1855 and 1991 Surveys of the San Andreas Fault: Implications for Fault Mechanics

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Abstract

Two monuments from an 1855 survey that spans the San Andreas fault in the Carrizo Plain have been displaced 11.0±2.5m right-laterally by the 1857 Fort Tejon earthquake and associated seismicity and afterslip. This measurement confirms that at least 9.5±.5 m of slip occurred along the main fault trace, as suggested by measurements of offset channels near Wallace Creek. The slip varied by 2 to 3 m along a 2.6 km section of the main fault trace. Using radiocarbon dates of the penultimate large earthquake and measurements of slip in 1857, we calculate a slip rate for the last complete earthquake cycle that is at least 25% lower than the late Holocene slip rate on the main fault trace. Comparison of short term broad aperture strain accumulation rates with the narrow aperture late Holocene slip rate indicates that the fault behaves nearly elastically over a time scale of several earthquake cycles. Therefore, slip in future earthquakes should compensate the slip rate deficit from the 1857 earthquake. An elastic model that is consistent with our observations suggests that the Wallace Creek slip deficit extends to a depth of at least 1-2 km.

Introduction

Models of earthquake recurrence, calculations of earthquake probability, and theories about the behavior and segmentation of strike-slip faults are often based on estimates of fault slip from measurements of offset landforms. Measurements of late Holocene slip rate and small offset stream charnels near Wallace Creek (figure 1) have led some to argue that the San Andreas fault there has recurrence intervals of 240 to 450 years. These unusually long intervals result from unusually large (9.5 to 12.3 m) offsets, the smallest of these (9.5m) being ascribed to the latest large earthquake in

1857 (Sieh and Jahns, 1984; Sieh *et al.*, 1989). It is difficult to prove that each offset corresponds to one earthquake, however. In fact, several channels 2-5 km southeast of Wallace Creek, which are offset only 6-7 m (Grant and Sieh, 1993), suggest that either dextral slip varied from 6 to 10 m within a few kilometers along strike during the 1857 earthquake, or that the individual offsets near Wallace Creek were actually formed by multiple earthquakes. This latter possibility could mean that the time between at least some past earthquakes was less than 240 years and that the maximum slip in 1857 may have been less than 9.5 m (Grant and Sieh, 1993).

To resolve this ambiguity and measure directly the amount of slip from the 1857 earthquake we recovered original monuments from an 1855 survey spanning the San Andreas fault near Wallace Creek and resurveyed them with the Global Positioning System (GPS). From these measurements and other observations we have inferred characteristics of the fault over one earthquake cycle and discuss them in relation to long-term properties of the fault.

The Rectangular Survey System

The rectangular survey system was established by the United States in 1785 to facilitate settling land in the western territories (White, 1983). Land was divided into townships 6 miles square by lines oriented east-west (township lines) and north-south (range lines) with corrections for magnetic declination (White, 1983). Townships were subdivided into 36 sections, each 1 mile square. In the mid-to late-1800's the land in the Carrizo Plain and Temblor Range was divided into townships and subdivided into sections. James E. Freeman sectioned and surveyed the land near Wallace Creek in 1855 and 1856. Freernan also surveyed township boundaries in the Temblor

Range in 1855 (figure 2). These townships were later subdivided by other surveyors.

During the 1800s surveyors used chains to measure horizontal distances. The chains *were* kept level and under tension during the surveys. The method of chaining is of low but sufficient accuracy to estimate line length changes of a few meters for a one mile section line. Distances were measured by a chain 66 feet (20.12m) long with 100 links. Eighty chains make up one mile (1609.26m). In establishing the township and range lines the distance along each section was measured twice, and the lines were remeasured when the land was subdivided (White, 1983). Six section lines were measured out consecutively. The first five lines were as close as possible to 80 chains in length The sixth line was adjusted to intersect the township boundary, and its deviation from 80 chains was recorded (White, 1983). The corners of each section were generally marked by a post in a mound of earth or stones. In some cases stones, approximately 35 X 30 X *8 cm,* were used in lieu of posts.

