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Earth Fissures and Localized Differential Subsidence

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Long linear tension cracks associated with declining groundwater levels at four sites in subsiding areas in south-central Arizona, Fremont Valley, California, and Las Vegas Valley, Nevada, occur near points of maximum convex-upward curvature in subsidence profiles oriented perpendicular to the cracks. Profiles are based on repeated precise vertical control surveys of lines of closely spaced bench marks. Association of these fissures with zones of localized differential subsidence indicates that linear earth fissures are caused by horizontal tensile strains probably resulting from localized differential compaction. Horizontal tensile strains across the fissures at the point of maximum convex-upward curvature, ranging from approximately 100 to 700 microstrains (0.01 to 0.07% per year), were indicated based on measurements with a tape or electronic distance meter.

INTRODUCTION

Earth fissures, long tension cracks with negligible vertical offset [*Holzer,* 1976], are widespread in the western United States where groundwater has been withdrawn from unconsolidated sedimentary deposits (Figure 1). Although most earth fissures occur in agricultural areas dependent on groundwater, some have occurred in urban areas such as Las Vegas, Nevada, and Phoenix, Arizona. Field evidence indicates that relative horizontal displacements across fissures are small. However, due to the void space created by their great depth and the erodability of the soil in which they form, they frequently are enlarged into wide and deep gullies by surface water flowing into them [*Holzer*, 1976]. The impressive surface appearance of many fissures is further enhanced by their lengths, which range from a few dekameters to as much as 3.5 km.

The areal and temporal association of earth fissures with land subsidence caused by groundwater withdrawal indicates that these fissures are man induced. The specific mechanism of formation has not been demonstrated, however, due to insufficient field data to test hypotheses. The first hypothesis proposed was that of *Feth* [1951]. He speculated that an earth fissure in 1949 in south-central Arizona was caused by tensile strains generated by localized differential subsidence resulting from localized variations of aquifer thickness. *Lofgren* [1971] speculated that horizontal displacements measured in subsiding areas were due to horizontal seepage forces, and suggested that these forces were capable of causing earth fissures. *Bouwer* [1977] suggested that earth fissures were caused by rotation of rigid slabs of overburden in response to regional differential subsidence. Based on the association of earth fissures with water table declines and field evidence which suggested fissures formed in and propagated upward from the zone drained by the water table decline, *Holzer and Davis* [1976] proposed that fissures were caused by desiccation related to water table declines. This mechanism is accepted as the cause of naturally occurring earth fissures that form polygonal patterns on many dry lakes in arid regions [*Neal et al.,* 1968].

To evaluate these mechanisms, we conducted precise geodetic surveys to measure surface deformation near four linear earth fissures in Arizona, California, and Nevada (Figure 1). The earth fissures investigated are in areas of land subsidence caused by man-induced compaction of unconsolidated deposits. Our surveys indicated the four fissures were coincident with zones of localized differential subsidence, and occurred near points of maximum convex-upward curvature in the profiles. Because horizontal tensile strains are inferred to be at a maximum at these points, we conclude that differential subsidence, probably caused by differential compaction, is the mechanism that caused the earth fissures. Horizontal extension was measured across all fissures.

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METHODOLOGY

Closely spaced bench marks were set in a line perpendicular to the trend of each fissure under investigation. Leveling was to first-order, class 1 standards [*Federal Geodetic Control Committee,* 1974] except where noted. Such leveling has a nominal accuracy of 1.5 mm $(K)^{1/2}$, where K is the distance in kilometers between marks. Changes of elevation with time at each fissure were computed based on relevelings to these same standards.

RESULTS

Sites 1 and 2

Sites 1 and 2 are 61 km southeast of Phoenix, Arizona, in the northern part of the Picacho Basin (Figure 2). An area of more than 1200 km^2 underlain by alluvium within this basin has subsided more than 30 cm in response to water level declines that locally have exceeded 100 m. Earth fissures are widespread (Figure 2). No bench marks with long-term histories of releveling are available, however, to evaluate directly subsidence near fissures at sites 1 and 2. Both fissures investigated began to form sometime between January 1970 and November 1975, based on either aerial photographs or reconnaissance. By November 1975, the ends of the fissure at site 1 had formed but had not yet joined to form a single continuous fissure. In May 1976, two bench marks, 30 m apart across the projection of the segments, were set in the gap between the segments with vertical and horizontal positions determined relative to each other. Subsequently, between February and October 1977, a fissure connecting the two segments formed between the two bench marks. At site 2, a similar pair of bench marks was set in May 1976 on the projection of the western end of another fissure. By October 1976, the western end of this fissure had extended between the two marks. At both sites, closely spaced bench marks were set in April 1978 along the lines defined by the pairs of bench marks. These

