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DIGITAL DATABASE OF RECENTLY ACTIVE TRACES OF THE HAYWARD FAULT, CALIFORNIA

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INTRODUCTION

[Version 1.1, minor revision, 2008; see last paragraph of introduction.]

The purpose of this map is to show the location of and evidence for recent movement on active fault traces within the Hayward Fault Zone, California. The mapped traces represent the integration of the following three different types of data: (1) geomorphic expression, (2) creep (aseismic fault slip), and (3) trench exposures. This publication is a major revision of an earlier map (Lienkaemper, 1992), which both brings up to date the evidence for faulting and makes it available formatted both as a digital database for use within a geographic information system (GIS) and for broader public access interactively using widely available viewing software. This pamphlet describes in detail the types of scientific observations used to make the map, gives references pertaining to the fault and the evidence of faulting, and provides guidance for use of and limitations of the map.

The term "recently active fault trace" is defined here as a fault trace that has evidence of movement in the Holocene or approximately the last 10,000 years. This definition also satisfies the legal definition of active fault used in the implementation of the Alquist-Priolo Act of 1972 (Hart, 1990). This map provides a starting point for planners by showing locations of fault creep and trench exposures of active traces.

A major scientific goal of this mapping project was to learn how the distribution of fault creep and creep rate varies spatially, both along and transverse to the fault. The results related to creep rate are available in Lienkaemper and others (1991, 1997, 2001) and are not repeated here. Detailed mapping of the active fault zone contributes to a better understanding of the earthquake source process by constraining estimates of (1) the probable recurrence times of major earthquakes, (2) the size of expected surface displacements, and (3) the expected length of ruptures accompanying these earthquakes. Following the 1989 Loma Prieta earthquake the Working Groups on California Earthquake Probabilities (1990, 2003) considered the Hayward Fault the most probable source of a major earthquake (magnitude 6.7 or larger) in the San Francisco Bay region in the next few decades.

This map also is of general use to engineers and land-use planners. The traces shown on the map are those that can be expected to have the most fault slip in future major earthquakes on the Hayward Fault. However, the small scale of the map (nominally 1:24,000) does not provide sufficient details of the local complexities of the fault zone for site development purposes.

Minor fault traces may not be recognized because many sections of the fault were already urbanized by 1939, the date of the earliest aerial photography for the entire fault. Thus, geomorphic features indicative of active faulting have been degraded or destroyed by human activity, especially secondary traces that have minor cumulative slip. For this reason, subsurface investigations are usually the main method of recognizing and precisely locating active fault strands in sites that lack reliable creep evidence. Mapping of creep evidence and monitoring of fault creep can be the most definitive method to precisely locate active traces.

Because subsurface investigations and other evidence of fault activity continue to become available, this map is considered current to June 30, 2008. Version 1.1 updates creep and trench evidence at only three sites: Berryman Reservoir and Memorial Stadium in Berkeley and Holy Redeemer College in Oakland. Some minor revisions have been made to 21 fault trace locations using 2007 LiDAR data available at: http://earthquake.usgs.gov/research/data/NoCal_GeoES_LiDAR_hs.kmz

GEOLOGIC SETTING

The Hayward Fault is a major branch of the San Andreas Fault system. Like the San Andreas, it is a right-lateral strike-slip fault, meaning that slip is mainly horizontal, so that objects on the opposite side of the fault from the viewer will move to the viewer's right as slip occurs. For a better understanding of the basic principles of strike-slip faulting and the relation of the Hayward Fault to this larger fault system see Wallace (1990).

Because this map documents only recently active traces of the fault, this text will touch only briefly on the early geologic history of the fault. The surface trace of the Hayward Fault follows a zone of crustal weakness that is mid-Cretaceous in age (99 ± 3 Ma) (Rose, 1978) or older (≥125 Ma) (Jones and Curtis, 1991), as suggested by a linear zone of keratophyric intrusive and volcanic rocks The earliest known offset occurred about 10 Ma, probably on a dominantly dip-slip fault (Graham and others, 1984). The presently dominant right-slip style may not have developed until after 8 Ma, and perhaps only as recently as 4 to 5 Ma (Jones and Curtis, 1991). Most late Tertiary geologic units are incompletely preserved on the southwest side of the fault due to erosion. Thus, the apparent matching of various tentatively correlated late Tertiary units across the fault has led to contradictory estimates of total right slip along the Hayward Fault Zone that range from a few kilometers or a few tens of kilometers (Graham and others, 1984; Fox and others, 1985; Liniecki-Laporte and Andersen, 1988) to as much as 190 km (Curtis, 1989; McLaughlin and others, 1990; Jones and Curtis, 1991). For more about the bedrock geology, the following references contain geologic maps that include parts of the Hayward Fault: Crittenden (1951), Robinson (1956), Radbruch (1957), Hall (1958), Case (1963), Radbruch and Case (1967), Radbruch (1969), Dibblee (1972), Bishop and others (1973), Wagner (1978), Dibblee (1980a, 1980b, 1980c, 1981), Borchardt and others (1988c), Graymer (2000) Graymer and others (1994, 1995, 1996 2002, 2005).

EARLIER MAPPING OF THE ACTIVE TRACES

Although a 40-km-long surface rupture on the southern Hayward Fault accompanied a major earthquake in 1868 (M7), this rupture was not mapped until after the great 1906 earthquake (Lawson, 1908). Another large earthquake, in 1836, had often been presumed to have occurred along the Hayward Fault (Louderback, 1947; Ellsworth, 1990; Lienkaemper and others, 1991), but further historical research supports a location south of the San Francisco Bay Area (Toppozada and Borchardt, 1998).

Radbruch-Hall (Radbruch, 1968a; Radbruch-Hall, 1974) compiled the 1868 rupture evidence of Lawson (1908) together with (1) bedrock fault traces, (2) newly recognized creep evidence, and (3) geomorphically recent traces. Herd (1977; 1978) interpreted Quaternary traces of the fault using 1939 aerial photographs. Hart (1979) and Smith (1980a; 1980b; 1981) compiled (1) the first 7 to 8 years of trenching results from Alquist-Priolo reports; (2) their geomorphic interpretations of Holocene traces from the 1939 aerial photographs; and (3) creep data from the literature and field work. Smith argued that many traces portrayed on earlier maps actually show no evidence of recent movement based either on his geomorphic analysis or from logs of trenches that crossed previously mapped bedrock or inferred fault traces.

