FINAL TECHNICAL REPORT
SEPTEMBER 1982

HOLOCENE BEHAVIOR OF THE SAN ANDREAS FAULT AT DOGTOWN, POINT REYES NATIONAL SEASHORE, CALIFORNIA

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Sponsored by the U.S. Geological Survey
Contract No. 14-08-0001-19841
Contract Amount: $43,135
Fiscal Year: 1981

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INTRODUCTION

This report presents the results of our research efforts toward determining the late Holocene paleoseismic history of the northern segment of the San Andreas fault that experienced surface faulting in 1906. Our study was confined to the stretch of the fault zone extending from San Juan Bautista on the south to the Point Arena area along the Mendocino County coast on the north, a distance of some 300 kilometers (Figure 1). During the great earthquake of 1906, this portion of the fault zone experienced well-documented surface faulting (Lawson, 1908). The southern portion of the reach active in 1906 also apparently experienced ground rupture in 1838, but few geological details of this earlier event were recorded (Louderback, 1947).

The first attempt to forecast large earthquakes on the northern segment of the San Andreas fault was made by H.F. Reid in 1910. Based upon his analysis of strain accumulation in the half century preceding 1906, Reid concluded that a 1906-type event might be anticipated once every hundred years. More recent work by Thatcher (1975) suggests alternatively that regional strain accumulation along the fault has been irregular and a recurrence interval of several hundred years might be more likely for major slip events on the northern segment of the fault.

Within the last decade, detailed geological studies at Wallace Creek and Pallett Creek in the central and southern segments of the San Andreas fault have provided well-documented geologic information regarding the prehistoric behavior of the fault in those areas (Hall and Sieh, 1977, Sieh, 1978). Until the present study, however, very little geological research has been focused upon determining the prehistoric records of the northern reach of the fault. Of particular importance in understanding the paleoseismic behavior of the San Andreas fault is the research completed by K. Sieh at Pallett Creek, northeast of Los Angeles (Figure 1), where a sequence of late Holocene marsh deposits is cut by the 1857 trace of the San Andreas fault. Detailed analysis of the stratigraphic records exposed in numerous exploratory excavations has resulted in clear evidence for the occurrence of many large earthquakes prior to the great earthquake of 1857. Radiocarbon dates from charcoal-bearing layers in the faulted sequence and analysis of earthquake-produced sedimentary structures at the Pallett Creek site have provided evidence for eight pre-1857 earthquake events. The interval of time between 1857-type earthquakes (i.e. M_S = 8.25+) ranges between 50 years and 300 years with average return frequency of approximately 160 years.

Sieh's very successful research efforts prompted us to investigate the northern segment of the fault in hopes of finding one or more sites similar to the Pallett Creek area. The initial phase of our research started in 1978 and involved a detailed photogeologic analysis of the entire length of the segment of the fault that broke in 1906. During this phase we searched for sites along the trace that have geologic settings similar to the Pallett Creek area. We also systematically analyzed all of the pertinent historical information dealing with the 1906 ground ruptures. In addition to the large volume of data presented in the State Earthquake Investigation Commission Report (Lawson, 1908), many previously unpublished, historic photographs of the San Andreas fault were studied so that the 1906 breaks more accurately could be located in the field. These historic data, coupled with our aerial photographic analysis and field reconnaissance survey of the entire length of the northern portion of the fault, allowed us to identify six sites along the 1906 segment that had a high potential for containing a detailed and decipherable paleoseismic record (Figure 2).

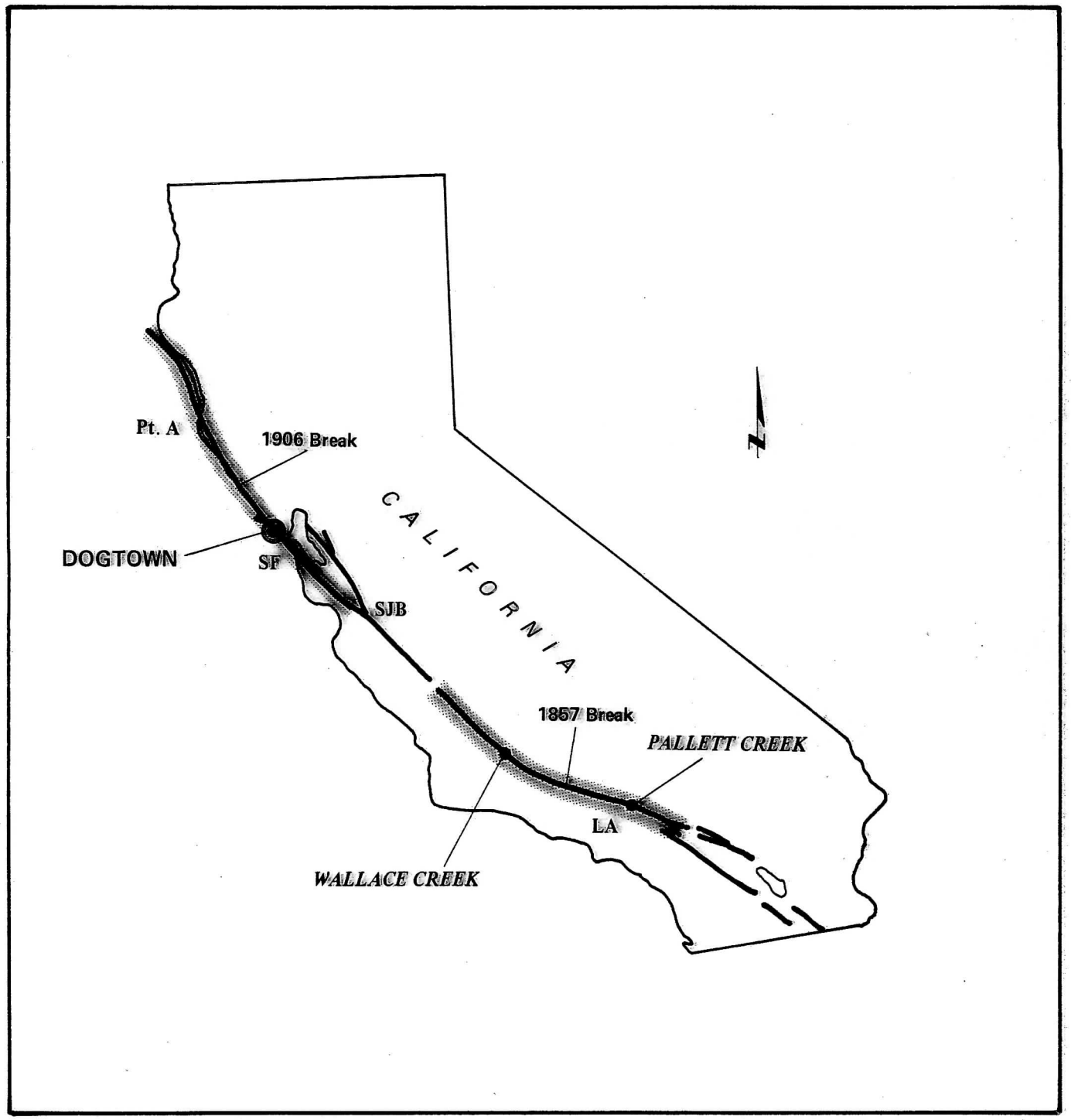


Figure 1. Index Map Showing the Dogtown Research Site and the Historically Active Reaches of the San Andreas Fault System. (LA-Los Angeles, SF-San Francisco, SJB- San Juan Bautista, Pt. A-Point Arena).

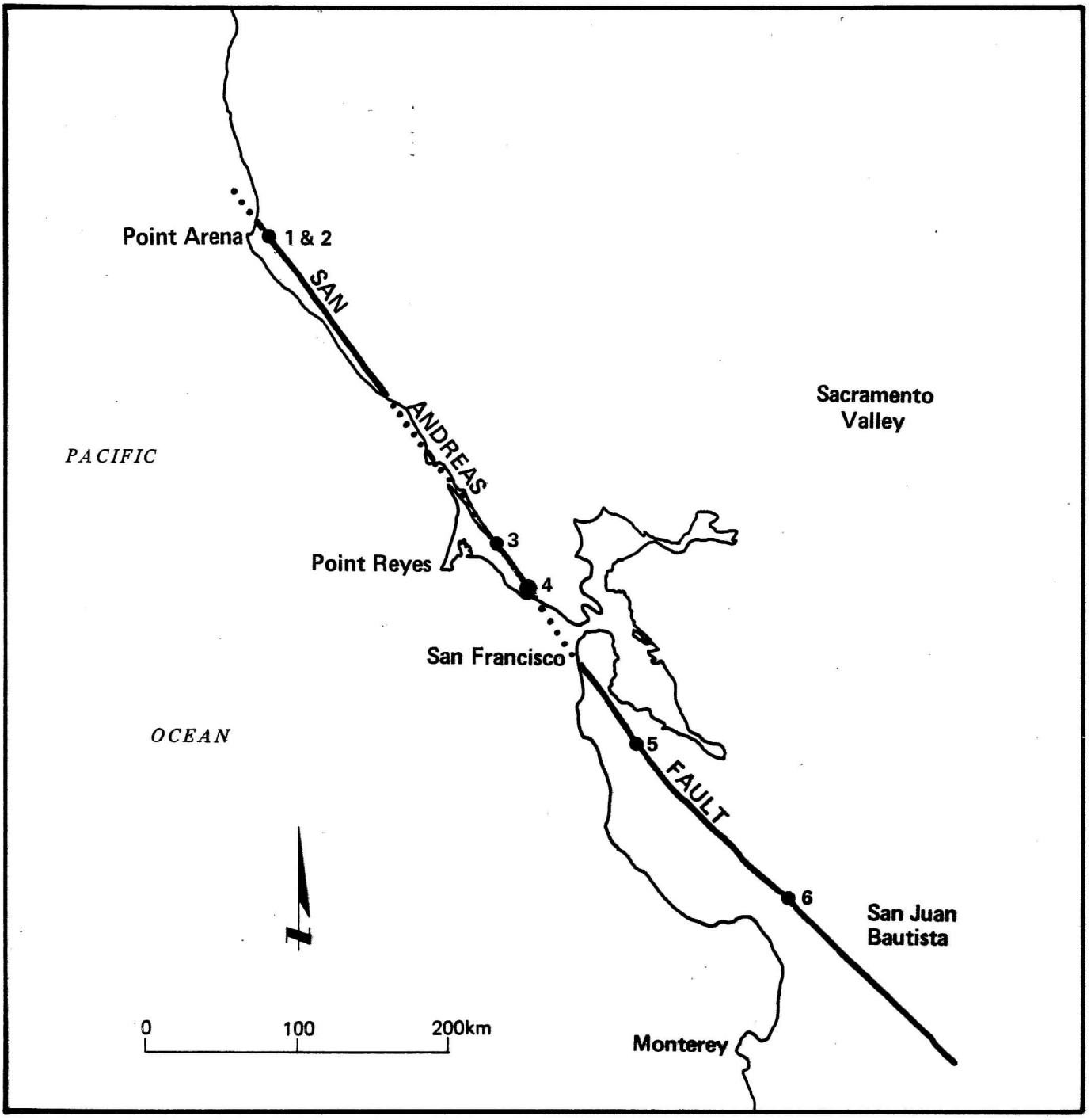


Figure 2. Location Map of Six Preliminary Research Sites Along the 1906 Trace of the San Andreas Fault.

Research Sites

1 – Garcia River (Olsen Ranch)
2 – Garcia River (Jones Ranch)
3 – Vedanta Retreat
4 – Dogtown
5 – Portola Valley
6 – Anzar Road

During research years 1979 and 1981, we were able to excavate preliminary exploratory trenches across the master trace of the San Andreas fault in three of the six sites (Garcia River, Anzar Road and Dogtown). Severe ground water problems were encountered along the Garcia River, while extensive bioturbation had destroyed the stratigraphic record at the Anzar Road site. Consequently, only the Dogtown locality proved to have a high potential for continued research. Late in the summer of 1979, we excavated seven exploratory trenches across the 1906 trace at Dogtown. Preliminary results of the trenching operation indicated that: (1) the 1906 trace could be identified; (2) several large pre-1906 earthquakes could be inferred from discontinuities in the exposed stratigraphic section; and (3) sedimentary layers displaced by faulting contained carbonaceous materials (i.e. charcoal and wood) suitable for radiocarbon dating.

Preliminary conclusions from this first phase of our work were that the Dogtown site had recorded four and possibly five or more pre-1906 earthquake events large enough to have caused displacement of the ground surface. Two of these events were recognized by unconformities truncating fault splays at different horizons within the exposed section. Two additional events were inferred from the juxtaposition of different sedimentary units near the bottom of the trenches. Radiocarbon dates calculated for charcoal-bearing layers exposed in the trenches indicated that five events we identified (including 1906) had taken place within the last 1410±100 radiocarbon years. As a result of this work, we made a preliminary estimate of an average earthquake recurrence interval of 280±20 years for the northern reach of the San Andreas fault at the Dogtown site (Hay, Cotton and Hall, 1981).

The final phase of subsurface research at the Dogtown site was completed late in the summer of 1981. The goals of this phase of work were to refine our recurrence interval estimates by generating more radiocarbon dates, to search for evidence of additional seismic events and to measure the amount of lateral slip that occurred during the various earthquake events recorded here in the sedimentary record. To accomplish our goals, seven exploratory trenches were placed across the mapped fault trace that was located as a result of our 1979 research. Although most of these trenches represented new locations along the fault, three excavations reoccupied former trench sites. Other new transverse trenches were excavated to supply additional information on the number of past earthquake events and their timing, and to better define the subsurface geometry of individual stratigraphic units.

