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SURFACE FOLDING, RIVER TERRACE DEFORMATION RATE AND EARTHQUAKE REPEAT TIME IN A REVERSE FAULTING ENVIRONMENT: THE COALINGA, CALIFORNIA, EARTHQUAKE OF MAY 1983

by

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ABSTRACT

The May 1983 Coalinga earthquake occurred on a reverse fault at the core of an anticline (Anticline Ridge). No surface breaks were observed but leveling lines indicate a coseismic uplift of 0.5 m. This suggests that fault motion at depth is expressed as folding near the surface. The beds and terraces of two antecedent streams are uplifted where they cross the anticline. In one place a ^{14}C date indicates that an uplift of about 10 m has occurred within a period of 2,500 years. A repeat time of about 350 years for the Coalinga event can be determined from the uplifted terrace and the ^{14}C data. Much of the topography of Anticline Ridge is post-Pleistocene and this provides a second method of estimating recurrence periods. The form of the observed uplift differs in some respects from that to be expected from many repetitions of the Coalinga event suggesting that other deformation processes occur; a shallow angle, southwest dipping fault is hypothesized. The presence of such a structure is supported by the reflection data in the Kettleman Hills to the south of the epicentral area. On this basis a longer period of 1,000 years is estimated. Although the observations in this paper are restricted to the epicentral region of the Coalinga earthquake, it is apparent that the structures of the northwestern Diablo Range front have developed by earthquake-related folding.

INTRODUCTION

An intimate relationship between faults and folds has been recognized for a long time by geologists. The mechanical relation between the two, however, has been studied using either analogue materials or computer models, and it has been assumed that ductile behavior is the primary process and brittle behavior is secondary. Some recent studies (King and Vita Finzi, 1981; King and Brewer, 1983; Cisternas et al., 1982), however, have shown that, in at least some cases, the finite strains observed as folds are produced by the sum of a series of sudden elastic strain increments each of which is associated with an earthquake. Between earthquakes stress in the folds is relaxed gradually by creep. An appreciation of this connection between earthquakes

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and fold formation provides a powerful tool for understanding both. In this paper we examine deformation in the region of the Coalinga earthquake and show that the seismic fault and recent geological structures can be related.

The Coalinga event occurred on a fault beneath an anticline structure (Anticline Ridge and Guijarral Hills). Similar structures occur along the length of the eastern edge of the Diablo Range and are known from observations of morphology and river drainage to have uplift rates of about 0.5 mm/year during the last million years (Lettis, 1983). In this paper we concentrate on the morphology of the epicentral region of the Coalinga earthquake and on the stream profiles of the Los Gatos and Zapato Chino Creeks in the same region. Although we do not extend our detailed discussion in this paper much beyond the epicentral region of the Coalinga earthquake, most of the eastern boundary of the Diablo Range can be studied in the way we describe here.

The main Coalinga event, of magnitude 6.5-6.7 Ms, apparently occurred on a plane dipping at 67°NE and striking N53°W. This orientation is well constrained by the records from the dense array of stations to the west of Coalinga near the San Andreas fault. The plane is identified as the fault plane by the leveling data and the hypocenter of the main shock (Stein, this volume). The auxiliary plane is less well determined, particularly in strike. Consequently, the horizontal component of the slip vector can vary within ±15° of N50°E.

The seismic moment of the event is greater than 2×10^{25} dyne-cm and less than 6×10^{25} dyne-cm (Uhrammer et al.; Kanamori, this volume). Bearing in mind that moment estimates are commonly low since they exclude later events within the main event coda and aftershocks, a nominal moment of 6×10^{25} dyne-cm is appropriate. This moment is provided if the fault extends from 4 km below the surface (there are no surface breaks) to 11 km (the approximate depth of the deepest aftershocks). Taking a displacement of 1.8 ± 0.5 m which fits the observed uplift, the fault must be 15 km long, rather less than the length of the aftershock zone. The surface projection of a surface that fits the seismic and geodetic data is shown in Figure 1.