Survey and Error Analysis

We seached microfiche copies of original field notes and plats (maps) of early surveys spanning the San Andreas fault in the Carrizo Plain. Then we examined recent (1950s) USGS topographic quadrangle maps of townships surveyed prior to 1857 to identify potential remaining section markers. We *recovered fifteen candidate* section markers, and checked Freeman's field notes and plats for authenticity. We conclude that Freeman accurately recorded natural landmarks and performed the survey.

Most section markers did not match Freeman's original description and had obviously been reset since the original survey. We searched records of resurveys and remonumentation filed with the Bureau of Land Management (BLM) and the San Luis Obispo County Surveyor to find the history of each recovered marker. Because the Carrizo Plain is sparsely populated, few resurveys have been made, and several remonumentations are not on record with the county. U. S. Geological Survey topographic maps indicate that by the 1950's nearly all of the monuments in the Carrizo Plain had been obliterated or lost.

We found and surveyed a total of 8 potential monuments. Four of the monuments were reset by twentieth century surveyors. One of the monuments is a replacement of a lost marker, and therefore is not in its original location. Two of the remaining three were reset without record, or the records were destroyed in a fire in San Luis Obispo, California, in 1981. Our measurements suggest that surveyors reset these monuments well outside their original locations. We eliminated from our study monuments that were reset without record because they may have been moved from their original locations. Of the rernaining *4* sites, two are the degraded, original monuments, and two appear to be in the locations of the original monuments (Grant, 1993). The original monuments (D and E) form a line spanning the fault. The other monuments (H and J) are on a range line that does not cross the fault. We were unable to find any other original pre-1857 monuments in the Carrizo Plain region to resurvey with GPS.

In 1991 we remeasured both lines. To minimize errors, we used GPS dual frequency receivers to remeasure horizontal distance between the monuments. GPS does not require line of sight so it was only necessary to observe at the end points. Conventional surveying techniques would have required traverses between the monuments, thus increasing measurement error. We collected data simultaneously for each of the lines measured, for a period of 1-3 hours. By simultaneously sampling data we eliminate the possibility of errors due to adjustment of a network. We used precise orbits obtained from Scripps Institution of Oceanography to process the data. Results are shown in Table 3-1. Formal errors in the GPS survey are 1-4 cm, which is representative of the true 1σ errors.

Errors in the original survey are much larger than the GPS errors. In the following discussion we mix units of meters and miles because the original survey was measured in miles and we are measuring deviations from one mile. The total measurement error is dominated by errors in the original chained survey and errors in recognizing the center of degraded original monuments. Historical resurveys of Freeman's 1855 survey (Figure 2) of T30S, R20E indicate that Freeman's average chaining error was less than 1:950 for a l-mile line. One interior section line established in 1856 was remeasured by John Reed in 1871, and 14 additional lines in the Temblor Range were remeasured by Howard Carpenter in 1893. Although we are unable to establish the absolute accuracy of the method of chaining we can use the repeated line measurements to estimate the precision of the method. Comparison of the repeat measurements with the originals, including our measurement of distance H-J, yields a root-mean-square (rms) error of 1.6 m for a 1 mile section line. All of the repeated measurements except line H-J were conducted in mountainous terrain. The largest deviation from one mile (3,4 m) is probably larger than Freeman's error because it was measured along a 'random" line while Reed was setting his compass. The largest deviation measured by Carpenter in "mountainous" terrain was 2.2 m. The terrain across line D-E is flat to rolling, so we assume that the average error of 1.6 m applies to our measurement line across the San Andreas.

There is additional uncertainty in determining the center of the monuments. For monuments D, H and J, the uncertainty is less than half a meter. Site E is marked by a diffuse mound of stones approximately 0.6m in radius. Uncertainty in surveying to the same position as Freeman increases the overall line-length error to 1.7m. The San Andreas strikes 48 degrees from measurement line D-E, so the fault parallel error is 2.5m (1σ).

