EARTH FISSURES AND RELATED SUBSIDENCE FEATURES ADJACENT TO THE TUCSON AQUEDUCT, CENTRAL ARIZONA PROJECT, PINAL AND PIMA COUNTIES, ARIZONA

A Report to the U.S, Bureau of Reclamation

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INTRODUCTION

Earth fissures are a geologic hazard that could interrupt delivery of water to users of the Central Arizona Project (CAP) Tucson Aqueduct. Since the first earth fissure reported in Arizona was discovered near Eloy in 1927 (Leonard, 1929), dozens more have formed in Picacho basin and Avra Valley. The planned location of the Tucson Aqueduct in Picacho basin was changed to minimize the likelihood of damage by fissures and land subsidence, but the hazard is so widespread that the potentially harmful areas could not be avoided entirely. In 1988, the "Sandario Road" fissure formed near Marana High School in Avra Valley. The area had been identified in a previous study as a zone of potential hazard. The fissure cracked the aqueduct but did not drain it, probably because the aqueduct was specially reinforced there due to the recognized potential for damage. Good planning minimized repair costs and, if the aqueduct had been in operation then, would have prevented an interruption in service.

Periodic monitoring of the Tucson Aqueduct is required because early detection of a problem is the best way to achieve a timely, less expensive solution. The U.S. Bureau of Reclamation (USBR) conducts bimonthly inspections of all known fissures located close to the CAP. The object of this investigation is to identify any additional existing features near the Tucson Aqueduct that should be included in the bimonthly inspections.

Earth fissures are open surface and subsurface tension cracks in unconsolidated and semiconsolidated sediment. Some exhibit vertical displacement. Most earth fissures are thought to result from the following steps: 1) the quantity of ground water withdrawn from an unconsolidated-sediment aquifer greatly exceeds the quantity of recharge; 2) the resulting increase of water-table depth causes aquifer sediment to compact; 3) sediment

compaction leads to land-surface subsidence; and, 4) stress results from differential subsidence, and fissures form where extensional horizontal stress is great. Human-induced lowering of the water table caused by overdraft appears to be required for most earth fissures to form, but some may result from natural processes. Such processes are water-table depth fluctuation caused by climatic change, and differential subsidence of unconsolidated sediment over basement irregularities. The nature of basin-fill sediments may also play a role: evaporites are present in Picacho basin and northern Avra Valley. They are predominantly anhydrite, gypsum, and halite.

The results of the investigation are summarized here and presented in detail in the Findings and Discussion sections (p. 10 and p. 15, respectively). Three potentially significant features were discovered, and a fourth was reported by a USBR geologist. Two of the features are informally called "cross-fan grooves" because they are long, narrow curvilinear depressions that cut across the predominant trend of distributary ephemeral stream channels on the surfaces of alluvial fans. It is unclear if they are earth fissures. The third feature discovered is an area of collapse pits or piping cavities. They are relatively small and shallow, but occur close enough to the aqueduct to be mentioned.

The final feature, reported by Leo L. Langland (geologist, USBR, written commun., 1993), is inferred from the results of seismic and gravity surveys. It is not visible at the ground surface. It is an inactive, range-bounding bedrock fault with substantial displacement. It is buried below the basin fill. Because considerable water-table lowering has occurred in the area, an earth fissure or differential subsidence could be localized along the ground surface above the fault. The danger is considered to be great enough that the location of a proposed terminal storage reservoir was changed because of the suspected presence of the

fault (Langland, oral commun., 1993). Generalized locations of three fissures in Avra Valley that have been reported in the literature are shown on Plate 5. They could not be verified during this investigation.

PURPOSE

The goal of the project is to determine if any previously unmapped earth fissures exist adjacent to the Tucson Aqueduct. If any had been discovered, relative ages and activity levels would have been determined from current fissure morphologies. Recommendations regarding monitoring the fissures' status and safe-guarding the aqueduct would also have been made.

