A Review of Geological Evidence for Recurrence Times of Large Earthquakes

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Abstract. The geological record of the past several thousand years contains valuable information for evaluating the earthquake potential of the earth's major fault systems. Geologists have begun to characterize past and, presumably, future behavior of active faults and recurrence intervals for large earthquakes by studying 1) uplifted marine terraces, 2) fault-scarp morphology, 3) physiographic features offset along faults, and 4) faulted or otherwise deformed young sediments.

Along the convergent plate margins of Alaska and Japan, for example, studies of uplifted marine terraces have aided in evaluating the likelihood of imminent rupture of faults in two seismic gaps. In Nevada, Utah, and eastern California, detailed studies of scarp morphology along normal faults of the Basin and Range Province are beginning to reveal the recurrence intervals, sizes, and patterns of prehistoric earthquakes. Studies of offset stream channels along the San Andreas fault have shown that right-lateral events of as much as 10 m have occurred repeatedly in the past with an average frequency of about two hundred years. Elsewhere along the San Andreas and on other faults in California and Japan, studies of faulted and deformed young sediments have enabled dating of specific prehistoric earthquakes or, at least, a determination of the minimum number of events that occurred during the deposition of the strata.

In the western U.S. and Japan and perhaps in other seismically active regions as well, there is good reason to believe that within the decade we will know the average recurrence intervals, regularity, and sizes of past large seismic events at several localities. Hopefully, this will enable forecasts of some future large earthquakes with uncertainties measured in decades rather than centuries and will provide a sound basis for hazard mitigation and for directing short-term predictive efforts to those fault segments in imminent danger of rupture.

Introduction

Purpose and Organization

An important element in the development of earthquake prediction and mitigation capabilities is knowledge of the long-term behavior of seismogenic faults. In a given earthquake-prone region the duration of the dormant period between large earthquakes, the regularity of that period, and the date of the latest event all aid in assessing whether or not an earthquake will occur in the near future.

Unfortunately, in most seismic regions, the period of historical and instrumental record is far too short to allow determination of the long-term seismic behavior for that region. However, the geologic record of the Holocene and late Pleistocene epochs is proving to be quite valuable in understanding long-term patterns of earthquake recurrence.

This paper calls attention to numerous studies of the geologic record that have aided in understanding the relationships of slip events on major faults in space and time. Although work in several tectonic settings around the globe is discussed, this is not an exhaustive review; rather, my intention has been to illustrate realized contributions and to suggest future contributions of geologic studies in evaluating long-term seismic behavior.

The first three sections of the main text describe and discuss studies of oceanic megathrusts, continental dip-slip faults, and strike-slip faults, in that order. Each of these three types of fault is associated with a distinctive geological environment, and each environment has fostered distinctly different approaches in studying long-term seismic behavior.

The fourth section of the main text outlines studies of the San Andreas fault. I have segregated these from discussion of other strike-slip faults because I wish to summarize and evaluate current understanding of the geologically recent behavior of that great fault.

The fifth major section discusses my perceptions of current problems and limitations and my impressions of new directions in which this field may be headed.

Importance of Past Seismic Behavior

Samplings from a broad spectrum of recent papers dealing with the evaluation of seismic potential [e.g. Allen, 1975; Kelleher *et al.*, 1973; and Shimazaki and Nakata, 1980] reveal the general belief in a reconstituted uniformitarian principle. Simply stated, that guiding principle is that the historical and more ancient seismic past is a key to the seismic future. The degree to which this is true determines the predictive value of studying historical and more ancient seismicity.

Concept of average recurrence interval. The historical record does indicate that in several areas large seismic events are, to a remarkable degree, repeat performances. Large subduction events off the southwestern coast of Japan and southern coast of Chile are celebrated historic examples.

History records large Chilean earthquakes in 1575, 1737, and 1837 that were very similar to the great earthquake of 1960 (Fig. 1A) [Lomnitz, 1970; Kelleher, 1972]. If one assumes that the historical record for this region is complete, three periods of 162, 100, and 123 years separate these four great Chilean events. History also records a remarkable series of great Japanese earthquakes between 684 and 1946 A.D. (Fig. 1B) [Ando, 1975; Ishibashi, 1980]. Failure of a 200-km-long segment of the Nankai Trough megathrust occurred in 684, 887, 1099, 1361, 1605, 1707, 1854, and 1946. A similar set of dates applies to the adjoining 200-km-long segment, although there are significant ambiguities in interpretating the historical records for that segment. The range in intervals between events along both segments may be exaggerated by the exclusion of undiscovered events between 1707 and 684 A.D. Nevertheless, the historically recorded events affecting the western 200-km-long segment have occurred 92 to 262 years apart.

These two examples from Chile and Japan and others lend credence and usefulness to the concept of an *average recurrence interval* -- a number indicating the average period between large events for a given region or source. The *average recurrence interval* is 180 yrs in the Japanese example and 128 yrs in the Chilean case. In these two historical cases actual recurrence intervals stray from the average value by as much as 45%, if one assumes both records are complete. Using only the records of the latest 2-1/2 centuries, which are almost certainly complete, no actual interval varies from the average by more than 23%.

The historical record strongly suggests that neither Chile nor Japan need fear a repetition of the events discussed above for at least half a century and perhaps longer. The variation in actual recurrence intervals, however, precludes a more precise forecast of the date of the next great earthquake at either locality. Nevertheless, knowing these historical recurrence intervals may prove to be critical in motivating efforts at hazard mitigation and in predicting future great events by geodetic or geophysical methods. Likewise, geological studies that augment the historical earthquake record by providing average recurrence intervals increase the possibility of forecasting or predicting future seismic activity.

Concept of repeated earthquakes. The degree to which large fault ruptures physically mimic or duplicate their "predecessors" is poorly known, since documentation of the displacements, rupture lengths, and other physical characteristics of large events is sparse. The few examples that do seem to be adequately documented suggest that the physical characteristics of sequential events can be remarkably similar or appreciably different. In the Japanese example discussed above, for example, segments C and D tend to lead A and B by several hours or years, but in 1707 and possibly in 887 A.D. they broke at once. Also, the rupture of segments C and D in 1854 extended to the east, into Suruga Bay. This extension did not occur when C and D last broke, in 1944 [Ishibashi, 1980] -- thus, the current concern that the heavily industrialized Suruga Bay area (Tokai District) may soon experience a large earthquake.

The concept that earthquake and fault ruptures repeat and have repeat times that cluster around an average recurrence interval may not be valid in some regions. The time of occurrence and characteristics of a fault rupture in a region containing many faults of similar size and degree of activity may be influenced by far more complex cycles of stress application, unloading, and redistribution than are envisioned for "simple" plate boundaries characterized by one predominant, master fault. The deviations from the average recurrence interval for a fault in a region of multiple large seismic sources may be so great that knowing the average recurrence interval has little predictive value.

The above cautions notwithstanding, the availability and completeness of the known record of *past* earthquakes governs to a large degree our ability to understand, forecast, and thus, to predict *future* large seismic events. As the historical period lengthens, well-documented spatial and temporal relationships of large earthquakes will emerge in much greater detail than is presently available. Until the historical/instrumental period is several average recurrence intervals long, however, the need for augmentation of the historical record and discovery of the more ancient record will remain acute.

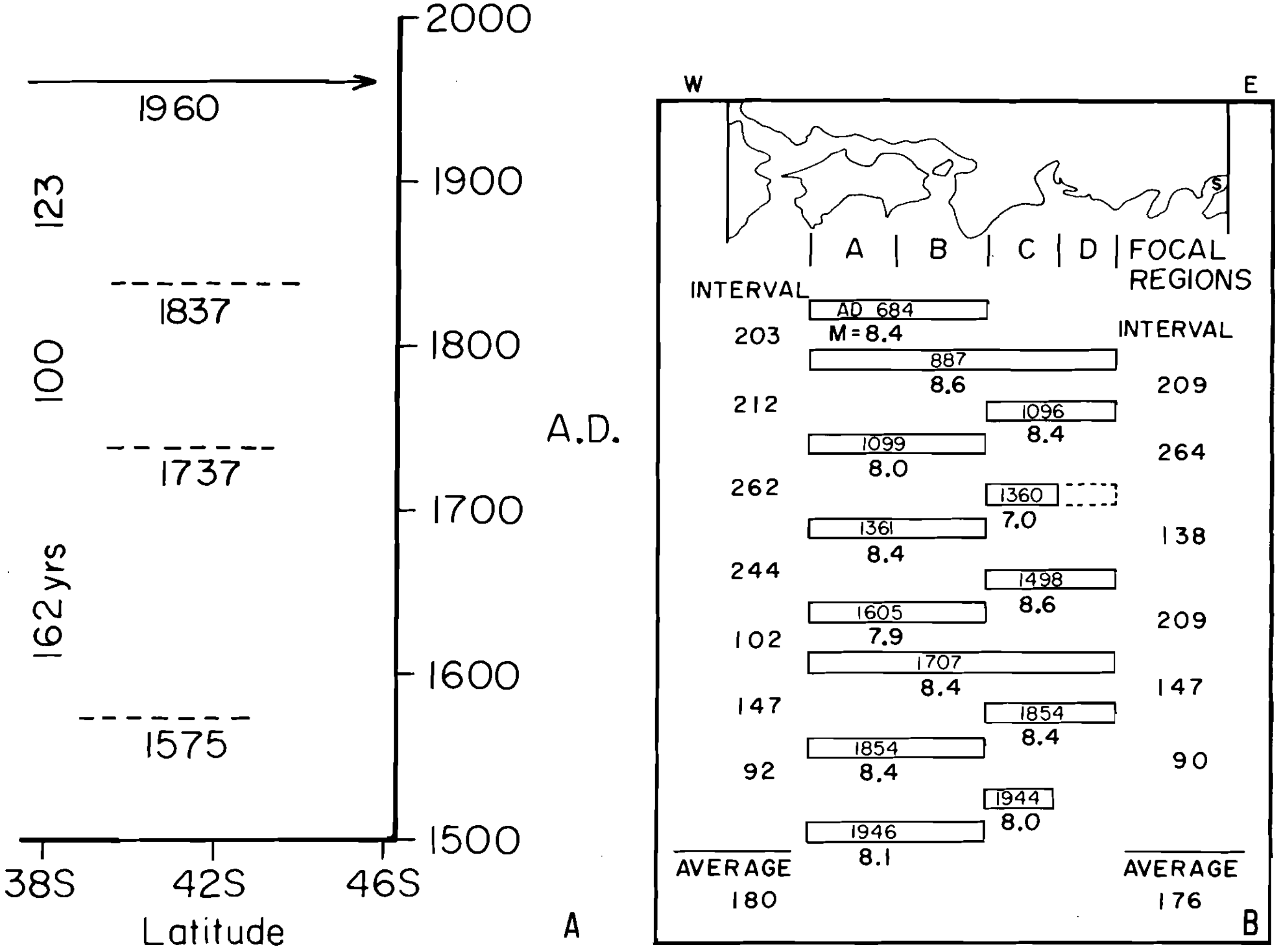

Fig. 1. A: Three large Chilean earthquakes in 1837, 1737, and 1575 preceded the great 1960 earthquake (from Kelleher, 1972). B: A remarkable series of large earthquakes has occurred between 684 and 1946 A.D. in coastal southwestern Japan [from Yonekura, 1975, based on Ando, 1975 and other sources]. Both the Chilean and Japanese localities demonstrate a degree of regularity in style and timing of large earthquakes. For a slightly different interpretation of the historical documents, see Ishibashi [1980, Fig. 1]. S = Suruga Bay.

Convention Regarding the Reporting of ^{14}C Dates

In the many studies discussed below, radiocarbon dating of materials is the principal means by which actual ages can be assigned to ancient earthquakes. In this paper I have adopted the following convention for reporting these radiocarbon dates: Dates based on ^{14}C analyses which have not been corrected for isotopic fractionation or for known temporal variations in atmospheric abundance of ^{14}C are given as "^{14}C yrs B.P." ("B.P." means "before 1950 A.D."). Corrected or calendar ages are given as "yrs B.P." or "A.D."

Emergent Shorelines and Great Subduction-Zone Earthquakes

Boso/Oiso Area, Japan

Studies of the history of coastal uplift as recorded in emergent shorelines and related marin terraces are currently the major avenue for determining the long-term spatial and temporal characteristics of large subduction zone earthquakes. Recent studies of the coastal terraces south of Tokyo, Japan [Matsuda et al., 1978 and Nakata et al., 1979] are exemplary. Not only are marine terraces providing information on the repeat time of great earthquakes there, but they are also enabling a relatively detailed understanding of mechanisms and spatial patterns. Geologically, the region is characterized by complex (and still somewhat enigmatic) active shallow-dipping structures related to subduction of the Philippine Sea plate (Figs. 2 and 3). Forecasting future events is critically important in this heavily populated, urbanized region which suffered devastation in the great earthquakes of 1923 and 1703.

The 1703 earthquake was accompanied by sudden emergence from the sea of a wave-cut platform and shoreline. Additional uplift of the shoreline and nearby region was measured geodetically following the 1923 event. The present elevation of the pre-1703 (Genroku) shoreline is the sum of the 1703 and 1923 uplifts minus subsidence that occurred between the events and after 1923 (Fig. 3). From these uplifts and other information, Ando [1974] deduced geometries for the main faults on which displacement occurred at the time of the earthquakes (Fig. 3). The 1703 earthquake may have been produced principally by dextral strike slip on segments B and C, and the southeastern part of segment A. The 1923 earthquake may have resulted from slip on segment A alone.

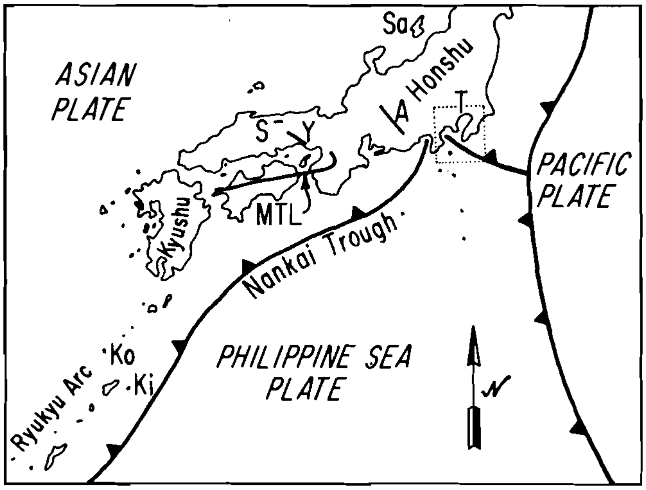

Fig. 2. Many geological studies pertinent to the assessment of seismic potential are being conducted in Japan and in the Ryuku Islands (adapted from Shimazaki and Nakata, 1980). A = Atera fault; Ki = Kikaijima; Ko = Kodakarajima; MTL = Median Tectonic Line; Sa = Sado Island; S = Shikano fault; T = Tokyo; Y = Yamasaki fault. Dot pattern indicates Boso/Oiso area south of Tokyo (Fig. 3); sawteeth are on upper plates of subduction megathrusts.