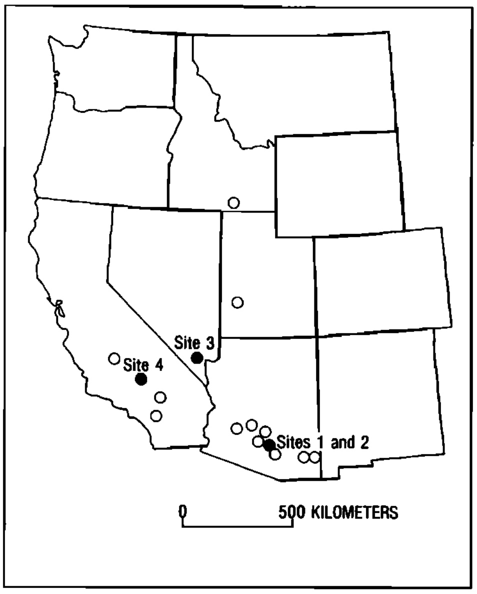

Fig. 1. Map showing locations of earth fissures associated with groundwater withdrawal in the western United States. Solid circles are locations of study areas described in this report.

lines run in both directions from the fissures with each line reaching stable crystalline bedrock on one end. On the basis of releveling of the lines in March 1979 and April 1980, both fissures are at points of maximum convex-upward curvature in the subsidence profiles (Figures 3*a* and 3*b*). Horizontal extension at sites 1 and 2 of 11 and 33 mm (corresponding to 380 and 1100 microstrains), respectively, was measured from May 1976 to April 1980 by precise chaining, accurate to ±1 mm, of the bench marks spanning the fissure (Figures 4*a* and 4*b*). The horizontal extension was measured at the point of maximum curvature in the subsidence profiles. At both sites, except at site 2 for the time period bounding the formation of the earth fissure, the extension appears to have occurred by a creeping motion, at least at the frequency of our measurements. Relative movement of the land surface across the fissures during this time period was dominantly horizontal and not vertical as shown by results from releveling of the bench mark pairs (Figure 4). Leveling before April 1978 was with a Philadelphia rod and theodolite, accurate to ±1.5 mm.

Site 3

Site 3 is in the northwestern part of the subsiding area in Las Vegas Valley, Nevada (Figure 5), and consists of two approximately parallel lines that are 0.71 km apart and cross the same fissure system. At the northern line the fissure system consists of a single fissure; at the southern line it consists of two parallel fissures that are 45 m apart. Within the valley, water levels locally have declined more than 50 m [*Harrill*, 1976] and the land locally has subsided approximately 1 m [*Holzer*, 1978*a*]. Many earth fissures have occurred (Figure 5). Approximately 2 km south of the southern line at site 3, 0.66 m of subsidence was measured from 1963 to 1972. The date of formation of the fissure system at site 3 is unknown. Fissures were not reported in this area by *Mindling* [1971]; however, parts of the fissure system at site 3 were observed by Holzer in February 1976. Based on these observations, garbage in the fissures, and the condition of the fissures, we speculate that they are not more than 10 years old. Bench marks on the southern line at site 3 were set and leveled by the Nevada Department of Highways as part of a network in April 1978. Although their leveling did not conform to first-order, class 1 standards, the procedures used and the shortness of the segment considered here indicate that the results probably are comparable to results from procedures adhering to first-order standards. The line was releveled in March 1979 by the U.S. Geological Survey to first-order standards, and the resulting changes in elevation are shown in Figure 3*c*. The second line was established north of the first line in March 1979, and was releveled in February 1980. Changes of elevation on this line are shown in Figure 3*d*. Because of the great distance to a bench mark demonstrably unaffected by groundwater withdrawal, changes of elevation on each line were computed relative to an arbitrary datum. The fissures in each subsidence profile occur near the part of the profile where its curvature is greatest and it is convex upward. Horizontal extension on the northern line at site 3, on the basis of chaining between the two bench marks spanning the fissure, of 2 mm (corresponding to 63 microstrains) was measured from March 1979 to February 1980. Horizontal control was not available to evaluate horizontal displacements on the southern line.

