Annual Precipitation. Temporal patterns of fissure activity are compared with climatic data to see if a relationship exists. One aspect of climate that may be used is average annual rainfall in the region including and surrounding Picacho basin. Average precipitation data from 1959 to 1986 (1986 is the most recent year for which data are readily available) were compiled for nine weather stations in south-central Arizona to reflect general patterns of regional precipitation. There are substantial differences in annual precipitation at stations which are located fairly close to eachother. Nonetheless, the regional average precipitation (Figure 17) shows that the early 1960's was relatively dry, the mid-1960's through the early 1970's had both wet and dry years, the rest of the 1970's was relatively dry with one very wet year (1978), and 1982 through 1986 was relatively wet with one very wet year (1983).

Comparison of the patterns of fissure development described above with annual rainfall patterns suggests that there is a general relationship between relatively dry intervals and high rates of fissure activity during the 1970's and 1980's. The relatively dry early and mid-1970's was a time of rapid fissure development. The interval from 1978 to 1985 had two very wet years and several relatively wet years; it was a period of minimal fissure development. This tentative relationship breaks down in the 1960's, however, because the relatively dry early 1960's was an interval of moderate rates of fissure development, and the relatively wet mid-1960's was a time of high rates of development. Fissure development rates on only the east side of Picacho basin show a somewhat stronger inverse relationship with general amounts of annual precipitation throughout the period from 1959 to 1986.

It is reasonable to theorize that relatively dry years may correlate with periods of rapid fissure development. Dry intervals could result in more ground-water pumping (to sustain crops) and less recharge of the aquifers. It is clear, however, that any relationship between annual precipitation, decline of the water-table altitude, and fissure development would be complicated by other factors. With additional research we intend to investigate other factors that might affect rates of fissure development. Such factors include annual temperature, discharge of the Santa Cruz and Gila Rivers (representing recharge potential), water-table altitude change, and land-surface subsidence.

Activity Rates and Intense Precipitation Events. Since Leonard (1929) reported the appearance of an earth fissure in 1927 following a severe rainstorm, other workers have commented on the relationship between intense precipitation events and fissure development. Old infilled fissures reopened in 1960 when rain from an intense storm collected in two shallow basins near the Casa Grande Mountains (Pashley, 1961). A fissure damaged the CAP aqueduct near Marana High School in Avra Valley in October 1988. Although only moderate rainfall occurred at the site on October 14 and 15, water ponded to a depth of 0.3 to 1.0 m (1 to 3.3 ft) near the base of an earthen dike adjacent to the aqueduct (Gary Ditty, pers. comm., 1988). By October 17, the fissure had opened and the water had drained into it.

Records of severe storms during the past 30 years in the vicinity of Picacho basin were evaluated in order to explore the relationship between intense precipitation events and earth-fissure development. The numbers of major storms and periods of concentrated precipitation that occurred during the intervals between air photo surveys were determined from climatological records (Sellers and Hill, 1984; Sellers et al., 1985; NOAA, 1959-1986). These data were compared with the numbers of fissures which were newly detected or newly lengthened during the same interval (Table 3). The number of storms, the number of new fissures that developed, and the number of existing fissures that propagated during each interval were characterized as many, some, or few. Correlations were designated as good, fair, or poor based on the similarity between characterizations of storm and fissure activity (for example, many storms and many active fissures is a good correlation; many storms and some active fissures is a fair correlation; many storms and few active fissures is a poor correlation).

A reasonably good qualitative correlation exists between the occurrence of major storms and the initial appearance of fissures in Picacho basin (Table 3). Of the eight intervals for which data are available, four show a good correlation, two show a fair correlation, and two correlate poorly. These relationships support previous workers' suggestions of a connection between intense precipitation and fissure formation. The correlation between major storm activity and propagation of existing fissures is not very good; the correlation between major storm activity and number of active fissures is only slightly better. These relationships imply that initial fissure development and subsequent propagation are controlled by several factors, including storm activity. There is apparently an increased likelihood of new fissures forming during and immediately following intense precipitation events. However, local water-table decline, which is a function of ground-water pumping and recharge rates, is also undoubtedly a major influence on rates of fissure initiation and propagation.