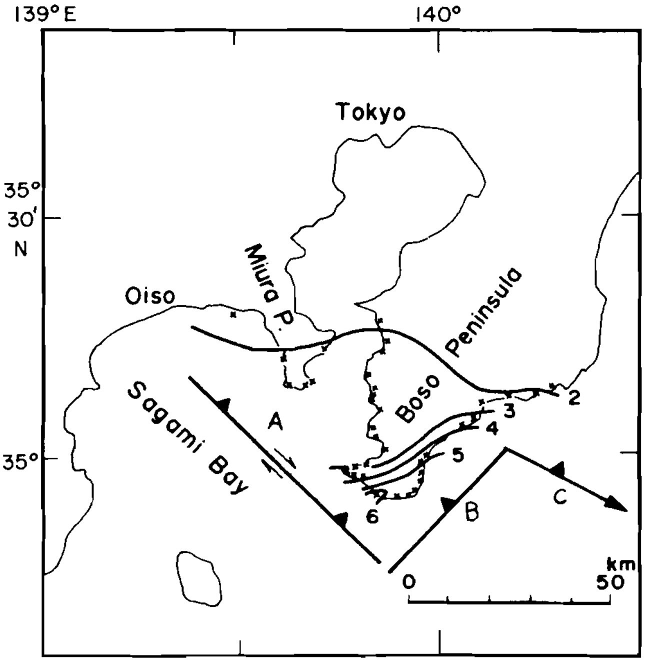

Fig. 3. Boso/Oiso area south of Tokyo. The contours (in meters) represent uplift associated with the great earthquakes of 1707 and 1923. They are based on the measured height above present sea level of the Genroku (pre-1703) shoreline. Crosses indicate localities of measurement [from Matsuda et al., 1978]. Uplift patterns for each earthquake were important in determining the rupture planes (A, B, and C) associated with the earthquakes [Ando, 1974].

Three progressively older and higher shorelines and platforms exist progressively landward of the Genroku shoreline and platform [Matsuda et al., 1978, Fig. 6]. Each shoreline displays a pattern of deformation very similar to, but of progressively greater magnitude than, the Genroku shoreline. Figure 4 illustrates the deformation of the oldest shoreline (Numa I). The similarity between this and the deformation of the youngest shoreline on the Boso Peninsula (Fig. 3) is remarkable. The dates of emergence from the sea of these older shorelines has been determined by Nakata et al. [1979]. Samples collected from the marine (pre-emergent) and non-marine (post-emergent) portions of the terraces yielded the radiocarbon ages plotted in Fig. 5A. These suggest emergence of Numa I ~5,500-6,150 ^{14}C yrs B.P., Numa II ~4,300 ^{14}C yrs B.P., and Numa III ~2,900 ^{14}C yrs B.P. Thus, three prehistoric great uplift events, or uplift sequences, very similar to the 1703/1923 sequence are documented in the marine terrace record on the Boso Peninsula. As the periods between events, or event sequences, are ~1,000 to ~2,000 ^{14}C yrs long, the occurrence another event like the 1703 or 1923 earthquake is considered remote [Matsuda et al., 1978, p. 1616].

However, one significant difference between the uplift pattern of the Genroku shoreline and the older shorelines has caused great concern [Matsuda

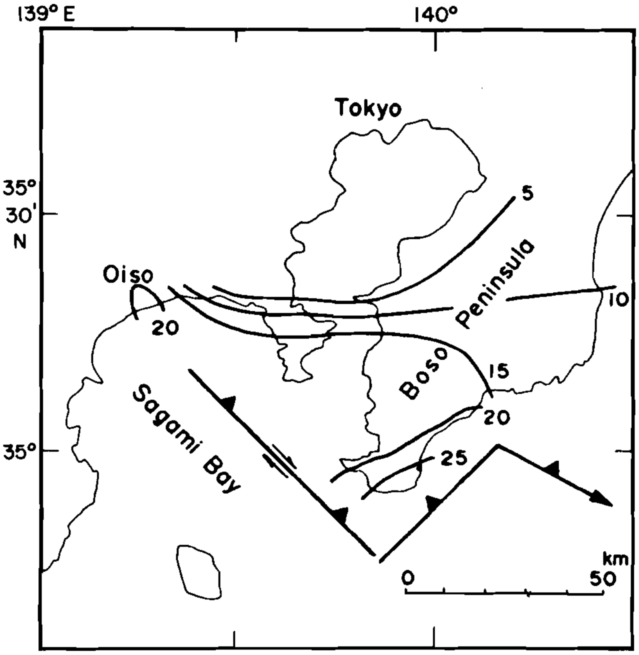

Fig. 4. The elevation of the Numa I shoreline above sea level ranges from a few meters to >25 m. The similarity of this pattern of deformation on the Boso Peninsula to that of the Genroku shoreline indicates that the 1707 and 1923 uplifts mimicked earlier uplifts [from Matsuda et al., 1978]. The dissimilarity of patterns in the Oiso region lead Matsuda et al. [1978] to forecast a great earthquake for that region.

et al., 1978, p. 1616-1617]. The 1703 and 1923 uplift in the Oiso region is much less than the uplift on the Boso Peninsula (Fig. 3), whereas the older terraces are at comparable elevations in both regions (Fig. 4). If the past is a key to the future, the Oiso area "is a candidate for a future large earthquake", involving several meters of uplift and rupture of nearby submarine and subaerial faults [Matsuda et al., 1978].

Middleton Island, Alaska

The coastal terraces of Middleton Island, in the northern Gulf of Alaska (M on Fig. 6), have also provided valuable long-term information concerning the recurrence of great earthquakes [Plafker and Rubin, 1978]. Here also is a flight of young terraces, the youngest of which was lifted 3-1/2 m above the present shoreline elevation during the great Alaskan earthquake of 1964. Mapping of the terraces and stratigraphic studies of the terrace deposits are yielding a detailed picture of several sudden uplifts of the island during the past ~5,000 yrs. Current estimates are that one or more closelytimed events are represented by each terrace and that a new terrace at least six to nine meters high has emerged about every 850 ^{14}C yrs, on the average (Fig. 7). Individual intervals shown in Fig. 7 deviate from this average by about 50%. The lesser intervals are similar to estimates of ~480-640 years made by dividing the "instantaneous" (i.e. several-million-year average) plate rate of 62 mm/yr [Minster and Jordan, 1978] into the maximum slip of ~30 to 40 m [Miyashita and Matsu'ura, 1978, Fig. 6] on the Alaskan-Aleutian megathrust associated with the 1964 earthquake. Plafker and Rubin note that the 1964 uplift is only one-third to one-half of the uplift values estimated for previous events. Because of this, they suggest, with certain reservations, that another large event may produce additional uplift within a period much shorter than the average recurrence interval. They suggest that this event may be the same event expected to rupture the ~200-km-long Yakataga seismic gap between the 1964 rupture and the Fairweather fault [Sykes, 1971]. The occurrence within a few

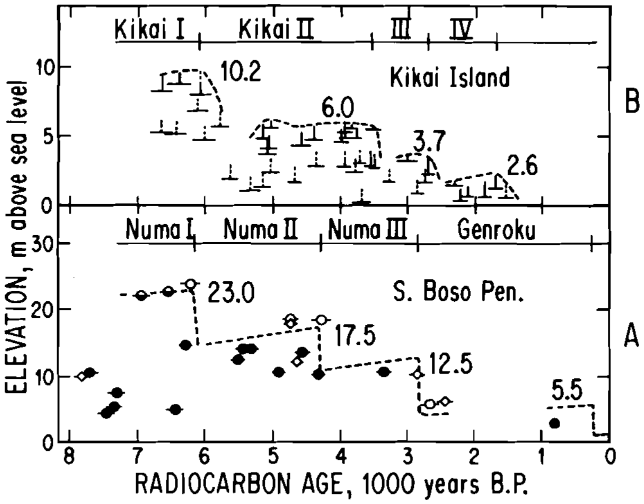

Fig. 5. A: Graph of ^{14}C ages of materials in the Numa I, Genroku, and two intermediate terraces indicates four sudden changes in sea levels, which are inferred to represent a great earthquake or great earthquake sequence. The open, half-closed and closed circles indicate the samples above, near and below the former sea level, respectively. No information is available for the sample shown by the diamond. B: Graph of coral terrace elevations and ages indicate large earthquakes on Kikaijima in the Ryuku Islands. Horizontal bars indicate the sampling elevation and the uncertainty in age. Top of the solid bar shows the estimated height of the former sea level. The broken curves show estimated uplift history assuming some interseismic subsidence. The numeral shows the present elevation of the former shoreline mainly determined from beach angle elevations [from Shimazaki and Nakata, 1980].

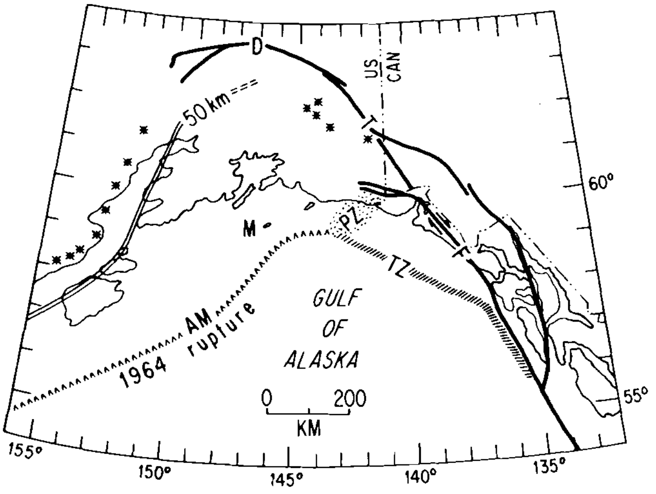

Fig. 6. In Alaska, geological studies have provided data pertinent to assessment of earthquake potential for the labelled structures: AM = Alaska-Aleutian megathrust; D = Denali fault; M = Middleton Island; PZ = Pamplona zone; T = Totschunda fault; TZ = Transition Zone; * = volcanos; double line is 50-km isobath of Benioff Zone [from Lahr and Plafker, 1980]

decades of such an earthquake similar in size to the 1964 event would even make 1000-yr-long recurrence intervals between terrace-producing earthquake sequences consistent with intervals calculated from plate rates.

Other Studies of Marine Terraces

On Kodakarajima, off southern Kyushu, Japan (Ko on Fig. 2), recent work by Nakata et al. [1979, p. 196-197] has revealed that a sudden uplift of $\lesssim$8 m occurred about 2,450 ^{14}C yrs B.P. A prior interval of gradual interseismic submergence seems to have lasted a few thousand years without interruption, and post-seismic uplift over a period of ~1000 yrs may have occurred also. They estimate an average recurrence interval of about 10,000 yrs for such seismic uplifts.

Nakata et al. [1979, p. 197-199] have also documented several periods of sudden uplift farther south, on Kikaijima, one of the northernmost of the Ryukyu Islands (Ki on Fig. 2, and Fig. 5B). These uplifts are inferred to have been seismic and occurred ~5,200-6,065; ~3,520; ~2,700; and ~1,700 ^{14}C yrs B.P. which yields recurrence intervals of ~1700-2500, ~800, and ~1000 ^{14}C yrs. (Average recurrence interval is between ~1200 and ~1400 ^{14}C yrs.) Inasmuch as no uplift has occurred in the past ~1700 ^{14}C yrs, this region should be considered well advanced in its current interseismic cycle. McCann et al. [1979, Fig. 1, p. 1125-1126] have stated that the megathrust in this region may not have the potential for a great earthquake, judging from the lack of great earthquakes during the short historical record. Here, then, is a situation in which geological extension of the seismic record may play a critical role in reassessing earthquake potential.

Ota et al. [1976] estimated that the average recurrence interval for major earthquakes like that which struck Sado Island in the Japan Sea off central Honshu, Japan (Fig. 1) in 1802 to be 5000 to 9000 years during at least the past 100,000 years and suggest that the interval before the 1802 event was $\lesssim$6,000 ^{14}C yrs. The estimate of average interval is based on the ratio of tilting observed in 1802 to tilt of a Pleistocene shoreline. Tilt of the older surface is similar in style to that of the younger, but much greater in magnitude. This type of analysis provides no information on deviations of actual intervals from the average.

Studies of elevated shorelines in other parts of the world are as yet few in number, but include a study by Taylor et al. [1980] of the Santo and Malekula Islands segment of the New Hebrides island arc. These authors related recent seismic patterns and bathymetry of the subducting oceanic

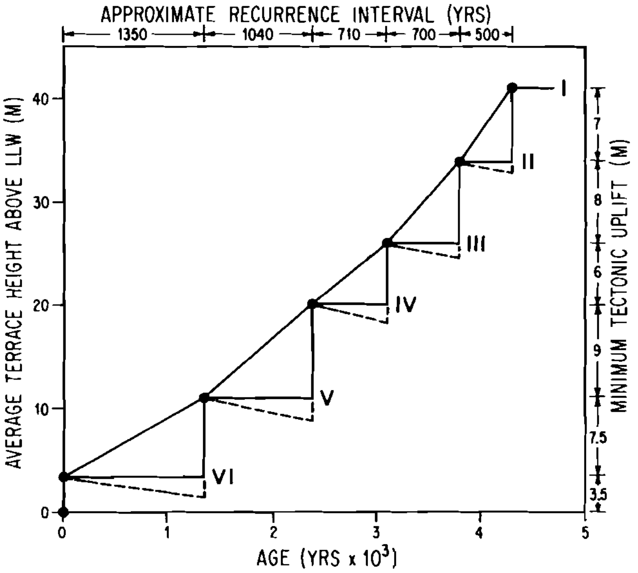

Fig. 7. Generalized diagram showing average terrace height [minimum tectonic uplift per event(s)] versus terrace age and approximate recurrence interval for Middleton Island. The solid curve shows an inferred uplift sequence assuming no interseismic vertical movement; the dashed line assumes some interseismic subsidence. The light solid line indicates the average uplift rate between terraces [from Plafker and Rubin, 1978]. The relatively small uplift of the youngest shoreline (3.4 m) in the great 1964 earthquake may indicate that a second large event will occur soon.

plate to patterns of terrace deformation on these islands which sit on the apex of the hanging wall of the New Hebrides megathrust.