OBSERVATIONS

Morphology of the Epicentral Region and the River Systems

Some broad features of the river systems in the epicentral region can be seen in Figure 1. The Los Gatos Creek used to flow along a course nearer to Anticline Ridge but now follows a course on the west side of Pleasant Valley before it swings towards the Guijarral Hills. It becomes more sinuous and then straightens again to cross the anticline. This is consistent with a broad uplift extending into the valley. A similar broad uplift may be associated with the Kettleman Hills. The way in which the Zapato Chino Creek swings away from the northwest end of the Kettleman Range suggests broad uplift. Also, the lower Canoas Creek (lower right-hand corner of Figure 1) which apparently used to join the Zapato Chino Creek no longer does so because of uplift.

Other features are visible in the general map. Lake or marsh deposits (Levis silty clay of early Holocene age; Lettis, 1981) are shown to the south and southwest of the Guijarral Hills. The larger of these regions is associated with an abandoned river course northwest of the Guijarral Hills that appears to have drained the former lake. The similarity between these features and the temporary lake that formed as a result of anticline uplift in the El Asnam, Algeria earthquake in 1980 (King and Vita Finzi, 1981) is striking. This suggests that larger or more frequent earthquakes can temporarily dam creeks crossing the anticline.

River and Terrace Profiles of the Los Gatos and Zapato Chino Creeks and the Age of the Los Gatos Creek Terrace

Profiles of the elevation of the beds of the Los Gatos (a) and Zapato Chino (b) Creeks and their associated terraces or fan surfaces are shown in Figure 2. Riverbed heights, indicated by solid circles, are taken directly from the latest edition (1979) of the 7-1/2° topographic maps (surveyed 1955-56). For the Los Gatos Creek, the height of the terrace relative to the riverbed was measured in the field. The results of these measurements are shown by triangles. Measurements of terrace height were also taken from the topographic map and these are shown by open circles. The difference between the two methods of establishing terrace profile about ±0.5 m. Consequently, the terrace level for the Zapato Chino Creek is taken from the topographic map alone.

Much of the San Joaquin Valley and Pleasant Valley have been subject to subsidence during the last 60 years as a result of the extraction of ground water by pumping (Bull, 1975). In Pleasant Valley the total movement is less than 0.5 m and may be ignored. The land downstream of our Los Gatos Creek profile (Figure 2a), however, has dropped by 6 m in this period and Munn et al. (1981) suggest that the form of the river and terrace profiles is due to this subsidence. To test their suggestion, we examined the 1937 edition of the 7-1/2° Guijarral Hills topographic map. The survey for this sheet was carried out in 1933 before appreciable subsidence had occurred, and we plotted part of the Los Gatos terrace and riverbed profile from that sheet. This covers the critical region from 10 to 20 km in Figure 2a. The results are indistinguishable from those we find using maps based on the 1955-56 survey or our 1983 measurements. We therefore conclude that the features we observe are tectonic in origin and are not the result of land subsidence due to pumping. Subsidence has not, as yet, modified the river profile.

On both profiles a solid line is drawn to indicate the form of an undisturbed river profile. It is apparent when this idealized profile is drawn that neither creek is in equilibrium. The Los Gatos Creek, however, is much closer to equilibrium than the Zapato Chino Creek. This may be explained by noting that the former has a catchment area of about five times the latter and has correspondingly greater erosional power.

To determine the amount that a terrace has been lifted, it is necessary to know its height relative to the riverbed when it was formed. Since the relevant height is determined by rare flood conditions, it is not directly observable. Bull (1964) discusses these questions for a region to the north of our area. Here we assume that the terrace heights upstream (0-5 km) and downstream (15-20 km) of the uplifted section are representative of flood heights, and we join them with a smooth curve whose distance from the idealized riverbed varies in a monotonic fashion. This is an idealized flood terrace level and is shown by hatching to indicate that it is uncertain. It can be seen that much of the lifted terrace is well above any likely flood level (Figure 2). The lower parts may not be.

