PREEARTHQUAKE AND POSTEARTHQUAKE CREEP ON THE IMPERIAL FAULT AND THE BRAWLEY FAULT ZONE[1]

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ABSTRACT

Taken together, 12 years of alinement-array data, 4 years of creepmeter records from four instruments, and 2 years of surveys from two nail files suggests that creep events on the Imperial fault 2 to 5 months before the October 15 earthquake are consistent with long-term trends and not indicative of any imminent event. No discernible creep occurred on the fault in the hours and days before the earthquake. Records of coseismic displacement imply that response of the soil to the fault slip at depth was brittle rather than plastic; they uniquely demonstrate that the minimum rate of surface fault displacement was 1.8 cm/s. Continuing measurements of afterslip show that all motion is due to discrete 0.2- to 1.5-cm creep events occurring less frequently over time. The accumulating displacement for the first 35 days after the earthquake is well approximated by linear logarithmic functions of time. Use of this accumulating displacement to predict future slip rates implies that for 6 years the afterslip rate from the 1979 earthquake should be greater than the 0.5-cm/yr average preearthquake creep rate. The maximum amount of slip on the surface trace of the Imperial fault associated with the 1979 earthquake, including afterslip, amounts to more than 60 cm.

INTRODUCTION

The earthquake of October 15, 1979, was associated with surface faulting along the Imperial fault for a distance of about 30 km. Surface faulting occurred simultaneously in the Brawley fault zone, and slip was triggered on the Superstition Hills fault and the southernmost segment of the San Andreas fault (Fuis, this volume; Sieh, this volume).

The Imperial fault and the Brawley fault zone together make up one of two segments of the San Andreas fault system where aseismic creep is known to occur regularly (Brune and Allen, 1967; Allen and others, 1972; Sharp, 1976; Goulty and others, 1978). The other segment is a 300-km-long zone in central California composed principally of the San Andreas, Calaveras, and Hayward faults (Nason, 1973). The first instrumentally observed creep on the Imperial fault was recorded at Worthington Road in 1967, where an alinement array had been installed across the fault in May 1967 and was repeatedly resurveyed (Allen and others, 1972; Goulty and others, 1978).

The Imperial fault has since been monitored for creep with a series of four fault-crossing alinement arrays. In 1975 three creepmeters were installed across the Imperial fault, and a fourth across the Brawley fault zone. These creepmeters have shown that the creep is episodic and occurs in 1- to 2-cm creep events at approximately 2-year intervals on the central segment of the Imperial fault in California (Goulty and others, 1978).

The 1979 Imperial Valley earthquake was associated with surface faulting primarily on the segment of the Imperial fault covered by the system of creepmeters and alinement arrays. This system provides a unique combination of observations of preearthquake creep, coseismic offsets, and continuing aftercreep.

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INSTRUMENTATION

Slip on the Imperial fault and in the Brawley fault zone has been monitored since October 1975 by four continuously recording taut-wire creepmeters (fig. 118). Each of these instruments initially utilized an Invar wire suspended between an anchor on one side of the fault and a tensioning device anchored on the opposite side. The wire passes through a buried pipe and intersects the fault at 45°. Failure of the Invar wires due to corrosion led to their replacement in 1978 with durable, but thermally more sensitive, stainless steel. The

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creepmeters at Heber Road and the Tuttle Ranch, each spanning 20 m, use a micrometer screw to measure motion and a linearly variable differential transformer as a transducer for the continuous-strip-chart recording system, as described by Yamashita and Burford (1973). Those at Ross Road and Harris Road, spanning 20 m and 12 m, respectively, employ direct reading by a dial-gage micrometer and a continuous-rotation deposited-film potentiometer as the displacement transducer for the recording system, similar to the design described by Smith and Wyss (1968). Servicing and reading of these instruments typically has taken place at 3-month intervals.

