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Earth-fissure movements in south-central Arizona, U.S.A.

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The University of Arizona, 1987

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EARTH-FISSURE MOVEMENTS IN SOUTH-CENTRAL ARIZONA, U.S.A.

by

James Keith Boling, Jr.

A Thesis Submitted to the Faculty of the

DEPARTMENT OF HYDROLOGY AND WATER RESOURCES

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THE UNIVERSITY OF ARIZONA

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ABSTRACT

Ground-water pumping has led to subsidence and many earth fissures in unconsolidated alluvial basins in Arizona. Earth fissures result from tensile failure; however, mechanisms producing the tensile forces are not well understood.

Horizontal displacement measurements (opening and closing) of seven earth fissures were made semi-monthly during 1976 to 1982 in the lower Santa Cruz Basin and Avra Valley. Permanent and temporary short-base extensometers with a resolution of ± 2.54 μm were developed and perfected which use dial gauges and transducers.

Among different fissure movements, the greatest total was 41.44 mm, the greatest single opening was 31 mm, and exclusive of that, the greatest net opening was 16.54 mm. Fissures opened and closed repeatedly, exhibiting smooth movements over long periods of time, punctuated by sudden jumps. Generally, old and new earth fissures exhibited similar behavior. Earth fissures tend to close after long, dry periods and to open after heavy rainfalls. The earth fissure with the greatest movement was closest to the area of the greatest subsidence.

CHAPTER 1

INTRODUCTION

Earth fissuring and other various effects of land subsidence due to water-level declines in at least seven ground-water basins in Arizona have been well documented (Platt, 1963; Schumann and Poland, 1969; McCauley, 1973; Cordova, 1975; Laney, Raymond, and Winikka, 1978). The spatial and temporal relations among water-level declines, land subsidence, and earth fissures have been clearly established (Schumann and Poland, 1969). Different research techniques included the following: 1) surveying (Robinson and Peterson, 1962), 2) recording of compaction and water-level decline, 3) drilling (Holzer, 1978a), 4) geophysical investigations (Jachens and Holzer, 1979; Holzer and Pampeyan, 1981), and 5) air-photo mapping (Laney et al., 1978).

Previous research resulted in various theories which relate the processes and forces involved wth tensile failure of earth fissures; however, the mechanisms producing the necessary tensile forces are not well understood (Leonard, 1929; Fletcher et al., 1954; Pashley, 1961; Peterson 1962, 1964; Jones, 1968; Schumann and Poland, 1969; Lofgren, 1972; Holzer and Davis, 1976; Bouwer, 1977; Jachens and Holzer, 1979; Johnson, 1980; Holzer and Pampeyan, 1981). Detailed measurement of horizontal earth-fissure displacements has been very limited. The study of earth fisssures and their displacements is required to better understand their origins, mechanisms, and relations with other hydrogeologic features and processes.

This study is an investigation of earth fissures, including field mapping and description of earth fissures, design, development, and installation of short-base, horizontal dial-gauge extensometers to measure earth-fissure displacements (openings and closings), and database compilation of earth-fissure displacements at seven different sites and water-level measurements near four of the seven sites, all in Arizona. It is hoped that this study will benefit the theoretical and practical understanding of earth-fissure origins, mechanisms, and development.

Objectives and Methods

This study has been primarily a field-oriented project intended to measure and analyze horizontal displacements of earth fissures in an effort to better understand earth fissures. The specific objectives were as follows:

1. To become familiar with the surface and subsurface extent of earth fissures and their horizontal displacements.
2. To develop the techniques required to measure horizontal earth-fissure displacements.
3. To generate an earth-fissure displacement data base used to characterize the signature of earth-fissure displacements.
4. To make a preliminary analysis of the data base for correlations among earth-fissure displacements, precipitation, and water-level fluctuations and/or declines.

A large portion of the research was devoted to the development and perfection of permanent and temporary short-base extensometers designed to measure discrete and continuous, horizontal earth-fissure displacements using accurate dial gauges and transducers. The extensometers were designed to be constructed cheaply and simply, to minimize thermal effect, to obtain small resolution, and to operate under all field conditions. These extensometers were the primary method by which discrete, small, horizontal earth-fissure displacements were recorded.

Semi-monthly and monthly, horizontal dial-gauge measurements of earth-fissure displacements were made at seven locations near the Picacho Mountains and Sacaton Mountains and in Avra Valley, Arizona. Displacement transducer measurements of horizontal earth-fissure displacements were made in Avra Valley. Water levels were measured in U.S. Geological Survey piezometers near the Picacho Mountains. Other measurements and observations were made elsewhere in south-central Arizona. Field work was conducted intermittently for approximately seven years from the beginning of 1976 to the end of 1982.

Definitions

The following definitions are offered to facilitate an understanding of the discussion of earth fissures, the measurement of their horizontal displacements, and land-surface subsidence as presented in this study:

1. Accuracy: "The degree of conformity with a standard or the degree of perfection attained in a measurement" (Bates and Jackson, 1980, p. 5).

2. Coarse: "Composed of large parts or particles; thick" (Webster's New Universal Unabridged Dictionary, 1983).

3. Coarseness: "The state or quality of being coarse" (Webster's New Universal Unabridged Dictionary, 1983).

4. Compaction (Poland, Lofgren, and Riley, 1972, p. 2):

   "Decrease in volume of sediments, as a result of compressive stress, usually resulting from continued deposition above them" (American Geological Institute, 1957, p. 8). In this glossary, compaction is defined as the decrease in thickness of sediments, as a result of increase in vertical compressive stress, and is synonymous with "one-dimensional consolidation" as used by engineers. The term "compaction" is applied both to the process and to the change in thickness.

5. Consolidation (Poland et al., 1972, p. 4):

   In soil mechanics, consolidation is the adjustment of a saturated soil in response to increased load, involving the squeezing of water from the pores and a decrease in void ratio (American Society of Civil Engineers, 1962). In our reports, the geologic term "compaction" is used in preference to consolidation, except to report and discuss results of laboratory consolidation tests, made in accordance with soil-mechanics techniques.

6. Earth fissure: A narrow vertical crack or fissure in the alluvium.

7. Fine: "Made up of minute particles . . . small; thin; minute" (Webster's New Universal Unabridged Dictionary, 1983).

8. Fineness: "The state or quality of being fine" (Webster's New Universal Unabridged Dictionary, 1983).

9. Fissure-gully: "Fissures intercept surface runoff and erode to form gully-like features along the trends of the fissures as water and eroded material travel downward. . . . This secondary erosional enlargement is termed 'fissure-gully' and thus is

distinguished from the initial cracking of the alluvial material" (Laney et al., 1978, Sheet No. 1).

10. Precision: "The degree of agreement or uniformity of repeated measurements of a quantity" (Bates and Jackson, 1980, p. 496).
11. Resolution: "The process or capability of making distinguishable individual parts" (Webster's Ninth New Collegiate Dictionary, 1985). In this report, resolution refers to the smallest displacement detectable by the instrumentation.
12. Strain: "Change in length of an object in some direction per unit undistorted length" (McGraw-Hill Dictionary of Scientific and Technical Terms, 1976).
13. Stress: "The force acting across a unit area in a solid material in resisting the separation, compacting, or sliding that tends to be induced by external forces" (McGraw-Hill Dictionary of Scientific and Technical Terms, 1976).
14. Subsidence: "Sinking or settlement of the land surface, due to any of several processes. As commonly used, the term relates to the vertical downward movement of natural surfaces although small-scale horizontal components may be present" (Poland et al., 1972, p. 8).

In this report, all dimensional, numerical values are given in metric units except for the Fahrenheit scale for temperature. This, along with the values of depth to water level and the values of the horizontal earth-fissure displacements in Appendix A and Appendix B, respectively, are in keeping with the data's original sources.

CHAPTER 2

FIELD AREA

Location

The field area is within the Basin and Range Lowland Physiographic Province of Arizona, a region characterized by large alluvial basins bounded by mountains of predominantly crystalline rock. Dial-gauge extensometer locations Rattler and Turnaround are near the Sacaton Mountains. Dial-gauge extensometer locations Mudflat, Princess, Scorpion, Stubby, and Waiting-to-Drill are near the Picacho Mountains. The Sacaton Mountains and the Picacho Mountains are in the lower Santa Cruz valley. Dial-gauge extensometer location AV-7 is just east of Ryan Field in Avra Valley (Figure 1). All dial-gauge extensometer locations are in alluvial material. Table 1 provides the exact locations and periods of operation.

Climate

The semi-arid study area is within the Sonoran Desert. Mean summer and winter temperatures are 89°F and 52°F, respectively. Precipitation occurs primarily in late summer and winter. Summer rainstorms are short, localized cloudbursts. The less intense winter rains are longer in duration and cover larger areas. The average annual rainfall is approximately 10 in.

The mean monthly precipitation values of Eloy and Picacho Reservoir, the closest climatological stations, were averaged to provide

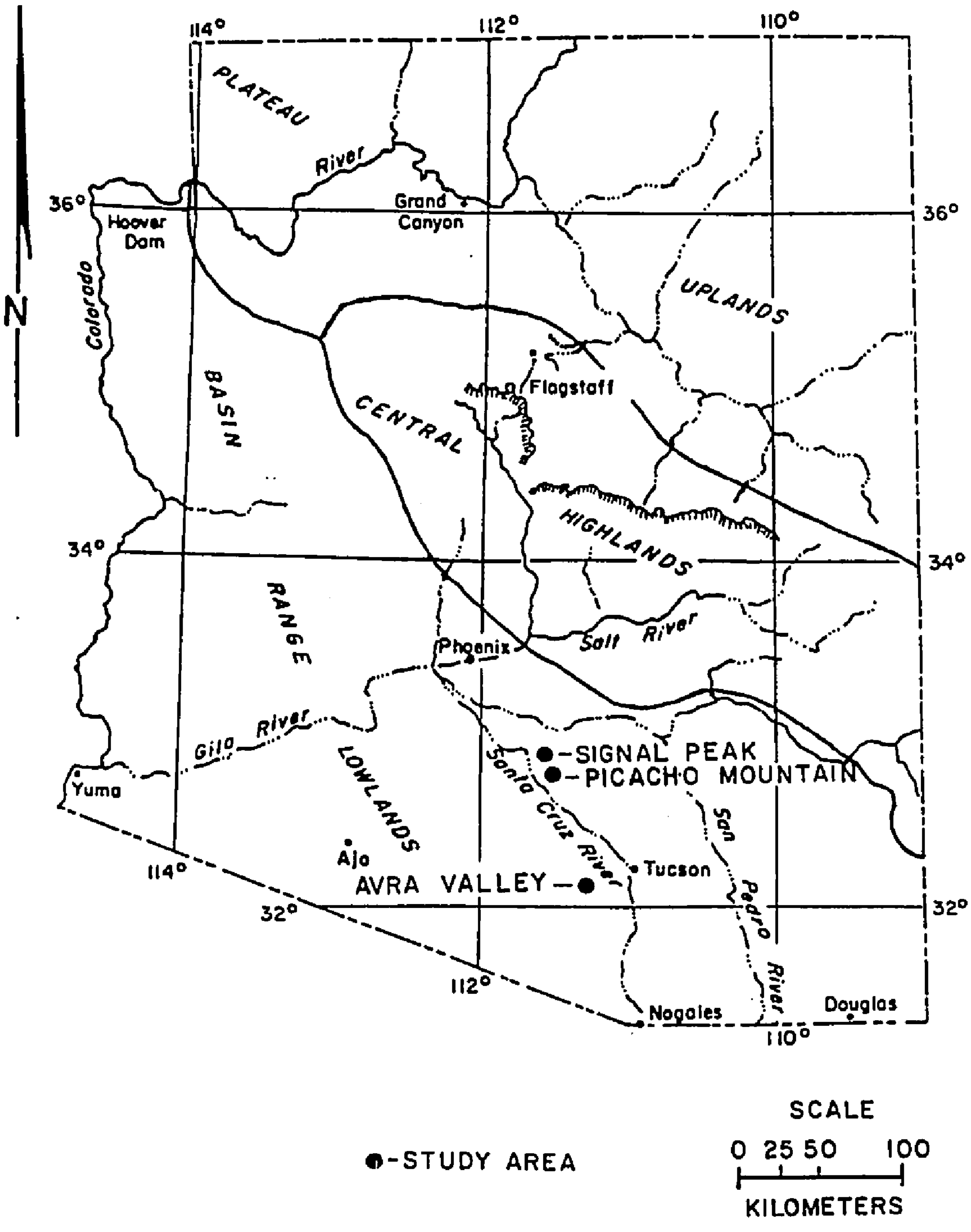


Figure 1. Map of Arizona showing the study area locations.

Table 1. Dial-gauge extensometer locations and periods of operation.

Dial Gauge	Location	Period of Operation
Mudflat	SE 1/4, SE 1/4, SW 1/4, Sec. 29, T.8S., R.9E., Red Rock Quadrangle, Arizona (15 min)	23 April 1976 to 26 November 1977 (destroyed)
Stubby	SE 1/4, SE 1/4, NE 1/4, Sec. 29, T.8S., R.9E., Red Rock Quadrangle, Arizona (15 min)	23 April 1976 to 31 December 1982
Princess	SE 1/4, SE 1/4, NE 1/4, Sec. 19, T.8S., R.9E., Red Rock Quadrangle, Arizona (15 min)	27 August 1977 to 31 December 1982
Waiting-to-Drill	SW 1/4, SW 1/4, NE 1/4, Sec. 36, T.8S., R.8E., Red Rock Quadrangle, Arizona (15 min)	30 August 1977 to 31 December 1982
Turnaround	SW 1/4, NE 1/4, SW 1/4, Sec. 32, T.5S., R.7E., Casa Grande East Quadrangle, Arizona (7.5 min)	4 September 1976 to 31 December 1982
Rattler	SW 1/4, SW 1/4, NW 1/4, Sec. 29, T.5S., R.7E., Casa Grande East Quadrangle, Arizona (7.5 min)	4 September 1976 to 31 December 1982
Avra Valley Well No. 7	SW 1/4, NE 1/4, SW 1/4, Sec. 16, T.15S., R.11E., San San Mission SW Quadrangle, Arizona (7.5 min)	30 August 1977 to 31 December 1982

a data base for possible correlations with dial-gauge extensometer readings near the Picacho Mountains. Sacaton climatological station provided the monthly precipitation data base for the dial-gauge extensometers near the Sacaton Mountains. The data for Eloy, Picacho Reservoir, and Sacaton climatological stations were from Climatological Data, Arizona (1976-1982). The precipitation data base for Avra Valley was obtained from Dolly Forren, who maintained a climatological station at Ryan Field in Avra Valley.

Picacho Basin Hydrogeology

The Picacho basin is underlain by thick, unconsolidated alluvium, anhydrite, and indurated conglomerate deposits, and is bounded by fault-uplifted mountains of plutonic, metamorphic, and volcanic rock. The sedimentary sequence extends as deep as 3,000 m (Peirce, 1976), of which at least the upper 750 m is unconsolidated alluvium (Hardt and Cattany, 1965). Because of nearby rock outcrops, most study sites are believed to overlie buried pediments, which is to say that the sites overlie or are mountainward of inferred basin-boundary faults. Depth to bedrock beneath the sites is on the order of 50 to 300 m. Geophysical investigations indicated that the local bedrock surface may be irregular (Pankratz, Ackermann, and Jachens, 1978; Jachens and Holzer, 1979). Tectonically, the region is relatively inactive.

The report by Hardt and Cattany (1965) provides a basis for interpretation of the Picacho basin ground-water system. Three hydrogeologic units were identified: lower and upper sand and gravel units separated by a unit of silt and clay. The three units extend to a depth of more than 750 m. The lower sand and gravel unit is a heterogeneous mixture of sand, gravel, and clay ranging up to 150 m in thickness, but is generally between 30 and 75 m thick. The middle silt and clay unit confines the lower unit ground water. In the absence of the silt and clay unit, the lower and upper units are indistinguishable and unconfined. Ranging in thickness from 0 to 600 m, the silt and clay unit is the least permeable and productive of the three units, but it does contain lenses of highly permeable, water-bearing material. The upper sand and gravel unit is similar to the lower unit lithologically and ranges in thickness from 15 to 185 m. This unconfined upper unit has the highest average permeability. However, the permeability varies both vertically and horizontally.

Natural ground-water movement in the Picacho basin is toward the northwest (Hardt and Cattany, 1965). Pumping from storage has created local potentiometric surface depressions which now affect the direction of ground-water flow. Ground-water levels have declined as much as 100 m since 1923, nearly reaching the bottom of the upper sand and gravel unit. Production wells now reach to depths of over 760 m (Holzer, Davis, and Lofgren, 1979).

Subsidence in the Picacho basin has been attributed to hydrocompaction, increased effective stress due to loss of buoyancy, and basin readjustment. Subsidence prior to significant pumping and irrigation is most likely due to basin readjustment (Christie, 1978). Flood irrigation has caused hydrocompaction of unsaturated, near-surface alluvium which is rich in clay. This reasonably accounts for a portion of the subsidence. Compaction of unconsolidated alluvium in response to the loss of buoyancy during decline of ground-water level due to ground-water extraction is believed to be the main cause of subsidence (Poland, 1967).

Avra Valley Hydrogeology

Sediments eroded from the surrounding mountains in addition to evaporite deposits and volcanic strata make up the alluvium of Avra Valley. The bordering sedimentary, volcanic, and metamorphic mountains, fault uplifted in part, are composed of sandstones, conglomerates, and limestones, andesites and rhyolites, and shales and granites.

Because the alluvium lacks distinct lithologic units and fossils, stratigraphic units were difficult to classify. Using data based on drilling samples taken every 1.5 m, Allen (1980) separated Avra Valley alluvium into three parts: surficial deposits, younger alluvium, and older alluvium.

The surficial deposits are composed of sand, silt, and clays with some scattered gravels. Due to a gap in the sampling record close to the surface (between 0 and 1 m), the boundary between the surficial deposits and the younger alluvium is poorly defined.

The younger alluvium extends from approximately 10 m to 85 or 116 m. This sequence is composed of thickly interbedded layers of coarse- and fine-grained sediments that vary in thickness from 1.5 m to 15 m. The sediments contain clastics derived predominantly from volcanics, and some material of granitic origin.

The older alluvium, which is the primary aquifer of Avra Valley, extends from 85 or 116 m to approximately 300 m. The older alluvium is characterized by its uniformity of grain size and lack of interbedding. It can be separated into an upper coarse-grained unit and a lower fine-grained unit. The sandy gravel to gravelly sand of the coarse-grained portion is similar to the overlying younger alluvium in rock type. The silt and clay of the fine-grained portion is massive to thinly bedded.

The basement contact between alluvial fill and bedrock is uneven. From the land surface, it drops off steeply on the eastern side and flattens along the western side, with irregularities in between.

Mapping

Detailed, large-scale mapping of fissures in the field area near the Picacho Mountains was done because of the large number and complexity of earth fissures in that area. A previous map by Schumann (1974), which included the Picacho field area, was done from the air with a helicopter. The Schumann map was of insufficient detail and did not show an accurate number of earth fissures in the area or their complexity. This investigation included the following: 1) general familiarization with earth fissures, 2) possible earth-fissure patterns, 3) possible relationship(s) between earth fissures and existing drainage patterns, and 4) rate of earth-fissure growth. Mapping was done on a sheet of Mylar which overlaid an air photo. Figure 2 was produced from a reduction of the original field map made of the Picacho study area located in the eastern half of Sec. 29, T.8S., R.9E., Red Rock Quadrangle, Arizona (15 min).

Figure 2. Detailed earth-fissure map of the Picacho study area. -- Sec. 29, T.8S., R.9E., Red Rock Quadrangle (15 min.).

