

Faulting Caused by Groundwater Level Declines, San Joaquin Valley, California

THOMAS L. HOLZER

U.S. Geological Survey, Menlo Park, California 94025

Approximately 230 mm of aseismic vertical offset of the land surface across the Pond-Poso Creek fault in the San Joaquin Valley, California, probably is related to groundwater withdrawal for crop irrigation. The scarp is approximately 3.4 km long and occurs in an area where the land subsided more than 1.5 m from 1926 to 1970. Modern faulting postdates the beginning of water level declines and associated subsidence. Movement detected by precise leveling surveys from February 1977 to March 1979 was seasonal, occurring during periods of water level decline. Fault offset was greater in the year with the lower seasonal low water level. The modern movement probably is caused by localized differential compaction induced by differential water level declines across the preexisting fault.

INTRODUCTION

Surface faulting is associated with land subsidence caused by groundwater withdrawal in Arizona [Holzer *et al.*, 1979], California [Clark *et al.*, 1978; Rogers, 1967], Texas [Kreitler, 1977; Van Siclen, 1967], and Mexico (G. Figueron Vega, oral communication, 1977). Although the relation between many of these surface faults and groundwater withdrawal is ambiguous because faulting caused by natural geologic processes cannot be excluded, some of this faulting is probably caused by the groundwater withdrawal. Arguments for a relation for individual faults include seasonal fault movement or correlation of fault movement with fluctuations of groundwater level [Holzer *et al.*, 1979; Nason *et al.*, 1974; Reid, 1973], temporal and areal association of modern surface faulting with groundwater withdrawal [Clark *et al.*, 1978; Holzer *et al.*, 1979; Lockwood, 1954], and restriction of modern subsurface fault offset to within the aquifer [Holzer *et al.*, 1979]. Because several of these surface faults have been demonstrated to connect to preexisting faults [Clark *et al.*, 1978; Holzer, 1978; Van Siclen, 1967; Woodward-Lundgren and Associates, 1974], man-induced declines of groundwater level may be capable of causing renewed movement on preexisting faults.

The Pond-Poso Creek fault is a preexisting fault in the southern San Joaquin Valley, California, along which modern aseismic surface faulting is occurring. Modern faulting is restricted to an area of land subsidence caused by water level declines and postdates the beginning of declines. Although modern movement has been attributed to tectonism, Holzer [1977] suggested that the movement might be related to groundwater withdrawal. In this report, measurements of fault movement and water levels are described that further support a relation between modern faulting and groundwater withdrawal. From February 1977 to March 1979 the fault moved at monitored sites only during periods of water level decline. During periods of water level recovery, fault movement ceased. In addition, annual fault offset was greater in the year with the lower seasonal low water level. Water level data and the estimated compressibility of the aquifer system suggest that the modern faulting was caused by differential compaction across a partial groundwater barrier associated with the Pond-Poso Creek fault zone.

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POND-POSO CREEK FAULT

The Pond-Poso Creek fault is a preexisting geologic fault that trends northwesterly for approximately 60 km from the eastern margin of the south San Joaquin Valley to near the center of the valley [Los Angeles Department of Water and Power, 1974]. The fault is exposed at the surface along its southeastern end, but elsewhere, except for the 3.4-km long scarp shown on Figure 1, is concealed by alluvium. Seismic reflection data collected in the vicinity of the active surface trace (Figure 1) indicate the Pond-Poso Creek fault in that area is an approximately 1-km-wide zone of four subparallel normal faults that trend northwesterly and dip from 50° to 70° to the southwest [Los Angeles Department of Water and Power, 1974]. Offset is greatest on the westernmost fault and decreases surfaceward. At a depth of 267 m, near the base of most irrigation wells in the study area, vertical offset across the westernmost fault is interpreted to be 15.2 m. Borehole data indicate the westernmost fault has caused approximately 11 m of offset of a distinctive clayey zone, identified as the Corcoran Clay Member of the Tulare Formation, at a depth of approximately 76 m [Los Angeles Department of Water and Power, 1974]. Total cumulative vertical offset of the Corcoran across the fault zone is estimated to be 24 m. The average rate of fault offset on the westernmost fault, since deposition of the Corcoran is less than 0.018 mm/yr based on an age of the clay of more than 600,000 years [Miller *et al.*, 1971]. Although the Pond-Poso Creek fault has been considered to be a capable fault, no historic earthquakes with magnitude greater than 4 can be associated with the fault [Los Angeles Department of Water and Power, 1974].

