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HOLOCENE SLIP RATE OF THE CONCORD FAULT AT GALINDO CREEK IN CONCORD, CALIFORNIA

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Final Technical Report to the United States Geological Survey

Contract No. 1434-HQ-97-GR-03102

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Components II.3: "Determine the nature and rates of crustal deformation," and II.5: "Identify active faults, define their geometry, and determine the characteristics and dates of past earthquakes".

ABSTRACT

The heavily urbanized Concord fault is the little-studied southern portion of what appears to be the Green Valley-Concord structure within the San Andreas system in the East Bay. This project is a continuation of the first paleoseismic work begun on the Concord fault in 1994. That project focused on the north side of Galindo Creek, uncovering a 5.7-ka channel fill ("Channel Fill B") on the west side of the fault. This phase of the project sought to discover the eastern counterpart to that channel fill.

In this project year, trenches T-8 through T-18 were excavated. T-8 was a fault-parallel trench excavated to determine the precise location of the hypothesized eastern piercing point formed by the 1939 creek channel prior to its burial during channelization in 1984. T-9 and T-17 were cross-fault trenches excavated to determine the precise location of the hypothesized eastern and western traces of the fault at the south end of the study site. T-10 was a fault-parallel trench excavated to uncover any channel fill deposits younger than 5.7 ka. T-11 was a cross-fault trench excavated to determine the precise location of the fault at the southern margin of Channel Fill B. T-12 was a cross-fault trench excavated to determine the location of the fault immediately north of the modern concrete-lined channel and to examine the soils on an older alluvial remnant. T-13, T-15, and T-16 were shallow trenches used to constrain the southerly extent of alluvial depo-

sition on the east side of the fault. T-14 was a fault-parallel trench excavated to uncover the northern margin of the young channel fill ("Channel Fill D") discovered in T-10. And finally, T-18 was a fault-parallel trench excavated to uncover the eastern piercing point formed by the northern and southern margins of Channel Fill B.

Results

Vertical Slip Rate

Channel fill deposits on the east side of the fault lie at higher elevations than those of the same age on the west side of the fault. In cross fault exposures, it was apparent that previously horizontal sedimentary units were drag folded to higher elevations by up to 3 m along the fault plane. Also, on the west side of the fault, the top of Channel Fill B (5.7 ka) was about 1.6 m lower than the top of Channel Fill D (2.4 ka). The median value for various measures of vertical slip was 0.45 ± 0.6 mm/yr. This rate was taken into account when matching units across the fault for determining the horizontal slip rate.

Horizontal Slip Rate

Many of the trenches required for this phase of the study were used to constrain or eliminate possible candidates for the eastern version of Channel Fill B. During our explorations we were especially surprised to find that one of the main reasons for selecting this site, a pronounced 24-m right-lateral bend in the historic channel of Galindo Creek was not produced by fault movement. This eliminated a possible eastern trace of the fault and decreased the post-6 ka offset by up to 65 m. In addition to locating the only trace of the fault precisely, other trenches south of Galindo Creek showed that no candidates for the eastern version of Channel Fill B were in that area. Instead, soil and sedimentary characteristics as well as ^{14}C ages indicated that the eastern counterpart of Channel Fill B exists in T-18 and T-12 north of the creek. Piercing points derived from projections along the northern margin of Channel Fill B3 (an inset channel fill dated at 6.0 ka on both sides of the fault) had an offset of 20 ± 3 m, while points from the southern margin had an offset of 19 ± 0.3 m. These offsets yield a horizontal slip rate of 3.4 ± 0.3 mm/yr.

We obtained a nearly complete cross section through 11-m wide Channel Fill D, which was abandoned at 2.4 ka. Unfortunately, this channel fill existed only on the west side of the fault. However, by assuming a constant width and by using a well-defined piercing point developed from the northern margin, we were able to relate its position to the historical channel of Galindo Creek on the east side of the fault. Modern debris and bedrock scour in trench T-13 constrained the southern extent of the creek channel on the east side of the fault. A piercing point derived from the scour location and the historical trend of the creek constrains the 2.4-ka offset to 13 m, yielding a maximum horizontal slip rate of 5.4 mm/yr.

Drag Folding

The Concord fault at Galindo Creek dips between 71° and 47°SW. Because there has been up to 3 m of vertical slip during the last 6.4 ka, many of the features seen in the trench exposures exhibit drag folding along the fault. Trench T-11 clearly shows the tendency for older units on the west to be dragged upward along the fault. We sampled cross sections through various drag-folded sedimentary units in trench T-11 and T-12. Particle size distribution analyses implied that the units were first deposited horizontally, later achieving their west-dipping orientation via tectonism. The analyses provided no support for the hypothesis that the steeply dipping features were a result of infilling within fissures produced during catastrophic earthquakes. Drag-folded units within the main shear zone are seldom discretely offset. In the cross fault exposures observed, drag folding was confined to a zone within 75 to 150 cm of the fault plane. Oblong clasts whose long axes were parallel the dipping fault plane appeared so only because the bed in which they were originally deposited was drag folded parallel the fault. Clasts did not appear to rotate independently of their surrounding matrices.

The horizontal slip rate (3.4 mm/yr) on this central segment of the Concord fault is about the same as the creep rate (2.6-3.5 mm/yr) measured a kilometer to the north. Thus a tentative conclusion might be that these drag features are especially characteristic of dipping faults that seldom, if ever, experience catastrophic ground rupture. On the other hand, fault traces just south of Galindo Creek are widely dispersed and creep evidence is scarce. The Galindo Creek site may not be representative of the hazard presented by the northern half of the fault.

INTRODUCTION

The Concord fault is a major N25°W-trending right-lateral fault of the San Andreas fault system (Fig. 1). It extends for about 18 km through the cities of Walnut Creek and Concord, beginning at the base of Mount Diablo and continuing northwesterly to Suisun Bay. An apparent bend beneath Suisun Bay distinguishes the Concord fault from its northern extension, the Green Valley fault, which continues an additional 35 km to the northwest (Jennings, 1994). A M7.1 earthquake on the Concord-Green Valley fault would severely impact the eastern part of the San Francisco Bay Area. Extremely heavy shaking would occur in a densely populated area along the fault in downtown Concord.

The fault might carry a significant portion of the Pacific-North American plate boundary slip at this latitude. To the west, the San Andreas fault moves at about 22± 2 mm/yr (Niemi and Hall, 1992; Prentice, 1989) and the Hayward fault moves at about 8±1 mm/yr (Lienkaemper and Borchardt, 1996). This leaves about 16 mm/yr of the 46 mm/yr predicted by the Nuvel 1 plate model (Kelson and others, 1992) to be divided among the San Gregorio, Concord, and others.

The Concord fault was originally discovered as a result of a lawsuit. Ranchers in the Ygnacio Valley alleged that pumping of groundwater by the Port Costa Water Company was adversely affecting their wells. Poland (1935) reviewed and summarized the resulting court documents and recognized that the prominent, linear, groundwater barrier through central Concord was a fault in the alluvium. He named this fault the Concord fault and showed it on his geologic map of the area. Sharp (1973) discovered evidence of creep and produced a strip map showing geomorphic features and offset cultural features along the fault. Numerous studies by consulting geologists, commonly involving trenching, were conducted in accordance with the Alquist-Priolo Act. These studies, as well as additional mapping of geomorphic features and evidence for fault creep led to the recently revised Alquist-Priolo Earthquake Fault Zone map of the fault (CDMG, 1991; Wills and Hart, 1990; 1992). Since 1980, Galehouse (1998) has monitored aseismic slip at two localities in the middle of the fault. Creep, averaging about 3 mm/yr, typically occurs in episodes involving rapid slip of 7-10 mm over a few months alternating with intervals of slow right slip of 1-2 mm/yr over several years.

Despite the significance of the Concord fault to earthquake hazards in this urban region, its long term slip rate has not been previously investigated. Slip rates used in regional strain-rate studies (Kelson and others, 1992) and probabilistic seismic hazard maps (Petersen and others, 1996) have usually assumed that the slip on the Concord fault must be greater than its creep rate. Commonly the 6 mm/yr creep rate measured at the one station on the Green Valley fault has been assumed to be the geologic slip rate on the Concord fault.

For this study we selected a locality (the only large relatively undeveloped site in central Concord) where the fault could be clearly mapped from historical aerial photographs taken for the USDA in 1939. The fault appears as a scarp and tonal lineament that apparently was associated with a sharp right lateral deflection in the channel of Galindo Creek. Although the parcel is currently vacant, an old railroad right-of-way follows its western boundary, a gravel pit formerly occupied its central portion, and a buried storm drain and a sewer line cross the site. In 1984 the old creek channel was filled and replaced with a large concrete lined channel on a straighter alignment than the historic channel. These site disturbances complicated the logistics of the investigation, but we were able to locate abandoned mid-Holocene stream channel deposits on both sides of the fault.

TECTONIC SETTING

The Concord fault is part of a group of faults that branch from the San Andreas fault south of the Bay Area, near Hollister. This system is dominated by the Calaveras fault, with slip of about 15 mm/yr (Kelson and others 1992; Petersen and others, 1996). At the latitude of San Jose, slip on the Calaveras is partitioned onto the Hayward and northern Calaveras faults. The Hayward fault accounts for approximately 8 ± 1 mm/yr of this slip (Lienkaemper and Borchardt, 1996) and the northern Calaveras accounts for about 5 mm/yr (Kelson and others, 1995). Slip on the Calaveras fault appears to diminish northerly, with very little or no Holocene slip north of Danville (Hart, 1981; Simpson and others, 1992). Much of the slip on the Calaveras fault may be transferred easterly to the right-lateral Greenville fault through compressional faults such as the Las Positas and Verona faults and the subsurface Mt Lewis seismicity trend. Right-lateral slip on the Greenville fault may be transferred westerly to the Concord fault through the thrust faults on the south side of the Mt Diablo uplift (Unruh and Sawyer, 1995). Any right-lateral slip remaining on the Calaveras fault north of Danville may also be transferred to the Concord fault through a series of left-lateral faults that were the source of earthquake swarms in 1970 and 1990 (Oppenheimer and Macgregor-Scott, 1992). A well-constrained slip rate on the Concord fault will allow more precise estimates of how much slip could be transferred from the Calaveras fault through to the Green Valley fault. It will improve our estimates of hazards related to these faults, as well as to the Concord fault itself.