Atwater (in prep.) has determined ages for fan and terrace material at locations marked A and B (on Figures 1 and 2). Point B is in a region where the terrace or fan level is not clearly lifted above flood level and the ^{14}C date of 490 ± 60 years may represent a high level deposition event and not date uplift. The date of 2,550 ± 130 years for detrital charcoal at Point A is more useful. The material was collected from a horizon within the terrace 4.5 m below the surface. The date indicates the time when the detrital material was deposited, and the surface of the terrace which overlies it must be younger. Hence the 2,550 years is a maximum time for the river to downcut in response to uplift.

DISCUSSION

Interpretation of the Form of the Terrace Profiles

The terraces are uplifted approximately along the axis of the anticline. Only the Los Gatos terrace passes near the fault that moved during the May 1983 earthquake, and the geodetic data available to compare with the terrace data is from a leveling traverse nearly 10 km to the northwest of the Los Gatos Creek. These geographical relations can be seen in Figure 1 and are indicated in sketched insets in Figure 3. The terrace profile produced by subtracting terrace height from the idealized flood level for the Los Gatos Creek (in Figure 2) is shown by a solid line (1) in Figure 3a. The vertical motion associated with the 1983 earthquake is presented in Figure 3b and the form of the topography along the same profile is shown in Figure 3c. The form of the topography and the seismic uplift are broadly similar. Despite the effects of erosion and deposition, this similarity is to be expected if Anticline Ridge has been created by many events similar to the recent earthquake.

Both the geodetic uplift (Figure 3b) and the topographic form of the anticline are broader than the zone of terrace uplift. However, in the region where the Los Gatos Creek crosses the anticline, the topographic ridge is narrower by a factor of two than it is along the geodetic profile. Although this is most clearly seen on the topographic maps, the general form can be seen in Figure 1 and the insets of Figure 3. A second dashed profile (2) is shown in Figure 3a. This is the true profile (1) stretched by a factor of two to represent the profile to be expected along section 2 (see inset Figure 3b). It may, therefore, be regarded as being created by normalizing the width of the terrace by the width of the ridge. In this way we can compare the earthquake uplift with the terrace uplift. The extrapolated terrace profile still exhibits differences in shape from the earthquake elevation changes. In particular there is terrace uplift in the zone of earthquake subsidence. This is not attributable to errors in terrace height determination or to our interpretation of the terrace formation process since the uplift is also evident in the river channel locations referred to earlier: The current Los Gatos channel lies on the southwest side of Pleasant Valley rather than heading northwest into the region of repeated earthquake subsidence.

Multiple Faults at Depth

The repetition of the May 1983 event may not alone be sufficient to explain the morphology in the epicentral region. The simplest alternative hypothesis is that the overall deformation results from motion on more than one fault. To find the nature of the other fault or faults we subtract the form of deformation that can be produced by repeated events of the type which occurred in May 1983 from the observed long-term deformation. The residual must result from other fault motion.

The process by which we separate the form of the terrace uplift into two contributions, one from the 1983 earthquake fault and the other from motion at depth is shown in Figure 4. Figure 4c shows the extrapolated terrace deformation from Figure 3a; Figure 4a shows the approximate form of the elevation changes caused by the earthquake from Figure 3b. The residual, a broad-domed uplift, is shown in Figure 4b. Such a deformation profile can be attributed to any shallow angle (or horizontal) slip surface at depth. We show only one of the possibilities, a shallow angle thrust fault dipping to the west.

A Repeat Time for the Coalinga Earthquake

The existence of a relation between the uplifted terraces and repeated earthquakes is compelling and offers a method of estimating earthquake repeat time. The introduction of two faults, however, complicates the procedure.