Discussion

Megathrusts pose particular difficulties in the study of earthquake recurrence. One of the most severe problems has been an almost complete lack of exposure of megathrust traces on land. This has effectively prevented direct stratigraphic, geomorphic, or structural studies of the surface trace of the fault at appropriate scales and in appropriate detail.

Geologic determinations of the recurrence characteristics of great megathrust earthquakes necessarily are based upon study of accessible secondary features, principally elevated and tilted former shorelines and wave-cut surfaces. The raised shorelines and associated marine terraces of the Nankai Trough, Japan and Middleton Island, Alaska are situated just inboard of major imbricate thrust faults that branch upward from the megathrust. Yonekura and Shimazaki [1980] suggest that these terraces owe their existence not to slip on the megathrust but to slip on these lesser imbricate thrusts. Thus the dates of emergence of the terraces may represent the dates of seismic slip along the imbricate fault, not necessarily the megathrust.

Terrace uplifts associated with the 1944 and 1946 Nankai Trough earthquakes and the 1964 Alaskan earthquake indicate that slip occurred along the appropriate imbricate thrusts in conjuction with slip along the megathrust during those events. The uplift history of the marine terraces of the Nankai Trough suggest that during some great megathrust earthquakes slip along the imbricate fault has not occurred [Yonekura and Shimazaki, 1980]. The degree to which this is also true of other megathrusts will influence the extent to which a complete record can be obtained from emergent shorelines. Perhaps in some regions only a maximum average recurrence interval will be recoverable from the terrace record.

Complete elimination of a seismically produced marine terrace by wave action is a possibility that may be difficult to recognize. In such a situation, one emergent wave-cut surface, shoreline angle, and terrace would represent more than one seismic upheaval and the average recurrence interval would be overestimated. Similarly difficult to assess may be the possibility that some recurrence intervals between large earthquakes are shorter than the time required to cut a new wave-cut platform and shoreline angle. Such a situation would lead to underestimation of the average recurrence interval. In both cases above, the upheaval produced by more than one earthquake would be attributed to a solitary event.

Another factor that complicates the use of marine terraces to characterize and date large earthquakes is that major changes in sea level have occurred during the past several thousand years. Thus, the elevation of uplifted wavecut platforms and shorelines relative to modern sea level may not be equivalent to the amount of tectonic uplift. This is especially true for those features more than a couple thousand years old. In fact, emergent shorelines only exist where the rate of tectonic uplft is greater than the average rate of sea-level rise.

Although reliable curves of sea level vs. time have been established on some coasts [e.g. in southern Florida, Scholl et al., 1969] recent work has demonstrated that melting of the late Pleistocene continental glaciers produced Holocene coastal responses that varied between points on the globe [Clark et al., 1978]. Thus, the sea-level curve from a tectonically stable coast cannot necessarily be applied to correct for sea level changes affecting marine terraces in an area of tectonic interest. Modeling of the effects of the melting icecaps by Clark et al. [1978] does suggest some general characteristics of the Holocene sea-level curve for many areas of interest, however. Corrections involving a monotonic Holocene rise in sea level may pertain to coastal Japan and southeastern Alaska, for example. Thus, the elevation of older terraces may progressively underestimate true tectonic uplift. Further refinement of models of sea-level change will enable greater confidence in detailed comparisons of earthquake size based on amount of uplift.

Some emergent shorelines are probably not tectonic. Along some coasts widespread mid-Holocene wave-cut surfaces and shorelines are slightly elevated above sea level. These may be the result solely of sea-level fluctuations unrelated to tectonic activity [Clark et al., 1978]. To the best of my knowledge, the possibility that continuous or episodic aseismic subduction could produce emergent shorelines has not been investigated.

One promising new area of research involves the application of regional deformational patterns deduced from marine terraces [e.g. Ota and Hori, 1980, and Ota and Yoshikawa, 1978] to forecasting the nature of future earthquakes. The wave-length of deformations in Japan, for example (Fig. 8), might be roughly equal to the rupture length of related active faults. Many of the studies mentioned above support this suggestion.

Dip-Slip Faults On Land

Geomorphic Studies in the Great Basin by Wallace

Wallace [1977] pioneered recent attempts to use fault-scarp morphology to assess the repeat times of large earthquakes in the Great Basin of the western United States. This pilot study in north-central Nevada [see Fig. 1 of Wallace, this volume] demonstrated that fault scarps several meters in height in alluvial materials degraded systematically over hundreds, thousands, and

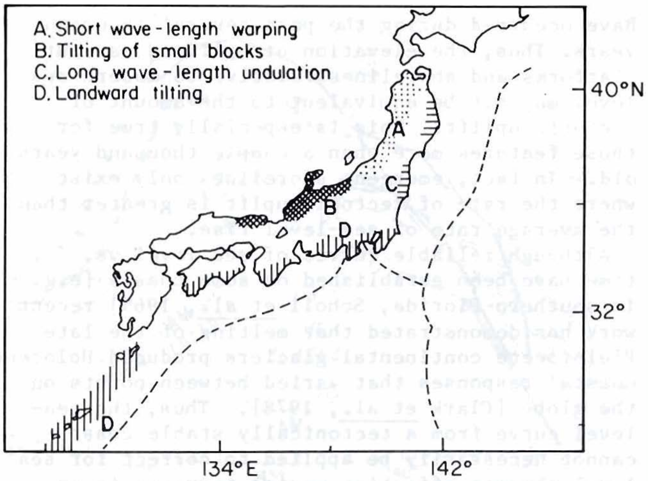

Fig. 8. Several styles and wavelengths of deformation are apparent from studies of the heights of former shorelines [from Ota and Yoshikawa, 1978]. Large historical earthquakes have mimicked these patterns, indicating that the deformational record preserved in marine terraces is an important key to the seismic future.

tens of thousands of years. With a few historical fault scarps and lakecliff scarps eroded by ancient Lake Lahonton about 12,000 yrs B.P. as calibrations, he was able to crudely date several pre-historic fault scarps in this arid region. Fig. 9 illustrates the distributions of principal (i.e. dominant) slope angles measured on several sets of fault scarps and the inferred approximate ages of the four scarp sets. He estimates average recurrence intervals of several thousand years for large events [Wallace, 1977, and this volume].

Along the fault scarp of the 1915 Pleasant Valley earthquake (M = 7.6, Richter, 1958) Wallace found geomorphic evidence for earlier events. Abrupt breaks in scarp profiles indicate at least two and possibly three older events. The principal slope of the youngest prehistoric event implies an age of about 10,000 yrs. Wallace [1978b] also estimated the magnitudes of the individual earthquakes represented by some of his scarps.

In addition, he observed that events cluster both in time and space [Wallace, 1977, 1978a]. "Most ranges shown [in Fig. 1 of Wallace, this volume] have been progressively tilted dominately eastward for approximately the last 10-14 million years... Individual clusters of scarps, such as on the west flank of the Humboldt Range or the west flank of the Tobin Range, display repeated movement during periods of time when other clusters of scarps nearby were inactive. For example, the faults on the west flank of the East Range have remained inactive for possibly several tens of thousands of years, while the faults along the Tobin and Humboldt Ranges, which bracket the East Range, were repeatedly active." The temporal and spatial distribution of large earthquakes as manifested by fault scarps in northern Nevada can be used for forecasting the sites of the next large earthquakes in this region. The observations also indicate that the number of large earthquakes accompanied by surface faulting during the 20th century is remarkably higher than usual. A careful study of the scarps of the penultimate event along each historic scarp might enable determination of whether this burst of recent activity has a prehistoric precedent in the late Pleistocene or earliest Holocene. Perhaps some faults ruptured during this postulated earlier burst of activity but have not ruptured recently. These might be candidates for rupture in the near future.

Owens Valley, Eastern California

On the western edge of the Great Basin, in eastern California, is the Owens Valley. Lubetkin [1980] has applied Wallace's method of geomorphic analysis to the Lone Pine fault, a small normal oblique-slip fault at the southern end of the valley, and argued that three events are probably represented by the 6-m-high scarp. The most recent event, associated with the great earthquake of 1872, is evidenced by the steepest 1-2 m of the scarp. The previous events occurred after ~10,000 to 21,000 ^{14}C yrs B.P., based upon the

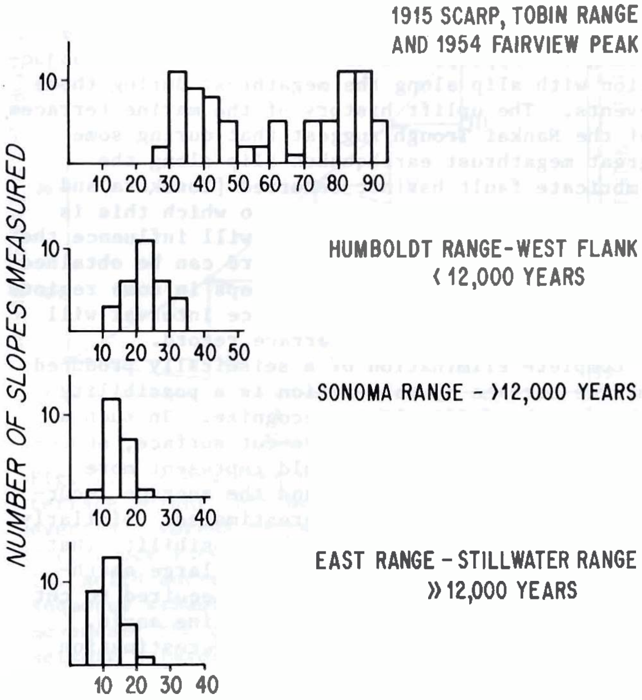

Fig. 9. Histograms of principal (i.e. dominant) slope angles on fault scarps, north-central Nevada. The slope angles indicate the age of the fault scarp and its associated earthquake [from Wallace, 1977].

inferred age of the faulted alluvial surface. This suggests an average recurrence of great earthquakes between ~3,300 and ~10,000 yrs. Lubetkin and Clark [1980] maintain that this interval is greater than that of the entire ~60 km length of the nearby mid-Owen's Valley fault zone, which last ruptured in 1872. Carver [1970, p. 74-88] studied a set of progressively deformed ancient shorelines farther south along the mid-Owen's Valley fault zone, and argued that the recurrence of events along the zone is between 700 and 1000 years.

The Wasatch Fault Zone, Utah

The ~370-km-long Wasatch fault zone delimits the eastern boundary of the Great Basin (Fig. 10) and poses a great threat to the major population centers of Utah, although it has not produced a large earthquake during the 133 years of historical record. Swan *et al.* [1980] have made an attempt to evaluate the recurrence intervals and sizes of earthquakes that occurred along this discontinuous zone of normal faulting during the Holocene. Their elegant study combined detailed geologic mapping, geomorphic analysis, and exploratory trenching at two localities -- Kaysville and Hobble Creek. Unfortunately, absolute chronologic control at both sites was very limited, but ~12,000 to ~15,000 yr ages for the youngest sediments of ancient Lake Bonneville and one ^{14}C date on a late Holocene unit at the Kaysville site enabled meaningful evaluations of earthquake recurrence.

At the Kaysville site, stratigraphic units and relationships in excavations clearly indicate two, and probably *only* two, large earthquakes since about 1,580 ± 150 ^{14}C yrs B.P. The authors suspect that the latest event occurred several hundred years ago and propose a 500- to 1000-yr average recurrence interval. Fault scarps more than 3 meters in height accompanied each event, although net *tectonic* movement between hanging- and foot-wall blocks was probably just under 2 m [Swan *et al.*, 1980, p. 1441]. They suggest that scarps of this height along a normal fault are compatible with a $M \approx 7+$ earthquake.

At the Hobble Creek site, the authors present evidence for six or seven faulting events since Lake Bonneville retreated from its Provo level

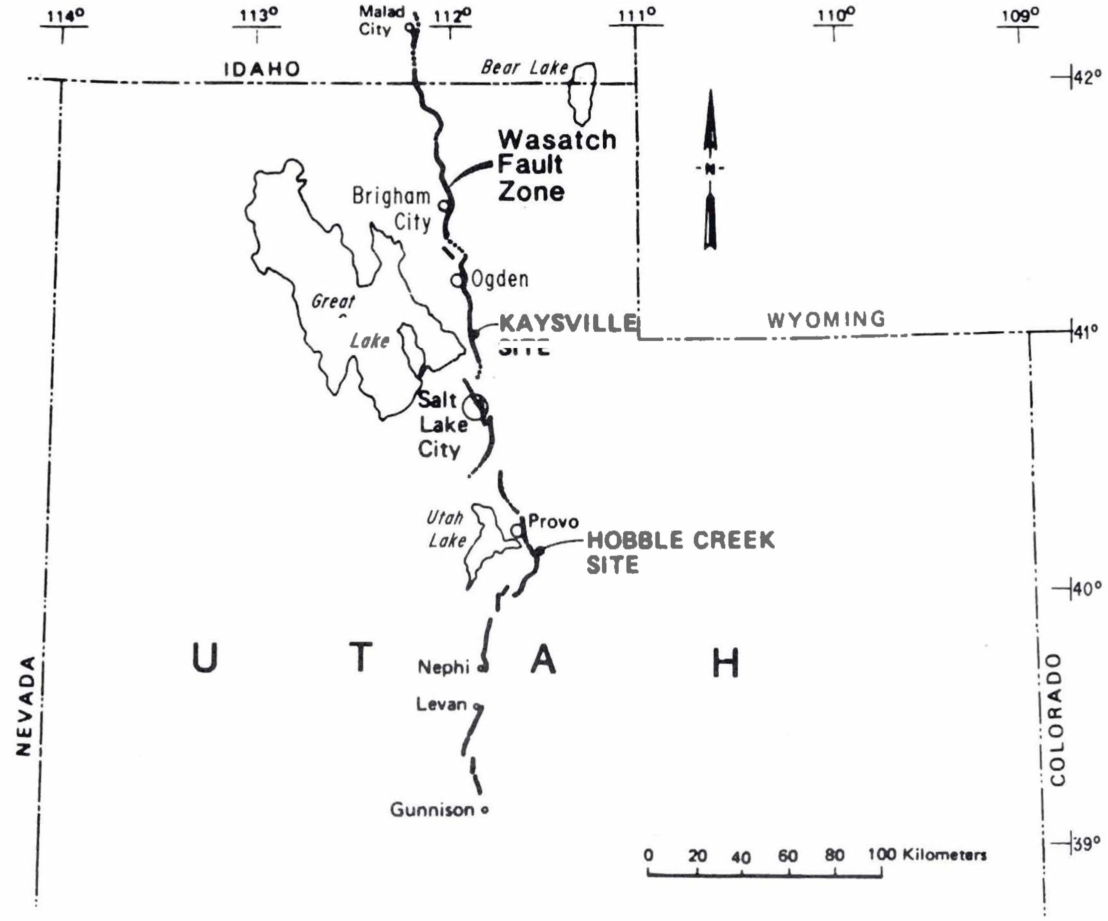

Fig. 10. The Kaysville and Hobble Creek sites have provided information on earthquake recurrence along the Wasatch fault zone [from Swan *et al.*, 1980].