At its southern end the Concord fault has been mapped along the base of Lime Ridge, a northwest trending extension of the Mount Diablo uplift. The fault may have several active strands here (Wills and Hart, 1992; Smith, 1992), being poorly defined by discontinuous scarps, breaks in slope, and tonal lineaments. As it approaches central Concord, the fault becomes more sharply defined geomorphically, and also begins to show clear evidence of creep. The main scarp passes through central Concord along a small sag pond immediately north of our trench site. Evidence for fault creep begins just south of our trench site, continues north through central Concord where it was measured at about 3 mm/yr, and terminates at the northern restraining bend. Evidence for creep further to the north is obscure, probably because the fault crosses modern flood plain and tidal sediments.

REGIONAL GEOLOGY

The Galindo Creek site that we chose for our paleoseismic investigation lies at the northwestern tip of Lime Ridge. The fault runs along the west side of the ridge, which rises and broadens to the south until it merges with the main part of the Mt Diablo uplift. As Lime Ridge has risen in the Quaternary, along with the rest of Mt Diablo, streams have been diverted to the north so that they flow around the northwestern tip of the ridge. Galindo Creek mostly drains the east side of Lime Ridge and part of the north flank of Mt Diablo before crossing the ridge at its northern end and flowing westward into Ygnacio Valley.

Where Galindo Creek crosses the northern end of Lime Ridge it has incised uplifted older alluvium and siltstone bedrock considered to be of the Pliocene Tulare Formation of Graymer and others (1994). The 1939 aerial photos of the USDA show this incised channel crossing the Concord fault, where it is sharply offset right-laterally. Our investigation focussed on finding the prehistoric downstream extensions of this incised channel, determining their ages and the distances they have been offset, and calculating a Holocene slip rate for the Concord fault.

SITE GEOLOGY

The site of our slip-rate investigation is a vacant parcel south of downtown Concord bounded on the west by Monument Boulevard and on the east by San Miguel Road. An elevated section of the Bay Area Rapid Transit (BART) crosses the east side of the site, parallel to San Miguel Road (Fig. 2). On the 1939 photographs the stream involved in our investigation, Galindo Creek, follows a meandering course along and around the northern end of Lime Ridge, becomes straight for about 30 m on the site, and is sharply deflected right laterally. This sharp right-lateral deflection suggested that the fault had offset the historic creek channel.

Siltstone of the Tulare Formation is exposed in the creek channel on the east side of San Miguel Road about 30 m east of the study site. The creek crosses under San Miguel Road in a concrete box culvert and extends across the study site in a concrete lined channel. The concrete channel was constructed in 1984 slightly north of the natural channel and on a straightened alignment. Today, 6-ka alluvium is exposed at the surface on the north side of the channel, while the south side has been disturbed by grading. Uplifted alluvium is also found in a small hill east of the fault at the northern end of the site near Monument Boulevard. The west side of the fault consists of a low lying area that has been disturbed by grading, both for Monument Boulevard and for the Sacramento Northern Railroad, which formerly ran parallel to Monument Boulevard. We anticipated that abandoned stream channels of Galindo Creek would be found west of the fault and north of the creek during trenching. This interpretation proved to be correct.

METHODS

During June 1994, we excavated seven trenches at the site, three of the trenches crossed the fault perpendicularly and four were parallel and west of it (Fig. 2). In July 1997, we excavated 11 trenches at the site, five of the trenches crossed the fault perpendicularly and five were parallel to it (Fig. 2). Both walls of the trenches were logged at 1:20 scale. The Galindo Creek watershed must have had numerous fires that preceded significant runoff events. Over one hundred small charcoal samples were collected, air dried, and examined in detail for quality. Only unabraded samples with distinct plant structure were used for ^{14}C analysis via accelerator mass spectroscopy. One large charcoal sample was dated by the conventional beta counting technique. In 1994, eight soil profiles were measured and sampled, and nine charcoal samples were dated (Snyder and others, 1995). In 1997, 5 soil profiles were measured and sampled, and 11 charcoal samples were dated.

Trenches were excavated with a rubber-tired, 36" backhoe to 5-m depths on the west side and to the Tulare Formation on the east side. Both trench walls were cleaned and logged at

1:20 scale by using standard methods (Borchardt, 1993; Lienkaemper and Borchardt, 1996). Clasts larger than 3 cm were measured individually. The datum for the site was the top of the storm drain cover labeled "Storm Drain Cover/Survey Station 1 (0 m)" in Fig. 2. An electronic water level was used to tie trench elevations to this one point, which was arbitrarily assumed to be at 0 m (it is actually 17.8 m above sea level). Trench positions and relief elevations were surveyed with electronic distance measuring equipment by Rogers/Pacific, Inc. in 1994 and by William Lettis and Associates, Inc. in 1997.

RESULTS AND DISCUSSION

FAULT CHARACTERISTICS

The Concord fault crosses the site at an average strike of N°25W, dipping between 71°SW and 47°SW (Fig. 2). The fault location is shown on Fig. 2 at the 0 and -4 m depths. Offsets were measured along the line marked "0". Trenches T-9 and T-17 showed that the right-lateral bend in the historic creek channel (labeled "OLD CREEK CHANNEL" on Fig. 2) was not fault related. Instead, it appears to have been produced by differential erosion of gently dipping siltstone and sandstone beds in the Tulare Formation. Throughout the study site, the location of the fault is always marked by the Tulare Formation on the east and alluvium on the west. The primary fault trace was discovered in T-9 right where it might be expected—at the contact between the Tulare Formation and the Holocene alluvium. The drag-folded nature of the units in this trench matched those found along the primary trace in T-11 to the north (Fig. 3).

ALLUVIAL STRATIGRAPHY

The site has four basic stratigraphic units: Tulare Formation (Plio-Pleistocene siltstone and sandstone), Pleistocene alluvium, Holocene channel fills, and Holocene overbank silts and clays.

The **Tulare Formation** consists of massive, generally calcareous, dark gray clayey siltstone and fine sandstone that weathers to yellow gray. These materials are similar to the Tulare Formation of Graymer and others (1994) who describe it as "non-marine, gray to maroon siltstone, sandstone and conglomerate". The age of this siltstone bedrock at Galindo Creek is constrained by a fossil upper jaw and skull fragment of the Plio-Pleistocene Camel *Camelops* that we found in T-1. The fossil is consistent with the age and non-marine origin of the Tulare Formation.

Pleistocene alluvium consists of coarse gravel and sand that generally is redder and more weathered than the Holocene alluvium from Galindo Creek.

Holocene channel fills along the fault mostly trend west-northwest from the ancestral Galindo Creek system, which enters the site from the east. Channel Fills A, B, C, and D now occupy former Channels A, B, C, and D.

Holocene overbank silts and clays along the fault were deposited during the flood stage of ancestral Galindo Creek. Younger overbank deposits, of course, tend to be deposited on top of the older channel fills, but occasionally they may fill the channels as well.

Although only Channel Fill B had dateable materials on both sides of the fault, Channel Fills C and D had features that helped to constrain the slip rate.

"Channel Fill A" is older than 7.2 ka and lies at greater than 3-m depths in T-2, T-3, and T-4 (Fig. 2). No datable charcoal was found in Channel Fill A and its complete configuration was impossible to discern because of its great depth. Significantly, gravel deposits were absent within 3 m of the surface for a linear distance of at least 40 m in T-2 and T-3 (Fig. 2).

"Channel Fill B" is up to 6 m wide and 3 m thick and trends northwesterly across the fault. Like the other channel fills, the dimensions of this channel were similar to those of the historic Galindo Creek channel. The deposit consists of gravelly silty sand, with lenticular deposits of gravel or sandy gravel. Charcoal samples had ages ranging from 5.7 ka to 7.2 ka (Table 1).

"Channel Fill C" is a 3-m thick sandy gravel beneath a 2-m thick clay loam overbank deposit found only on the east side of the fault in T-12. Channel C was cut after Channel B was abandoned at 5.7 ka. The top of the gravel in the fill had a 3.6-ka age. The extent of Channel C on the west side of the fault appears constrained by the presence of 6.4-ka lag gravel from Channel B.

"Channel Fill D", uncovered only on the west side of the fault in T-10, T-12, and T-14, is about 11 m wide and up to 2 m thick. Channel D once crossed west-northwesterly across the fault, much like the historic channel. This channel was wider and shallower than the historic Galindo Creek channel. Like the other Galindo Creek deposits, this one consists of gravelly silty sand, with lenticular deposits of gravel or sandy gravel. Charcoal samples ranged from 2.4 ka to 2.8 ka where it was positively identified on the west side of the fault (Table 1).

SLIP RATE

Vertical Slip Rate

As seen from its prominent west-facing scarp, vertical slip along the Concord fault is significant. At Galindo Creek the Plio-Pleistocene Tulare Formation was seen in all trenches on the east side of the fault, but not on the west side of the fault. Thus the east side is undergoing uplift relative to the west side. An estimate of the vertical slip rate is needed for understanding and measuring the horizontal slip rate.

We measured vertical offset on several dated units that either were dragged vertically along the fault, appeared on both sides of the fault, or represented climax deposits of varying ages on the west side of the fault (Table 2). As explained in a later section, we believe that sedimentary units within 1.5 m of the fault have been drag folded. Thus the 5.7-ka surface of Channel Fill B4 was plastically deformed vertically along the fault plane in T-11 (Fig. 3). On its eastern end the surface was at least 2.12 m higher than on its western end less than a meter away. This implies that the vertical slip rate is at least .37 mm/yr (Table 2). This measurement is a minimum because the 5.7-ka surface approaches within 30 cm of the surface of the soil where it has been subjected to destruction via pedoturbation, particularly cultivation. The surfaces of two underlying units also appear to be plastically deformed vertically (Fig. 3). The eastern end of the 6.4-ka unit, for instance, is 3.02 m higher than the western end, yielding a vertical slip rate of .47 mm/yr (Table 2).

Channel fill units measured far from the area affected by drag folding gave similar results for dated units on either side of the fault. For instance, three 6.0 ka samples on the east side were 1.98 to 3.34 m higher in elevation than two 6.0 ka samples on the west, yielding vertical slip rates between 0.33 and 0.57 mm/yr (Table 2).