The modern surface faulting occurs on the northern part of the Pond-Poso Creek fault. Because the scarp formed by modern faulting (Figure 2) is continuously modified in cultivated areas between roads, the scarp is preserved only where it intersects paved roads and in a small uncultivated area immediately north of Peterson Road. Connection of these scarps suggests that a more than 3.4-km-long segment of the fault is active. Because the paved roads have been periodically regraded and resurfaced, total historic or modern offset of the land surface can be only estimated. An upper limit to historic offset as of 1974, however, was established by trenching of the fault between Elmo Highway and Peterson Road (Figure 2). At a depth of 3 m from the land surface, approximately 230 mm of vertical offset was observed [Los Angeles Department of

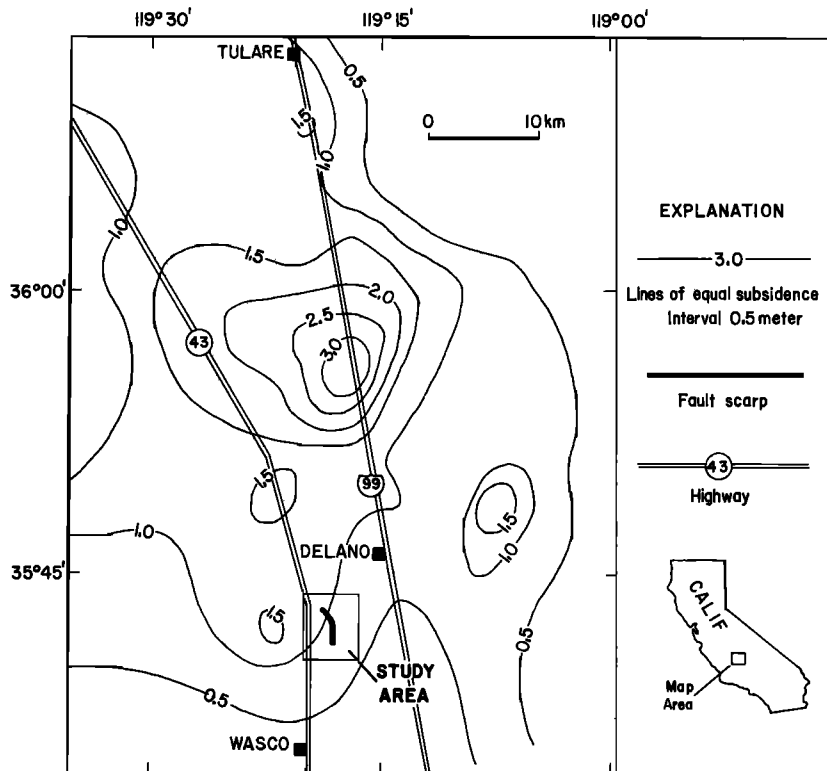


Fig. 1. Map of Tulare-Wasco, California, subsiding area, modern fault scarp formed by the Pond-Poso Creek fault, and study area. Land subsidence, 1948-1970, modified from Poland *et al.* [1975].

