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Paleoseismic investigation of the Maagama Fault, near Talmage, California

Robert S. Bogar
San Jose State University

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**PALEOSEISMIC INVESTIGATION OF THE MAACAMA FAULT,
NEAR TALMAGE, CALIFORNIA**

**A Thesis Presented to
The Faculty of the Department of Geology
San Jose State University**

**In Partial Fulfillment
of the requirements for the Degree
Master of Science**

**By
Robert S. Bogar
August, 1999**

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APPROVED FOR THE DEPARTMENT OF GEOLOGY

Dr. John W. Williams

Dr. Deborah R. Harden

Dr. Carol S. Prentice

APPROVED FOR THE UNIVERSITY

ABSTRACT

PALEOSEISMIC INVESTIGATION OF THE MAACAMA FAULT, NEAR TALMAGE, CALIFORNIA

By Robert S. Bogar

The Maacama fault zone (MFZ) is interpreted as the northern extension of the Hayward and Rodgers Creek faults within the San Andreas fault system. The few studies conducted on the MFZ have in large part been unsuccessful in providing accurate slip-rate, recurrence-interval or slip-per-event estimates. As a result, seismic hazards associated with a future rupture of the MFZ have not been adequately determined. This investigation identified fault-ruptured fluvial sediments in the Howell Creek drainage near Talmage, California. Stratigraphic relationships in coarse sediments indicate that coseismic dextral slip was less than about 1 m near the surface, suggesting that only one surface-rupture earthquake displaced sediments at the site. Radiocarbon results from detrital charcoal suggest that a large surface-rupture earthquake occurred sometime after 310 years BP. However, this investigation also raised the possibility that the earthquake may have occurred sometime after about 5,280 years BP. In addition, this study proposes a possible mechanism for aseismic creep currently acting across the MFZ. This hypothesis suggests that fault strength reduction may occur along creeping segments of the MFZ because of a petrologic fabric in the Franciscan Central belt melange that is aligned favorably with the orientation of fault motion on the MFZ.

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INTRODUCTION

This report documents a paleoseismic investigation conducted across the Maacama fault zone (MFZ) at a site located approximately 3 km south of the town of Talmage, California (Fig. 1). This investigation included excavation and detailed logging of two trenches, photographic documentation of both trenches, a site survey using theodolite equipment, radiocarbon analysis, and data interpretation. This report describes the design, implementation, results, and conclusions of this investigation.

In recent years, the Working Group on California Earthquake Probabilities (Working Group, 1996) developed fault motion estimates for the MFZ and the Rodgers Creek fault zone (RCFZ). These estimates were largely derived from paleoseismic and other investigations conducted on the Hayward fault zone (HFZ) (Working Group, 1996). Although geophysical and seismic investigations indicate that the Hayward, Rodgers Creek, and Maacama fault zones are part of a regional structure (Upp, 1989; Ellsworth and others, 1982), results from the few paleoseismic investigations conducted across the MFZ have not provided sufficient data regarding slip rate, recurrence interval, or coseismic slip to independently corroborate this assumption. As a result, seismic hazards associated with the MFZ have not been adequately determined. The objectives of this investigation were: (1) to identify and estimate the timing of paleo-earthquake events on the MFZ, and (2) to provide estimates of the average recurrence interval and slip rate for the MFZ.

Figure 1. Regional fault map showing the Maacama fault zone and Pliocene-Pleistocene basins. (Modified from Hearn and others, 1988.)

BACKGROUND

The San Andreas fault system (SAFS) accommodates motion imposed by the northwestward movement of the Pacific plate relative to the North American plate (Atwater, 1970). The MFZ is the most northerly of three major southeast/northwest trending faults located approximately 40 km east of the San Andreas fault zone (Fig. 1). These three faults are, from northwest to southeast, the MFZ, the Healdsburg-Rodgers Creek fault zone (RCFZ), and the Hayward fault zone (HFZ) (Fig. 1). The MFZ is the least studied of these three fault zones.

Paleoseismic investigations such as this one provide us with a method to characterize Holocene fault behavior. Under optimum conditions, radiocarbon dating of earthquake-displaced sediments and overlying unaffected sediments can be used to provide estimates of the timing of prehistoric earthquakes. These investigations can also provide additional data to analyze seismic hazards, such as the slip rate and amount of slip per event.

The MFZ underlies several small but rapidly growing towns in the northern California Coast ranges, including the towns of Ukiah and Willits (Fig. 1). A large earthquake on the MFZ would endanger these populations as well as smaller towns, including Laytonville, Talmage,

Hopland, and Cloverdale, all of which have developed near or across fault segments of the MFZ (Fig. 1). A large earthquake would also endanger Highway 101, a major element of the transportation system in northern California.

Evolution of the San Andreas Fault System

The subduction of the west edge of the Farallon plate beneath the North American continent began 28 to 26 million years ago, marking the transition from an oblique convergent margin to a transform margin (Atwater, 1970). Plate reconstruction models suggest that since that time this transform margin has lengthened at a rate of 30–40 mm/yr as the Mendocino triple junction (MTJ) migrated northward to its current location off the coast of Mendocino in northern California (Atwater, 1970; Levander and others, 1998; Fig. 2). According to this model, the MTJ passed the latitude of the Ukiah area sometime during the Pleistocene (Atwater, 1970). The subduction of the Gorda plate north of the MTJ occurs along the Cascadia subduction zone (Fig. 2). Jachens and Griscom (1983) interpreted gradients in the magnetic field and isostatic residual gravity field to trace the leading edge of the Gorda plate up to 150 km inland.