All the instruments are limited to a maximum range of about 2.5 cm and, where possible, are installed so that dextral fault motion increases the separation between piers. Stretching of the wire thus appears as sinistral motion that is easily distinguished from dextral-creep signals. When the 2.5-cm range is exceeded, the wire may stretch, break, or slip in its clamp, and so the record of that and later events is lost. Such a breakdown occurred during the 1979 Imperial Valley earthquake at the Heber Road and Ross Road sites, where coseismic motion was probably several tens of centimeters, and once subsequently at Ross Road between service calls.

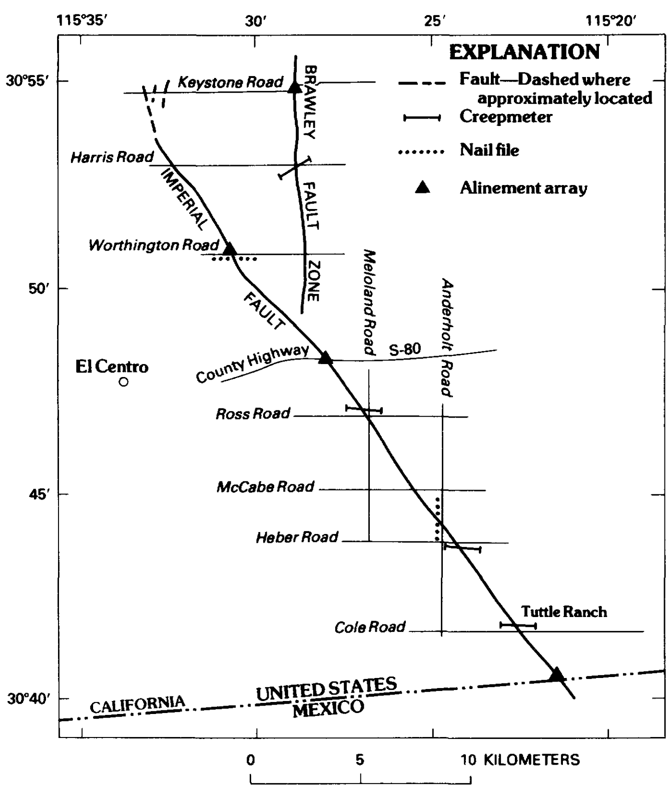

FIGURE 118.—Locations of creepmeters and nail files on Imperial fault and in Brawley fault zone in Imperial Valley.

At two other sites along the Imperial fault, nail files were installed in late 1977. Each nail file comprises seven steel studs embedded initially in a straight line at 4.6-m intervals along the edge of the pavement where the fault crosses the road; thus, roughly half the studs are on either side of the fault. The nail files are surveyed by measuring the deviations of intermediate studs from a line joining the end points. In our analysis of the nail-file measurements we assume that rigid motion between the end points of the nail file (approx 28 m) is taken up entirely on the fault surface. Uniform shear between end points, however, would not be detected and would make the measured offset values smaller than the actual relative motions of the end points.

The nail files were regularly resurveyed at 3-month intervals and beginning 8 hours after the 1979 earthquake, and have since been resurveyed much more frequently. At first, the nail files were resurveyed by stretching a fine wire between the end points and measuring the deviation of each intervening point with a rule. On calm days this technique gives reproducible readings to ±0.1 cm of resolved fault motion, although a moderate breeze may reduce the precision to ±0.3 cm. This difficulty has led to using a theodolite to measure deviations from the line defined by the wire in the previous method, thus avoiding wind contamination while retaining the ease and speed of measurement that initially made this method of monitoring fault slip attractive.

More cumbersome to resurvey and analyze, fault-crossing alinement arrays afford information on deformation that may be distributed outside the base line of a nail file. Several alinement arrays across the Imperial fault and the Brawley fault zone, with base lines of approximately 75 m, have been maintained and resurveyed at least once every year since 1968 (Goulty and others, 1978). Results from these arrays relevant to the 1979 earthquake will be reported at a future date.