Water and Power, 1974]. This amount is compatible with estimates of total historic offset based on the regraded road surfaces. The date of the beginning of surface faulting can be established only approximately. A profile of the land surface in the uncultivated area north of Peterson Road, which was regraded in 1971 and left undisturbed, indicated 136 mm of fault offset as of September 1978. Based on the amount of offset observed in the trench and the average rate of fault offset determined from the height of the scarp at the creepmeter site, faulting is estimated to have begun in or after the late 1950's. This date is supported by the observation of county highway maintenance personnel that fault offset of paved roads was not noticed until sometime between 1956 and 1966 (H. Silva, oral communication, 1976) and by reports of local farmers that surface effects from faulting in cultivated areas were first noticed in the 1950's.

HYDROLOGY AND LAND SUBSIDENCE

The freshwater bearing zone in the study area is divided into a confined and an unconfined aquifer, and the Corcoran Clay is the principal confining bed between the two [Davis *et al.*, 1959]. The freshwater bearing zone is underlain by saline water at a depth of approximately 580 m [Page, 1973]. Groundwater production is restricted to above the interface between the freshwater and saltwater; most irrigation wells in the study area are less than 320 m deep. The confined aquifer is extensively developed for crop irrigation. The study area, however, also relies heavily on imports of surface water from the Friant-Kern Canal. Both the water table in the unconfined aquifer and the potentiometric surface of the confined aquifer have been significantly modified by groundwater withdrawals. Water surfaces in both aquifers in the study area

slope westward toward closed water level depressions west of the study area [California Department of Water Resources, 1977b]. Some of the history of groundwater development in the study area is reflected in the hydrograph of well 25/25-28R1 (Figure 3), which is perforated in the confined aquifer. The early history of groundwater development is poorly documented, but Mendenhall *et al.* [1916] reported that wells were free flowing in 1905. By the early 1930's, significant water level declines had occurred (Figure 3). After World War II the cultivation of new acreage requiring additional groundwater withdrawal accelerated the water level declines [Lofgren and Klausling, 1969]. With completion of the Friant-Kern Canal in 1951, groundwater pumpage and associated water level declines decreased relative to the postwar period. The hydrograph indicates that the long-term decline of water levels was not completely arrested in the study area by the surface water imports. The hydrograph of 25/25-28R1 also reveals that water levels in the confined aquifer fluctuate annually approximately 20 m, reflecting a strong seasonal demand for groundwater.

The study area lies within the Tulare-Wasco subsidence area, which is part of the extensive subsiding region in the San Joaquin Valley [Poland *et al.*, 1975]. Land subsidence caused by declining groundwater levels has been documented in the study area by Lofgren and Klausling [1969]. Based on maps of subsidence [Lofgren and Klausling, 1969; Poland *et al.*, 1975], approximately 2 m of subsidence occurred at the fault from 1926 to 1970. Slightly more than half of this subsidence is estimated to have occurred from 1948 to 1970 (Figure 1). Because of the large seasonal water level fluctuation in the Tulare-Wasco area, compaction causing the land subsidence is predominantly seasonal; most of the annual compaction occurs