12,000 to 13,000 yrs B.P. Various considerations bracket the average recurrence interval between 1,500 and 2,600 years. The calculated average scarp height suggests that each offset may correspond with earthquakes of $M \approx 7$.

The Wasatch fault zone (Fig. 10) consists of several distinct segments. Because recurrence intervals at the two study sites are different, Swan et al. [1980] suggest that some or all of the fault segments produce events at different times. Estimating that there might be 6 to 10 individual seismogenic segments, they suggest that an event somewhere along the zone ought to occur every 50 to 430 years, on the average. Since the current seismic hiatus of >133 years is well within this range, they state that "a moderate-to-large magnitude earthquake (magnitude 6-1/2 to 7-1/2) may be due or past due somewhere along the Wasatch fault zone."

Cordillera Blanca Fault, Peru

The Cordillera Blanca fault is a 200-km-long normal fault whose trace lies parallel to and ~100 km inland from the Peruvian coast between 8-1/2° and 10°S latitude (Fig. 11A). The structure spectacularly cuts ancient alpine glacial moraines that protrude from the western front of the high Cordillera Blanca of the Peruvian Andes. At two sites studied by Yonekura et al. [1979], rates of slip are estimated to be ~2 and ~3 mm/yr. Younger moraines display lesser offsets than older moraines and indicate to the investigators that 2 and 3 m offsets may occur with each event, implying an average recurrence interval of about 1000 years. Whether the fault breaks in unison or in segments is unknown. If it does break in unison, a moment, M_0, of about 6 x 10^{27} dyne-cm is likely. Yonekura et al. [1979] associate no large historical earthquake with slip along the fault, although four large earthquakes have occurred recently along or near the subduction zone to the west (1940, M = 8; 1966, M = 7.5; 1967, M = 7.0; 1970, M = 7.6; Fig. 11B).

The recognition and initial characterization of the Cordillera Blanca fault illustrates the need for careful geologic studies in refining synoptic maps of earthquake potential. Here is one place where the likelihood of a large earthquake may be considered low on the basis of a seismological analysis of recent large events along the subduction zone [McCann, 1979]. Nevertheless, the village of Yungay (Fig. 11A), devastated by a landslide loosened from the steep western fault escarpment of the Cordillera Blanca by the large 1970 event may have yet another

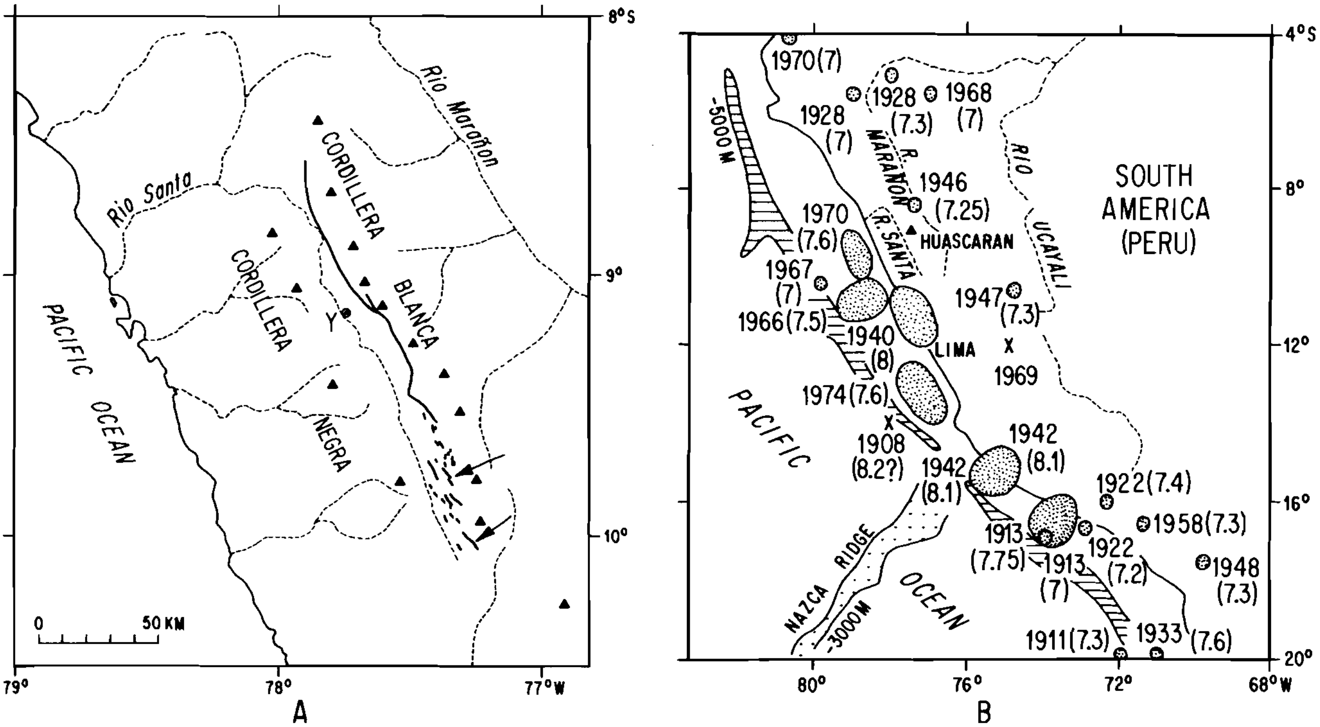

Fig. 11. The Cordillera Blanca fault is an active ~200-km-long normal fault about 100 km east of the coast of Peru. A: Geologic studies at two sites (arrows) indicate that the trace cuts young glacial moraines and may generate great earthquakes about every thousand years. Y = Yungay. B: Focal regions for earthquakes ($M_S > 7.0$ in Peru, 1904-1975 [from Yonekura et al., 1979]. The existence of the Cordillera Blanca fault indicates that the subduction megathrust is not the only source region for large earthquakes in this region.

source for large events only a few kilometers to the east.

Reverse Faults in California

Several reverse faults in California have been studied to determine earthquake recurrence intervals. Three studies illustrate the use of small fault-related stratigraphic units in identifying prehistoric earthquakes. These are discussed below. An excavation placed across the surface trace of one of the faults on which slip occurred during the San Fernando earthquake of 1971 (M_L = 6.6) (S on Fig. 14) revealed a wedge-shaped rubbly stratigraphic unit that may have been derived, at least in part, from a fault scarp produced before the 1971 event [Bonilla, 1973, p. 179-181]. Wood near the base of the wedge yielded a ^{14}C age of ~200 ± 100 ^{14}C yrs B.P. The age of the sample provides a maximal age of about three centuries for the scarp and the earthquake that accompanied its formation.

Near Ventura, California (V on Fig. 14), late Quaternary rates of uplift, folding, and faulting are quite rapid [Lajoie *et al.*, 1979, p. 9-10]. Analysis of the Javon Canyon fault, a local high-angle reverse fault, where it is exposed in a natural outcrop, reveals 3.3 m of slip since ~2500 ^{14}C yrs B.P. [Sarna-Wojcicki *et al.*, 1979]. Three superposed colluvial wedges in the sediment below the fault plane indicate that three slip events account for this movement. Similar relationships along a small reverse fault zone near Santa Cruz, California (SC on Fig. 14), have been interpreted by Weber *et al.*, [1979, p. 117] as indicating 4 to 5 faulting events within the past 10^5 years.

Strike-Slip Faults

Investigations of the recent behavior of active strike-slip faults are numerous, especially those dealing with the determination of geologically recent slip-rates using offset geomorphic features. Also, the number of workers using trenching to expose subsurface evidence is rapidly increasing. Both approaches are discussed below.

Determination of the geologically recent rate of slip along a strike-slip fault can be useful in evaluating earthquake recurrence intervals. This is especially true if the amount of offset along the fault during one or more large earthquakes is known. In the simplest case, where slip associated with each earthquake is uniform along the fault and the slip value associated with each earthquake is identical to that of previous and later events, the average long-term slip-rate divided into the slip per event yields the average recurrence interval. Since no one has yet identified such a simple case, the interpretation of geologically determined rates of slip never yields such an unambiguous value for the average recurrence interval. Nevertheless, estimates of the average interval can be meaningful in assessing earthquake potential.

Denali Fault, Alaska

Studies of the Denali fault [Sieh and Cluff, 1975] illustrate how the determination of slip rates and slip per event can be utilized. During the latest part of the Pleistocene Epoch glacial ice covered most of the 320-km long segment of the Denali fault between 144°W and 150°W. Subsequent to final deglaciation between ~10,000 and ~14,000 yrs B.P., various features of glacial origin (e.g. Fig. 12A) have been offset in a right-lateral sense along the fault. Most of these and other offsets, which were measured from vertical aerial photographs, are between 117 m and 143 m. If all of the features were produced during the latest deglaciation sometime between 10,000 and 14,000 yrs B.P., the fault-slip rate must be between 8 and 14 mm/yr. The oldest portion of a neoglacial moraine at 149°27'W is offset 35 ± 2 m (Fig. 12B). At 8-14 mm/yr, such an offset would accumulate in 2400 to 4600 yrs. This is compatible with Denton and Karlén's [1973] observations that a period of glacial expansion in Alaska occurred between 2400 and 3200 yrs B.P.

Coupled with estimates of the average displacement per earthquake, the slip rate along the Denali fault has been used to derive an average recurrence interval [Sieh and Cluff, 1975]. The most reasonable assessments of slip per event are those derived from measurements of small offsets along the fault. At 144°08'W, aerial photographic and field studies indicate a 15-m offset of two channels (Fig. 13A). The westernmost channel also has an older channel segment offset about 30 m. The lack at this locality of channels with offsets of intermediate value strongly suggests that the latest two events resulted in 15 m offsets. Walls of small channels draining northward into Augustana Creek (~146°50'W) display offsets as small as 11 m at one site and 7-1/2 to 9 m, 15 to 20 m, and 32 m, at another (Figs. 13 B and C). (These values were measured from very-low-altitude vertical aerial photographs, and are approximate). In summary, the range of offset values for the latest event at the few measured sites is 7-1/2 to 15 m. Division of this range of values by the 8 - 14 mm/yr slip rate yields an average recurrence interval somewhere between 540 and 1880 yrs. Trees that are about 150 yrs old are growing on an unfaulted moraine constructed across the fault at about ~145°45'. Thus, no appreciable slip has occurred there in at least the past century and a half [Stout *et al.*, 1973]. Clearly, more precise and more numerous offset values determined by field measurements *and* direct radiocarbon dating of offset features would enable more precise and useful evaluations of the likelihood of a great earthquake along the Denali fault. Precise dating of individual events, a

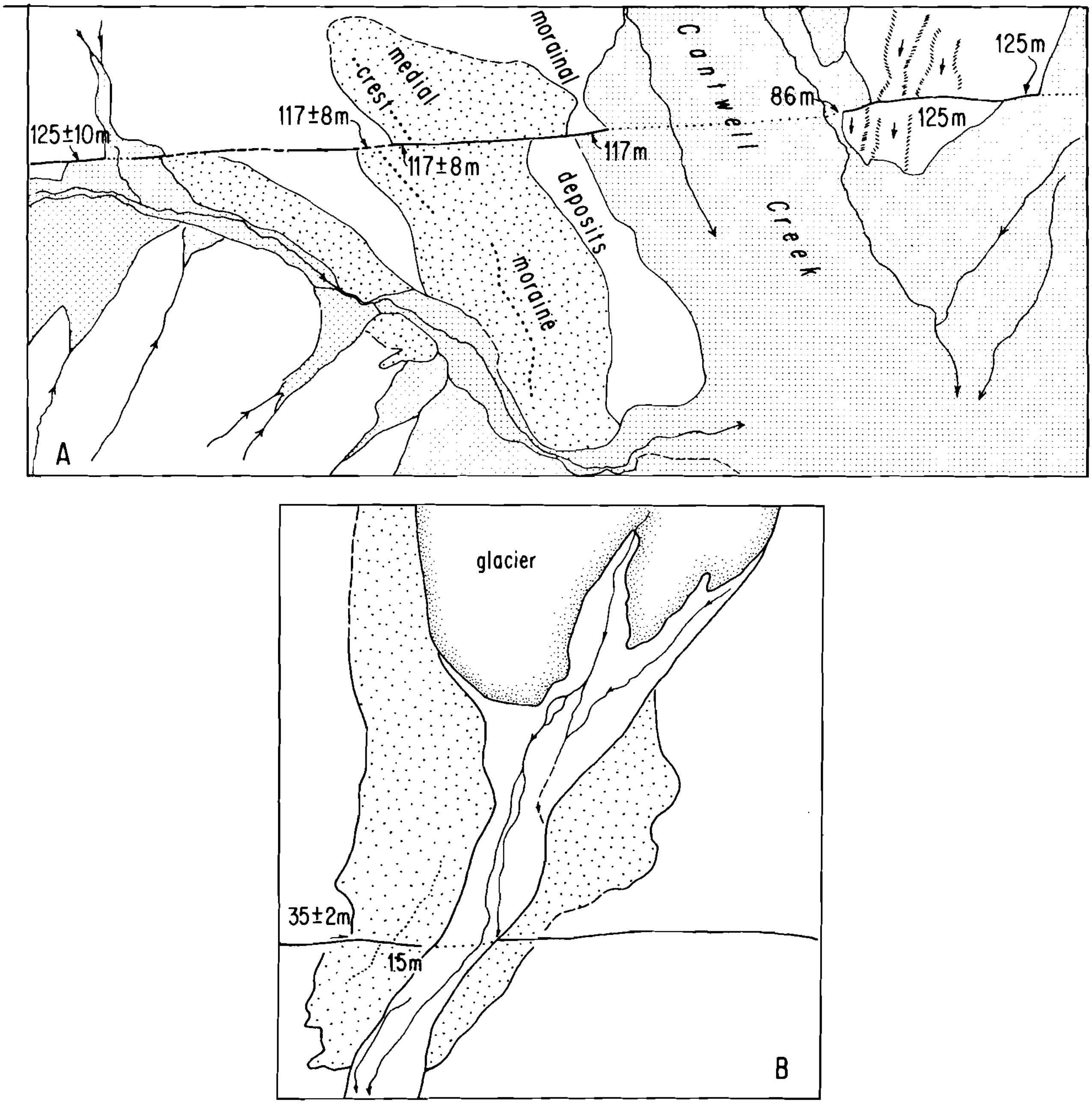

Fig. 12. A: Along the Denali fault, many glacial features created in latest Pleistocene time have been offset between 117 and 143 m [Sieh and Cluff, 1975]. At this site at 149°20'W, offsets of moraines and bedrock surfaces are between 117 and 125 m. A long-term slip rate of 8 to 14 mm/yr is derived from these types of data. Irregular dot pattern indicates well-defined glacial deposits; regular pattern indicates well-defined Holocene alluvial and colluvial deposits; hachures define walls of grooves eroded into bedrock. B: The oldest part of a neoglacial morainal complex is offset ~35 m at 149°27'W and thus may be ~2400 to ~4600 yrs old.

topic discussed below, would enable testing whether great events on the Denali fault might be closely related in time to great events on the Alaskan-Aleutian megathrust.