If we ignore the broad uplift and our interpretations of multiple faults and attribute the dated part of the terrace uplift to motion on the Coalinga earthquake fault alone (i.e., 10 m in 2,500 years, an uplift rate of 4 mm/yr), then, with a surface uplift for each event of 0.5 m, we find an improbably short repeat time of about 125 years. If we conclude that the broad uplift is real and subtract it from the total uplift, then the part attributable to the 1983 earthquake fault is 3.5 m (1.4 mm/yr). This gives a longer repeat time of about 350 years and we suggest that this is more consistent with the geomorphic evidence. If the remaining uplift is attributable to a sub-horizontal fault, it is appropriate to consider whether this fault is seismically active. If it is, then in the long term, motion on the Coalinga fault will be associated with other earthquakes on the deeper fault. An examination of the geodetic data (Stein, this volume) indicates that the Coalinga earthquake fault extends to the base of the aftershock activity 10-13 km deep. A connecting low angle fault will thus most probably be beneath the seismogenic depth and therefore not be associated with earthquakes.

A much longer term estimate of the recurrence time for the Coalinga earthquake may be made from the geological information. The youngest deposits whose distribution is not controlled by the existence of the anticline are of Eocene age (40 My). Hence some deformation may have occurred at any time since then. However, much of the deformation is considered to date from the mid-Pleistocene (Harding, 1976). This view is based on the observation that the 200 m of topographic expression conforms very closely to the shape of the subsurface structure and that Pleistocene beds with dips of 20-40° fringe the anticline. If each earthquake gives an uplift of slightly more than 0.5 m, similar to the recent event, then about 400 events have occurred since that time. The Pleistocene extends from 10,000 to 1.6 million years. Taking the mid-Pleistocene as 0.5 million years gives an earthquake repeat time of 1,250 years.

CONCLUSIONS

Distorted river courses and profiles of uplifted river terraces indicate a history of activity on the same fault beneath Anticline Ridge that moved about 1.8 m to cause the May 1983 Coalinga earthquake. Carbon dating indicates an age of 2,500 years or less for an uplifted terrace on the Los Gatos Creek indicating a repeat time for such earthquakes of about 350 years.

A substantial proportion of Anticline Ridge has apparently formed during the last 500,000 years, and this suggests a longer repeat time of 1,250 years. Because of inaccuracies in the data available to determine these repeat times and because earthquakes do not necessarily repeat regularly but may occur in bursts followed by periods of quiescence, these repeat times must be regarded as having large uncertainties. The fact that the long-term and short-term repeat times are quite similar suggests a relatively regular temporal behavior, but the existence of the lake deposits indicates the possibility of periods of greater activity. It seems reasonable, however, that earthquakes are not less frequent than one every 2,000 years or more frequent than one every 200 years.

Anticline Ridge and the Guijarral Hills lie in a region of en echelon offset in the linear anticline structures of the Diablo Range front. The Big Blue Hills form an elongate feature to the northwest, and the Kettleman Hills form a similar feature to the southeast. Both apparently have similar uplift rates to Anticline Ridge and are presumably cored by active faults. These faults must be regarded as a seismic hazard. Because of the linearity of the fold features, their associated faults are presumably long and linear. They may, therefore, move in less frequent but larger earthquakes than the Anticline Ridge fault.

The deformation of the river terraces in the Coalinga region probably cannot be explained by repeated motion on the steeply dipping fault alone. Therefore, a shallow angle fault at a depth of 10 km or more is suggested. This fault is beneath the seismogenic zone and, therefore, moves by creep. At this depth the fault should be considered to include zones of deformation such as the ductile shear zones observed in exhumed terrains (e.g., Sibson, 1982). The geodetic data does not determine whether this structure dips to the east or to the west. However, an interpretation of the reflection profile across the Kettleman Hills (Wentworth et al., this volume) looks similar to our Figure 4c and shows both the shallow southwest dipping plane and the high angle northeast dipping plane. A projection of the shallow plane would reach the surface immediately to the east of the Kettleman Hills.