Site 4

The fissure in California, site 4, is along a segment of the Garlock fault in Fremont Valley, California (Figure 6), where man-induced water level declines of more than 80 m have oc-

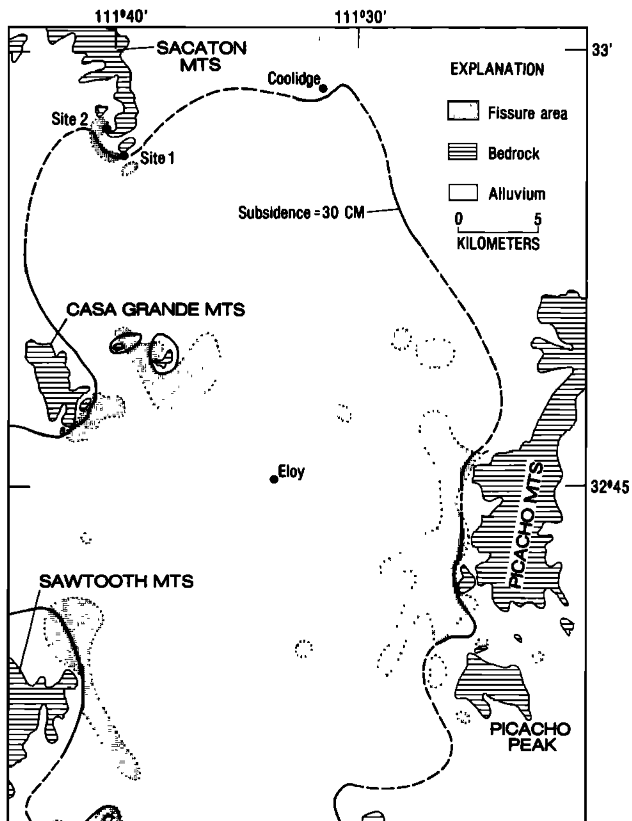

Fig. 2. Location of sites 1 and 2 and earth fissure areas in the Picacho Basin, Arizona. Line of 30-cm subsidence, 1934–1977, from *Jachens and Holzer* [1979]; earth fissure areas from *Laney et al.* [1978] and unpublished data.