In this report and map, earlier mapping is brought up-to-date using new findings from trenching and creep investigations. New methods are introduced for integrating on a single map geomorphic interpretations with a far greater amount of trenching and creep data than was available to previous map compilers. This map also focuses in much greater detail than its predecessors on the demonstrability of recent movement for each trace shown.

ORGANIZATION OF DIGITAL FILES

Lienkaemper (1992) presented the entire length of the Hayward fault on a single oversized printed sheet at a scale of 1:24,000. As such, the map was rather unwieldy. To take advantage of advances in digital technology, the current map is made accessible online in various convenient formats through viewing programs at http://pubs.usgs.gov/ds/2006/177/ and at http://quake.wr.usgs.gov/research/geology/hf_map/index.html. Informal users may zoom in on large or small areas of interest. Those with a deeper interest in a specific section of the fault may view and print page-sized maps of the fault composed at 1:12,000-scale and labeled with evidence supporting the location and activity level of each fault trace.

More technical users may wish to query the GIS database and develop their own map views of the fault using either ArcGIS software (proprietary) or ArcReader (free on internet). As with all GIS data, the reader must be aware of scale limitations of each set of data. Accuracy limits of these data sets will be discussed further below and in the metadata of each GIS file. Full documentation of the database fields is included in the metadata of each GIS file and will not be repeated here.

The projection of all GIS files in the download package is UTM10-NAD27 to conform to a requirement of the USGS Quaternary fault map that is currently in preparation.

METHODOLOGY

MAP ABBREVIATIONS

This fault strip map takes a much different approach than its predecessor strip maps of other California fault zones (summarized in Wallace, 1990) by presenting evidence of fault activity in highly abbreviated labels (see abbreviation lists, Appendixes 1 and 2). This was done for two reasons: (1) geomorphic features, visible on 1939 aerial photographs, are now largely destroyed by urbanization, and the map serves as a comprehensive archive of this evidence; and (2) creep and trench data are now greater in density per kilometer along the Hayward Fault than any other active fault in the world.

Considerable abbreviation was required to comprehensively combine the geomorphic, creep, and trench data on a single map sheet. Much simplification was required in some areas because of map-scale limitations. More trenches may exist at some sites, but they were too close together to plot or were distant from the fault trace. To minimize cluttering the map where data are dense, labels may appear next to multiple trenches and relate to the same cited reference. Map users needing further site detail should refer to the reference cited. Immediately adjacent creep localities that share a common description are sometimes described by a single label midway between the two creep symbols.

KILOMETER GRID

For indexing features discussed in this report, the map includes a kilometer grid oriented along the average strike of the Hayward Fault, N. 35° W. The km 0 mark is located where the fault intercepts the shoreline at San Pablo Bay near Point Pinole. This grid coincides with the grid on the 1:100,000-scale Hayward Fault map in Lienkaemper and others (1991, 1997, 2001), but it differs from Nason's (1971) distances from Point Pinole, which are 0.4-0.7 km less for a given locality. This grid is available in the GIS data package as a shape file.

The idealized grid, a great circle path near the fault, is rectified against latitude and longitude on the base map at each 5-km interval. Maximum discrepancies of 10-20 m result from distributing closure errors on the base map, but most positions can be referred to uniquely on the grid to within ± 10 m (0.01 km), in accord with the National Map Accuracy Standard of 12 m for well-located objects on 1:24,000-scale maps (Thompson, 1979). As with the original (1992) hand-drafted grid the digital version is only rectified against map coordinates at the fault trace.

FAULT LOCATION FROM GEOMORPHIC EXPRESSION

Geomorphic interpretation, both on aerial photographs and in the field, is a critical element in identifying recently active fault traces (Wallace, 1990). The block diagram (fig. 1) illustrates some of the typical landforms produced by strike-slip faulting. Most of these geomorphic features result when horizontal sliding along the fault brings

different materials into contact at the fault, for example,
bedrock against unconsolidated