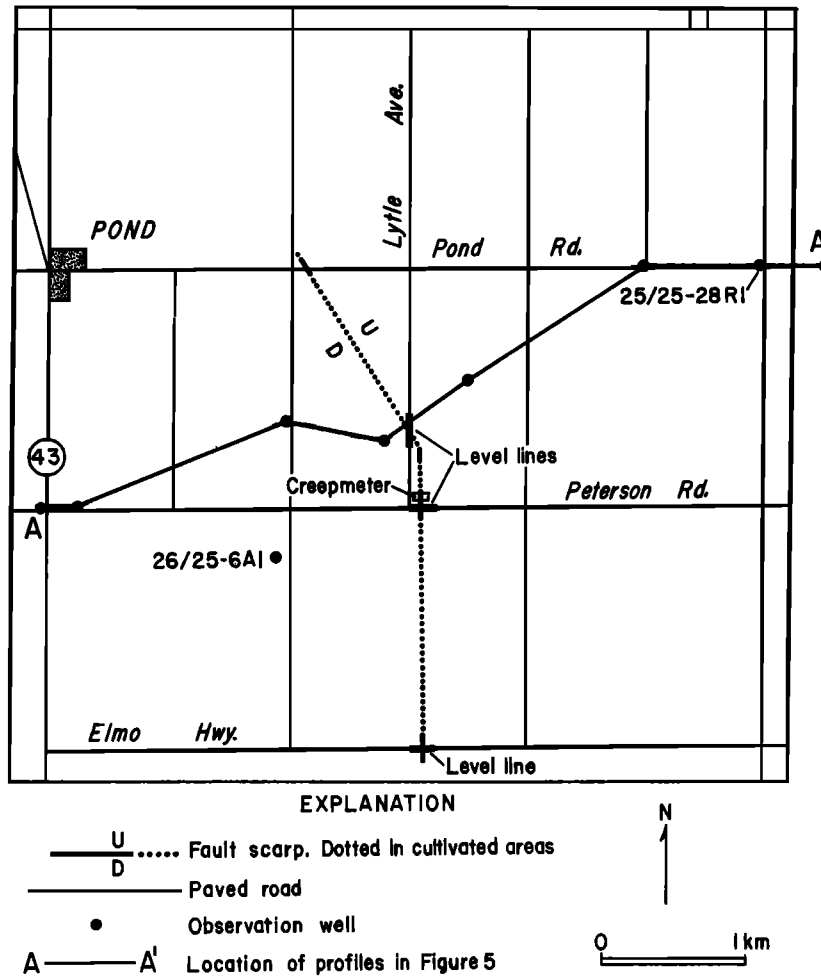


Fig. 2. Map of study area with modern fault scarp, fault monitoring sites, and wells referenced in text. See Figure 1 for location of study area.

during the summer period of groundwater withdrawal [Lofgren and Klausung, 1969].

FAULT MONITORING

Level lines to monitor fault movement were established in 1977 on three paved roads intersected by the modern fault scarp (Figure 2). Bench marks consisted of 64-mm-long P-K nails driven flush with the pavement along the center line of the roadways. Bench marks were spaced symmetrically about the surface scarp from 1.5 to 46 m from the scarp. All leveling before March 1978 was performed with a Jena Dahlta 010A theodolite and Philadelphia rod with a micrometer. Measurements were reproducible to 1 mm with this system. Leveling after February 1978 was performed with a Zeiss Ni-1 automatic level and invar survey rods, a system designed for precise geodetic leveling. In September 1977 a tiltbeam or creepmeter with a nominal sensitivity of 0.097 mm/m [Nason, 1971] was established across the fault 67 m north of Peterson Road (Figure 2). The creepmeter was read manually. Because the ends of the tiltbeam were 1.7 m apart, the tiltbeam presumably measured only vertical offset across the fault.

Results from monitoring are summarized in Figures 4a and 4b. Only measurements of differential vertical displacement of the bench marks closest to and on either side of the fault are shown because results from level lines indicated that adjacent

sides of the fault moved uniformly to a distance from the fault covered by the level lines. All of the records are dominated by fault movement during the summer months. The record at Elmo Highway is the longest and indicates 17.5 mm of fault offset, downthrown to the west, from May to September 1977 (Figure 4a). An additional 2 mm of fault offset may have occurred from September to November. From November 1977 to March 1979 no fault offset was detected. At Peterson Road,

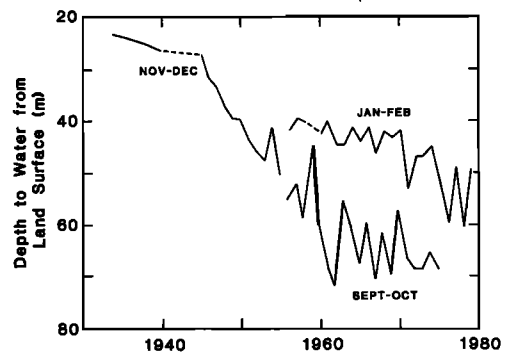


Fig. 3. Graph of water levels for different months in irrigation well 25/25-28R1 (see Figure 2 for location). January–February and September–October measurements are approximately the highest and lowest annual water levels, respectively.