PRESEISMIC CREEP

Creep records (fig. 119) for the 4 years preceding the 1979 earthquake show that creep was sporadic in the central part of that segment of the Imperial fault exhibiting earthquake-associated surface displacement. No slip was observed during the first 18 months of instrument observation; then, during several days in April 1977, 1 to 2 cm of dextral slip was observed on both the Ross Road and Heber Road creepmeters (Goulty and others, 1978). These events were followed by almost 2 years of quiescence, when the two nail files were added to the array. Then, between June 15 and November 27, 1978, 1.5 cm of dextral creep occurred at Worthington Road, followed by 1.3 cm at Ross Road on May 23, 1979; 0.6 cm at Anderholt Road between November 30, 1978, and August 20, 1979; and two slip events at Heber Road, on May 27, 1979 (sinistral event discussed below), and August 2, 1979, that produced 0.4 cm of net dextral offset. Whereas the creep sequence in 1977 proceeded from south to north on the Imperial fault, this later sequence began in the north and apparently propagated southward, although the time of creep on the Anderholt Road nail file is not well constrained. In 4 years of creepmeter records, more than 90 percent of the total recorded creep is accounted for by discrete creep events, each of which exhibited several hours of accelerating displacement, 1 to 2 hours of fast creep producing 75 percent of the total slip, and a deceleration phase lasting as long as a day until it was buried in the thermal noise of the instrument. This pattern was empirically described by Crough and Burford (1977).

The creepmeter records show two well-defined episodes of motion on the Imperial fault. Although the second episode occurred 2 to 5 months before the earthquake (fig. 119), these motions cannot properly be construed as precursory indications of the imminent earthquake. The alinement array at County Highway S–80, which was installed in 1967 and has been resurveyed regularly, has shown four intervals of motion during the past years that range from 1 to 2 cm in amplitude and 2 to 4 years in separation (fig. 120). Thus, on the basis of this longer, though discontinuous, record, the recorded creep events in May and August 1979 are consistent with the observed frequency and amplitude of creep episodes on the Imperial fault for the 12 years before the earthquake.

The creepmeter records for the 10-day period immediately before the earthquake also preclude precursory surface motions. Figure 121 shows about 2 days of record from the Tuttle Ranch, Heber Road, and Harris Road creepmeters for the period beginning 30 hours before the earthquake; the record from the Ross Road instrument was lost owing to recorder malfunction. None of the records shows any unusual signals before the earthquake-induced offset, which starts instantaneously on each record.

The 0.12-cm sinistral signal on the record from the Heber Road creepmeter for May 27, 1979, mentioned above, occurred over a 16-hour period; displacement is

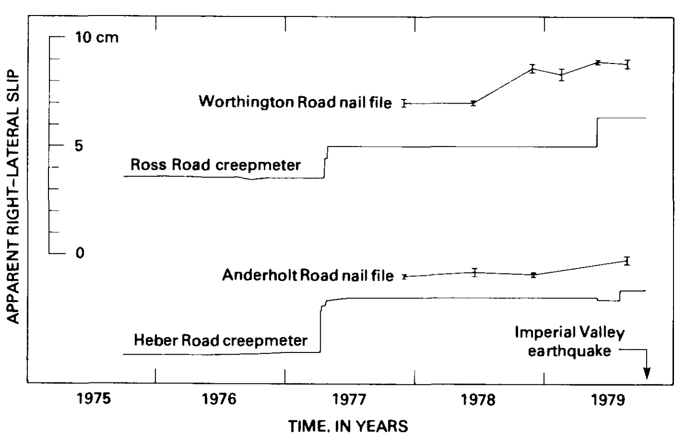

FIGURE 119.—Creep on Imperial fault before 1979 earthquake as a function of time at two creepmeter sites and along two nail files. All traces plotted on same scale; sequence of sites from north to south is displayed from top to bottom (see fig. 118 for location). Nail files show error bars.