In addition to placing trenches across the fault trace, we hoped to measure lateral displacements of sedimentary units along the strike of the fault in exploratory trenches placed parallel to, and on each side of the fault trace. We anticipated that if lateral stratigraphic boundaries or channels could be correlated across the fault, we could determine the amount of offset for individual prehistoric earthquakes and be able to calculate their average slip rates. Two longitudinal trenches were excavated, one on the west side of the fault and at the northern end of the research site, and one on the east side of the fault and at the southern end of the site (i.e. Pacific Plate Lateral and North American Plate Lateral, respectively). Due both to rapid changes in lithologies primarily caused by fluvial cutting and filling and the lack of linear features transverse to the fault, we were unsuccessful in matching displaced features across the trace of the fault. We found, as might be expected, that the former channels of Pine Gulch Creek tended to follow that active fault trace, not cut across it. Consequently, no clear subsurface record was discovered within these two trenches that would allow us to measure the amount of offset per faulting event.

As a final attempt to establish amounts of horizontal offset, we excavated a single trench directly along the trace of the fault. Even after careful logging of this trench, we were still unable to establish this vital part of the paleoseismic record at the Dogtown site. The three lateral trenches did reveal, however, that the late Holocene layers underlying the Dogtown site have been gently deformed.

The primary results of our final year of research now indicate that the Dogtown site has experienced three 1906-type earthquakes in the past 1410±100 radiocarbon years. The average return period for large and great earthquakes at the site lies between 455 to 217 years. However, we believe that such estimates represent recurrence intervals that are probably too long. Although it is our opinion that the Dogtown site is the most informative one yet discovered along the entire 1906 fault trace, it has not been the equivalent of Pallett Creek.

RESEARCH SITE SELECTION CRITERIA

The entire research year of 1978, the initial year of this project, was devoted to a detailed photogeologic study and a field reconnaissance of the 1906 segment of the San Andreas fault system in order to locate several field sites with a high potential for providing paleoseismic data. Sites that will yield useful information on past earthquakes are extremely rare along most segments of the San Andreas fault. Measurable data on recurrence intervals, slip rates and earthquake size are best preserved in the geologic record by young sedimentary deposits through which the fault passes.

Aside from logistical considerations such as site accessibility to trenching equipment and approval from the landowner to carry out the intended research, the most important site selection criteria are geologic. It is a relatively simple task to "go fault finding" and expose the San Andreas fault in an exploratory trench. However, few sites will provide an adequate sedimentary sequence, the proper style of fault rupture, or suitable carbonaceous materials for radiocarbon dating. For example, locating the fault in bedrock units that are older than late Pleistocene will not provide dateable carbon necessary for determining the timing of paleoearthquakes. Nor is it productive to place exploratory trenches within sag ponds. Because of their relatively similar lithologies, the complex faulting usually associated with them, and the intermixing of carbonaceous materials (bioturbation that invariably occurs when they dry out during the summer), sag ponds will not record a decipherable paleoseismic history. The most likely site conditions conducive to preserving the history of past earthquakes are found along those segments of the fault having a simple style of faulting (i.e. single trace) and cutting through a sequence of young, but varied, alluvial and/or lacustrine sediments.

As a result of our initial year of research in 1978, we were able to locate six potential sites along the 1906 segment that might provide valuable paleoseismic data (Figure 2). Table 1 outlines the primary technical data that were used to select the potential research sites. The geologic criteria outlined in this table were used to evaluate each site. All of the sites except Dogtown were eliminated as a result of detailed site specific studies.

TABLE 1 - Technical criteria for selection of possible exploratory trench sites along the 1906 break of the San Andreas fault.

Geologic Criteria

1. Site has well-documented history of the location and amount of 1906 ground displacement.

2. Site has water table deep enough to permit exploratory trenching to approximately 5 meters (minimum depth approximately 2 meters).

3. Site located on a section of the fault where physiographic evidence suggests that all or most of the Holocene faulting has been narrowly concentrated (i.e. the region is not characterized by multiple, branching or subsidiary faults).

4. Stratigraphy of the upper 4 to 5 meters of the site characterized by multiple, distinct, and laterally-continuous sedimentary units containing a sufficient amount of charcoal or wood suitable for radiocarbon dating.

5. Site is locus of Holocene deposition where sediments accumulate rapidly enough to form a record between successive surface faulting events.

Logistical Criteria

1. Site is accessible to backhoe and other equipment.

2. Permission for access to investigate site can be secured from landowner.

The Dogtown area provided the "best fit" we could find for both the geologic and logistical criteria outlined in Table 1. The research site is located within the boundaries of Point Reyes National Seashore and, thus, the logistical criteria were easily met. The specific site selected for subsurface study was located astride a single trace of the 1906 break well-documented by G.K. Gilbert (Lawson, 1908). The Dogtown trenches were located between offset fencelines at the Strain Ranch on the north and a row of offset eucalyptus trees near Dogtown on the south (Figure 3). Additionally, physiographic features at the site, such as a low scarp along the west edge of a sag pond and an offset stream channel bank of Pine Gulch Creek immediately north of the site allowed us to locate the 1906 fault with little difficulty.

The geologic environment of the Dogtown site is well suited for recording paleoseismic data, but is far from ideal. The area is one of active stream and lacustrine deposition in a subsiding valley which thus has provided a thick and variable late Holocene sedimentary record. The valley walls of Pine Gulch Creek, located immediately north of our exploratory trenches, gave the first indication that the Dogtown site would be productive. The stream has entrenched 3 to 4 meters within the alluvial deposits of the valley floor exposing easily recognizable and laterally continuous sedimentary layers in its banks. Additionally, the depth of the entrenched stream below the valley floor suggested that shallow ground water would not be a critical problem.

REGIONAL GEOLOGIC AND TECTONIC SETTING

The Dogtown research site is situated in what Galloway (1977) referred to as the Olema trough, a narrow, linear valley flanked by Inverness Ridge on the west and Bolinas Ridge on the east. The Olema trough is a structurally controlled depression from 0.8 to 1.6km wide and 21km long that is the primary corridor bounding the San Andreas fault zone. The drowned ends of this trough form Bolinas Lagoon on its southeastern end and Tomales Bay on the northwest. The predominant topographic features of the rift valley are low northwest-trending ridges and depressions which are the result of either tectonic activity along the San Andreas fault (faulting and warping) or subsequent erosion of the tectonically sheared and broken bedrock materials which underlie the valley. The Marin County segment of the San Andreas fault contains some of the most pristine examples of fault produced topographic features found anywhere along the system.

Geologically, the Dogtown research site is located between two very dissimilar bedrock terranes. The mountainous region of Inverness Ridge located west of the site is underlain by granitic and associated metamorphic basement complex of the Salinian block, while to the east, the Bolinas Ridge area is underlain by the complexly deformed and lithologically heterogeneous rocks of the Franciscan assemblage (Figure 4). Structurally, the San Andreas fault forms the boundary between these two basement complexes, a geologic relationship created along the entire length of the San Andreas fault zone throughout the Coast Ranges of central California by millions of years of plate movement (Atwater, 1970). Overlying the granitic rocks of the Inverness Ridge area is a relatively thin veneer of Monterey Shale of Miocene age. To the east, the Franciscan rocks underlying the Olema trough and the western flank of the Bolinas Ridge are covered by marine sands and silts of the Merced formation of Plio-Pleistocene age and scattered exposures of the slightly younger Olema Creek Formation. Within the Olema trough, these younger Tertiary sedimentary rocks form the primary bedrock that underlies most of the fault-related topographic features. Within the immediate area of the Dogtown site, the Merced formation forms the bedrock on which the late Holocene sediments of the Pine Gulch Creek drainage have accumulated. It is in these youngest sediments that the paleoseismic record of several late Holocene earthquakes has been preserved.

The Dogtown trenching site is located at or very near the junction between the master trace of the San Andreas fault and the Seal Cove - San Gregorio fault (Figure 5). Recent geologic investigations to the southeast on both of these faults establish that, on the average, at least 2.2cm of elastic strain can be expected to accumulate across the Dogtown region per year. From shoreline angles of marine terraces displaced by the San Gregorio fault zone at Año Nuevo, Weber and Cotton (1980) have calculated that this fault has moved at an average annual rate of from 7-11mm/year since the Sangamon high sea level stand. These figures accord well with the work of Graham and Dickenson (1978) who found onshore geologic features offset 115km in the last 13 million years for a long-term strain rate across the San Gregorio fault zone of 9mm/year since the middle Miocene. A stream channel that has been displaced 44 feet within the last 1130±160 radiocarbon years B.P. near San Andreas Lake establishes that the San Andreas fault has a minimum annual strain rate of at least 1.2 to 1.3cm/year (Hall, Nelson and Fowler, 1982). Both the San Gregorio fault and the San Andreas fault north of San

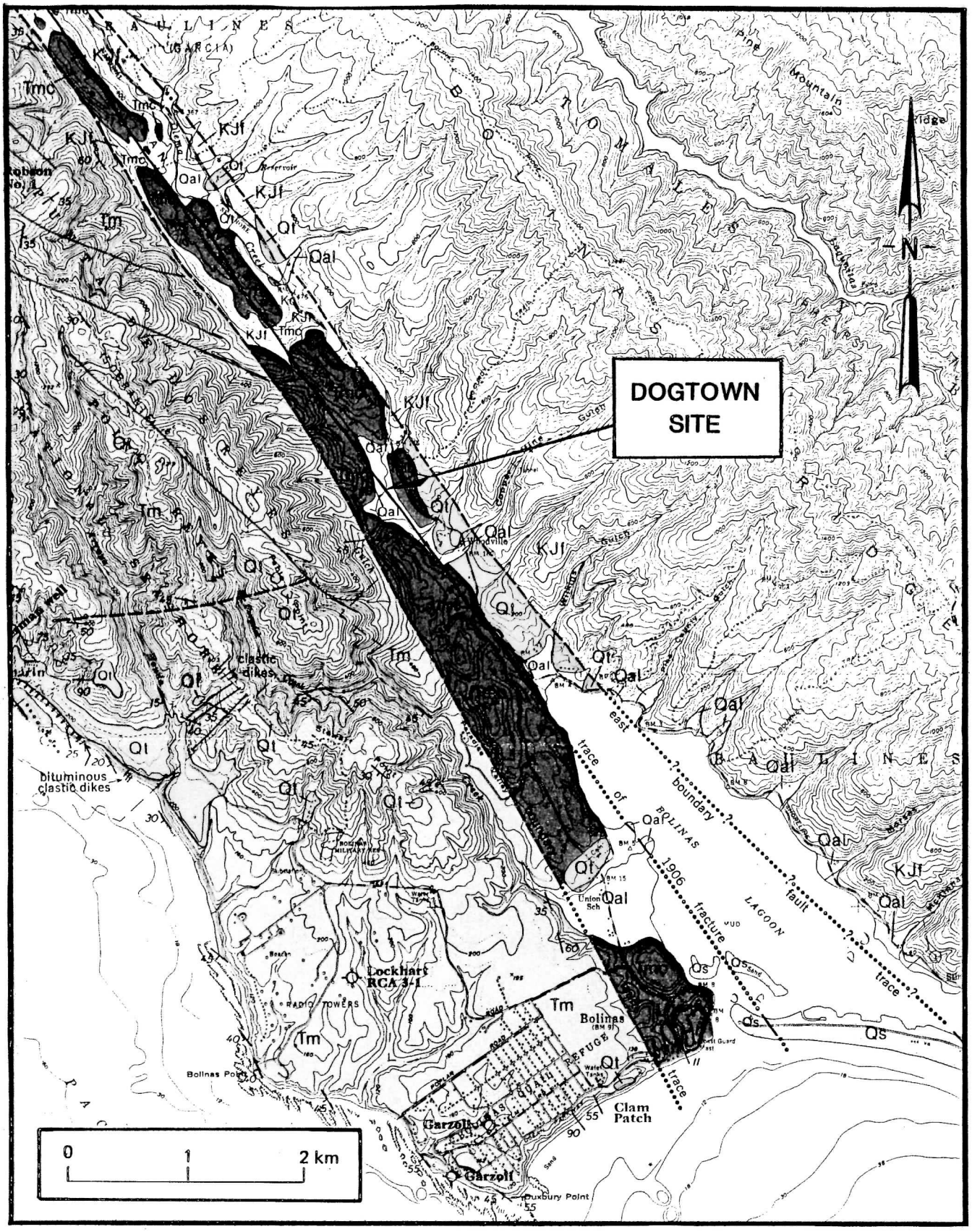


Figure 4a. Geologic Index Map of the Dogtown Research Site (Galloway, 1977)

GEOLOGIC MAP UNITS

Quaternary

Qal

Alluvium

(Unconsolidated deposits of clay, silt, sand, and gravel underlying bottom lands of main stream valleys; materials transported and deposited by the streams.)

Qt

Terrace deposits

(Unsorted and unconsolidated rock fragment debris deposited on stream and wave cut surfaces.)

Tertiary

Tmc

Merced Formation

(Blue-gray siltstone and soft, easily erodible, brown to tan sandstone, pebbly in places.)

Tdc / Tds

Drakes Bay Formation

Tdc—(Mainly fine-grained, tough, compact, cream to brown siltstone interbedded with massive gray to yellowish silty mudstone.)