The SAFS is located along the western edge of the North American plate (Castillo and Ellsworth, 1993). This system of parallel, right-lateral faults accommodates shear imposed by the northward motion of the Pacific plate relative to the North American plate (McLaughlin and Nilsen, 1982). This fault system, typically 80–90 km in width, relieves shear stresses north of the latitude of Santa Rosa by accommodating right-lateral movement on three major subparallel fault

Figure 2. Main features of the present day North American – Pacific plate boundary, including Mendocino Triple Junction (MTJ), and Riviera Triple Junction (RTC). (Modified from Baldwin, 1996.)

zones. These fault zones include, from west to east, the San Andreas, Maacama, and Bartlett Springs fault zones (Fig. 1).

Tectonic Motion of the San Andreas Fault System

In recent years, very long baseline interferometry (VLBI) has provided estimates of Pacific-North American plate motion (Clark and others, 1987). VLBI utilizes widely spaced radio telescopes to simultaneously record extragalactic radio sources. This process is repeated over time to estimate relative displacement between data points. This relative displacement is modeled as being largely accommodated by slip occurring on faults located between the Pacific-North American plate margin and the stable North American craton. Conclusions from a geodetic VLBI study by Ward (1990) indicate that relative Pacific-North American motion is approximately 46.8 mm/yr and that between 15 and 20 mm/yr of Pacific-North American motion is accommodated by faults east and north of the San Francisco Bay. Current slip rate estimates for the northern segment of the San Andreas fault account for a maximum of 23 mm/yr of slip (Baldwin, 1996; Prentice, 1989). Current slip rate estimates for the MFZ (9 mm/yr) and the Bartlett Springs fault zone (6 mm/yr) account for approximately 15 mm/yr of fault motion (Working Group, 1996). The remaining slip, of approximately 9 mm/yr, suggests either that current slip rate estimates are too low, or that significant strike-slip motion is accommodated on other faults.

The slip rates across the Maacama and Bartlett Springs fault zones were estimated largely by analogy from slip rates of the Hayward-Rodgers Creek and Concord-Green Valley fault zones

(Working Group, 1996). No study has provided geologic data to calculate the long-term slip rate for either fault zone.

A recent investigation by Cole and Hay (1998) included field mapping of offset Tertiary stream channels in the Foothills fault system of the western Sierra Nevada. According to the authors, results of this investigation indicate that the Late Cenozoic history of the Foothills fault system includes a significant component of dextral slip. The Cole and Hay investigation (1998) did not provide a slip rate. However, it may indicate that a significant component of dextral motion is accommodated by faults east of the Bartlett Springs fault zone.

Surface Expression of the Maacama Fault Zone

The MFZ was first identified in 1913 by Holoway as part of an investigation of the geomorphology of the Russian River (Pampeyan and others, 1981). As part of this investigation, Holoway described a line of “structural weakness” extending north from near Healdsburg to the Laytonville area (Pampeyan and others, 1981). The MFZ was named in 1951 by Gealey, who cited evidence of Quaternary movement along the fault in the Healdsburg quadrangle (Pampeyan and others, 1981).

The first comprehensive mapping of the MFZ was conducted in the 1970s by Harding-Lawson Associates (1977). This investigation utilized aerial photography review and limited ground reconnaissance to create a series of eight fault maps covering an area from southeast of

Hopland to northwest of Willits (Fig. 1). Several years later, investigations by Pampeyan and others (1981), and Upp (1989) included detailed mapping along the length of the MFZ. These investigations utilized aerial photography as well as extensive ground reconnaissance to identify geomorphic features typically associated with active faults. These geomorphic features include scarps, trenches, notches, ridges, offset streams, sag ponds, lineaments observed in bedrock, aligned springs, and contrasts in vegetation reflecting variations in the depth of ground water or soil differences across the fault zone. Many of these features are obscured by landslides south of the Ukiah Valley (Pampeyan and others, 1981). North of the Ukiah Valley, the MFZ displays fault traces that cross ridgetops, indicative of recently initiated tectonic activity (Pampeyan and others, 1981). This trend of more youthful appearing fault geomorphology to the north is consistent with the northward development of the MFZ south of the Mendocino triple junction (as modeled by Atwater, 1970).

In addition to the geomorphic features listed above, these investigations identified offset cultural features in the Ukiah and Willits areas that indicate active aseismic fault creep (Galehouse, personal communication, 1998). These cultural features include right laterally displaced curbs and sidewalks, and *en echelon* cracks in distressed pavements (Pampeyan and others, 1981; Upp, 1989).

Segmentation and Geomorphology of the Maacama Fault Zone

A study by the United States Army Corps of Engineers (1978) utilized the relationship between length of surface rupture and earthquake magnitude to calculate a maximum credible earthquake of M 7.5 for the MFZ. For this calculation, investigators assumed that 75 km, or one half of the 150 km mapped fault length, could rupture during a large earthquake. More recently, the Working Group (1996) defined three major fault segments of the MFZ, each capable of producing large-magnitude (M 6.9 or greater) earthquakes. As characterized by the Working Group (1996), these three segments consist of discrete, subparallel fault strands extending over 180 km, from less than 20 km northeast of Santa Rosa, in Sonoma County, to north of Laytonville in northern Mendocino County (segments H4, H5, H6 on Fig. 3). As proposed by the Working Group (1996), the southernmost fault segment of the MFZ spans 41 km, from near the northern end of the RCFZ to a 15° right bend at 123° longitude. The central segment of the MFZ trends northwest and spans 60 km northward from the 15° bend to 20 km south of Willits. The placement of this segment boundary is considered tentative and was defined largely by analogy to the Hayward fault, which apparently displays similar segmentation characteristics along linear portions of the fault (Working Group, 1996). North of the MFZ is the Garberville-Briceland fault (Fig. 3), which extends northward near the transition to the Cascadia subduction zone.