Another measure of vertical slip is the change in elevation undergone by the climax portion of a channel fill after it has been abandoned by the active stream on the subsiding side of the fault. One needs to assume that there is no general fan buildup, regional changes in base level, or other significant changes in the hydrology during the period under consideration. Thus the calculations in Table 2 assume that both Channel B (5.7 ka) and Channel D (2.4 ka) were abandoned under similar circumstances. Each channel, being subject to lengthening due to right-lateral offset along the fault, became choked with gravelly debris as its gradient decreased. This caused Galindo Creek to take a shortcut to the south where the gradient was higher. Channel Fill B continued to subside, being buried by fine overbank silts and clays from still-active Channel D. When Channel D, in turn, was abandoned, both channel fills continued to subside, preserving their elevation-age relationship. In other words, the difference in elevation (1.63 m) between the top of Channel Fill D and the top of Channel Fill B is a direct result of subsidence during the period between the two abandonments (3.25 ky, Table 2).

The various measures of the vertical slip rate range from 0.33 to 0.57 mm/yr, with the median being 0.45 ± 0.06 mm/yr (Table 2). Attempts to correlate channel units across the fault need to take this amount of vertical slip into account.

Horizontal Slip Rate

The determination of the horizontal slip rate at Galindo Creek was difficult. Although pre-historic channel gravels tend to be displaced northward and preserved on the west side of the fault, they are seldom preserved on the east side. Channel Fill B was the only deposit having identical ages on both sides of the fault. The piercing points derived from it were subject, however, to the vagaries of drag folding. Although the data from the other channels were incomplete, they were instrumental in constraining the rate. Thus we have developed a general model that fits the incomplete data provided by this still active stream. The model includes reasonable and necessary assumptions about the former channel width, channel trajectory, and the effect of drag folding near the fault. Below we explain the alluvial detail and cross-fault data that support the model and our best estimate for the slip rate.

Channel Fill A

Exploration of this channel fill achieved two objectives: First, it showed that this >7.2 ka channel lies at depths greater than we could reach with our standard trenching methods. Although the top of the gravel fill was at the 3 m depth, its thalweg was always at depths greater than the bottom of the trench (at 5 m). Second, it showed that no young channel fills existed along the fault northwest of trench T-4, which was more than 60 m from Galindo Creek. That area was eliminated from further consideration in the trenching program.

Channel Fill B

Channel Fill B (7.2 to 5.7 ka) contains the only sand and gravel at the site having correlative ages on both sides of the fault. It had four relatively distinctive stages of deposition following its initial rapid incision. The carbon ages within the fill are concordant and remarkably precise, falling into four main groups. Channel Fill B1, 7.2-6.9 ka, was confined to a narrow, 2-m wide channel that was apparently unaffected by the presence of the fault. Channel Fill B2, 6.4-6.2 ka, and Channel Fill B3, 6.0-6.1 ka, were deposited outside the confines of the Tulare bedrock and had a tendency to broaden and meander at the fault scarp. Channel Fill B4, 5.9-5.7 ka, representing the last gasp of the channel, was a 30-cm thick lag gravel that was up to 11 m wide on the west side of the fault. It was absent on the east probably because there had been about 60 cm of uplift there since the channel was established at 7.2 ka.

Only Channel Fill B3 could be matched with certainty on either side of the fault. Channel Fill B4 was dated only on the west and Channel Fill B1 was excavated completely only on the east. Channel Fill B2 was not dated on the east. The complicated genesis of Channel B must be considered in determining the appropriate piercing points and calculating the slip rate.

Channel B1: The 7.2-6.9 ka Degradation and Aggradation

Channel B started with a rapid entrenchment into the Tulare Formation to the -3 m elevation on the east side of the fault. This early entrenchment produced a stream bed that was about a meter deep and two meters wide (Fig. 4). Delicate overhangs in the soft, still calcareous Tulare siltstone indicate that both the cutting and the filling occurred rapidly. Channel Fill B1 was not recognized on the west side of the fault. This was probably because the 0.45 mm/yr relative subsidence caused it to be buried deeper than the 5 m depth of the excavations. Although a 6.9-ka age was obtained at the -4.6 m depth in T-5, we were unable to observe the base and the margins of the channel. Thus we could not use Channel Fill B1 for determining the offset along the fault.

Channel Fill B2: The 6.4-6.2 ka Aggradation

Channel fill materials containing charcoal of this age were well within reach of our excavating equipment on both sides of the fault. Unfortunately, the charcoal ages of this material are all from the west side of the fault. It may be possible that the gravelly sand-capped alluvium in the east wall of T-18 at station 116 between -1.2 and -1.7 m is this age (Fig. 4). It is overlain by Channel Fill B3, which contains 6.1-ka charcoal. A similar sequence exists in T-11 where 6.0 ka charcoal was found in Channel Fill B3 above gravelly sand-capped alluvium dated at 6.4 ka (Channel Fill B2) (Fig. 3). Nonetheless, the areal configuration of Channel Fill B2 was not adequately identified for establishing independent piercing points that could be used for determining the slip rate.

Channel Fill B3: The 6.0-6.1 ka Aggradation

Channel fill materials containing 6-ka charcoal were well within reach of our excavating equipment on both sides of the fault. Channel Fill B3 is about a meter thick and 5.5 m wide on the east and 9 m wide on the west (Fig. 5 and Fig. 4). At elevation -3.6 m, the northern margin of Channel Fill B3 was at station 81 in the west wall of T-4 and at station 79 in the east wall (Fig. 5; see also Snyder and others, 1995, Figures 10 and 11). In T-1 it was at station 28 in the north and south walls (Snyder and others, 1995, Figures 4 and 6). In plan view, these points form a line that pierces the fault plane at Point A (Fig. 5). The northern margin of Channel Fill B3 on the other side of the fault was clearly observed in T-18 (Fig. 4) and T-12, forming a line that pierces the fault at Point B (Fig. 5). Both piercing points were formed by materials dated at 6.0±0.1 ka, yielding a measured offset of 20±3 m (17.1 to 22.0 m). Similar constructions resulted in Points C and D for the southern margin, yielding a measured offset of 19±0.3 m (18.6 to 19.2 m). By using 6.0±0.1 ka as the age of abandonment and the above offsets, we get slip rates ranging from 3.1 to 3.7, with the average being 3.4±0.3 mm/yr.

Channel Fill B3 yielded two carbon ages at depths between -2.8 and -3.6 m on the west and three carbon ages at depths between -0.28 and -0.87 m on the east (Fig. 5). These ages ranged from 5.95 to 6.04 ka (Table 1). One advantage of the Channel Fill B3 configuration was its extremely limited westerly extent in T-11 (Fig. 3 and Fig. 5). Only a small amount of the truncated 6-ka gravel fill exists south of T-11 on the west side of the fault.

Channel Fill B4: The 5.9-5.7-ka Aggradation

This channel fill was the last gasp of Channel B. It produced a 30-cm thick gravelly deposit that overtopped Channel Fill B3 and spread across the surrounding area on the west side of the fault. The best examples of this phase of alluvial deposition exist in T-1 (north margin) and in T-11 (south margin) (Fig. 3). The deposit was quickly overlain by fine overbank deposits as the focus of sedimentation moved to the south, to the vicinity of the modern drainage. Unfortunately, we have no 5.7-ka ages from the east side of the fault. Thus it is impossible to determine a horizontal slip rate from Channel Fill B4.

Channel Fill C: The 5.7 ka Degradation and 3.9-ka Aggradation

A single charcoal specimen taken from the top of this deposit, dated at 3.9 ka, was discovered in the channel fill in T-12 on the east side of the fault (Table 1). Cross-cutting relationships confirmed that this channel was clearly younger than Channel B3, but its trajectory was irregular, even appearing to be fault-parallel for a short distance. The -1.8 m elevation of the 3.9 ka sample on the east corresponds to a present elevation of -4.1 m on the west.

No gravel of this age was found on the west side of the fault. However, there is a prominent 6.4-ka lag gravel that serves as a marker bed extending between T-11 (Fig. 3) and the north end of T-10 at the -1.5 m elevation (Fig. 6). In T-10 it is uninterrupted until station 102, where the area to the south is cut by what appears to be a subtle westward trending channel filled with silt and clay instead of gravel. Although no satisfactory slip rate could be determined from Channel Fill C, the silty channel fill appears to constrain the slip rate. If the scour margin in T-10 is projected toward the fault at the same strike as the northern margin of Channel Fill D, it would pierce the fault plane about 26 m north of the historical position of the northern margin of Galindo Creek. If the scour occurred at 5.7 ka, as expected, then the maximum allowable slip rate would be 4.6 mm/yr.

Channel Fill D: The 2.4-ka Aggradation

This shapely channel fill was up to 2.3 m thick, about 11 m wide, and had charcoal with ages of 2.6 and 2.8 ka in T-10 (Fig. 6). Its northern margin also was found in T-14, where it yielded an age of 2.4 ka—which we consider the age of abandonment. A line from the northern margin in T-10 to the northern margin in T-14 projects to the fault plane at Point E (Fig. 5). We have no material from the east side with that age, so we cannot calculate the slip rate directly. Nevertheless, we can get an estimate of the maximum slip by considering the historical location of Galindo Creek. From its historical location we know that the northern margin of Galindo Creek crossed the fault at Point F (Fig. 5). Thus the maximum offset for the northern margin of Channel D appears to be the distance between Points E and F—11 m.

We can use similar reasoning to determine the offset of the southern margin of Channel D. Unfortunately, at least a meter of the southern margin in T-10 was destroyed when Galindo Creek was channelized in 1984. Despite this, we can assume that the width of Channel D was uniformly 11 m (Fig. 6) and that the southern margin had the same trajectory as the northern margin. The southern margin of Channel D would then reach the fault plane at Point G (Fig. 5). The historical location of the southern margin crossed the fault 6.5 m south of this point. The historical location was confirmed by the discovery of 1984-gravel fill in trench T-13 (Fig. 7).

There is reason to believe, however, that the southern margin in T-13 actually may have been still further to the south at 2.4 ka. The log of trench T-13 shows that the Tulare bedrock was scoured to the -0.7 elevation at least as far south as station 143 (Fig. 7). By considering the configuration of Channel Fill D in the log of T-10 (Fig. 6) and uplift of 0.45 mm/yr, we expect scour to reach present-day elevations varying between .5 m and -2. m on the east side of the fault. Bedrock in T-13 was as high as -0.7 m (station 143, Fig. 7), so only the shallowest part of Channel Fill D could have reached that far south. Due to relative subsidence on the west, the equivalent point for the base of the channel would be at -1.7 m, which is at station 115 in T-10 (Fig. 6). From the configuration in T-10 it appears that the southern margin could have been no more than 4.5 m further to the south than the historical margin. Any 2.4-ka gravel deposits left in the T-13 exposure apparently were removed during stream activity that ended in 1984.