CHAPTER 3

EARTH FISSURES

Description

The earth fissures in south-central Arizona occur at the land surface as linear and curvilinear features that are generally segmented rather than continuous, in places forming an en echelon pattern. Typically, they have one leading edge, rarely two, that is characterized by a hairline earth fissure or depressions that are separated one from the other and continue the trend of the earth fissure. A wide variety of patterns exist, from simple lineations to complex polygons. Earth fissures may be tens of meters in length; often, they are hundreds of meters and up to kilometers in length. The initial width is believed to be only a few millimeters to centimeters (Figure 3). The diversion of overland and stream flow rapidly erodes the sides of earth fissures, increasing the width to several meters in some places. Laney et al., (1978) used the term "fissure gully" to describe eroded earth fissures (Figure 4). Because of the abrupt lowering of local base level produced by earth fissures, intercepted stream channels are subject to rapid gullying and headward erosion. The large amounts of runoff, stream flow, and sediment received by earth fissures suggest their subsurface extent is very great. Johnson measured one earth fissure to a depth of 25 m (1979) and suggested that earth fissures may be as deep as 100 m, or more (1980). Commonly, minor fissures form near or parallel to a

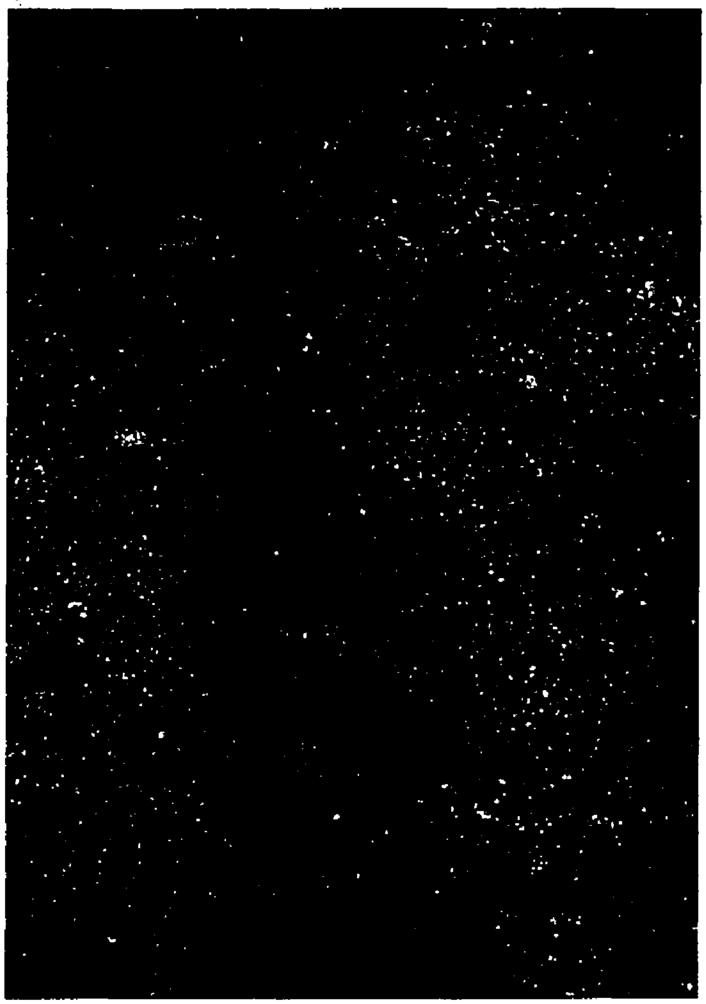


Figure 3. Earth fissure, hairline, leading edge.

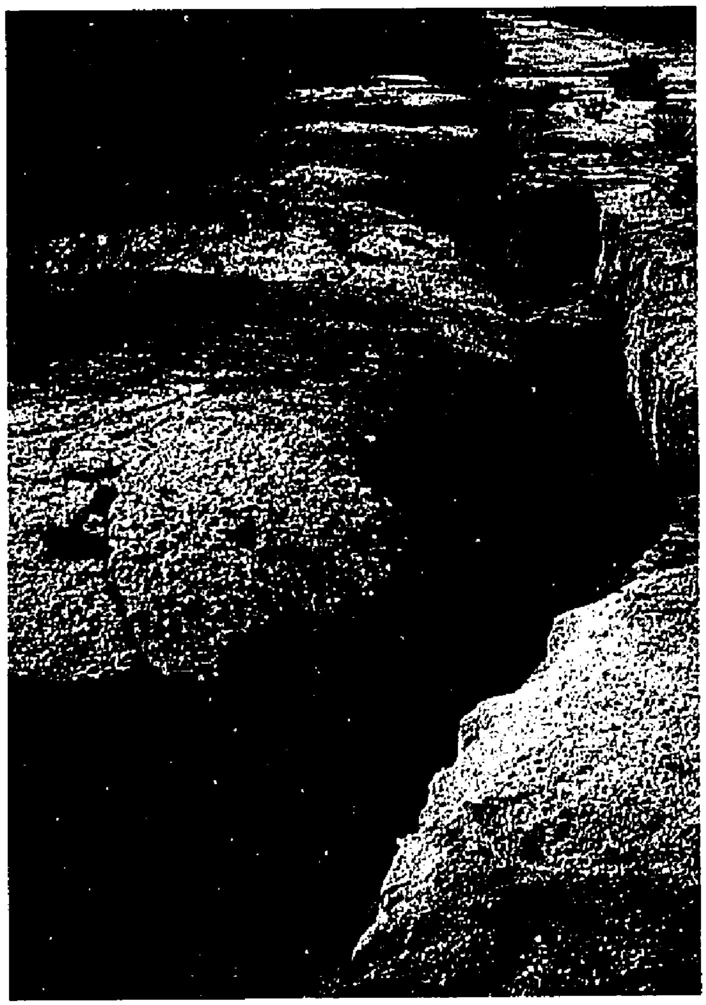


Figure 4. Eroded fissure-gully.

pre-existing fissure. These features may be due to deep-seated strain, or simply a result of local, near-surface settling or reduction in horizontal stresses.

In most places, the earth fissures in this study do not exhibit vertical offset. The Picacho fault is a spectacular exception, with over 60 cm of offset at various locations along its 15 km length.

Damage

Earth fissures have caused physical damage and public concern. Highways, canals, and pipelines of all sizes as well as railroads have been damaged (Figures 5 and 6). Extensive damage to several flood-control dikes and dams has been caused by earth fissures. Vertical offset of earth fissures has the greatest damage potential, especially to large buildings. Brick- and block-construction homes could be damaged by simple horizontal spreading of earth fissures without vertical movement.

The potential negative aspects of ground-water recharge by earth fissures far exceed the positive potential of possible direct recharge to the aquifer. Earth fissures provide an avenue for rapid and deep recharge of water directly to the aquifer, resulting in the serious possibility of ground-water contamination. Petrochemicals from ruptured pipelines, agricultural chemicals, urban runoff, and direct dumping of liquid and solid wastes are potential sources of ground-water contamination by direct injection into aquifers via earth fissures.

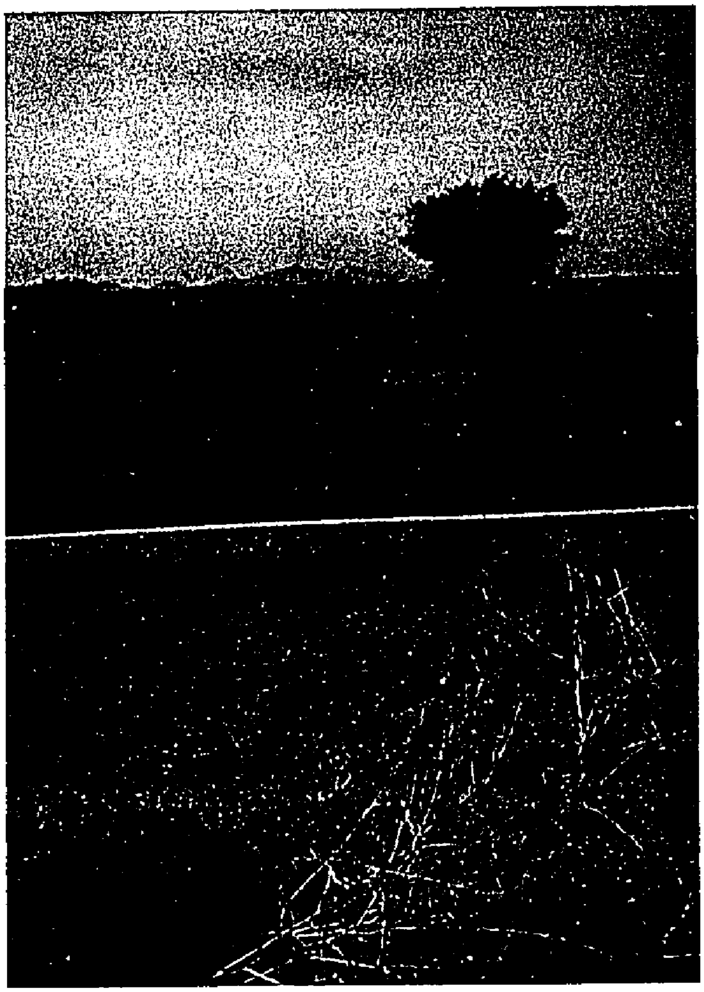


Figure 5. Earth-fissure damaged road.

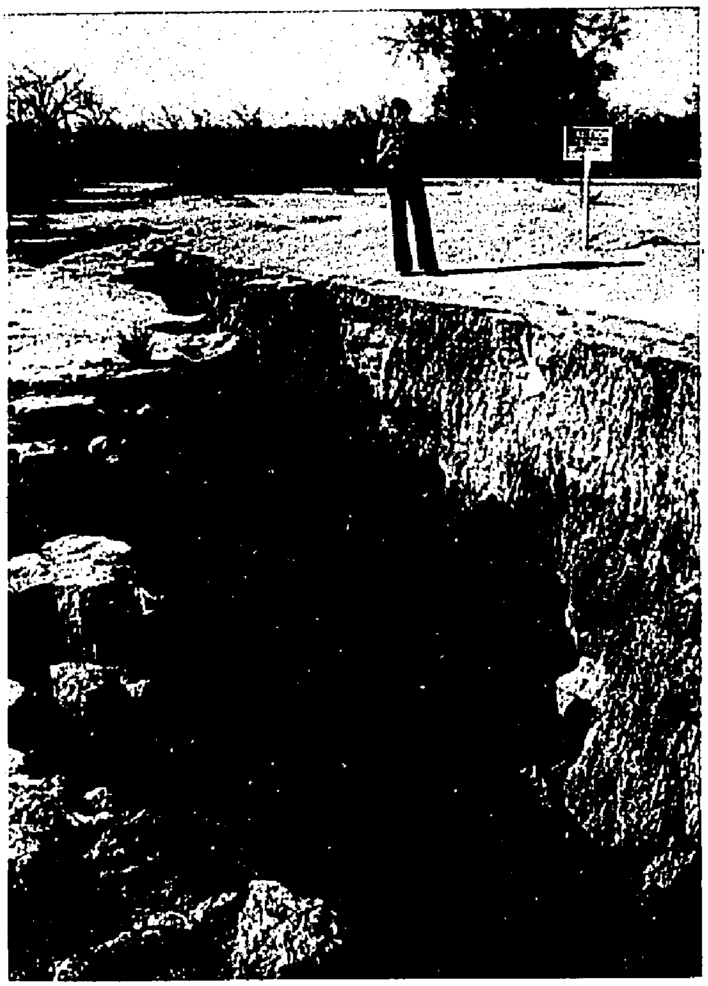


Figure 6. Petrochemical pipeline transected by an earth fissure.

Previous Work

Leonard (1929) reported the first "earth fissure" in southern Arizona. Reporting in the Bulletin of the Seismological Society of America, he discussed a linear ground-surface feature exhibiting horizontal strain in alluvial material:

> An earth fissure or crack in the ground, believed to be of unusual origin, occurred on or about September 11, 1927, at a point some 3 miles southeast of Picacho, Arizona. . . . It was discovered early in the morning of September 12, after a severe rain and wind storm of the afternoon and night before.
>
> The fissure may be characterized as a short vertical rift, extending in a general northeast-southwest direction for approximately 1000 feet, in unconsolidated or at best but feebly coherent silty and sandy playa material. It is located along the southern side of a slightly depressed playa-like area on the eastern border of the extensive intermontane plain or basin area of the Santa Cruz River, and at the foot of the western drainage slope of the Picacho Mountains. When first formed, the rift ranged in width from a mere fracture in its end portions up to probably less than 6 inches in parts. . . . Caving on the walls along the wider sections of the crack evidently commenced soon after the rupture took place, widening some of them up to 2 and 3 feet and incidentally partly filling the fissure, so that its actual depth could not be determined. The greatest measured depth found was only 15 feet. (p. 765)

Leonard considered subsidence and collapse into open caverns of subsurface drainage unlikely. He concluded that an earthquake in northern Mexico had directly or indirectly caused the Picacho earth fissure.

Feth (1951) next reported earth fissures in an area parallel to the west front of the Picacho Mountains. He reported that "after two heavy rains had fallen over the area, there were indications that locally the fissures were acting as sinkholes, conducting runoff to a considerable depth" (p. 24). Feth concluded that the earth fissures resulted from strains due to subsidence of poorly consolidated alluvial materials overlaying the edge of a buried pediment.

Fletcher et al. (1954) considered the earth fissures in the Picacho area to be the result of an erosional phenomenon termed "piping." They claimed that these pipes or pipe-like channels intersected the surface, appearing as large earth fissures. In a replying discussion, Heindl and Feth (1955) rejected the piping explanation because the earth fissures had no ready outlet. Due to the clean walls with sharp edges, they suggested tensional breaks resulting from differential subsidence across a buried pediment edge.

Pashley (1961) reported that earth fissures appeared near Casa Grande during a heavy thunderstorm in July 1957. He noted that the fissures lacked any relationship to surface drainage. Pashley documented the flow of an estimated 20 liters per second into an earth fissure from a ruptured irrigation ditch. This flow rate continued for about 18 hours before the earth fissure filled. During this period, several cubic yards of dirt dumped into the earth fissure by a bulldozer had no apparent effect. Pashley suggested earth fissuring was caused by hydrocompaction.

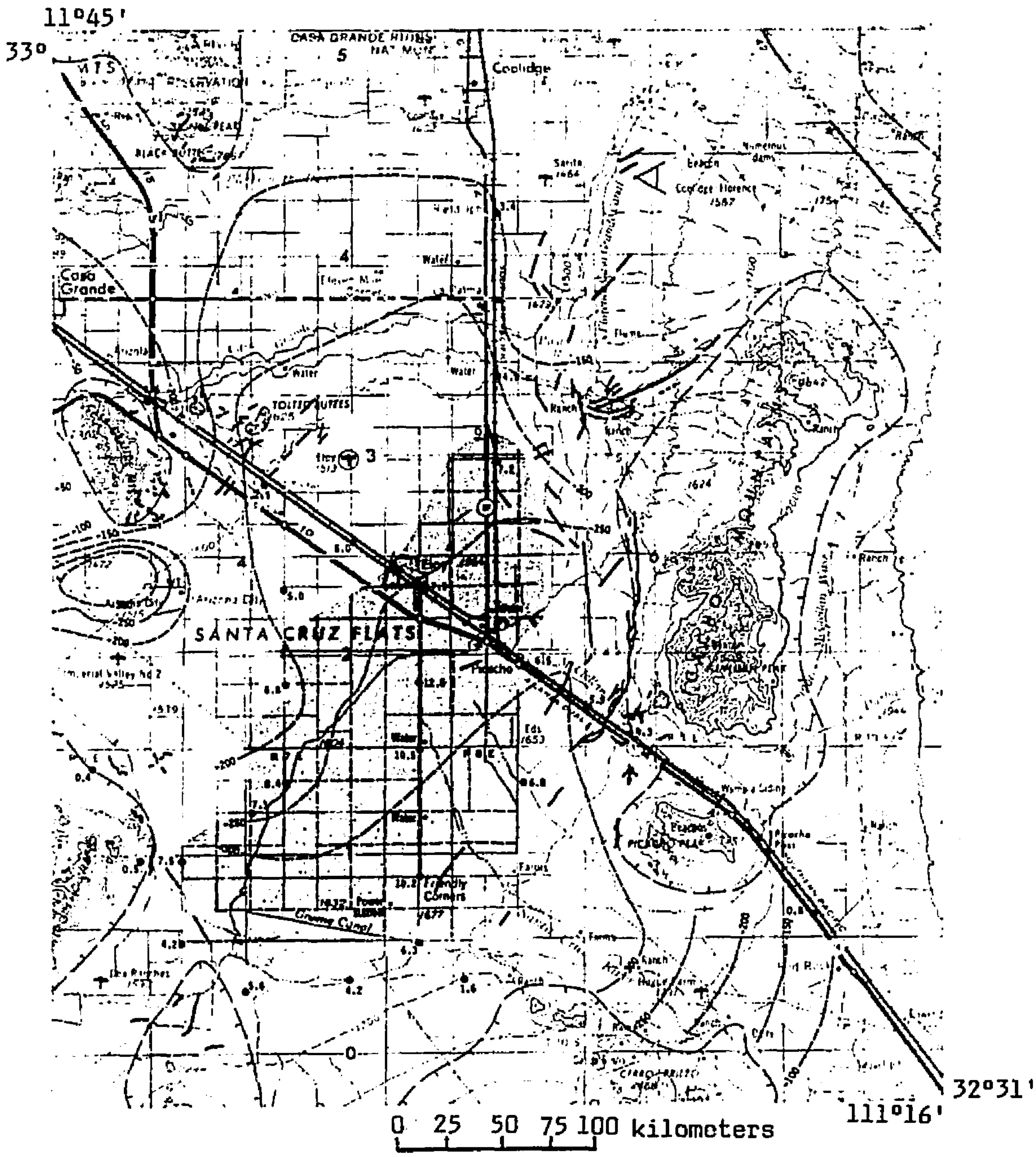
Widespread earth fissuring was reported in the Picacho basin and southern Arizona by Robinson and Peterson (1962). They noted the important, concurrent processes of ground-water level decline, land subsidence, and earth fissuring. Peterson (1962, 1964) observed the correlation of anomalous gravity highs and the locations and trends of earth fissures. He supported the hypothesis that earth fissures were tensional breaks due to differential subsidence over buried pediments and fault scarps.

Indeed, Figure 7 clearly supports the relationship among water-level declines, land subsidence, and earth fissuring as suggested by Schumann and Poland (1969). They declared that these processes were related and artificially induced. Although Leonard's earth fissure of 1927 formed prior to significant ground-water declines and subsidence, early pumping may have caused sufficient water-level declines to induce earth fissuring. Locales of land subsidence are superimposed over areas of significant water-level declines. Earth fissure lineations are peripheral to land-subsidence areas and perpendicular to natural drainage systems. It is widely accepted that water-level declines, land subsidence, and earth fissures are interrelated, considering their spatial and temporal relationships.

Lofgren (1971) proposed horizontal seepage forces, generated by a pumping well, as a possible fissuring mechanism. Holzer and Davis (1976) and Holzer (1977) suggested horizontal contraction of sediments, due to capillary stress build-up in the dewatered zone, as a result of ground-water level declines. This mechanism may explain the semi-closed patterns sometimes formed by earth fissures (Holzer and Davis, 1976; Holzer, 1977).

Bouwer (1977) suggested that earth fissures are caused by the rotation of large, rigid blocks of alluvium about a bedrock irregularity that acts as a pivot point (Figure 8).

Jachens and Holzer (1979) completed geophysical work of particular importance with respect to earth fissures examined in this study. Both gravity and magnetic surveys were made at eight sites in the Picacho basin. Jachens and Holzer (1979) observed:



SHADED AREA Approximate area of land subsidence > 7 feet

--(-200)-- Approximate line of equal water level change, 1923-1977; interval 50 feet

• 5.6 Land subsidence of representative bench marks, 1952-1977

Earth fiissures as of 1977

Figure 7. Water-level decline, subsidence, and earth-fissure map of the Picacho study area. -- After Laney et al. (1978).

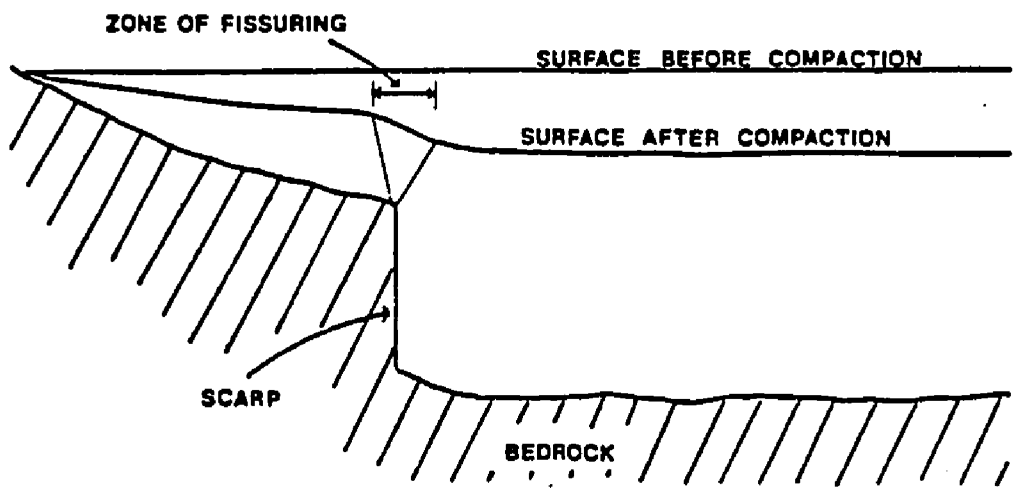


Figure 8. Earth fissuring due to differential compaction of alluvium over a bedrock scarp.