Tds—(Basal glauconitic greensand. Mostly bright green to greenish gray sandstone rich in glauconite and containing much biotite, quartz grains, and shale pebbles. Locally stained rusty brown with iron oxides.)

Tm

Monterey Shale

(Mainly thin-bedded to massive, gray to brown organic shales, and thin bedded, commonly highly contorted cherts. Contains sandstone beds in a few places.)

Jurassic-Cretaceous

KJf

Franciscan rocks, undifferentiated

(Disrupted and sheared graywacke, shale, conglomerate, chert, and serpentine in and near the San Andreas fault zone.)

SYMBOLS

Contact between adjacent geologic units. Mostly approximately located except in rare well-exposed locations. Queried where grossly approximate.

1906 trace
SAN ANDREAS FAULT
(dotted where concealed)

Other fault traces
(dotted where concealed)

Aerial photo lineament

31
Strike and dip of beds

72
Strike and dip of overturned beds

90
Strike of vertical beds

Component dip

Horizontal beds

Axis of anticline

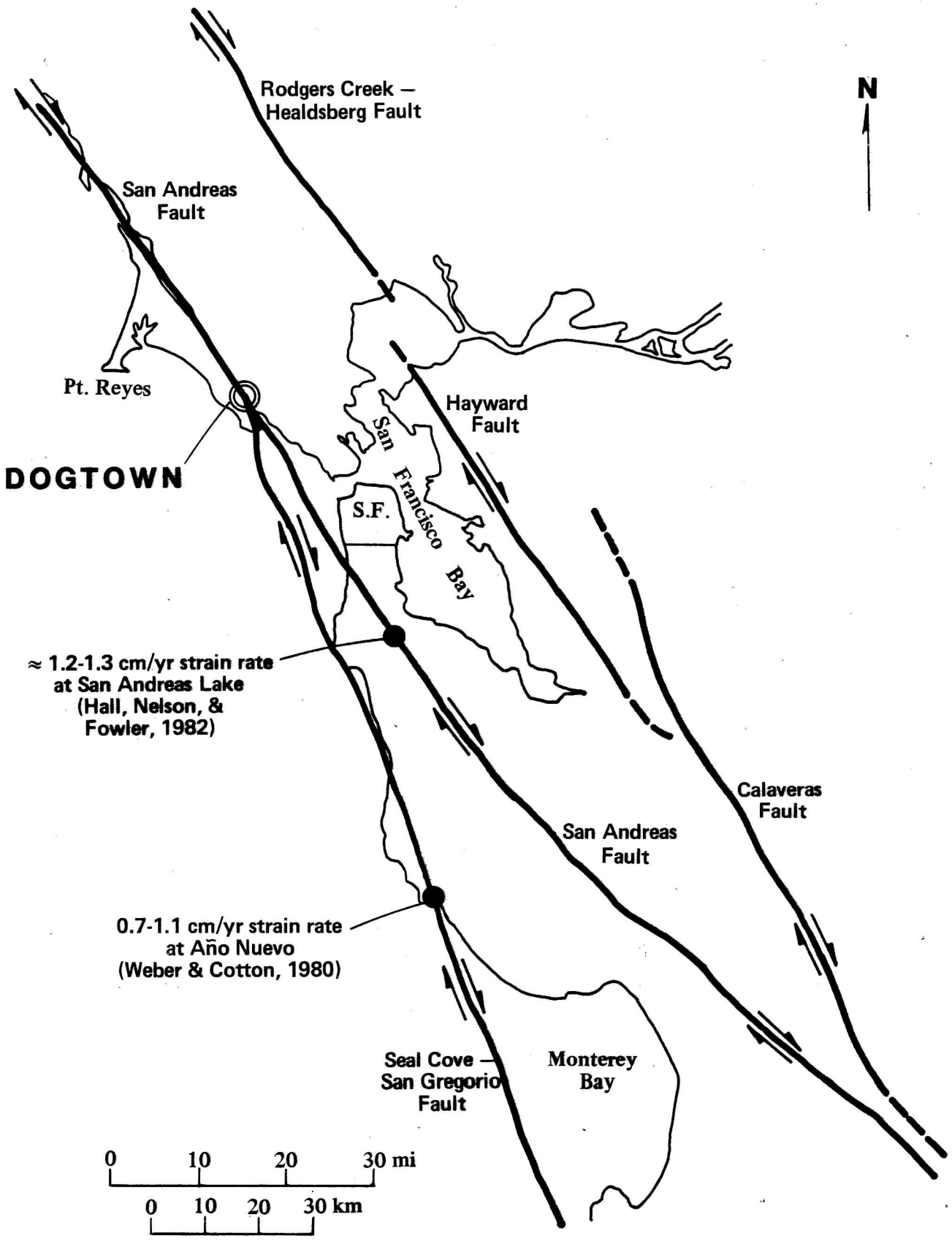
Axis of syncline
(dotted where concealed)

Axis of overturned syncline
(dotted where concealed)

Abandoned dry exploratory well

Figure 4b. Explanation of Dogtown Geologic Map

Figure 5. Regional Tectonic Setting of the Dogtown Research Site



Juan Bautista are characterized by the absence of tectonic creep, which implies that elastic strain energy is accumulating across them. It may be argued that northwest of the junction of these two faults, regional strain rates will be the sum of the rates for each fault or approximately 2.2cm/year.

The Geologic Map of California (Jennings, 1977) shows the northwesterly extension of the Seal Cove - San Gregorio fault, as determined by submarine acoustic profiling, connecting with a fault exposed in the sea cliff at Bolinas that separates Monterey formation of Miocene Age on the west from Merced formation of Plio-Pleistocene Age on the east (Wagner, 1977 and Galloway, 1977). Galloway (1977) calls this the West Boundary Fault of the San Andreas fault zone (Figure 4). Exactly where the strain is transferred from the Seal Cove - San Gregorio fault to the San Andreas fault is not known. Stream channels some 200m west of Galloway's mapped trace of the West Boundary Fault are systematically deflected in a right-lateral sense near Dogtown (Figure 6). These deflections may be lithologically controlled or they might indicate that this fault zone is active. Even if the latter case is true, we believe it can be argued that the greater portion of this transfer occurs southeast of Dogtown. Assuming: (1) that 15 feet, the largest offset Gilbert measured at Dogtown in 1906, is a typical amount of slip for great earthquake events along this reach of the fault, and (2) that the average strain rate is the full 2.2cm/year, then it can be argued that a value for average recurrence frequency of 208 years could be assigned to this segment of the fault. From our current understanding, this value appears to be a reasonable figure. If, however, it is assumed that by the latitude of Dogtown none of the San Gregorio's strain has been transferred to the San Andreas, then a recurrence frequency of 352 years results, a figure that certainly is far too large.

At Olema, which is 13 kilometers northwest of Dogtown, all 2.2cm/year of strain accumulation is concentrated on the active trace of the San Andreas fault because the West Boundary Fault has merged with it (Galloway, 1977). In 1906, the maximum displacement recorded here was a 16 foot shift of the Skinner Ranch barn off its foundation (Lawson, 1908, Figure 22). From these data, a recurrence frequency of 222 years can be computed, a value remarkably similar to the 214±36 years (a maximum figure) calculated for 1906-type slip events on the San Francisco Peninsula (Hall, Nelson and Fowler, 1982). The Seal Cove - San Gregorio fault has not produced a significant ground rupture event during historic time, although Weber and Cotton (1980) have calculated an average recurrence frequency of between 225 and 400 years for major earthquakes (M_s = 7.5) on this system. The relative timing or coupling of slip events between the San Andreas and San Gregorio fault systems is unknown.

Galloway (1977) also delineated an East Boundary Fault on his geologic map of the Point Reyes Peninsula (Figure 4). This fault has recently been located by submarine acoustic profiling along the northeastern margin of Bolinas Lagoon and was probably active in 1906 with dip slip motion when the Lagoon subsided 30cm (Lawson, 1908, p. 72). For a more thorough discussion of the geology of Bolinas Lagoon, see Hall (1977). With the exception of a northeast-facing scarp of unknown origin east of the trenching site, the East Boundary Fault is not physiographically expressed in the Dogtown area. Consequently, we do not feel that the East Boundary Fault currently plays a significant role in the release of right-lateral shear strain along the San Andreas fault zone.

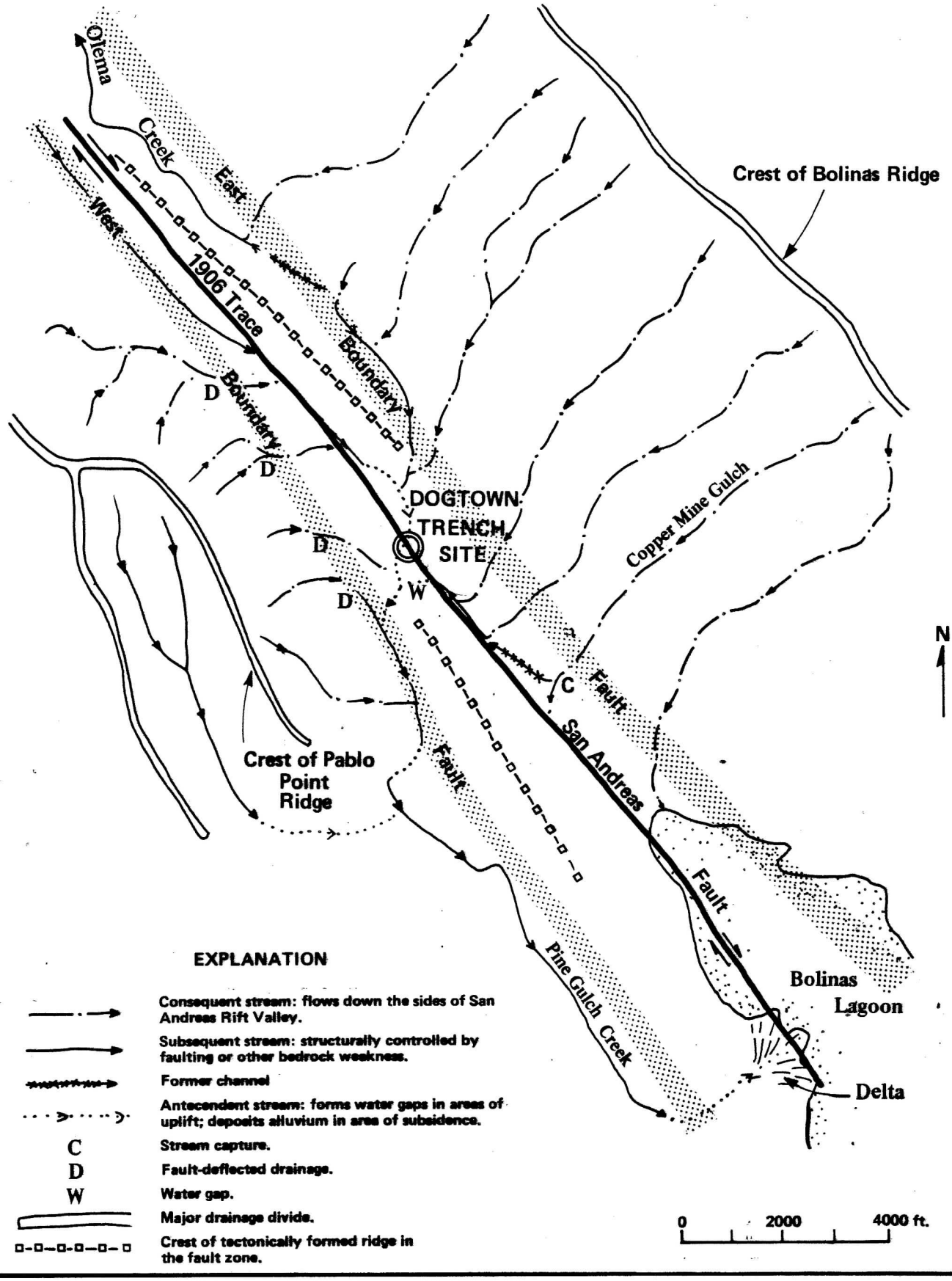
GEOMORPHIC CHARACTERISTICS OF THE DOGTOWN RESEARCH SITE

The Dogtown research site is located on the floor of an actively subsiding alluviated valley characterized by the complex and tectonically controlled drainage of Pine Gulch Creek and its tributaries (Figure 6). G.K. Gilbert photographed this valley looking to the north from the crest of the tectonic ridge west of Dogtown (then Woodville) on 3/30/07 (Figure 7). Comparison of this photograph with the valley today reveals that many striking changes have taken place, particularly in the expansion of forested areas during the last 75 years. Two important geologic changes have also occurred. First, the pond west (left) of the bedrock knob with the orchard planted on it (now an oak-bay-eucalyptus forest) has been drained to form a marsh. Second, the channel of Pine Gulch Creek, which meanders across the valley floor between the Strain Ranch house and the bedrock knob, appears to have incised its channel some 2 to 3 meters since 1907. This entrenchment, which probably resulted from human activity like lumbering or grazing, lowered the water table sufficiently at the Dogtown site for us to expose 3 to 4 meters of section in the backhoe trenches. The depth of downcutting has been controlled by outcrops of consolidated Merced sandstone which are exposed in the channel of Pine Gulch Creek where it flows around the western side of the bedrock knob.