Castillo and Ellsworth (1993) examined more than a decade of contemporary microseismicity along the northern San Andreas fault system. Their study indicates that the MFZ is defined by discrete fault planes that dip 50°-70° to the northeast, compared with the near-

LEGEND

H3 RODGERS CREEK FAULT	C4 GREEN VALLEY FAULT	L05 WEST NAPA FAULT
H4 MAACAMA FAULT, SOUTH SEGMENT	C5 HUNTING CREEK-BERRYESSA FAULT	L08 COLLAYOMI FAULT
H5 MAACAMA FAULT, CENTRAL SEGMENT	C6 BARTLETT SPRINGS FAULT	GV04 GREAT VALLEY FAULT
H6 MAACAMA FAULT, NORTH SEGMENT	C7 ROUND VALLEY FAULT	
H7 GARBERVILLE-BRICELAND FAULT	C8 LAKE MOUNTAIN FAULT	

Figure 3. Simplified fault map showing the three segments of the Maacama fault zone. (Modified from Working Group, 1996.)

vertical orientations of the Hayward and Calaveras fault zones to the southeast. Castillo and Ellsworth (1993) interpret these data to indicate that the Maacama and Bartlett Springs fault zones formed during Cascadia subduction and are in the early stages of evolution toward the near-vertical orientations displayed by the older and more southerly Hayward and Calaveras faults. According to this analysis, the Maacama-Hayward fault system may eventually replace the North Coast and Peninsula segments of the San Andreas fault as the major fault between the Pacific and North American plates.

A recent seismic refraction study by Henstock and others (1997) was undertaken to study the connectivity of the three major fault zones making up the SAFS north of Santa Rosa in northern California: the San Andreas fault (SAF), the MFZ, and the Bartlett Springs fault zone (BSFZ). This investigation revealed that linear slices of the North American plate penetrate as much as 3.2 km (2 miles) into the mantle. The locations of these crustal offsets are in good agreement with mapped fault traces of the SAFS. These results suggest that these three fault zones in northern California are not connected at depth and provide additional constraints for future modeling of this complex system.

Historical Seismicity

The written record of earthquakes in some regions of northern California dates back to the early 1700's, when Franciscan missionaries colonized the west coast of North America (Wong, 1991). Earthquakes occurring prior to the development of seismograph instrumentation were

documented by local European immigrants near many Bay Area faults (Budding and others, 1991; Harding-Lawson Associates, 1977). However, north of San Francisco, the low population density precluded comprehensive reporting of earthquake events until later years. In the Ukiah area the historical record begins around 1850. Early documentation of earthquakes typically consists of descriptions of damage to domestic structures and includes only the largest earthquake events. Possibly the largest historical earthquakes in the region occurred in the Ukiah area on September 26, 1868, estimated magnitude VIII on the modified Mercalli intensity scale, and on October 8, 1869, estimated magnitude VIII on the Rossi-Forel intensity scale (Simon and others, 1978). These earthquakes are described as “very severe” and “severest shock ever felt” (Simon and others, 1978).

Increased accuracy of earthquake epicentral locations became possible in the 1930's, with the installation of seismograph stations in San Francisco (1931), Ferndale (1933), and Fresno (1935; Wong, 1991). However, Harding-Lawson Associates (1977) suggests that epicentral locations developed prior to about 1950 along the MFZ should be viewed as approximate, because of the relatively few seismograph stations in the area.

A significant increase in seismic activity began in the study area in 1959, shortly after workers finished construction of the Coyote Dam, located approximately 5 km north of central Ukiah and 1 km east of the MFZ. Immediately following the impoundment of Lake Mendocino, a M 3.6 earthquake was felt in the surrounding region. Several M 5.2 earthquakes were recorded

near Ukiah in 1962 and 1969. An analysis by Topozada and Cramer (1978) of the California Division of Mines and Geology indicates that both of these earthquakes, in addition to a M 4.5 earthquake in 1977, occurred after exceptionally large changes in the reservoir water level. Thus, several of the more recent moderate-magnitude earthquakes in the Ukiah area appear to correspond to rapid refillings of Lake Mendocino behind Coyote Dam. Empirical data from the same study used surface-rupture length to provide a conservative or “upper limit” estimate for a maximum credible earthquake (MCE) of M 7.5 on the Maacama. A seismicity map included as Figure 4 documents seismic activity from 1969 through 1991 (Fig. 4).

It is unclear whether surface rupture has occurred on the MFZ in historic time. Wesnousky (1986) associated surface ruptures with earthquakes greater than M 6.5: “...moderate events $M < 6.5$ may also generally be demonstrated to be the result of displacement along faults with mappable surficial traces, though surface ruptures are not commonly in evidence.” (p. 12,589) Based on the historical record, the United States Army Corp of Engineers (1978) estimated that seven moderate earthquakes, ranging from M 5.0 to M 5.5, have occurred on the Rodgers Creek and Maacama faults during the last 200 years. These earthquake magnitudes are well below the M 6.5 intensity level that is associated with surface rupture by Wesnousky (1986).

As previously mentioned, the largest earthquakes apparently occurring on the MFZ occurred in 1868 and 1869 in the Ukiah area. These earthquakes were assigned intensities of VIII on the modified Mercalli and Rossi-Forel scales, respectively. Assigning Richter or moment

Figure 4. Regional map of seismic activity from 1969 to 1991 on the Maacama fault zone and surrounding areas (the Geysers geothermal area was omitted for clarity). (Modified from Sydnor and Sowma-Bawcom, 1991.)

magnitudes to historic earthquakes on the MFZ is problematic. A previous investigation by Tuttle and Sykes (1992) assigned Richter or moment magnitudes to historic earthquakes by correlating shaking intensities of recent large-magnitude earthquakes with shaking intensities recorded in newspaper damage reports of 19th century earthquakes. Because no large-magnitude earthquakes have occurred in the Ukiah area in recent years, this method of analysis can not be used to evaluate historic earthquakes. However, based on the apparent intensities of these earthquakes, it seems possible that either or both of these earthquakes may have resulted in surface rupture of the MFZ.