> At the sites close to bedrock outcrop, a distinct, consistent spatial correlation exists between earth fissures and the geophysical data. These fissures are associated with convex-upward gravity or magnetic anomalies, some of which are local maxima, whereas others are simply convex-upward changes of slope superimposed on steep gradients. At the sites where ground failure is relatively far from bedrock outcrop, an association between ground failure and geophysical anomalies is not obvious and may not exist. (p. 577)

They concluded that localized, differential compaction (Figure 9) was the cause of most earth fissures that they investigated:

> Most ground failures investigated in Picacho basin, particularly the fissures near exposed bedrock, are spatially correlative with local convex-upward gravity or magnetic anomalies or both.
>
> The most likely cause of the geophysical anomalies correlated with earth fissures . . . is local relief in the bedrock surface. In particular, results from quantitative modeling . . . suggest that many fissures occur over local bedrock highs.
>
> The occurrence of many earth fissures in Picacho basin over bedrock irregularities suggests that the fissures are spatially associated with zones of localized differential compaction. . . . Calculation of horizontal displacements associated with differential compaction was applied . . . to test whether horizontal strains generated across bedrock irregularities could be adequate to cause tensile failure. . . . Results indicate that horizontal tensile strains generated by this mechanism are greatest at the locations of observed earth fissures.
>
> Localized differential compaction may be the dominant source of tension causing earth fissures at most of the sites investigated. (p. 582)

Johnson (1980) studied earth-fissure erosion characteristics in the Picacho basin. He monitored ephemeral stream regimes to determine earth-fissure depths and earth-fissure capacities to cause erosion and receive water and sediment. Speculating on the depths and subsurface extent of earth fissures, he concluded: "Fissures are as much as 100 meters, or greater, in depth and of extensive subsurface lengths. . . . Results clearly support the assertion that earth fissures are related to

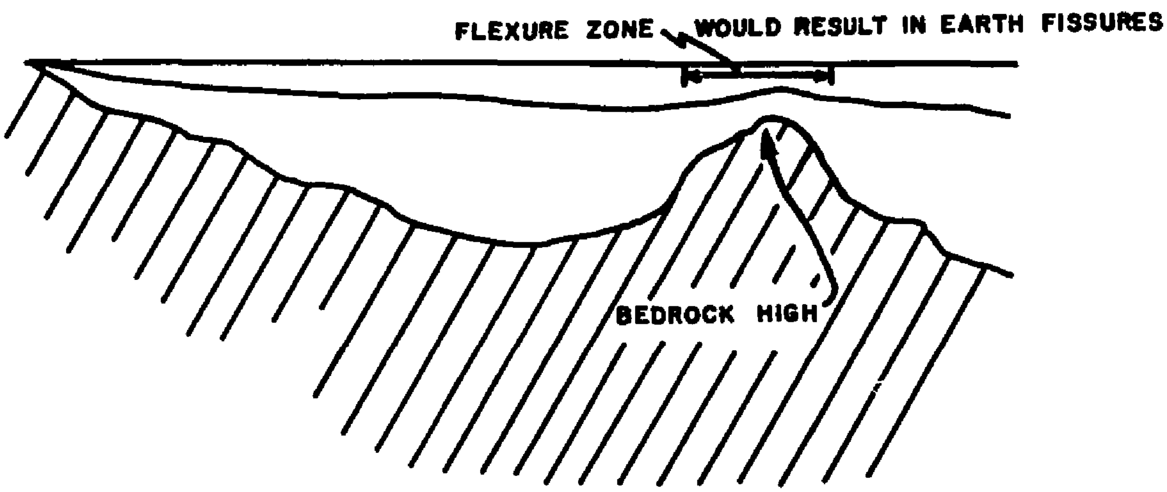


Figure 9. Earth fissuring due to differential compaction of alluvium over a bedrock high.

stresses originating relatively deep within the basin; that is, to present-day ground-water depths" (p. 129).

Holzer and Pampeyan (1981) reaffirmed the conclusions of Jachens and Holzer (1979). Holzer and Pampeyan (1981) conducted precise geodetic surveys to measure surface deformation near two linear earth fissures in Arizona. They surveyed closely spaced bench marks set in lines perpendicular to earth fissures. They concluded: "Earth fissures . . . in Arizona . . . are associated with zones of localized differential subsidence. Because the fissures occur near the point of maximum convex-upward curvature in the profiles, we conclude that the earth fissures were caused by horizontal strains induced by differential subsidence . . . caused by differential compaction" (p. 227).

Mechanisms

Earth fissures result from tensile failure; however, the tensile stress-producing mechanisms are not well understood. There are many possible mechanisms which may operate independently or in combination to produce the required tensile forces. Researchers must avoid the natural tendency to classify earth fissures into genetic groups because such classification may result in an oversimplification of the explanation of the earth fissure. Several mechanisms working independently or in conjunction with one another may be required to account for the diverse geographic and physiographic locations of earth fissures in southern Arizona.

Possible mechanisms include the following: desiccation of surface sediments, large-scale piping and subsequent soil collapse, lurching of soil during earthquakes, hydrocompaction, phase change of sedimentary minerals, incipient landslide movement, tectonic creep along strike-slip faults, rotation of coherent alluvial blocks or slabs, horizontal seepage forces, small horizontal forces associated with water-level declines, and differential compaction localized by facies changes in alluvial sediments or by irregular bedrock surfaces underlying alluvial material. All of the above mechanisms may produce earth fissures, but, in the southern Basin and Range Physiographic Province of Arizona, the lack of earthquakes and other recent tectonic activity, the great depth of earth fissures, the coincidence of earth fissures and groundwater level declines, and the abundance of linear earth fissures on the periphery of alluvial basins favor the last three earth-fissure mechanisms.

Desiccation of Surface Sediments

Desiccation could cause tensional fissures analogous to those of mud cracks. Quasi-polygonal patterns of fissures in the Willcox, Arizona, area tend to support this theory (Anderson, 1978). However, fissures due to this mechanism would be expected to form during a dry period. In contrast, most of the linear fissures in the field areas of this study have been first reported after heavy rains.

Piping

Fletcher et al. (1954) and Jones (1968) proposed that earth fissures were caused by piping. This erosional process formed subsurface tubes or pipes which acted as conduits for water. These subsurface pipes appeared as earth fissures when the tops collapsed. While acknowledging the existence of piping, Heindl and Feth (1955) rejected piping because there was no free discharge from the earth fissures studied. Earth fissures formed by piping would be expected to have wide bottoms. The bottoms of the earth fissures in this study narrowed to a close, which suggested a tensional process.

Lurching of Soil During Earthquakes

Leonard (1929) suggested that "the Picacho fissure was probably produced, either directly or indirectly, by seismic vibrations" (p. 774) which originated in northern Mexico approximately 300 kilometers away. However, a heavy rain also preceded opening of the fissure. At that time, no one knew the valley was susceptible to regional subsidence, so the earthquake hypothesis provided a reasonable explanation. Figure 10, a seismicity map of Arizona, indicates the study areas are in a relatively quiet zone. How the effects of the adjacent active areas may be felt and how the resultant fissuring potential of such effects may be determined is open to conjecture.

Hydrocompaction

Pashley (1961) suggested hydrocompaction as a cause of earth fissuring. Hydrocompaction occurs when low-density, high-porosity, moisture-deficient deposits compact as they are completely wetted for the first time. The Inter-Agency Committee on Land Subsidence in the San Joaquin Valley (1958) referred to the vertical downward movement of the land surface that results from this process as "shallow subsidence." Bull (1964) and Lofgren (1971) referred to it as "near-surface subsidence."

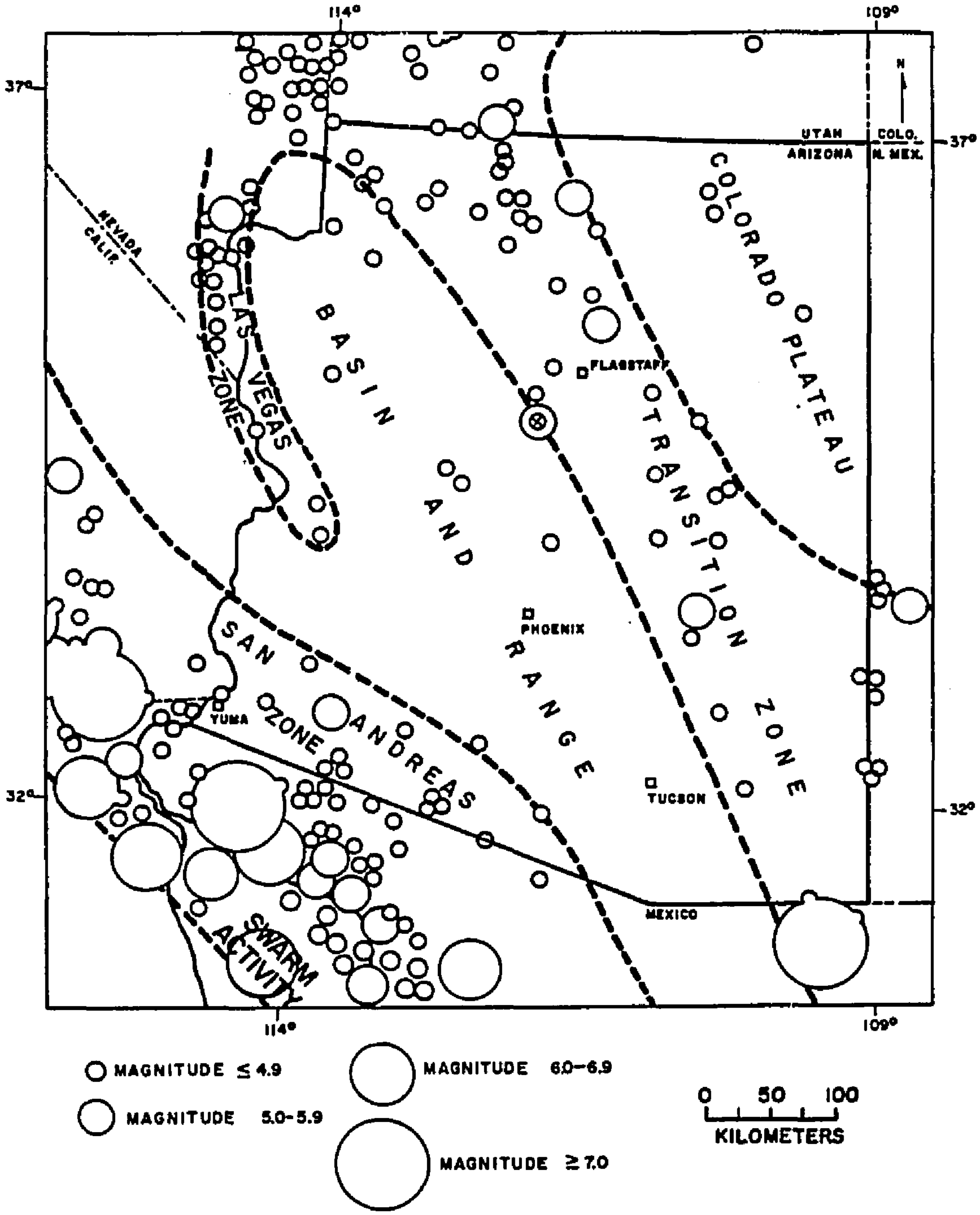


Figure 10. Arizona seismicity map. -- After Sumner (1976).

Rotation of Coherent Alluvial Blocks or Slabs

Bouwer (1977) suggested that earth fissures resulted from the rotation of large, rigid, finite slabs of alluvium as a response to subsidence over bedrock irregularities (Figure 11). Subsequent earth fissures between existing earth fissures and the mountain front tend to discredit this mechanism. An inordinate tensile strength would seem to be required for the alluvium. However, measurements made by Boling and Carpenter (1978) lend support to the concept of large block action of alluvial material. Figure 12 depicts one fissure that abruptly opened 31 mm within a 14-hour period, while one nearby parallel fissure opened 1.6 mm, and another nearby parallel fissure closed 2.1 mm. All of this movement occurred after a large rainfall. Perhaps this suggested that alluvium between parallel earth fissures acted as a unit.

Horizontal Seepage Forces

Lofgren (1972) proposed that horizontal seepage forces produced earth fissures. The lateral migration of water generated horizontal seepage stresses, due to viscous drag of water flow down gradient. The horizontal seepage forces exerted tensional forces on the alluvial material, which resulted in earth fissures. The concentration of linear earth fissures on the peripheries of alluvial basins supports this theory. However, the existence of a few earth fissures near the centers of ground-water extraction, that should be areas of contraction, is evidence against the theory.

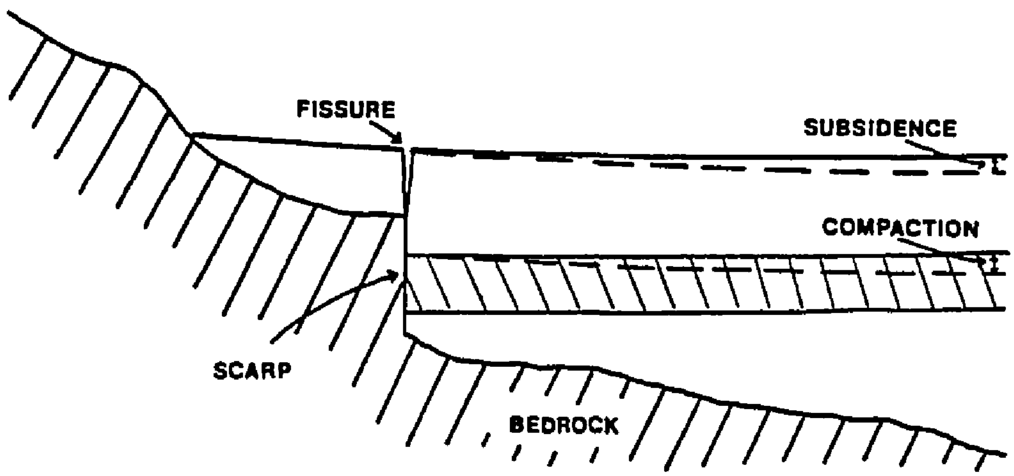


Figure 11. Earth fissuring due to rotation of alluvial slab about a bedrock scarp as a result of compaction of underlying sediments. -- After Bouwer (1977).

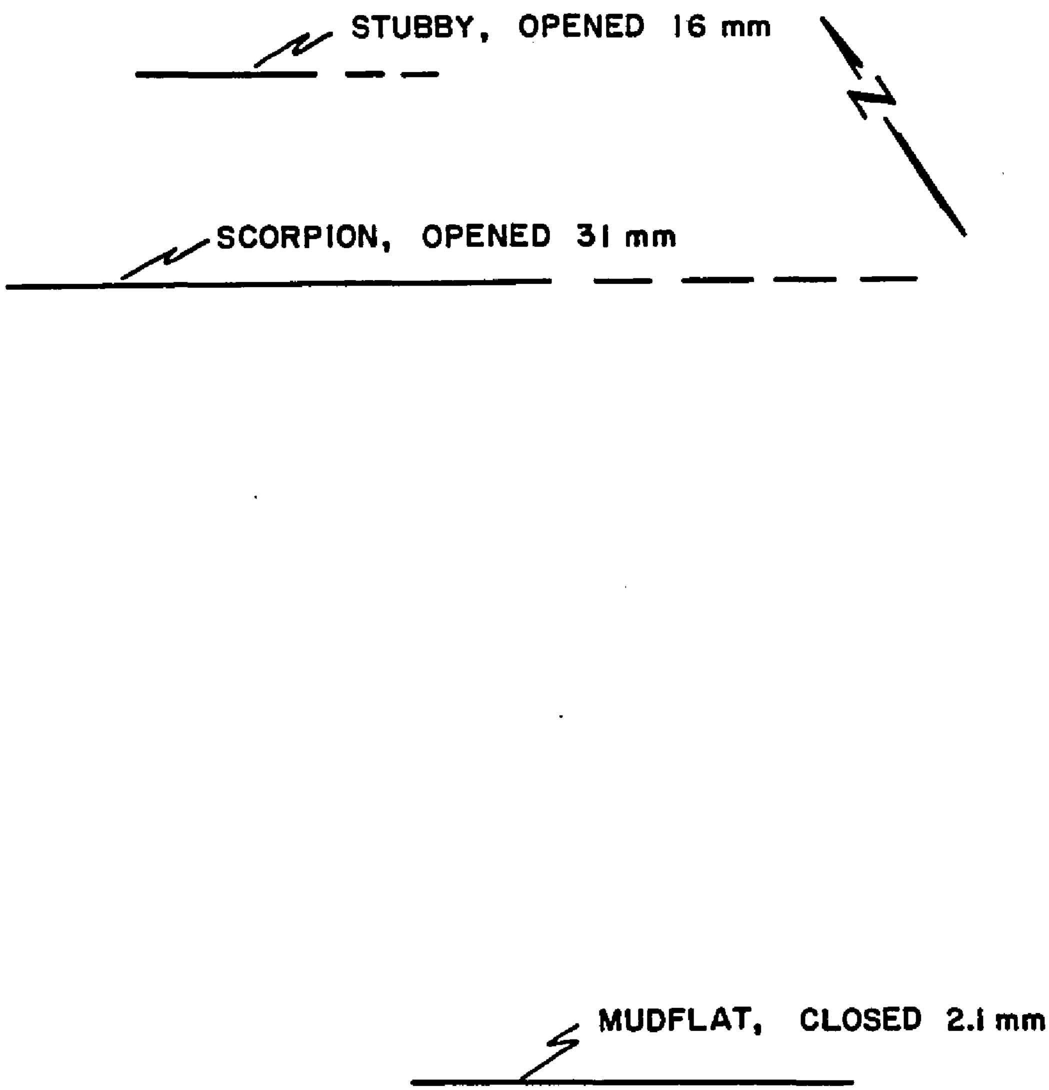


Figure 12. During a 14-hour period, Stubby opened 16 mm, Scorpion opened 31 mm, and Mudflat closed 2.1 mm, which suggested that desert alluvium may act as a coherent block.

Small Horizontal Forces Associated with Water-Level Declines

Holzer and Davis (1976) proposed small horizontal forces associated with water-level declines. Essentially, this hypothesis proposed that intergranular capillary stresses due to sediment dewatering were additive in their effect. Fissuring occurred where built-up capillary tensile stresses exceeded the tensile strength of the alluvium. This incipient fissure propagated laterally within the capillary fringe, upward from the capillary fringe, and perhaps downward below the water table. With time, these subsurface fissures propagated to the land surface. Field evidence of eroded portions of earth fissures beneath unruptured ground (Figure 13) and collapsed bridges (Figure 14) suggested that the earth fissures originally formed at depth. Furthermore, the areal and temporal relationships of earth fissures, water-level declines, and land subsidence were established by Schumann and Poland (1969).

The author suggests that the fluctuating character of water levels as they are lowered over a long period may contribute to this mechanism. Water-level fluctuations may produce repeated packing of individual grains. Water-level declines would result in a closer packing of individual grains due to a loss of buoyancy and capillarity. A subsequent water-level rise may provide sufficient buoyancy to the individual grains to allow them to partially separate. If so, the next water-level decline should produce even closer packing.

Figure 13. Earth fissure beneath unruptured alluvium.

Figure 14. Earth fissure beneath ruptured bridge.

Differential Subsidence

Differential subsidence due to differential compaction over different bedrock irregularities (Figures 8 and 9) has been proposed as a mechanism of earth-fissure formation. Essentially, shear and tensional stress accumulated in alluvium above a bedrock irregularity as a result of differential compaction. Earth fissuring occurred when tensional stresses became greater than the tensile strength of the alluvium. Vertical offset occurred in poorly consolidated alluvium over bedrock irregularities where shear forces dominated (Sanford, 1959).

If some amount of cohesive strength and plasticity were accorded to the subsiding alluvium, a different earth fissuring mechanism would be possible. In this case, the bedrock irregularity, such as a scarp, would serve as a structure about which the overlying alluvium would flex. Tensile stresses, dominant in the alluvial material above the bedrock irregularity, would result in multiple parallel earth fissures. Such is the case with most of the earth fissures measured in this study.