The alluviated valley of the Dogtown site owes its existence to a complex set of geologic circumstances, a few of which can be deduced from a combination of photointerpretation, mapping, and logging of trench wall exposures. The Dogtown Valley lies in a gap or "step-over" between two tectonically elevated ridges underlain by the Merced formation. North of the trenching site the active trace of the San Andreas fault lies along the southwest margin of a ridge, while south of the site the active trace forms the northeast margin of a different ridge (Figure 6). As this southern tectonic ridge moved in a northwesterly direction, consequent southwest-flowing streams from Bolinas Ridge, like Copper Mine Gulch, were deflected to the northwest in order to maintain connection with a water gap (W) carved across the tectonic ridge. The combination of increased channel length of these deflected streams after a slip event, coupled with subsidence of the block east of the active trace, has caused alluviation in the southern half of the Dogtown Valley. Local subsidence also appears to have controlled alluviation in the northern half of the Dogtown Valley as well. Here the active San Andreas fault trace trends from 5 to 7 degrees more northerly than its regional trend, which creates a tensile component across the fault and promotes crustal subsidence (Hay, Cotton and Hall, 1980). In addition, a pulse of alluviation which accompanied the end of the late Pleistocene (Tioga stage) glaciation (Hardin and Marchand, 1980) might also have partially filled preexisting valleys with gentle gradients. The thickness of young, unconsolidated sedimentary deposits beneath the Dogtown Valley is not known at present.

A plane table map of the Dogtown trenching site (Figure 8) shows several important topographic features, even though there was no topographic expression of the active fault trace on the valley floor where the trenches were excavated. From a possibly offset meander scar of Pine Gulch Creek northwest of Trench 1, the alluviated floor of the Dogtown Valley slopes very gently (1 to 2.5 degrees) southwestward to a sag pond surrounded by a marsh. These latter two features clearly demonstrate the local subsidence that is occurring along the eastern side of the San Andreas fault. The rather steep and

Figure 6. Drainage Patterns in the Vicinity of Dogtown



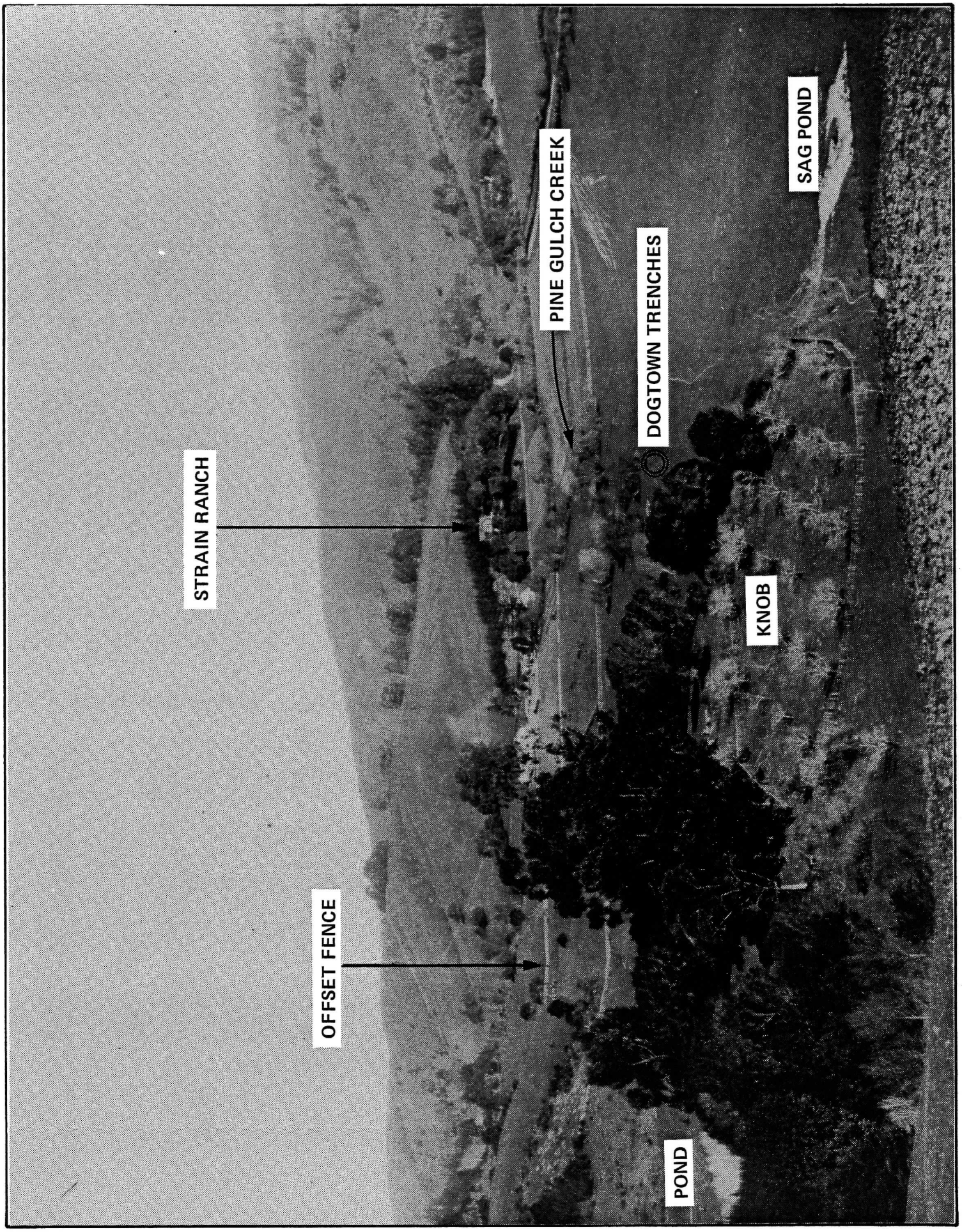


Figure 7. Photo of Dogtown Research Site in 1907. G.K. Gilbert photo no. 3033, Courtesy of U.S. Geologic Survey.

linear (N 35 W) northeastern margin of the bedrock knob just west of the trenching site is probably a fault scarp against which alluvium of Holocene age has been deposited.

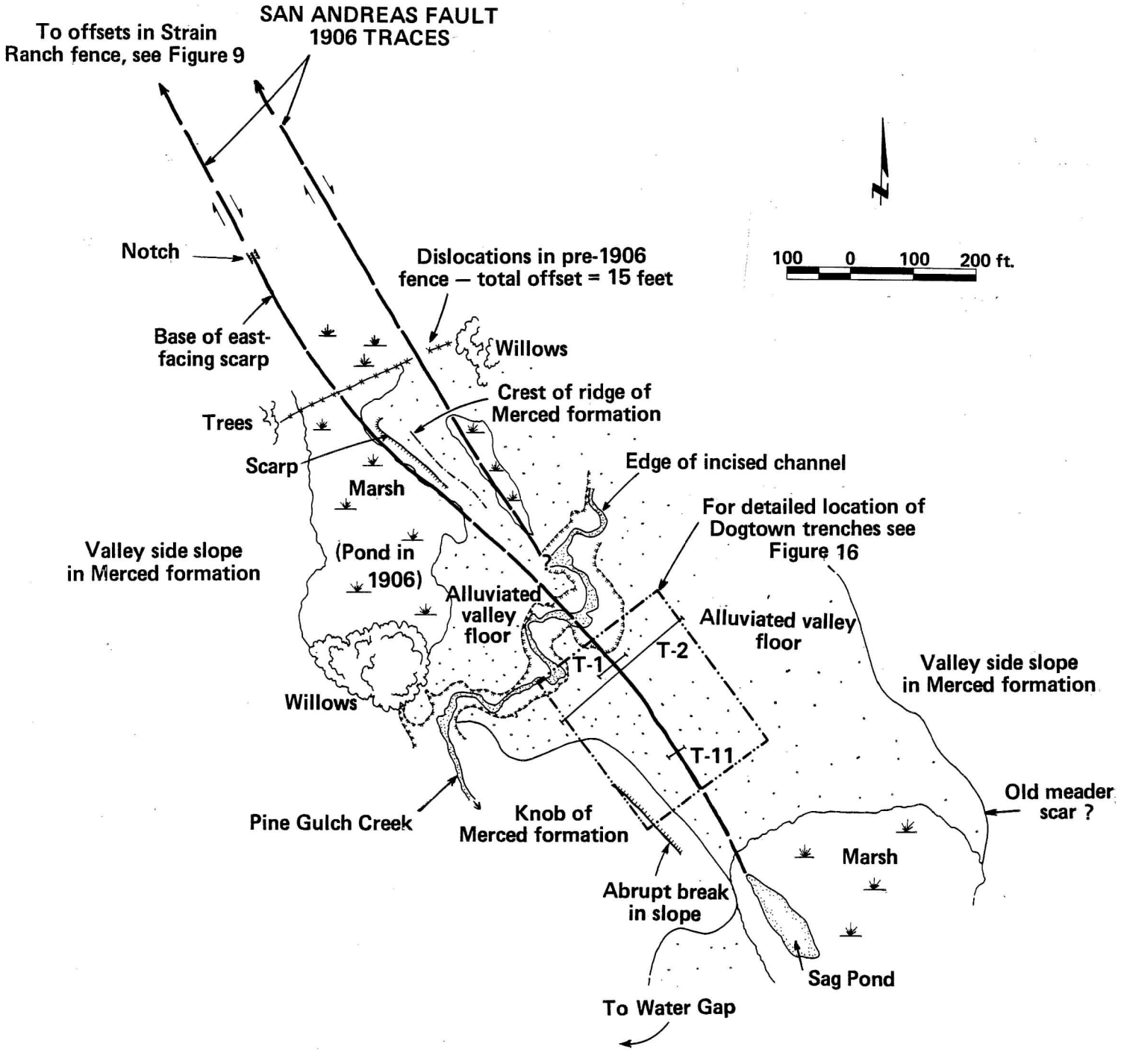
Northwest of the trenching site, Gilbert observed that the 1906 faulting split into two traces which could be followed to the vicinity of the Strain Ranch (Figure 8). The eastern strand follows an elongate marsh, passes beneath what is now a gate in a still extant pre-1906 fence, and marks the eastern limit of ground warping recorded by the offset fence west of the Strain Ranch (Figure 9). The western and major strand follows a well-defined fault scarp along the steep southwestern margin of an elevated fault slice ridge of Merced formation north of Pine Gulch Creek, passes through a notch along the eastern margin of the Dogtown Valley and produced the 2.6m offset in the Strain Ranch fence. The splaying of the active fault trace and the adjacent marshes both indicate local subsidence and probably owe their existence to a more northerly trend of the San Andreas fault here which has created a tensile component across this area. Precisely the same relationships between fault strike, rupture zone width, and dip-slip components of faulting were observed in the Dogtown trenches, but reduced in scale by one or two orders of magnitude. For details, see the section entitled "Fault Pattern."

STRATIGRAPHY

The Dogtown trenches expose a heterogeneous and laterally variable sequence of unconsolidated to semi-consolidated fluvial and lacustrine sediments of late Holocene age. Channel gravels and overbank silts from Pine Gulch Creek and its tributaries spread southeastward across the floor of the Dogtown valley and are interfingered with fine-grained marsh and sag pond deposits to create complex facies changes throughout the research site. Appendix A contains fifteen graphical logs showing the geologic relations along the San Andreas fault as exposed in eleven trenches placed perpendicular to its regional trend and the logs of three trenches excavated parallel to the fault. Additionally, three graphically altered logs exhibiting horizontally compressed versions of the three parallel trenches are included which make stratigraphic relationships easier to visualize. The depositional environments represented by the layers exposed in the trench walls can still be found today on the floor of the Dogtown valley.

The "Upper Gray Gravel" consists predominantly of silty sandy gravels that represent channel deposits mixed with some overbank silt from Pine Gulch Creek. Bioturbation and the other pedogenic processes accompanying the production of a distinct A-horizon have partly destroyed the original stratification of this unit and make it virtually impossible to trace the 1906 shears all the way up to the earth's surface. It is likely that no significant amount of deposition has occurred on the alluviated valley floor in the vicinity of the Dogtown trenches in the last several decades. Pine Gulch Creek failed to overtop its incised channel even during the exceptionally heavy winter rains of 1982. Both the Upper and Lower Red Gravels are well-bedded fluvial channel deposits whose clasts have become coated with iron oxides deposited by fluctuating groundwater. The Upper Silt and the Lower Silt are overbank flood deposits of Pine Gulch Creek. By contrast, the Dark Gray Clay and Blue Gray Clay are sag pond deposits that contain scattered logs, small chunks of wood and matted layers of aquatic plant remains.