Recent Seismicity

An analysis of approximately 20 years of seismicity indicates a pattern of dispersed microseismicity approximately 12 km in width along the length of the MFZ (Ellsworth and others, 1982). Earthquake hypocenters beneath the MFZ have been located as deep as 12-15 km beneath the towns of Laytonville and Willits, and as shallow as about 7 km near Clear Lake (Castillo and Ellsworth, 1993; Fig. 1). Focal-mechanism solutions of seismicity across the MFZ commonly display oblique-reverse slip motion (Castillo and Ellsworth, 1993). This contrasts with focal-mechanism solutions of seismicity on the HFZ, which display a more pronounced component of strike-slip motion. These results are interpreted to reflect the more advanced development of the HFZ with respect to the MFZ (Castillo and Ellsworth, 1993).

A paleoseismicity study conducted by Budding and others (1991) analyzed the lateral dispersion of epicenters across the Rodgers Creek fault zone. Microseismic activity in this zone is characterized by epicenters located close to the main trace north of Santa Rosa, in contrast to a broad zone of epicentral locations south of Santa Rosa (Fig. 4). The authors conclude that the southern segment of broad seismicity represents a locked segment that releases during mainshock rupture. However, this hypothesis does not apparently apply to the MFZ, where several areas that display a broad pattern of seismicity are known to display aseismic or microseismic creep. Several investigations of on the RCFZ have identified no aseismic creep (Budding and others, 1991). These apparent differences in seismic behavior may reflect the two distinct geologic environments that the fault zones displace. These environments are examined below.

Moment Magnitude for the MFZ

An empirically derived relationship between moment magnitude and rupture area can be used to approximate the potential magnitude of a seismic event. The calculation of moment magnitude (M_w) utilizes physical characteristics of a fault zone or segment, including the rupture length at depth, assumed to equal 1.3 times the surface rupture length (Wells and Coppersmith, 1994) and the rupture width, assumed to be 12 km for the MFZ (Working Group, 1996). These fault characteristics can be used to derive an area of rupture that is applied in the empirical relationship by Wells and Coppersmith (1994):

$$M_w = 4.07 + 0.98 \log a, \text{ where } a = \text{area in km}^2.$$

The southern extent of the MFZ, as defined by the Working Group (1996), extends approximately 40 km south from a 15° bend in the main fault trace. Currently, the moment magnitude assigned for the southernmost segment is Mw 6.9 (Working Group, 1996). The Working Group (1996) has assigned the central segment of the MFZ, which has a reported length of 60 km, a moment magnitude of Mw 7.1. The northern segment, which has a reported length of 81 km, also has been assigned a moment magnitude of Mw 7.1 (Working Group, 1996). Using the above formula, it was calculated that a rupture of the entire 181 km of the fault zone (including the southern, central and northern segments) would result in a moment magnitude of Mw 7.3.

Geologic Setting

The northern California Coast Ranges are underlain predominantly by rocks of the Franciscan Complex, which form several distinct, northwest-trending belts, between the Coast Range Ophiolite on the east and the San Andreas fault on the west (Orchard, 1979). The Franciscan Complex has been interpreted to represent the remnants of an accretionary wedge formed by the underplating of sediments that were scraped off during subduction of the Farallon plate beneath the western margin of North America (Hamilton, 1969). Wakabayashi (1992) used regional geology and comparisons to modern arc-trench systems to suggest that strike-slip faulting associated with oblique subduction took place east of the Franciscan Complex in the vicinity of the magmatic arc. According to Wakabayashi (1992), offset of conglomerate suites, as well as other field relations, indicate that large strike-slip displacement (>500 km) did not occur within the Franciscan Complex during subduction.

Rock types that comprise the Franciscan Complex include pervasively sheared sandstone, shale, and serpentinite, and lesser amounts of volcanic rocks, chert, and limestone (Irwin, 1991) of Jurassic to Eocene age. Bailey and Irwin (1959) subdivided the Franciscan Complex into three fault-bounded, northwest-southeast trending belts, based largely on metamorphic grade and associated rock types: Coastal belt, Central belt, and Eastern belt. The project site is located near the boundary between the Coastal and Central belts. Orchard (1979) identified Central belt rock assemblages, including the Low Gap Road melange and the Lookout Peak graywacke, west of the Ukiah Valley and the project site. Mapping by Pampeyan and others (1981) and McLaughlin (1978) indicates that the MFZ cuts through Central belt rocks north of the project site near Laytonville and south of the project site near the Geysers area (Fig. 5). These observations suggest that a significant length of the MFZ displaces rocks along the western side of the Central belt (Fig. 5).

The Central belt of the Franciscan Complex consists predominantly of melange. The Central belt melange is metamorphosed to prehnite/pumpellyite-facies grade (Orchard, 1979), with occurrences of prehnite more common in the western areas of the Central belt (Jayko, personal communication, 1998). The melange matrix consists of argillite, lithic graywacke, and aquagene tuff and contains blocks and slabs of resistant graywacke, greenstone, chert, limestone, ultramafic rock, blueschist, eclogite and amphibolite (Blake and others, 1995). The Coastal belt is characterized by zeolite-facies metamorphism (Orchard, 1979). Rocks of the Coastal belt

Figure 5. Geology of Northern California. Modified by the author from Blake and Jones (1974), Jennings (1977), and Sydnor and Sowma-Bawcom (1991).

Franciscan Complex consist of graywacke and shale with minor amounts of limestone, chert, and volcanic rocks.