Turner (cited in Feth, 1951) suggested that fissures were caused by "strains set up by subsidence of unconsolidated and weakly consolidated valley-fill materials off the edge of the buried pediment" (p. 26). In 1955, Heindl and Feth also favored differential subsidence across a buried pediment edge.

Peterson (1962, 1964) supported the hypothesis that differential subsidence caused earth fissures as tensional breaks over buried pediments and fault scarps. He cited the mutual occurrence of anomalous gravity highs with the locations and trends of some earth fissures.

Most recently, Jachens and Holzer (1979) correlated earth fissures with bedrock irregularities. They suggested that "localized differential compaction may be the dominant source of tension causing earth fissures at most of the sites investigated" (p. 582).

Holzer and Pampeyan (1981) also favored the hypothesis that differential subsidence over bedrock irregularities was the cause of most earth fissures. They concluded "earth fissures were caused by horizontal strains induced by differential subsidence . . . caused by differential compaction" (p. 227).

Probably one or more of the mechanisms described above and others not described must work independently or in conjunction with one another to originate, propagate, and maintain all the earth fissures in the alluvial basins of the Basin and Range Physiographic Province in Arizona.

Suggested Etiology

Most earth fissures examined by the author are believed to have been initiated at depth and propagated to the surface. The ideas in the following suggested etiology are those of the author unless specifically stated otherwise.

A negative pressure area was generated in the capillary zone above the water table due to water-level declines (Holzer and Davis, 1976). These cumulative negative pressures developed at depth pulled individual particles together over an extensive area. Thus, tensile failure produced an earth fissure along a vertical plane at points of weakness in the tensile stress field. The stress field, induced by water-level declines, should continue to affect the earth fissure.

With time, the earth fissure's subterranean extent should be enlarged vastly, due to one or more of the tensile stress-producing mechanisms previously mentioned. After the initial earth fissure forms, enlargement should propagate in two dimensions along the vertical plane of the existing earth fissure. Because of the concentration of existing tensile stress within the capillary zone, the earth fissure should enlarge laterally more rapidly than vertically. The lateral extent would be bounded by the bedrock-alluvium contact. Vertical development would be bounded above by the land surface and could be bounded below by the saturation zone. Tensile stress may not extend below the saturated zone because saturated alluvium may not maintain tensile stress.

Total separation should not occur along the vertical earth-fissure plane. A patchwork of bridges between the two walls of the earth fissure would maintain contact at irregular points and areas of superior tensile strength. Therefore, a stress field should be maintained within the vertical plane of the earth fissure, and the earth fissure should continue its subterranean enlargement.

Eventually, the vertical earth-fissure plane should intersect the horizontal land-surface plane, forming a linear, surface earth fissure. It would appear as a hairline earth fissure. The earth fissure should be continuous within the portion of less tensile strength along the land-surface, earth-fissure intersection line, and it should be discontinuous within the portion of greater tensile strength.

Stream flow and overland flow would be intercepted by the earth fissure at the surface and flow into the earth fissure, forming gullies along the continuous portions and depressions at the discontinuous portions. The down-gradient movement of water and sediment should internally saturate and erode existing bridges or contact areas along the subsurface, vertical earth-fissure plane. Subsequently, more tensile strain and a new equilibrium would result as the previously established stress field is relaxed. Presumably, this internal erosion of earth fissures and resulting opening explains why so many earth fissures are reported after heavy rains.

As the flow rate of water and sediment decreases, the transported sediment would fall from suspension. A new patchwork bridge system should be established between the two walls of the earth fissure within its vertical plane. Water-level declines and/or other mechanisms may produce a new stress field supported by the wall-to-wall contact area. Subsequent injection of runoff into the earth fissure may again internally erode these contact areas, resulting in new strain and a new equilibrium.

The end result should be a cycle, developed to maintain equilibrium within the earth fissure. The cycle should fluctuate between periods of stress and strain as the result of induced tensional and compressive stress forces and their relaxation, respectively. The equilibrium-disequilibrium cycle should continue as long as tensile and compressive mechanisms and runoff events affect the earth fissures. This fluctuating cycle due to alternating tensile and compressive stresses and their relaxation is suggested to explain why earth fissures open and close over time.

This suggested etiology of initial earth-fissure development at depth may explain most earth fissures on the peripheries of alluvial basins. Hairline fissures and dimples have been observed in the field as the leading edges of opening fissures. Eroded portions of fissures beneath unruptured ground also suggest that fissures propagate upward from depth (Holzer and Davis, 1976). Holzer (1977) reported the largest horizontal displacement known to him to be roughly 6.4 cm, based on the split trunk of a mesquite tree which straddled the earth fissure. Schumann and Poland (1969) conclusively established the temporal and areal relationships among ground-water level decline, land subsidence, and earth fissuring.

As one tries to understand earth-fissure development closer to the basin centers, one must consider the increased probability that differential compaction over bedrock irregularities is a contributing if not dominant earth-fissure formation mechanism (Jachens and Holzer, 1979; Holzer and Pampeyan, 1981). Indeed, earth fissures that form in the centers of alluvial basins may initially develop in flexure zones at the surface as the result of differential compaction about bedrock irregularities.

CHAPTER 4

INSTRUMENTATION

During the course of this study, a wide range of design and experimentation resulted in the development and refinement of a device to measure horizontal displacement (opening and closing) of earth fissures. The result was the perfection of permanent and temporary short-base extensometers to measure horizontal earth-fissure displacements with a resolution of ± 2.5 μm. The exact design and installation procedures are detailed below.

The magnitude of earth-fissure movement considered significant changed during the course of the study. Increased quality and sophistication of specialized instrumentation led to smaller and smaller earth-fissure displacement having more and more significance. To what point this trend can be extended remains unknown at this time. At some point, noise will surely mask significant measurement.

In order that others may avoid some of the mistakes and errors incurred during the course of this study, some of the early experiments and methods of measurement of earth-fissure movement will be mentioned first. The first method of study utilized precise survey chaining techniques between bench marks. Bench marks were installed by the following method. A 0.15-m diameter hole was augered to a depth of 0.5 m. A metal rod of at least 20-mm diameter and 1.5-m length was driven vertically into the hole. A maximum of 30 mm extending above the ground surface helped avoid vandalism. Nails were inserted halfway into the walls of the holes. The hole was then filled with concrete packed in place around the rod and nails. A minimum of water was used in the concrete to reduce cracking and increase stability. The rod-and-cement bench marks proved to be long-lasting and stable. The requirement of two people to stretch the tape limited the use of this technique. More importantly, short-distance (less than 2 m) measurements of earth-fissure movements by this technique were too coarse. Precise survey chaining, which utilizes temperature-compensating calculations, combined with adequately stable bench marks, does serve a very useful purpose for long-distance, yearly, and/or preliminary measurements.

A simple lever mechanism with a multiplication factor of ten was employed in an effort to increase the fineness of measurement. This crude device was fragile and easily disturbed by animals. Also, it was very susceptible to erroneous readings because of dirt and dust accumulating at the pivot and attachment points. Again, the measurements of earth-fissure movements made with this device were too coarse.

The final device (Figure 15) which satisfied the measurement requirements of this study drew upon the previous bench mark design, but little else. Machinist dial gauges and Pyrex glass tubes attached to the vertical metal rods in buried trenches yielded measurements of sufficient fineness. This study resulted in the design and development of permanent and temporary short-base extensometers to measure horizontal movements of earth fissures and earth strain with a resolution of ± 2.5 μm. The design and installation procedures are detailed below.

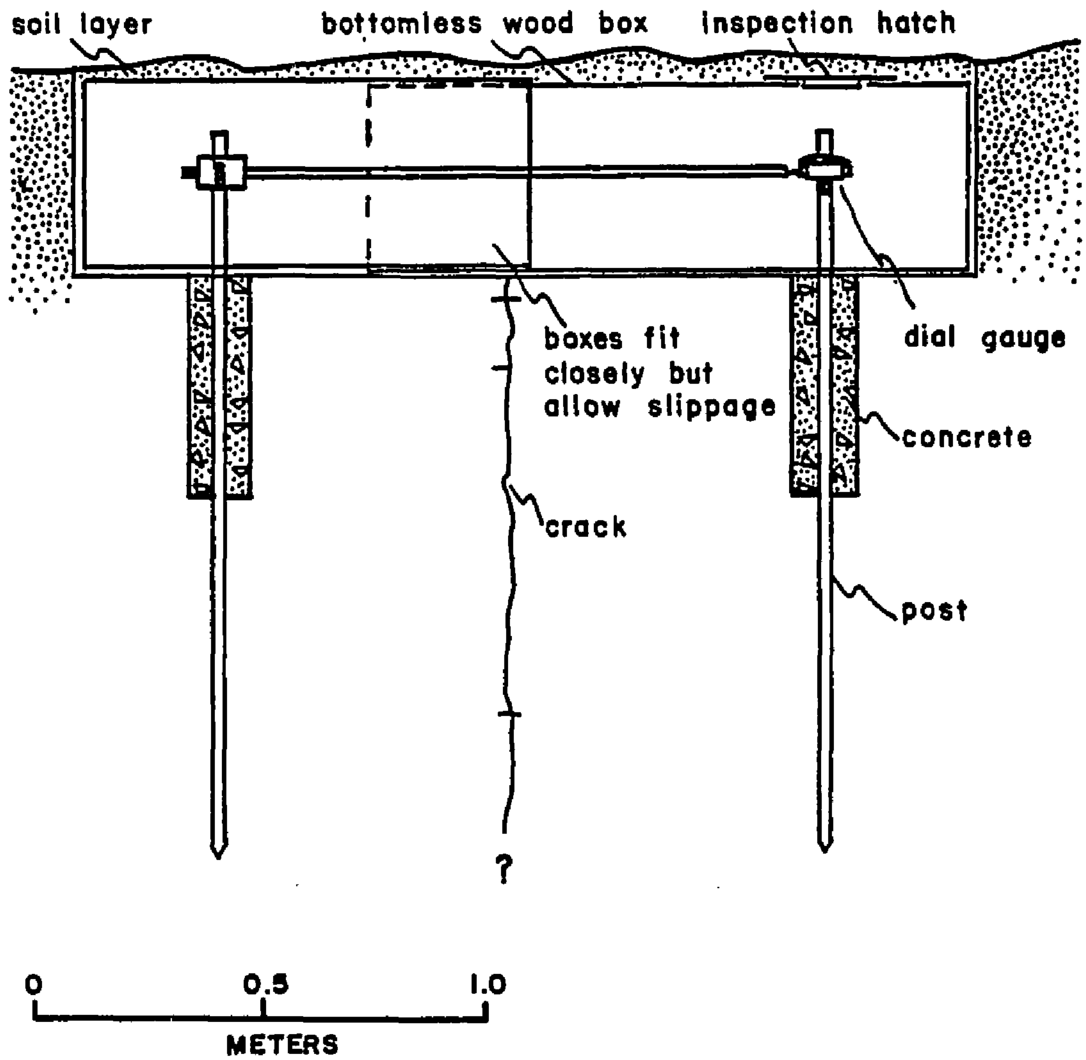
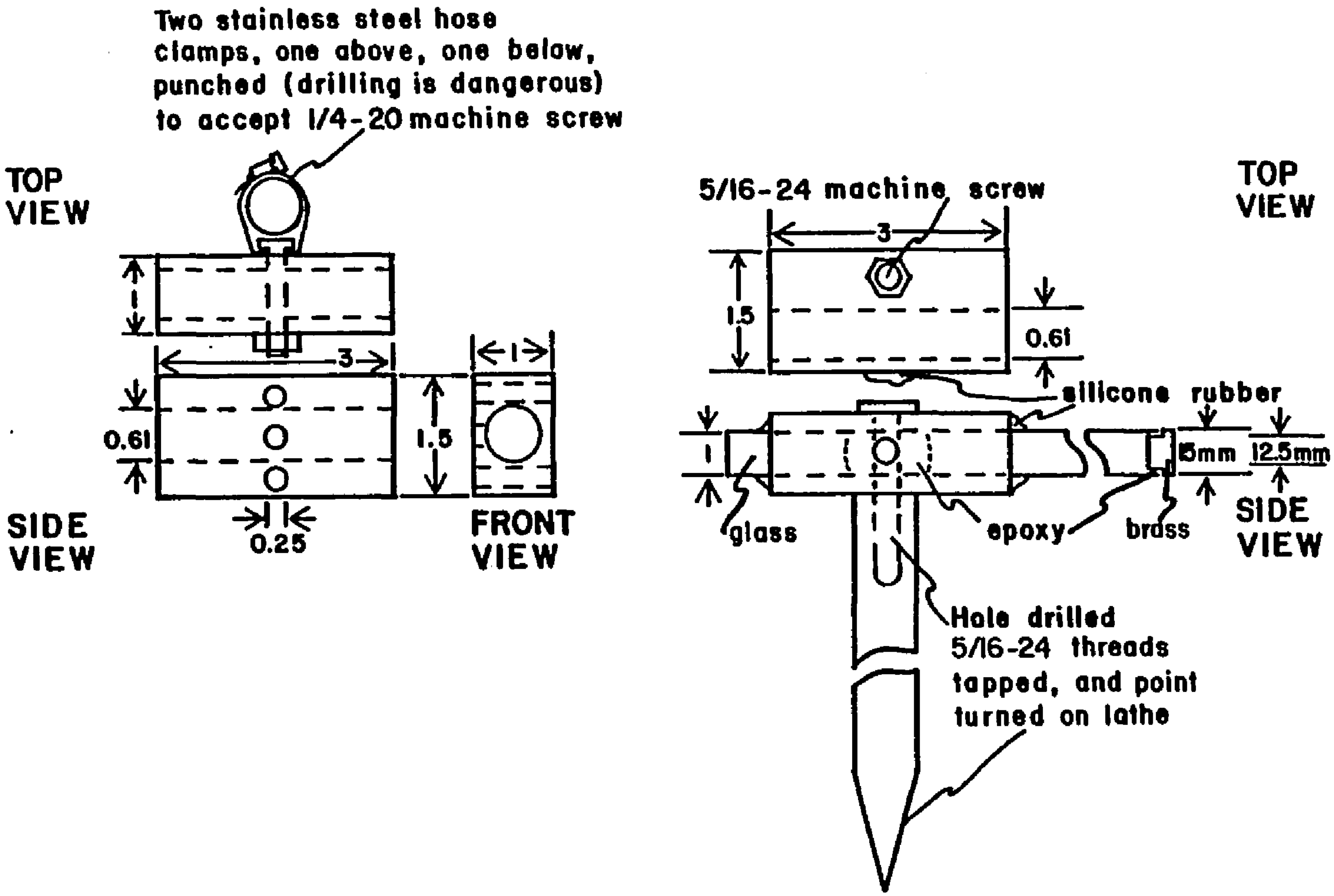


Figure 15. Wooden box extensometer.

Dial gauges were installed in trenches dug across cracks (Figure 15). The trenches were approximately 1.5 m long, 0.3 m wide, and 0.5 m deep. A 0.5-m deep hole was augered in each end of the trench; a 1.5-m long, 19-mm diameter, mild steel rod was driven vertically into the bottom of each hole; and concrete was poured into the augered holes up to the bottom of the trench and packed in place, leaving the vertical steel rods projecting 50 to 150 mm into the trench. A 15-mm outside diameter, 1.0-m to 1.3-m long, glass tube was epoxied into an aluminum holder attached to one vertical steel rod by positioning the glass in the aluminum block, introducing quick-setting epoxy in the side access hole, and rotating the glass to draw the epoxy inside.

Two types of aluminum block, glass-rod fixtures were prepared before going into the field: side-mounted and top-mounted (Figure 16). A side-mounted holder has three 0.25-in. holes in the side and a 0.61-in. hole lengthwise to hold the glass rod. Because of significant irregularities in the outside diameter of the glass, the hole for the glass was hand-reamed after drilling to assure a close fit without binding. The side-mounted holder was attached to a vertical steel rod using hose clamps and 1/4-20 pan head machine screws through the top and bottom 0.25-in. holes. The center 0.25-in. hole was to allow the introduction of epoxy to hold the glass tubes.

A top-mounted holder has one 0.25-in. hole through the side, one 5/16-in. hole in one side of the top, and a 0.61-in. hole lengthwise in the other half to hold the glass rod. Again, the glass-rod hole was hand-reamed after drilling. A 5/16-24-in. machine screw through the top



a) Side-mounted.

b) Top-mounted.

Figure 16. Glass-tube fixtures.

hole was used to attach the top-mounted glass-rod holder to the predrilled and tapped vertical steel rod. Washers were used for vertical adjustment. The 0.25-in. hole in the side was for the introduction of epoxy.

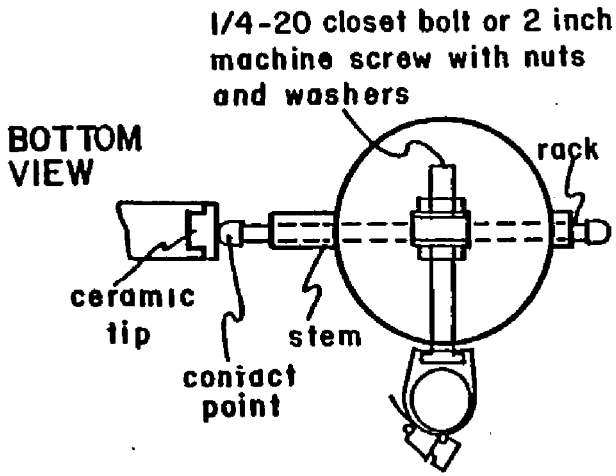
A dial gauge was attached to the other vertical rod so that the dial gauge's contact point pushed against a flat tip epoxied to the end of the glass tube. The dial gauges were Brown & Sharpe model 8231-941 or Starret model 25-881, with a range of 25 mm and a resolution of ± 0.5 μm.

Three types of dial-gauge fixtures were made up before going into the field (Figure 17). A fixed, back-mounted, dial-gauge holder consisted of a 1/4-20 closet bolt or 2-in. pan head machine screw with nuts and washers. The dial gauge back was attached to the closet bolt with the nuts and washers. The head of the closet bolt was then attached to the vertical steel rod with a stainless steel hose clamp.

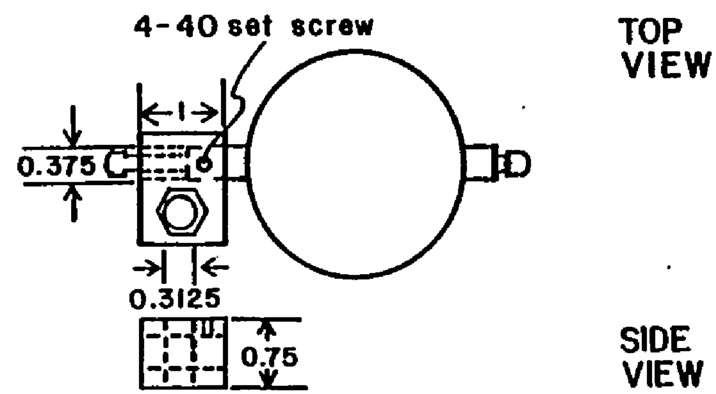
A fixed, stem-mounted, dial-gauge holder aluminum block has a 0.25-in. hole in the bottom half of the block and a 0.375-in. hole in the top half drilled lengthwise through the side for the dial gauge. A small hole for a 4-40-in. set screw was drilled through the top into the 0.375-in. hole for the dial gauge. This set screw was used to hold the dial gauge in place. A 5/16-24-in. machine screw through the 5/16-in. hole was used to attach the fixed, stem-mounted, dial-gauge holder to the predrilled and tapped vertical steel rod. Washers were used for vertical adjustment.

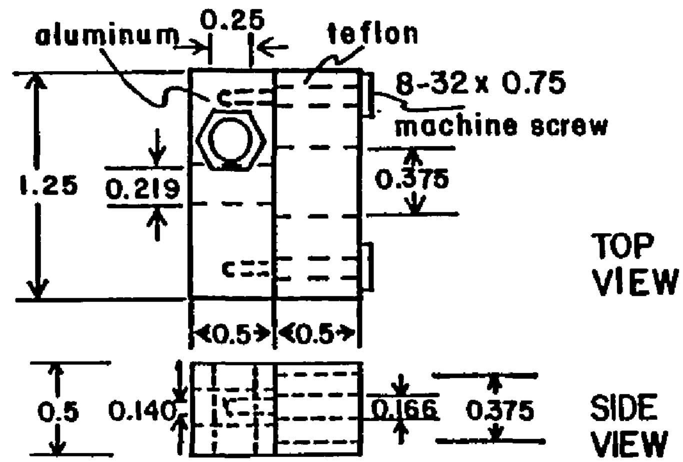
The dial gauge was backmounted or stem mounted, and the glass tube was initially positioned to allow for roughly 6 mm closing and

a) Fixed back-mounted.



b) Fixed stem-mounted.





c) Insertable stem-mounted.