Again by assuming that Channel D on the east side of the fault had the same trajectory as its northern margin on the west side, we can project the southern margin to Point H. The offset between Points G and H yields a maximum of 13 m for Channel Fill D. It is highly unlikely that the offset could have been greater than this during the last 2.4 ky. Trenches south of T-13 had no evidence for scour in the Tulare Formation (Fig. 5). T-15 had Tulare at +0.6 m and T-16 and T-9 had Tulare at +0.2 m. Although we do not have a complete exposure between T-13 and T-9, it seems improbable that remnants of a 11-m wide channel fill could have formed in that area without signs of scour in those trenches. If Galindo Creek ever crossed the fault south of T-13, it had to have done it before uplift brought the Tulare Formation to the +0.6 m elevation. That amount of uplift would require them to be at least 6.9 ka (calculated from 3.1 m of uplift at an absolute rate of 0.45 mm/yr)—much earlier than the filling of Channel D.

The 13-m offset is thus the most likely maximum for Channel D. The maximum slip rate is thus 5.4 mm/yr for the last 2.4 ka.

Summary of the Horizontal Slip Rate Model

The preferred measurement of the horizontal slip rate at Galindo Creek remains the 3.4±0.3 mm/yr rate determined on the 6-ka Channel Fill B3. This value is well within the maximum values determined for Channel Fill C (<4.6 mm/yr) and Channel Fill D (<5.4 mm/yr). The 3.4-mm/yr rate is similar to the creep rates (2.5-3.5 mm/yr) determined farther north along the Concord fault. Major earthquakes involving the Galindo Creek site may be rare. On the other hand, the fault appears to be dying out to the south—fault traces just south of Galindo Creek are widely dispersed and creep evidence is scarce. The Galindo Creek site may not be representative of the hazard presented by the northern half of the fault.

DRAG FOLDING

One outstanding characteristic of the Concord fault at Galindo Creek is its tendency to exhibit extensive drag folding, which is a result of ductile, rather than brittle tectonic deformation (Cetin, 1997, 1998). In our cross-fault trenches older units on the west tend to rise in elevation as they approach the fault, while older units on the east tend to drop in elevation as they approach the fault (Fig. 3 and Fig. 8). Although, in hindsight, the drag-folding explanation now seems obvious, there is an alternative explanation for these westerly dipping beds: gravitational infilling after catastrophic earthquakes have ruptured the ground. Thus we devised an experiment that would clearly distinguish between plastic deformation and gravitational infilling. In the first instance the sediments would have been laid down in roughly horizontally beds and subsequently dragged vertically along the fault plane. In the second instance the vertical component is a result of gravitational infilling supplied by materials derived from the surface. We sampled several beds, being careful to obtain specimens from the top, middle, and bottom to observe sedimentary or gravitational trends in particle size distribution (Fig. 3, Fig. 8, and Table 2).

Sediment Variability in Trench T-11

A horizontal section through the near-fault feature in the north wall of T-11 was obtained to study sediment variability of steeply dipping units mapped adjacent to the fault (Fig. 3). From west to east, Samples 97B240, 230, 241, and 242 had the following laboratory determined textures: gravelly loamy sand, sandy clay loam, gravelly sandy loam, and sandy clay loam (Table 3). The high textural variability is especially obvious from gravel contents of 69.7, 0.0, 46.7, and 4.9.

Next, horizontal variability was examined within the a steeply dipping sandy clay loam unit. West to east Transect No. 1 consisted of Samples 97B227 and 228; west to east Transect No. 2 consisted of Samples 97B229 and 230. If we assume that plastic deformation was the active agent, then the west side of each of these beds would have been the top and the east side would have been the bottom during fluvial deposition. The test for horizontal variability then becomes a test for initial vertical variability. Although all four samples were quite similar, slight upward fining may be indicated by lower sand and higher silt and clay contents in the tops as compare to the bottoms. Furthermore, Transect No. 2 (higher in the section) had slightly more sand and less silt and clay than Transect No. 1. Downward fining does not support the gravitational infilling hypothesis (McAlpin, 1996).

Two transects were sampled from west to east in a second unit (Fig. 3; Table 3). Transect No. 3 had a slight indication of downward fining, with the sand/silt ratio decreasing toward the east. Transect No. 4 was relatively uniform except for the upward fining implied by the decrease in gravel content toward the east. All samples in Transect No. 4 had more gravel than those in Transect No. 3, which was at a lower elevation. Again, this permissive evidence for downward fining does not appear to be indicative of current gravitational influences. The particle size distribution in Sample 97B242, still higher in the unit, is nearly identical to the that of the samples in Transect No. 4. That sample has slightly less gravel, possibly because, like the samples in Transect No. 3, it is from the distal part of what once was a horizontal bed.

Other samples from Trench T-11 support the drag-folding hypothesis. Samples 97B240 and 243, for instance, had 70 and 72% gravel and their <2 mm fractions both had 85% sand (Fig. 3; Table 3). This remarkable similarity was obtained despite a vertical separation of over 1 m. Also, Samples 97B241 and 244 had relatively similar laboratory classifications of gravelly sandy loam and gravelly loamy sand, despite a vertical separation of 2 m.

Sediment Variability in Trench T-12

The detail log of the west side of the Concord fault in Trench T-12 shows evidence for early sedimentation and drag folding followed by late sedimentation (Fig. 8). Units 1 through 4 appear to be drag folded along the fault plane. Specimens taken from three places along the length of Unit No. 1, a sandy clay loam, had similar particle size distributions (Table 3). Unit No. 2, a gravelly sandy clay loam, showed the same type of internal consistency. The units were first laid down horizontally and then tectonically deformed against the fault. The effect is only significant within 75 cm of the fault plane and only involves plastic deformation. There are no discrete fault offsets within the plastically deformed units or at their contacts with their nondeformed distal sections.

Of particular note is the orientation of clasts that are oblong in cross section (Fig. 8). These clasts tend to be horizontal where Unit No. 2 is horizontal and steeply dipping where the unit is steeply dipping (compare the clast east of sample 254 with the one east of sample 247). Similarly, the clasts on the east side of Unit No. 3 have the same orientation as the nearby fault plane. Clasts with a vertical component of orientation obtain that orientation, not as an individual clast, but as part of a sedimentary bed that has obtained that orientation. A corollary is the following: Vertical clast orientation is only expected along faults having a vertical component of motion. A strike-slip fault with pure horizontal movement will not have clasts vertically oriented along the fault plane.

A late phase of sedimentation is obvious in T-12 (Fig. 8). Horizontal to slightly east-dipping sand and gravel units overlie plastically deformed Unit No. 1. Surprisingly, the depositional contact between these beds remains intact, although the steeply dipping portion of Unit No. 1 is only half as thick as the horizontal portion. The late phase sedimentation apparently was gentle and of short duration, with nearly all of the clasts next to the contact being less than 3 cm in diameter. While there is no evidence for drag folding within the late phase sedimentary units, they are not within the 75-cm distance that seems most amenable to plastic deformation in this trench.

CONCLUSIONS

At Galindo Creek, the Concord fault had a horizontal slip rate of 3.4±0.3 mm/yr and a vertical slip rate of 0.45±0.06 mm/yr for the last 6,000 years. During an extensive trenching campaign we uncovered four major channel fills that were offset along the fault. Charcoal dates (6.0±0.1 ka) from gravels on both sides of the fault were encountered in Channel Fill B3. The northern margin of this channel was offset 20 m, while the southern margin was offset 19 m. Other channel fills were either too deep for satisfactory excavation (Channel Fills A and B1) or had dates only on one side of the fault (Channel Fills B2, B4, C, and D). Channel Fill D, dated at 2.4 ka on the west, nonetheless provided useful information in combination with data from the historical location of Galindo Creek. A projection of its northern margin on the west and the discovery of the historical scour of Galindo Creek on the east positively limits the horizontal slip rate to less than 5.4 mm/yr.

Early speculations about a rapid slip rate were quashed by excavations showing that a prominent right-lateral bend in Galindo Creek appearing on 1939 photos was produced by differential erosion instead of tectonic offset. The relatively large vertical component of motion along the fault produced conclusive evidence for drag folding along the fault. Older beds on the east were dragged downward, while older beds on the west were dragged upward along a fault plane that dipped between 71° and 47°SW. Plastic deformation was intense within 75 or 150 cm of the fault plane. Discrete offsets of individual sedimentary beds were rare and we were unable find unequivocal evidence for catastrophic ground rupture.

The horizontal slip rate (3.4 mm/yr) on this central segment of the Concord fault is about the same as the creep rate (2.6-3.5 mm/yr) measured to the north. Thus a tentative conclusion might be that these drag features are especially characteristic of dipping faults that seldom, if ever, experience catastrophic ground rupture. On the other hand, fault traces south of Galindo Creek are widely dispersed and creep evidence is scarce. The Galindo Creek site may not be representative of the hazard presented by the northern half of the fault.

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REFERENCES

Borchardt, Glenn, 1993, Soil stratigraphy for trench logging: Soil Tectonics, Berkeley, California, 69 p.

CDMG (California Division of Mines and Geology), 1991, Official Earthquake Fault Zone Maps of the Clayton, Vine Hill, and Walnut Creek quadrangles, scale 1:24,000.

Cetin, Hasan, 1997, How did the Meers fault scarp form? Paleoearthquake or aseismic creep? A soil mechanical perspective: Engineering Geology, v. 47, p. 289-310.

Cetin, Hasan, 1998, Near-surface folding along an active fault: seismic or aseismic? Tectonophysics, v. 292, p. 279-291.

Galehouse, J.S., 1998, Theodolite measurements of creep rates on San Francisco Bay region faults [abs.], U.S. Geological Survey NEHRP Web Page (http://erp-web.er.usgs.gov/reports/abstract/1998/nc/g3111fin.htm), 6 p.

Graymer, R.W., Jones, D.L., and Brabb, E.E., 1994, Preliminary geologic map emphasizing bedrock formations in Contra Costa County, California: A digital database: U.S. Geological Survey Open-File Report 94-622, 10 p.

Hart, E.W., 1981, Evidence for recent faulting, Calaveras and Pleasanton faults, Diablo and Dublin quadrangles, California: Division of Mines and Geology Open File Report 81-9, 2 pl.

Jennings, C.W., 1994, Fault activity map of California and adjacent areas with locations and ages of Recent volcanic eruptions: California Division of Mines and Geology Data Map Series Map No. 6, scale 1:750,000.