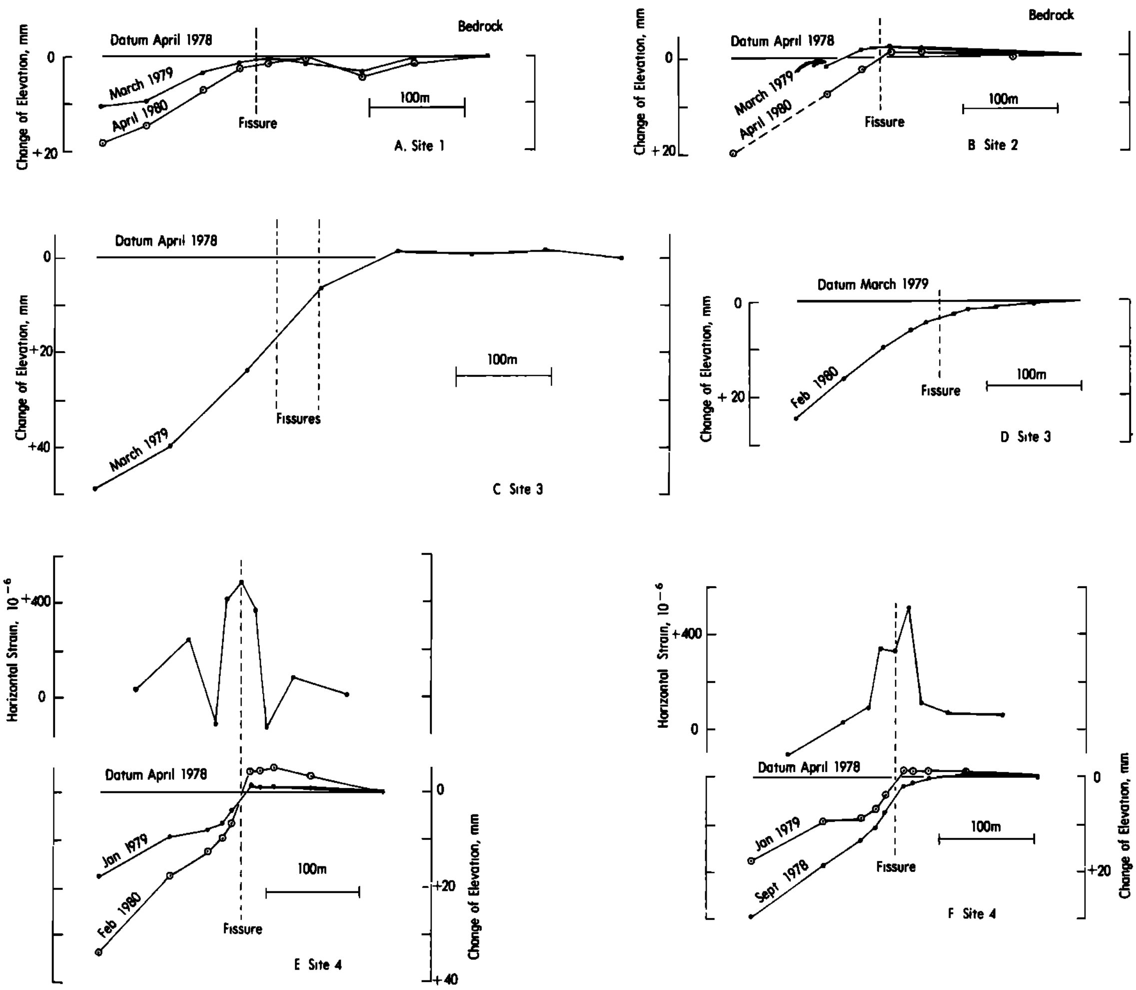

Fig. 3. Profiles of changes of elevation on level lines perpendicular to earth fissures (subsidence is positive). (*a*) Site 1, Picacho Basin, Arizona. (*b*) Site 2, Picacho Basin, Arizona. (*c* and *d*) Site 3, Las Vegas Valley, Nevada. Level line in Figure 3*c* is parallel to and 0.71 km south of line in Figure 3*d*. Both lines cross same fissure system. (*e* and *f*) Site 4, Fremont Valley, California. Horizontal strains at site 4 were computed from measured changes in horizontal position of bench marks from April 13, 1978, to February 15, 1980, and September 14, 1978, in Figures 3*e* and 3*f*, respectively (extension is positive).

curred [*Koehler*, 1977]. Ground failure is extensive within the area of Fremont Valley affected by water level declines (Figure 6). Although leveling data are sparse, more than 30 cm of land subsidence within the valley can be documented. That at least some, if not all, of the subsidence is caused by man-induced compaction of sediments rather than tectonism is indicated by protruding water well casings within the valley. Additional arguments for a nontectonic origin of surface displacements in Fremont Valley were summarized by *Clark et al.* [1978]. The fissure at site 4 formed between 1971 and 1975 (M. M. Clark, personal communication, 1979). A line of closely spaced bench marks was set and leveled in April 1978. As at site 3, level surveys did not extend to a demonstrably stable bench mark, so that changes of elevation are relative and not absolute. Relevelings of the line show that the fissure occurs at the point of maximum convex-upward curvature in the subsidence profile (Figure 3*e*). Computed horizontal strains at site 4 (Figure 3*e*), based on repeated measurements with an electronic distance meter, suggest that horizontal extension occurred at the point of maximum convex-upward curvature. Rebound from September 1978 to January 1979 provides further evidence that the surface displacements are related to declines of groundwater level rather than tectonism (Figure 3*f*). The rebound correlates with large water level recoveries observed on that side of the Garlock fault. Similar rebound occurred from September 1979 to February 1980, but the results are not shown. *Riley* [1969] documented elastic expansion of aquifers caused by water level recoveries, and the magnitude of the response observed here is consistent with such a mechanism.