Figure 17. Dial-gauge fixtures.

20 mm opening. The range of movement could be extended by changing dial-gauge contact points. Later, large earth-fissure opening or closing could be accommodated in the same fashion.

Earlier extensometers were enclosed by interleaving bottomless wooden boxes (Figure 15). The boxes were generally built in the field to fit the trench. A box was built in two interleaving halves which spanned the earth fissure to minimize frictional coupling between fissure movement and the instrument housing. The top of the box had an inspection hatch to read the dial gauge and had 1 in. of styrofoam insulation on the bottom side to reduce thermal fluctuations. The trench was dug sufficiently deep that the whole box could be covered with soil and be undetectable from the surface. The box and top were strong enough to withstand wandering cattle stepping on the installation.

Later extensometers developed by M. C. Carpenter were enclosed with 100-mm polyvinylchloride (PVC) pipe (Figure 18). The long section of pipe was put on before positioning and gluing the glass tube. The tee and coupling were slotted along the bottom on a table saw so they could be slipped on around the posts from the ends. Silicon rubber was used to seal the pipe joints and the open slots around the posts. It was necessary to allow the rubber to cure completely before installing the dial gauge and closing the installation because of corrosive gases produced in curing.

In spite of burial and thermal insulation, the wooden boxes sometimes acted as solar stills and trapped moisture inside. In these cases, the dial gauges were enclosed in plastic bags and sealed with rubber bands around the stem of the dial gauge. Otherwise, if

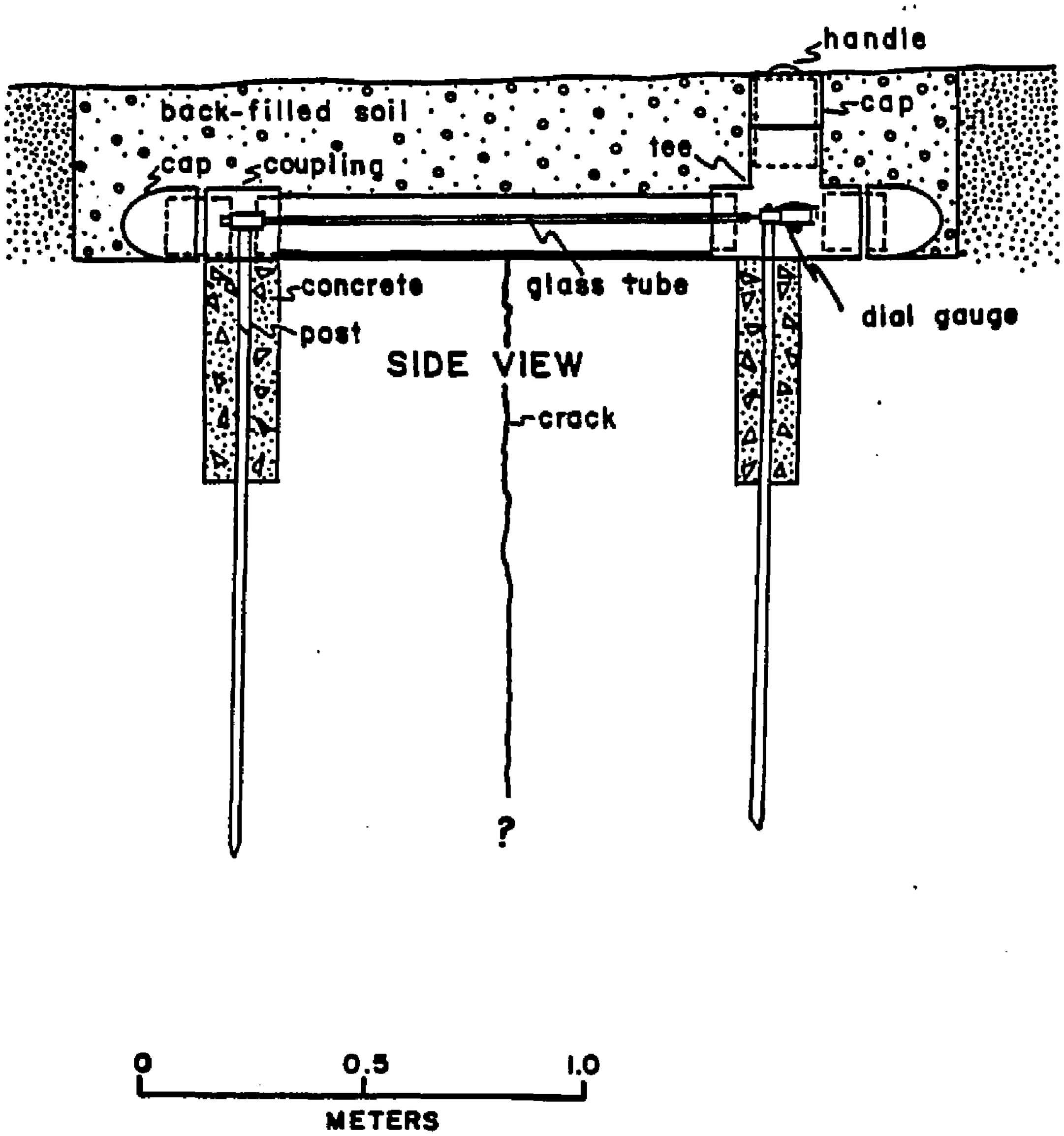


Figure 18. Polyvinylchloride extensometer.

necessary, a piece of thick plastic was laid over the dial gauge to keep off dirt. The installations often filled with water after heavy rains. Plastic bags were not used in extensometer installations which were subject to flooding because the plastic bag trapped water around the dial gauge.

A flooded extensometer installation could usually be repaired in a short time. The dial gauge could be field-stripped, cleaned, oiled, and replaced. Several spares were always carried in case a replacement was needed. Wet dial gauges brought back to the lab and allowed to dry would rust, often beyond repair. Wet dial gauges had to be completely disassembled, cleaned, and oiled the day they were taken out of the field.

The dial-gauge readings were made in the same fashion each time. Five readings were made by pulling back on the dial-gauge rack and releasing it gently. The average reading was recorded. When the readings were highly variable, ten readings were made and the average was recorded. Usually, the range for all readings was within twice the limit of the resolution of the installations.

The temperature inside the dial-gauge extensometer was recorded at each reading. A thermometer was left in each installation and was read immediately after the installation was opened. This practice obviated having to wait for a thermometer to equilibrate to the temperature inside the installation that could have been changed by opening the extensometer.

Thermal effect was minimized by using materials with very low coefficients of thermal expansion, controlling temperature fluctuations with insulation, exploiting the stability of soil temperature, and using compensating design. Materials with low coefficients of thermal expansion such as fused quartz glass (5.8×10^{-7} °C^{-1}) and Pyrex glass (3.2×10^{-6} °C^{-1}) were used as much as possible between centers of posts, and the use of high coefficient materials such as aluminum ($\approx 2.5 \times 10^{-5}$ °C^{-1}) was minimized. The method of epoxying minimized the amount of aluminum which could cause thermal effects, while allowing the aluminum fixture to support the glass tube in spite of significant irregularities in the outside diameter of the glass. These irregularities caused problems with several other methods of clamping glass to metal. Tips of brass, aluminum, or copper could be used because of their short length. Burial of extensometers provided insulation and temperature stability. The tops of all installations were insulated with 1 in. of styrofoam.

All extensometer installations were in areas subject to grazing and/or hunting. Because of this, all installations were buried and camouflaged. After each reading, a great deal of care was taken to restore each site to a natural appearance. This often involved sprinkling of dry wash material over the silt and the use of a creosote branch to brush away footprints.

A dial-gauge extensometer was capable of measurements with a resolution of ± 2.54 µm if the dial gauge was left in place. Establishing precise colinearity between the dial-gauge rack and the glass tube greatly improved resolution. Only one time over a seven-year period at seven different extensometers was realignment of the dial-gauge rack and glass tube necessary. This fact asserts that there was no shear component in earth-fissure displacements. Polishing tarnished dial-gauge tips and brass or aluminum glass-tube tips did not change readings, so corrosion was not considered important enough to change to stainless steel in any part of the extensometer.

It was possible to test the dead band of the extensometer by standing on one side of the earth fissure and pushing and pulling with a shovel against a stake on the other side of the earth fissure. After each bidirectional stress, the dial gauge returned to its unstressed reading, indicating that the soil was elastic and the dead band was less than the resolution of the dial gauge. These tests were also performed with a small winch-and-cable system to test for binding in the PVC installations.

The installations were buried and camouflaged to eliminate destruction by man or other animals, as well as to minimize thermal effects. The wooden boxes were inexpensive, easy to install, and easy to repair. However, because they leaked and sometimes acted as solar stills, they deteriorated with time. Also, they were subject to termite damage. A pesticide strip left inside the installation discouraged the termites. Treatment of the wood should help prevent termite damage and rotting, though this was never tried. Some wooden extensometer installations lasted more than seven years and some only lasted three years. Moisture was the controlling factor in most cases. The more often an installation was flooded, the more often it needed repair.

The PVC pipe was troublesome to install and repair, though repair was seldom necessary. The PVC pipe was virtually sealable and lasted for a long time. With many, many years, the PVC may become brittle because of the very high desert heat, but this never happened during the course of this study. The biggest problem with the PVC pipe was the cost. Pipe with a diameter of 100 mm provides barely enough room for adjusting the dial gauge or making readings. The relation between increased pipe size and increased cost was exponential. Larger pipe was much more expensive.

It was a concern that the extensometer installation itself might create erroneous earth-fissure displacements. Because installation of the dial-gauge extensometer required that the desert material be disturbed, it was a concern that the measurements would not truly represent earth-fissure displacements. Several factors argue against this. The vertical metal rods were driven into undisturbed material and concreted in place. The trenches were dug just large enough for the installations, with a minimum of backfilling. The surface of the buried installation was returned to its original condition as much as possible. This afforded the same characteristics of runoff and plant and animal life as the surroundings. From the surface, it was nearly impossible to distinguish an installation from its surroundings. Last, but not least, the duration of emplacement should have allowed for any re-equilibration necessary.

A rough comparison with long-base extensometers lends validity to the horizontal strain measurements of our short-base, dial-gauge extensometers. Bench-mark measurements that spanned the dial-gauge extensometer measurements at the Sacaton Mountain area agreed with dial-gauge measurements (Holzer, 1978b). This indicates that movement was horizontal and that rotational failure at the edge of the fissure was not a problem. Short- and long-base extensometer measurements of fissured and non-fissured materials at Apache Junction, Arizona, showed the same trends and patterns (Carpenter, 1984). This also minimizes the possibility of edge effects. Soil expansion due to an increase of soil moisture was not a problem, because most fissures opened after rainfalls.

CHAPTER 5

RESULTS

Mapping

The author developed a thorough familiarity with earth fissures by making a detailed, large-scale map of the earth fissures in the Picacho field area. Earth fissures typically form on the periphery of alluvial basins that have undergone large water-level declines and land surface subsidence. Individual earth fissures may suggest certain patterns but there is no typical pattern formed by earth fissures. The earth fissures examined in this study occurred at the land surface as linear and curvilinear features which were segmented rather than continuous.

Earth-fissure formation and development was observed to be a dynamic process. Earth fissures continued to open and close with time and to extend their length by the propagation of a leading edge that was characterized by hairline cracks or small depressions. Due to the inflow of large amounts of runoff and sediment, earth fissures formed fissure-gully erosional features. Earth fissures were often observed to fill with sediment, and thus appear healed. Later, they would often re-initiate drainage and, essentially, flush accumulated material and continue to absorb runoff and sediment.

Earth fissures typically exhibited horizontal displacements due to tensional failure. They rarely exhibited any vertical offset.

Water-Level Data

During the course of this study, the author provided assistance to the United States Geological Survey (USGS) for drilling and logging of three piezometers in the Picacho field area approximately 5 km east of Picacho, Arizona, in the NW 1/4 section of section 20, T.8S., R9E. (Figure 19). The piezometers formed a line which was roughly N50°W to the Picacho fault. At this location, the Picacho fault had 0.7 m of offset with a strike of N13°E and a suggested dip of 70°W (Holzer et al., 1979). Two piezometers were drilled on the downthrown side of the Picacho fault and one was drilled on the upthrown side. The middle piezometer was located close to the Picacho fault in a successful attempt to drill through the fault (Figure 20). All piezometers were approximately 230 meters deep, with screened well points approximately 150 meters below the ground-water level. Grove and Fault piezometers functioned as normal piezometers; however, Mountain piezometer did not at all times (Figure 21).

Water-level measurements were made semi-monthly by conventional methods using 200-ft and 500-ft steel tapes (Appendix A). The water levels were measured to correlate them with earth-fissure displacements. No correlation was noted among water-level measurements at the USGS piezometers and earth-fissure displacement measurements in the Picacho area. Water levels fluctuated seasonally from a spring high of approximately 137 m to an autumnal low of approximately 168 m below the land surface.

Data from the water-level measurements suggested the Picacho fault acted as a hydrologic barrier (Figures 20 and 21) that could

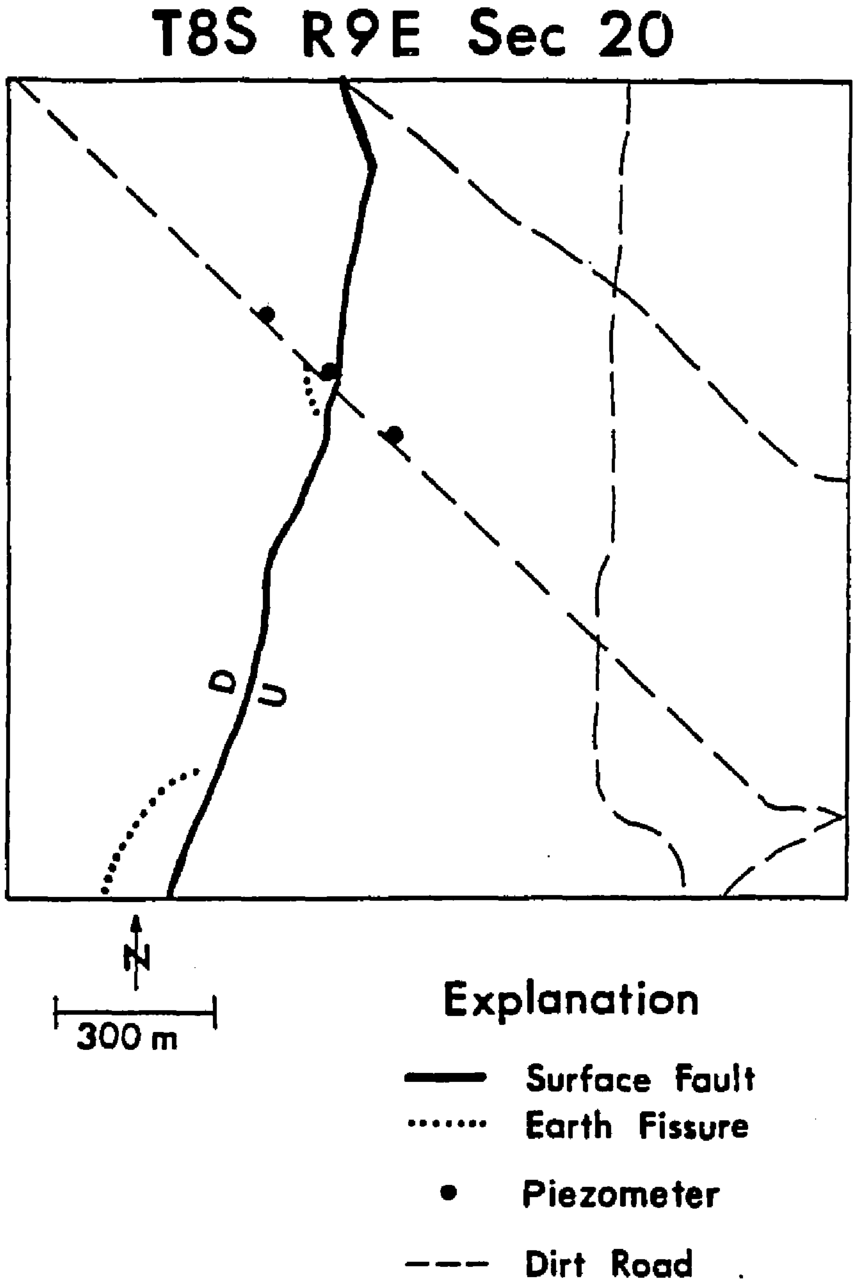


Figure 19. U.S. Geological Survey piezometer location map.

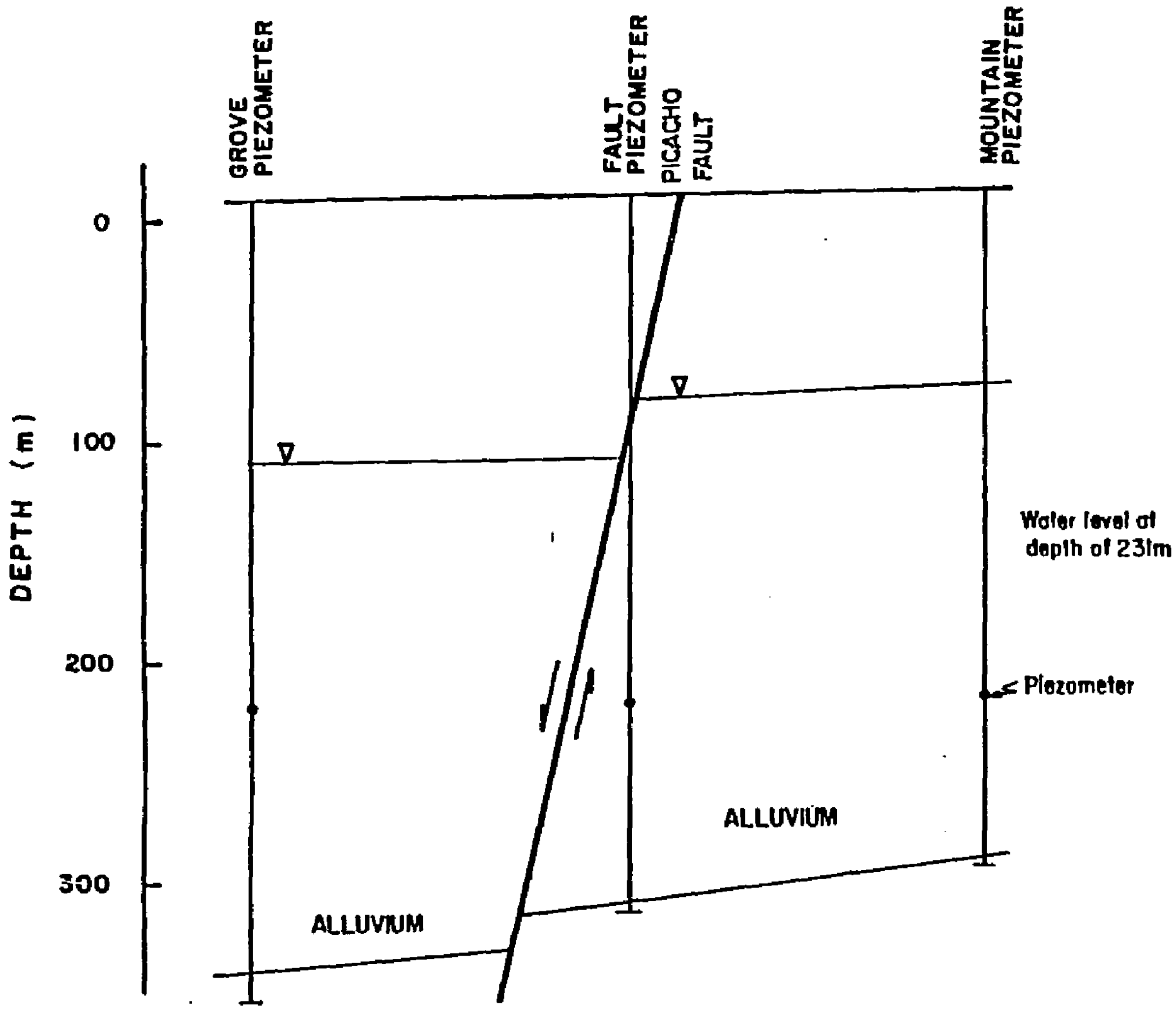


Figure 20. Cross-section view of the Picacho fault and U.S. Geological Survey piezometers with water levels.