Kelson, K.I., Lettis, W.R., and Lisowski, Michael, 1992, Distribution of geologic slip and creep along faults in the San Francisco Bay region, *in* Borchardt, Glenn, and others, eds., Proceedings of the Second Conference on Earthquake Hazards in the Eastern San Francisco Bay Area: California Department of Conservation, Division of Mines and Geology Special Publication 113, p. 31-38.

Kelson, K.I., Simpson, G.D., Lettis, W.R., and Haraden, C.C., 1995, Holocene slip rate and earthquake recurrence of the northern Calaveras fault at Leyden Creek, northern California: Journal of Geophysical Research, v. 101, no. B3, p. 5961-5975.

Lienkaemper, J.J., and Borchardt, Glenn, 1996, Holocene slip rate of the Hayward fault at Union City, California: Journal of Geophysical Research, v. 101, no. B3, p. 6099-6108.

McCalpin, J.P., ed., 1996, Paleoseismology: San Diego, CA: Academic Press, 576 p.

Niemi, T.M., and Hall, N.T, 1992, Late Holocene slip rate and recurrence of great earthquakes on the San Andreas fault in northern California: Geology, v. 20, no. 3, p. 195-198.

Oppenheimer, D.H., and N. Macgregor-Scott, 1992, The seismotectonics of the eastern San Francisco Bay region, *in* Borchardt, Glenn, and others, eds., Proceedings of the Second Conference on Earthquake Hazards in the Eastern San Francisco Bay Area: California Department of Conservation, Division of Mines and Geology Special Publication 113, p. 11-16.

Petersen, M.D., W.A. Bryant, C.H. Cramer, T. Cao, M.S. Reichle, A.D. Frankel, J.J. Lienkaemper, P.A. McCrory, and D.P. Schwartz, 1996, Probabilistic seismic hazard assesment for the State of California: California Department of Canservation, Division of Mines and Geology Open File Report 96-08, 33 p.

Poland, J.F., 1935, Ground-water conditions in Ygnacio Valley, California: Stanford University, unpublished M.A. thesis, 83 p.

Prentice, C.S., 1989, Earthquake geology of the northern San Andreas Fault near Point Arena, California: Ph.D. Thesis, California Institute of Technology, Pasadena, 246 p.

Sharp, R.V., 1973, Map showing tectonic movement on the Concord fault, Contra Costa and Solano Counties, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-505, scale 1:24,000.

Simpson, G.D., W.R. Lettis, and K.I. Kelson, 1992, Segmentation model for the Northern Calaveras fault, Calaveras Reservoir to Walnut Creek, *in* Borchardt, Glenn, and others, eds., Proceedings of the Second Conference on Earthquake Hazards in the Eastern San Francisco Bay Area: California Department of Conservation, Division of Mines and Geology Special Publication 113, p. 253-259.

Smith, G.A., 1992, The Ygnacio segment and the southern terminus of the Concord fault, *in* Borchardt, Glenn, and others, eds., Proceedings of the Second Conference on Earthquake Hazards in the Eastern San Francisco Bay Area: California Department of Conservation, Division of Mines and Geology Special Publication 113, p. 319-323.

Snyder, D.L., Wills, C.J., and Borchardt, Glenn, 1995, Slip rate and earthquake recurrence on the Concord fault at Galindo Creek, California: Final technical report for the U.S. Geological Survey National Earthquake Hazards Reduction Program, 37 p.

Unruh, J.R., and Sawyer, T.L., 1995, Late Cenozoic growth of the Mt. Diablo fold and thrust belt, central Contra Costa County, California, and implications for the transpressional deformation of the northern Diablo Range [abs.]: Abstracts, 1995 Pacific Section Convention, American Association of Petroleum Geologists, San Francisco, p. 47.

Wills, C.J., and E.W. Hart 1990. The Concord fault, Contra Costa County, California: California Division of Mines and Geology Fault Evaluation Report FER-231. (unpublished)

Wills, C.J., and Hart, E.W., 1992, Progress in understanding the Concord fault through site specific investigations, *in* Borchardt, Glenn, and others, eds., Proceedings of the Second Conference on Earthquake Hazards in the Eastern San Francisco Bay Area: California Department of Conservation, Division of Mines and Geology Special Publication 113, p. 311-317.

ACCOUNTS OF THIS WORK

Snyder, D.L., Borchardt, Glenn, and Wills, C.J., 1994, Initial paleoseismic study of the Concord fault, California [abs.]: EOS, Transactions of the American Geophysical Union, v. 75, no. 44, p. 684.

Snyder, D.L., Wills, C.J., and Borchardt, Glenn, 1995, Slip rate and earthquake recurrence on the Concord fault at Galindo Creek, California: Final technical report for the U.S. Geological Survey National Earthquake Hazards Reduction Program, 37 p.

Wills, C.J., Snyder, D.L., and Borchardt, Glenn, 1994, Preliminary results of paleoseismic studies of the Concord fault at Galindo Creek, Concord, California [abs], *in* Prentice, C.S., Schwartz, D.P., and Yeats, R.S., eds., Proceedings of the Workshop on Paleoseismology: U.S. Geological Survey Open-File Report 94-568, p. 200-201.

Table 1. Charcoal samples dated along the Concord fault at Galindo Creek.

T-	*Field* No.	*Lab. No.* (Beta*)	*Station* m	*Elev.* m	*Wall*	*Conv. Age* yr B.P.	*Std. Dev.* yr	*Cal. BC* yr	*Cal. Age* ka	*Std. Dev.* ky	*Chan-nel*
12	97B175	114791	3.5	-1.77	S	B1	70	5240	7.24	0.07	B1
5	94B127	74473	69.0	-4.60	W	6040	60	4930	6.93	0.09	B1
11	97B200	114795	8.7	-2.94	N	5540	100	4360	6.36	0.09	B2
6	94B123	74472	6.3	-1.09	N	5480	40	4340	6.34	0.05	B2
4	94B160	74474	73.0	-1.50	E	5430	70	4320	6.32	0.09	B2
5	94B234	74470	66.5	-4.20	E	5410	60	4250	6.25	0.07	B2
5	94B058	74478	54.5	-3.20	E	5330	60	4220	6.22	0.09	B2
18	97B177	114792	115.6	-0.81	E	5280	80	4070	6.07	0.09	B3
5	94B128	74477	71.9	-2.79	E	5250	60	4040	6.04	0.09	B3
12	97B088	114788	7.2	-0.87	N	5200	70	3985	5.99	0.10	B3
11	97B093	114789	9.7	-3.62	N	5180	70	3975	5.98	0.10	B3
18	97B173	114790	111.7	-0.28	W	5110	60	3950	5.95	0.06	B3
5	94B059	74476	55.0	-2.00	W	5050	60	3910	5.83	0.08	B4
5	94B151	74475	65.2	-1.74	E	5000	60	3780	5.78	0.08	B4
4	94B153	74471	75.9	-2.47	E	4890	80	3670	5.67	0.10	B4
12	97B087	LLL	19.6	-1.84	S	3610	50	1945	3.94	0.05	C
10	97B084	LLL	112.8	-2.17	W	2600	40	800	2.80	0.04	D
10	97B081	114787	111.9	-0.62	E	2540	70	780	2.78	0.10	D
14	97B188	114794	115.5	-1.53	W	2380	90	405	2.41	0.15	D
8	97B086	LLL	161.0	-1.68	E	400	40	1470#	.53	0.04	Hist

*All C-14 analyses performed by Beta Analytic, Inc., 4985 S.W. 74 Court, Miami, FL 33155 (www.radiocarbon.com), except for those marked LLL, which were analyzed by Lawrence Livermore Laboratory through a cooperative agreement with the U.S. Geological Survey.

#Sample 97B086 is A.D. (Hist = historical).

Table 2. Measurements of the rate of vertical offset along the Concord fault at Galindo Creek.

Feature Offset	Elevation on West, m	Elevation on East, m	Vertical Offset, m	Age of Feature, ka	Slip Rate, mm/yr
			Drag Assumed in Trench T-11		
5.7 ka Surface	-2.32	>-0.20	>2.12	5.66	>0.37
6.0 ka Surface	-3.1	-0.20	2.90	5.98	.48
6.4 ka Surface	-3.44	-0.42	3.02	6.36	.47
			Measurements Independent of Drag		
6.0 ka ages (±0.1)	-2.79, -3.62,	-0.81, -0.28, [-0.42*]	1.98 to 3.34	5.99, 5.98, 5.95, 6.04, 6.07	.33 to .57
6.3 ka ages (±0.1)	-3.20, -4.20, [-3.47]	[-0.75],	2.45 to 3.45	6.22, 6.34, 6.25, 6.36	.39 to .55
7.0 ka ages (±0.2)	-4.60	-1.77	2.83	6.93, 7.24	.39 to .41
			Climax Deposits on the West Side of the Fault		
Top of Channel Fill B vs. Top of Channel Fill D**	B: -2.28 m to -2.32 m at 5.66 ka	D: -0.62 m to -0.72 m at 2.41 ka	1.56 to 1.7	3.25 ky	0.47 to 0.52
Range					0.33 to 0.57
Median					.45±0.06

*Pallinspastically corrected for obvious drag folding.

Table 3. Particle size distribution of sedimentary beds.