PHYSICAL SETTING

GEOGRAPHIC SETTING

The Tucson Aqueduct is located in Picacho basin, Avra Valley, and Tucson basin in Pinal and Pima Counties (Figure 1). The basins are broad, interconnected alluviated expanses with little relief. They are bounded by steep, narrow mountain ranges that reach elevations of 792 m (2,600 ft) at Desert Peak to 2,880 m (9,450 ft) in the Santa Rita Mountains. The aqueduct is in the basins, but it is close to some of the mountains. It is located right at the base of the southern Picacho Mountains, less than 2 km (1.2 mi) from Desert Peak, 5 km (3.1 mi) from the Tortolita Mountains, 1 km (0.6 mi) from the Tucson Mountains, and less than 1 km (0.6 mi) from Black Mountain. From northwest to southeast, it extends from approximately 32° 52′ 47" north latitude and 111° 26′ 25" west longitude to 31° 59′ 57" and 110° 59′ 30". The basins slope gradually down to the northwest, from an elevation of 853 m (2,800 ft) at the aqueduct's terminus in Tucson basin to 469 m (1,540 ft) at its beginning in Picacho basin. Most of the land

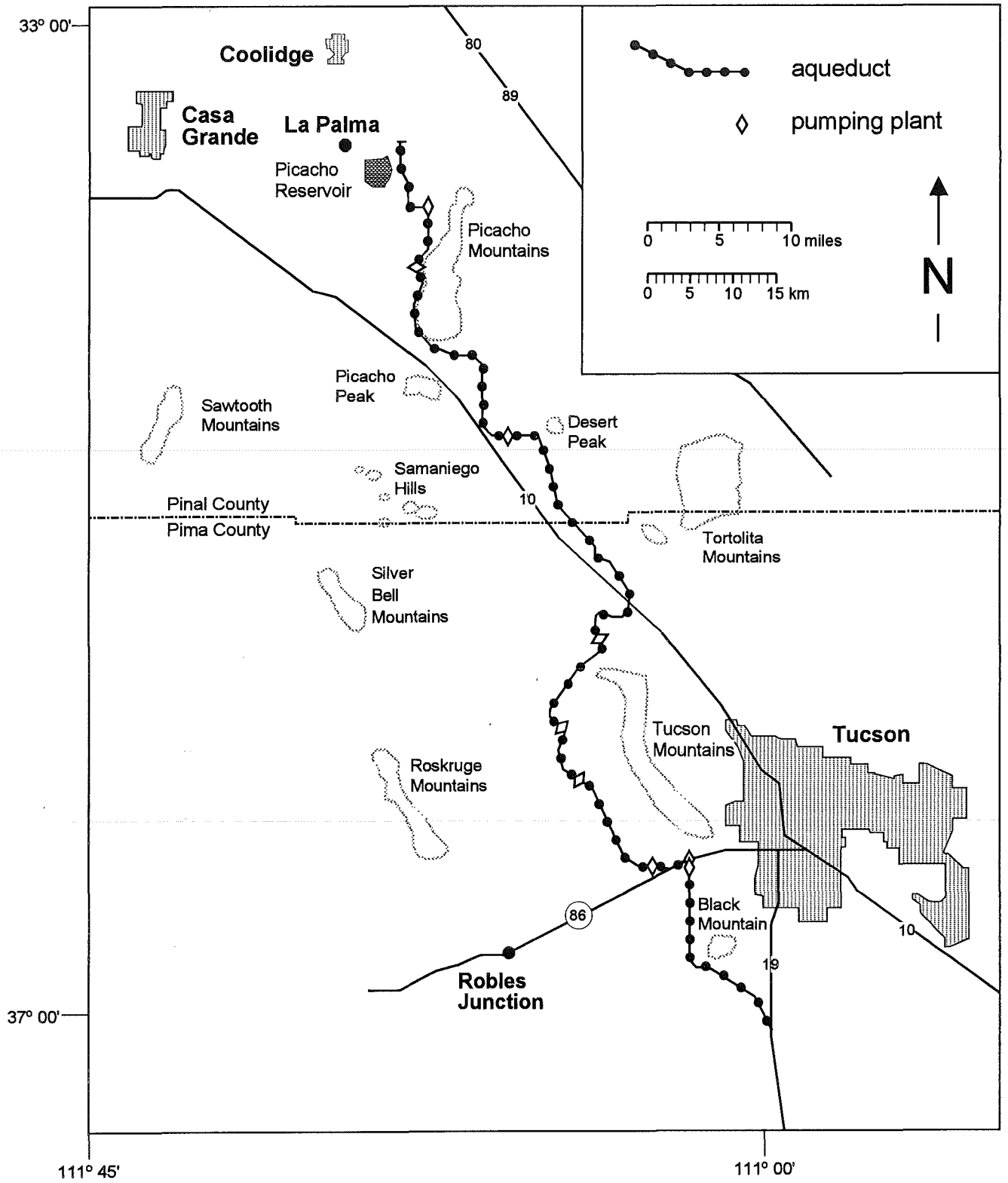

Figure 1. Index map showing the location of the Tucson Aqueduct.

adjacent to the aqueduct is undeveloped. Some is used for livestock grazing, some for agriculture, and small areas are residential. The principal towns in the area are Picacho, Red Rock, and Marana.

GEOLOGIC SETTING

The aqueduct is in the Basin and Range physiographic province. 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, Avra Valley, and Tucson basin.

The Basin and Range disturbance began approximately 13 Ma (Scarborough and Peirce, 1978; Eberly and Stanley, 1978; Shafiqullah and others, 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 Ma 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.