Results

The length change of line D-E corresponds to 11.1m of dextral displacement parallel to the fault, if one does a simple trigonometric correction, assuming purely dextral slip between two blocks. Assuming a constant strain rate during the 136 years since the 1857 earthquake, and velocities estimated from recent surveys (Lisowski *et al.,* 1991), we calculate that line length D-E has increased 0.1m due to post-seismic strain accumulation since the 1857 earthquake. This amount of post-seismic displacement is small compared to the errors associated with the survey. Time-dependent effects such as visco-elastic relaxation following the earthquake are negligible over such a short distance from the fault. Subtracting 0.1m of post-seismic deformation, we calculate that markers D and E were displaced 11.0±2.5 m relative to each other by the 1857 earthquake and associated foreshocks, aftershocks and afterslip.

Discussion

There are two important conclusions from the above result. First, since there have been no large earthquakes on the San Andreas fault in the Carrizo Plain since 1857 (Wood, 1955) and the monuments were displaced 11.0±2.5m, the 9.5±.5 m offsets at Wallace Creek were formed by the 1857 earthquake and associated seismicity and afterslip. To the best of our knowledge, this is the largest amount of documented fault slip from any historic earthquake in the contiguous United States. To first order, the large amount of slip is consistent with the amount of strain expected to be released after the 350 to 450 year interval between 1857 and the most recent large earthquake in A.D. 1405-1510 (Grant and Sieh, submitted; Grant, 1993).

Second, the slip along the main trace of the San Andreas varied from 6.6 to 6.9 m at Phelan fan (Grant and Sieh, 1993) to 9.5±.5 m at Wallace Creek, 2.6 km away. The magnitude of variation in slip is similar to that reported during the 1992 Landers earthquake in southern California (Rubin and McGill, 1992). This has several implications for the interpretation of geomorphic offsets. Geologists frequently use measurements of geomorphic offsets to estimate the dates and magnitudes of prehistoric earthquakes (Sieh and Jahns, 1984; Working Group on California Earthquake Probabilities, 1988; Lienkaemper and Sturm, 1989; McGill and Sieh, 1991). *When* interpreting geomorphic offset measurements, geologists commonly assume that the smallest offset in a given area resulted from slip in the previous earthquake. Larger offsets are then interpreted as the result of more than one earthquake, especially if the larger offset is a multiple of a smaller offset measurement. Therefore, several meters variation in slip over a few kilometers distance during past large earthquakes could lead to misinterpretation of the dates or sizes of prehistoric events. Near Wallace Creek, the 2 to 3 m difference in slip during the 1857 earthquake has led to large differences in estimated dates of the penultimate earthquake (Sieh *et al.*, 1989; Grant and Sieh, 1993). Uncertainties in the interpretation of geomorphic offsets suggest that radiocarbon dating of previous earthquakes is preferable to dates estimated from analysis of geomorphic offsets.

Further implications of our results depend on the interpretation of the 11.0 ± 2.5 m offset of monuments D and E. Within the margin of error, the fault-parallel displacement of D and E is indistinguishable from the amount of slip (9.5±.5 m) at Wallace Creek. However, examination of slip rates and results of elastic modeling suggest that the different measurements reflect real differences in the amount of deformation associated with the 1857 earthquake.

Given that the geomorphic offsets were produced by one earthquake, we can use them to estimate the average slip rate at the fault over one earthquake cycle. The most recent large earthquake prior to 1857 occurred in A.D. 1405-1510 (Grant, 1993; Grant and Sieh, submitted). Thus, the time span of the last complete earthquake cycle is 400±53 years, and the average slip rate during this cycle at Wallace Creek is 24±4 mm/yr. At the Phelan and Bidart fans (figure 1) the average slip rate over the cycle is only 16±2 and 18±3 mm/yr, respectively. These rates are lower than the late Holocene average slip rate of 33±3 mm/yr (recalculated from Sieh and Jahns, 1984) at Wallace Creek by about 25-50%. Stated differently, if we assume elastic strain accumulated at the late Holocene slip rate, then13±2 m of slip should have accumulated during the last earthquake cycle, yet <10 m of slip were released along the section of fault studied. (All errors reported here are 2σ.) Therefore, either a slip defiat resulted from the 1857 earthquake, or the slip rate of the fault is lower than far-field deformation rates or Holocene slip rates.