The part of the deformation associated with the earthquake fault is readily identifiable but the evidence for motion on the shallow angle aseismic structure is less clear. However, if the average slip rate on this feature is about 5 mm/yr, then horizontal strains of about 10^{-8}/year should be easily detected geodetically over time periods of 25 years or more.

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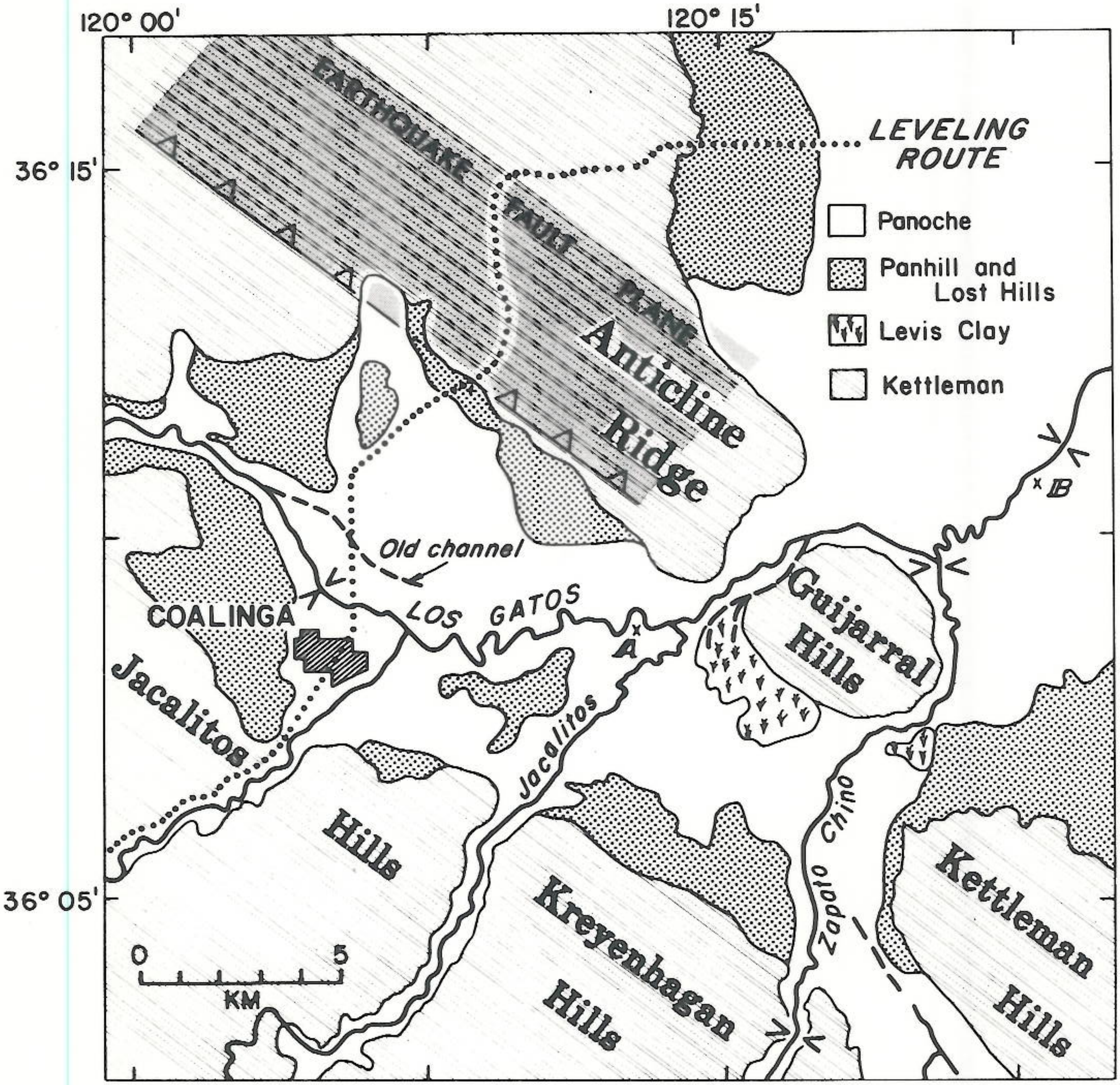