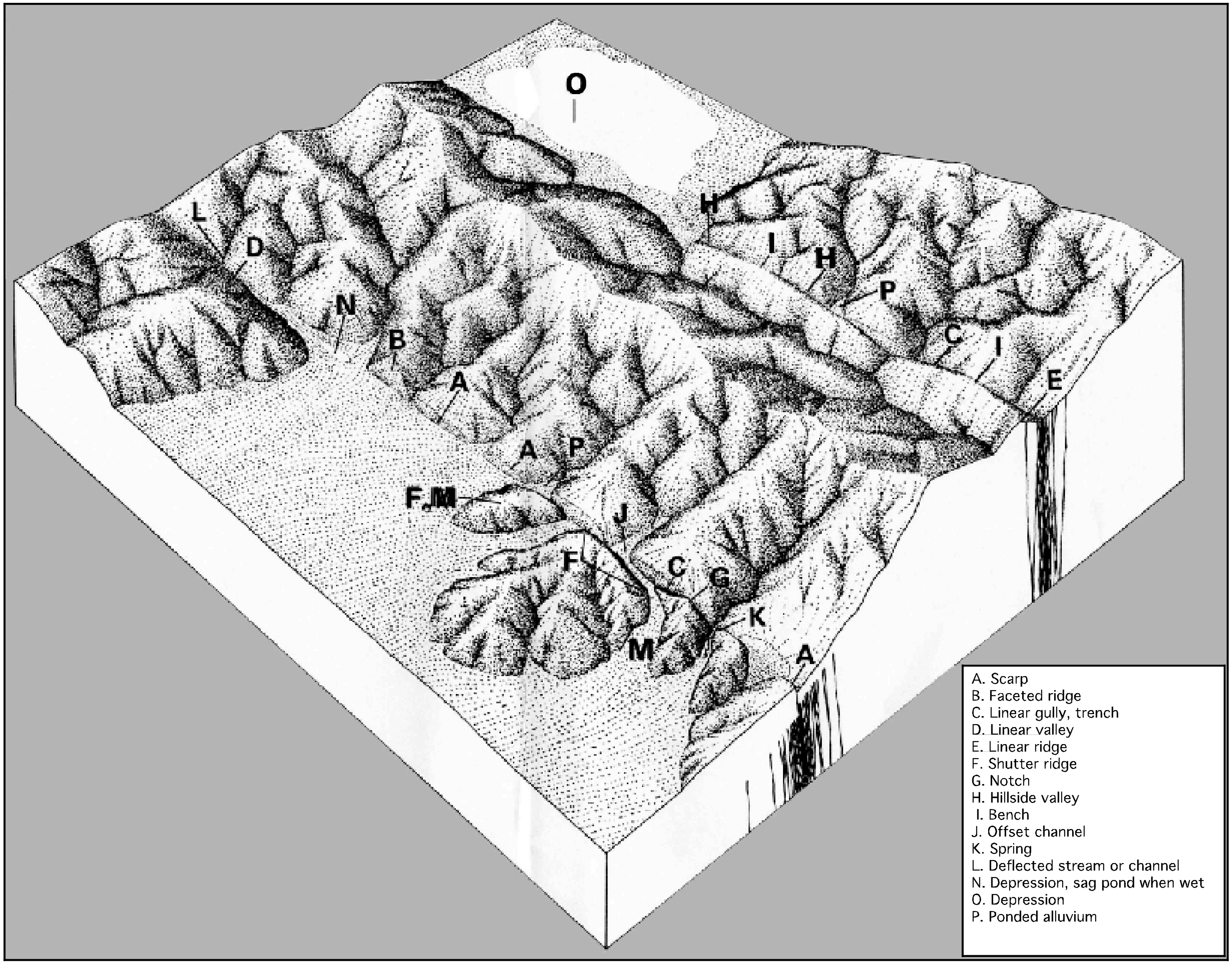

Figure 1. Block diagram showing landforms produced along recently active faults (Sharp, 1972).

alluvium or colluvium. The most visible effect is that fault slip causes abrupt disruptions in the natural drainage system, including interrupted subsurface water flow, and results in offset streams and the formation of ponds and springs.

Most disrupted streams along the Hayward Fault are offset right-laterally and vary widely in the total amount of offset. The two largest stream offsets occur on large streams and show accumulated slip of 2-3 km. Many smaller streams have offsets ranging from tens of meters to a few hundred meters. These smaller streams, particularly those entrenched in weak alluvium, tend to escape their right-laterally offset lower channels and flow straight across the fault again. Some streams have captured the headwaters of adjacent streams and form apparent left-lateral offsets. The repetition of these processes over millennia creates linear valleys along the fault trace, which are commonly called "rift" valleys. These narrow strike-slip rifts in the San Andreas Fault system are in most locations primarily erosional features and are not genetically related to true rift valleys that are caused by extension, such as those in eastern Africa and along oceanic spreading centers.

These geomorphic expressions of faulting occur at many scales. The size of a geomorphic feature tends to relate inversely to its age. Typically, smaller features result from the most recent fault movements. For example, assuming that late Pleistocene slip rate has been similar to the Holocene rate of about 9 mm/yr (Lienkaemper and Borchardt, 1996), we deduce that the largest offsets of streams on the Hayward Fault reflect tens of thousands of years to a few hundreds of thousands of years of fault slip. Conversely, the smallest recognized right-lateral offset of a gully is 2-3 m and is the result of a combination of fault creep and coseismic slip associated with the earthquake in 1868 (and possibly earlier earthquakes too).

Because the most recent fault features are the smallest and most fragile, few have survived the intense urbanization of the East Bay that has occurred since World War II. Fortunately, aerial photographs of the entire fault were taken in 1939 (U.S. Department of Agriculture, BUU-BUT series, scale 1:20,000, available from National Archives, Washington, D.C.) These 1939 photographs are the primary source of geomorphic evidence of recent fault traces. For greater detail, I used 1:6,000-scale (1966, U.S. Geological Survey, WRD series) and 1:4,000-scale aerial photographs (1991, U.S. Geological Survey, HFZ series, color). Other miscellaneous USGS 1:24,000-scale aerial photographic series from the 1940's and 1950's were marginally useful in some areas to resolve uncertainties in interpretation.

I did not consider all fault features to be equally useful in accurately delineating complex patterns of recent faulting. Each feature is unique and reflects varying amounts of fault-trace complexity. However, erosion and degradation of features by human activities often obscures this geomorphic evidence and can lead the analyst to incorrect or crudely approximated fault-line interpretations. For example, a well-preserved, narrow, straight fault scarp (sn) can be confidently attributed to a simple narrow style of fault rupture. Other scarps have formed by broadly distributed surface rupturing (sb). Evidence from well-preserved geomorphic expression, detailed creep investigation, or trenching may confirm that the fault zone is truly broad and complex and not simply a degraded narrow scarp (sn). Generally one cannot differentiate the broad fault scarp that represents widely distributed slip from a narrow one that has been broadened by erosion and degraded by human activities.

The codes G1 (strongly pronounced), G2 (distinct), and G3 (weakly pronounced) are a system to classify my overall judgment about the reliability of geomorphic features for accurately locating recent fault traces. For example, considerable fault complexity might appear as a feature of only G3 quality, or alternatively the fault trace might originally have been narrow and simple but was later altered by agricultural or other human activity. We cannot certainly distinguish the original character of such a feature without either earlier photographic or subsurface evidence.

Recency of faulting from geomorphic expression is a separate idea, but difficult to completely separate in fact. I did not specifically intend the G1, G2, and G3 classification to be an evaluation of certainty that traces are of Holocene age. I intend it to be mainly a scale of clarity. Not surprisingly, fault traces that are geomorphically more distinct (G1, G2) can be precisely delineated and, thus, tend to confirm Holocene activity. Unfortunately, the weakly pronounced traces (G3) in most cases reflect degradation by human activities, so we cannot geomorphically delineate the fault precisely. However, I believe that most of the G3 traces shown on the map are Holocene active.