Despite the apparent discrepancy between pre-1857 strain accumulation and strain release in 1857, we do not believe that the current rate of elastic strain accumulation differs from the late Holocene slip rate. Geodetically determined accumulation rates from networks spanning several tens of kilometers across the Carrizo Plain are indistinguishable from millenial slip rates measured geologically across the ~20-m-wide main fault zone at Wallace Creek (Sieh and Jahns, 1984; Lisowski *et al.*, 1991; Feigl *et al.*, 1992). Dislocation models that fit trilateration data and recent GPS results indicate that 31-35 mm/yr of accumulation is occurring over a 175-km-wide zone spanning the fault. These rates are similar to the 32±2mm/yr rates of fault slip measured across the creeping section of the San Andreas fault (Lisowski and Prescott, 1981) and the late Holocene rate at Wallace Creek. Since these measurements span short and long measurement apertures, and short (≤ 10 years) and long (≥ 3000 years) time spans, the slip rate of the fault at Wallace Creek is equivalent to the far-field strain accumulation rate, and is invariant when averaged over several earthquake cycles. Thus, despite the large amount of surface slip that accompanied the 1857 earthquake in the northern Carrizo Plain, the amount of slip was deficient when averaged over the time since the penultimate earthquake.

If this slip deficit hypothesis is correct, it is interesting to estimate how deeply the 1857 slip deficit may have extended. Assuming isotropic homogeneous elastic properties, we have calculated the predicted displacement of marks D and E for different fault slip distributions. In the absence of subsurface geologic data, we chose a simple 2-part fault slip model in which constant slip occurs in the lower part and horizontally varying but vertically constant slip occurs in the upper part (figure 3). Note that this is a quasi-one-dimensional model since we do not specify the 2-dimensional details of slip in either the upper or lower part. We varied the thickness of the upper part, and the amount of slip at depth The lower part extends 15 *km* to the base of the seismogenic zone. The results (figure *4) indicate* that the upper part of variable slip is thin and probably does not extend much deeper than about 1 or 2 km because there is a steep gradient in the curve at 1 to 2 km. The upper part could be even thicker, however, suggesting more than llm of slip at depth. Therefore, if the behavior is elastic, the surface slip during the 1857 earthquake, as represented by geomorphic offsets, probably does not reflect the total average slip on the fault at depth.

All of the prior arguments are based on the assumption of elastic behavior. Permanent anelastic deformation along the fault could also explain the apparent discrepancy between the displacement of D and E and the lower geomorphic offset measurements along the fault trace. The slip rate data, however, indicates that the deformation is almost entirely elastic when averaged over several seismic cycles, as described above. This is consistent with the results of theoretical and laboratory models of strike slip faulting that show the slip varies from cycle to cycle (i.e., short-term inelasticity) but the long-term rate is constant, i.e., elastic (Rundle, 1989; King, 1991).

There may be a small amount of anelastic deformation along the section of the San Andreas fault near Wallace Creek. Several linear ridges and small scarps sub-parallel to the fault are probably active folds and thrusts. These structures may accommodate some co-seismic deformation However, since the broad aperture strain accumulation rate is the m as the -20-m aperture fault slip rate at Wallace Creek, the component of anelastic deformation attributable to movement on secondary structures must be within the measurement error of the slip rate, on the order of 1-3 mm/yr *when averaged over* **several** *earthquake* **cycles. The** *elastic* behavior of the " fault suggests that either the 1357 slip deficit resulted from dynamic slip "overshoot" during the A.D. 1405-1510 earthquake, or the surface slip in future large earthquakes should compensate the deficit.