97B No.	Total			Sand					Silt					Ratios				
	Sand 2-0.05	Silt 0.05-0.002	Clay <0.002	vcos 2.0-1	cos 1.0-0.5	ms 0.5-0.25	fs 0.25-0.1	vfs 0.10-0.05	csi 0.05-0.2	msi 0.2-0.005	fsi 0.005-0	Gravel >2 mm of whole sample	Texture	cos/fs	fs/vfs	s/si	csi/msi	msi/fsi
				% of less than 2 mm														
Trench T-11																		
							Transect No. 1											
227	44.5	26.9	28.6	1	0.7	5.5	17.8	19.5	15	7.3	4.6	0	cl	0.0	0.9	1.7	2.1	1.6
228	49	24.1	26.9	3	1.9	6.5	17.1	20.5	11.8	8.2	4.1	0	scl	0.1	0.8	2.0	1.4	2.0
							Transect No. 2											
229	55	22.2	22.8	2.5	2	9.9	23.1	17.5	10	8.5	3.7	0	scl	0.1	1.3	2.5	1.2	2.3
230	57	20.5	22.5	4	5.4	8.2	19.9	19.5	9.7	6.8	4	0	scl	0.3	1.0	2.8	1.4	1.7
							Transect No. 3											
234	69.5	12.7	17.8	1.3	10.7	18.5	24.5	14.5	4.9	5.9	1.9	1.7	sl	0.4	1.7	5.5	0.8	3.1
235	67.2	14.9	17.9	3	11.5	16.1	20.4	16.2	5.2	5.8	3.9	3	sl	0.6	1.3	4.5	0.9	1.5
236	46	28.1	25.9	1.4	3.1	8.5	15.4	17.6	13	8.4	6.7	0.6	scl	0.2	0.9	1.6	1.5	1.3
							Transect No. 4											
237	60	18.8	21.2	1	3	15.2	21.8	19	6.7	6.8	5.3	3.1	scl	0.1	1.1	3.2	1.0	1.3
238	58	21.4	20.6	1	2	13.4	24.6	17	10.3	6.7	4.4	7.5	scl	0.1	1.4	2.7	1.5	1.5
239	60	18.5	21.5	3	3.5	12	22.5	19	8.3	6.7	3.5	10.2	scl	0.2	1.2	3.2	1.2	1.9
							General Sediment Variabilty											
240	85	7	8	25	20	17.2	12.3	10.5	3	3	1	69.7	gls	1.6	1.2	12.1	1.0	3.0
241	78.5	9.7	11.8	20	16	15.3	13.1	14.1	4	5	0.7	46.7	gsl	1.2	0.9	8.1	0.8	7.1
242	60.6	18.6	20.8	2	3	12.6	23.6	19.4	9.4	5.4	3.8	4.9	scl	0.1	1.2	3.3	1.7	1.4
243	85	5	10	17	14.5	18.6	23.4	12	1.5	2	1.5	72	gls	0.6	2.0	17.0	0.8	1.3
244	88.3	4.1	7.6	19	15	23.4	21.1	9.8	2.7	1.2	0.2	66.4	gls	0.7	2.2	21.5	2.3	6.0
Trench T-12																		
							Unit No. 1: Fine Unit Variabilty											
247	53.3	24.7	22	2	4.7	8.4	17.9	20.3	11.2	9	4.5	0	scl	0.3	0.9	2.2	1.2	2.0
248	40.5	32.2	27.3	1	3	6	11.3	19.2	13.7	13.3	5.2	0	cl	0.3	0.6	1.3	1.0	2.6
249	51	26.8	22.2	4	7.1	9.8	14.6	15.5	13.5	11.5	1.8	0	scl	0.5	0.9	1.9	1.2	6.4
							Unit No. 2: Gravelly Unit Variability											
254	65	14.9	20.1	20	9	7.5	11	17.5	8.7	5.1	1.1	nd	gscl	0.8	0.6	4.4	1.7	4.6
255	61.6	16.1	22.3	20	9	6	9.3	17.3	9.1	3.3	3.7	nd	gscl	1.0	0.5	3.8	2.8	0.9
256	68	17.3	14.7	20	14	10.6	11.4	12	12.3	3.7	1.3	nd	gsl	1.2	1.0	3.9	3.3	2.8

Figures

Fig. 1. Principal active faults of the eastern San Francisco Bay area showing the location of the Galindo Creek study site along the Concord fault.

Fig. 2. Site map of the Galindo Creek study site showing the locations of trenches excavated in 1994 (T-1 to T-7) and in 1997 (T-8 to T-18). The right-lateral deflection in the old creek channel was removed when the channel was relocated and lined with concrete in 1984.

Fig. 3. Drag folding as seen in the north wall of Trench T-11. Three-digit numbers refer to 97B field numbers of samples collected for particle size distribution. Numbers preceded by a "Ch" refer to charcoal specimens. (k = krotovina; cmtcf = common medium thick clay films).

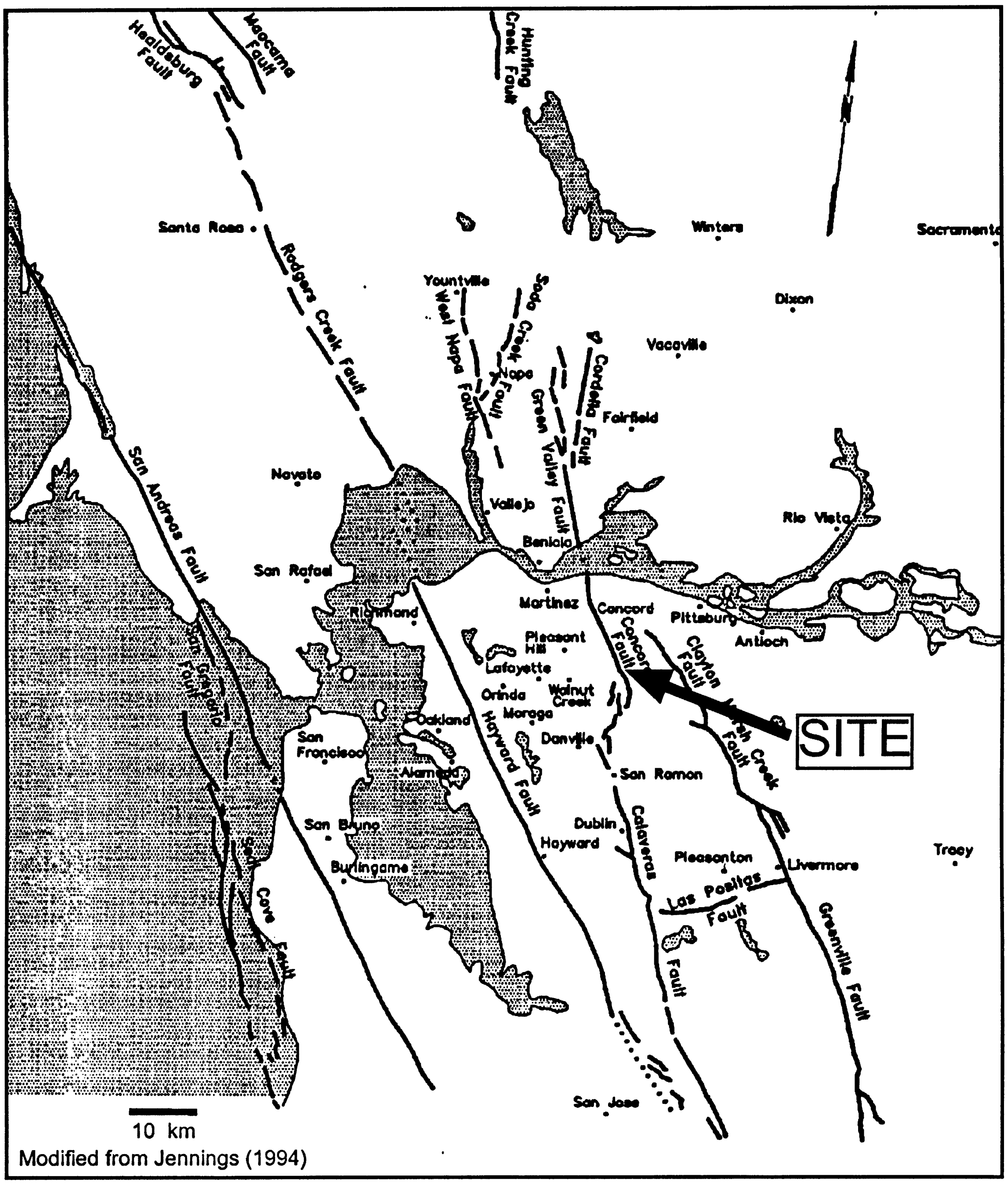
Fig. 4. Log of the east wall of Trench T-18 cut obliquely (38°) across Channel Fill B as it approaches the scarp on the east side of the Concord fault at Galindo Creek. Uplift produced drag folding within 2.3 m and scarp erosion within 4 m of the fault.

Fig. 5. Slip rate model.

Fig. 6. Log of the west wall of Trench T-10 cut obliquely (47°) across Channel Fill C on the west side of the Concord fault at Galindo Creek.

Fig. 7. Log of the west wall of Trench T-13 cut obliquely (36°) across the buried historic channel on the east side of the Concord fault at Galindo Creek.

Fig. 8. Detail log of the south wall of Trench T-12 showing drag folding of early sediments followed by late sedimentation.



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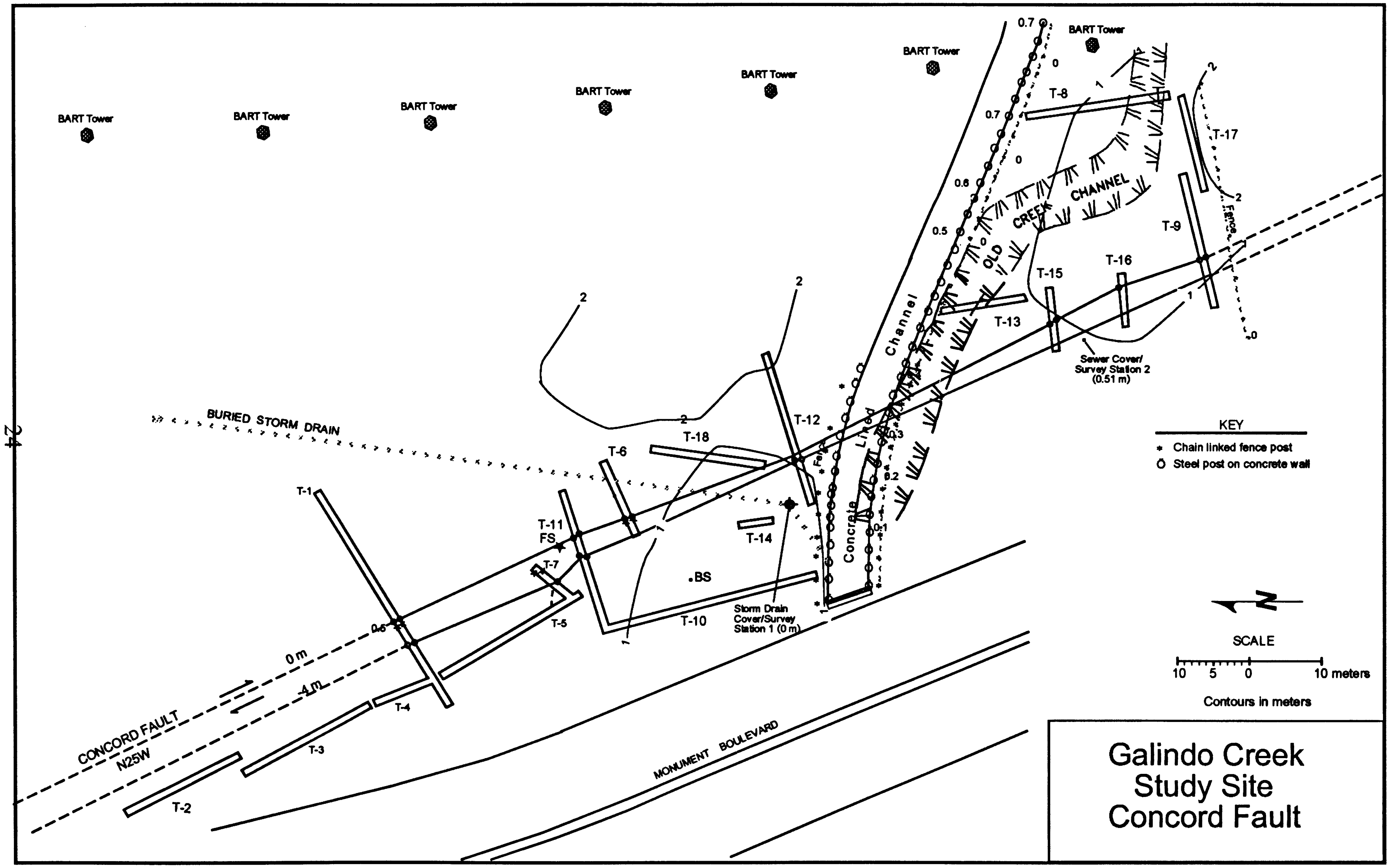