Fairweather Fault, Alaska

Plafker et al. [1978] estimated the average recurrence interval for the Fairweather fault in southeastern Alaska (Fig. 6) using a stream channel that bends right-laterally ~55 m along the fault and a nearby offset of 3-1/2 m that accompanied the 1958 ($M_S = 7.9$) Lituya Bay earthquake. Faulting at this locality has produced an uphill-facing scarp and diversion of the stream around the scarp may be responsible in part for the 55-m value. Nevertheless, the 55 m may be due entirely to displacement along the fault. A maximum age for the stream is based on a radiocarbon date of 940 ± 200 ^{14}C yrs B.P. on wood in the most recent neoglacial moraine in the area. The wood is in a soil buried by the moraine and thus gives a maximal age for the moraine and associated glacier. The glacier that formed the moraine was 300 m thick at the site of the offset stream and had to melt before the stream could form. Thus, an even longer period occurred between wood formation and creation of the the channel. The minimum slip rate for the fault would thus be 55 m/(940 + 200) yrs = 48 mm/yr, and the actual rate can be expected to be significantly higher.

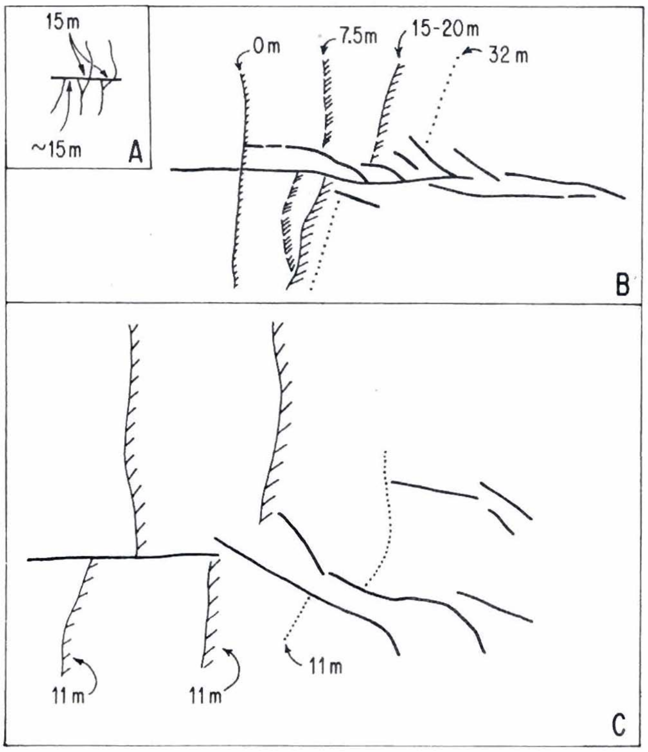

Fig. 13. Youngest offsets along the Denali fault range from 7-1/2 m to 15 m [Sieh and Cluff, 1975]. At a rate of 8 - 14 mm/yr, the range of average recurrence intervals for events of this size is 540 to 1880 years. A: Small tributaries to Jack Creek, 144°08'W. B and C: Small tributaries to Augustana Creek, ~145°52'W. Thick lines are faults; hachures are on channel banks whose bases are indicated by lines; dotted lines indicate offset linear ridge.

Plafker et al., using their best guess of about 58 mm/yr, derive an average recurrence interval of about 60 yrs for events producing 3-1/2 m offsets such as occurred nearby in 1958. Suggestions by Sykes [this volume] that slip along the Fairweather fault occurred in 1899 and 1847, as well as in 1958, are consistent with this estimate of average recurrence interval.

Median Tectonic Line, Japan

Extensive analyses of offset channels and fluvial terraces have yielded a complex but consistent record of recent right-lateral slip along the several active faults of the Median Tectonic Line fault system in southwestern Japan (Fig. 2) [Okada, 1968, 1970, 1973, 1980; Okada and Sangawa, 1978; Sangawa, 1978a, 1978b; Sangawa and Okada, 1977]. Rates of slip are highest (5 to 10 mm/yr) along the central segment of the fault system and decrease toward the ends of the ~300-km-long system. The most recent great earthquake probably occurred between 0 A.D. and the beginning of the historical period (~700 A.D.), as judged by a lack of great earthquakes during the historical period and a faulted alluvial fan containing logs with an age of 1860 ± 90 ^{14}C yrs B.P. in the central region of the fault [Okada, 1980, p. 99, 101]. Elastic strain accumulation at 5 to 10 mm/yr would produce a potential offset of 10 to 13 m during this most recent 1300- to 2000-year period of dormancy. Okada [1980, p. 101] concludes by forecasting a "severe" earthquake produced by slip along the faults of the Median Tectonic Line within a few hundred years. Therefore, a current priority is a more complete and detailed determination of past recurrence intervals [Okada, pers. comm., 1980 and 1981].

Atera Fault, Japan

The current status of knowledge concerning the active 80-km-long Atera fault in central Japan (Fig. 2) is similar to that for the Median Tectonic Line. Sugimura and Matsuda [1965] estimated the ages of terraces progressively offset ~70 to ~140 m left-laterally along the fault and published an estimated slip rate of 2-4 mm/yr. Okada [1975] confirmed this estimate by determining a 2-5 mm/yr late Pleistocene/Holocene slip rate using radiocarbon ages of offset river terraces at a different locality. The judgement of Okada [1975] is that an historical earthquake (M = 7.4) in 762 A.D. was the latest event associated with rupture of the Atera fault. At the determined rates, 2-1/2 to 6 m of potential fault slip may have accumulated between then and the present.

Recent studies of the Atera fault have also focussed on dating of individual seismic events. One fresh artificial exposure of the fault revealed a downwardpointing wedge of irregular, faulted, peat and rubble layers that probably accumulated as colluvial fill and marsh deposits in a swale along the fault [Hirano and Nakata, 1980]. The investigators interpreted contacts with gravel rubble resting upon peat to indicate prehistoric seismic events. The age of these contacts are ~9300, ~5500, and ~3100 ^{14}C yrs B.P. Perhaps the gravel represents caving of scarps that were refreshened during earthquakes at these times. Non-seismic causes for the formation of the rubble at these times has not been ruled out, however. At least one of the earlier events can be defended on the basis of more severe disturbance of units below a layer that formed about 4800 ^{14}C yrs B.P. Substantial disruption of a 3000-yr-old peat in this section also indicates an event more recent than the three proposed above. Even more events than those four discussed above could be represented in the exposure, because the complexity of disturbances and relationships in the exposure might very well mask other events.

Okada and Matsuda [1976] studied a road cut along the Atera fault which exposed sand-gravel beds interbedded with black organic beds. They argued that the sand and gravel beds represented caving of the scarp formed after earthquakes about 13,000, 11,400, 8,300 and <4,300 ^{14}C yrs B.P. Okada [written comm., 1981] explains that each of the coarse beds on the downthrown block is derived from the upthrown block across the fault, which is as one would expect for a scarp-derived deposit. Additional support for the four-earthquake interpretation is that each organic layer is more severely deformed than superjacent layers [Okada, 1981, written comm.], although this is readily apparent only for the layer ~8,300 ^{14}C yrs old.

Synthesis of the above mentioned studies and further refinement of the dates and characteristics of Holocene seismic events along the Atera fault may very well demonstrate that large earthquakes occur along the Atera fault every one thousand years or so. Depending upon how greatly actual recurrence intervals deviate from the average value, a forecast of the behavior of this fault during the next one hundred years or so might be attainable.

Yamasaki and Shikano Faults, Japan

In excavations at a site along the Yamasaki fault in western Honshu, Japan (Fig. 2), Okada *et al.* [1980] have found evidence of an earthquake that occurred between the 8th and 12th centuries A.D. A stratum assigned an 8th-century age on the basis of pottery fragments and a date of 1170 ^{14}C yrs B.P. is broken by faults, whereas a 12th-century bed, dated using radiocarbon and pottery, is not. The source of a M = 7.1 earthquake in 868 A.D. has been placed nearby on the basis of historical records, and Okada *et al.* [1980] consider this to be a likely candidate for association with the faulting event recognized in the excavation.

Other excavations, along the Shikano fault, in western Honshu, Japan (Fig. 2), indicate two events during the Holocene [Ando *et al.*, 1980]. The latest event slightly disrupts strata deposited ~1,500 ^{14}C yrs B.P. and is believed to be faulting related to the 1943 Tottori event. An older event more severely disturbs strata with ^{14}C ages of 8,000 and 9,000 yrs B.P. These results on the Yamasaki and Shikano faults are encouraging and suggest that further work could lead to knowledge of the average recurrence interval.

Totschunda, Boconó, Clarence, Wairau, and Wairarapa Faults

Other faults for which geologically recent slip-rates have been estimated include the Totschunda in southeastern Alaska (Fig.6) [Richter and Matson, 1971, $\gtrsim$9-33 mm/yr], the Boconó in Venezuela [Schubert and Sifontes, 1970, ~7 mm/yr], and the Clarence in New Zealand [Kieckhefer, 1979, $\gtrsim$4 mm/yr]. All of these values are based on offsets of latest Pleistocene or Holocene features that have not been directly dated and are roughly correlated with features dated by radiocarbon elsewhere in these regions. None of these authors venture an estimate of average recurrence interval, though hazardous guesses of slip per event, based on fault length, could be combined with the slip rates to derive intervals.

A flight of eight river terraces on the Waichine River in New Zealand is progressively offset 12 to 99 m right-laterally along the Wairarapa fault [Lensen and Vella, 1971]. Indirect age assignments for the offset features imply latest Pleistocene/Holocene slip-rates of 3.4 to 6.0 mm/yr. Assuming the historical 1855 earthquake was associated with about 3 m of slip, Lensen and Vella [1971, p. 119] propose that the average recurrence interval is between 500 and 900 years.

A very similar set of circumstances to that outlined above occurs along the Wairau fault where it crosses the Branch River in New Zealand. Lensen [1968] used the same approach to derive a fault-slip rate at this locality. He then interpreted several small offsets as indicating individual slip events of 5 to 7 m. The average recurrence interval thus derived is between 500 and 900 years.

Raymond Fault, California

The 15-km-long Raymond fault, in the heavily populated Los Angeles metropolitan area (R on Fig. 14), has been the subject of recent studies by Crook *et al.* [1978]. In addition to geologic mapping and geomorphic and pedologic approaches in assessing the fault's longer-term geologic history, they utilized trench excavations across the fault to assess its recent history of movement. They identified in late Pleistocene/Holocene deposits evidence of several prehistoric earthquakes -- at least 5, and perhaps 8, between

~1,630 and ~36,000 ^{14}C yrs B.P. [Crook et al., 1978, p. 78-82]. If these represent all the events that occurred in this span of time, the average recurrence interval is between 4500 and 9200 ^{14}C yrs. If, as the authors suspect, not all events are represented, these would be maximum values for the average recurrence interval. They suggest that 3,000 years might be a more accurate value. Although the events already identified by Crook et al. [1978] may represent the majority of the late Pleistocene and Holocene earthquakes along the Raymond fault, a stratigraphic record with greater sensitivity to closely-timed earthquakes needs to be found. The fault's location within a populous urban area mandates acquisition of more precise knowledge concerning its most recent behavior.

Garlock Fault, California

Two independent studies of Pleistocene features offset along the Garlock fault (G on Fig. 14) indicate an average slip rate of about 10 mm/yr [Carter, 1980; Clark and LaJoie, 1974]. Clark [1973] estimated offsets of about 3 to 5 m for several small channels that cross the fault. If these were offset during the latest large event and are representative of slip values for earlier events as well, the average recurrence interval would be between 300 and 500 years. Burke [1979] has recognized 9 to 17 prehistoric earthquakes in an excavation that exposed the Garlock fault breaking sediments younger than ~15,000 ^{14}C yrs. He feels that this may not represent all the earthquakes that have occurred along the Garlock fault during this period, so the maximum average recurrence interval is about 1-1/2 millenia.

Studies of the Geologically Recent Behavior of the San Andreas Fault

Geomorphic and stratigraphic studies at several localities along the San Andreas fault system have provided a partial understanding of the long-term (i.e. millenial) behavior of that major plate boundary, including recurrence intervals of large earthquakes and fault slip-rates. This section consists of an outline and evaluation of these studies.

