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VARIABLE RATES OF LATE QUATERNARY STRIKE SLIP ON THE SAN JACINTO FAULT ZONE, SOUTHERN CALIFORNIA

By

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Three strike-slip displacements of strata with known approximate ages have been measured at two locations on the San Jacinto fault zone. Minimum horizontal offset between 5.7 and 8.6 km in no more than 0.73 m.y. northeast of Anza indicates ≥8-12 mm/yr average slip rate since late Pleistocene time. Two measures of more recent displacement are based on trenching studies of stratigraphic offsets on the Coyote Creek fault in western Imperial Valley. Horizontal slip of 1.7 m has been calculated for the youngest sediment of Lake Cahuilla since its deposition 275 to 480 years BP. The corresponding slip rate is ≥2.8 but ≤5.0 mm/yr. Right-lateral offset of 10.9 m measured on a buried stream channel older than 5000 but younger than 6800 years BP yields average slip rates for the intermediate time period, 400 ± to 6000 ± BP, of 1-2 mm/yr. The average rates of slip for these three time intervals indicate a major relatively quiescent period for the San Jacinto fault zone from about 4000 B.C. to about 1600 A.D.

To the extent that long-term variations in seismic activity of major strike-slip faults elsewhere are known, the fluctuations in slip rate for the San Jacinto fault zone do not appear to be abnormal. If the San Jacinto and adjacent segments of the San Andreas fault alternately assume dominant roles in absorbing motion between the Pacific and American plates, perhaps even more recently than 400 years ago, the San Andreas fault in the northern Salton Trough expressed most of the motion but has since become relatively inactive.

INTRODUCTION

Among the several reported estimates of the rate of right-lateral slip on the San Jacinto fault zone [Sharp, 1967; Brune, 1968; Clark et al., 1972; Thatcher et al., 1975; Savage and Prescott, 1976; Anderson 1979], only two measures of long-term horizontal slip based on geologic data have been made. Clark et al. [1972] estimated horizontal slip rates for the Coyote Creek fault segment of the zone based on earthquake recurrence times determined from a 3000-year record of vertical separation of flat-lying lake deposits and the vertical component of slip at one point along the surface rupture of the 1968 Borrego Mountain earthquake. Their judgement of the most likely right-lateral slip-rate, 3 mm/yr, was based on a complex set of assumptions, among them that the ratio of horizontal-to-vertical slip components remained constant for at least 3000 years. Their results were comparable to Sharp's [1967] minimum estimate of the average rate of Quaternary slip measured on the main trace of the San Jacinto fault zone north of the town of Anza (Fig. 1). His estimate of the horizontal slip rate, >2.5 mm/yr was designated as a minimum for two reasons: (1) the determination was based on the minimum horizontal separation of distinctive gravel on the southwest side of the fault relative to the correlative source terrane of the clasts on the opposite side; and (2) the gravel was assigned a Pleistocene age on regional geological considerations, and, in the absence of a tighter age constraint, a maximum age of 2 m.y. was used in the slip rate computation.

In this paper, three independent measures of slip rate for different intervals of late Quaternary time are examined. The first slip rate discussed is a reconsideration of the minimum estimate by Sharp [1967] with slightly modified measures of displacement of the tracer gravel bed near Anza and a 0.73-m.y. constraint on the maximum age of the gravel bed. Two new measures of slip based on trenching studies of the Coyote Creek fault strand of the San Jacinto zone cover intervals of time from the present to about 400 years ago and a period of time between about 400 years to at least 5000 years BP. The slip-rate estimate for the most recent period of time is partly drawn from data of Clark et al. [1972] for the main trace of the Coyote Creek fault but does not use data from the branch fault on which most of their conclusions were based. Slip-rate estimates for the intermediate time period have been made from a newly obtained measure of right-lateral slip of the edge of an ancient drainage channel that contains a charcoal-bearing sedimentary layer.

Unless otherwise indicated, carbon-14 ages reported in this paper have been converted from standard carbon-dating years to "actual" years according to the tree-ring calibration method of Damon, Long, and Wallick [1972]. The standard deviation figures given after the ages incorporate contributions from both the analytical procedure and the dendrochronologic calibration. Carbon-14 ages and the standard deviation figures have been rounded to the nearest five years.

LATE QUATERNARY DISPLACEMENT NEAR ANZA

The segment of the San Jacinto fault zone north and northeast of Anza (Figure 2) contains geologic features whose relations permit estimating the long-term Quaternary slip rate. The separate branches of the fault zone, with the exception of the Thomas Mountain fault, coalesce there into a single fault trace. Because the total slip on the Thomas Mountain fault is small (1.5 km) and much of its trace shows no evidence of movement in late Quaternary time [Sharp, 1967], the slip rate for the Clark fault alone may only slightly underestimate the rate for the San Jacinto fault zone as a whole.

In the area near Anza shown in Figure 2, the Clark fault [Sharp, 1972] separates a high-standing ridge of crystalline rocks at Thomas Mountain from Quaternary continental clastic deposits assigned to the Bautista Beds of Frick [1921] southwest of the fault in northern Anza Valley. Sharp [1967] described the main stratigraphic features of the gravels southwest of the fault and how they reveal a picture of contemporaneous right slip on the fault as sediments were shed from Thomas Mountain. The estimate for minimum right-lateral separation of the gravel is here increased slightly on the basis of the distribution of exposure of distinctive crystalline rocks and drainage patterns in the source terrane on southeastern Thomas Mountain.

Amount of Displacement

The distribution of four contrasting types of crystalline rock exposed on the southwest slope of Thomas Mountain are shown on Figure 2 in relation to the surface distribution of gravel deposits displaced farthest in the right-lateral direction by the fault. Three of the crystalline rock types are distinctive kinds of Cretaceous plutonic rocks; the fourth is made up of metamorphic layered gneiss, schist, and amphibolite older than the plutonic rocks. Metamorphic rocks crop out in a thin septum (labelled A) between two plutons of tonalitic and adamellitic composition as well as in a much larger area that extends at least 1.5 km beyond the southeastern part of the area of Figure 2.

The offset marker gravel bed lies directly in contact with the fault shown on the left side of Figure 2. The gravel contains clasts derived chiefly from a metamorphic rock source; the igneous rocks contained in it, a small proportion of the gravel, have not been derived from any of the three distinctive plutonic bodies shown. The composition of the gravel rules out the small septum at A as the source of the clasts because drainages sampling the septum collect tonalite and adamellite in even greater relative abundances, but these rock types have not been found in the marker gravel. The source of the clasts thus appears to be the large area of exposed metamorphic rocks labelled B (includes small unmapped bodies of other plutonic rocks) on the right side of Figure 2.