South of the MFZ, the RCFZ displaces rocks of very different composition from the Franciscan Complex. The RCFZ cuts through the Late Miocene to Pliocene Sonoma Volcanics, the Late Miocene Petaluma Formation, and the Plio/Pleistocene Glen Ellen and Huichica Formations (Chin and others 1993). The Sonoma Volcanics contain ash, andesite, dacite, rhyolitic flows, and associated sedimentary rocks. The Petaluma Formation consists predominantly of claystone, siltstone, and mudstone. The Glen Ellen and Huichica Formations consist of fluvial gravel, silt, sand, and clay, with tuff interbeds (Chin and others, 1993).

The communities of Ukiah and Talmage are located in the Ukiah Valley, a northward-trending pull-apart basin in Mendocino County, California (McLaughlin and Nilson, 1982). The Russian River drains the Ukiah Valley and the surrounding Coast Ranges. Large volumes of Plio-Pleistocene fluvial and lacustrine sediments, known informally as the Ukiah beds, underlie much of the Ukiah Valley. The Ukiah beds, formed from the erosion of surrounding Franciscan rocks, consist of siltstone, sandstone, and conglomerate (Orchard, 1979; Upp, 1989). Locally, the Ukiah beds consist of steeply dipping, well indurated to highly weathered conglomerate beds. Some resistant outcrops of the steeply dipping gravel display orange surface staining, while other outcrops are a distinct blue-gray color (Fig. 6). The lateral and vertical extent of the Ukiah beds has not been determined.

Figure 6. Photograph of the Ukiah beds, near a right lateral bend in Howell Creek, northeast of the trenching site. Photograph taken by the author in August 1996. View is to the northwest.

Previous Investigations

Upp (1989) conducted a detailed paleoseismic investigation at two sites located on the north segment of the MFZ near the town of Willits (Fig. 5). This study included trenching and radiocarbon dating of sediments near the crest of the Laughlin Range, approximately 7 km southeast of Willits, and in the Upp Creek drainage near Twin Lakes, approximately 2 km northwest of Willits. Two exploratory trenches were excavated across closed depressions at the Laughlin Range site. Sediments exposed at the Laughlin Range site record offsets from two or three large magnitude earthquakes. Two detrital charcoal samples were collected from trench sediments and submitted for radiocarbon dating. These included one sample located about 1.5 m below ground surface, in sediments clearly truncated by the oldest faulting event, and a second sample located about 2.5 m below ground surface and approximately 7 m east of the fault zone. Radiocarbon dating of the two available charcoal samples indicated that the oldest earthquake event occurred sometime after $16,200 \pm 150$ years BP, with one episode possibly occurring after deposition of the second charcoal sample, or within the past $8,300 \pm 95$ years (Upp, 1989). Several soil horizons mantling the fault zone apparently post-date all fault motion. Three exploratory trenches were excavated at the Upp Creek site in a drained sag pond near Twin Lakes. Upp (1989) encountered evidence of a single faulting event at the Twin Lakes site along Upp Creek. However, no organic material suitable for age dating was found in displaced stratigraphy at the site. Radiocarbon dating of bulk samples of apparently undisturbed colluvial soils at both sites suggest that fault movement has not occurred in the past $1,400 \pm 70$ years at the Laughlin Range site or in the past $2,000 \pm 60$ years at the Twin Lakes site (Upp, 1989).

In 1992, Prentice conducted a paleoseismic investigation on the central segment of the MFZ in Talmage, California (Galehouse and others, 1992). Prentice concluded that a large earthquake caused surface folding, but no surface rupture, some time after 1500 AD. This interpretation is based on radiocarbon ages of a peat layer at the base of a folded sedimentary sequence overlying the fault (Prentice, personal communication, 1996). Radiocarbon analysis of unfolded sediments did not provide a minimum age for the timing of this event.

Ongoing aseismic creep has been viewed as the minimum possible long-term slip rate (Upp, 1989; Williams and Jones, 1995). Galehouse (personal communication, 1998) recently calculated current creep-rate estimates of 6.5 mm/yr in Willits and 3.8 mm/yr in Ukiah, using theodolite measurements of right-laterally offset roadside curbs and other offset cultural features. Because the observed creep rate has been variable over many months or years, slip-rate estimates are based on more than 6 years of repeated measurements in Willits and over 5 years of measurements in Ukiah (Galehouse, personal communication, 1998).

In a study by Bilham and Bodin (1992), slip rates of San Francisco Bay area faults were modeled as frictionless zones of weakness in an elastic plate of uniform thickness. Slip rates were found to vary according to the modeled connectivity with adjoining fault zones. The authors developed various models that utilized current slip-rate estimates for the Hayward, Rodgers Creek, and Maacama fault zones. The model that most accurately reflected current slip-rate estimates connected the Calaveras, Hayward, and Rodgers Creek faults, leaving the MFZ

unconnected to the Rodgers Creek fault. This model provided a slip rate estimate of 10.1 mm/yr on the MFZ.

Utilizing the creep rate provided by Galehouse (personal communication, 1998) as a minimum slip rate, and the maximum slip rate modeled by Bilham and Boden (1992), the actual slip rate for the Maacama fault zone is probably between about 7.0 and 10.1 mm/yr. This is consistent with a slip rate of 9 ± 2 mm/yr currently assigned to the MFZ by the Working Group (1996). However, geologic investigations have not provided an independent slip rate for the MFZ.