Figure 1. Simplified map of the surface deposits in the epicentral region of the May 1983 Coalinga earthquake. The approximate surface projection of a fault plane for the earthquake consistent with the seismic and geodetic data is shown. The distribution of surface deposits is taken from a detailed discussion and map in the Soil Survey of the Coalinga region (1952). The present river courses are shown by solid lines, and old river courses are shown by dashed lines. A dotted line indicates the course of the geodetic traverse. Note that the width of the structure where it is crossed by the geodetic line is about twice the width of the structure crossed by the Los Gatos creek.

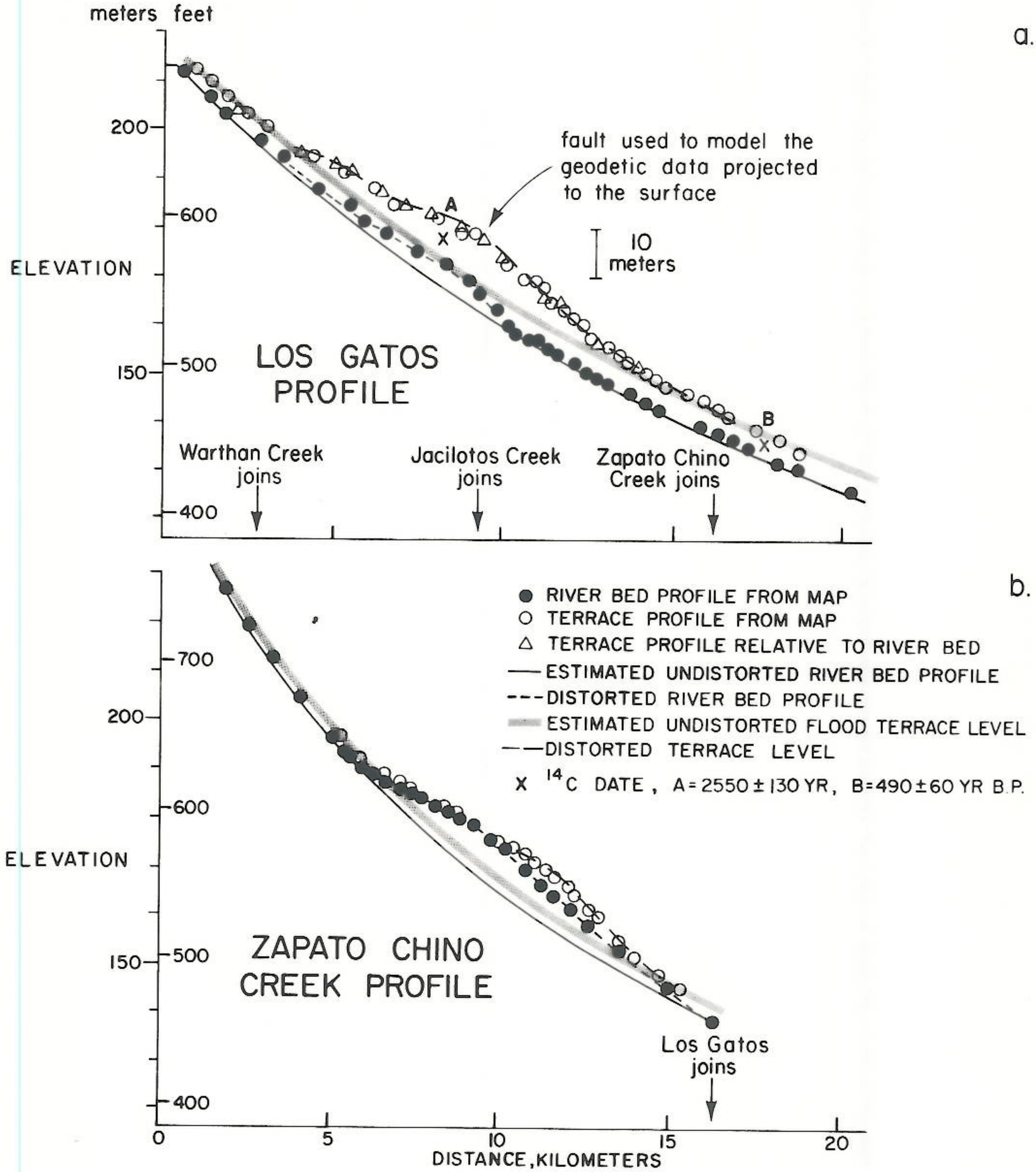

Figure 2. River terrace profiles. All of the points except those marked by triangles, which were measured in the field, are taken from the 7-1/2° topographic maps. The profiles follow the courses of the river except for some of the extreme meanders where the profile follows a direct route. The errors involved are just discernible in the profile but are less than ±0.3 m.