Displacement of the gravel cannot be precisely determined because of several complicating factors. Between the main Clark fault trace and the branching Buck Ridge fault (Figure 2), the metamorphic rocks are now partly covered with fine-grained sediments of pregravel age, and the past distribution of this material may have been much more extensive. While the gravel was being deposited, metamorphic rocks in area B may have been exposed only more distantly from the offset gravel than at present so that displacement as measured now from the nearest exposure of source rocks might underestimate the real offset. The former extent of the gravel northwest of its present exposure area is unknown because of erosional truncation and burial by younger terrace deposits, and this uncertainty also leads to underestimation of the displacement. In any case, the displacement must be at least 5.7 km measured from the northwesternmost part of the gravel to point C in Figure 2, assuming that outcrops northeast of all fault strands in this part of the zone could have contributed to the gravel. A liklier minimum estimate would be about 6.6 km (point D, Figure 2), because drainages in the interval C to D are now, and probably were formerly, laden with adamellite and gabbro debris, lithologic types not found in the offset gravel. The location of point D is arbitrary in that this limiting choice disposes of clast types not found in the displaced gravel, but this point could be moved as much as 2 km southeast [Sharp, 1967, Plate 1] and not violate any of the geologic relations. Thus, slip amounting to 8.6 km cannot be ruled out.

Age of the Gravels

The geologic map, Figure 3, shows the stratigraphic relation of the marker gravel to underlying strata that are now more precisely dated than by Sharp [1967]. The section of continental beds southwest of and beneath the gravel consists primarily of sandy, silty, and clayey beds of fluvial and lacustrine origin. Within the finest sediments are several layers of very light gray to white rhyolitic ash. On the basis of its purity, one of the uppermost ash beds was selected for trace-element analysis. A. M. Sarna-Wojcicki of the U.S. Geological Survey prepared the material for the neutron activation analysis produced the trace-element abundances shown in Table 1 [written communication, 1978].

The collected sample of rhyolite ash correlates with the airfall ash at the base of the Bishop tuff which erupted about 500 km north of Anza about 0.73 m.y. ago [Dalrymple et al., 1965]. Defining a similarity coefficient of 1.00 to represent an identical pair, the 17 elements analyzed in the ash sample yield a similarity coefficient of 0.98 [Sarna-Wojcicki et al., 1979].

This clearly distinguishes it from other known tephra units erupted from this source area from tephra units generated at other source areas in the western United States. Sarna-Wojcicki et al.,[1979], moreover, argue from stratigraphic data and from evidence for xenocrystic contamination that the reported age for the ash from the Bishop tuff may be slightly too great.

Additional uncertainties affect the age estimate of the displaced gravel. Structural complexity and incomplete exposure make the total number of ash beds within the geologic units of Figure 3 uncertain. Although at least two ash beds may lie at stratigraphically higher levels, structural repetition of apparently lower ash beds cannot be ruled out. Some amount of time should be allowed for the accumulation of approximately 30 m of sediment above the dated horizon and possibly additional time for erosion at the top of the fine clastic section before deposition of the overlying gravelly section. Since the present data will not permit quantification of these relevant, but possibly brief, time elements, the age of the displaced gravel is taken to be equivalent to that of the underlying Bishop ash bed.

RIGHT-LATERAL SLIP RATE NEAR ANZA

Using the minimum, likely, and possible amounts of offset on the tracer gravel bed near Anza discussed here, together with the maximum possible age provided by the dating of the underlying rhyolite ash, a table of average horizontal-slip rates for the San Jacinto fault zone through late Quaternary time can be constructed. The data summarized in Table 2 show that, for those strands of the fault zone southwest of Thomas Mountain, the fault has moved on the average over the past 0.73 million years at a minimum rate between 8 and 12 mm/yr. As stated, the likelihood of a younger actual age of the gravel and the possibility of a concealed extension, together with the omission of the Thomas Mountain fault from the rate measurement, suggest that the actual values of slip rate should be somewhat greater.

HOLOCENE RATE OF SLIP ON THE SAN JACINTO FAULT ZONE

Historic Slip Rate

From the geodetic data of Whitten [1956], Sharp [1967] estimated the current rate of movement across the San Jacinto fault zone roughly at the latitude of Borrego Springs to be about 25 mm/year between 1941 and 1954. In San Jacinto Valley, Savage and Prescott [1976] determined a similar strain rate for the fault zone if it is locked to a depth of 20 km, but their data only required that the ratio of the slip rate to depth of the locked zone be 1.2×10^{-6} (for example, 12 mm/year for a 10-km depth). Thatcher [1979] has pointed out the problems in interpreting Whitten's data as a measure of secular strain introduced by possible major coseismic slip during the 1942 and 1954 magnitude >6 earthquakes that affected this region. Brune [1968] calculated a 15 mm/year slip rate on the San Jacinto fault zone based on seismic moment data from major historic earthquakes. Although slip rates derived from seismic moments might err by a factor as large as 2, Brune's rate is similar to the long term late Quaternary average slip rate as measured geologically near Anza.

Latest Holocene Right-Lateral Slip Rate

At the latitude of the Vallecito Mountains (Figure 1), the San Jacinto fault zone is expressed at the surface by a single major active fault strand, the Coyote Creek fault. The major strand farther northeast, the Clark fault, is not traceable as far east as the 116th meridian as a late Pleistocene or Holocene feature. Farther southeast toward Imperial Valley, northeast-trending faults, as well as unfaulted fold axes (not shown in Figure 1), make a southeastward extension of the Clark fault unlikely, at least as a geologic structure with displacement concentrated in a narrow zone. No other through-going, northwest-trending fault branches have been located after an intensive search in the region around the southeastward projection of the Clark fault. The only apparent alternative for a southeastward continuation of displacement would be an unusually wide zone of shear with offset distributed on multitudes of minute faults. Although some suggestion of faulting of this kind is evident in the badland exposures in this area, none have been found to clearly displace young Holocene deposits. If the Clark fault indeed dies out in the Quaternary deposits of northwestern Imperial Valley, then present right-lateral shear strain across the San Jacinto fault zone must be assumed to be taken up in its southern reach along the Coyote Creek fault [see Sharp, 1975]. Latest Holocene slip on the Coyote Creek fault should be comparable to that of the fault zone near Anza, on the principle that over long intervals of time, displacement at every point along a fault must approximate the true slip.

The small rectangle east of the Vallecito Mountains labeled T in Figure 1 marks the location of two trenching studies of the Coyote Creek fault. The first of these studies by Clark et al. [1972] established that the uppermost flat-lying lake deposits corresponding to the last high-water stand of Holocene Lake Cahuilla were displaced vertically 0.45 m at the main trace of the Coyote Creek fault. They reasoned that, by comparison with displacement during the 1968 Borrego Mountain earthquake, 4.5 1968-sized earthquake events were necessary to account for the vertical offset of the youngest lake layer, dated by them to be 860 $\pm$ 200 carbon-14 years (dendrochronologically uncalibrated) as measured on pelecypod shells contained in the lake deposit.