Rodgers Creek Fault Zone Paleoseismicity

The RCFZ extends south from near the southern end of the MFZ (near Santa Rosa) to San Pablo Bay, immediately north of the HFZ (Fig. 5). A paleoseismic investigation by Budding and others (1991) exposed offset channels in late Holocene alluvial deposits on an apparently locked segment of the RCFZ. Results of that study provided a minimum slip rate of 2.1 to 5.8 mm/yr for the past 130 years, a maximum “preferred” recurrence interval of 248 to 679 years, and a surface offset of $2 +0.3, -0.2$ m during the most recent event. Aseismic creep is not currently displayed on the RCFZ. The most recent recurrence estimate for the RCFZ fault is 230 years (Working Group, 1996).

Hayward Fault Zone Paleoseismicity

As mentioned previously, current estimates of several seismic parameters of the MFZ, including slip rate, recurrence interval, and segmentation, have been defined by analogy to the HFZ (Working Group, 1996). These estimates reflect the belief that these fault zones release strain by similar mechanisms, as part of a common regional tectonic system. The following discussion of Hayward seismicity is included due to the paucity of geologic data for the MFZ and to emphasize the relationship between the MFZ and the HFZ.

A recent paleoseismic investigation conducted on the Hayward fault zone in Union City, California measured offsets of alluvial deposits (Lienkaemper and Borchardt, 1996). Results of this study provided a minimum geologic slip rate of 8.0 ± 0.7 mm/yr over the past 8,270 years. The authors considered this slip rate a minimum estimate because of evidence from an earlier investigation, which identified fault deformation distant from the fault zone (Lienkaemper and others, 1991).

In other investigations, creep rates between 5 mm/yr and 10 mm/yr have been identified at sites along 60 km of the Hayward fault zone, southeast of San Pablo Bay (Williams and Jones, 1995). It is not known whether fault creep affects the rate of elastic strain accumulation across the HFZ (Williams and Jones, 1995). The most recent estimate of the recurrence interval for the northern and southern segments of the Hayward fault is 210 years (Working Group, 1996).

THIS INVESTIGATION

Site History and Geomorphology

The project site is located at an elevation of approximately 195 m on the lower fluvial terrace of Howell Creek. Howell Creek is an ephemeral stream that originates approximately 5 km east-southeast of the project site, at an elevation of about 670 m in the Mayacmas Mountains. During wet periods, Howell Creek directs runoff from the east into the Ukiah Valley where it meets the Russian River, approximately 3 km southwest of the project site (Fig. 7).

No surface rupture or folding features are displayed across the surface of the lowest Howell Creek terrace. However, tectonic motion is illustrated locally by a linear drainage and offset terrace riser immediately south of the trenching site and by a prominent pressure ridge, about 30 m in height, approximately 0.5 km north of Howell Creek (Fig. 7). According to Olive Twining, current owner of the project site property, the uppermost deposits on this terrace were disturbed by sheep and cattle grazing beginning by about 1890 and by vineyard cultivation in the 1930's (personal communication, 1996). In addition, following flooding of Howell Creek in 1965, a levee was constructed along the north side of the floodplain. According to Dave Sagehorn, a long-time Ukiah resident, flooding of Howell Creek also occurred in 1935, and the site was grazed by sheep or cattle from about the 1860s to the 1920s (personal communication, 1996). Currently,

Figure 7. Project site vicinity fault map. Modified from Upp (1989). Map features include saddle (s), notch (n), sag pond (sp), linear drainage (ld), bench (b), swale (s), creep (c), pressure ridge (pr), marsh (m), linear valley (lv), and shutter ridge (sr). Faults are shown as solid lines, or dotted where concealed by Holocene deposits. Scarps are solid lines with hatchures on down side. Roads are shown as dashed lines, houses as solid dots. Pressure ridge near the top of the figure is shown in Figure 14.

the area supports sparse vegetation and is used to graze cattle. Numerous ground squirrels have disturbed shallow sediments at the site.

Several features that are characteristic of fault displacement can be identified on aerial photographs (Fig. 8). These features located southeast of the project site include a saddle, a notch, and a sag pond (Fig. 8). Upp (1989) mapped these features and aligned springs as a partially obscured fault segment subparallel to the main fault trace of this investigation (Fig. 7). Near the north end of this fault segment a series of three or more prominent terraces, located approximately 100 m northeast of the project site, occur near a right-lateral bend in Howell Creek upstream from the trench site.

Methodology

Based on a survey of available black and white aerial photographs (scale = 1:12,000) of the Ukiah area, four sites were selected as potential trenching locations. During field reconnaissance of these sites, tectonic features noted during the aerial photograph review were identified and examined. Potential sites were examined for onsite or near-site fault features, late Holocene deposition blanketing a fault trace, and site access. Each site was informally ranked based on these parameters.

Figure 8. Stereo aerial photographs of the Howell Creek drainage and the project site area. Photographs show a linear drainage (ld) south-southwest of the project site. A lineation (designated near both ends by l) east of the linear drainage is characterized by a saddle (s), a notch (n), and a sag pond (sp)(Upp, 1989; see Fig. 7). Ub indicates an outcrop of Ukiah beds, shown in Figure 6. Aerial photographs taken on September 6, 1989; scale 1:12,000.

The selected project site is adjacent to Howell Creek, an intermittent stream located approximately 3.0 km south of Talmage and approximately 5 km southeast of Ukiah (Fig. 7). The Howell Creek site was chosen because of the following site-specific conditions: (1) Holocene deposition over the Maacama fault trace provided sediments to record prehistoric earthquakes; (2) the fault trace could be accurately located across the Howell Creek floodplain by projecting to the northwest from an offset terrace riser; and (3) site access was granted by Olive Twining, the property owner.