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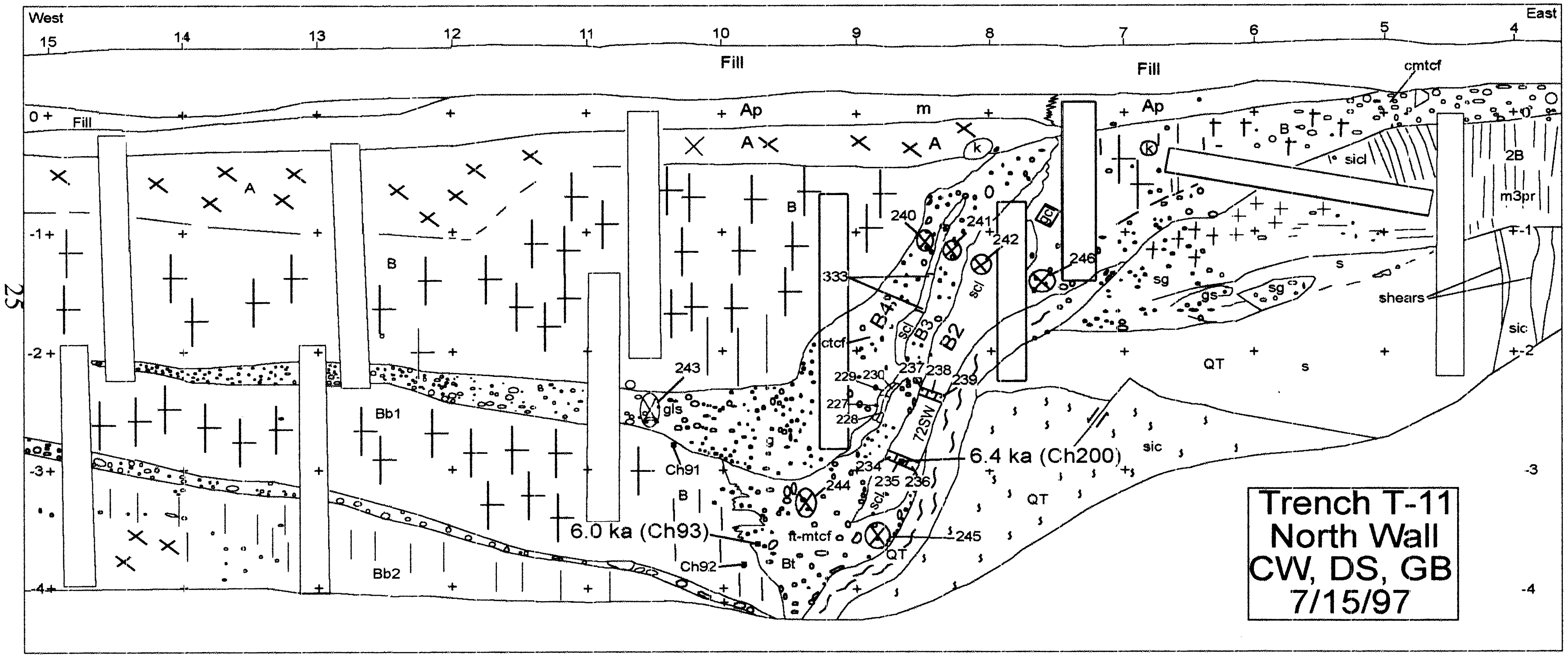

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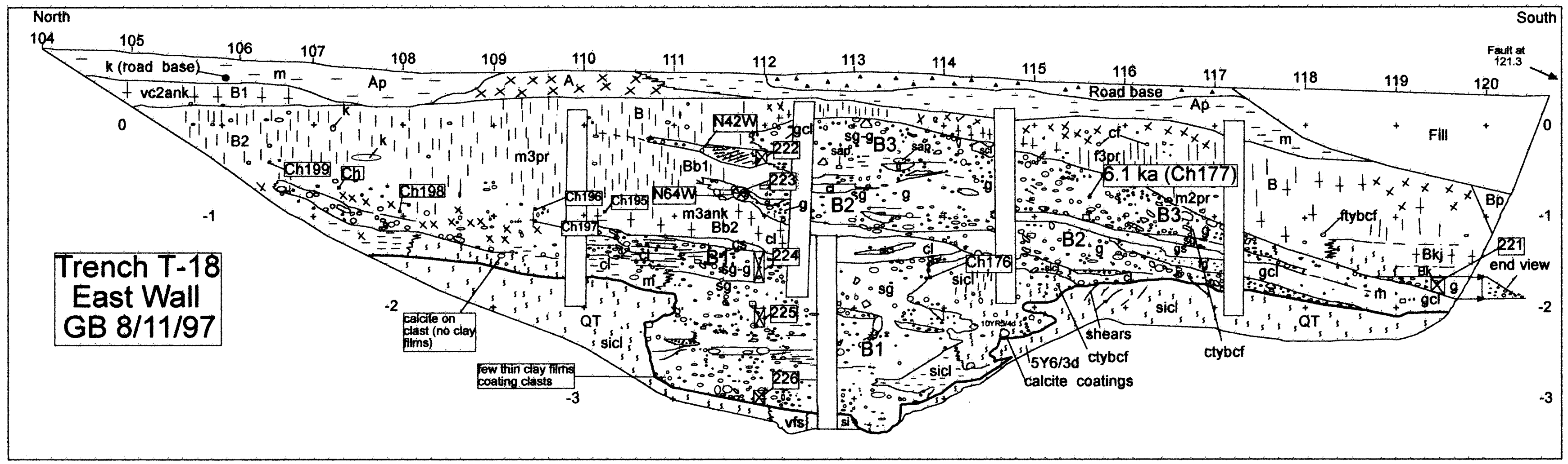

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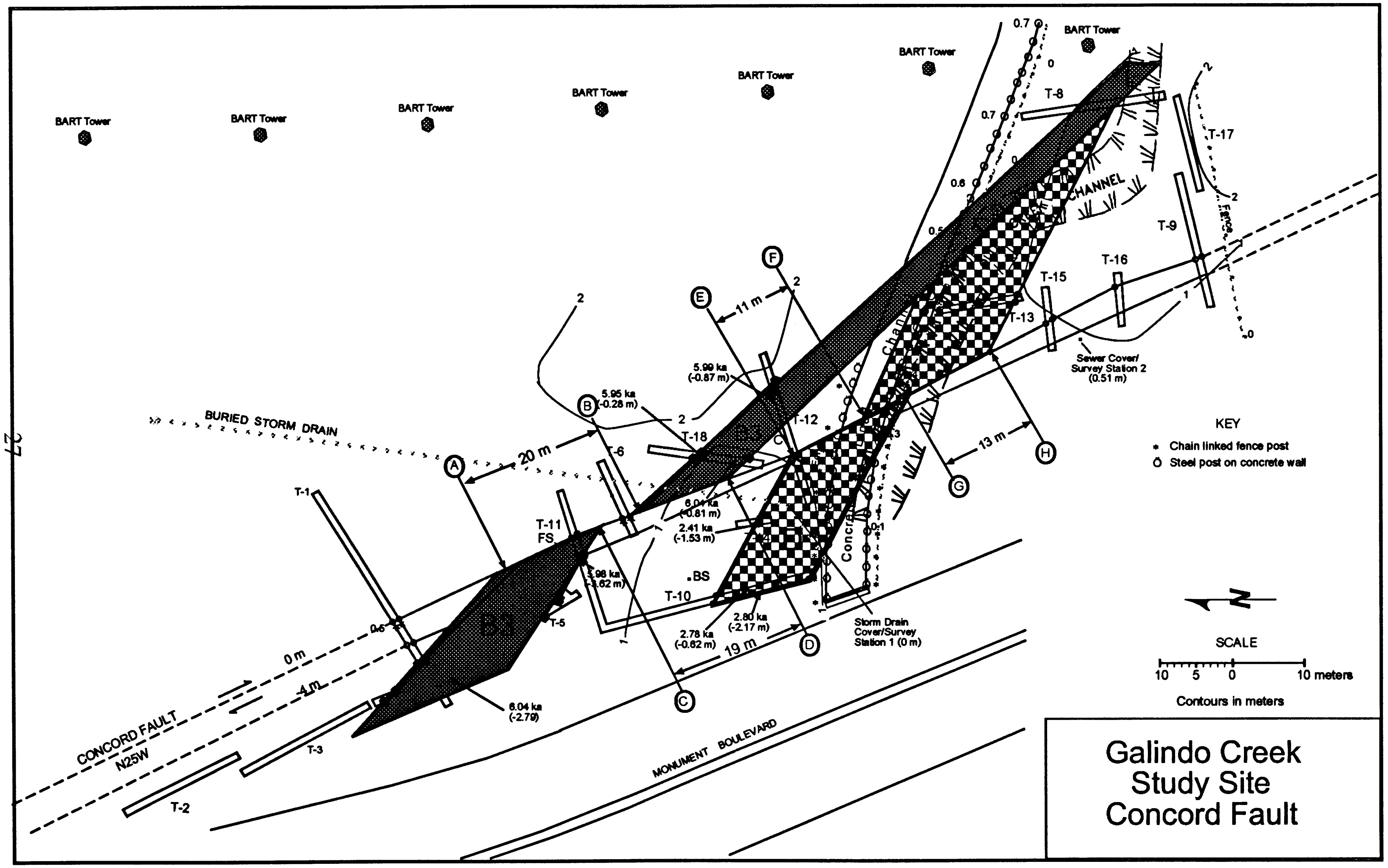

Fig. 5 Slip rate model.