Even distinct geomorphic features (G1, G2) need to be corroborated. For example, near Lake Temescal (km 20-21) at least two earlier maps confidently plotted the active Hayward Fault using aerial photo-interpretation of geomorphic expression. I would have described the geomorphic feature that they mapped as a G2-quality linear fault scarp if I had not learned that the feature actually is a long-abandoned railroad cut that is obscured by a canopy of trees. Recent trenching and creep data suggest that the active fault trace may be 60-100 m to the southwest of the old railroad cut (California Department of Transportation, 1991; Rutherford and Chekene, 1991).

I also use geomorphic expression as one means of estimating the uncertainty of fault location more quantitatively, as shown on the map by the variable lengths of gaps between dashes in the fault linework as described in the map explanation. Fault-related geomorphic features separate smoother and generally more stable areas on opposite sides of the fault. The width of these features is measurable on aerial photographs. For geomorphic features such as a G3-quality linear scarp that is neither narrow nor distinct, I plot the center of the feature and estimate the uncertainty in locating the active trace as half the width of the feature. Where precise trench or creep data are available, these establish the lateral position of the fault, and I use the lower quality geomorphic features only for the orientation and continuity of the fault trace. For example, creep data may show that the active trace is high or low, rather than mid-slope, on a fault scarp that is geomorphically indistinct. Higher quality (G1 and G2) geomorphic features tend to agree well with locations of active traces as identified in trenches and from creep evidence.

The fault traces plotted on the map ideally show the center of each intense zone of shearing that can be reasonably discretized and plotted distinctly at a scale of

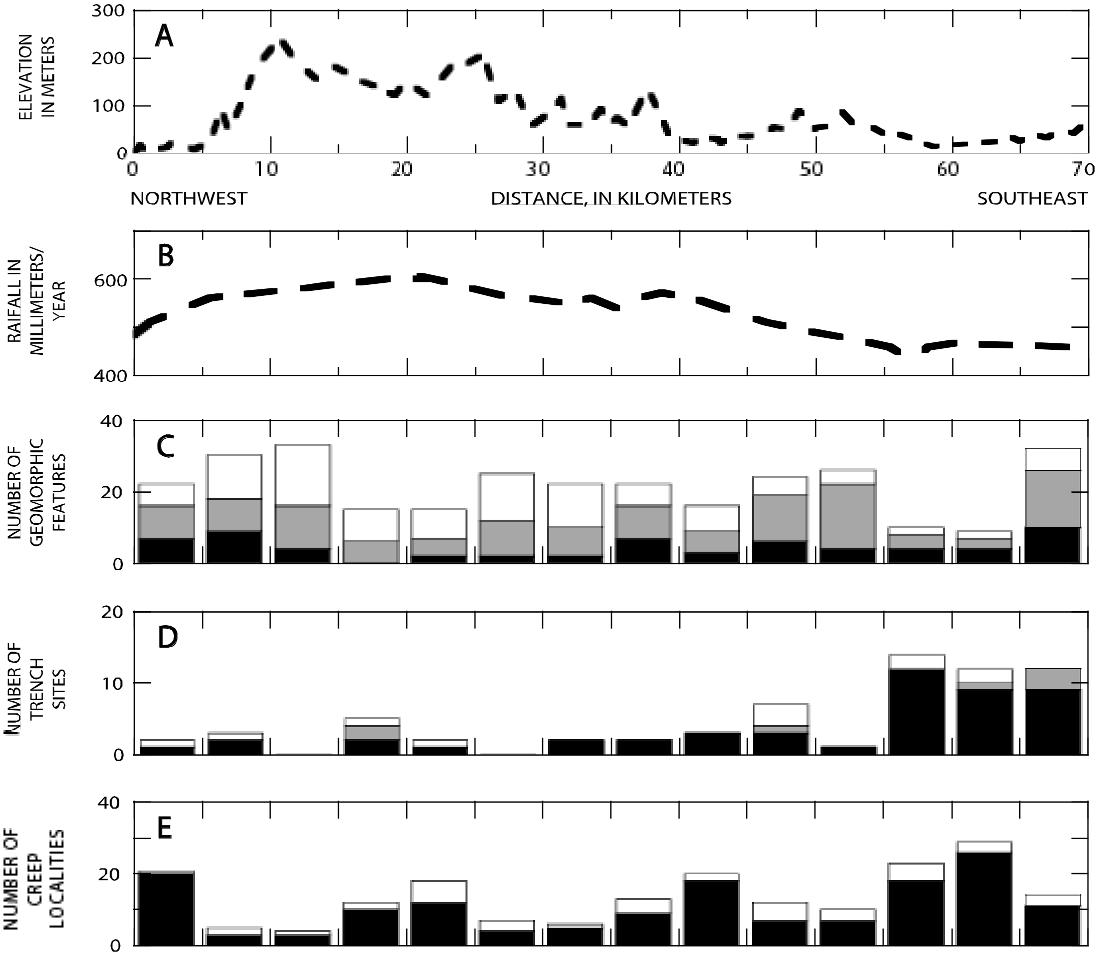

FIGURE 2. Summary histograms show amount and quality of faulting evidence from plate 1 as a function of distance along the fault. A) elevation of fault zone; B) average annual rainfall along fault zone (Rantz, 1971); C) fault-related geomorphic features (black, G1; gray, G2; white, G3); D) trench sites (black: H1, H2; gray: HP, P, U; white: H?, F?, NF); E) creep localities (black: C1, C2; white, C3). See figure 1 for location of kilometer grid. Note: this figure not updated from 1992 edition.

1:24,000. Although 90 percent of well-defined cultural features on the base map are required to be located within ±12 m of their correct position at a scale of 1:24,000, many positions of cultural and natural features that I relied on to transfer the fault traces do not meet the rigorous definition of well defined. In my judgment, ±≤20 m is a reasonable estimate of the general reliability of the fault-trace plotting error. Especially in this revised digital edition much of the data are plotted much more accurately than this standard. This is particularly true in the case of creep data and trenching data. Most of the creep data were documented in the field on aerial photos of 1:6000- and 1:4000-scale with accuracy of about 1-2 meters. These points were generally easy to transfer to the USGS digital orthophoto quadrangles (doqs) with little loss of precision locally. Relative accuracy over larger areas is estimated as similar to National Mapping Standards of ≤±12m for 90 percent of well-located base map features. Trench locations are generally taken from copies of paper maps from reports in publicly accessible files. For the digital recompilation these maps were scanned and georeferenced by fitting them to common points on grayscale USGS doqs using ArcGIS software. In most cases average registration errors (estimated by the software) for these trench maps ranged between 2-3 meters. The newer color doqs used to present the digital data agree well with the older grayscale doqs. The color doqs are more detailed and accurate than the older ones but were not available in time for most of the recompilation of creep and trench evidence.