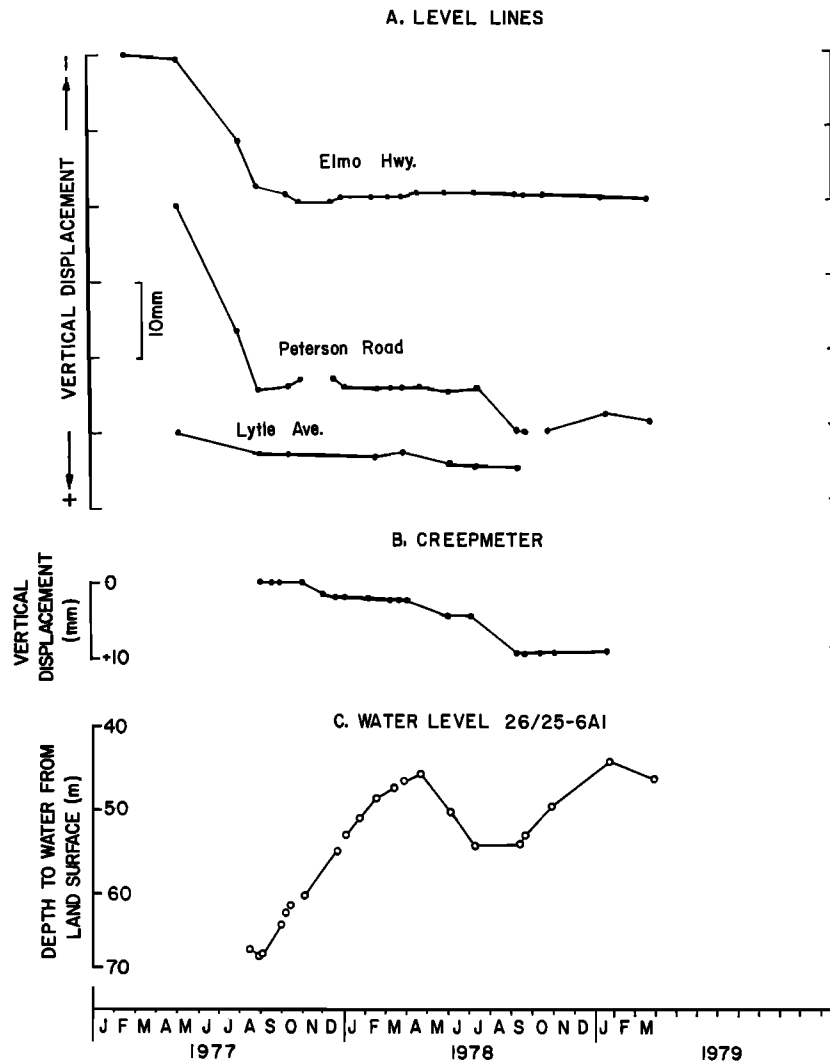


Fig. 4. Differential vertical displacement of bench marks ± 1.5 m from fault scarp at paved roads, February 1977 to March 1979 (increase in height of fault scarp is positive). (b) Creepmeter record, September 1977 to January 1979 (increase of height of fault scarp is positive). (c) Depth to water in well 26/25-6A1, August 1977 to March 1979.

monitoring began in May 1977. During the period from May to September 1977, contemporaneous with the surveys at Elmo Highway, 24.5 mm of fault offset, downthrown to the west, was measured (Figure 4a). From September to November, 1.5 mm of fault offset in an opposite sense to that of the summer may have occurred. The bench marks were subsequently destroyed and were reset in December 1977. No renewed offset was detected until the period from July to September 1978 when 5.5 mm of offset was measured. Taping between the bench mark pair across the fault at Peterson Road, accurate to 1 mm, detected no horizontal movement associated with the faulting in 1978. Measurements 8 days apart in September indicate that fault movement had halted prior to the date of the first measurement in September. Bench marks again were destroyed and were not reset until the end of October. Fault offset at Lytle Avenue from May 1977 to September 1978 was barely detectable. Approximately 3 mm of offset, downthrown to the south, occurred from May to September 1977 (Figure 4a). Results from the creepmeter (Figure 4b), 67 m north of Peterson Road, are in approximate agreement with the results from the monitoring at Peterson Road. The offset of 1.8 mm measured by the creepmeter in November-December