DISCUSSION

Lee and Shen [1969] documented in both laboratory and analytical investigations that differential subsidence related to differential compaction causes horizontal strain. Where subsidence profiles are convex upward, horizontal strains are tensile, attaining maximum values at points of maximum curvature. The association of the earth fissures at sites 1 to 4 with zones of localized differential subsidence and their occurrence near points of maximum convex-upward curvature in the profiles indicate that the mechanism documented by *Lee and Shen* [1969] probably applies to these sites. This is the same mechanism proposed in concept by *Feth* [1951] to explain the 1949 fissure in south-central Arizona. Based on a geophysical

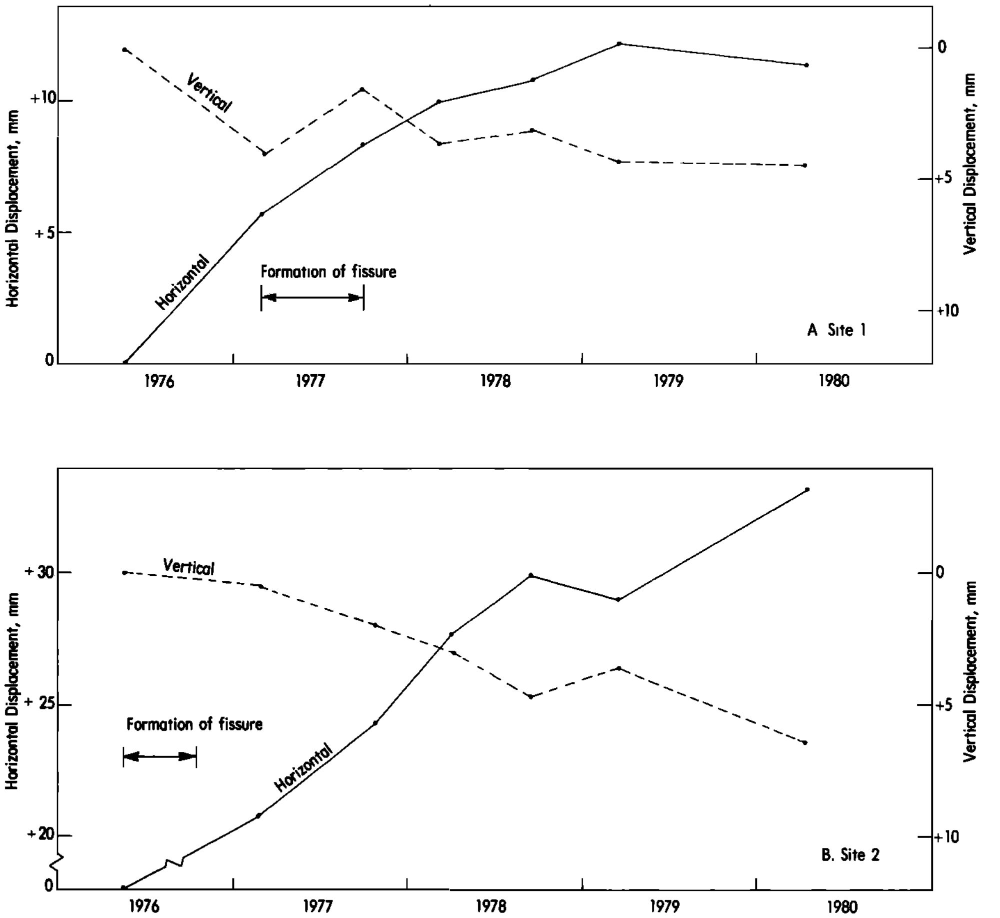

Fig. 4. Relative horizontal and vertical displacements of bench mark pairs spanning fissures at sites 1 and 2, Picacho Basin, Arizona. Displacement of basinward bench mark relative to bench mark closest to crystalline bedrock is shown (extension and subsidence are positive).

investigation of earth fissures in south-central Arizona, *Jachens and Holzer* [1979] concluded that many fissures there were located over convex-upward changes in slope of the bedrock surface buried beneath the alluvial aquifer. Sites 1 and 2 of this report correspond to their sites 4 and 5, respectively. Their results indicate that the differential subsidence observed at sites 1 and 2 is caused by differential compaction related to variations in aquifer thickness determined by depth to bedrock. Subsurface conditions at site 4 in the present investigation also indicate that differential compaction has caused the observed differential subsidence. *Koehler* [1977, Figure 3] inferred that the unconsolidated deposits forming the principal aquifer in Fremont Valley thicken northward across the Garlock fault, which is compatible with our subsidence profile. He also concluded that the Garlock fault is a partial groundwater barrier. During the period covered by our leveling, we observed greater water level declines on the downthrown, or north, side of the fault than on the upthrown side. Hence, differential compaction at site 4 may have been caused by a combination of different thicknesses of compressible materials and differential water level declines across the Garlock fault. Such conditions are similar to conditions identified by *Holzer* [1978*b*] along the trend of the fissure studied by *Feth* [1951] in Arizona. *Holzer* [1978*b*, p. 14] suggested that differential compaction occurred across a preexisting fault that was a partial groundwater barrier. No subsurface information is available