Picacho basin, Avra Valley, and Tucson basin are deep structural depressions with more than 2,440 m (8,000 ft) of sediments overlying bedrock (Pool, 1986). A schematic structural section

of the basins is shown in Figure 2. The sediments are terrigenous deposits of middle to late Cenozoic age. Units that pre-date the Basin and Range disturbance include 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 floors and walls of the basins, most of the pediments, and the mountains.

The sediments that overlie the bedrock are informally referred to as lower and upper basin fill. The lower basin fill is thousands of meters (feet) thick, and includes gravel, conglomerate, sand, silt, clay, mudstone, and evaporites. It is equivalent to the Pantano Formation and the lower and middle Tinaja beds, and to the lower alluvium (Hanson and others, 1990). The upper basin fill ranges from less than 30 m (100 ft) to approximately 500 m (1,640 ft) thick, and consists mainly of gravel, sand, and clayey silt. It is equivilent to the upper Tinaja beds and Fort Lowell Formation, and to the upper alluvium and stream alluvium. The sediments tend to be coarser grained near their source areas (in most cases, the mountains) and finer grained near the basin centers. The lower basin fill was deposited between the middle Miocene and approximately 7 Ma. The upper basin fill was deposited from approximately 7 Ma to the present (Pool, 1986).

HYDROLOGIC SETTING

Picacho basin is drained by the Gila River and its tributaries, the Santa Cruz River, Brady and McClellan Washes, and a number of other ephemeral streams. The drainage system in Avra Valley comprises the Santa Cruz River and its tributaries, Los Robles, Blanco, and Brawley Washes. In the vicinity of the aqueduct, Tucson basin is drained by the Santa Cruz River and many small tributaries. Streamflow is generally short-lived and only occurs in response to precipitation. Annual precipitation averages