Figure 8. Map of Dogtown Research Site and Vicinity



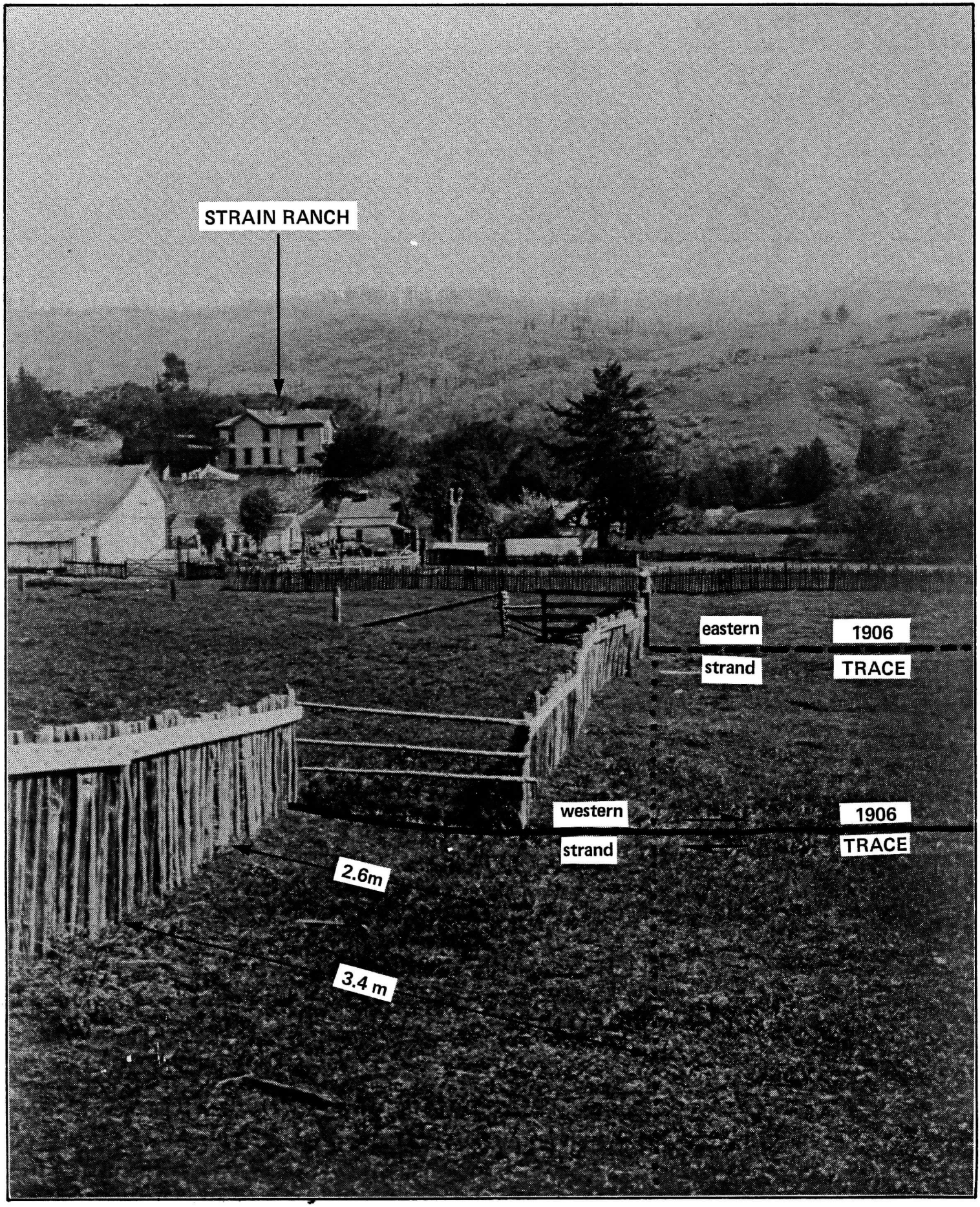


Figure 9. Deformed Fence West of the Strain Ranch. Camera Aligned with Straight Part of Fence Beyond Eastern Strand. G.K. Gilbert photo no. 3028, coutesy of the U.S. Geologic Survey.

The Black Gravel and the related Blue Gravel, which grade laterally and vertically into each other, have an origin that is more difficult to discern. Both are gravelly sand silts to gravelly silty clays that are unsorted and lacking in stratification or other primary sedimentary structures. These units may be a large mudflow that covered the floor of the Dogtown Valley, but more likely represent marsh or marginal sag pond environments where alluvial gravels have been interstratified with finer grained sediments then mixed and homogenized by pedogenic processes. The Black Gravel is penetrated by abundant root casts which have enabled groundwater to oxidize locally the very dark gray (10YR 5/1) to black (10YR 2/1) matrix and the pebbles within it. Pebbles of Franciscan graywacke are commonly well indurated but pervasively oxidized. The Blue Gravel is lithologically very similar to the Black Gravel. Although some local stratification is discernible within it, the Blue Gravel differs primarily in the gley hues of its clasts which indicates this unit has experienced reducing conditions. Franciscan graywacke clasts are commonly very friable and usually grayish green (5G 5/2) in color. Root casts or other cavities in the Blue Gravel are usually colored a striking lapis lazuli blue which inspired this unit's field name. The Blue Gravel is found beneath either the Dark Gray Clay or the Black Gravel, both of which are relatively impermeable and impede or prevent the downward percolation of groundwater. The Black Gravel is, by contrast, overlain by a permeable unit, the Lower Silt. The field evidence suggests that these two gravel units were either deposited slowly or, once deposited, there followed a hiatus in deposition long enough for them to become extensively bioturbated. In fact, geologic conditions following the deposition of the Black Gravel might be nearly identical to those at the Dogtown research site today for the Upper Gray Gravel.

A brief geologic history of the Dogtown site for the late Holocene can be reconstructed from the sediments exposed in the Dogtown trenches. Initially a sag pond existed, the deposits of which are found in the core of an anticlinal warp in the northern half of the Pacific Plate lateral trench. This sag pond was subsequently filled by alluvium from the Pine Gulch Creek system. Next followed a time of nondeposition long enough to allow pedogenic processes to homogenize and destroy the stratification within the stream deposits. Then another sag pond formed that was largely confined to the eastern side of the San Andreas fault. The thickest clay accumulation in this sag pond occurs along the axial portion of a synclinal warp indicating that deposition and folding were occurring simultaneously. The northern portion of this sag was, in turn, filled with an interbedded sequence of channel gravels and overbank silts from Pine Gulch Creek. The gravels were probably deposited when the channel of Pine Gulch Creek followed the active San Andreas trace along the site of the Dogtown trenches and then flowed through a water gap cut across the southern end of the knob of Merced formation (Figure 8). The southern portion of the younger sag still exists as a closed depression immediately southeast of the Dogtown trenches. Because Pine Gulch Creek currently flows along the northern margin of the Merced knob, very little sediment is now reaching this sag pond. An average of from 1 to 1.5m of sediment per thousand years, however, has accumulated at the Dogtown research site during late Holocene time.

HISTORIC SEISMICITY

Two great earthquakes with comparable intensities occurred on the northern reach of the San Andreas fault during the previous century, one in late June, 1838, the other on April 18, 1906. Although residents on the San Francisco peninsula observed ground rupture in the form of a fissure stretching from near San Francisco to Mission Santa Clara in 1838 (Louderback, 1947), it is not known whether fault slip extended northwestward into Marin County or beyond during this earthquake. Louderback (1947) suggested that the greater intensity reported at Monterey in 1838 than during the 1906 earthquake might indicate that fault rupture extended farther to southeast in 1838 than it did in 1906. The Dogtown investigations produced no decipherable evidence for ground rupture along the San Andreas fault in Marin County in 1838.

The 1906 fault rupture is, however, superbly documented by the work of G.K. Gilbert, both in his field notes and in the Report of the State Earthquake Investigation Commission (Lawson, 1908). Gilbert first visited the section of the San Andreas fault near Dogtown on May 11, 1906, and took the first of two photographs of a warped and offset fence west of the Strain Ranch. Figure 9 shows this fence as it appeared in 1907 after repairs. Gilbert spent the next several weeks making a reconnaissance survey of the fault and the effects of earthquake shaking throughout the Point Reyes area. Nearly a year later (March 30, 1907), he again visited the region of the Dogtown site (then known as Woodville) to make more detailed observations and measurements. Excerpts from his field notes and annotated interpretations of his sketches are given below:

> "Saturday, March 30. Olema to Woodville by buggy and return on foot."
>
> [Gilbert first made a sketch map of a line of eucalyptus trees on a property line west of Dogtown that was displaced 13½ feet by a left-stepping en echelon fault trace.]

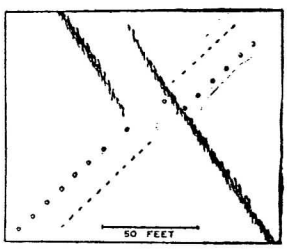


Figure 10: Sketch map prepared by Gilbert of offset eucalyptus trees (Lawson, 1908, Fig. 18).

"Where Bolinas Creek [now Pine Gulch Creek] leaves the main rift valley it first follows a trough between the west wall and a cowhill. On the other [NE] side of the hill is a creek from the S. which joins it, then it follows a narrow way for a few hundred feet, and crosses an opening, with a ranch, before entering the canyon proper. In the canyon it turns sharp angles. My working hypothesis at present is that it is antecedent to the complete uplift of the western block, and to the rift trough, which is considerably below the Tomales-Bolinas Valley. Above Strain's, it follows a straight rift valley."

"The Strain fence south of the one photographed [Figure 9] is crossed by two or more fault cracks and its ground plan is:"

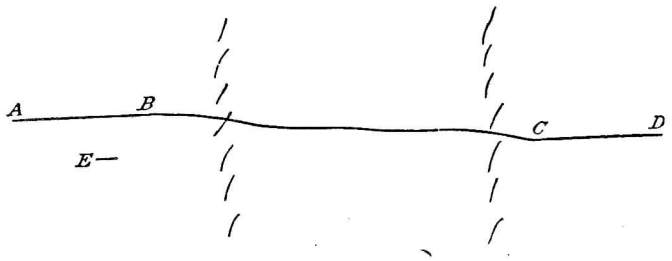


Figure 11: Plan of deformed fence line 800' NW of Dogtown trenches. From Lawson (1908, Fig. 20)

"The distance A-E is 15'."

Gilbert then made a sketch map that showed all the key geomorphic and offset cultural features along the San Andreas fault between Dogtown and the Strain Ranch. See Figure 12 for a copy of Gilbert's original sketch and our interpretation of it.

Gilbert's observations and photographs have been an invaluable resource in our search for a suitable trenching site for recurrence interval investigations. His sketch (reproduced in Figure 12A) establishes that the Dogtown site meets two of our major site selection criteria -- that the 1906 faulting is both well-documented and was concentrated on a single strand. This sketch also helped us locate the portion of the active trace on the alluviated valley floor of Pine Gulch Creek. Finally, Gilbert's measurements establish that between 13½ to 15 feet of right slip occurred through the Dogtown site in 1906.