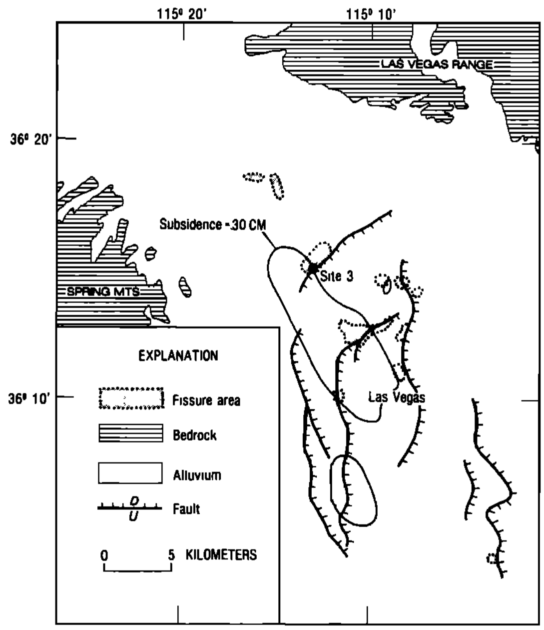

Fig. 5. Location of site 3, earth fissure areas, and preexisting fault scarps in Las Vegas Valley, Nevada. Line of 30-cm subsidence, 1963–1972, and faults from *Harrill* [1976]; earth fissure areas from *Patt and Maxey* [1978] and *Mindling* [1971].

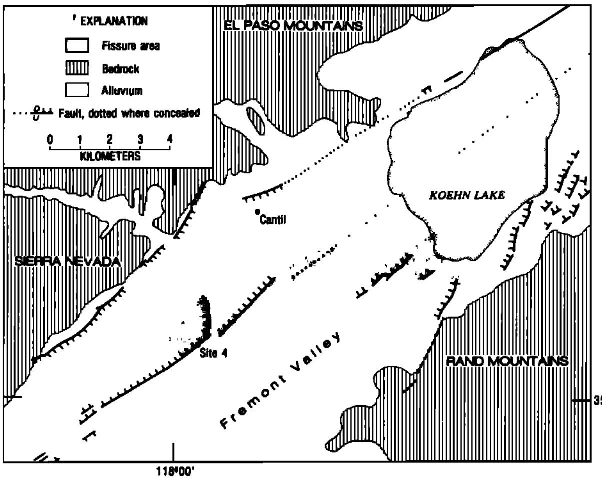

Fig. 6. Location of site 4, earth fissure areas, and preexisting faults in Fremont Valley, California. Faults modified from *Clark* [1973]; earth fissure areas based on unpublished data.

near the fissure system at site 3 in Las Vegas Valley. The fissure system occurs along the base of a preexisting fault scarp (Figure 5) and trends parallel to it.

Recognition that these four different sets of earth fissures are associated with zones of localized differential subsidence indicates a method, based on precise vertical control surveys of closely spaced bench marks, by which locations of potential earth fissures can be identified in areas with declining groundwater levels. Such surveys easily could be conducted near planned or existing major engineered structures as well as within urban areas where earth fissures are a potential hazard. The results presented here, obtained after only 2 years of monitoring, indicate that evaluations might be made after relatively short time periods. Whether this conclusion can be extended to all fissures in alluvium remains to be demonstrated. The fissures investigated here are linear to curvilinear; fissures forming polygonal patterns were not included in this study [e.g., *Holzer*, 1980]. Because such fissures are believed to form in response to soil moisture changes, it is not clear to us that differential subsidence would be associated with such fissures.

CONCLUSIONS

Earth fissures at four sites in Arizona, California, and Nevada 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. The differential subsidence probably was caused by differential compaction.

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