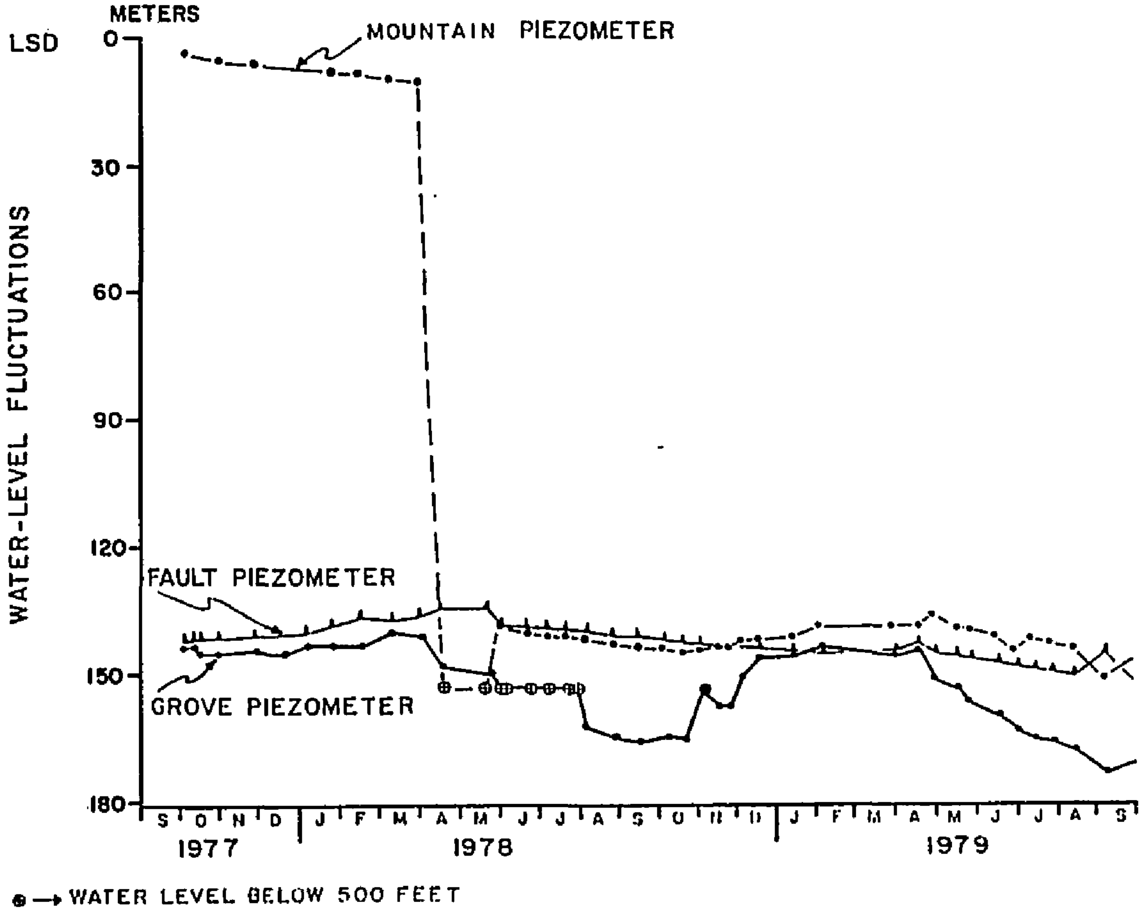


Figure 21. U.S. Geological Survey piezometer water-level fluctuations.

produce differential compaction. As long as the thickness of the dewatered sediments on each side of the fault remain constant, the induced stress should be the same. However, with different water levels on different sides of the fault, the induced stress should be different, correspondingly. The side with the lower water level should compact more than the other side, resulting in differential compaction and offset, which is the case along the Picacho fault.

Earth-Fissure Displacements

The major result of this study thus far has been the development of temporary and permanent short-based, dial-gauge and transducer extensometers to quantitatively measure horizontal displacements of earth fissures accurately and precisely with a resolution of ±2.5 μm. The extensometers were designed to be constructed inexpensively and simply, to minimize thermal effect, and to obtain high resolution. Measurements made in the Sacaton field area agreed with measurements made along a line of bench marks which spanned a dial-gauge extensometer. Measurements were made in Avra Valley with short-base, horizontal dial-gauge and transducer extensometers across the same earth fissure. The dial-gauge extensometer closing rate of 42 mm per day for the period January to March 1978 agreed with the transducer extensometer closing rate of 37 μm per day on 4-5 January 1978 (Figures 22 and 23). Dial-gauge measurements from 29 December 1977 to 28 January 1978 produced a closing rate of 34 μm per day. These measurements agreed with each other by 88 and 92 percent, respectively, using two types of measurements, dial

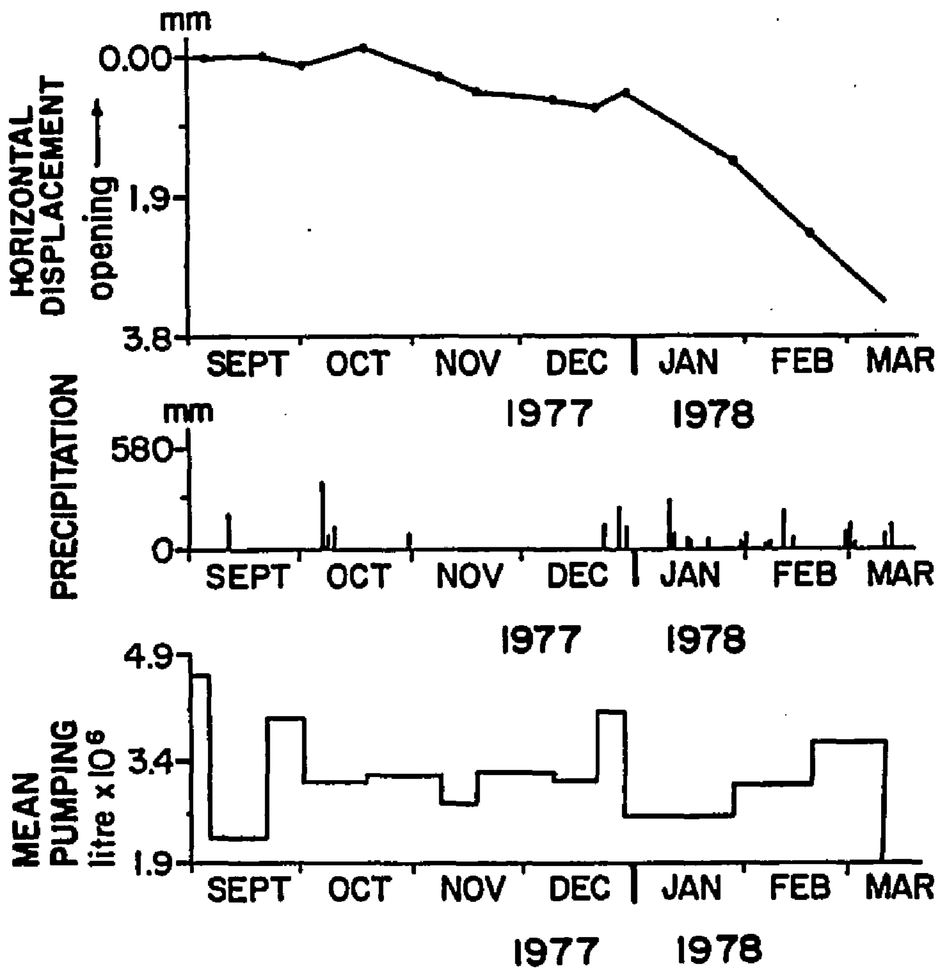


Figure 22. Dial-gauge measurements of horizontal earth-fissure displacements, precipitation, and mean pumping at Avra Valley Well No. 7, September 1977 to March 1978.

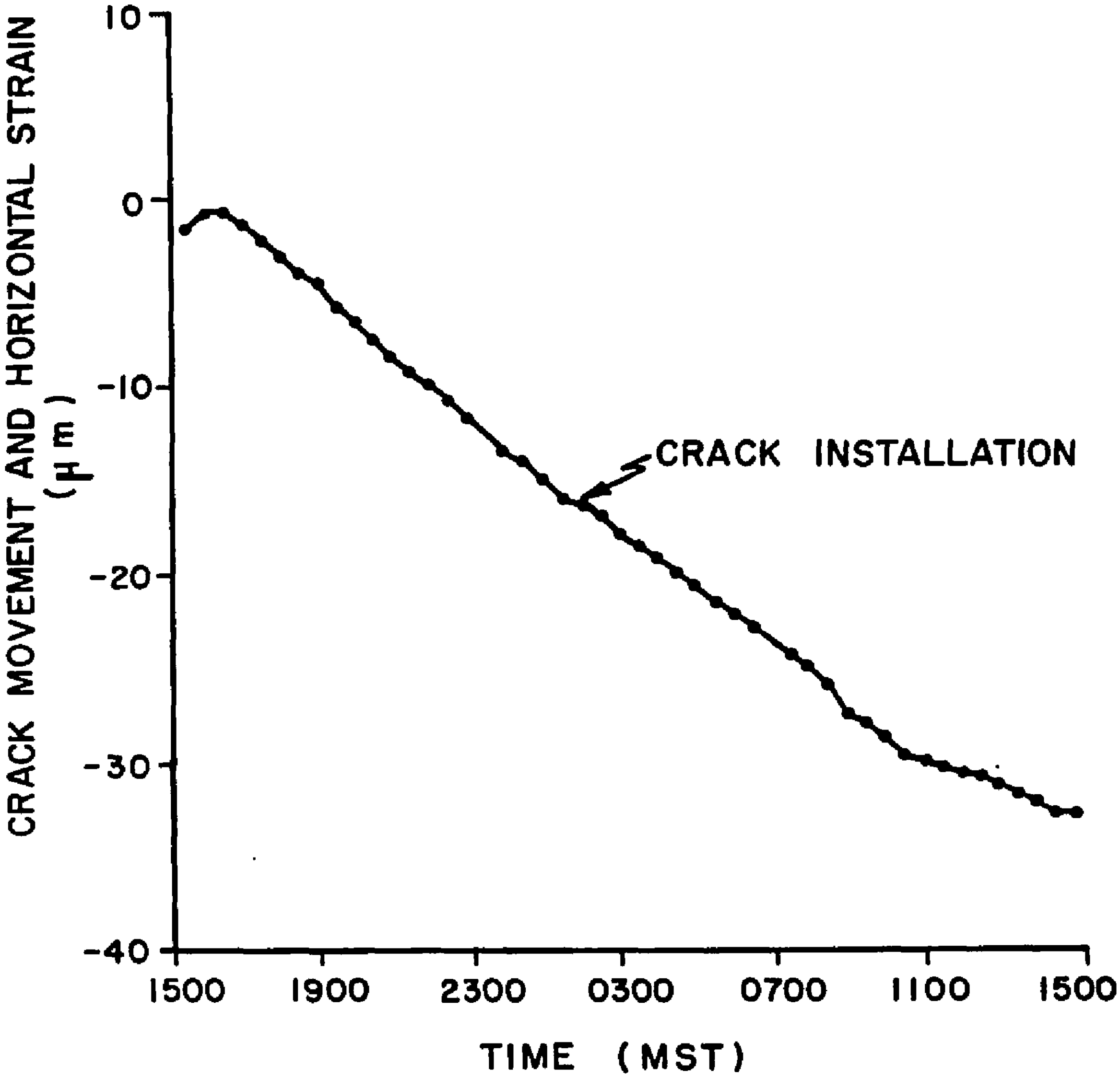


Figure 23. Transducer measurements of horizontal earth-fissure displacements at Avra Valley Well No. 7, 4-5 January 1978.

gauges and transducers, which were overlapping and differed by two orders of magnitude in their range of measurement.

Earth-fissure movements did not stop after the initial opening (Figures 24 and 25), but continued to open and/or close with time. Dial-gauge extensometer measurements indicated that earth fissures open and close relatively smoothly over long periods, with occasional sudden jumps as seen in Figure 25 of the Sacaton field area. The maximum rate of smooth earth-fissure closure averaged 5.0 μmhr^{-1} over a 14-day period, and the maximum rate of smooth earth fissure opening averaged 4.1 μmhr^{-1} over a 17-day period. No difference in the character of movement of old and new earth fissures was noted.

Sudden movements of earth-fissures occurred occasionally, usually after a heavy rainfall (Figure 26). Often, earth fissures in the same area moved simultaneously. On the evening of 23 July 1976, a rainfall of 31 mm caused an opening of approximately 25 mm of one earth fissure, while one nearby parallel earth fissure opened 1.6 mm, and another nearby parallel earth fissure closed 2.1 mm (Figure 26). This suggested that the desert alluvium had greater structural integrity than previously suspected. Perhaps coherent blocks of alluvium existed between earth fissures.

Measurements indicated that earth fissures in this study opened and/or closed over long periods of time. In general, earth fissures closed over long, dry periods. Earth-fissures tended to open after periods of high ground-water pumping followed by high rainfall (Figure 22). At one municipal well, that was pumped as part of a large well field in Avra Valley, a possible correlation existed among high

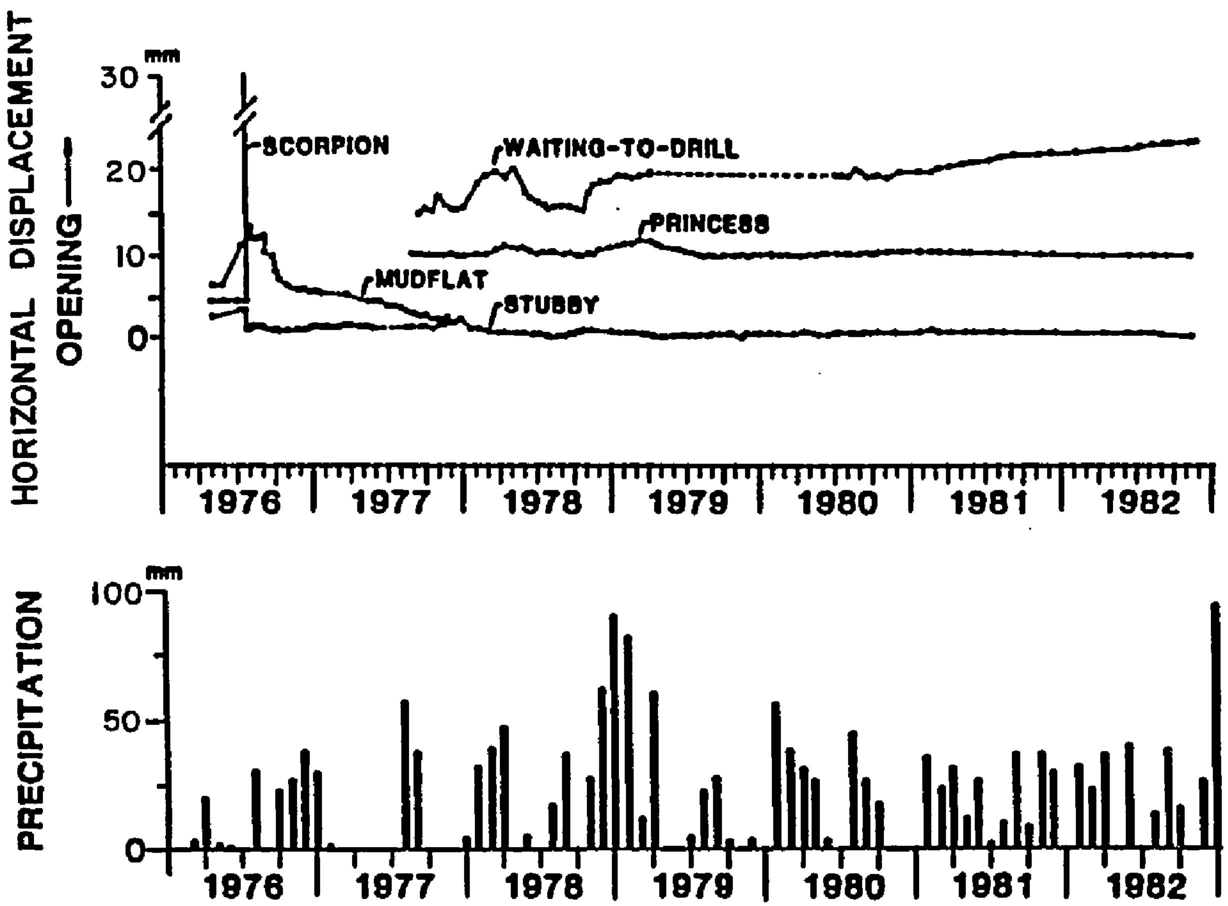


Figure 24. Horizontal earth-fissure displacements and precipitation at the Sacaton study area, 1976-1982.

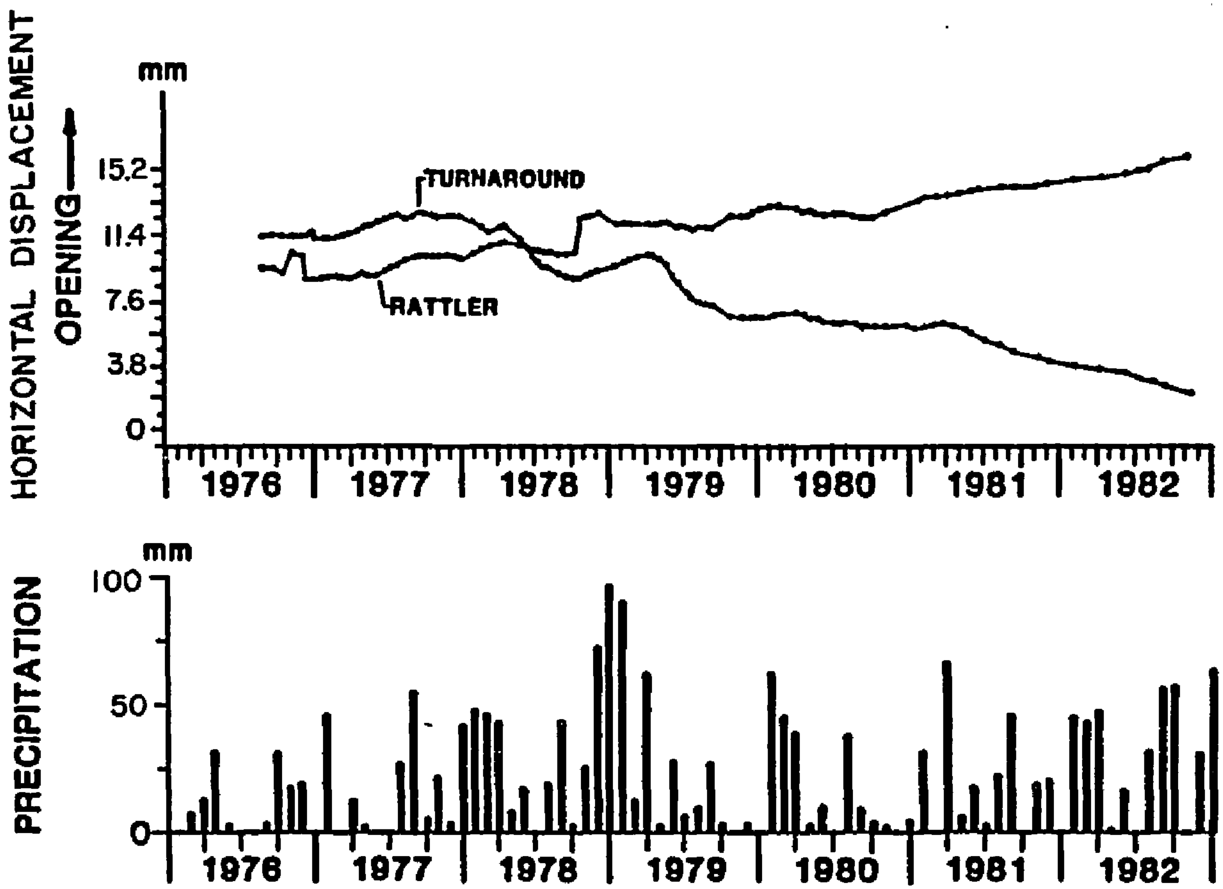


Figure 25. Horizontal earth-fissure displacements and precipitation at the Picacho study area, 1976-1982.