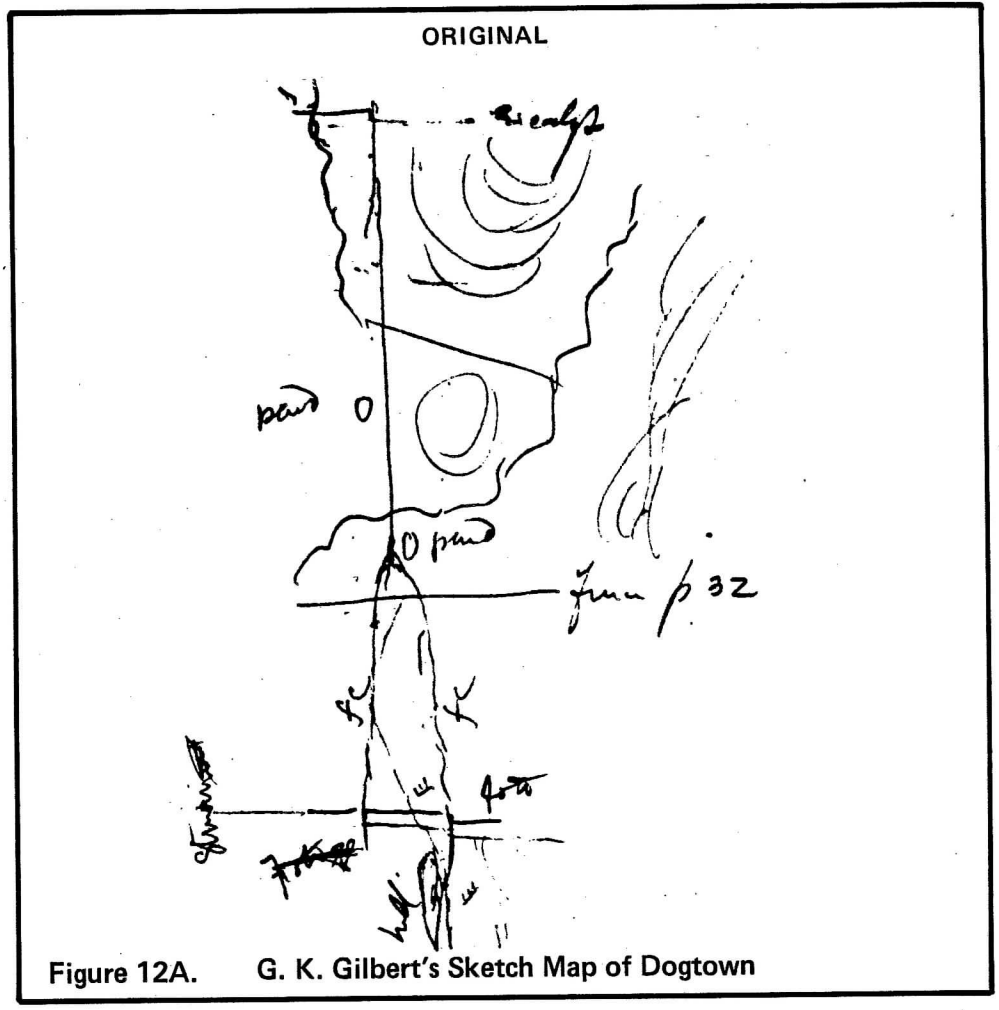


Figure 12A. G. K. Gilbert's Sketch Map of Dogtown

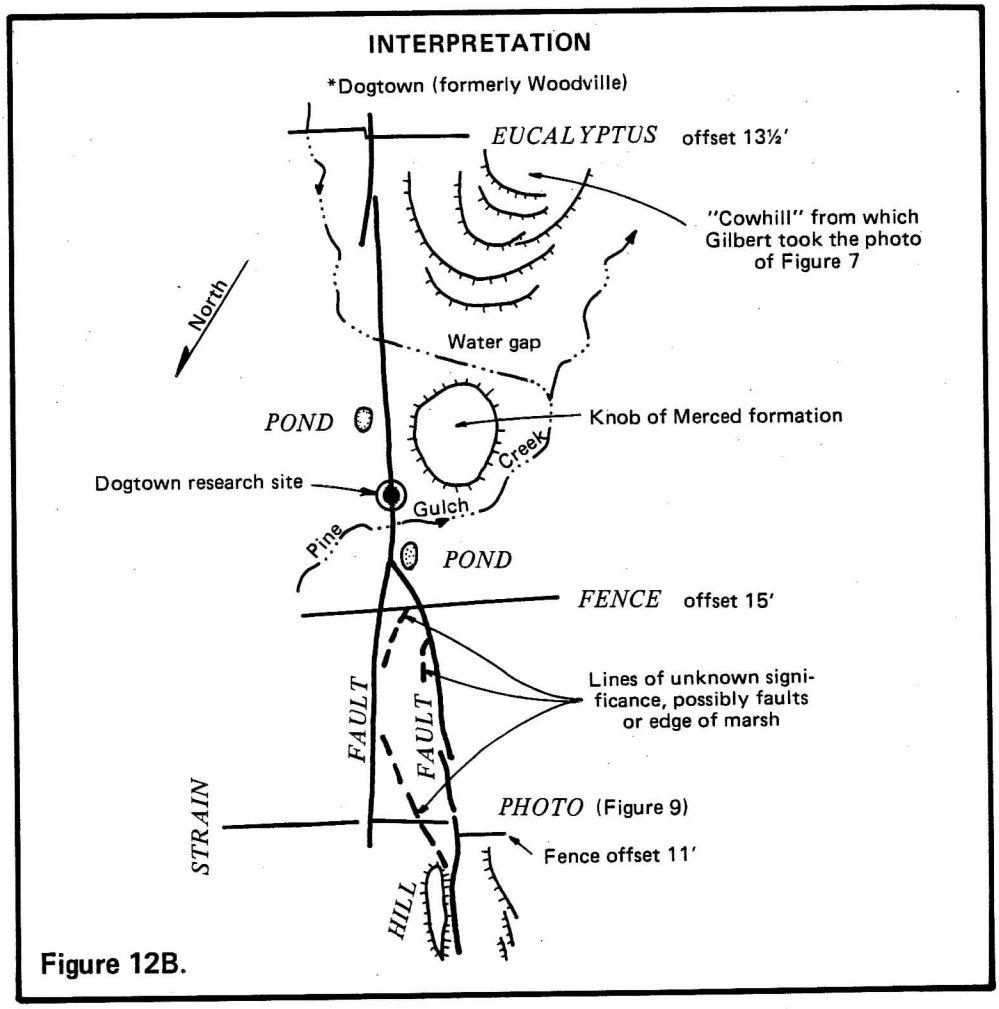


Figure 12B.

PALEOSEISMICITY

In a fluvial setting such as at Dogtown, there seems to be only one reliable way to recognize individual or discreet ground rupturing events in the subsurface. This is done by identifying the local unconformities that sometimes develop by erosion and subsequent sedimentation or simply by sedimentation following an earthquake. For such a record to be preserved, however, succeeding ruptures must be along slightly different splays so as not to obliterate the previously formed unconformable truncation of a fault (Figure 13).

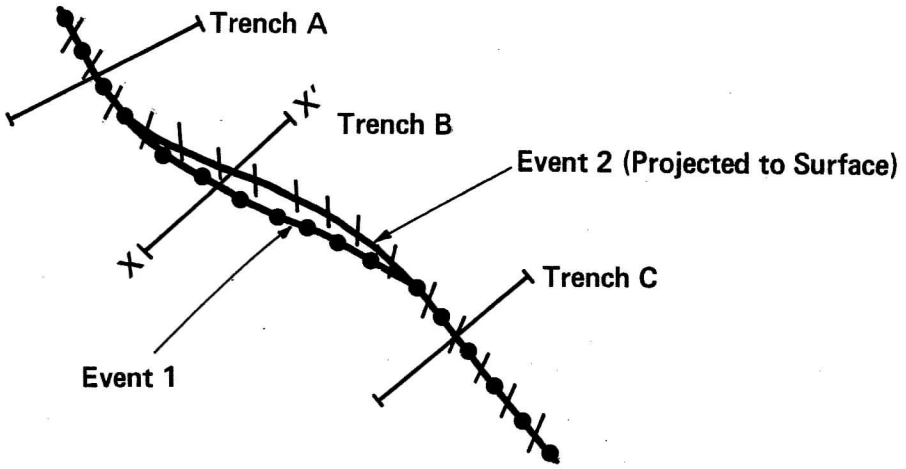
Juxtapositions of different stratigraphic units along the fault proved to be of little value in recognizing prehistoric ground movement events at the Dogtown site. We first believed that it might have taken many 1906-type slip events of three to six meter offsets to explain the distribution of contrasting lithologies seen across the fault in the lower or older portions of many trenches (see Figure 14a, 14b for example), but trenching parallel to the fault, staying on one side of it or the other, showed that rapid facies variations, thickness changes, minor folding, and channeling characterized the Dogtown depositional setting. Thus, abrupt rock contrasts had nothing necessarily to do with fault slip. Further, the sediments at the Dogtown site did not liquefy during past earthquakes and produce "sand blow" structures, such as those used by Sieh (1978) to recognize several seismic events at Pallett Creek.

Unconformities in the sequence, then, remained our only reliable indicators of major earthquakes. These unconformities, however, did not provide a basis for determinations of horizontal slip rates or of the sizes (in terms of lateral displacement) of individual ground rupturing events. All that can be said is that each unconformity was caused by an earthquake large enough to produce ground rupture, presumably a seismic event in the $M_L \geq 6.0$ range.

At Dogtown, we recognized three pre-1906 ground rupturing events recorded by unconformities exposed on several trench walls. Figure 15 presents the best evidence for each of these events. By collecting samples of carbonaceous material (usually charcoal or wood) contained as detritus within sedimentary layers, it was possible to establish ages for each earthquake, although only within broad limits. Our best current estimates are summarized in Table 2. For a list of all radiocarbon dates from the Dogtown site, see Appendix B.

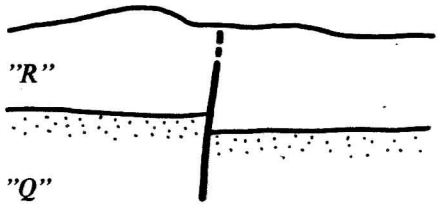
A widely used approach in estimating average recurrence frequencies is to divide the number of seismic events (four at Dogtown) into the youngest date that predates the oldest recognized ground rupture (1,410, radiocarbon age, + 32 years since 1950 = 1,442 years). The value of 1,410 radiocarbon years B.P., however, first should be adjusted to calendar years B.P. by using calibration curves based on dendrochronology. The 1,410 value for radiocarbon years B.P. adjusts to about 1,310 calendar years B.P. when this is done (Stuiver, 1978), giving an average recurrence frequency at Dogtown of 335 + 25 years. This estimate is a <u>maximum</u> value.

MAP VIEW



Event 2 is older than Event 1

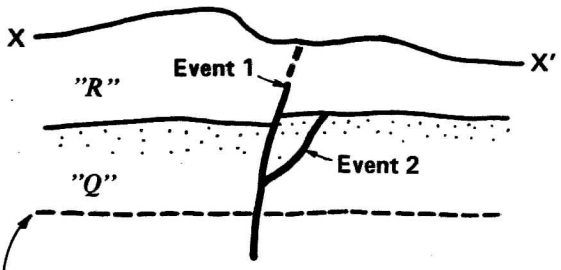
TRENCHES A & C



Event 1 is along the same break as the older event 2, therefore only one event can be recognized.

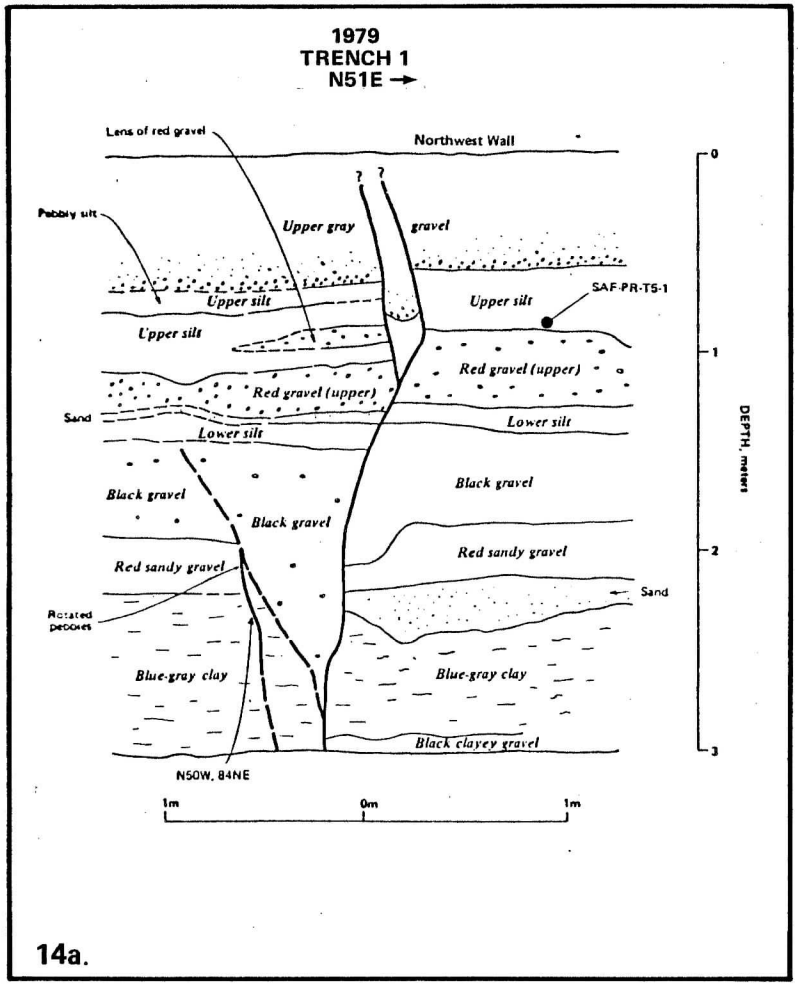
TRENCH B

Event 1 occurred on a different splay than Event 2, therfore both events can be recognized.



Note: If erosion had cut to this horizon in Q prior to the deposition of unit R, Event 2 could not be distinguished from Event 1.

Figure 13. Diagrams Showing Difficulties in Recognizing Individual Paleoseismic Events.



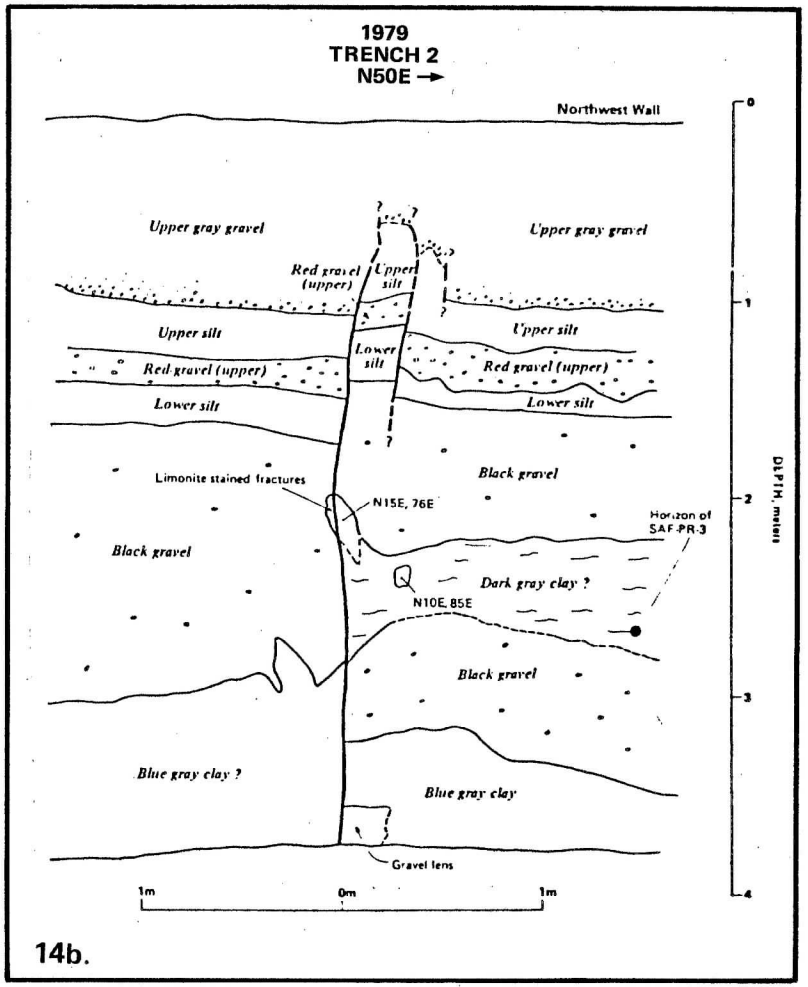
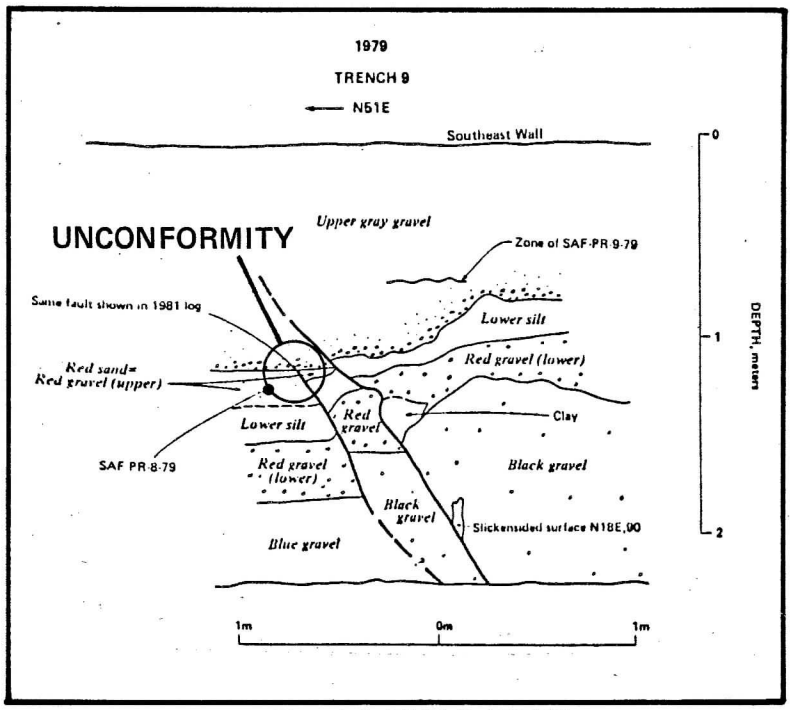


Figure 14a,b. Trench Logs Showing Contrasting Lithologies Across the San Andreas Fault

For full scale versions of these logs, see Appendix A, Plate 1.