A separate issue from the accuracy of cartographic plotting is the accuracy of the position of fault trace between points on the fault that are well located by creep, trench logging, or narrow geomorphic features. Detailed mapping and surveying of creep evidence show that the deformation zone of the main creeping trace is as much as 20-m wide (Nason, 1971; Lienkaemper and others, 1991). Although individual creeping traces can be less than a few meters wide, the fault zone tends to be complex and not linear at large scales, so I chose ≤±20 m as a reasonable upper bound for the delineation error (meandering of the principal strands of well-located fault traces between exactly located points). Exactly located points can in all cases be plotted to within ≤±12 m, because basemaps have improved since the last edition of this map.

The above discussion is rather involved, but the practical outcome is that faults shown as being located within ≤±20 m (see explanation for fault symbols) are reliably located within ±12 m, compared to other features, of where the map shows them to be on the doq base maps. The larger estimates of uncertainty (≤±40 m and ≤±60 m) derive mostly from aerial photo-interpretation on segments of the fault where creep and trenching data are sparse. Even highly degraded geomorphic features constrain the position of the principal fault trace within interpretable boundaries. The dash length of fault linework is fixed to cover 30 m on the map for two reasons: (1) the portrayal of uncertainty can be varied over short distances, and (2) using the dash length as a frame of reference, with a little practice, the map user can distinguish the two lengths between dashes (40 m and 60 m on the map). These approximate dash gap lengths and line weights were set in the digital map for a data frame reference scale of 1:12,000 and work fairly well for a range of 1:6,000 to 24,000.

Differing from the 1992 edition, solid lines are now used to portray fault traces for well-located traces, because available basemaps are much improved. However, where active traces are known in great detail, they tend to be complex structures that form en echelon patterns and are multi-stranded in a way that usually does not generalize easily into a single smooth fault trace. Therefore, the line on the map should be thought of as being near the center of an active zone of complex faulting.

The uncertainty estimates are not intended to represent the total width of the zone of active faulting. Many cultural features that were surveyed for creep offset (Lienkaemper and others, 1991, 1997) show significant secondary active faulting and rotations several tens of meters from the main active trace. Commonly these secondary traces have no extant geomorphic expression. Larger errors in location than have been estimated may exist, and many unrecognized secondary active traces may exist. Therefore, map users who need site-specific information must verify the local evidence for faulting to satisfy their particular requirements.

Geomorphic fault-zone features tend to be more distinct in the southern (km 35-70) and northernmost (km 0-10) parts of the mapped region as shown in figure 2C. This tendency may partly depend on rainfall (fig. 2B) and elevation (fig. 2A). However, it may be more important that the El Cerrito to Oakland areas (km 10-35) were substantially more developed than the adjacent regions in 1939, the date of the earliest complete aerial photography that was used to analyze the fault. Two other factors that are both secondary effects of rainfall (and indirectly of elevation) reduce the distinctness of geomorphic features in the hilly areas from Oakland to El Cerrito (km 10-35): (1) heavier vegetation, especially oak and eucalyptus woodlands; and (2) more slope instability (soil creep and landsliding).

An apparent scarcity of geomorphic data in two areas of the map (km 40-45 and km 55-65) is largely an artifact of map-editing decisions. Actually, many geomorphic features of high quality show in these areas in the 1939 aerial photographs, but at a scale of 1:24,000 they could not be labeled as comprehensively as elsewhere. The trench and creep data are extremely abundant in these areas, and because it is essential to fully annotate the more exact creep and trench data, little space remained to annotate the geomorphic data. Consequently, the geomorphic annotation is less detailed in these areas than elsewhere, although more important features are still noted, particularly those that are most relevant to the accurate delineation of the fault traces.

FAULT LOCATION FROM CREEP EVIDENCE

Fault creep, the common name for aseismic slip observed along the surface trace of a fault, has now been recognized along many branches and segments of the San Andreas Fault system (Calaveras, Concord, Green Valley, Hayward, Imperial, Maacama, central San Andreas, Sargent, and Superstition Hills Faults). Creep was first discovered on the central San Andreas Fault in 1956

(Steinbrugge and others, 1960), and we now deduce that creep has been occurring on that fault for at least several decades. A few years later, creep was discovered on the Hayward Fault in a few locations (Blanchard and Laverty, 1966; Bolt and Marion, 1966; Bonilla, 1966; Cluff and Steinbrugge, 1966; Radbruch and Lennert, 1966). In later years many other creep localities along the Hayward Fault were reported (Radbruch, 1968b; Nason, 1971; Bishop and others, 1973; Smith, 1980a, 1980b, 1981; Burford and Sharp, 1982; Hirschfeld and others, 1982; Lennert, 1982; Taylor, 1982, 1992; Lennert and Curtis, 1985; and many others too numerous to cite here.) Because there are so many places where creep evidence is publicly accessible in the field, and it continues to grow and change, I have annotated the map primarily with my own observations (1985-2005) and cited others only in places where I relied heavily on earlier work, such as survey measurements, creep offsets in tunnels and on private lands, and where the creep evidence has been altered or destroyed or where previous documentation was especially thorough and detailed. I only note on the map those surveyed features and creep monitoring arrays that I used to locate the fault trace or discriminate traces that are creeping from those that are not.