There are several implications of the 1857 slip deficit and surficial slip variation for earthquake forecasting and fault mechanics. If the surficial slip during an earthquake is only roughly equivalent to the amount of strain accumulated since the last earthquake, then the size of past or future events and the "characteristic" properties of fault segments are difficult to estimate accurately from geomorphic offsets. Even if the date of an earthquake could be predicted, elastic strain accumulation models may overestimate or underestimate the amount of slip at the surface trace of a fault during the earthquake by up to 2S% or more. In the design of critical structures that cross active faults, it would be prudent to anticipate greater amounts of co-seismic slip than the amount estimated from long-term elastic strain accumulation models. .

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Line	Horizontal Distance (m)	Δ Mile (1609.265m)	Formal Error(m)	Fault Slip (right-lateral)	Post-Seismic Accumulation	Fault Parallel Displacement
D-E	1616.713	+7.448	0.009	11.1 m	0.1 m	11.0 m
H-J	1608.064	-1201	0.040	N/A	N/A	N/A

TABLE 1: Line lengths, formal errors, total displacement," post-seismic accumulation and fault-parallel displacement.

Figure **Captions:**

Figure 1: "Location map of the San Andreas fault in southern California. Resurvey of 1855 section lines in the **Carrizo** Plain enable estimation of **coseismic dextral** displacement. The 1857 rupture is in bold **(Sieh,** 1878). Inset map shows Wallace Creek, measured line D-E, and location of small stream channels offset **9-10m** and **~7m (Sieh** and **Jahns,** 1984; Grant and **Sieh,** 1993). Buried charnels at the apex of the **Phelan** fan are offset **6.6-6.9m** (Grant and **Sieh,** 1993). Geodetic measurements suggest about **11m** of **coseismic** offset.

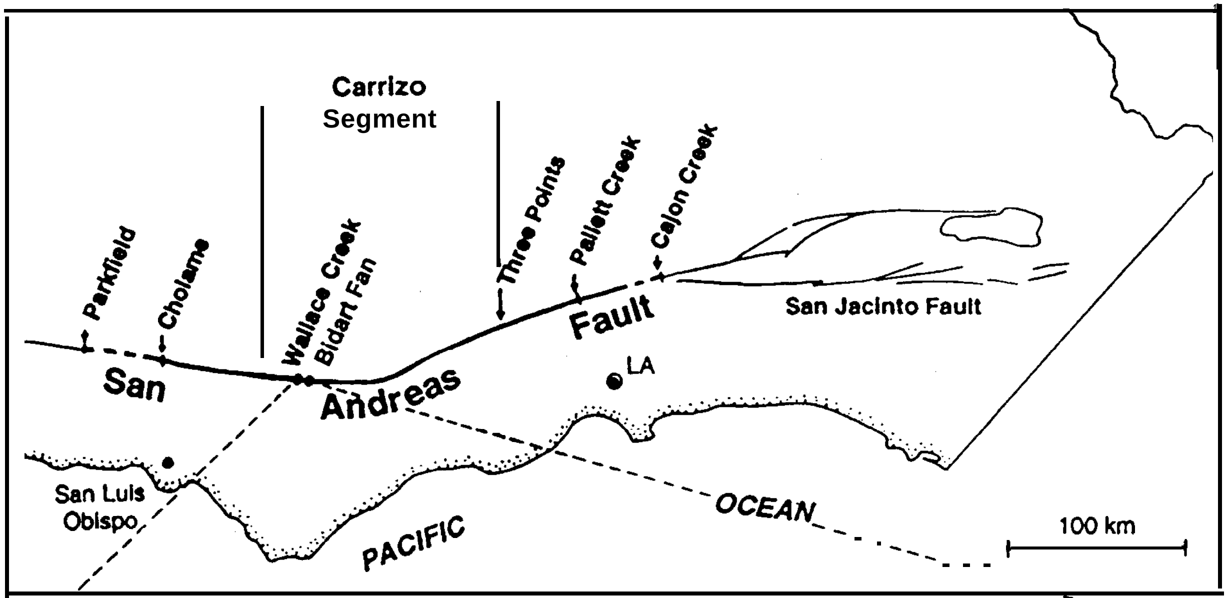
Figure **2:** Map of surveyed section lines and land-survey grid, Township 30 south, Range 20 east **(T30S R20E)** and part of Township 31 south, Range 20 east **(T31S R20E),** referenced to the Mount Diablo Meridian and Baseline, California. Exterior sections are numbered. Each section is approximately one mile square. Line types indicate areas surveyed by **Freeman,** resurveyed by Carpenter, **Reed,** and U.S. Differences in horizontal distance between