Pre-1906
EVENT 1

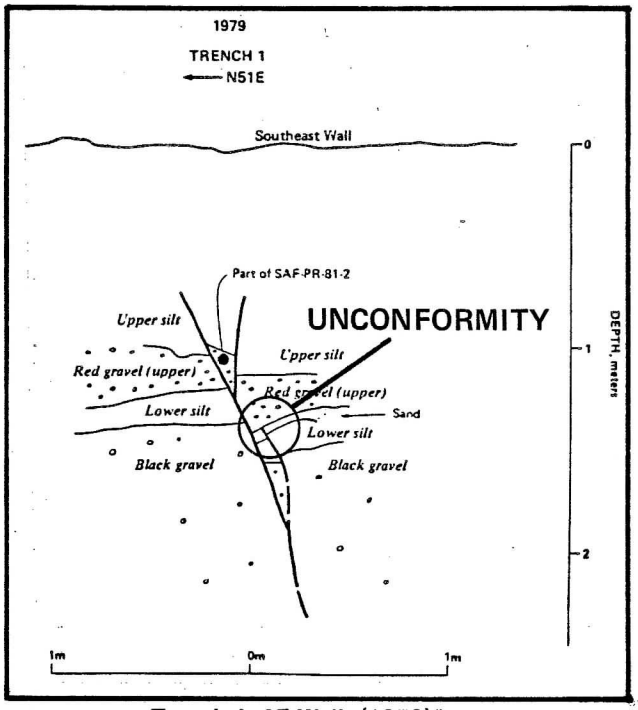
Between 380 ± 85 and 490 ± 150 B.P.



Trench 9, SE Wall, (1979)*

Pre-1906
EVENT 2

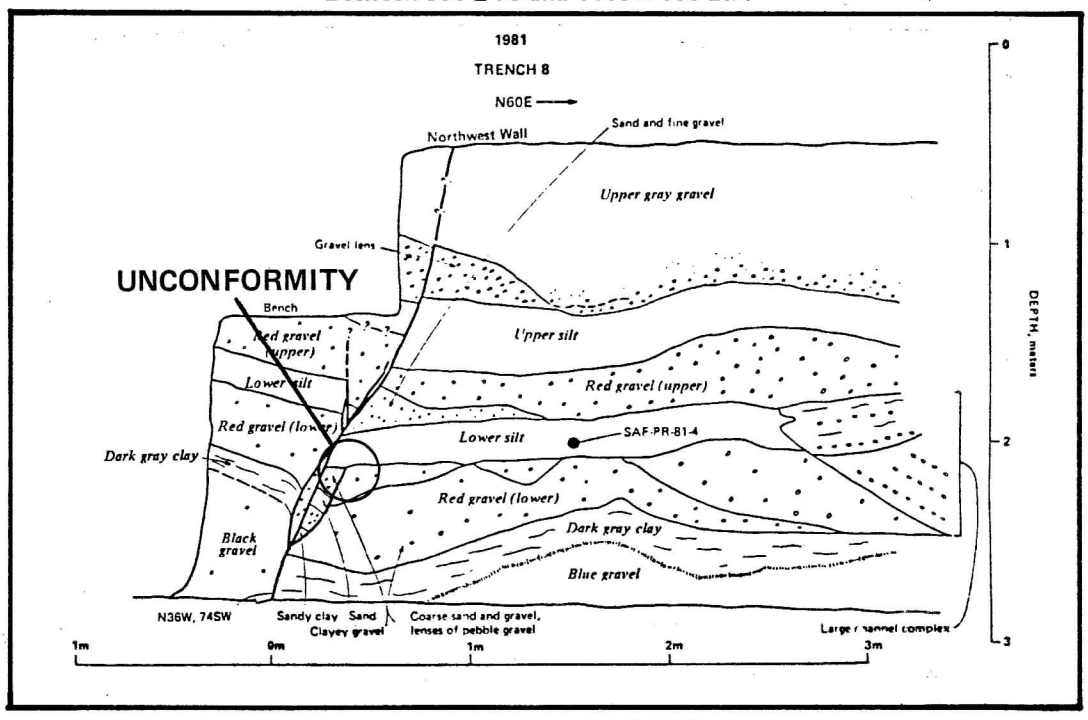
Between 490 ± 150 and 880 ± 75 B.P.



Trench 1, SE Wall, (1979)*

Pre-1906
EVENT 3

Between 880 ± 75 and 1410 ± 100 B.P.

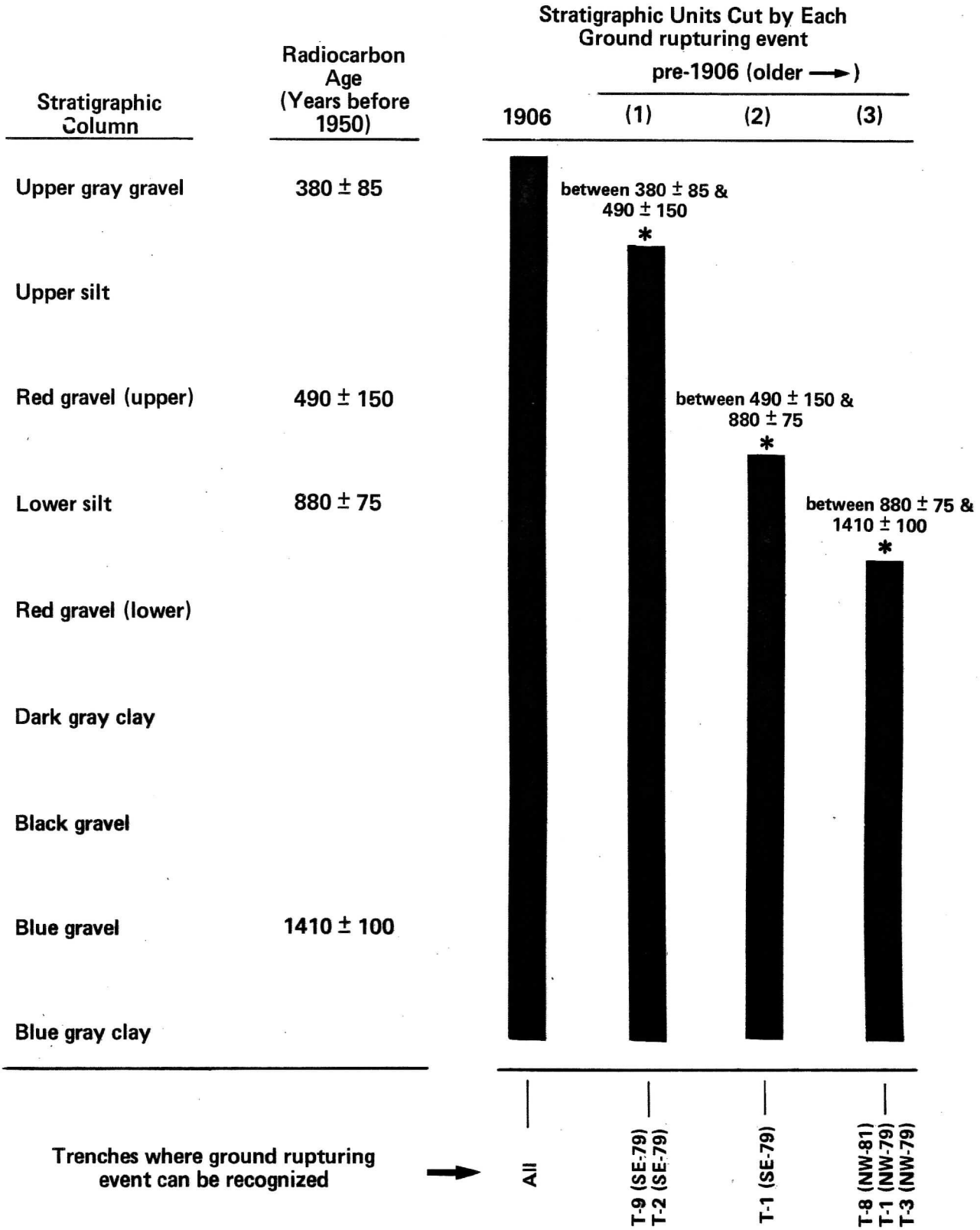


Trench 8, NW Wall, (1981)*

Figure 15. Best Evidence for Pre-1906 Ground Rupturing Events at Dogtown

* For full scale versions of these maps, see Appendix A, Plates 1, 3, & 4.
B.P. = Radiocarbon years before 1950.

TABLE 2


Stratigraphic Column
Radiocarbon Age (Years before 1950)
Stratigraphic Units Cut by Each Ground rupturing event
1906
pre-1906 (older →)
(1)
(2)
(3)
Upper gray gravel
380 ± 85
Upper silt
Red gravel (upper)
490 ± 150
Lower silt
880 ± 75
Red gravel (lower)
Dark gray clay
Black gravel
Blue gravel
1410 ± 100
Blue gray clay
between 380 ± 85 & 490 ± 150
*
between 490 ± 150 & 880 ± 75
*
between 880 ± 75 & 1410 ± 100
*
Trenches where ground rupturing event can be recognized
All
T-9 (SE-79)
T-2 (SE-79)
T-1 (SE-79)
T-8 (NW-81)
T-1 (NW-79)
T-3 (NW-79)

Recurrence frequency determination requires the recognition of a certain number of slip events occurring over a measured interval of time. Errors can occur in two ways. First, ages computed from radiocarbon analysis are always greater than the age of the sediment that contains the carbonaceous material. The wood or charcoal submitted for radiocarbon analysis may be much older than the sedimentary layer in which it was ultimately deposited, particularly within a drainage basin containing redwoods. Consequently, when multiple dates were available for a stratigraphic horizon, we chose the youngest one for recurrence calculations. Second, the actual number of events may be improperly estimated. At Dogtown, discreet slip events were recognized in trenches by splays (seen in cross section) within the rupture zone that were unconformably overlain by younger sediments. Due to the branching and braided pattern of splays in the fault zone, and because of the likelihood that not all such unconformities will be seen in a finite number of trenches (see Figure 13), the three pre-1906 ground ruptures seen at Dogtown probably are fewer than the total number of major slip events that have occurred there during the time interval represented by the strata seen in the subsurface.

Recurrence frequency values are quotients that result from dividing the number of events into the amount of time. Clearly, if time is always too long, because of the inherent characteristic that radiocarbon dates are maximum ages for the sediment, and if the number of events recognized is frequently too few, then the recurrence frequency time is invariably too long.

Our experiences in Trench 9, first excavated in 1979 and subsequently re-excavated in 1981, make this likelihood very apparent. Plate 4 (App. A), logged in 1979, shows a pre-1906 rupture splay unconformably overlain by the Upper Gray Gravel unit. When this location was re-excavated two years later, the southeast trench wall was cut back no more than a foot or so farther to the south than before, yet the unconformably overlain splay was no longer exposed (Plate 4, App. A). The diagrammatic relationship in Figure 13 shows the locations of Plate 4-a = Trench B and Plate 4-b = Trench C with respect to the rupture surfaces developed both prior to 1906 and again during the 1906 earthquake.

We believe there is a better approach than the method discussed previously for determining the average recurrence frequency of large earthquakes at Dogtown. Recall that 335 $\pm$ 25 years was the average recurrence frequency value given, and also recall that we pointed out why this is surely too long. We have evidence for three pre-1906 ground rupturing events, the earliest of which occurred after 1,410 $\pm$ 100 and before 880 $\pm$ 75 radiocarbon years ago (see Table 2). If these two ages are corrected to calendar years (Stuiver, 1978), the plus 100 years error possibility is added to the older value, the minus 75 years error possibility is subtracted from the younger value, and both values are adjusted to years before 1906, then the oldest of the three pre-1906 earthquakes occurred sometime after 1,366 years prior to 1906 and before 651 years prior to 1906. Average recurrence frequency between the 1906 earthquake and the earlier three earthquakes recorded at Dogtown thus ranges between 455 years and 217 years. Taking into account that these are both maximum values, we are inclined to favor a value near the shorter end of this time range.