Averaged over several decades, rates of creep ranged from 3-6 mm/yr along most of the Hayward Fault (km 0-62), but they were distinctly higher, 8-10 mm/yr, near the south end (km 63-67). No evidence for creep has been recognized south of km 69. For more detail on long-term creep rates see Lienkaemper and others (1991, 1997, 2001) and Galehouse and Lienkaemper (2003). For earlier creep rates from alinement arrays, see Harsh and Burford (1982); Wilmesher and Baker (1987); and Galehouse (1991); from creepmeters, see Yamashita and Burford (1973); Nason and others (1974); Schulz and others (1982); Schulz (1989); and from regional and local trilateration surveys, see Prescott and Lisowski (1983); Lisowski and others (1991).

Field recognition of creep evidence has been discussed in several field guides on the Hayward Fault, including: Nason and Rogers (1970); Taylor and others (1982); Wahrhaftig (1984); Bortugno (1988); Lienkaemper (1989). Hirschfeld (1982) is a good introduction to recognizing and understanding the significance of en echelon pavement cracks in the field. Smith (1982) discusses the common pitfalls in mistaking nontectonic phenomena for evidence of fault creep. Lienkaemper and others (1991) discuss many of the most distinctly offset curbs, fences, and other cultural features along the entire length of the fault and show detailed plots of each one. A wealth of additional field observations along the fault is available from many sources within the Field Guide (Taylor and others, 1992) and the Proceedings (Borchardt and others, 1993) of the Second Conference of Earthquake Hazards in the Eastern San Francisco Bay Area.

Like geomorphic expression, not all creep evidence is equally reliable for proving the existence of and establishing the precise positions of the active traces of the fault. The creep reliability ratings C1 (strongly pronounced), C2 (distinct and certain), and C3 (inconclusive) are intended to distinguish evidence about which I am reasonably confident (C1 and C2) from evidence that might be attributable to yet unidentified nontectonic causes (C3), such as soil creep, landsliding or fill failure, expanding tree roots, broken water pipes, vehicular collision, uneven loading or thermal and shrink-swell phenomena in pavements and slabs and their underlying soil, differential settlement, and other soil-structure interactions.

Where nontectonic forces are known to be acting, and they provide a more credible explanation of a deformed or distressed feature, nothing is recorded on the map. That is, creep best explains all C3 localities, but the creep is not yet strongly developed nor adequately corroborated by additional nearby evidence. C1 quality ratings are assigned sparingly, only for creep evidence that is especially obvious in the field. Many features given C2 ratings are straight features that have distinct offsets as seen in the results of alinement surveys, such as those in Lienkaemper and others (1991), but the offsets may be distributed over several meters and, thus, may be less obvious in the field. Conversely, many C3 features, such as offset fences that have not been surveyed yet, might be reclassified as C2 when surveyed.

Creep evidence of all three reliability ratings serves to locate the fault precisely for purposes of this map and agrees well with good quality geomorphic evidence. Rare exceptions to this are the two water tunnels, San Pablo (km 12.93) and Claremont (km 19.99). The active trace locations in the tunnels are only approximately known from original sources (Blanchard and Laverty, 1966; Lennert and Curtis, 1985). Connecting the geomorphic trace to the approximate location of creep in these tunnels would suggest steep (but not vertical) northeastward dips. However, the more precisely located creep evidence in the Bay Area Rapid Transit tunnels (km 20.28) (Brown and others, 1981) appears to lie vertically below the geomorphic trace. The exact creep locations in the water tunnels must be verified before drawing any conclusions regarding dip.

Much speculation has been offered regarding the scarcity of creep observations in the hilly areas from El Cerrito to Oakland (km 5-35). Figure 2E summarizes the number of creep localities shown on the map. Roughly similar to the situation for geomorphic features, higher rainfall and steep slopes add to the difficulty in reliably locating the active fault traces using creep evidence. More tree roots and various slope stability problems in these hilly areas make creep recognition more difficult. Because these areas were generally built up much earlier, the fault must intercept many older cultural features. In most places this would make creep evidence easier to identify, but because most slopes are steep, the roads, curbs, and fence lines tend to be curved. Therefore, broadly distributed creep offsets are extremely difficult to judge reliably, and other creep effects are rarely distinguishable from abundant nontectonic disruptions.

FAULT LOCATION FROM TRENCHING EVIDENCE

Prior to 1992 most trenches across the Hayward Fault were done as part of site-oriented fault investigations to satisfy legal requirements of the Alquist-Priolo (AP) Special Studies Zones Act of 1972 (Hart and Bryant, 1997) which is administered by the California Geological Survey (CGS, formerly California Division of Mines and Geology, CDMG), Sacramento, California. For a summary of some products related to the AP Act see Wills (1991). Hundreds of AP reports have been filed for the Hayward Fault Zone. These reports are now available on CD (Wong and others, 2003) from CGS (Menlo Park). Most AP investigations were conducted on parcels that showed no probable evidence of active traces, but trenching was usually required to demonstrate that no concealed secondary fault traces exist where development was planned. The majority, 38 of 69, trench sites that contained trenches across major active fault traces (38/69; 55 percent) are along the southernmost part of the fault (km 55-70, fig. 2D; only pre-1992 shown), because most development along the rest of the fault occurred before the 1972 Alquist-Priolo Act. From 1992-2005 only about 10 additional AP sites have become available that include trenches crossing the fault. However, the current map includes evidence from several other trenching studies that have been done for other purposes: site studies for public utilities and other public entities, scientific investigations, and various other site-specific reports that have not been filed with the AP program.

About seventy AP reports contain logs of trenches that cross Holocene-active traces. Many of these trenching investigations involved large tracts and multiple trenches. The map shows only those trenches that crossed or came near to Holocene-active fault traces and traces that show latest Pleistocene to Holocene (?) activity.

For engineering purposes, it would be interesting to know the approximate likelihood of being able to demonstrate the existence and location of a Holocene-active fault trace at a given site using the methods of trench logging that have actually been used to date. To get a rough idea of what proportion of trenching sites show distinct evidence of Holocene faulting, I summed the different categories of trenching evidence (see Trench Exposures" explanation) for those 69 trenching sites that had trenches across independently identified "major active fault traces" (MAFT sites.) The logs show distinctly Holocene fault traces (H1, H2 evidence) at most MAFT sites (50/69; 72 percent), but evidence is at best weakly conclusive or permissible of faulting (H?, F?, NF) at some MAFT sites (11/69; 16 percent). At a few other MAFT sites (8/69; 12 percent) significant faulting was evident, but evidence of Holocene age was not clearly demonstrable (HP, P, U). The above percentages reflect the most conclusive evidence at a given site, but other exposures at the same site in some cases showed inconclusive results. I suspect that in most cases of weak or permissible evidence (H?, F?, NF), the fault was identified only because the investigator was cued by nearby geomorphic or creep evidence. The category NF as included in the above statistics covers a few difficult cases where no discrete fault offset appears in the trench log, but investigators acknowledge a highly approximate location of the trace from miscellaneous indirect evidence.