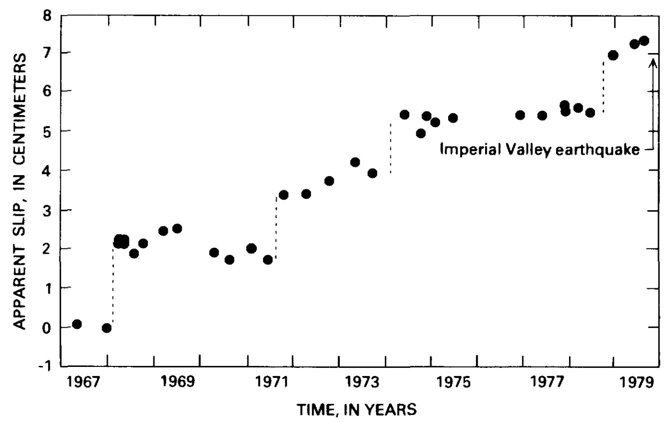

FIGURE 120.—Creep events between 1967 and 1979 at County Highway S–80 alinement array. Extended from Goulty and others (1978).

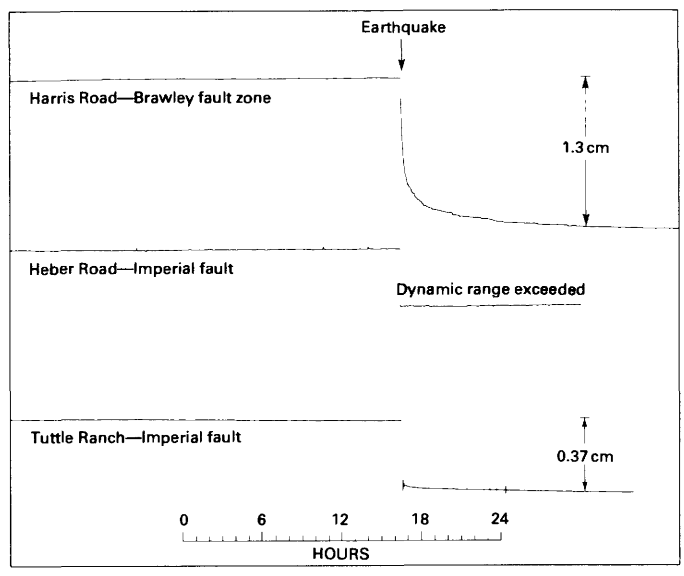

FIGURE 121.—Traced copies of records from creepmeters on Imperial fault and in Brawley fault zone, showing October 15, 1979, earthquake, displayed with same time scale. Records indicate quiescence on faults before event. Instruments on Imperial fault show that surface faulting was instantaneous, within resolution of instruments. Record for Brawley fault zone shows that slip behavior at surface resembled creep.

distributed more evenly over time than a typical dextral-creep signal. This event is probably real because nothing within the instrument has been known to produce such a signal, although it may represent a compressive strain of 6×10^{-5} rather than actual slip on the fault, because the effects would be instrumentally indistinguishable. This much strain is large but appears reasonable from initial studies, in which case the event may be related to deep-seated processes that also produced the 1.3-cm dextral event at Ross Road 4 days earlier.

Thus, although creep events occurred on the Imperial fault at no less than three sites within 6 months before the earthquake, we consider these events to be consistent with the observed long-term pattern of creep and not to be precursory indicators of the earthquake.

COSEISMIC DISPLACEMENT

Coseismic displacement of at least several centimeters occurred at the surface along most of the Imperial fault in California during the 1979 earthquake. Because the dynamic range of the creepmeters deployed along the fault is about 2.5 cm (3.5 cm of motion resolved on the fault), the instruments in the central segment of the fault were broken immediately by slip on the fault. However, the displacement at the Tuttle Ranch, near the southernmost extent of observed surface offset, was only 0.37 cm, and the instrument was able to continue in operation. We note in figure 121 that the Tuttle Ranch creepmeter record shows 12 minutes of shaking from seismic waves of the main event and first aftershocks, entirely confined to the period after the offset. The record was drawn by an Esterline Angus impact-type recorder on pressure-sensitive paper; an impact mark is made every 2 s. The presence on the original record (not shown in fig. 121) of only three impact marks that could have been made during the offset implies that the offset occurred in less than 8 s. The shaking observed from three subsequent aftershocks confirms that the creepmeters record strong surface waves. This behavior is important because the instruments have no other time base than the somewhat variable chart-recorder speed, and thus events can be precisely related in time only from the record of ground shaking.