New stratigraphic features found in a second series of trenches at nearly the same location near the high shore line of Lake Cahuilla show that locally a $\leq$6 cm-thick accumulation of detrital plant material lies about 8 cm below the youngest lake deposit. The age of this material (USGS Sample 297a) is 405 ± 75 dendrochronologically corrected years BP. Inasmuch as the detrital plant material grew prior to transport and deposition at the site and a layer of at least 6 cm of sand separates this deposit from the base of the overlying lake silt, the age of the silt deposit must be somewhat younger than 405 ± 73 years. Charred shoreline tules on the east side of Imperial Valley dated by Hubbs et al. [Sample LJ-102, 1960] at 220 ± 100 carbon-14 years (295 ± 110 dendrochronologically corrected years BP) suggest that the latest high-lake stand was of about the same age or possibly slightly younger than the layer of plant debris. In any case, the 860 ± 200 (845 ± 205 dendrochronologic years) BP age is inconsistent with the stratigraphic data, and the excessive age probably is at least partly attributable to solution of ancient carbonate materials in the drainage of the Colorado River, the primary source of water in Lake Cahuilla.

Early historic observations and the stratigraphic evidence presented here only loosely constrain the rate of strike-slip movement on the Coyote Creek for the past 400 ± years. Using 4.5 slip events determined by Clark et al. [1972] and the 0.38-m maximum horizontal slip of the 1968 earthquake [Clark, 1972], horizontal slip of about 1.7 m is estimated for the Coyote Creek fault since deposition of the youngest lake sediment. All slip events on the Coyote Creek fault associated with earthquakes of 1968 size are here assumed to equal the maximum measured at Borrego Mountain in 1968 despite the statistical data of Bonilla and Buchanan [1970] and Slemmons [1977] on displacements measured at other places from around the world, as well as slip estimates for historic earthquakes along the San Jacinto fault zone by Thatcher et al. [1975, Table 1]. These data suggest that the surface movement on the Coyote Creek fault in 1968 was smaller than might have been expected. The accuracy of slip determined from seismic moment and the applicability of slips observed worldwide are probably inadequate to justify an estimate of the variability of slip for a succession of seismic events for one location on a fault.

The slopes shown in Figure 4 are determined by the calculated horizontal slip and the range of probable age of the youngest lake deposits underlain by the dated plant-debris bed. The age of the plant debris is shown with a horizontal bar labelled A that represents the measured age ± one standard deviation. Depending on the unknown lengths of time between growth and deposition of the plant debris and that represented by the thin sand section above the dated horizon, the true age of the base of the lake deposits could be along or to the left of line A. The constraint for the minimum age of the lake is based on observations of the landscape made during the 1774 expedition of Captain Juan Bautista de Anza returning from San Francisco to Mexico [Bolton, 1930], indicating that Lake Cahuilla was dry at that time. Recessional shorelines that represent annually lower lake levels are spaced vertically at slightly more than 1.5 m near the highest lake level west of the Salton Sea [Wilke, 1976,] and similar shorelines just above the eastern shore of the Salton Sea have been measured to average about 1.23 m difference in elevation. Assuming an average evaporation rate of about 1.4 m/yr, the 96 meters of water in Lake Cahuilla would have evaporated in about 70 years. From this an age of about 275 years BP should approximate the minimum age of the youngest deposit of Lake Cahuilla at its high shoreline (point B, Figure 4). Wilke [1978] has interpreted traverses made during the Coronado Expedition in 1540 to indicate that Lake Cahuilla was not then at its high stand, but this historic evidence is inconclusive as to whether the time of the last high stand of the lake was pre- or post- 1540. The geologic evidence discussed here permits this stand to have been later than 1540.

Dividing the calculated horizontal offset of the youngest lake deposit by a minimum age constrained by the time of Anza's expedition and evaporation rate yields an upper bound on the slip rate of about 5 mm/yr (Figure 4). The lower bounding rate obtained from the maximum likely age of the deposit of plant debris, is about 3 mm/yr.

The slip rate for the past 400 ± years on the Coyote Creek fault appears to be less than the current rate as estimated from seismic-moment data by Brune [1968] for the period 1912 to 1963 (dotted line in Figure 4). Because this period includes part of the interval since the disappearance of Lake Cahuilla, the average rate of slip for the period prior to 1912 back to 400± years BP might have been approximately 1 mm/yr (dashed line in Figure 4).

To employ more data points from the work of Clark et al. [1972] would invite potentially more serious errors because their measured displacements were made on a branching subsidiary fault, not on the main trace of the Coyote Creek fault. Perhaps an even greater problem with their progressively older and larger vertical components of slip is that the conversion to horizontal slip is necessarily based on the tenuous assumption of a constant ratio of horizontal to vertical slip components from event to event. Although this assumption is here incorporated in the estimation of the horizontal slip for the base of the youngest lake deposit, the data come from the main trace of the Coyote Creek fault and indicate only a small number of slip events. The likelihood for greater error probably increases with the length of the time interval under consideration and the number of slip events.

Early Holocene Right-Lateral Strike Slip

New trenching on the Coyote Creek fault at nearly the same location has exposed a buried stream channel whose course has been found to be about normal to the complex set of fault breaks. This paleochannel has been right laterally displaced 10.9 m since its incision into underlying fluvial and lake sediments (Figure 5). Precise dating of the channel is somewhat a problem, because what has been measured for displacement is the erosional truncation of a prechannel marker bed. The erosional event must be younger than the truncated marker bed but older than the channel-filling deposits. Detrital charcoal found in the channel-filling sediments (USGS Sample 494) has been dated at 5155 ± 125 dendrochronologically corrected years BP. Although the measured age of the charcoal records the growth time of the wood from which it was derived, rather than the time of deposition in the channel-filling deposits, approximately 3 meters of channel-filling sediments underlie the charcoal-bearing layer. These older but undatable channel-filling sediments represent deposition at least partly during the time interval while the wood material was growing, being converted to charcoal, and transported and deposited in the channel. The two effects tend to compensate for one another; that is, the time interval between the growth of the wood and charcoal deposition is at least partly represented by channel deposits lower in the section than the charcoal-bearing layer.

The marker bed truncated by the channel is a lithologically distinctive lacustrine silt that contains abundant small gastropods of the genera *Hydrobia* and *Physa*. Shells collected in silty sand at the base of the marker layer (USGS sample 286) consisted of about 95 percent *Hydrobia* and 5 percent *Physa*; they were carbon-14 dated at 6700 ± 90 years BP dendrochronologically corrected age for USGS Sample 286). The actual age of the marker bed is probably somewhat younger than this age because of its stratigraphic position and the possibility of contamination by ancient carbonate if the Colorado River supplied the water in which the shells grew.