The above results for trenching across recognizable main traces of the fault suggest we may not always identify secondary traces when they do exist, particularly where no Holocene cover exists. Most consultants and reviewers are conservative and presume pre-Holocene (HP, P, U) shears are active or treat weak or permissible evidence of faulting (H?, F?, NF) as genuinely active traces for purposes of development. Therefore, some building exclusion zones might avoid nonexistent or inactive fault traces, and other exclusion zones might reflect incorrectly located active traces. These problems can be avoided in some cases by adopting the following practices: (1) placing corroborative trenches through nearby areas that are more likely to have stratified Holocene units; (2) logging both trench walls in detail where faulting is suspected including noting orientations of soil shears and slickensides; and (3) in monotonous fine soil horizons, performing array sampling of soil transverse to the fault and plotting clay-sand ratios or other factors indicating subtle material contrasts (Borchardt and others, 1988b). For further discussion of factors affecting the visibility and recognition of faulting in exploratory trenches, and for a more detailed treatment see Bonilla and Lienkaemper (1990, 1991).

DISCUSSION

Ideally, this strip map of the Hayward Fault is one in a series of progress reports that summarizes our present knowledge of active fault traces. It is important for both scientific and engineering reasons that we continue to discover and map all the active traces and monitor creep distribution in greater detail so that we can better understand and cope with this highly urbanized fault zone.

In some areas the main fault trace continues to be located with large uncertainty, for example (1) near Point Pinole (km 0.0-1.1); (2) near Wildcat Creek (km 6.3-7.9); (3) in Kensington (km 11.9-13.6); (4) near Lake Temescal (km 20.3-21.3); and (5) in central Oakland between High Street and 82nd Avenue (km 28.1-32.0). Except near Lake Temescal, the dominant problem is the ambiguity produced by the interaction of the fault zone and landsliding. Particularly in the case of central Oakland, the fault may also be genuinely complex with multiple strands and en echelon stepovers.

Where multiple strands exist, the most active strand does not in all cases correspond to the most geomorphically distinct trace. For example, north of the Masonic Home in Union City (km 54) two active traces are spanned by the trilateration array, UNION (Prescott and Lisowski, 1983). Surprisingly, the geomorphically more distinct eastern trace exhibits no creep above the detectable limit (<1 mm/yr), while the geomorphically weaker western trace creeps at about 5 mm/yr. Geomorphic distinctness is a better indicator of relative activity at the MAR trilateration array in El Cerrito (km 9) (Prescott and Lisowski, 1983). The MAR array spans only the western and geomorphically less pronounced of two active traces and shows no creep (<1 mm/yr), while the slightly more pronounced eastern trace creeps at about 5 mm/yr at nearby Olive Avenue (km 8.35).

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.

APPENDIX 1

MAP ABBREVIATIONS

C - CREEP EVIDENCE

1 - strongly pronounced fault creep
2 - distinct and certain creep evidence
3 - inconclusive evidence for creep
? - additional uncertainty in tectonic origin
aa - alinement array
cb - concentration of cracks in above-grade structure
cc - concentration of cracks in concrete slab
cp - concentration of pavement cracks
cr - clockwise rotation of sidewalk
cs - curb separating from sidewalk or pavement
cw - clockwise rotation of wall
ec - en echelon left-stepping cracks in pavement
jo - opening of joints or cracks in concrete
pp - multiple patches in pavement
pu - compressional pop-up or buckle in concrete
ra - right-laterally offset aqueduct, water pipe, or tunnel
rb - distortion of above-grade structure (including separating additions and stairways)
rc - right-laterally offset curb or form line or railing
rf - right-laterally offset fence line
rp - right-laterally offset painted line
rr - right-laterally offset railroad tracks or guardrail
rs - right-laterally offset sidewalk
rt - right-laterally offset line of trees
rw - right-laterally offset wall
so - surveyed offset feature
u - unspecified evidence

G - GEOMORPHIC FEATURES

1 - strongly pronounced feature
2 - distinct feature
3 - weakly pronounced feature
? - additional uncertainty in tectonic origin
af - alignment of multiple features as listed
as - arcuate scarp
bt - downthrown surface tilts back toward fault
df - depression formed by some aspect of fault deformation, undifferentiated
dr - sag, depression formed in right stepover of fault trace
gi - linear break (or gradual inflection) in slope
hb - linear hillside bench
hv - linear hillside valley

ls - fault scarp height enlarged by landsliding
lv - linear valley or trough
mp - Youngest traces disturbed by human activities. Mapped trace bisects disturbed zone. Location uncertainty (dash gap in linework) equals half width of disturbed zone.
n - notch
pr - pressure ridge in left stepover
rr - right-laterally offset ridge line
rs - right-laterally offset stream or gully
sb - broad linear scarp (implies multiple traces)
sc - scissor point, sense of vertical separation reverses
se - subsoil exposed
sl - linear scarp, undifferentiated
sn - narrow linear scarp (implies dominant trace)
sp - spring
ss - swale in saddle
vl - line of vegetation

T - TRENCH EXPOSURES (and other geologic evidence)

H1 - Holocene age of offset determined by radiocarbon (^{14}C) dating
H2 - Modern soil or alluvial unit distinctly offset, or contains features conclusive of shearing, such as gouge, rotated pebbles, transported materials in shear zone, and filled fissures over distinct Pleistocene faults
H? - Inconclusive signs of Holocene offset, such as steps in base of soil or apparent shears in clay-rich materials. Without corroboration such evidence neither proves nor disproves either existence or age of faulting
H - Active trace reported in trench, trench logs not in public file
HP - Distinct faulting in unconsolidated alluvium of possibly Holocene or more likely latest Pleistocene age
F? - Feature shown as fault in log resembles nontectonic feature such as bedrock-alluvial contact, buried terrace riser, or landslide plane
NF - No fault observed
P - Distinct evidence of significant faulting in Pliocene or Pleistocene sediments
RC - Roadcut log
WB - Ground water barrier
U - Age of faulting unobtainable because surficial deposits removed

REFERENCE CODES (see also Abbreviated Map References and text for full references.)