The Heber Road creepmeter record displays an instantaneous offset without any intervening stray marks or evidence of shaking before the offset. Therefore, we conclude that at least 3.5 cm of motion occurred on the fault within 2 s at most before the arrival of strong shaking. This result is not surprising, in that particle velocities of many tens of centimeters per second would be expected and were in fact observed at the nearby Imperial Valley College (Thomas Heaton, oral commun., 1979). However, the record implies that the rupture propagated upward to the surface at about the shear-wave velocity and that the soil failure was brittle and in concert with the underlying rock, rather than plastic and delayed, as has been observed with creep (Goulty and Gilman, 1978). This record comes closer to measuring the actual rate of surface fault displacement than any other known observations.

No coseismic record was obtained from the Ross Road creepmeter owing to previous chart-recorder malfunction.

The creepmeter record at Harris Road, within the Brawley fault zone, is shown at the top of figure 121. The 1979 motion in the Brawley fault zone was principally vertical, downward on the west side. The Harris Road instrument is installed backward owing to siting restraints (see fig. 118), and dextral motion corresponds to contraction of the instrument. Thus, vertical motion on the fault would appear as sinistral motion on the record but would be recorded at much lower gain because the angle between the fault and the wire is close to 90° for that component of slip. The record shows contraction that represents primarily the dextral component of a principally vertical displacement. Fortuitously, the signal amounts to only 1.3 cm, and so the instrument remained on scale. Except for the instantaneous start of the event, again before the recording of ground shaking, the record is identical to that of creep events at other times at Ross Road (fig. 122; Goulty and others, 1978). This result suggests either that the soil did not accurately follow the motion of the rock at depth or that the motion at depth was actually a triggered creep process associated with the earthquake.

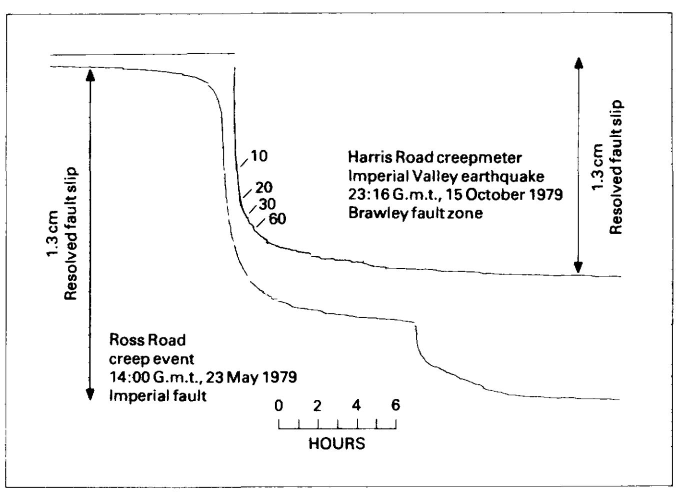

FIGURE 122.—Signal at Harris Road in Brawley fault zone, showing movement associated with earthquake (upper curve), in comparison with creep event recorded 5 months earlier at Ross Road on Imperial fault (lower curve), shown at same time scale. Numbers on upper curve indicate minutes after onset of displacement, determined from original record.

In summary, the recorded surface motions on the faults indicate several modes of behavior. At Heber Road the soil apparently failed by brittle fracture that suggests elastic response and presumably accurately reflects the underlying rock displacement. In contrast, all but 7 percent of the slip in the Brawley fault zone appears to be better characterized as creep triggered by the earthquake.

POSTSEISMIC CREEP

Afterslip on the Imperial fault from the 1979 Imperial Valley earthquake has been monitored by three techniques. Figure 123 shows the records from two creepmeters and two nail files, all in the aftercreep zone. Data from four fault-crossing alinement arrays, which should make a significant contribution to the other studies, are currently being studied.