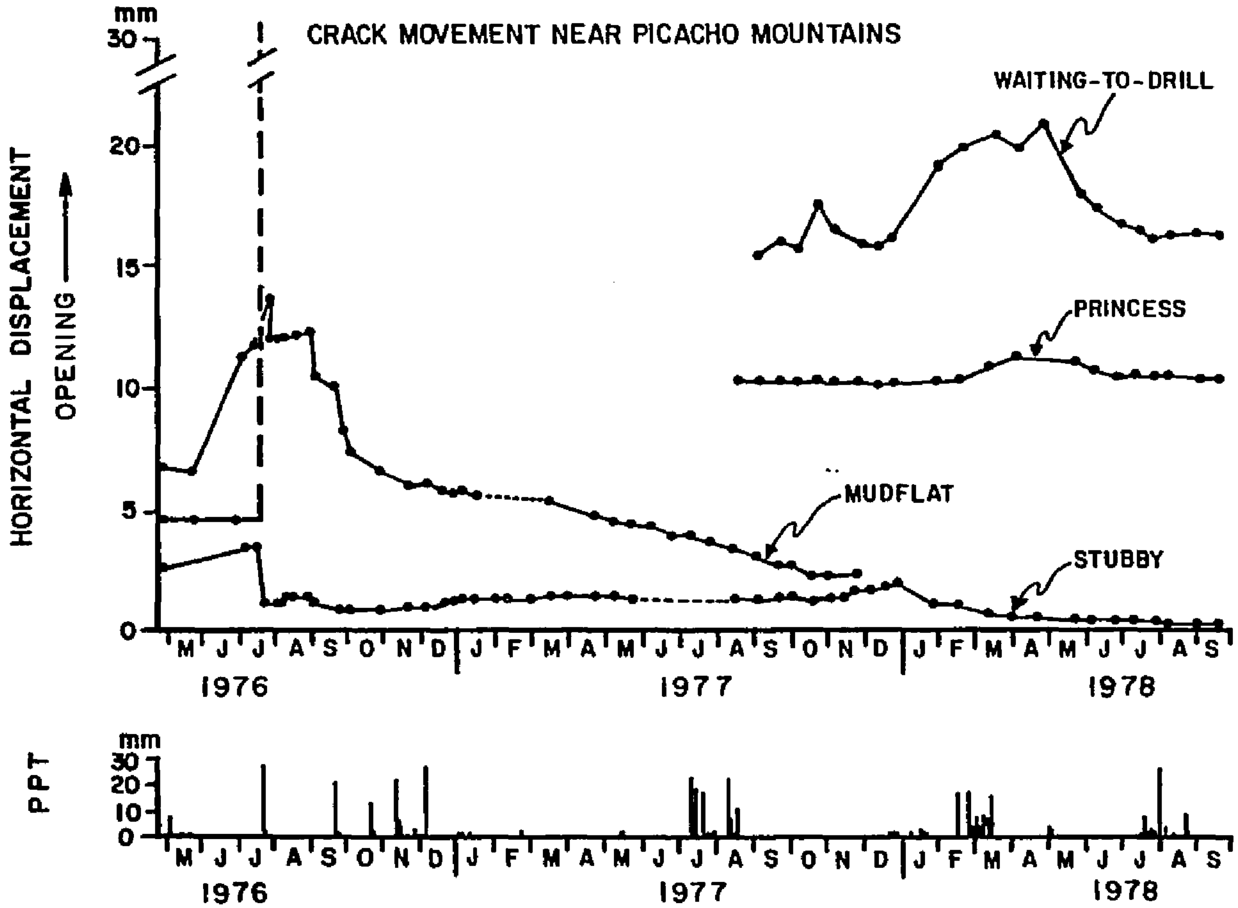


Figure 26. Horizontal earth-fissure displacements and precipitation at the Picacho study area, May 1976 to September 1978.

pump rates, rainfall, and earth-fissure opening (Figure 22). This indicated that stresses induced by ground-water pumping were more likely causes of earth-fissure opening than were soil moisture effects because earth fissures also closed during long, dry periods.

No correlation was found to exist among the water-level measurements from the USGS wells and earth-fissure displacements in the same area.

The earth-fissure closest to the area of the greatest amount of total subsidence had the greatest total amount of movement.

Filling of earth fissures with material had no effect on the earth fissures. Earth fissures near housing areas were characteristically used as dumping sites. One particularly active earth fissure opened perpendicular to a petrochemical pipeline in the Picacho field area. At least two attempts were made by the pipeline company to fill the fissure, completely, with local desert alluvium. Figure 27 shows a photo sequence, which spans about one year, during which the pipeline earth fissure was completely filled with desert alluvium. In each case, the fill material had no effect--the earth fissure simply reopened and continued to absorb copious amounts of water and sediment from runoff.

All horizontal earth-fissure measurements are contained in Appendix B.

a) Approximately two months after infilling.

b) Approximately four months after infilling.

Figure 27. Reopening of earth fissure over petrochemical pipeline after infilling with alluvium.

c) Approximately one year after infilling.

Figure 27--Continued.

CHAPTER 6

SUMMARY AND CONCLUSIONS

Several aspects of this thesis merit concluding comments. One of the primary efforts was to describe earth fissures in detail and to discuss the different possible mechanisms which may have produced sufficient tensional stress to form earth fissures. Recent demographic studies strongly suggest that the population of the Southwest will continue to grow and to exert an increased demand for water. Therefore, water-level declines, land subsidence, and earth fissures will continue to form in the alluvial basins. The author hopes that this discussion of earth fissures and their possible mechanisms will facilitate future inquiry by others interested in earth fissures.

Holzer and Davis (1976) originated the idea of the initial earth fissure in the capillary zone due to cumulative negative pressures generated by water-level declines. However, the idea of a fluctuating disequilibrium-equilibrium cycle to explain the character of the horizontal earth-fissure displacements was that of the author. After the initial earth-fissure formation at depth, the earth fissure's subterranean extent was enlarged due to continued tensile stresses generated by one or more possible mechanisms. After the earth fissure reached the land surface, successive runoff events flowed into the earth fissure, internally eroding it. A cycle that fluctuated between disequilibrium and equilibrium followed. Disequilibrium existed because of tensile and compressive stresses within the discontinuous, vertical plane of the earth field due to stress-producing mechanisms which continued to act upon the earth fissure. Equilibrium resulted from the relaxation of the stress fields within the earth fissure by internal earth-fissure erosion from runoff, earth-fissure inflow events. This fluctuating, disequilibrium-equilibrium cycle may explain the opening and closing character of horizontal earth-fissure displacements.

This study was a field-oriented project designed to measure and analyze horizontal displacements of earth fissures. A major portion of the research was devoted to the development and perfection of permanent and temporary short-base extensometers to measure horizontal earth-fissure displacements with a resolution of ± 2.54 µm. The dial-gauge and transducer extensometers were designed to be constructed inexpensively and simply, to minimize thermal effect, and to obtain high resolution accurately and precisely. The detailed description of this instrumentation is believed to be a significant contribution to research methods of this type. A literature review of earth fissures did not suggest any simple and inexpensive method to measure small, horizontal earth-fissure displacements. Although more testing of the method described here is necessary, it is hoped that future researchers will find some useful and helpful suggestions to aid them in making measurements of earth-fissure displacements.

Dial-gauge measurements indicated that earth fissures open and close relatively smoothly over long periods, with occasional sudden jumps that usually follow heavy, runoff-producing rainstorms. Generally, earth fissures closed over long, dry periods and opened after heavy rainfalls. In a given area, earth fissures often opened and closed simultaneously, which suggested that desert alluvium has greater structural integrity than previously suspected. No difference was observed in the characters of old and new earth-fissure displacements. The earth fissure with the greatest amount of movement was the closest to the area of maximum subsidence.

CHAPTER 7

RECOMMENDATIONS FOR FUTURE RESEARCH

A major result of the research thus far has been the development of short-base extensometers that use dial gauges and transducers to measure horizontal earth-fissure displacements accurately and precisely. Future research must expand the present data base with the inclusion of ancillary measurements. Accessible water and subsidence wells must be properly located to study active earth fissures, because correlation of water-level fluctuations and declines, subsidence, and horizontal earth-fissure displacements is imperative. A distinction must be made among mechanisms that produce sufficient stress to create earth fissures, mechanisms that trigger earth-fissure formation, and mechanisms that maintain earth-fissure formation.

Future research should specifically include the following: 1) discrete and continuous measurements of horizontal earth-fissure displacements must be continued in present study areas and expanded to areas of different hydrogeologic characteristics; 2) earth fissures must be mapped on a sufficiently large scale; 3) detailed water-level fluctuations and land-surface subsidence must be recorded; 4) many short- and long-base extensometers must be deployed; 5) independent and overlapping horizontal displacements must be made to test among different measurement techniques; 6) rainfall must be measured at selected sites; and 7) earth-fissure displacements, water-level changes, and land-surface subsidence must be analyzed and correlated using conventional and recently developed analytical procedures, including spectral, harmonic, and time-series analyses.

APPENDIX A

WATER-LEVEL MEASUREMENTS

This appendix contains water-level measurement data from three U.S. Geological Survey piezometers: Grove, Fault, and Mountain.

Piezometer readings, 1977-1978 (depth to water in feet, LSD)

Date	Piezometer		
	Grove	Fault	Mountain
05 Oct 77	476.13	470.23	13.66
11 Oct	474.02	469.87	-
18 Oct	480.42	469.25	-
03 Nov	480.14	468.26	19.26
29 Nov	468.695	466.22	22.02
21 Dec	479.026	464.35	23.931
07 Jan 78	473.465	461.39	-
28 Jan	467.31	458.03	26.74
18 Feb	471.63	450.05	28.27
11 Mar	462.20	452.53	29.44
22 Mar	494.79	444.75	> 500.55
02 Apr	467.16	450.00	30.88
18 Apr	490.73	446.22	> 500.55
01 Jun	> 500.55	456.66	456.81
04 Jun	> 500.55	457.22	459.67
24 Jun	> 500.55	461.06	460.70
07 Jul	> 500.55	463.09	460.55
22 Jul	> 500.55	465.50	462.40
29 Jul	> 500.55	466.70	463.23
05 Aug	537.61	467.52	462.75
29 Aug	546.11	-	464.52
14 Sep	549.61	470.60	466.69

Piezometer readings, 1977 (depth to water in feet, LSD)

Date	Piezometer Grove	Fault	Mountain
05 Oct 77	478.33	474.93	14.56
11 Oct	476.22	474.57	-
18 Oct	482.62	473.95	-
03 Nov	482.34	472.96	20.16
29 Nov	470.90	470.92	22.92
21 Dec	481.23	469.05	24.83

Piezometer readings, 1978 (depth to water in feet, LSD)

Date	Piezometer Grove	Fault	Mountain
07 Jan 78	475.67	466.09	-
28 Jan	474.51	462.73	27.64
18 Feb	473.83	454.75	29.07
11 Mar	464.4	457.23	30.34
02 Apr	469.27	454.49	31.54
18 Apr	492.84	450.71	> 500.55
22 May	496.90	449.24	> 500.55
01 Jun	> 500.55	461.15	457.67
04 Jun	> 500.55	461.71	460.33
24 Jun	> 500.55	465.55	461.36
07 Jul	> 500.55	467.58	461.21
22 Jul	> 500.55	469.99	463.06
29 Jul	-	471.19	463.89
05 Aug	539.72	472.01	463.41
29 Aug	548.22	475.09	465.18
14 Sep	551.72	477.04	467.35
02 Nov	> 500.55	478.02	471.09
16 Nov	519.6	476.89	471.79
20 Nov	511.72	476.11	471.82
02 Dec	497.77	472.79	471.15
14 Dec	482.07	471.91	471.97

Piezometer readings, 1979 (depth to water in feet, LSD)

Date	Piezometer		
	Grove	Fault	Mountain
13 Jan 79	481.60	467.05	474.30
03 Feb	474.92	463.31	478.20
06 Mar	466.22	458.84	473.21
01 Apr	481.49	458.27	476.86
14 Apr	477.14	457.56	473.10
28 Apr	> 500.55	450.59	477.5
14 May	507.4	460.69	478.29
24 May	519.59	461.70	479.88
11 Jun	529.4	464.14	483.15
01 Jul	539.89	467.03	486.72
14 Jul	546.89	469.40	488.80
28 Jul	550.89	471.26	491.12
15 Aug	558.89	474.21	494.82
08 Sep	574.29	499.5	477.6
06 Oct	564.89	481.89	502.89
01 Nov	541.89	480.69	499.83
23 Nov	525.94	478.44	496.29
08 Dec	514.46	477.00	494.15
23 Dec	503.48	474.50	491.52

Piezometer readings, 1980 (depth to water in feet, LSD)

Date	Piezometer		
	Grove	Fault	Mountain
06 Jan 80	502.65	475.66	488.93
02 Feb	484.88	469.15	484.2
23 Feb	477.50	466.61	480.40
28 Mar	508.58	468.10	482.16
16 Apr	524.79	484.77	466.95
04 May	530.64	469.12	488.01
17 May	521.	470.55	489.55
01 Jun	530.9	472.15	491.48
21 Jun	536.1	469.40	494.30
12 Jul	549.08	471.98	498.8
26 Jul	563.	480.	502.
16 Aug	559.	482.55	499.
30 Aug	571.	484.1	506.
12 Sep	572.2	485.09	506.6
10 Oct	557.9	485.91	506.1
29 Oct	538.9	484.89	505.4
20 Dec	516.	479.45	495.65

Piezometer readings, 1981 (depth to water in feet, LSD)

Date	Piezometer		
	Grove	Fault	Mountain
31 Jan 81	503.	475.09	491.56
25 Feb	496.	474.22	489.84
14 Mar	494.50	473.05	488.50
12 Apr	488.15	473.69	491.29
10 May	> 500.55	476.4	494.8
30 May	553.1	478.3	495.7
22 Aug	566.33	484.45	504.12
24 Sep	576.1	486.2	506.3
08 Nov	532.1	486.70	505.0
27 Dec	504.5	479.8	495.8

Piezometer readings, 1982-1984 (depth to water in feet, LSD)

Date	Piezometer		
	Grove	Fault	Mountain
20 Feb 82	493.9	477.22	492.40
06 Jun	559.2	480.1	500.6
10 Jul	568.8	486.36	504.8
07 Aug	569.8	488.39	508.0
22 Sep	539.5	486.5	508.1
20 Nov	513.8	485.7	502.6
01 Feb 83	495.3	480.48	495.45
09 Apr	490.23	475.30	491.3
22 Jun	522.66	476.78	493.88
19 Oct	505.3	480.9	496.3
12 Jan 84	480.81	471.6	487.37

APPENDIX B

HORIZONTAL EARTH-FISSURE DISPLACEMENT MEASUREMENTS

Turnaround extensometer readings, 1976-1983

Date	Reading (in.)	Temperature (°C)	Date	Reading (in.)	Temperature (°C)
04 Sep 76	0.0459	-	05 Aug 78	0.0712	37.2
26 Sep	0.0476	26.9	29 Aug	0.0881	36.1
22 Oct	0.0426	26.6	14 Sep	0.0965	34.2
20 Nov	0.0451	20.6	05 Oct	0.1022	33.2
05 Dec	0.0451	15.1	19 Oct	0.1055	30.0
20 Dec	0.0465	16.4	02 Nov	0.0967	25.0
31 Dec	0.0475	14.4	16 Nov	0.0931	17.2
			02 Dec	0.0880	15.0
01 Jan 77	0.0468	14.5			
03 Jan	0.0426	12.0	13 Jan 79	0.0724	12.1
24 Jan	0.0380	16.0	03 Feb	0.0629	11.3
10 Feb	0.0366	15.1	17 Feb	0.0590	15.0
01 Mar	0.0410	16.5	06 Mar	0.0514	16.9
15 Mar	0.0466	18.0	01 Apr	0.0448	17.5
30 Mar	0.0508	18.5	14 Apr	0.0445	22.1
22 Apr	0.0586	24.0	28 Apr	0.0515	25.9
06 May	0.0655	26.1	14 May	0.0689	28.0
21 May	0.0694	28.4	24 May	0.0883	29.2
06 Jun	0.0770	31.0	11 Jun	0.1085	33.0
26 Jun	0.0832	33.0	02 Jul	0.1323	33.1
11 Jul	0.0898	36.2	12 Jul	0.1418	36.1
27 Jul	0.0947	36.7	28 Jul	0.1500	38.7
16 Aug	0.0889	32.1	15 Aug	0.1580	32.1
03 Sep	0.0926	37.1	29 Aug	0.1621	38.8
20 Sep	0.0987	32.1	26 Oct	0.1860	27.2
01 Oct	0.0976	32.0	23 Nov	0.1890	17.0
18 Oct	0.0952	30.1	08 Dec	0.1889	17.5
03 Nov	0.0937	24.9	23 Dec	0.1875	15.3
26 Nov	0.0941	24.0			
09 Dec	0.0949	15.7	06 Jan 80	0.1888	14.5
21 Dec	0.0956	15.5	02 Feb	0.1825	12.1
29 Dec	0.0946	15.9	23 Feb	0.1795	16.8
			01 Apr	0.1770	20.0
28 Jan 78	0.0798	12.8	20 Apr	0.1843	27.2
18 Feb	0.0700	12.3	02 May	0.1875	24.5
11 Mar	0.0554	17.6	19 May	0.1910	28.3
02 Apr	0.0414	21.4	07 Jun	0.1972	32.0
18 Apr	0.0387	22.1	02 Jul	0.2007	33.5
22 May	0.0690	30.3	12 Jul	0.2013	37.0
04 Jun	0.0860	32.0	26 Jul	0.2020	37.0
24 Jun	0.1110	37.0	20 Aug	0.2047	34.2
07 Jul	0.1226	36.4	30 Aug	0.2068	36.1
22 Jul	0.1353	37.7	12 Sep	0.2881	34.2
22 Jul	0.0707	[reset]	02 Oct	0.2899	33.6

Turnaround extensometer readings, 1976-1983--Continued

Date	Reading (in.)	Temperature (°C)	Date	Reading (in.)	Temperature (°C)
29 Oct 80	0.2908	24.2	08 Nov 81	0.1164	23.0
20 Dec	0.2906	17.5	26 Dec	0.1094	13.2
29 Jan 81	0.2819	15.0	20 Feb 82	0.1010	17.5
26 Feb	0.2767	18.3	03 Apr	0.0938	20.1
26 Feb	0.0961	[reset]	06 Jun	0.1047	31.0
14 Mar	0.0915	19.0	10 Jul	0.1122	35.5
12 Apr	0.0944	23.8	07 Aug	0.1155	36.6
10 May	0.1002	28.7	23 Sep	0.1084	33.9
30 May	0.1037	31.2	20 Nov	0.1114	19.2
23 Jul	0.1092	37.0			
22 Aug	0.1125	37.5	09 Apr 83	0.0213	19.5
24 Sep	0.1154	33.4	09 Jul	0.0907	37.1

Waiting-to-Drill extensometer readings, 1977-1982

Date	Reading (in.)	Temperature (°C)	Date	Reading (in.)	Temperature (°C)
30 Aug 77	0.3192	35.0	01 Apr 79	0.1180	15.5
02 Sep	0.3137	34.0			
20 Sep	0.2917	32.0	11 Jun 80	0.4328	[reset]
01 Oct	0.3030	31.6	21 Jun	0.4394	41.5
18 Oct	0.2362	28.6	12 Jul	0.4468	39.0
03 Nov	0.2740	24.6	26 Jul	0.4500	36.0
26 Nov	0.2917	20.0	16 Aug	0.3821	30.0
09 Dec	0.2964	16.0	30 Aug	0.4699	36.1
21 Dec	0.3014	16.3	12 Sep	0.5350	34.3
29 Dec	0.2883	16.1	25 Sep	0.5230	33.1
			10 Oct	0.4031	32.5
23 Jan 78	0.1713	12.9	29 Oct	0.5298	21.0
18 Feb	0.1462	12.0	17 Dec	0.5392	17.6
11 Mar	0.1270	10.5			
02 Apr	0.1555	21.0	31 Jan 81	0.4158	15.0
18 Apr	0.1147	22.3	26 Feb	0.4196	18.0
22 May	0.2212	30.1	14 Mar	0.3792	18.5
04 Jun	0.2423	33.4	12 Apr	0.4690	23.8
24 Jun	0.2650	37.9	10 May	0.4752	27.4
07 Jul	0.2741	37.8	30 May	0.4658	32.0
22 Jul	0.2804	37.0	23 Jul	0.0077	36.2
05 Aug	0.2742	24.6	22 Aug	0.4331	34.2
29 Aug	0.2692	34.2	24 Sep	0.0230	32.0
14 Sep	0.2690	34.2	08 Nov	0.0380	23.5
05 Oct	0.2850	32.0	27 Dec	0.4190	12.0
19 Oct	0.2850	32.0			
02 Nov	0.2296	23.2	20 Feb 82	0.3875	15.6
16 Nov	0.1920	15.1	03 Apr	0.3580	19.4
02 Dec	0.1652	14.2	06 Jun	0.4671	32.2
14 Dec	0.1672	11.8	10 Jul	0.4245	33.4
			07 Aug	0.4327	33.8
13 Jan 79	0.1403	11.9	23 Sep	0.4623	32.0
03 Feb	0.1398	9.9	23 Sep	0.4277	[reset]
17 Feb	0.1398	14.0	20 Nov	0.4412	17.5
06 Mar	0.1350	14.9			