Trenches 1 and 2 were excavated by backhoe in July and August of 1996, respectively, at approximate right angles to the projected fault trace (Fig. 9). The fault trace orientation (N26°W) was interpreted from maps by Pampeyan and others (1981) and Upp (1989), and from aerial photographs. The trenches were extended to approximately 30 m and 15 m in length, respectively, at a maximum depth of about 3 m (trench depth was limited by a shallow ground water table). Trench 1 was located in the approximate center of the Howell Creek floodplain. Trench 2 was located on the south side of the flood plain near the terrace riser (Fig. 9). Trench 2 was excavated following logging of Trench 1 in an attempt to corroborate the faulted stratigraphy observed in Trench 1 and to provide additional charcoal for radiocarbon age dates.

Following excavation, each trench was cleaned and gridded at one meter by one-half meter increments. Section corners were located by tape measure relative to two horizontal base line strings placed using a water level. Exposed strata were documented in detail on 8-1/2 by 11-

Howell Creek Trench Site

Figure 9. Topographic map by the author of the Howell Creek trench site near Talmage, California. Linear fault trace shown oriented to the northeast is the inferred main trace of the Maacama Fault. Howell Creek is represented at the top of the diagram.

inch grid paper at a scale of 20:1. Composite logs of Trench 1 are contained in Plate 1. Composite Logs of Trench 2 are contained in Appendix A.

Following logging activities, each trench was photographed using a 35mm camera outfitted with 20mm wide-angle lens and mounted on an aluminum frame. The frame made it easy to orient the camera perpendicularly to and at a constant distance from the trench walls. Typically, each exposure encompassed a one meter by one-half meter section of the trench wall, although often two exposures were required adjacent to the shores which had been left in place. Exposures from Trench 1 were digitized by scanning and assembled using Adobe PhotoShop and CorelDraw software. (See Plate 5 for a photomosaic of Trench 1.) Currently, workers at the United States Geological Survey are developing quality-control procedures to enable trench logging on computer-enhanced color photographs. For the purposes of this investigation, trenches were photographed for documentation and display purposes only.

The project site was surveyed relative to an arbitrary datum using a TOPCON theodolite (accurate to at least ± 2.5 mm in 1 km double-run leveling), and electronic distance meter (EDM) provided by San Jose State University. The goals of the site survey were to locate the trenches accurately relative to surrounding landmarks, although only Trench 1 had been excavated at the time of the site survey. The location and elevation of Trench 1 was tied into the project site base map by surveying grid-corner nails within the trench. A total of 137 data points, collected on August 5 and 6, 1996, were used to construct the site map (Fig. 9). Elevation data were gridded

and mapped using Golden's SURFER software. Smoothing of several contours was conducted in AutoCad software.

In order to determine absolute ages of sediments exposed in the trench walls, detrital charcoal was sampled at various locations in both trenches. A total of 15 detrital charcoal samples was collected from both trenches: 7 samples from Trench 1 and 8 samples from Trench 2. Prior to removing a sample, it was described in detail and located on the trench log. Samples were then removed from the trench wall using a clean stainless steel pocket knife (cleaned between samplings), and samples were wrapped in aluminum foil for transport to an analytical laboratory. Samples of adequate size were split into duplicate samples for analysis by independent laboratories. The sample-naming convention used for all samples includes the trench number (T1 or T2), year sampled (1996), panel number, section number, side of trench (north="N" or south="S"), and the unit number (samples taken from the same sample section were differentiated using "A" and "B" designations). Sample locations are indicated on trench logs in Plate 1.

Site Stratigraphy

Both trenches exposed 1 to 2 m of fine-grained overbank deposits that overlie coarse fluvial deposits of Howell Creek. Overbank deposits consist of massive medium- to fine-grained sand and silt. Occasional pebble- to cobble-size clasts are incorporated into the fine-grained overbank deposits. The underlying coarse channel deposits consist of two distinct stratigraphic units that appear to be laterally continuous beneath the Howell Creek floodplain. These units were

delineated based on differences in clast size, clast composition, matrix color, and matrix composition. The upper channel deposits of Trench 1 were further subdivided into three units near the fault, based on differences in clast size and inferred depositional environment. The upper channel deposits are generally poorly sorted, but display occasional well-sorted pebbly and sandy interbeds. Deposits that characterize the units are described in detail below. Unit numbers are given for reference with trench logs in Plate 1 (Trench 1 logs) and Appendix A (Trench 2 logs). Figures 10 and 11 are photomosaics of faulted sediments on the north and south walls of Trench 1, respectively.

Overbank deposits of Unit 10 consist of one to two m of light-brown silt and fine sand and represent deposition in a low-energy fluvial environment (Figs. 10 and 11). These deposits appear massive and do not display substantial lateral or vertical textural variability. Recent bioturbation in the form of large burrows was encountered in Trench 2 to a depth of approximately 0.5 m. Ground squirrels, common in the project site area, were observed in surface burrows and are the presumed excavators. Sediment-filled burrows, or krotovina, were noted at various depths throughout this unit. Scattered pebbles and cobbles, typically consisting of metasedimentary rock, were encountered in the uppermost sediments of this unit (Plate 1). Abundant roots and rootlets were encountered in the uppermost 0.5 m of this unit.

Figure 10. Photomosaic of Panels 14 and 15 of the north wall of Trench 1. Section designations are left of Panel 15. The fine-grained unit in Section A is Unit 10; brown coarse-grained units include (top to bottom) 20, 24, and 28; greenish silty gravel of Unit 30 is shown in Sections D and E of Panel 15. Individual panels are 1 m in width. Sections A-D are $\frac{1}{2}$ m in height. Strings used for gridding are visible near the edges of some photographs.

Figure 11. Photomosaic of Panels 14 and 15 of the south wall of Trench 1 (image reversed to allow comparison with Figure 10). Section designations are left of Panel 15. The fine-grained unit in Section A is Unit 10; brown coarse-grained units include (top to bottom) 20, 24, and 28; greenish silty gravel of Unit 30 is shown at the bottom of Section D, Panel 15. Individual panels are 1 m in width. Sections are $\frac{1}{2}$ m in height. Strings used for gridding are visible near the edges of some photographs.