The Worthington Road and Anderholt Road nail files were resurveyed 8 and 19.5 hours after the earthquake, respectively, and subsequently were resurveyed six more times in the month following the earthquake. Repair and resetting of the creepmeters at Heber Road and Ross Road was impractical during the first week after the earthquake because the creep rate was so high that the instruments would have required almost daily servicing, owing to their limited 2.5-cm range. The creepmeters were placed back in service on October 23 and 24, 1979, and have since been maintained as necessary.

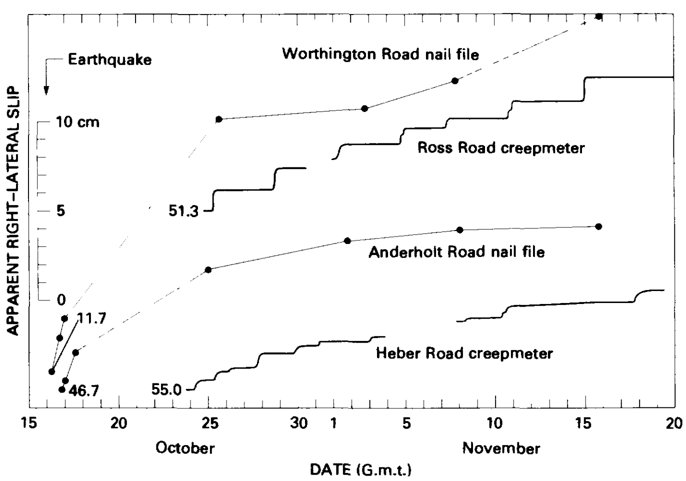

FIGURE 123.—Creep on Imperial fault after earthquake, recorded by creepmeters and nail-file surveys. All traces are shown on same scale; sequence of sites from north to south is displayed from top to bottom (see fig. 118 for locations). Numbers next to each trace indicate offset (in centimeters) accumulated between preearthquake period and time of first measurement after earthquake. For creepmeters, offset values are calculated from preliminary results of mekometer-network surveys (Chris Crook and Peter Wood, oral commun., 1979). Drafting of individual creep events is illustrative but does not necessarily accurately represent displacement histories.

Figure 123 illustrates the history of displacement as a result of creep on the Imperial fault for the first 35 days after the earthquake. The nail files permit an absolute determination of the total offset that occurred between August 20, 1979, and the postearthquake resurveys. Total-offset data were not available from the creepmeters because the range of each had been exceeded. We instead relied on preliminary data reductions of mekometer surveys (from trilateration networks across the fault) near the creepmeter sites to recover the extent of cumulative offset before restarting the instruments (Chris Crook and Peter Wood, oral commun., 1979). We also used these data reductions to recover the amount of offset between October 31 and November 1, 1979, when the range of the Ross Road creepmeter was exceeded between service trips. This procedure is justified by the close agreement between these two measurements where both data sets are complete. The hiatus in the Heber Road creepmeter record represents only a failure in the chart recorder. The amount of total motion was obtained from micrometer measurements made with the instrument itself.

Both creepmeter records show that virtually all the accumulating creep is due to discrete events, each lasting about 1 day, and that most of the displacement occurred during 1- to 2-hour periods. At Ross Road the events are all 1 ± 0.5 cm in amplitude and show no trend in size as a function of time; the events simply occur less frequently with increasing time. The same effect was observed at Heber Road, although the amplitude is smaller (0.5 ± 0.3 cm) and events are more frequent.

Displacement as a function of time for the two nail files, for which the longest span of observations is available, is well represented by linear functions of $\log_{10} t$, where t is the postearthquake time. A similar relation was observed for the 1966 Parkfield, Calif., earthquake by Smith and Wyss (1968). Figure 124 plots the displacement on the Anderholt Road and Worthington Road nail files as a function of the logarithm of postearthquake time (in hours). The two dashed lines, described by the equations

$$\text{Disp}=44+8.5\log_{10} t$$

and

$$\text{Disp}=3+8.7\log_{10} t,$$

approximate the observed displacements for Anderholt Road and Worthington Road, respectively, during the first 5 months after the earthquake. Interestingly, the coefficients of $\log_{10} t$ are very near the values observed by Scholz and others (1969) for displacements during the first 2 years after the 1966 Parkfield earthquake. This result suggests that we may use these equations to predict crudely the average creep rate for at least the next few months. If these relations are projected far into the future, using the slower Anderholt Road creep rate and a background preearthquake creep rate of about 0.5 cm/yr (see fig. 120), then the projected aftercreep rate on the Imperial fault associated with the 1979 earthquake will take at least 6 years to fall below the average creep rate observed during the past 12 years.