Figure 6 shows the limiting average lines relating displacement to time for the period between formation of the erosional channel and the beginning of deposition of the youngest lake bed. The horizontal arrows on the 10.9-m data points in Figure 6 reflect the facts that the age of channel-filling beds (line D, 5155 ± 125 years BP) probably underestimates the time of channel cutting and that the time of prechannel marker bed accumulation (line E, 6700 ± 90 years BP) is older than the erosion of the channel. The limiting average rates of horizontal slip are from somewhat more than one to about 2 mm per year for the period 400 ± to 6000 ± BP.

Near the origin of figure 6, the limiting average slip lines from Figure 4 are reproduced to point up that, with all the uncertainties in the actual ages of the various stratigraphic units, there remains a suggestion of at least a slight but perhaps a substantial average rate increase around 300 to 500 years ago on the Coyote Creek fault relative to its average level of activity for the preceding approximately 6000 years. The exact timing of a major change in average slip rate is indeterminate; it conceivably could be younger or older than approximately 300 to 500 years BP. This uncertainty is represented by the arrow extensions through the data points A and B in Figure 6. Whether the change in rate of slip was abrupt or gradual and how much earlier or later than the accumulation of the youngest lake deposit it might have occurred cannot be answered with the present data. For example, the longer the slip rate might have continued back in time at the average for the past 300 to 500 years, the greater the overestimation of the average slip rate from that time back to 6000 years. An average slip rate of the order of 1 mm/year is therefore possible for much of this interval of time, but the onset of the change could then be older than 500 years BP. A similar argument can be made for the slip rate to have increased more recently than 275 years ago to a value larger than shown in Figure 6.

CONCLUSIONS

Right-lateral slip rates for three time intervals have been presented from geologic data collected at two locations 75 km apart along the San Jacinto fault zone. Comparison of these slip rates may contain some pitfalls, principally those that relate to the distinction between continuity of surface faulting and continuity of displacement and the distribution of slip now and in the past among the various strands within the complex zone.

If most of the 24-kilometers of right slip on the San Jacinto fault zone [Sharp, 1967] had occurred prior to middle Pleistocene time, burial of the then most-active traces, in particular the Clark fault, in northwestern Imperial Valley may account for the present lack of continuity of major strands of the zone at the surface. However, inasmuch as activity of buried faults necessarily must have ceased because the overlying sedimentary cover is not displaced, the fact that the Clark fault dies out southeastward may reflect a situation that has prevailed only from middle Pleistocene time. From Borrego Springs southeastward, the Coyote Creek fault now appears to be the only fault strand in the zone with the characteristics of a through-going major strike-slip fault [Sharp, 1975], although it too displays surficial complexities and discontinuities at several places (see Figure 1).

From these considerations, the Coyote Creek fault could be younger than the main part of the displacement on the entire fault zone within which it lies. Its right-lateral displacement of less than 5 km in Coyote Canyon northwest of Borrego Springs [Sharp, 1967] is consistent with such an age relation to the main zone, but the small displacement there does not constitute proof of its relative youth, and indeed the total displacement and even age of the Coyote Creek fault may increase away from Coyote Canyon toward the southeast.

One of the most important tectonic implications suggested by this data is that the San Jacinto fault zone in its southern reach along the Coyote Creek fault for much of the past 6000 ± years has moved appreciably slower than the average rate for the past 730 thousand years. Although the timing is less certain, there is additionally a suggestion of acceleration of slip rate in the past 400 ± years to a level that may now be approaching the average rate since late Pleistocene time. Moreover, if the rate of movement for the past 400 ± years, which includes the entire historic record of earthquakes along the San Jacinto fault zone, has been similar to the average performance of the fault zone over the past 730 thousand years, it requires that a major increase in the average rate has taken place in relatively late Holocene time. Such a change may have taken place abruptly either before or after the time of accumulation of the youngest deposit of Lake Cahuilla, or it may have gradually accelerated through a time interval that spans the last high stand of the lake.

The fluctuation in slip rate in the past 6000 ± years for the San Jacinto fault zone could be characteristic of its long-term behavior. Although there are now no data points between 6000 ± and 730,000 years BP, the fact that periodic and appreciable changes in the rate of movement are possible within that interval of time as well indicates that maximum rates of slip may exceed the average 8-12 mm/yr rate. Although the capacity for slip along the San Jacinto fault zone may be great enough to periodically absorb all of the motion between the Pacific and American plates, the absence of slip data for the southern San Andreas fault zone for the corresponding period of time will not permit a definite conclusion to be drawn.

In view of the role of the San Jacinto fault zone as the most seismically active member in the San Andreas system of faults in southern California within the roughly 100-year record of historic earthquakes, if movement is now accelerating toward its more typical long-term rate, we might expect that future frequency of moderate-sized and possibly even large seismic events could increase. Alternatively, if the San Jacinto fault zone is now already moving at a rate comparable to its average for late Quaternary time, possibly the present level of seismicity will not increase substantially.

The changes in rate of movement indicated by the data in this paper suggest that the San Jacinto fault might be regarded as "typical" insofar as the long-term historic behavior of strike-slip faults have been worked out elsewhere on the earth. Ambraseys' [1971] analysis of the 2000-year historic record of earthquakes in northern Turkey suggests seismically quiescent periods for the Anatolian fault. Although geologic data on slip for the corresponding period do not exist, seismic inactivity for the six centuries between 500 and 1100 AD may have been associated with reduced rates of strain accumulation and fault slip. Cyclical patterns in the 3000-year record of seismicity in China have been described by Mei [1960] and McGuire [1979] but to this time have not been clearly related to individual fault zones.