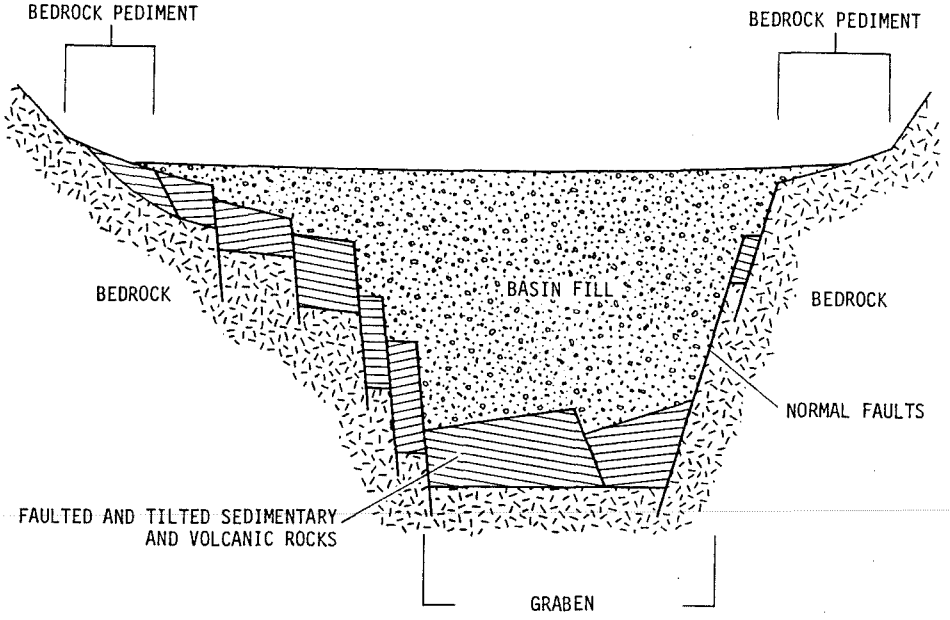

Figure 2. Generalized structural section of Picacho basin, Avra Valley, and Tucson basin (from Pool, 1986).

approximately 21 cm (8.2 in.) in Picacho basin, 25 cm (10 in.) in Avra Valley, and 30 cm (12 in.) in Tucson basin. In the higher mountain ranges adjacent to the basins, as many as 76 cm (30 in.) of precipitation falls.

Although surface water is ephemeral, vast quantities of ground water are present in the basins. Most of it is within the basin fill. The aquifer systems consist of many alluvial aquifers that are interconnected to various degrees. 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 (Anderson, 1986). Aquifers in Picacho basin are recharged by ground-water outflow from Avra Valley, which occurs between Picacho Peak and the Silver Bell Mountains. Avra Valley receives recharge from the south via Altar Valley, and from the east (near Rillito) by ground-water outflow from Tucson basin. The Santa Cruz River also provides some recharge to Avra Valley. In Tucson basin, recharge occurs by infiltration along some of the mountain fronts, and along the Santa Cruz River and its tributaries (Hanson, 1989).

Significant rates of ground-water withdrawal began in Arizona around 1910 (Schumann and Poland, 1970). The withdrawal rate has greatly exceeded the combined rates of natural and artificial recharge since the mid-1930s (Holzer, 1981). The water table has been lowered during this century by as much as 91 m (300 ft) in Picacho basin (Konieczki and English, 1979), 46 m (150 ft) in Avra Valley (Hanson and others, 1990), and more than 30 m (100 ft) in Tucson basin (Hanson, 1989). Increased effective stress caused by water-table decline has caused aquifer-sediment compaction and ground-surface subsidence. To date, as much as 4.7 m (15.4 ft) of subsidence has occurred in southern Picacho basin (Schumann, 1986). Northwestern Avra Valley has subsided as much as 0.3 m (1.1 ft; Strange, 1983), and a portion of Tucson

basin has subsided at least 0.15 m (0.5 ft; Hanson, 1989).

APPROACH

Two methods were used to search for previously unidentified fissures adjacent to the Tucson Aqueduct: interpretation of aerial photographs and field checking. Stereo-paired 23 cm x 23 cm (9 in. x 9 in.) black and white air photos were used. The photos were taken along a series of straight-line segments, and each segment was centered over the aqueduct. A new segment began wherever a change in the aqueduct's trend removed it from view along the previous flight line. The photos were acquired in April 1992 at two scales. Reaches 1 through 3, from the aqueduct's beginning at milepost 248.8 (near Picacho Reservoir) to milepost 291.7 (the Santa Cruz River siphon), are covered at a nominal scale of 1:14,770 (1 cm = 148 m or 1 in. = 1,231 ft). The photos of Reaches 4 and 5, from milepost 291.7 to milepost 320.8 (Black Mountain Pumping Plant), have a nominal scale of 1:7,385 (1 cm = 74 m or 1 in. = 615 ft).