A2456 - Trench log or creep evidence in Alquist-Priolo report AP-2456, available on CD from California Geological Survey [Wong and others, 2003]
C200 - Trench log or creep evidence in non-Alquist-Priolo consultant’s report filed at CDMG.
G70 - Non-Alquist-Priolo unpublished report referenced in abbreviated references as G70.

APPENDIX 2

ABBREVIATED MAP REFERENCES

(See text for full references)

A29	Soil Engineering Construction Company (1973)
A64	Gribaldo Jones and Associates (1970a)
A70	Berlogar Long and Associates (1975)
A108	Rose (1974)
A170	Burkland and Associates (1975)
A380	Woodward-Clyde Consultants (1976)
A436	Woodward-Clyde Consultants (1977)
A459	Terrasearch Incorporated (1977a)
A477	Cooper-Clark and Associates (1974)
A511	Burkland and Associates (1976a)
A538	Engeo Incorporated (1977)
A602	Terrasearch Incorporated (1977b)
A618	Burkland and Associates (1977b)
A671	Burkland and Associates (1972)
A672	Burkland and Associates (1976b)
A679	Burkland and Associates (1973)
A704	Terrasearch Incorporated (1977c)
A716	Burkland and Associates (1976c)
A727	Woodward-Clyde Consultants (1978b)
A735	Gribaldo Jones and Associates (1978)
A744	Woodward-Clyde and Associates (1970b)
A784	Hull and Associates (1976)
A807	Purcell Rhoades and Associates (1976)
A808	Hillebrandt Associates (1978)
A871	Terrasearch Incorporated (1978)
A943	Burkland and Associates (1978)
A1075	Hull and Associates (1979)
A1080	Earth Systems Consultants (1979)
A1153	Cotton and Associates (1979)
A1153	Jones, W.F., Incorporated (1980)
A1240	Earth Systems Consultants (1980a)
A1281a	Myers Associates (1980)
A1281b	Earth Systems Consultants (1987b)
A1299	Merrill and Seeley Incorporated (1979)
A1304	Earth Systems Consultants (1980c)
A1339	Myers Associates (1981)
A1356	Zickefoose and Associates (1981)
A1473	Earth Systems Consultants (1981)
A1475	Burkland and Associates (1977a)
A1519	Kaldveer and Associates (1982)
A1705	Myers Associates (1984)
A1898	Earth Systems Consultants (1983, 1986)
A1992	Harding Lawson Associates (1987)
A2046	Myers Associates (1987)
A2288	Purcell Rhoades and Associates (1989)
A2341	Myers Associates (1989)
A2430	Soares and Associates (1986)
A2454	Earth Systems Consultants (1985)
A2456	Earth Systems Consultants (1990)
A2457	Crosby and Associates (1989)
A2458	Earth Systems Consultants (1988a)
A2459	Lettis and Associates (1991)
A2460	Cleary Consultants Incorporated (1989)
A2461	Earth Systems Consultants (1988b)
A2462	Earth Systems Consultants (1987a)
A2514	California Department of Transportation (1991)
A2516	Terrasearch Incorporated (1991)
A2522	Kaldveer and Associates (1981)
A2529	Harding Lawson Associates (1986)
A2530	Lennert and Curtis (1985)
A2566	Epigene Incorporated (1990)
A2582	Cooper Engineers (1986)
A2586	Epigene Incorporated (1986)
A2589	Hull and Associates (1981)
A2590	Terrasearch Incorporated (1990)
A2601	Harding Lawson Associates (1991)
B66	Bonilla (1966)
B77	Burkland and Associates (1977c)
B81	Brown, Brekke, and Korbin (1981)
B88A	Borchardt, Lienkaemper, Budding, and Schwartz (1988a)
B88B	Borchardt (1988)
BL66	Blanchard and Laverty (1966)
BM93	Borchardt and Mace (1993)
BS82	Burford and Sharp (1982)
C86	Cotton, Hall and Hay (1986)
C341	Woodward-Clyde Consultants (1978c)
C375	Woodward-Clyde Consultants (1978a)
C487	Earth Systems Consultants (1980b)
CC68	Cooper-Clark and Associates (1968)
CS66	Cluff and Steinbrugge (1966)
E06, E08	Engeo Incorporated (2006, 2008)
FER101	Smith (1980a)
G01	Geomatrix (2001)
G70	Gribaldo Jones and Associates (1970b)
G91	Galehouse (1991)
G94	Geomatrix (1994)

G96	Geomatrix (1996)
G2007	Geomatrix (2007)
GC93	Geotechnical Consultants Inc (1993)
GEI90	Geotechnical Engineering Inc. (1990)
H82A	Hirschfeld (1982)
H82B	Hirschfeld, Ridley, and Nason (1982)
HB82	Harsh and Burford (1982)
L82	Lennert (1982)
L01	Lienkaemper and others (2001)
L03	Lienkaemper and others (2003)
L05	Lienkaemper and others (2005)
L91	Lienkaemper, Borchardt, and Lisowski (1991)
L97	Lienkaemper Galehouse (1997)
N71	Nason (1971)
NC70	Nason, R.D. and Carey, J.P., 1970, unpublished data; see Woodward-Clyde (1970a).
PL83	Prescott and Lisowski (1983)
RC91	Rutherford and Chekene (1991)
RH74	Radbruch-Hall (1974)
RL66	Radbruch and Lennert (1966)
TP82	Taylor and Page (1982)
W91	Williams (1991)
W07	William Lettis &Associates, Inc. and URS Corporation, 2007
WB87	Wilmesher and Baker (1987)
WC70	Woodward-Clyde and Associates (1970a)
WL72	Woodward-Lundgren and Associates (1972)