At Dogtown, we had hoped to recognize channels or other distinctive rock units that approach the fault from one side, undergo offset some measurable distance along the fault, and emerge on the other side. Lateral slip

rates might then have been determined. To this end, we excavated long trenches parallel to, and approximately two meters away from, the narrow rupture zone of the San Andreas fault (see Figure 16). Lateral facies changes, channel instabilities present at the time of sedimentation, and channel trends sub-parallel to the fault, however, made it impossible to correlate any units or features across the fault (Appendix A, Plates 10 & 11). Although discreet slip events were clearly recognizable, their amounts of lateral movement could not be determined.

Coarse-grained fluvial sediments of late Holocene age are not normally well consolidated. The uppermost unit at Dogtown, the Upper Gray Gravel, falls into this category. This material may be 300 or 400 years old and, thus, have been affected by a ground rupturing event that may have occurred between 1906 and 380 $\pm$ 85 radiocarbon years ago. Yet, due to the sediment's granular unconsolidated nature and extensive bioturbation, such a pre-1906 break has not been recognized.

It seems to us that many factors suggest that average recurrence frequency determinations resulting from subsurface excavations such as those at Dogtown are apt, always, to yield values that are clearly maximums, and these values are typically suggestive of much longer intervals of time between large paleoearthquakes than actually have occurred.

FAULT PATTERN

Previous studies of regions in California where tectonic activity is controlled by shearing along the San Andreas fault enabled us to "postdict" accurately the geometry and style of movement of several active faults as a function of their strike (Hay, Cotton and Hall, 1980). Ruptures that are parallel in strike to the predominant San Andreas trend ($\approx$N 40 W) are characterized by steep dips, narrow widths, and horizontal right slip. Traces that strike more to the west or the east of the San Andreas trend show gentler dips and broader rupture zones, with imbricate thrusting seen on the faults striking more westerly and normal slip producing graben-like troughs on the more easterly striking breaks.

At Dogtown we discovered similar variations on a small scale along the 1906 San Andreas break itself. Eleven exploratory trenches were excavated with a trend approximately perpendicular to the 1906 trace (Figure 16). Beginning at the northwest end where the fault strike is N 39 W, four significant changes in strike occur in the 65 meters between Trench 1 and Trench 11. Between Trench 1 and Trench 5, the strike of the fault as seen in clay units near the bottom of each trench, is N 39 W, and the rupture zone is nearly vertical and very narrow (see Appendix A, Plate 1-c for example). From Trench 5 to near Trench 8, the fault strikes N 16 W, dips are about 60 to the west, and normal offset occurs (Plate 3-b). At Trench 8, the fault begins to splay in an upward direction, and the strike between Trench 8 and Trench 9 swings around to N 48 W. The rupture at Trench 9 (Plate 4-b) splays upward within a relatively wide zone. Here, as expected from its more westerly strike, the offsets between the splays are in the reverse sense. N 32 W is the fault trend at Trench 10, and the fault is once again narrow and nearly vertical in dip (Plate 4-c). Trench 11, however, exposed a rupture zone that is dramatically different from any seen in other trenches (Plate 4-d). The rupture zone is quite wide and graben-like, and the strike of the zone, as determined from measuring actual rupture surfaces as well as by taking bearings from one trench wall to the other, ranges between N-S and N 22 W.

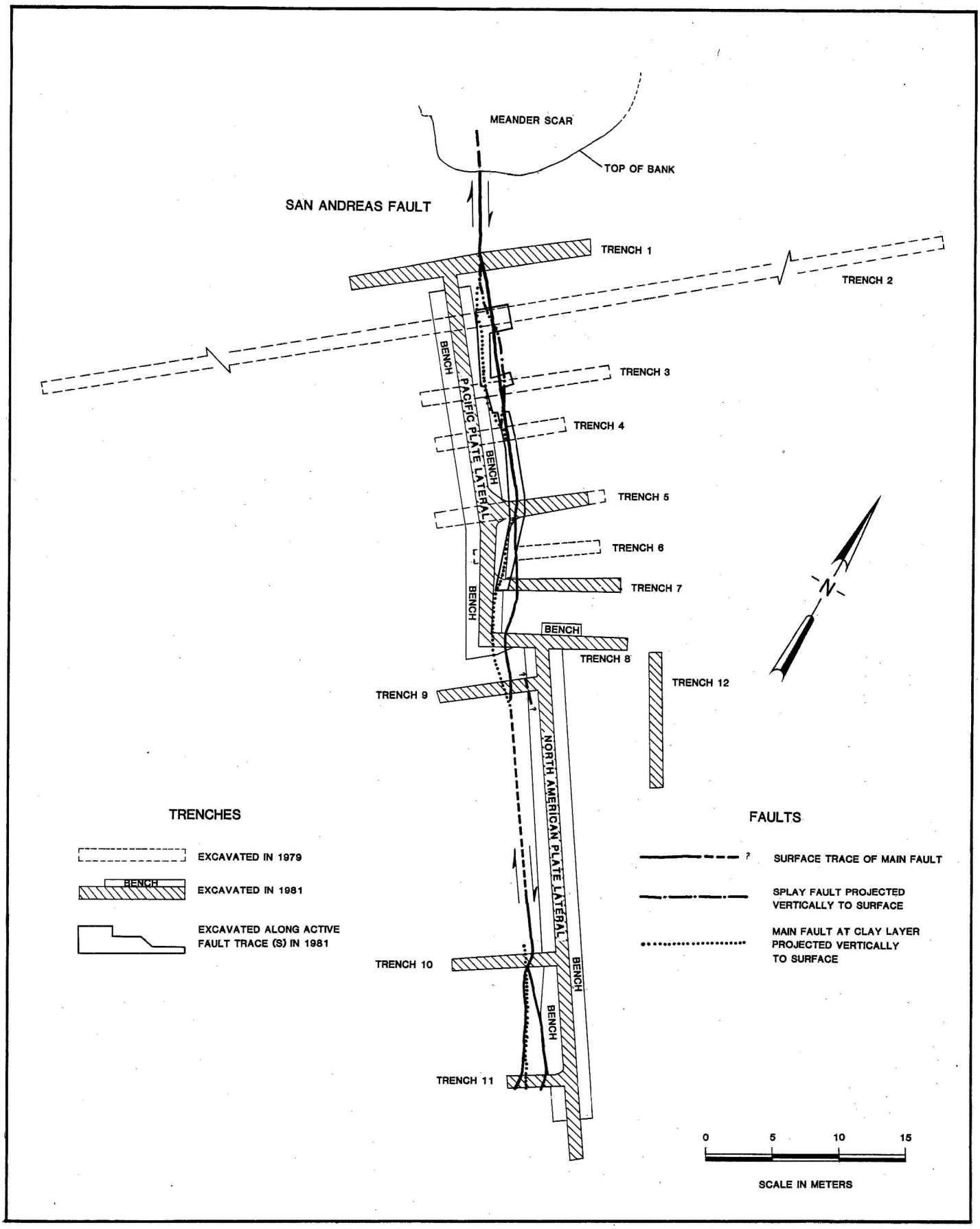


Figure 16. Map Showing Location of the Dogtown Trenches

Here at Dogtown, within a small zone of the San Andreas fault itself, we observed the same relationships between rupture style and fault strike that had been recognized previously on a regional scale. The overall trend of the fault at Dogtown is N 33 W. Fault segments that strike significantly (10-20 degrees) more westerly than that display compressional effects (reverse slip, splays, non-vertical dips, etc.), while those with more northerly strikes are characterized by broad zones with tensional effects (sags, normal slip, non-vertical dips, etc.). These observed relationships provide a tool for making nearby predictions of the location of any fault whose movements have been controlled by horizontal right shear stresses. The main trend will be in a counterclockwise direction from ruptures having graben-like zones, and a clockwise direction from upward splaying exposures having reverse offsets. The direction of the horizontal shear couple can likewise be estimated from narrow, vertical rupture zones that lack significant components of dip slip movement.

CONCLUSIONS

Dogtown was discovered following an exhaustive search along the 1906 break of the San Andreas fault for settings meeting five geologic criteria and two logistical criteria that we had developed previously to facilitate finding a potentially productive research site for paleoseismic studies. Geomorphic characteristics at Dogtown, coupled with late Holocene tectonic and fluvial processes in this region, produced the necessary stratigraphy for recording paleoseismic events. The work of G.K. Gilbert following the 1906 earthquake documented that that rupture had occurred over a very narrow and recognizable zone, thus facilitating our initial trench-site selections.

Three pre-1906 ground rupturing earthquakes were recognized by unconformities exposed in the walls of our trenches at Dogtown. Our data indicates that the average recurrence frequency between them and the 1906 event lies between 455 years and 217 years. It is likely, however, that since both these values are maximums, the correct recurrence frequency is near the shorter end of this time range. Slip-rate considerations for the San Andreas and San Gregorio faults south of Dogtown also support the view that 1906-type earthquakes are apt to occur with an average recurrence frequency of 200-230 years.

Careful mapping (both in cross section and map view) of the 1906 break at Dogtown enabled us to recognize a systematic relationship between the strike of the fault and its geometry and style of rupture. Traces that strike more to the west or the east of the dominant San Andreas trend show gentler dips and broader rupture zones, with imbricate thrusting seen on faults striking more westerly and normal slip producing graben-like troughs on the more easterly striking breaks.

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APPENDIX A

LITHOLOGIC DESCRIPTIONS

Upper Gray Gravel: Sandy silty gravel to pebbly sandy silt; light to medium brown (10YR 8/2-5/4); subangular to rounded pebbles ¼"-2" derived pred. from Franciscan graywacke and greenstone with minor Monterey shale; extensive bioturbation has destroyed most stratification, abundant root hair holes and worm burrows, moderately developed A-C profile; soft, very friable, slightly sticky and slightly plastic; fluvial origin.

Upper Silt: Silty fine sand to clayey silt with rare, scattered pebbles up to 1½"; gray to light yellow (10YR 6/1-6/4); some laminations preserved; scattered detrital charcoal; slightly hard and firm; fluvial origin.

Red Gravel (Upper): Silty sandy gravel to sandy silty gravel; yellowish brown (10YR 5/6) to reddish yellow (7.5YR 6/8); clast morphology and composition similar to Upper Gray Gravel but clasts coated with iron oxides; stratified with scour and fill structures; moderately sorted, soft and friable; fluvial origin.

Lower Silt: Pebbly clayey silt; gray to yellowish brown (10YR 5/1-5/4); laminated, slightly hard and firm; fluvial origin.

Red Gravel (Lower): Silty, fine sandy gravel with iron oxide stained clasts; same as Red Gravel (Upper); fluvial origin.

Dark Gray Clay: Sandy clayey silt to silty clay; gray to very dark gray (10YR 5/1-3/1); laminated in places with scattered logs and carbonized reed fragments; firm, sticky and plastic; sag pond/marsh origin.

Black Gravel: Gravelly sandy silt to gravelly silty clay; very dark gray (10YR 5/1) to black (10YR 2/1) matrix enclosing oxidized pebbles of predominantly Franciscan graywacke, greenstone and Monterey shale; unsorted and unstratified; firm to very firm, slightly plastic; fluvial/marsh origin modified by pedogenesis.

Blue Gravel: Same as Black Gravel except for minor local preserved stratification; pebbles of Franciscan graywacke have gley hues most typically grayish green (5G 5/2) formed under reducing conditions; root casts and other cavities colored intense lapis lazuli blue; firm, slightly plastic; fluvial/marsh origin.

Blue Gray Clay: Very similar to Dark Gray Clay except for intense blue coloration of scattered root casts and cavities; sag pond origin.

APPENDIX B

RADIOCARBON DATES

UNIT (in stratigraphic order)	SAMPLE #	LOCATION	RADIOCARBON AGE (years before 1950)
Upper Gray Gravel	SAF-PR-9-79	T-9 SE (79)	380 ± 85*
Upper Silt	SAF-PR-T5-1	T-1 NW (81)	740 ± 115
Red Gravel (Upper)	SAF-PR-8-79	T-9 SE (79)	1245 ± 105
	SAF-PR-T7-2	T-5 NW (79)	2130 ± 90
	SAF-PR-81-1	Pac. Plate Lateral	490 ± 150*
	SAF-PR-81-2	T-1 SE and T-9 SE	780 ± 110
Lower Silt	SAF-PR-T6-5	T-3 NW (79)	880 ± 75*
	SAF-PR-81-3	Pac. Plate Lateral	1330 ± 120
	SAF-PR-81-4	T-8 NW (81)	1230 ± 130
Red Gravel (Lower)	--	--	--
Dark Gray Clay	SAF-PR-81-6	T-10 SE (81)	1690 ± 210
Black Gravel	SAF-PR-3-79	T-2 NW, SE (79)	2230 ± 105
	SAF-PR-81-5	Pac. Plate Lateral	1890 ± 100
Blue Gravel	SAF-PR-4-79	T-2 SE (79)	1410 ± 100*
Blue-Gray Clay	--	--	--

*Dates chosen for recurrence frequency calculations.