Based on its historical behavior, the San Andreas fault can be divided into four distinct segments (Fig. 14). The northern segment produced a great earthquake in 1906 [Lawson et al., 1908]. The south-central segment produced a great earthquake in 1857 [Agnew and Sieh, 1978; Sieh, 1978b]. Both of these segments have been characterized by extraordinarily low levels of microearthquake activity since their respective great earthquakes

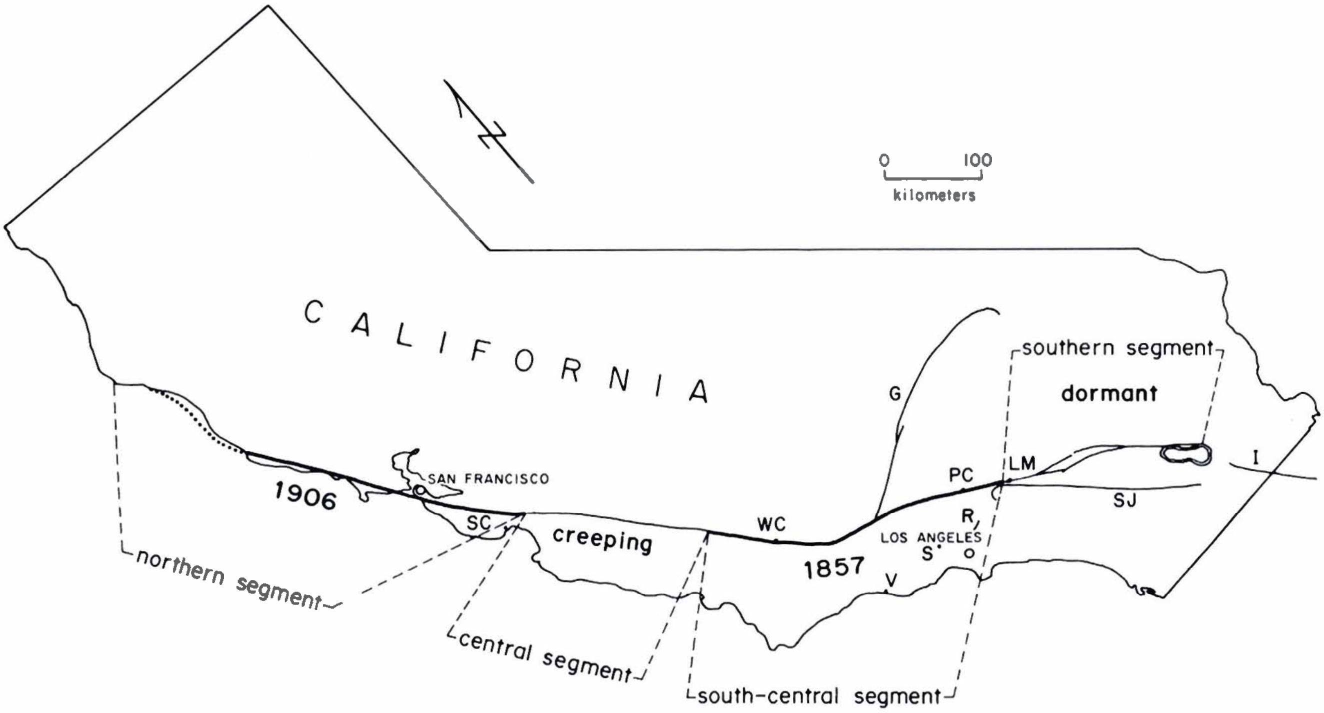

Fig. 14. On the basis of its historical behavior, the San Andreas fault can be divided into four segments. Forecasting the location and size of future great earthquakes generated along the fault requires understanding the degree to which this historical behavior characterizes the long-term behavior of the fault. WC, PC, and LM indicate Wallace Creek, Pallett Creek, and Lost Marsh. G = Garlock fault, I = Imperial fault, R = Raymond fault, SC = Santa Cruz, SF = San Fernando fault, SJ = San Jacinto fault zone, V = Ventura.

[see, for example, Carlson et al., 1979]. The central segment, in contrast, has been undergoing creep continuously throughout the twentieth century [Burford and Harsh, 1980] and is characterized by a high level of activity below $M_L \approx 6$ [Brown and Wallace, 1968]. The southern segment of the fault has not produced a great earthquake during the ~210 years of historical record, and creep, though suspected or recognized locally [Keller et al., 1978; Allen et al., 1972] is very minor.

To what degree does this historical pattern represent the behavior of the geologically recent past and the future? Allen [1968] has proposed, on the basis of long-standing geological and geometric characteristics of and contrasts between the creeping and dormant segments, that the historical behavior is representative of the long-term behavior. Irwin and Barnes [1975] have observed that the fault suffers creep only where a stratigraphic section of Franciscan Formation capped by relatively impermeable Great Valley Formation abuts it. They suggest that capping of the Franciscan may cause buildup of high pore pressures in the fault zone which greatly reduces the shear strength of the fault and enables creep. Exactly to what extent the historical behavior of the fault represents its long-term behavior is unknown. Nevertheless, the studies outlined below indicate that, at least in part, historic and ancient behavior are similar.

Geomorphic Evidence of Individual Large Events

Geomorphic features indicate that during at least the past thousand years or so great earthquakes have been the principal mode of strain relief along the south-central segment of the San Andreas fault. In 1857 right-lateral slip along this stretch varied along strike from ~3 to ~10 m (Fig. 15). These values were determined principally by measuring the offset of small gullies cut during periods of heavy rainfall in the decades before the earthquake [Sieh, 1978b]. The smallest offsets at Van Matre Ranch are ~8 m (Fig. 15 and Table 1). These are attributed to the 1857 event. Younger channels display no offsets, implying that there has been no appreciable slippage since the 1857 earthquake and associated aftercreep occurred. Three older channels are separated by about 16 m along the fault (Table 1). These probably record both the 1857 and a previous slip event of ~8 m. Offsets of ~26 m (Table 1) probably accumulated in three increments: ~8 m in 1857, ~8 m during a previous large earthquake, and ~10 m during the next previous earthquake. The geomorphic data along this portion of the fault seem to indicate that sudden, large, 8- to 10-m slip events characterize this segment of the fault. Similarly, though less convincingly, where slip in 1857 was ~3-4 m, previous events seem to have been of similar size [Sieh, 1977, Fig. 23].

These observations could fit at least two hypothetical models of large earthquake behavior (Fig. 16). In a uniform-slip model, large earthquakes must be twice as frequent where the slip is half as great as at Van Matre Ranch. In the uniform-earthquake model the nonuniform slip function of the latest earthquake repeats. Such a model requires substantial deformation in one or both of the blocks separated by the fault. Determination of the actual long-term slip rate at several carefully selected localities along the south-central segment enables a test of which, if either, model is appropriate.

Long-Term Slip Rates

Investigations at two localities along the south-central segment are providing information about the long-term rate of fault slip. These localities are Wallace Creek and Lost Marsh (WC and LM in Fig. 14).

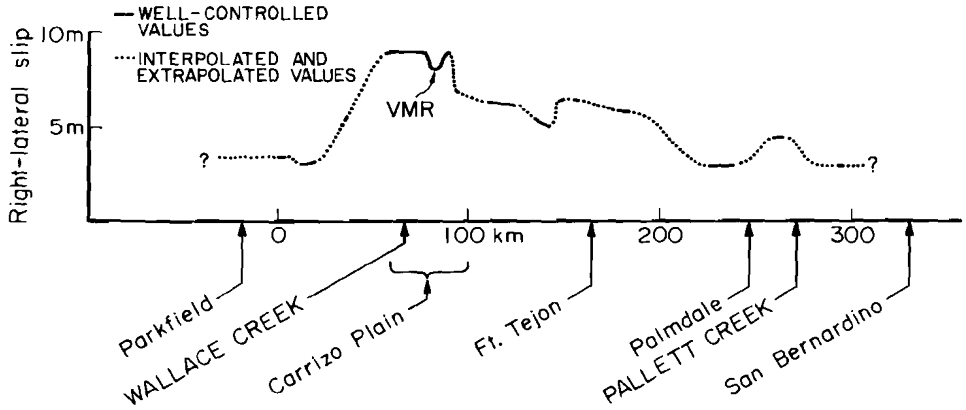

Fig. 15. Small channels and other features indicate that the great 1857 earthquake was associated with the values of fault slip shown here [from Sieh, 1978b]. Is this pattern characteristic of earlier earthquakes along the south-central segment as well? VMR indicates the location of Van Matre Ranch.

TABLE 1. Offset gullies at the Van Matre Ranch indicate that the magnitude of fault slip accompanying the last two prehistoric events there was very similar to the ~8 m of slip in 1857 [from Sieh, 1977].

Site #	Offsets (meters)		
50	7.6 ± 1.5		27.9 ± 1.8
49	8.5 ± 1.5		
48	7.8 ± 0.6 (48-F)	15.8 ± 1.2 (48-E)	
47	$8.2^{+1.5}_{-0.3}$ (47-C)		24.4 ± 1.0 (47-A)
46	$8.2^{+0.6}_{-1.5}$	16.3 ± 0.9	25.1 ± 0.9
45		15.2 ± 0.9	
44			27.7 ± 2.7

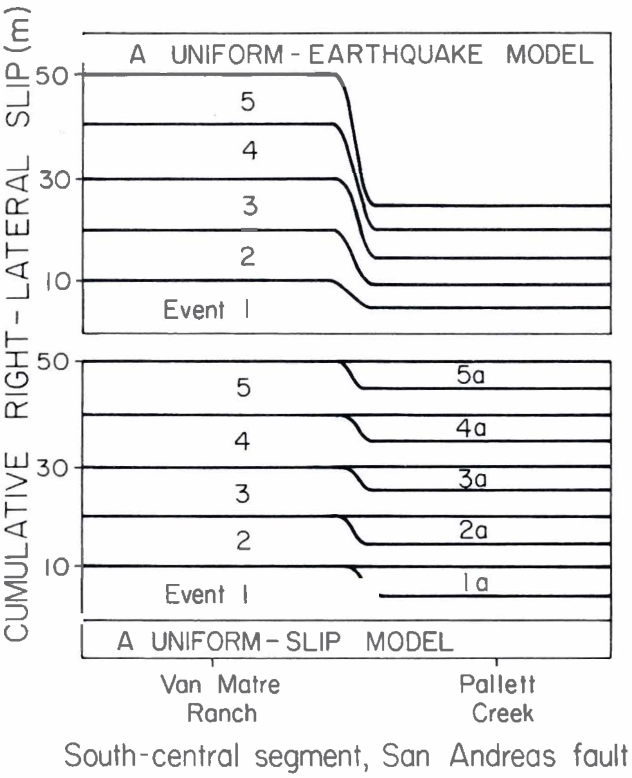

Fig. 16. The suggestion that slip at any one locality does not vary greatly from one earthquake to the next leads to two plausible models relating great earthquakes. In the uniform-earthquake model, all great earthquakes (1 through 5) have non-uniform slip functions like that of the 1857 earthquake. In the uniform-slip model, alternation of 1857-like events (1 through 5) with other large events (1a through 5a) accomplishes uniform slip along this 400-km-long stretch of the fault.

Wallace Creek is an ephemeral stream which flows perpendicular to the fault in a channel incised into an old alluvial fan (Fig. 17). Where it first reaches the fault, it turns northwestward and flows 130 m along the fault. It then leaves the fault and flows out into a valley. An older channel, created long ago by Wallace Creek, leaves the fault 250 m farther northwest. Detailed surficial and subsurficial studies of the geology associated with creek development [Sieh and Jahns, 1980] suggest the history illustrated in Fig. 18. Trenches at several locations revealed stratigraphic relationships critical to understanding the rate of slip of the fault. Trench #5 (Fig. 19) exposed late Pleistocene-early Holocene(?) alluvium (solid black). This alluvium was incised sometime after 19,000 ^{14}C yrs B.P. and before 5900 B.P. The channel then accumulated slope debris and fluvial gravels (unstippled and stippled, respectively) until sometime after about 3900 B.P. Some time after 3900 B.P., incision again occurred and the modern channel began to fill with slope debris and fluvial gravel (unstippled and hachured, respectively). The 130-m offset has occurred since deposition of the youngest of the stippled units and overlying slope debris, that is, since incision of the modern channel. The age of the youngest stippled deposits (<3900 yrs B.P.) is a maximum time for accumulation of the 130 m offset of the modern channel. The 380 m offset began to accumulate much earlier, after incision of the alluvium (solid black). Therefore, the 380 m offset is older than or approximately equal to the age of the oldest stippled deposits and slope debris (i.e. >5900 yrs old). Because 130 m has accumulated in no more than 3900 yrs, the minimum slip rate is 33 mm/yr; and because 380 m has accumulated in no less than 5900 yrs, the maximum slip rate is 64 mm/yr.

The average long-term slip rate at Wallace Creek is appreciably greater than it is about 250 km to the southeast, at Lost Marsh (LM in

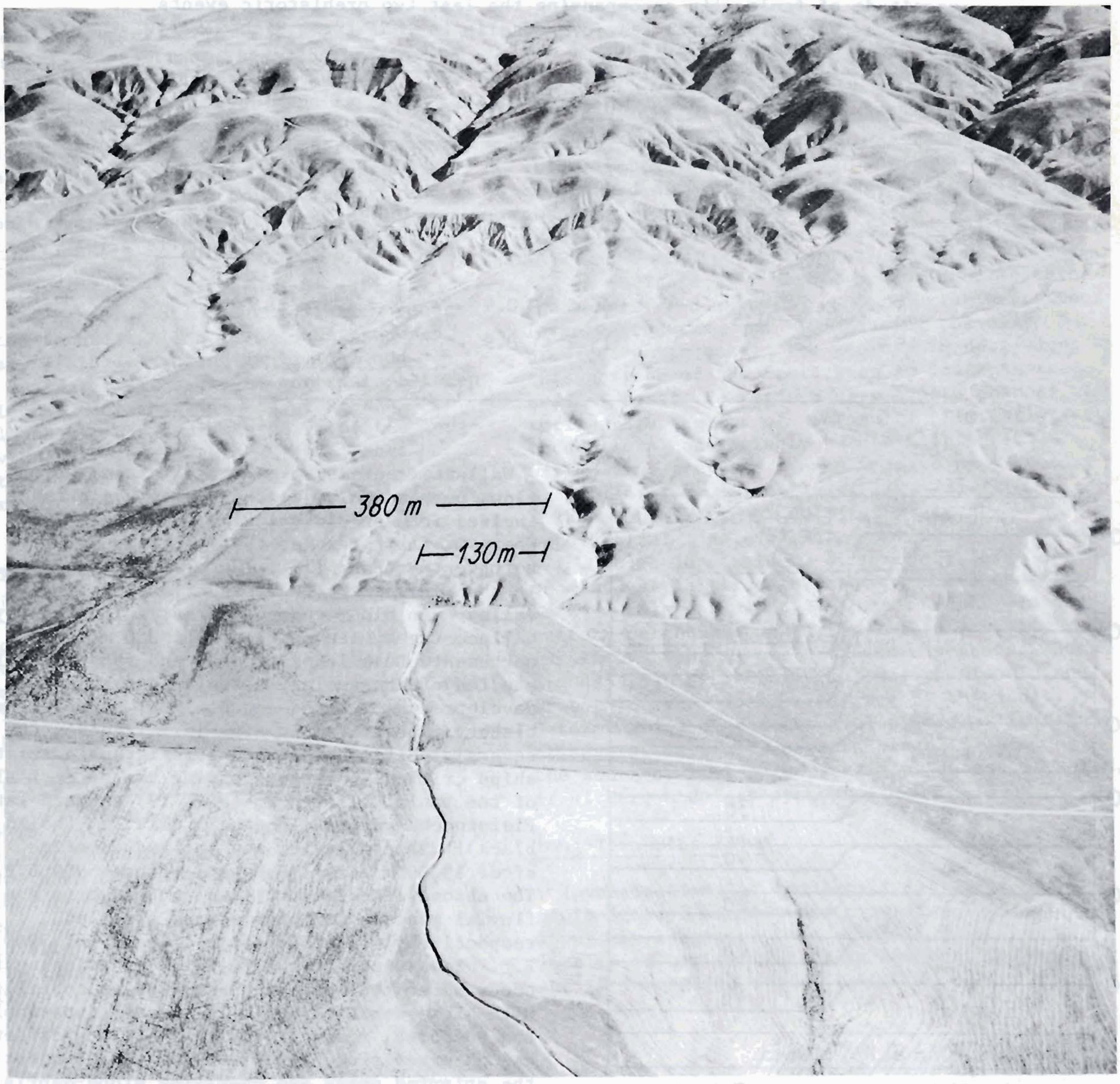

Fig. 17. Models relating great earthquakes along the San Andreas fault can be tested by comparing the long-term slip rates of the fault at localities such as Wallace Creek, which is shown here. The modern channel is offset ~130 m and an older one is offset ~380 m. Photo courtesy of R. E. Wallace, U. S. Geol. Survey.