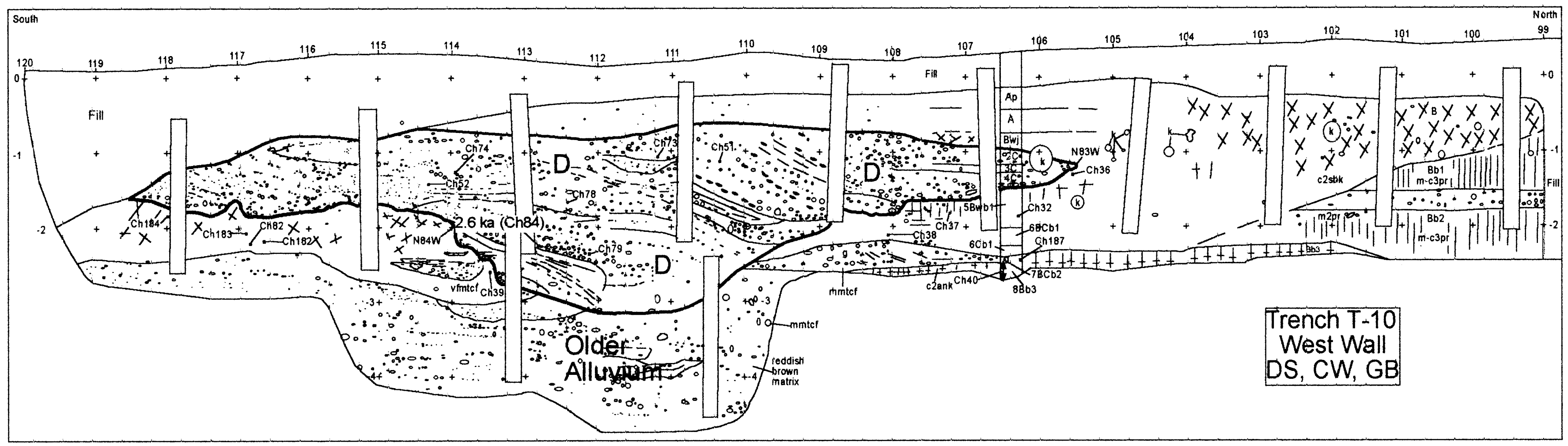

Fig. 6. Log of the west wall of Trench T-10 cut obliquely (47°) across Channel Fill D on the west side of the Concord fault at Galindo Creek.

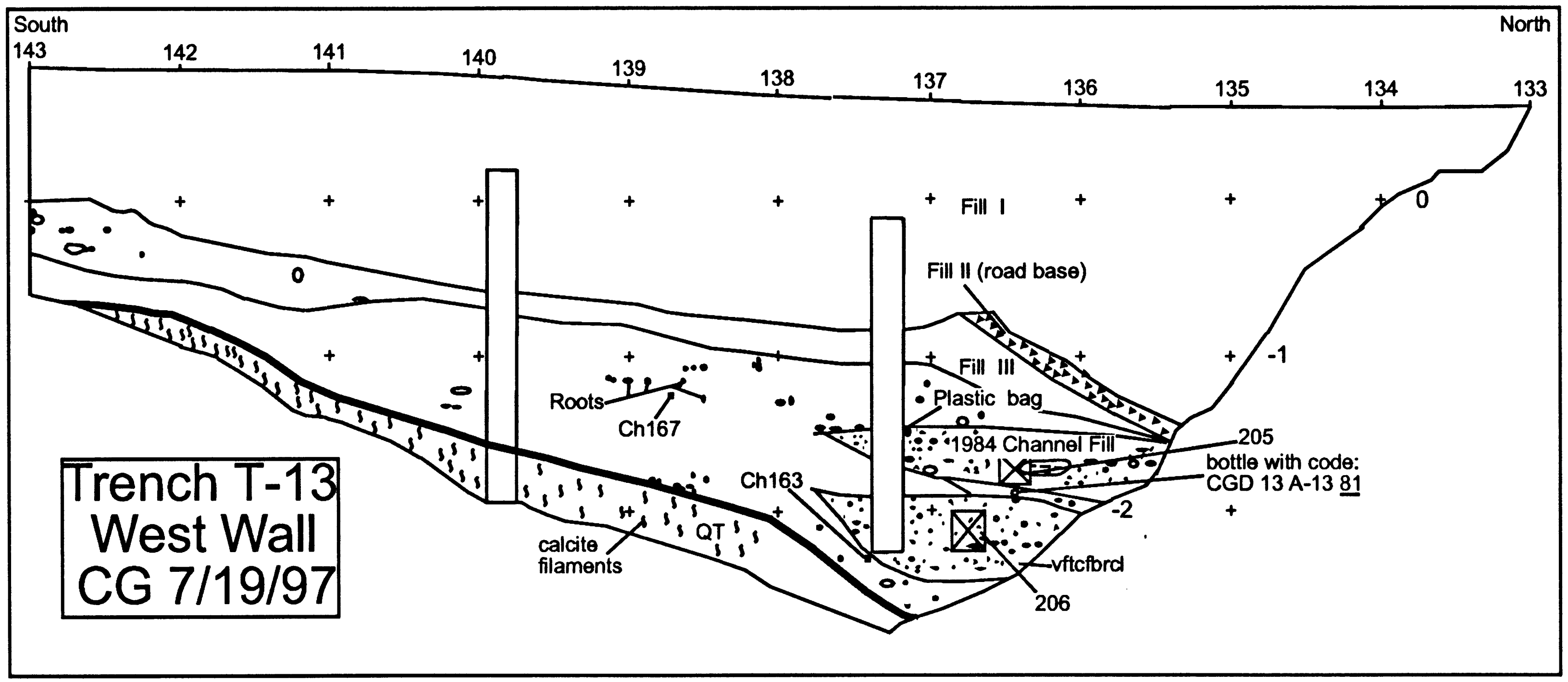

Fig. 7. Log of the west wall of Trench T-13 cut obliquely (36°) across the buried historic channel on the east side of the Concord fault at Galindo Creek.

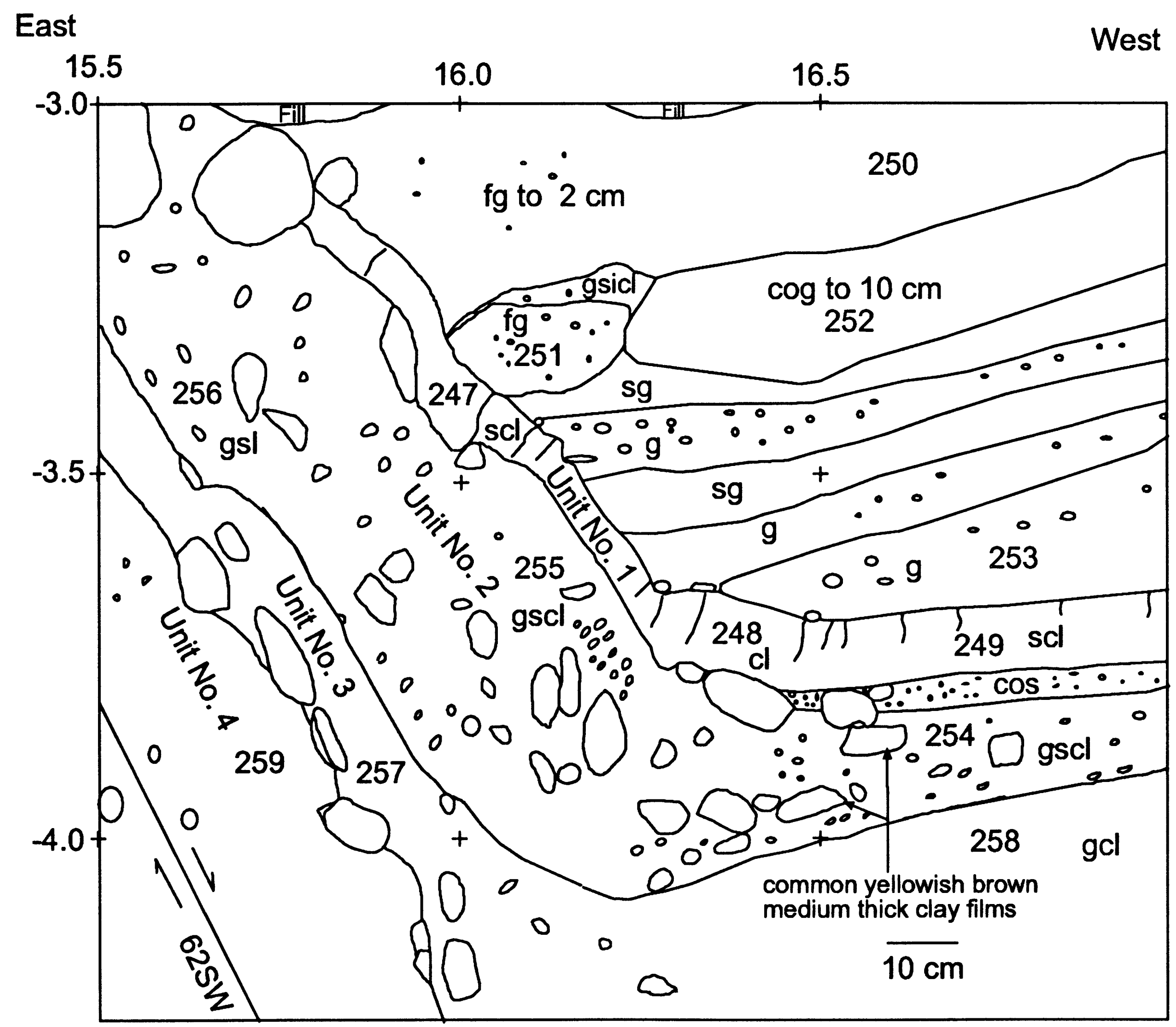

Fig. 8. Detail log of the south wall of Trench T-12 showing drag folding of early sediments followed by late sedimentation.