The rates of slip on the San Jacinto fault zone presented in this paper can be reported in an alternative form, the earthquake recurrence time, for a given point in the fault zone. To make the conversion of slip rate to recurrence time, one must arbitrarily decide on what maximum movement is to be expected per slip event, and/or what the maximum magnitude of the associated earthquake might be. For the ranges of slip rate of the fault zone over the different time periods and the equivalent earthquake recurrence times, summarized in Table 3, three values of horizontal slip have been used. The maximum slip observed for the 1968 Borrego Mountain earthquake leads to the shortest estimates of recurrence time. Displacement of 0.6 m for a "normal" M_s 6.7 earthquake from magnitude-displacement relations revised from Bonilla and Buchanan [1970] yields intermediate results. Allowing that earthquakes on the San Jacinto fault zone may reach magnitude 7, an expectation consistent with the historic record of seismicity [Thatcher et al., 1975], the longest recurrence times result if "normal" 1.2 m displacements for that magnitude are used. Note that if the magnitude of the 1968 earthquake at Borrego Mountain and its displacement are the most expectable for a moderate seismic event on the San Jacinto fault zone, rather than the statistically derived larger slips, surface faulting approximately once per century at a given point is predicted. To carry the implications further, if a total length of the San Jacinto fault is taken to be 215 km, divided by a 33-km rupture length for a M_S 6.7 earthquake [Clark, 1972], then earthquakes equivalent in size to the 1968 event might occur with a frequency less than 7.4 years for the entire zone, when the fault zone is slipping at its average rate for the past 730 thousand years. The fact that earthquakes of about this magnitude have occurred about every 11 years in historic time [Thatcher et al., 1975] is supportive and independent evidence that the slip rate on the San Jacinto fault zone has sped up from a lower rate during the quiescent period and may be now approaching the average slip rate for the past 730 thousand years.

What are the regional tectonic implications of a greatly reduced rate of movement on the San Jacinto fault zone? If migration of dominance of earthquake activity and slip rate is postulated for the San Jacinto and San Andreas fault zones as alternating active boundaries of the Pacific plate, then a relatively quiescent period in the slip record for the San Jacinto zone may imply a corresponding period of high activity for the San Andreas fault zone. Not only does the historic record for Turkey support the credibility of this relation, but the San Andreas fault in the Coachella Valley region shows abundant geomorphic evidence of youthful activity; yet historic seismic activity on this part of the San Andreas is extremely low. If one of the two fault zones alternately dominates, the San Jacinto data suggest that perhaps as recently as 400 ± years ago, plate motion south of the Transverse Ranges was expressed mainly as slip on the San Andreas fault.

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TABLE 1. Trace-element abundances in rhyolite ash samples*

Sample	Sc	Mn	Fe	Rb	Cs	La	Ce	Sm	Eu	Tb	Dy	Yb	Lu	Hf	Ta	Th	U
1	2.95	266	0.51	188	5.4	20.0	46.8	3.65	0.04	0.57	4.02	2.64	0.37	3.60	2.10	20.8	6.70
2	3.06	265	0.54	187	6.0	19.4	47.1	3.74	0.04	0.56	4.10	2.70	0.37	3.74	2.15	21.0	6.69
Approximate Analytical Error																	
	0.03	3	0.02	9	0.2	0 06	0.08	0.02	0.01	0.03	0.11	0.05	0.02	0 08	0.01	0.1	0.07

Sample 1: Collected at point shown by circled dot, Figure 3, by R.V. Sharp.
Sample 2: Airfall ash at the base of Bishop Tuff collected at Insulating Aggregates Quarry., Bishop. CA., by A.M. Sarna-Wojcicki.

*Abundances of all elements reported in ppm, except Fe, in atomic percent. Samples prepared by A.M. Sarna-Wojcicki.
Analyst, Harry Bowman, Lawrence Berkeley Laboratory, CA.

TABLE 2. Slip rates for the San Jacinto fault zone

Maximum Age (my)	Displacement distance (km)		Slip rate mm/yr	
	Minimum:	5.7	Minimum:	8
0.73	Likely:	6.6	Likely:	9
	Possible:	8.6	Possible:	12

TABLE 3. Earthquake Recurrence Time (yrs)

Time period (yrs BP)	Range of slip rate mm/yr	1968 slip*	Normal slip **	M_{s}= 7 Normal slip†
Present to	>2.8	<130-140	<210	<430
400 ±	<5.0	>80	>120	>240
400 ± to	>1.4	<270	<430	<860
6000 ±	<2.0	>190	>300	>600
Present to	>8	<50	<70-80	<150
0.73×10^6	<12	>30	>50	>100

* Maximum 1968 slip = 380 mm reported by Clark [1972].

** "Normal" slip for M 6.7 event = 0.6 m, from data revised from Bonilla and Buchanan [1970]. ‡

† "Normal" slip for M 7.0 event = 1.2 m from data revised from Bonilla and Buchanan [1970]. ‡

‡ Supplied by M.G. Bonilla (written communication, 1978).

FIGURE CAPTIONS

Fig. 1. San Jacinto fault zone in the Peninsular Ranges and western Imperial Valley. Unpatterned area represents exposure of late Cenozoic, chiefly Quaternary, deposits. Patterned area represents crystalline basement rocks. T, location of two trenching studies of Coyote Creek fault. Faults shown by heavy lines, dotted where concealed. CF, Clark fault; HSF, Hot Springs fault; TMF, Thomas Mountain fault; BRF, Buck Ridge fault; CCF, Coyote Creek fault; SHF, Superstition Hills fault; SMF, Superstition Mountain fault. Many of the unnamed faults in the Imperial Valley region are previously unmapped structures. Fault nomenclature after Sharp [1972].

Fig. 2. Geologic map of area near Anza (see Figure 1 for location). Faults shown by heavy lines, dotted where concealed. CF, trace of Clark fault; BRF, Buck Ridge fault. Qa, Quaternary alluvium; Qb, Pleistocene Bautista Beds of Frick [1921]; Qbm, Bautista marker gravel used to determine displacement on the faults; Kt, Ka, Kg, Cretaceous tonalite, adamellite, and gabbro, respectively; pkm, Cretaceous and older metamorphic rocks. Circled letters A-D explained in text.

Fig. 3. Geologic map showing stratigraphic relations between rhyolite ash beds and marker gravel north of Anza (see Figure 2 for location). Faults shown by heavy lines, dashed where approximately located,

dotted where concealed. Hachures on faults drawn on down thrown side. Depositional contacts and ash beds (near letters r) shown by light lines, dashed where approximately located, dotted where concealed. Geologic units indicated by symbols and patterns: Qb_1, Qb_2, Qb_3, late Pleistocene Bautista Beds of Frick [1921] composed chiefly of gravel, sand, and silt and clay, respectively (boundaries between different principal lithologic units not mapped); Qa, young Quaternary alluvium; Qoa, older Quaternary alluvium; Kt, Cretaceous tonalite. Topographic contours in feet. Circled dot, location of Sample 1, Table 1.

Fig. 4. Graph of latest Holocene right-lateral displacement on Coyote Creek fault in western Imperial Valley. Line A represents age of layer of plant debris $\pm$ one standard deviation and amount of horizontal offset of base of latest sedimentary layer of Lake Cahuilla. Point B, estimated minimum age of drying of Lake Cahuilla. Point C, maximum surface displacement of 1968 Borrego Mountain earthquake. Solid lines represent limiting average slip rates for the time interval in actual years before present. Dotted line, historic slip rate estimated from seismic moment data of earthquakes between 1912 and 1963 [Brune, 1968]. Dashed line, possible average minimum slip rate prior to 1912. Origin on time scale is 1978.