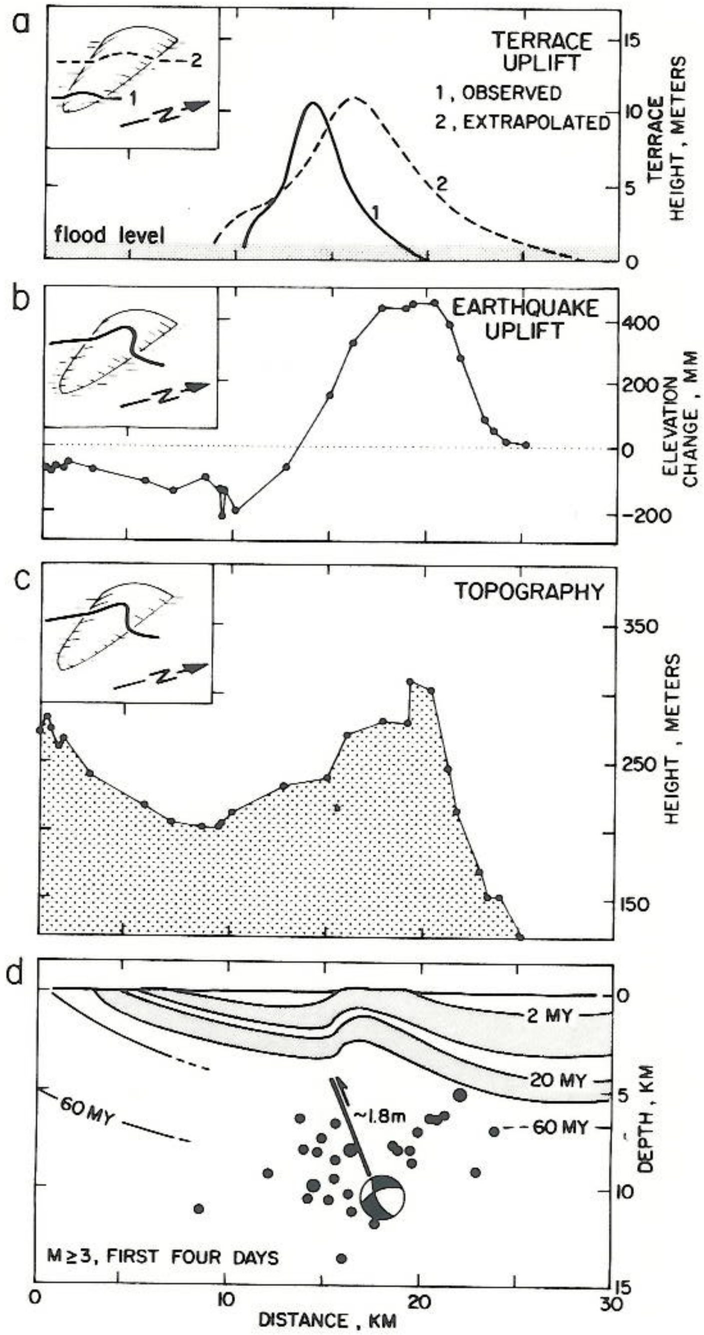

Figure 3. The terrace uplift for the Los Gatos creek taken from Figure 2a is indicated by a solid line (1) in a). In the same figure, a profile extrapolated to the position shown in the inset sketch is shown by a dotted line (2). The 1983 earthquake uplift is shown in b) for the route shown in the accompanying sketch. The uplift is projected perpendicular to the fault strike. The topography for the same profile is shown in c). A simplified geological structure taken from Fowkes 1982 is shown in d). The location and mechanism of the main shock (Eaton 1983) (projected on the sphere below the plane of the paper) and the location of the larger aftershocks (Reasenberg et al. 1983) are also shown.

Figure 3. (a) The Bouguer anomaly for the [illegible] event taken from Figure 2a is indicated by a solid line (A-A'). In the same figure, a profile extrapolated to the position shown in the inset (A-A') is shown by a dotted line (A2). The 1989 earthquake uplift is shown in b (profile route shown in the