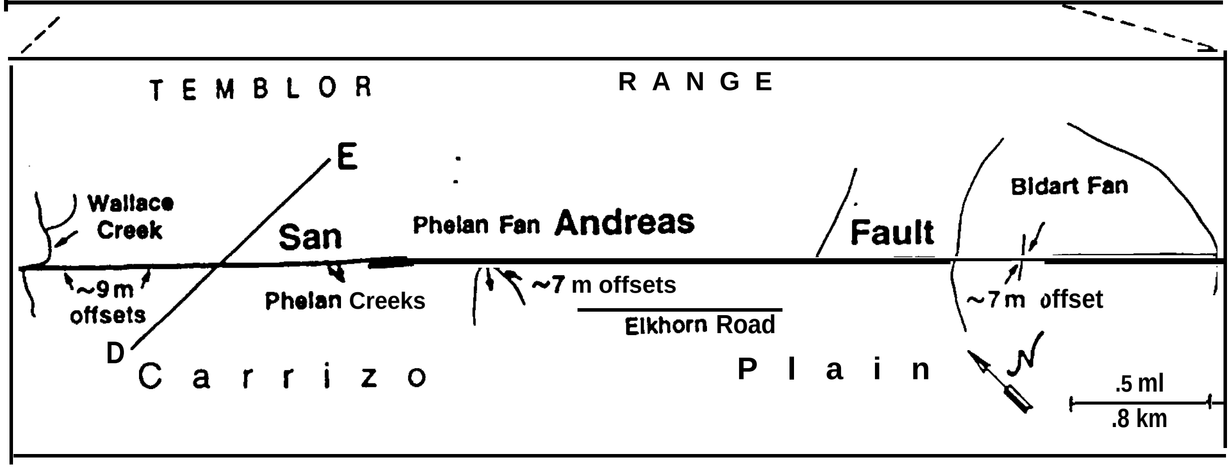
Freeman's survey and resurveys are shown in meters and chains next to the resurveyed lines. The endpoints of lines D-E and H-J are marked with corresponding letters.

Figure 3: Dimensions of the two-part model used in the elastic dislocation model. The figure shows a section along the San Andreas fault with the locations of monuments D and E projected onto the fault. Vertically constant right-lateral displacement is imposed on each part. Displacement of the upper part varies horizontally with 9.5 m of slip imposed from Wallace Creek northward, 7 m of slip imposed from the Phelan fan southward, and a linear interpolation of slip between Wallace Creek and Phelan fan.

Figure 4: Displacement of monuments D and E calculated from the elastic dislocation model for varying thicknesses of the upper part, and slip of 9.5, 11.3 or 15 m on the fault in the lower part Properties of lower part are constant horizontally and vertically to a depth of 15 km. Results suggest that the upper, variable-slip part of the fault is at least 1 kilometer thick.