Eighty-one pairs of photos were interpreted for Reaches 1 through 3, and 110 pairs were checked for Reaches 4 and 5. Thus for a shorter section of the aqueduct (Reaches 4 and 5), more photos were used and as shown on Plates 4 and 5, photo coverage only extends approximately 0.85 km (0.5 mi) on either side of the aqueduct. Coverage extends approximately 1.7 km (1.1 mi) on either side of Reaches 1 through 3. No air photos were supplied for Reach 6, where the aqueduct is a buried pipe. The photos were provided by the USBR.

After the air photos were interpreted, field checking began. Terrain on each side of the entire aqueduct was examined on foot, except those portions of Reaches 1 and 2 that were mapped during earlier investigations. The previously mapped terrain (Plates 1 and 2) is from milepost 252.0 (the county road bridge

approximately 2.25 km [1.4 mi] northwest of Brady Pumping Plant), to milepost 265.9 (the wildlife bridge approximately 10.6 km [6.6 mi] south of Picacho Pumping Plant). Fissure locations in this area are identified in Slaff and others (1989) and Slaff and Pearthree (1991).

Wherever possible, field checking was done on undisturbed natural ground because that is where features associated with fissures are most likely to be evident. In a few places, conditions prohibited walking on undisturbed natural ground relatively close to the aqueduct. These conditions include private property, dense vegetation, and disturbed ground that extends well away from the aqueduct. Out of the total of 235.6 km (146.4 mi) examined on foot, approximately 6 km to 8 km (3.7 mi to 5 mi) were disturbed ground. All suspicious features identified during air photo interpretation were examined in the field. Reach 6, for which no air photos were provided, was also examined on foot. Field checking was performed from April to July 1993.

Available sources were consulted for additional information about earth fissures and subsidence near the Tucson Aqueduct. The sources include published and unpublished reports and investigators who have worked in the area.

FINDINGS

No confirmed earth fissures were discovered. However, a few features of questionable origin do exist near the aqueduct, so minor additional monitoring by the USBR is recommended. Details are provided below.

AERIAL PHOTOGRAPH INTERPRETATION

Fifteen suspicious, previously unmapped features were noted on the air photos. They are narrow curvilinear areas that are

visible because of plant alignments or because they are a slightly different shade of gray than the adjacent terrain. Very young and young earth fissures are difficult to identify on air photos because some are discontinuous and most are narrow and lack concentrations of plants growing along them. Thus, faint curvilinear traces on the photos were noted despite the low probability that they are fissures. Lineaments parallel to the edges of mountains were of special interest because structural control causes many fissures to exhibit such orientation.

FIELD EXPLORATION

Of the fifteen features noted on the air photos, two may be related to fissures or subsidence, so they are shown on Plates 2 and 3. Each is discussed in detail below. One of the features is an 800 m- (2,650 ft)-long declivity trending northwest across an alluvial fan less than 1 km (0.6 mi) south of the Picacho Mountains (Plate 2). It is in the northern portions of sections 1 and 2, T.9S., R.9E. It is up to 1 m (3 ft) wide and 0.3 m (1 ft) deep, and partly filled with coarse sand and granules, as are the many distributary stream channels on the alluvial fan. This feature resembles a distributary, but is oriented almost normal to the dominant southwest trend of the channels. Thus it has no real catchment area and may be sand-filled because it crosses stream channels and intercepts their bedload. On the other hand, it appears to slope down to the southeast, and may be merely a "cross-fan groove". It is a continuous feature, easily followed in the field.