Fig. 5. Map of displaced channel edge on Coyote Creek fault in western Imperial Valley. Light lines indicate edge of channel. Heavy lines represent fault strands, two of which moved during the 1968 Borrego Mountain earthquake (heavy dots).

Fig. 6. Graph of late Holocene right-lateral displacement for the Coyote Creek fault in western Imperial Valley. Solid lines represent limiting average slip rates for the time interval in actual years before present. Dotted line, historic slip rate from Brune [1968]. Bar at D represents age range of youngest detrital charcoal found in channel (5155 ± 125 years BP). Bar at E, range of maximum age of marker bed truncated by channel (6700 ± 90 years BP). Points A and B from Figure 4. Horizontal arrows on data bars indicate direction toward actual slip curve. Sloping arrows, uncertainty in the end points of the limiting rate lines. Origin on time scale is 1978.

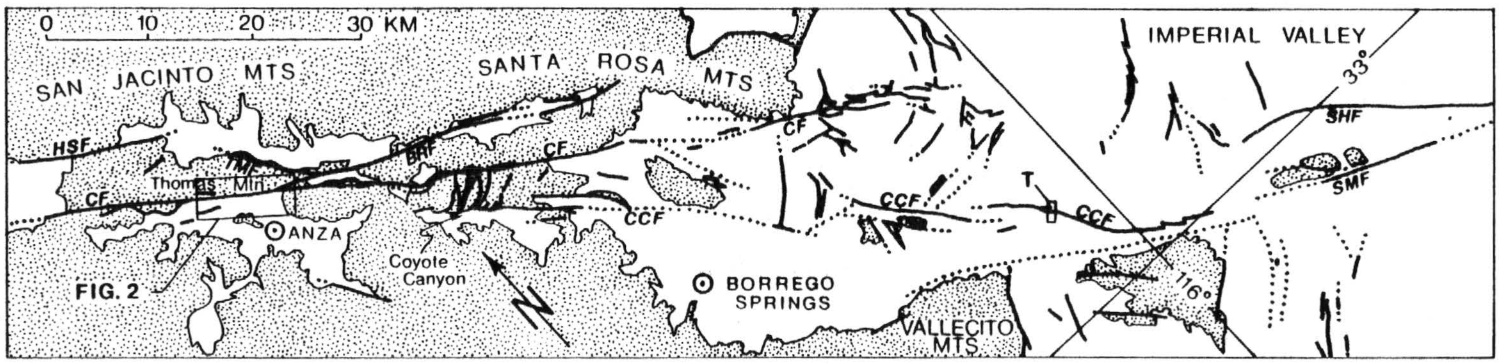

0 10 20 30 KM
SAN JACINTO MTS
SANTA ROSA MTS
IMPERIAL VALLEY
33°
HSF
CF
Thomas Mtn
ANZA
FIG. 2
Coyote
Canyon
N
CCF
BORREGO
SPRINGS
VALLECITO
MTS
T
SHF
SMF
116°

FIG. 1

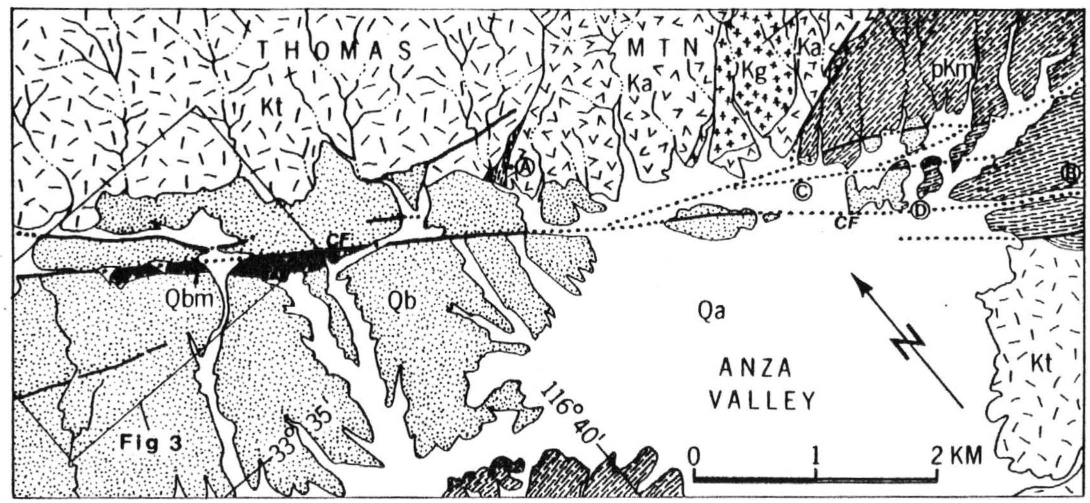
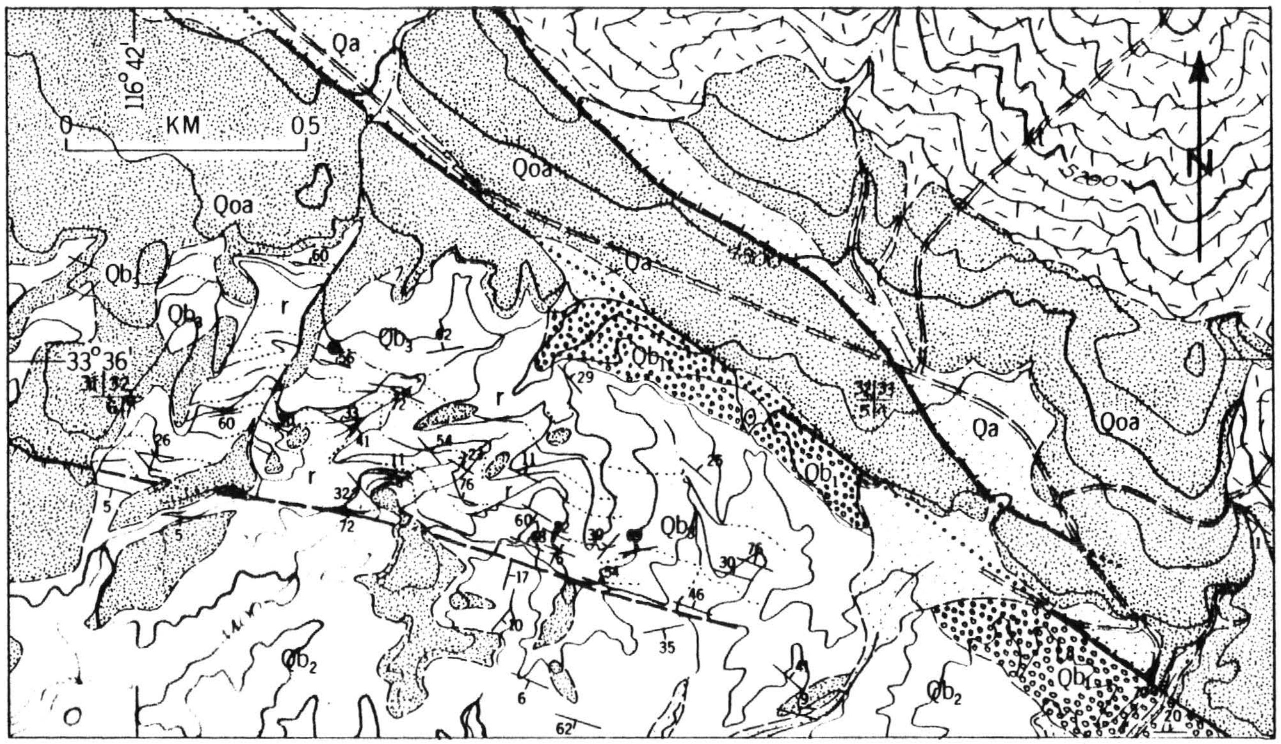