1857 Rupture





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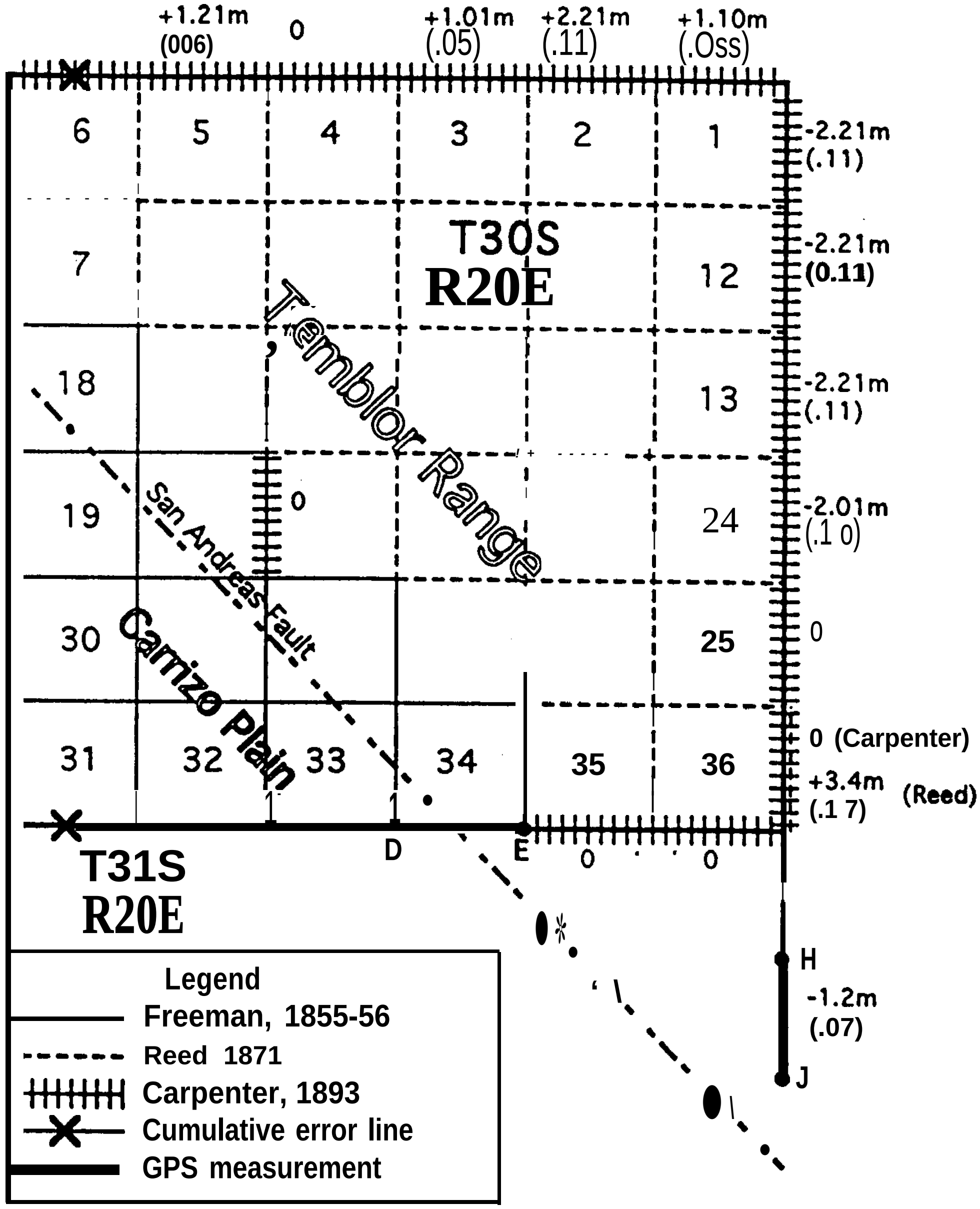
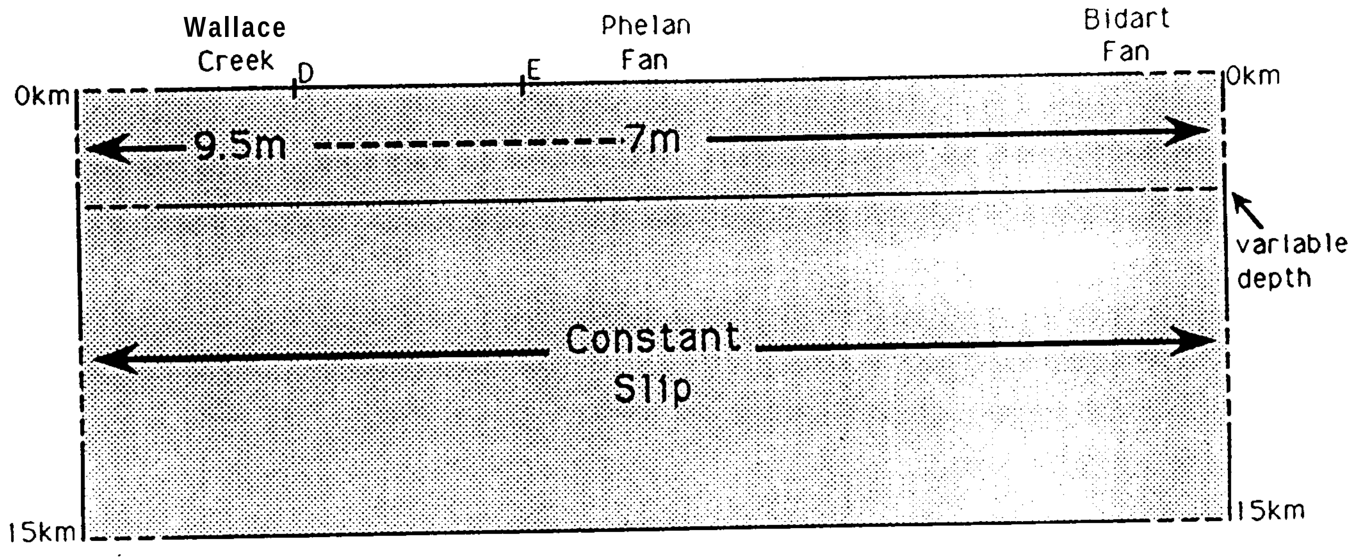