Conditions make the site favorable for fissures: It probably overlies a pediment, and large-scale ground-water overdraft has occurred in Picacho basin (to the west) and Avra Valley (to the southeast). Water levels declined along the Santa Cruz River south of Picacho Peak by more than 52 m (170 ft) between 1940 and 1981 (Anderson, 1988). The largest amount of land subsidence

recorded in Avra Valley between 1948-1952 and 1980 is approximately 0.3 m (1.1 ft; Anderson, 1988, fig. 7). The subsidence occurred southeast of Picacho Peak. The "cross-fan groove" south of the Picacho Mountains may be a young earth fissure even though its morphology is not typical of a fissure. It should be examined periodically. If piping, lengthening, or widening occurs, it should be monitored more closely.

Similar uncertainty exists regarding the origin of another feature (Plate 3) that was first identified on the air photos. It is located in section 19, T.10S., R.11E., and is approximately 520 m (1,700 ft) long, up to 2 m (6.6 ft) wide, and 0.5 m (1.6 ft) deep. It trends north-northwest, normal to the ephemeral channels nearby on the piedmont. Compared with the feature on Plate 2, it is less continuous, more marked by aligned plants, and harder to follow in the field. Only short sections of it are partly filled with sand and gravel, and it does not disrupt the courses of small drainage channels that cross it. It lacks the typical form of a young fissure. (It is not a deep, narrow crack with steeply sloping walls). Approximately 1 km (0.6 mi) west of the feature, the water table declined 30 m (100 ft) between 1940 and 1978 (Hanson and others, 1990). This feature is less likely to be an earth fissure than is the one in sections 1 and 2 (discussed above). Nonetheless its proximity to the aqueduct makes monitoring advisable, at least by checking air photos taken in the future.

Two pits caused by localized collapse or piping are located in section 32, T.6S., R.9E., approximately 150 m (500 ft) upslope from the aqueduct in Reach 1 (Plate 1). One is 0.3 m (1 ft) in diameter and 0.1 m (4 in.) deep, but the other is slightly larger in diameter, 0.6 m (2 ft) deep, and its diameter increases with depth to approximately 0.8 m (2.6 ft) at the bottom. The pits are difficult to find because of dense vegetation cover. Other pits may be present in the area. A hazard would exist only if

the pits become much larger and more abundant, or are the precursors of a fissure. Monitoring is probably unnecessary.

The "Sandario Road" fissure is in section 27, T.12S., R.11E. (Plate 4). It was discovered on 17 October 1988 after runoff ponded against the upslope dike of the aqueduct in Reach 4 (Gary A. Ditty, civil engineer, USBR, oral commun., 1988). It was approximately 262 m (860 ft) long, up to 4.8 m (16 ft) wide, and at least 3.1 m (10 ft) deep on 24 October 1988. The west side was down-dropped by as much as 4 cm (1.6 in.) of vertical displacement. The fissure crossed the aqueduct and caused some of the seams in the concrete to separate slightly. Because the area previously had been recognized as prone to fissure formation, this portion of Reach 4 was reinforced during construction. As a result, no leakage occurred.

Repair work began shortly after the fissure was discovered. The seams in the concrete were sealed with a rubber caulking compound. The wide portions of the fissure were excavated to a depth of approximately 3 m (10 ft) and backfilled with a lean mixture of bentonite and cement in an attempt to prevent additional water from entering. A berm of native soil was constructed above the fissure, and a cutoff channel was excavated upslope from and beside the fissure. The object of both procedures was to prohibit ponding by diverting overland flow away from the fissure.

The "Sandario Road" fissure was examined during this investigation for signs of lengthening, reactivation, and erosion. None was found. There has been a higher than normal rate of erosion of the downslope dike in this vicinity, but it is not clearly related to the presence of the earth fissure. If it has not already been done, it is recommended that a piezometer be installed in a shallow boring near where the fissure crosses the aqueduct so that a leak could be detected.

A few areas of concern in Avra Valley are shown on Plate 5. These are sites where earth fissures have previously been reported to occur (Caito and Sogge, 1982; Raymond and Bartell, 1985). The fissures were backfilled with sediment soon after they formed, and in some cases their exact locations were not reported, so they could not be identified during field checking for this investigation. Their generalized locations are shown on Plate 5 so that they can be monitored if any reactivation, lengthening, or new fissures occur in the future. They are discussed in more detail below.