1977 occurred during the recordless period at Peterson Road and hence was not confirmed by independent measurements. The piers of the creepmeter consisted of steel rods driven to only 1.4 m and supported laterally to a depth of only 1.1 m by concrete. Hence the November-December movement detected by the creepmeter may have been a consequence of settlements caused by the nature of the installation itself. The offset of 1.9 mm detected at the creepmeter from April to May 1978 was not confirmed by measurements

TABLE 1. Annual Surface Water Deliveries to Study Area From Friant-Kern Canal

Year	Delivery
1970	18.50
1971	16.74
1972	14.61
1973	15.24
1974	17.15
1975	17.56
1976	6.88
1977	3.65
1978	12.62

In 10^6 m³.

at Peterson Road which casts suspicion on its origin as well. Offset of 5.0 mm from June to September agrees with the measurement at Peterson Road. The creepmeter was disabled after January 1979.

WATER LEVEL MONITORING

Water levels in both domestic and irrigation wells were measured in the study area. In addition, the water level in an abandoned irrigation well was measured during each geodetic survey. Irrigation wells in the study area in general are perforated in the confined aquifer. Domestic wells, in general, are completed in the water table aquifer.

The seasonal variation of water levels was monitored by repeated measurements in an abandoned irrigation well, 26/25-6A1, approximately 1 km west of the fault scarp (Figure 2). Records on file with the California Department of Water Resources report that the well is perforated from 61 to 213 m. In addition to showing a large seasonal fluctuation of water level the hydrograph (Figure 4c) also illustrates the effect on water levels from a drought in the mid-1970's. In 1976 and 1977, imports of surface water via the Friant-Kern Canal were greatly curtailed by the drought (Table 1) and the deficiency was made up by pumping groundwater. In 1978 the return of surface water supplies to their predrought quantities reduced groundwater withdrawals. The slightly smaller delivery of surface water in 1978 relative to pre-1976 deliveries (Table 1) was caused by abnormal spring and fall rainfall in 1978 that reduced the demand for surface water. In response to decreased groundwater production following the drought the lowest water level measured in 1978 was 14.0 m higher than the lowest water-level measured in 1977.

Water levels were measured in 26 accessible wells in January 1978 and 21 wells in July 1978. Less complete surveys were conducted in September 1978 and January 1979. With a few exceptions, when measurements were separated according to the principal aquifer tapped by the well, water levels were consistent for each aquifer. Water levels in wells reported to be perforated in both aquifers, in general, were consistent with water levels in wells reported to be perforated only in the confined aquifer. In January 1978 the difference between water levels in shallow and deep wells, i.e., wells tapping the unconfined and confined aquifers, respectively, was approximately 35 m. The potentiometric surface for the confined aquifer, shown in an east-west profile in Figure 5, sloped in a westerly direction. During the summer of 1978, water levels in

deep wells on the west side of the fault scarp declined approximately 12 m as contrasted with declines of 3 m or less on the eastern side of the fault scarp. This response, in part, was caused by the distribution of pumping during the summer. The area west of Highway 43 (see Figure 2), although under cultivation, received negligible surface water and hence was largely dependent on groundwater. Pumping in 1978 east of Highway 43 in the study area was minor. Despite the large declines measured in the deep wells, water levels in shallow wells changed less than 1 m from January to July.