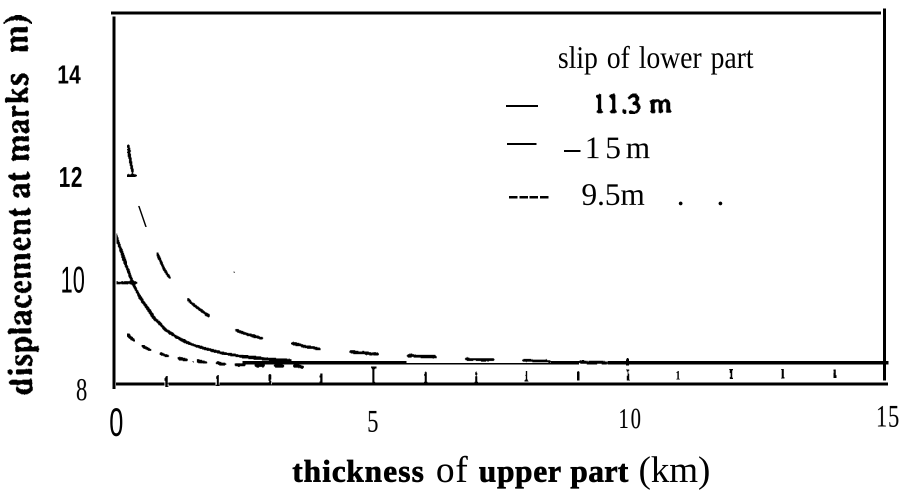
+1.21m
(006)
0
+1.01m
(.05)
+2.21m
(.11)
+1.10m
(.Oss)
6
5
4
3
2
1
7
T30S
R20E
12
18
13
19
0
24
30
25
31
32
33
34
35
36
Temblor Range
San Andreas Fault
Carrizo Plain
-2.21m
(.11)
-2.21m
(0.11)
-2.21m
(.11)
-2.01m
(.1 0)
0
0 (Carpenter)
+3.4m
(.1 7)
(Reed)
D
E
0
0
T31S
R20E
H
-1.2m
(.07)
J
Legend
Freeman, 1855-56
Reed 1871
Carpenter, 1893
Cumulative error line
GPS measurement



Wallace
Creek
D
E
Phelan
Fan
Bidart
Fan
0km
0km
9.5m
7m
variable
depth
Constant
Slip
15km
15km

3

4



displacement at marks m)
14
12
10
8
0
5
10
15
thickness of upper part (km)
slip of lower part
11.3 m
15 m
9.5m