Including the relatively small amount of projected afterslip, the 6-year total displacement associated with the 1979 earthquake on the surface trace of the Imperial fault has the following values:

Locality	*Displacement (cm)*
Worthington Road	50
Ross Road	72
Anderholt Road	80
Heber Road	79
Tuttle Ranch (Cole Road)	1

In the area where major slip occurred, the sites with the smallest offsets (Worthington Road and Ross Road) show the highest aftercreep rates (fig. 123). The offset values converge to approximately 50 to 80 cm; thus, the surface may be catching up with the more evenly distributed slip at depth.

In summary, we have documented the aftercreep from the 1979 Imperial Valley earthquake at these sites entirely as discrete events of rather uniform amplitude that occur with such decreasing frequency that the total displacement is presently well fitted by linear functions of $\log_{10} t$. Projecting the creep rate into the future suggests that afterslip from the earthquake should dominate creep processes on the Imperial fault for at least the next 6 years

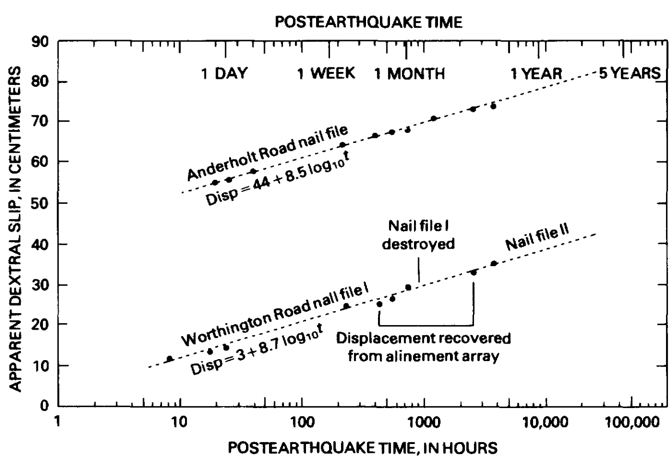

FIGURE 124.—Displacement (Disp) on Anderholt Road and Worthington Road nail files as a function of postearthquake time (t). Fix of regression lines suggests that approximate creep rates may be predicted at least several months in advance.

CONCLUSIONS

1. Creep events observed at three sites on the Imperial fault 2 to 5 months before the 1979 Imperial Valley earthquake are consistent with the long-term pattern of creep on the fault and do not qualify as anomalous behavior precursory to the earthquake.
2. No creep was observed at any of the sites on the Imperial fault or in the Brawley fault zone during the 10 days preceding the earthquake.
3. The coseismic surface displacements on the Imperial fault started at or before the arrival of heavy shaking and proceeded faster than 1.8 cm/s. The coseismic surface displacements in the Brawley fault zone started at or before the arrival of heavy shaking but proceeded at a slower, exponentially decaying rate. The displacement history several seconds after the initiation of motion is virtually identical to that seen in regular creep events.
4. Afterslip on the fault amounted to as much as 20 cm during the 35-day period beginning 8 hours after the earthquake. This aftercreep, where recorded by creepmeters, occurred in discrete creep events of 0.2- to 1.5-cm amplitude.
5. The total afterslip as a function of time is approximated well by linear functions of $\log_{10} t$. Projection of the observed creep rate into the future implies that the rate of aftercreep associated with the 1979 earthquake will be greater than the average preearthquake creep rate for the next 6 years.
6. The total surface slip on the Imperial fault associated with the earthquake, including projected afterslip, should accumulate to between 50 and 80 cm at Worthington Road, Anderholt Road, Ross Road, and Heber Road.

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The Imperial Valley, California, Earthquake of October 15, 1979

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