Fig. 14). There a study of offset fluvial terrace risers has yielded a tentative average slip rate of 25 mm/yr for the Holocene epoch [Weldon and Sieh, 1980]. These values favor the uniform earthquake model, in which the 1857 earthquake is the characteristic event along the south-central segment. The non-uniform slip associated with the 1857-earthquake is consistent with the non-uniform long-term slip along that stretch of the fault. If the uniform-earthquake model is valid, the next event to occur along the south-central segment will be similar in static characteristics to the 1857 earthquake.

The slip-rate determination at Wallace Creek enables calculation of an average recurrence interval. Repeated nine- to ten-meter offsets seem to characterize the segment of the fault near Wallace Creek, so the 33-64 mm/yr limits on slip rate imply an average recurrence interval between 140 and 300 years. These data lead to the conclusion that a great event involving the Wallace Creek site within the next few decades is

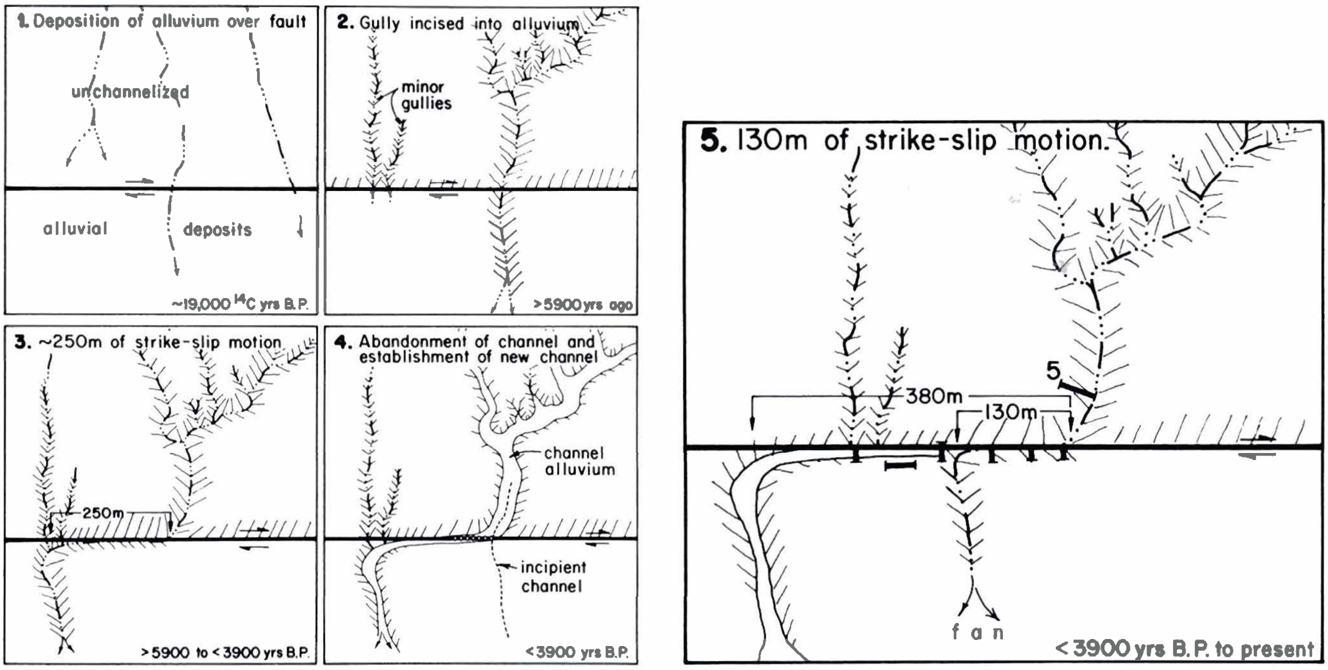

Fig. 18. Extensive surficial and subsurfical studies of Wallace Creek suggest the history indicated above. Thick bars indicate locations of trenches; trench #5 is numbered.

certainly well within the realm of possibilities.

We might also suspect from the Wallace Creek data that the central (creeping) reach of the fault is capable of being involved in great earthquakes. This suspicion stems from the probability that the long-term slip rate at Wallace Creek (33-64 mm/yr) is in excess of the historical creep rate along the central segment [≲32 mm/yr; Burford and Harsh, 1980]. A 1 to 32 mm/yr deficit in creep would result in a 100 to 3200 mm slip deficit per 100 years, which might well be relieved during great earthquakes on either the northern or south-central segments. This also raises the possibility of occasional future "superquakes" involving rupture of the northern, central, and south-central segments, since major seismic rupture through the central segment would provide physical linkage of its neighboring great-earthquake-generating segments.

Dating of Individual Prehistoric Events

At Pallett Creek (PC in Fig. 14) individual prehistoric earthquakes are recorded in the datable deposits of a late Holocene marsh [Sieh, 1978a]. The fault has broken these deposits repeatedly during the past 2000 yrs and rapid depositional rates have ensured that all or most earthquake ruptures and related phenomena are buried and preserved before the next large event.

Four types of evidence for prehistoric earthquakes exist here: 1) sandblows and other evidence of seismically induced liquefaction (Figs. 20 and 21), 2) fissures (Figs. 22 and 23), 3) fault scarps along the main fault (Figs. 24 and 25), and 4) lateral offsets (Fig. 26). Together, there is evidence for nine large events since about 500 A.D.

Sieh [1978a] did not convincingly demonstrate that displacements during each of the recognized events were as large as in 1857, but suggested that patterns and magnitudes of vertical deformation for at least six of the prehistoric events were similar to those of 1857. Whether all are as large as the 1857 event or not, all of the nine youngest events do have direct and indirect evidence that movement along the San Andreas was involved. The direct evidence is in the form of buried scarps at the proper horizons (e.g. Fig. 25). The indirect evidence is in the form of anticlines and other coseismic deformation. Davis [1981] reports evidence from excavations 125 km northwest of Pallett Creek for three episodes of slip along the San Andreas since the 16th century. These could well correlate with the latest three events at Pallett Creek. If so, the latest three events at Pallett Creek should be regarded as great earthquakes.

The data from Pallett Creek indicate an average recurrence of large earthquakes on the San Andreas fault of about 160 yrs [Sieh, 1978a]. Individual recurrence intervals vary by up to several decades, although this may be more a function of the uncertainty in ^{14}C age determinations than an indication of actual irregularities. Variation of several tens of percent in recurrence inter-

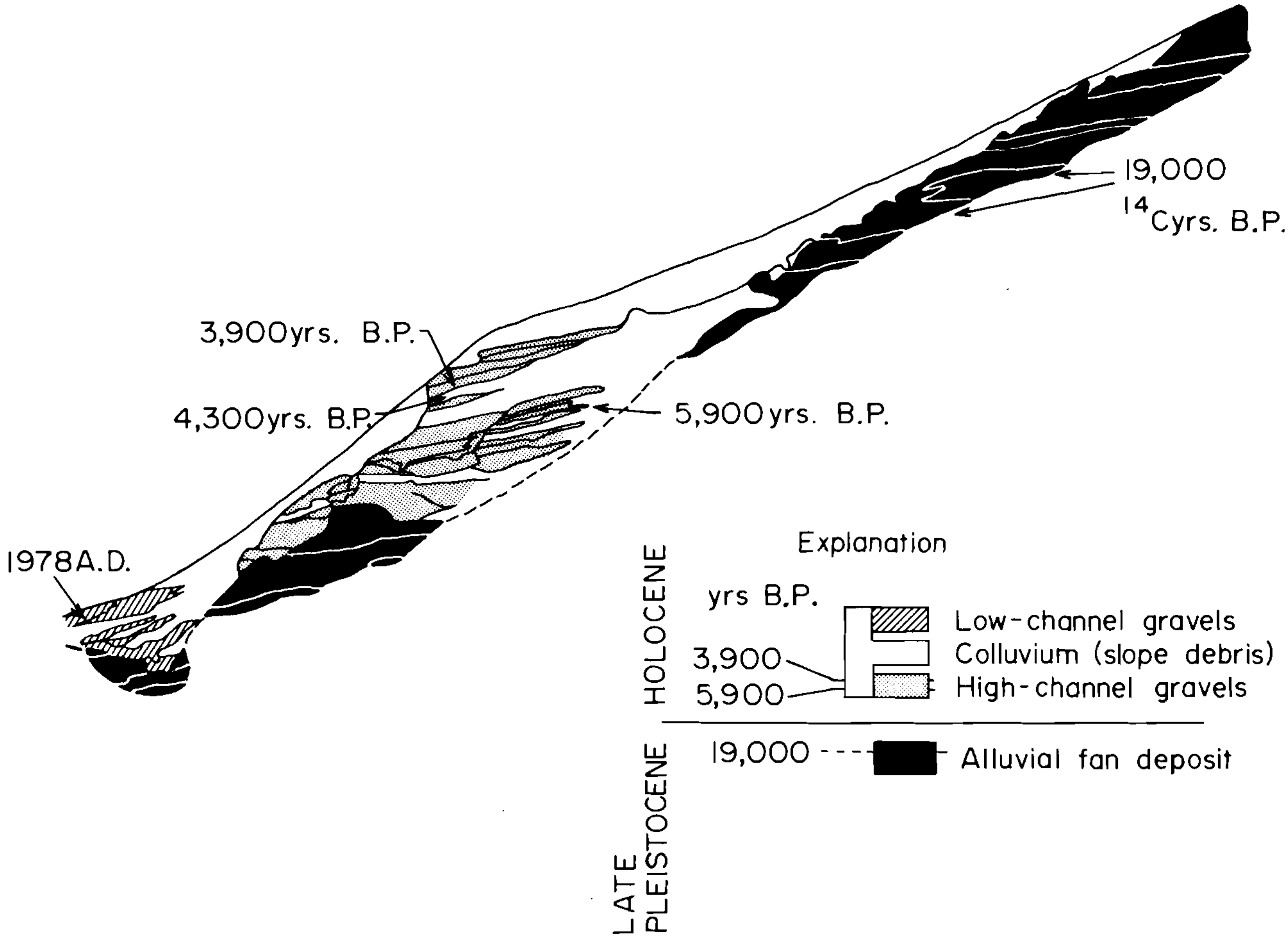

Fig. 19. Trench #5 clearly displays several deposits and stratigraphic relationships critical to determining a fault slip rate at Wallace Creek. Solid black = late Pleistocene alluvial fan deposit; stipple = old channel deposit; hachures = modern channel deposit; no pattern = slope debris.

vals, however, is certainly a possibility, especially in view of the known historical variability in recurrence of large earthquakes in Japan and Chile discussed above. I conclude that the probability of a large event involving all or part of the south-central reach of the San Andreas fault within the next several decades is high.

Problems and Directions

Absolute Dating

The power of the geological approaches illustrated above is limited greatly by the resolution of the dating techniques currently employed. At the present time, conventional ^{14}C analyses produce ages with uncertainties ($\pm 2\sigma$) of nearly a century, at best. Such large uncertainties preclude resolution of several types of problems, especially in regions characterized by average recurrence intervals of only a few centuries or less.

(1) Ancient seismic disturbances recognized in excavations at widely separated localities along a major fault might have identical radiocarbon ages and yet be separated in real age by a century. The converse situation is also possible -- seismic disturbances at different localities, with radiocarbon ages differing by a century, could represent the same earthquake.

(2) Recognition of the clustering of large seismic events within a decade or a century is prohibited by present levels of analytical uncertainty.

(3) Meaningful assessments of the variation of actual recurrence intervals about an average value is impossible at the present time for faul with average recurrence intervals of a few centuries or less.