THOMAS
MTN
Kt
Ka
Kg
pKm
CF
Qbm
Qb
Qa
ANZA
VALLEY
Fig 3
33° 35'
116° 40'
0
1
2 KM

FIG. 2



FIG

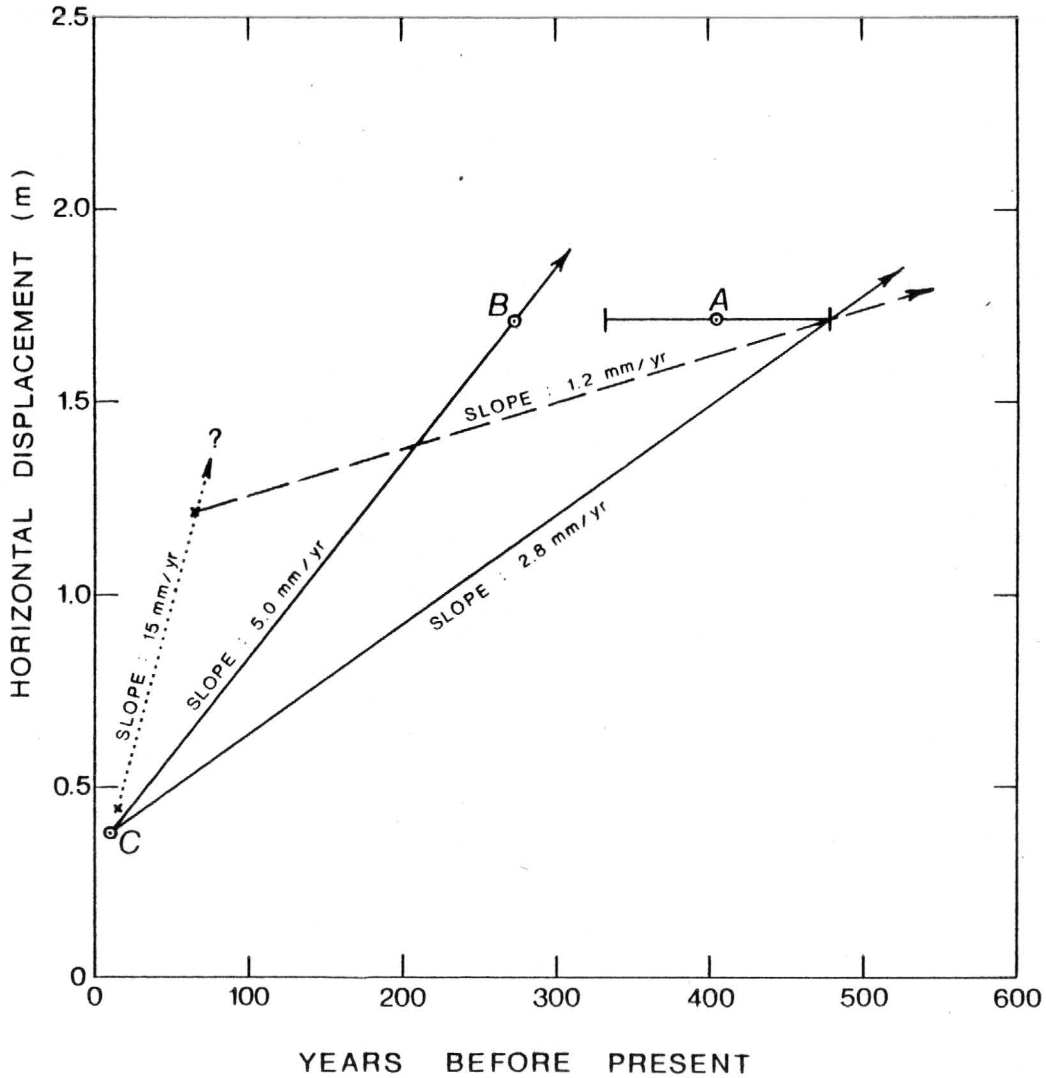

HORIZONTAL DISPLACEMENT (m)
YEARS BEFORE PRESENT
2.5
2.0
1.5
1.0
0.5
0
0
100
200
300
400
500
600
A
B
C
?
SLOPE : 1.2 mm/yr
SLOPE : 15 mm/yr
SLOPE : 5.0 mm/yr
SLOPE : 2.8 mm/yr