DISCUSSION

Movement of the Pond-Poso Creek fault in 1977 and 1978 only during the summer period of groundwater withdrawal suggests a relation between modern faulting and declines of groundwater level. Comparison of the records of fault movement with the hydrograph of monitor well 26/25-6A1 further supports such a relation (Figure 4). In both 1977 and 1978, fault movement essentially stopped during periods of water level recovery. The greater amount of fault movement in 1977 relative to 1978 also is consistent with the water level observed in the monitor well. The seasonal low water level was 14.0 m lower in 1977 than in 1978, indicating greater stressing of the system in 1977.

These observations, which suggest that the modern faulting is related to water level declines, do not by themselves indicate the specific mechanism of faulting. For example, a minor reduction of horizontal stress at a normal fault already near failure could trigger fault movement. Although this mechanism cannot be excluded, water level and aquifer compressibility data suggest that differential compaction localized across the Pond-Poso Creek fault is a more likely mechanism. A fault-controlled partial groundwater barrier is suggested by the 20-m difference of water levels across the fault zone observed in irrigation wells in July 1978 (Figure 5) and by matching to historical water levels, groundwater levels computed by a digital computer model of the confined aquifer system [California Department of Water Resources, 1977a]. In addition, a water level difference of 9.1 m localized across the modern scarp was reported in closely spaced, undeveloped, 152-m deep exploratory test holes drilled in 1974 [Los Angeles Department of Water and Power, 1974]. Based on an appropriate ratio of subsidence to water level decline of 0.03 [Lofgren and Klausung, 1969, Figure 69], a water level difference localized across the preexisting fault of only 7.8 m would be required to cause the 230 mm maximum possible historic fault offset as of 1974.

The record of fault movement on the Pond-Poso Creek fault and the presence of a preexisting fault inferred to be a partial groundwater barrier are similar to conditions reported by Holzer [1978] and Holzer et al. [1979] at the Picacho fault in southcentral Arizona, a fault on which modern movement was attributed to groundwater withdrawal. In those studies it also was concluded that observed seasonal movement was caused by localized seasonal differential water level declines across a preexisting fault. The record of fault movement on the Pond-Poso Creek fault also is similar to some of the records of movement on faults in the Houston, Texas, subsidence area. Some but not all of the movement on monitored faults there correlated with water level fluctuations [Gabrysch and Holzer, 1978; Kreitler, 1977; Reid, 1973]. Evidence for fault-controlled partial groundwater barriers there is inconclusive

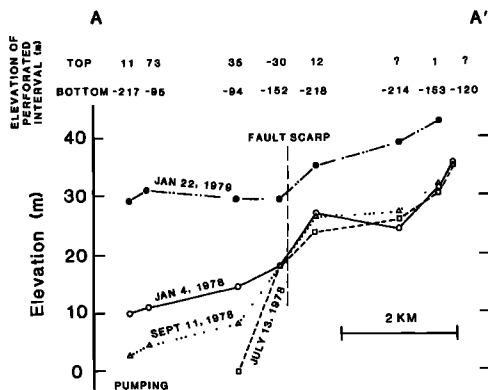


Fig. 5. Profiles of water levels in irrigation wells, January 1978 to January 1979. Elevation (in meters) of top and bottom of reported perforated interval in each well is shown. Top of confined aquifer is approximately at mean sea level. See Figure 2 for location of profiles.

(see Kreitler [1977] and Gabrysch and Holzer [1978] for discussion of the evidence).

CONCLUSIONS

Modern offset of approximately 230 mm since the 1950's on the Pond-Poso Creek fault is temporally and areally correlated with man-induced water level declines. Fault movement from February 1977 to March 1979 was seasonal, occurring during annual periods of water level decline. In addition, fault offset was greater in the year with the lower seasonal low water level. Based on these observations, modern faulting probably is related to declines of groundwater level. Seasonal differential water level declines observed across the preexisting fault zone suggest that the fault is a partial groundwater barrier. A localized differential decline directly beneath the modern scarp is suggested by water levels measured in undeveloped test holes. If such localized declines have occurred, then localized differential compaction across the preexisting fault may be the cause of the modern fault movement.

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