Application of dendrochronologic and paleomagnetic methods and new radiocarbon techniques may eventually help overcome these problems to some extent. Along the San Andreas fault, for exampl the youngest prehistoric events might someday

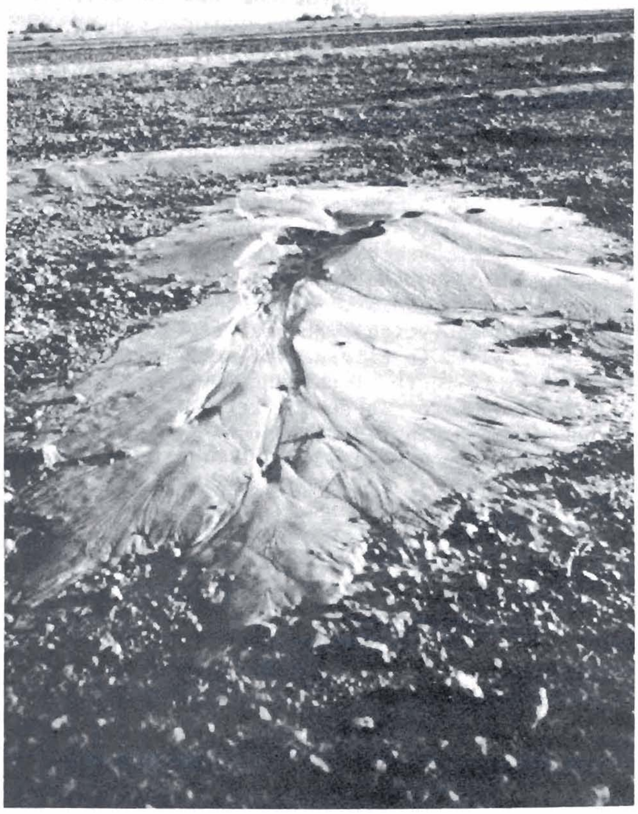

Fig. 20. Sandblow cone in plowed field after recent earthquake illustrates the type of feature preserved among the strata of Pallett Creek. The sand was deposited as a fountain of water and sand exited the ground from a small central crater. Feature is about 1 meter across.

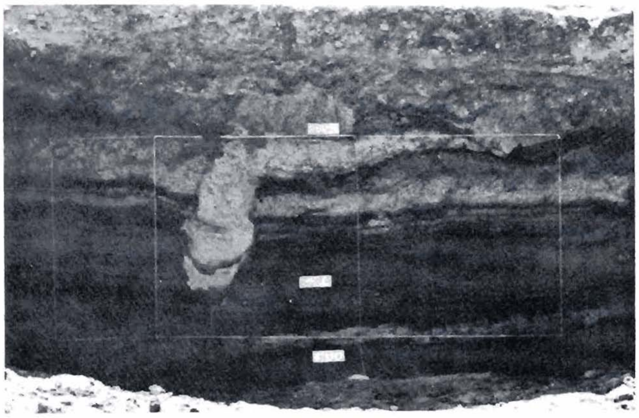

Fig. 21. Cross-sectional view of a sandblow (between arrows) in the stratigraphic record at Pallett Creek. This feature was created during an earthquake in about 1740 A.D. The sand was ejected from a fissure along the San Andreas fault.

Fig. 22. Secondary fissure related to ground failure resulting from a recent earthquake in Mexico illustrates another type of feature preserved in the strata of Pallett Creek.

be dated to within half a year by analysis of the annual growth rings of trees affected by heavy shaking during these events. Meisling and Sieh [1980] have shown that several conifers near the fault display effects of the 1857 earthquake; older trees might record similar effects from large events in the 17th or 18th centuries. La Marche and Wallace [1972] may, in fact, have identified a predecessor of the 1906 earthquake in the ring record of an ancient redwood north of San Francisco.

New methods of radiocarbon analysis may indirectly enable reduction of uncertainties to about a decade. Short-term irregularities in the relationship of analytical ^{14}C age to real, or calendar, age have been found by determining the ^{14}C age of individual tree rings whose ages span the past 500 years [Stuiver, 1978]. The record of such fluctuations could be determined for the past several thousand years by analyzing the rings of bristlecone pines. This will be facilitated by the advent of new direct-counting

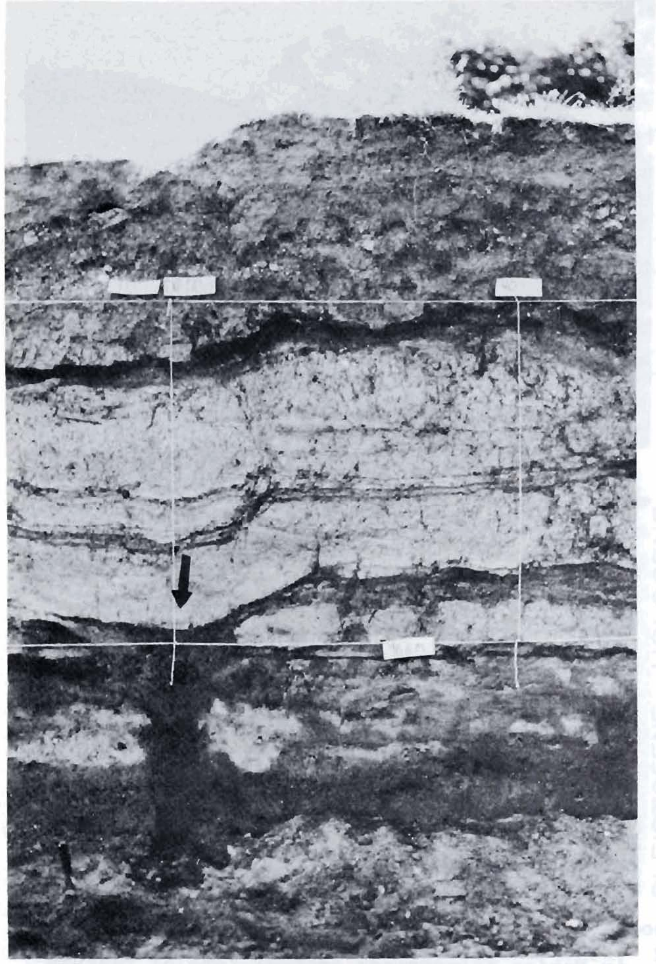

Fig. 23. This fissure (arrow) preserved in the geologic record at Pallett Creek is one of many features that indicate an earthquake occurred in about 1500 A.D. The string outlines a one-meter square.

methods that do not require large samples [Maugh, 1978]. In critically important studies where appropriate carbonaceous mate spans several decades or centuries, the ^{14}C age vs. real age curve of the sample or samples could be matched against the dendrochronologically established curve and a more refined age determined.

Enormous benefits may soon be realized by the development of direct radiocarbon dating [Maugh, 1978]. This method will require only milligrams of carbon, whereas present conventional methods require grams. Innumerable attempts to date strata have failed for lack of enough carbonaceous material. This new method promises to enable determination of average recurrence intervals and earthquake dates where it is now impossible.

Another dating problem is more readily corrected than the problem of precision discussed above. Because of variations in the rate of ^{14}C production in the atmosphere, the concentration of ^{14}C in the atmosphere and in organic matter has not been constant. Fractionation of ^{14}C between organisms and the atmosphere also occurs. Thus ^{14}C ages must usually be corrected to obtain calendar ages. An extreme example would be a radiocarbon age of 6000 yrs. B.P. This would correspond to a calendar age of about 6700 yrs. Conventions in reporting dates determined by radiocarbon analysis vary among users. Some report ^{14}C ages corrected for these factors, others do not. Routine specification of official laboratory sample number, ^{14}C age, $\delta^{13}C$ value, real age, and analytical uncertainty (1σ or 2σ) would greatly aid in eliminating ambiguities that exist currently in the literature. Equations, tables or graphs for these corrections are given by Broeker and Olson [1961], Damon _et al._ [1972], and Yang and Fairhall [1972].

Seismic Areas Without Surface Faulting

In many regions large earthquakes have been accompanied by little or no surface faulting. Notable examples in the United States are the subduction events of the Aleutians and southern coastal Alaska, the great 1811-12 earthquakes of the upper Mississippi embayment, and the Charleston, S.C., and Boston, Mass., earthquakes of 1886 and 1755. Many great subduction earthquakes (and the great decollement earthquakes of the Ganges plain on the southern flank of the Himalayas) have also not been associated with surface fault rupture. Direct stratigraphic, geomorphic, and structural studies of the faults that caused these earthquakes are precluded by their lack of surface exposure. Only in the unusual coastal areas discussed above, where emergent beaches

Fig. 24. Slip on this scarp along the Imperial fault was about 20 cm of dip-slip and 20 cm of dextral strike-slip when this photo was taken about 3 days after the Imperial Valley earthquake of 1979. Scarps of similar height, but with appreciably greater components of horizontal slip, are buried in the strata at Pallett Creek.

have been utilized in determining recent seismic behavior, have indirect methods of investigating the causative faults been applied extensively with great success.

Sims' [1975] study of seismically deformed soft-sediments has raised the possibility that liquefaction and other non-tectonic surficial seismic phenomena might also be recoverable indicators of ancient earthquakes whose causative faults are inaccessible. Sandblows and liquefaction-related ground failures were certainly widespread during the 1811-12 earthquakes in the Upper Mississippi Valley [Penick, 1976], the 1886 Charleston earthquake [Dutton, 1889], and the great 1897 and 1934 Indian earthquakes [Oldham, 1899 and Geol. Survey India, 1939], and similar features from older events are probably preserved in Holocene strata in these areas. Buried sandblows in the regions of the 1964 Alaskan earthquake or 1703 and 1923 Japanese earthquakes might provide evidence for or against the hypothesis that not all megathrust events there are represented by emergent shorelines.

Recognition of More Complex Patterns

Gaining even a simple knowledge of the average recurrence intervals of the earth's major faults will require enormous efforts. As new and more precise data become available, however, more complex patterns could emerge. Perhaps in some regions systematic relationships between major faults with similar average recurrence intervals will emerge. Does the timing of rupture of the Denali fault (Fig. 6), for example, relate in any systematic way to events on the Alaskan-Aleutian megathrust? Could the recurrence intervals of some faults (the Nankai Trough megathrust, (Fig. 2), for example) vary secularly over many average intervals as a function of time elapsed since the latest great earthquake on a related fault (the Median Tectonic Line, for example)? Slip events along the Garlock and White Wolf faults (Fig. 14) are believed to occur less frequently than events on the nearby south-central segment of the San Andreas fault [Burke, 1979; Stein, 1981]. Are events on the San Andreas fault systematically delayed (or advanced) by occasional large slip events on these related faults?

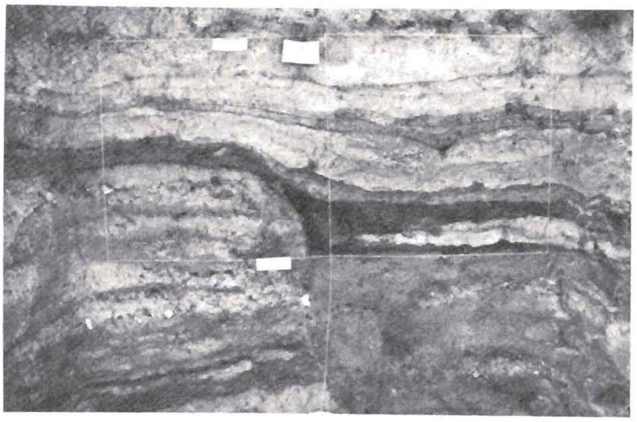

Fig. 25. This scarp represents faulting along the main trace of the San Andreas fault during a large earthquake in about 1500 A.D. Lateral slip of over 2 m accounts for the difference between correlative units on opposite sides of the fault. No fault slip has occurred since deposition of the unfaulted layers overlying the fault.

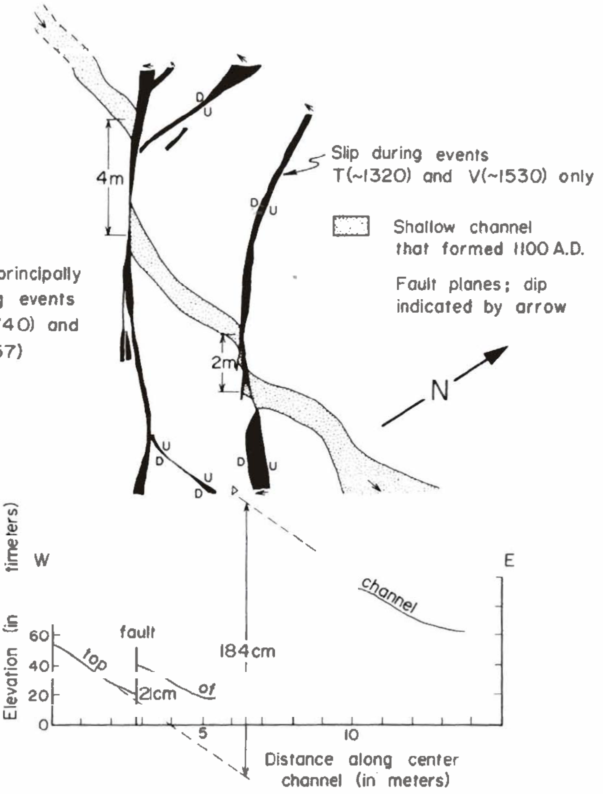

Fig. 26. Plan and cross-sectional views of offset channel at Pallett Creek. Six meters of right-lateral offset has been accomplished during at least four large earthquakes.

More complete information on the prehistoric behavior of large faults might reveal that contiguous fault segments have distinctly different average recurrence intervals. Hay et al. [1981] present evidence that the northern reach of the San Andreas fault (Fig. 14) ruptures at least every three centuries, on the average; and it is known that the southern reach of the San Andreas fault has not produced a great earthquake for at least the past 210 yrs -- the period of historical record. Both values are greater than the average recurrence interval on the south-central segment at Pallett Creek. Are these permanent differences in average interval or do the apparent differences simply reflect the incompleteness of our knowledge?

Conclusions

Geological studies play an important role in the characterization of earthquake hazard and in earthquake prediction because they extend understanding of the spatial and temporal behavior of active faults beyond the limits of the historical and instrumental record into the more ancient past.

Several geomorphic, stratigraphic, and structural approaches have met with varying degrees of success in determining the dates of ancient earthquakes and their average and individual recurrence intervals and in characterizing ancient fault ruptures and deformations. Several other promising approaches have not yet been fully implemented.

Current technical limitations, especially in the realm of geochronology, greatly limit the level of detail at which the history of ancient earthquakes can be resolved. However, new methods may soon help remove some of these limitations. Nevertheless, even considering current momentum in this field of investigation, the long-term spatial and temporal history of most major faults, especially in underdeveloped countries, probably will remain obscure for the next several decades. Unfortunately, many of these faults will produce large earthquakes before their recurrence characteristics can be known and utilized in hazard mitigation or earthquake prediction. In such places, post-earthquake geological field investigations of these faults may well be invaluable in determination of their spatial and temporal behavior for future hazard mitigation or prediction.

In areas where vigorous programs of geological investigation are pursued, determination of recurrence intervals and dates of large earthquakes and behavioral characteristics for the major faults or fault segments might reveal systematic migrations, clusterings, or other interactions of large earthquakes that have value in prediction or hazard mitigation.

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* [J] indicates article in Japanese.
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