Mudflat extensometer readings, 1976-1977

Date	Reading (in.)	Temperature (°C)	Date	Reading (in.)	Temperature (°C)
23 Apr 76	0.5208	-	03 Jan 77	0.5830	12.4
21 May	0.5211	-	15 Jan	0.5905	10.0
02 Jul	0.3424	-	29 Jan	-	[destroyed]
17 Jul	0.3174	-	10 Feb	0.0590	[repaired]
17 Jul	0.2495	[reset]	12 Feb	0.0435	[reset]
24 Jul	0.1879	-	01 Mar	0.0437	14.5
25 Jul	0.2420	-	01 Mar	0.1056	[reset]
01 Aug	0.2437	-	15 Mar	0.1104	18.0
05 Aug	0.2449	-	30 Mar	0.1180	17.2
10 Aug	0.2452	28.5	22 Apr	0.1388	24.0
17 Aug	0.2427	30.0	06 May	0.1452	26.0
28 Aug	0.2383	32.5	21 May	0.1492	29.5
03 Sep	0.3042	31.9	06 Jun	0.1541	32.5
18 Sep	0.3205	26.9	26 Jun	0.1669	35.5
18 Sep	0.4216	[reset]	11 Jul	0.1692	37.2
26 Sep	0.4931	26.9	27 Jul	0.1744	36.2
02 Oct	0.5277	32.6	16 Aug	0.1861	32.5
29 Oct	0.5572	21.2	03 Sep	0.1996	37.9
20 Nov	0.5715	19.0	20 Sep	0.2112	35.9
05 Dec	0.5789	16.1	01 Oct	0.2128	33.0
20 Dec	0.5833	13.9	18 Oct	0.2250	29.8
31 Dec	0.5864	12.8	03 Nov	0.2253	25.6
			06 Nov	0.2254	[destroyed]

Stubby extensometer readings, 1976-1983

Date	Reading (in.)	Temperature (°C)	Date	Reading (in.)	Temperature (°C)
26 Apr 76	0.4962	-	28 Jan 78	0.0427	11.8
03 Jul	0.4542	-	18 Feb	0.0467	11.7
17 Jul	0.4571	-	11 Mar	0.0590	15.6
17 Jul	0.2626	[reset]	02 Apr	0.0615	20.0
24 Jul	0.3440	-	18 Apr	0.0622	23.0
24 Jul	0.3494	[reset]	22 May	0.0634	30.0
25 Jul	0.3497	-	04 Jun	0.0638	31.0
01 Aug	0.3476	-	24 Jun	0.0645	38.0
05 Aug	0.3461	-	07 Jul	0.0641	34.4
10 Aug	0.3372	32.8	22 Jul	0.0662	34.6
17 Aug	0.3367	29.9	24 Jul	0.0662	34.4
28 Aug	0.3361	32.9	05 Aug	0.0696	33.4
03 Sep	0.3484	31.2	29 Aug	0.0740	33.9
26 Sep	0.3575	25.7	14 Sep	0.0747	32.0
02 Oct	0.3588	32.2	05 Oct	0.0747	31.8
29 Oct	0.3590	23.0	19 Oct	0.0742	30.5
20 Nov	0.3564	19.9	28 Oct	0.0711	21.2
05 Dec	0.3525	18.2	02 Nov	0.0708	24.9
20 Dec	0.3475	15.5	16 Nov	0.0681	15.8
31 Dec	0.3415	13.0	02 Dec	0.0671	14.8
			14 Dec	0.0658	11.5
03 Jan 77	0.3409	15.7			
15 Jan	0.3397	12.0	13 Jan 79	0.0733	12.0
29 Jan	0.3412	15.2	03 Feb	0.0792	10.2
10 Feb	0.3407	15.9	17 Feb	0.0816	14.9
01 Mar	0.3378	16.5	06 Mar	0.0841	15.5
15 Mar	0.3366	17.9	01 Apr	0.0885	15.3
30 Mar	0.3338	17.7	14 Apr	0.0925	21.3
22 Apr	0.3335	25.0	28 Apr	0.0944	25.3
06 May	0.3344	25.0	14 May	0.0946	26.0
21 May	0.3394	29.0	24 May	0.0941	28.1
06 Jun	-	[destroyed]	11 Jun	0.0938	31.5
16 Aug	0.0382	[repaired]	01 Jul	0.0930	36.0
03 Sep	0.0386	34.9	12 Jul	0.0927	35.0
20 Sep	0.3085	31.4	28 Jul	0.0919	37.1
01 Oct	0.0369	30.1	15 Aug	0.0905	30.1
18 Oct	0.0362	29.7	29 Aug	0.0920	34.7
03 Nov	0.0345	26.1	08 Sep	0.0901	36.8
16 Nov	0.0315	20.0	06 Oct	0.0875	32.2
26 Nov	0.0280	24.1	26 Oct	0.0810	25.7
09 Dec	0.0204	15.4	23 Nov	0.0740	15.0
21 Dec	0.0159	15.2	08 Dec	0.0694	17.0
29 Dec	0.0126	15.6	23 Dec	0.0642	14.9
			29 Dec	0.0614	13.0

Stubby extensometer readings, 1976-1983--Continued

Date	Reading (in.)	Temperature (°C)	Date	Reading (in.)	Temperature (°C)
06 Jan 80	0.0684	14.0	14 Mar 81	0.0414	18.0
02 Feb	0.0578	15.2	12 Apr	0.0394	23.7
23 Feb	0.0637	15.0	10 May	0.0890	28.2
28 Mar	0.0663	16.9	30 May	0.0382	30.5
18 Apr	0.0627	26.8	23 Jul	0.0433	37.6
04 May	0.0602	25.2	22 Aug	0.053	35.4
17 May	0.0588	26.8	24 Sep	0.0422	32.8
01 Jun	0.0577	28.8	08 Nov	0.0261	24.5
21 Jun	0.0582	34.9	27 Dec	0.0095	14.1
12 Jul	0.0576	36.1			
26 Jul	0.0579	35.5	20 Feb 82	0.4980	8.7
16 Aug	0.0601	33.0	03 Apr	0.0019	20.0
30 Aug	0.0603	34.9	06 Jun	0.0107	30.5
12 Sep	0.0646	30.0	10 Jul	0.0121	34.0
25 Sep	0.0640	32.0	07 Aug	0.0158	34.2
10 Oct	0.0654	31.8	23 Aug	0.0340	33.0
29 Oct	0.0598	22.9	20 Nov	0.0164	19.5
17 Dec	0.0422	18.5			
			01 Feb 83	0.0210	12.0
31 Jan 81	0.0328	14.6	09 Apr	0.0188	18.0
26 Feb	0.0382	19.0	09 Jul	-	[destroyed]

AV-7 extensometer readings, 1977-1982

Date	Reading (in.)	Temperature (°C)	Date	Reading (in.)	Temperature (°C)
30 Aug 77	0.1908	46.1	06 Mar 79	0.4197	11.7
04 Sep	0.1911	32.5	11 Mar	0.4204	15.0
20 Sep	0.1916	28.9	01 Apr	0.4238	16.3
01 Oct	0.1946	29.9	07 Apr	0.4206	18.5
18 Oct	0.1838	26.1	06 May	0.4116	25.5
08 Nov	0.2028	18.0	14 May	0.4097	26.0
17 Nov	0.2098	17.7	24 May	0.4108	28.4
09 Dec	0.2138	13.4	03 Jun	0.4197	28.0
21 Dec	0.2198	13.3	11 Jun	0.4172	29.0
29 Dec	0.2115	14.4	24 Jun	0.4229	33.1
			12 Jul	0.2410	[reset]
28 Jan 78	0.2516	10.0	28 Jul	0.2436	34.0
18 Feb	0.2964	11.9	29 Aug	0.2481	30.6
11 Mar	0.3359	13.0	08 Sep	0.2501	32.8
02 Apr	0.3561	18.2	06 Oct	0.2519	28.1
18 Apr	0.3504	18.7	02 Dec	0.2538	13.0
04 Jun	0.3320	28.0	05 Dec	0.2537	12.8
24 Jun	0.0000	[rusted]	08 Dec	0.2540	13.0
22 Jul	0.0426	27.5	08 Dec	0.2465	[reset]
22 Jul	0.0260	[reset]	16 Dec	0.2462	11.1
29 Jul	0.0285	32.0	23 Dec	0.2462	11.1
05 Aug	0.0319	33.4	29 Dec	0.2465	10.3
29 Aug	0.0554	30.0			
04 Sep	0.0610	34.0	05 Jan 80	0.2471	10.9
10 Sep	0.0620	30.1	19 Jan	0.2474	12.7
16 Sep	0.0631	29.1	02 Feb	0.2484	13.5
23 Sep	0.0632	28.7	23 Feb	0.2490	13.0
08 Oct	0.0630	28.9	04 Mar	0.2544	17.5
15 Oct	0.0625	27.5	25 Mar	0.2569	16.0
22 Oct	0.0666	23.2	20 Apr	0.2577	23.2
05 Nov	0.0736	19.0	02 May	0.2587	23.5
11 Nov	0.0805	18.9	19 May	0.0000	[rusted]
18 Nov	0.0793	14.6	07 Jun	0.1678	30.0
26 Nov	0.0701	13.2	21 Jun	0.1678	32.0
02 Dec	0.0695	12.0	12 Jul	0.1670	33.2
10 Dec	0.0687	11.8	23 Jul	0.1665	31.8
16 Dec	0.0703	11.6	23 Jul	0.2333	[reset]
			06 Aug	0.2440	33.6
23 Jan 79	0.0790	9.7	20 Aug	0.2480	33.8
23 Jan	0.4078	[reset]	30 Sep	0.2525	30.2
27 Jan	0.4078	7.9	29 Oct	0.2549	20.2
03 Feb	0.4087	9.8	20 Dec	0.2560	14.2
10 Feb	0.4166	9.9			
16 Feb	0.4170	12.8	31 Jan 81	0.2485	11.3

AV-7 extensometer readings, 1977-1982--Continued

Date	Reading (in.)	Temperature (°C)	Date	Reading (in.)	Temperature (°C)
26 Feb 81	0.2480	11.	02 Mar 82	0.4243	16.8
14 Mar	0.2477	12.1	08 Mar	0.4246	16.7
12 Apr	0.2475	23.2	20 Mar	0.4277	15.1
10 May	0.2481	26.5	03 Apr	0.4222	18.0
30 May	0.2509	29.0	12 Apr	0.4220	21.6
23 Jul	0.2557	34.0	20 Apr	0.4232	25.1
22 Aug	0.2587	34.0	22 Apr	0.4234	22.0
24 Sep	0.2658	28.2	28 Apr	0.4241	24.9
07 Nov	0.2679	21.2	07 May	0.4251	25.0
26 Dec	0.2635	9.5	24 May	0.4269	30.2
			06 Jun	0.4288	28.5
10 Jan 82	0.2637	12.0	20 Jun	0.4299	31.2
17 Jan	0.2641	9.7	29 Jun	0.4302	32.
23 Jan	0.2635	10.0	07 Jul	0.4306	30.0
31 Jan	0.4245	10.0	17 Jul	0.4296	33.0
07 Feb	0.4244	11.5	25 Jul	0.4293	33.5
15 Feb	0.4243	14.5	04 Aug	0.4287	32.4
20 Feb	0.4246	14.0	23 Aug	-	[destroyed]

Princess extensometer readings, 1977-1983

Date	Reading (in.)	Temperature (°C)	Date	Reading (in.)	Temperature (°C)
27 Aug 77	0.0750	-	12 Jul 79	0.2432	38.0
03 Sep	0.0783	33.5	28 Jul	0.2493	39.0
20 Sep	0.6772	33.0	15 Aug	0.2557	34.0
01 Oct	0.0766	29.0	29 Aug	0.2590	36.1
18 Oct	0.0745	30.0	08 Sep	0.2605	37.9
03 Nov	0.0751	26.1	06 Oct	0.2639	33.5
26 Nov	0.0757	24.5	26 Oct	0.2645	27.2
09 Dec	0.0760	15.6	01 Nov	0.2637	27.1
21 Dec	0.0762	15.4	23 Nov	0.3270	16.7
29 Dec	0.0762	16.0	08 Dec	0.2781	17.2
			23 Dec	0.2775	15.1
28 Jan 78	0.0733	12.0			
18 Feb	0.0697	11.8	06 Jan 80	0.2774	14.0
11 Mar	0.0517	15.4	02 Feb	0.2756	10.2
02 Apr	0.0375	21.8	23 Feb	0.2827	15.2
18 Apr	0.0341	23.9	28 Mar	0.2804	17.0
22 May	0.0408	31.1	18 Apr	0.2820	24.9
04 Jun	0.0494	32.2	04 May	0.2827	27.1
24 Jun	0.0635	36.8	17 May	0.2885	28.2
04 Jul	0.0569	36.3	01 Jun	0.2850	28.4
22 Jul	0.0615	37.1	21 Jun	0.2880	34.2
05 Aug	0.0638	37.6	12 Jul	0.2910	35.6
29 Aug	0.0660	34.9	26 Jul	0.2927	36.5
14 Sep	0.0683	33.2	16 Aug	0.2957	35.9
05 Oct	0.0735	32.1	30 Aug	0.2951	36.4
19 Oct	0.0735	29.5	12 Sep	0.2952	32.1
19 Oct	0.0756	[reset]	25 Sep	0.2956	33.2
02 Nov	0.0723	25.0	10 Oct	0.2963	32.9
16 Nov	0.0706	16.2	29 Oct	0.2954	23.3
02 Dec	0.0504	14.9	17 Dec	0.2942	17.5
14 Dec	0.0452	11.7			
			31 Jan 81	0.2882	14.5
13 Jan 79	0.0330	11.9	26 Feb	0.2361	19.5
03 Feb	0.0270	10.0	14 Mar	0.2834	18.2
17 Feb	0.0168	13.9	12 Apr	0.2880	23.8
17 Feb	0.2085	[reset]	10 May	0.2841	28.0
06 Mar	0.1906	14.0	30 May	0.2865	32.0
01 Apr	0.1982	16.0	23 Jul	0.2976	38.5
14 Apr	0.2104	20.1	22 Aug	0.2973	36.9
28 Apr	0.2164	28.9	24 Sep	0.2997	32.4
14 May	0.2195	27.5	08 Nov	0.2987	23.5
24 May	0.2240	29.0	27 Dec	0.2912	13.8
11 Jun	0.2290	33.2			
01 Jul	0.2394	37.1	20 Feb 82	0.2878	16.7

Princess extensometer readings, 1977-1983--Continued

Date	Reading (in.)	Temperature (°C)	Date	Reading (in.)	Temperature (°C)
03 Apr 82	0.2875	19.2	20 Nov 82	0.2852	18.8
06 Jun	0.2918	30.5			
10 Jul	0.2957	34.4	01 Feb 83	0.2692	12.1
07 Aug	0.2922	35.5	09 Apr	0.2651	20.0
23 Sep	0.2822	33.2	09 Jul	0.2868	36.0

Rattler extensometer readings, 1976-1983

Date	Reading (in.)	Temperature (°C)	Date	Reading (in.)	Temperature (°C)
04 Sep 76	0.2097	32.7	29 Aug 78	0.2038	37.2
26 Sep	0.1335	28.2	14 Sep	0.2046	34.9
22 Oct	0.1226	24.9	05 Oct	0.2850	32.0
20 Nov	0.1681	20.4	19 Oct	0.2026	30.2
05 Dec	0.1626	15.4	02 Nov	0.1955	26.1
20 Dec	0.1088	16.8	16 Nov	0.1921	18.0
31 Dec	0.1059	14.8	02 Dec	0.1877	16.5
01 Jan 77	0.1042	16.7	13 Jan 79	0.2093	13.3
03 Jan	0.1058	12.9	03 Feb	0.2100	11.7
29 Jan	0.1088	17.0	17 Feb	0.2106	15.1
10 Feb	0.1106	15.3	06 Mar	0.2102	17.0
01 Mar	0.1121	19.5	01 Apr	0.2097	19.2
15 Mar	0.1116	17.8	14 Apr	0.2107	23.4
30 Mar	0.1104	19.6	23 Apr	0.2805	28.3
22 Apr	0.1140	25.6	14 May	0.2112	29.1
06 May	0.1159	27.2	24 May	0.2136	32.3
21 May	0.1163	28.7	11 Jun	0.2152	33.9
06 Jun	0.1178	31.1	02 Jul	0.2182	34.9
26 Jun	0.1259	34.0	12 Jul	0.2199	37.9
11 Jul	0.1312	36.9	28 Jul	0.2197	39.4
27 Jul	0.1366	37.3	15 Aug	0.2183	32.9
16 Aug	0.1505	31.2	29 Aug	0.2200	32.5
03 Sep	0.1578	36.8	26 Oct	0.2135	28.0
20 Sep	0.1622	32.0	08 Dec	0.1925	18.0
01 Oct	0.1621	31.4			
18 Oct	0.1635	29.4	06 Jan 80	0.1776	15.5
03 Nov	0.1631	24.8	06 Feb	0.1686	12.6
26 Nov	0.1672	19.8	23 Feb	0.1659	17.0
09 Dec	0.1621	15.6	01 Apr	0.1705	18.2
21 Dec	0.1582	15.8	20 Apr	0.1776	28.2
29 Dec	0.1563	16.8	02 May	0.1781	25.9
			19 May	0.1821	29.0
28 Jan 78	0.1655	13.0	07 Jun	0.1847	33.5
18 Feb	0.1777	12.5	02 Jul	0.1862	34.8
11 Mar	0.1882	17.2	12 Jul	0.1886	38.7
02 Apr	0.1848	22.8	26 Jul	0.1877	38.2
18 Apr	0.1818	23.0	20 Aug	0.1938	34.8
22 May	0.1848	31.8	30 Aug	0.1946	36.8
04 Jun	0.1880	33.7	12 Sep	0.1942	35.0
24 Jun	0.1919	83.2	02 Oct	0.1884	34.5
07 Jul	0.1952	37.9	29 Oct	0.1778	24.2
22 Jul	0.1983	38.5	20 Dec	0.1535	17.7
05 Aug	0.1994	38.0			

Rattler extensometer readings, 1976-1983--Continued

Date	Reading (in.)	Temperature (°C)	Date	Reading (in.)	Temperature (°C)
29 Jan 81	0.1415	15.8	20 Feb 82	0.0390	18.7
26 Feb	0.1390	19.8	03 Apr	0.0880	22.5
14 Mar	0.1375	20.0	06 Jun	0.1008	32.8
12 Apr	0.1422	24.6	10 Jul	0.1065	37.5
10 May	0.1459	30.0	07 Aug	0.1111	38.0
30 May	0.1470	32.5	23 Sep	0.4427	32.0
23 Jul	0.1396	38.0	20 Nov	0.4416	19.6
22 Aug	0.1891	36.9			
24 Sep	0.1883	34.1	09 Apr 83	0.4010	20.2
08 Nov	0.1223	23.5	09 Jul	0.4312	37.0
26 Dec	0.1010	14.3			

Scorpion extensometer readings, 1976

Date	Reading (in.)	Temperature (°C)	Date	Reading (in.)	Temperature (°C)
17 Mar 76	4.1797	[started]	23 Apr 76	4.0313	-
12 Mar	4.1406	-	03 Jul	4.1094	-
09 Apr	3.9844	-	24 Jul	5.1	[destroyed]

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