The "Snyder Hill Road" fissures are located in section 35, T.14S., R.11E. and section 2, T.15S., R.11E. (Caito and Sogge, 1982; Plate 5). An unspecified number of fissures were found along the middle and sides of the road on 12 July 1981. A strong storm occurred in the area the previous night. The cracks were approximately 3.2 km (2 mi) long, of unreported width, and "...deep enough that a broom dropped into [one of them] could not be heard when it hit bottom" (Caito and Sogge, 1982). The fissures were backfilled with 612 cu m (800 cu yds) of sediment on the day they were discovered. No signs of piping or reactivation were observed during field checking in July 1993.

Caito and Sogge (1982) also reported a fissure in sections 30 and 31, T.14S., R.12E. near Bopp Road (Plate 5). Raymond and Bartell (1985) reported two or more fissures a short distance to the east, near the intersection of Bopp and San Joaquin Roads. These locatons are close enough to the aqueduct (0.8 km [0.5 mi]) to be of concern, but no fissures were found when the sites were visited in July 1993.

One other site of potential concern has been identified on Plate 6. It is in section 22, T.15S., R.12E. A gravity survey of Avra Valley by West (1970) shows a steep gradient at this location, which suggests that it may overlie a fault that displaces

bedrock. The existence of the fault is corroborated by seismic and gravity surveys conducted in 1993 by the USBR (Leo L. Langland, geologist, USBR, written comm., 1993). The fault probably continues to the north-northwest for at least another 3.2 km (2 mi). This type of range-bounding normal fault is thought to exert structural control over some fissure locations in Picacho basin (Pankratz and others, 1978) and elsewhere. The fault in section 22 could localize differential subsidence or an earth fissure at the ground surface above it. The same is true for some of the other faults suspected to exist below the east side of Avra Valley.

DISCUSSION

As expected, most of the suspicious features noted on the air photos (13 out of 15) are not potential hazards to the aqueduct. Lineaments occur for many reasons. Because some fissures appear as faint traces on air photos, all lineaments that could not be ascribed to other causes during photo interpretation were examined in the field. The lineaments were found to be: 1) chance alignments of plants; 2) unusual erosion patterns; 3) distributions of different plant species; 4) old fence lines; 5) ground-surface texture or desert pavement grain-size differences; 6) human-caused furrows; 7) stock or wildlife trails; and, 8) combinations of the above features.

During the fieldwork, some features were observed that mimic those produced by differential subsidence and earth fissures, or that are related to different types of subsidence or shallower extensional horizontal stress. Small closed depressions (up to a few meters [several feet] long and 1 m [3 ft] deep) are common in poorly compacted artificial fill. Shallow fill occurs in many places where the land has been graded adjacent to the aqueduct dikes. Smaller closed depressions occur in some areas where vegetation has been disturbed and roots create voids as they rot.

Both of these types of closed depressions were observed in several places along the aqueduct.

Another type of feature (observed mostly on the upslope side of the aqueduct where the dikes have caused runoff to pond) is cracks caused by soils with a strong tendency to change volume. Commonly, these soils are rich in smectite, a clay mineral that has a much larger volume when wet than when dry. As they dry, these soils form polygonal and (or) curvilinear cracks up to 3 cm (1.2 in.) wide and 0.5 m (1.6 ft) deep.

Another kind of subsidence that occurs along portions of the aqueduct is hydrocompaction, also known as near-surface subsidence. It is the partial collapse, upon wetting, of low-density silty and sandy sediments. It commonly results in fissures and depressions that coincide with the area where water was applied. The fissures are not as deep or wide as earth fissures, and they tend to occur in a concentric pattern where a lot of water was applied. A portion of Reach 3, mostly in section 25, T11S., R.11E. (from milepost 289.5 to 291.0) has been damaged repeatedly by hydrocompaction. Repairs have been required at least three times to date. The areas adjacent to all six reaches were examined for evidence of hydrocompaction, but none was found.

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