Photo Date	no. of intense storms	new fissures per year	fissures extended per year	fissures active per year	Correlation with Storms: new fissures	Correlation with Storms: fissures extended	Correlation with Storms: all active fissures
Many (M):	**> 5**	**> 11**	**> 11**	**> 30**			
Some (S):	**3 to 5**	**6 to 11**	**5 to 11**	**10 to 30**			
Few (F):	**< 3**	**< 6**	**< 5**	**< 10**			
Dec-63	8 **M**	6.7 **S**	4.4 **F**	11.1 **S**	*	-	*
Aug-67	6 **M**	13.4 **M**	6 **S**	19.4 **S**	+	*	*
Jun-69	1 **F**	26.2 **M**	12.5 **M**	38.7 **M**	-	-	-
Nov-71	3 **S**	10.3 **S**	5 **S**	15.3 **S**	+	+	+
May-75	4 **S**	6.6 **S**	6 **S**	12.6 **S**	+	+	+
Dec-76	2 **F**	7.6 **S**	22.7 **M**	30.3 **M**	*	-	-
Jan-78	1 **F**	3.7 **F**	3.7 **F**	7.4 **F**	+	+	+
May-85	11 **M**	1.4 **F**	0.7 **F**	2.1 **F**	-	-	-
		TOTALS:		**GOOD (+)**	**4**	**3**	**3**
				FAIR (*)	**2**	**1**	**2**
				POOR (-)	**2**	**4**	**3**

Table 3. Frequency of intense precipitation events in the Picacho basin area and fissure activity. Numbers of intense storms between aerial photo surveys were determined from weather records (Sellers and Hill, 1984; Sellers et al, 1985). Frequencies of intense storms and rates of fissure activity are characterized as many (**M**), some (**S**), or few (**F**). Correlations between storm frequencies and fissure activity are based on the relative similarities (for example, many storms, many new fissures, good correlation; many storms, few new fissures, poor correlation).

Influence of Surficial Deposits on Earth-Fissure Development

Another purpose of the investigation was to determine if soil and sediment type affect fissure form and/or development. There is clearly a connection between sediment type and fissure form. Truly noncohesive sediments (such as loose sand) form elongated depressions rather than fissures. At the other extreme, soils with very thick, well developed petrocalcic (caliche) horizons may possess enough tensile strength to stop a fissure from forming in them. Most older surficial deposits are more indurated than younger deposits, primarily owing to calcic soil horizons, so the walls of fissures developed in them are more resistant to erosion. Fissures in sediment composed of silt and sand with little cohesion tend to lose their original wall slopes and floor forms much more quickly than those developed in coarser-grained deposits. Several fissures illustrate these relationships: One located to the west of Picacho Peak (332 in Table 1) occurs in partly consolidated, coarse gravelly alluvial-fan deposits (unit f2 on Plate 1). It developed before December 1975. However, it appears to be quite young because the soil and sediment tend to preserve its very steep walls, rough irregular floor, its relatively narrow width and great depth. Conversely, some fissures that are young appear to be old. Fissure 6442 in Table 1 occurs in a deposit of predominantly silty clay (unit T2 on Plate 6). Even though the fissure formed between 1971 and 1975, it has gently sloping walls, a flat floor, and is very shallow.

Soil and sediment type seem to have little effect on fissure development and propagation rates. At several locations in Picacho basin, a fissure that developed during a single interval between air photo surveys extends across two or more types of deposits. Each surficial map unit is cut by at least one fissure in the basin, implying that all surficial deposits in the area are susceptible to fissure development.

SUMMARY

In summary, earth fissures pose a significant hazard to engineered structures in Picacho basin. Many of the fissures occur near the edges of the basin and adjacent to isolated bedrock outcrops. Fissure morphology is related to fissure age and to other factors including subsidence rate, weather patterns, and fissure orientation with respect to surficial drainage pattern. Rates of fissure lengthening in the portions of the basin covered in this report varied from 296 m/yr (971 ft/yr) between 1978 and 1985 to 5068 m/yr (16,627 ft/yr) between 1963 and 1967. The average lengthening rate for all active fissures during the past 30 years is 76 m/yr/fissure (250 ft/yr/fissure). Variations in rates of fissure development with time appear to correlate inversely with general trends in annual precipitation. Intense storms (and runoff ponding) probably trigger the appearance of new fissures, so facilities and their surroundings should be inspected carefully at such times. Surficial deposits affect the forms of fissures but have little influence on rates of lengthening and formation of new fissures.

Future studies might address the following topics: 1) rates, amounts, and locations of water-table drawdown with respect to fissure locations and propagation rates; 2) temporal and spatial patterns of development of geographic groups of fissures (for example, do groups tend to lengthen rapidly and then develop more complicated patterns?); 3) prediction of future patterns (and possibly rates) of formation in areas of currently active fissures using large-scale aerial photographs, extensive field-checking of suspect features, and geophysical, sedimentological, and other data.

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