accompanying insets). The uplift is projected perpendicular to the fault strike. The topography for the same profile is shown in (c). A simplified geological structure taken from [illegible] (1987) is shown in (d). The location and mechanism of the main shock [illegible] (1990) [illegible] the plane of the [illegible] and the location of the [illegible] aftershocks [illegible] et al. (1990) are also shown.

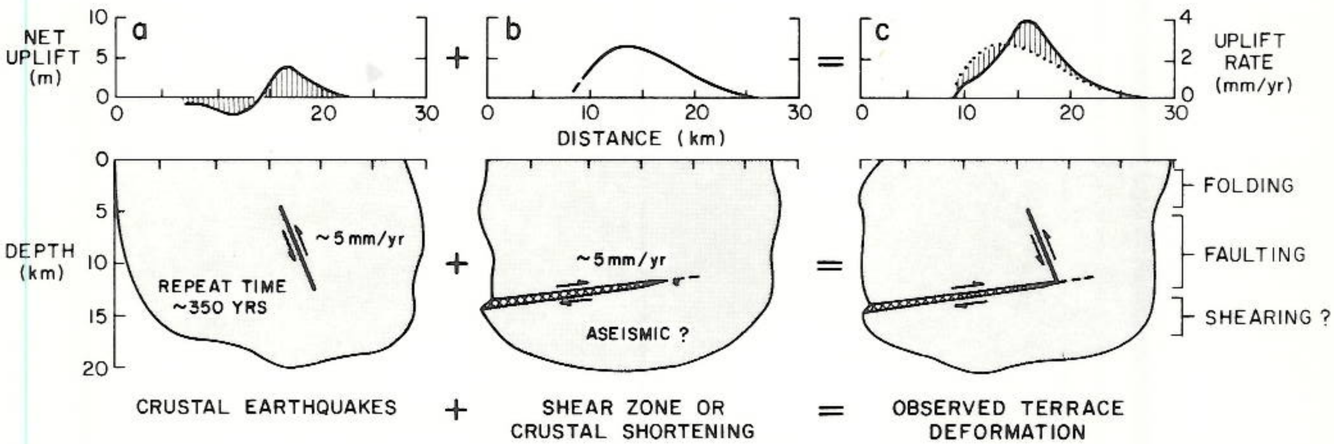

Figure 4. Interpretation of the deformation of the Los Gatos terrace. The deformation forms of diagrams a) and b) sum to provide the observed profile which is shown by a solid line in diagram c). The deformation profile in diagram a) can be produced by the earthquake fault and in diagram b) by a shallow slipping plane at depth. The data does not determine whether the plane extends to the east or to the west and does not determine the dip although it must be shallow. The westward dipping plane is chosen because it appears on reflection profiles for the Kettleman hills (Wentworth et al. 1983).