FIG. 4

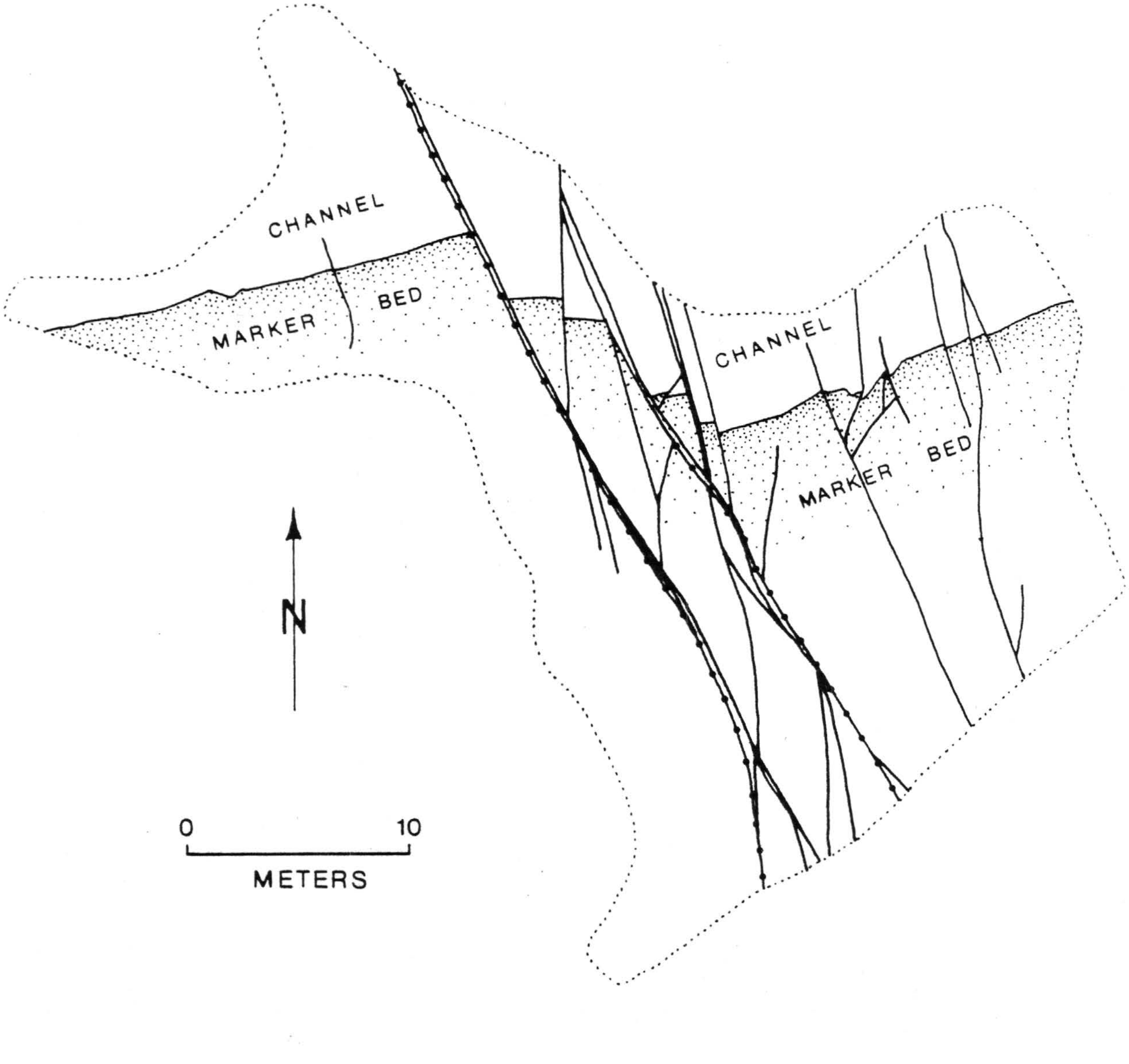


FIG. 5

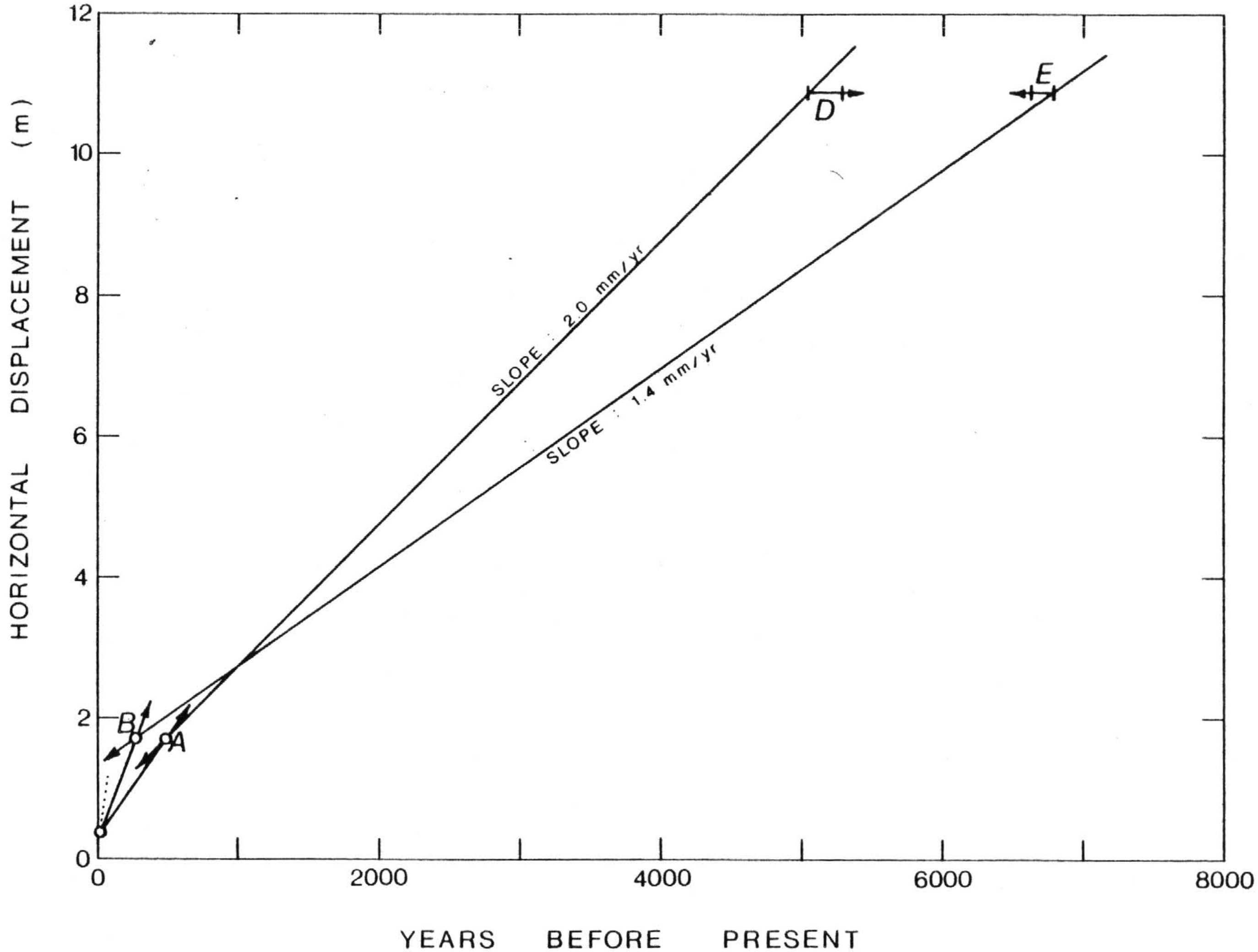

HORIZONTAL DISPLACEMENT (m)
YEARS BEFORE PRESENT
0
2
4
6
8
10
12
2000
4000
6000
8000
SLOPE : 2.0 mm/yr
SLOPE : 1.4 mm/yr
A
B
D
E

FIG 6