Underlying the fine-grained overbank deposits are 1 to 2 m of coarse channel deposits of Unit 20, representing deposition in a relatively high-energy fluvial environment (Figs. 10 and 11). These deposits are typically poorly sorted, with subrounded to subangular clasts ranging to 35 cm in diameter. Clasts typically include siltstone and sandstone, and orange-weathered conglomerate, possibly derived from the Ukiah beds. Less abundant clasts include red and green chert and actinolite schist, presumably of Franciscan origin. A distinctive gravel bed in the fault zone of Trench 1 displayed air voids between angular clasts in fault-disrupted sediments (Figs. 10 and 11). Discontinuous, thin, pebbly beds occurred near the exposed fault in Trench 1. Fine-grained matrix material within this unit typically consisted of brown to gray (10YR 5/3) moderately well-indurated silt to coarse sand. In places the matrix appeared very similar in texture and color to overlying floodplain deposits.

Unit 20 was subdivided into three units near the fault in Trench 1, including – from youngest to oldest – Unit 20, Unit 24, and Unit 28 (Figs. 12 and 13). Deposits of Units 20 (described above) and 28 are virtually indistinguishable in texture and composition. Unit 24 separates these units near the fault zone. Fluvial deposits of Unit 24 are finer in texture than adjacent deposits and typically consist of brown to gray, medium-to coarse-grained sand interbedded with rounded to subrounded, pebbly gravel. These deposits are poorly stratified and poorly imbricated and represent deposition in a lower energy environment than adjacent units.

Figure 12. Log of faulted north wall of Trench 1 shows Howell Creek stratigraphy and fault geometry. The pink stratum (Unit 24) is a fault-offset lens of sand with pebble-sized gravelly interbeds. Vertical rectangles are areas obscured by trench shores. Dotted/dashed lines are inferred contacts behind shores. Section designations are left of Panel 16.

Figure 13. Log of faulted south wall of Trench 1 shows Howell Creek stratigraphy and fault geometry (image reversed to allow comparison with Figure 12). The pink stratum (Unit 24) is a fault-offset lens of sand. Vertical rectangles are areas obscured by trench shores. Dotted/dashed lines are inferred contacts behind shores. Letters (A-E) are Section designations. Triangle in Section D, Panel 15, is location of charcoal sample T1-96-15DS-20A.

Exposed from the base of Unit 20 to the trench floor was a cobble-sized (Trench 1) to boulder-sized (Trench 2) gravelly unit of unknown thickness (Unit 30). Cobbles of this unit are typically poorly indurated, rounded to subrounded, siltstone and fine sandstone. This unit appears similar in clast composition to weathered Ukiah beds exposed in an outcrop approximately 100 m upstream from the project site (Fig. 6). In addition, interclast matrix of this unit, consisting of silt- to clay-sized particles, is characterized by a distinct olive-green color (5Y 7/3), similar to the color (5Y 5/3) of weathered Franciscan identified at the Laughlin Range site by Upp (1989). Based on these observations, it appears likely that this unit consists of the Ukiah beds. Blue discoloration of fine-grained, interclast matrix was encountered in both trenches around roots and rootlets, below the water table, about 2 m below the ground surface at the time of this study.

Fault Exposure and Geometry

Both the north and south walls of Trench 1 display a narrow fault trace in the lowermost Unit 30 gravel and a widening-upward fault zone in Unit 20 gravel. The fault zone in Unit 20 is characterized by apparently rotated gravel clasts. The fault zone does not continue through the overlying deposits of Unit 10 suggesting that the unit was deposited after the most recent surface-rupture event. Strata across the fault zone appears displaced by up to 0.5 m of vertical separation.

Vertical separation of bedding can be caused in a pure strike-slip environment by lateral juxtaposition of undulating or inclined bedding. However, Howell Creek sediments appear tectonically uplifted on the west side of the fault. This interpretation is based on two observations.

First, the vertical separation of all the units exposed in the trench is consistent with the upward displacement on the west side of the fault (Figs. 10 – 13, Plate 1, Appendix A). Second, westerly uplift is suggested by a small bench located on a ridge immediately south of the trenches. This bench is reflected as a flat area on the southern edge of the site topographic map (Fig. 9). A small pressure ridge, located approximately 3 km north of the project site near the site of the Prentice investigation (Galehouse and others, 1992), provides an example of localized uplift on the MFZ (Fig. 14).

A comparison of the amount of apparent vertical separation in Unit 30 and 24 suggests that the displacement of Unit 30 was apparently greater than Unit 24 (Figs. 12 and 13). This may indicate that Unit 30 was fault-displaced prior to the deposition and subsequent faulting of the overlying coarse channel deposits. Prior faulting is also suggested by the blunt morphology of the uplifted southwestern side of Unit 30 on the north wall of Trench 1 (Panel 15, Section D on Figs. 10 and 12). This blunt boundary is located near the top of the uplifted side of Unit 30 (north wall), where an angular wedge would be expected if a single rupture had occurred through exposed sediments at the site. This morphology suggests the following scenario: Unit 30 was faulted to create a scarp that was subsequently eroded to a height of approximately 0.25 m and draped by coarse channel deposits. A second faulting event occurred sometime later, again faulting Unit 30, as well as overlying deposits.

Figure 14. Photograph of a small pressure ridge located approximately 3 km northwest of the Howell Creek project site. Photo taken by the author in June 1996. View is to the northwest.

The strike of the Maacama fault segment across the Howell Creek drainage is approximately N22W. The strike of the fault was measured by sighting down the surface projection of the fault plane exposed in both trenches. This trend, when extended to the south, intersects a break in the slope that forms a bench located immediately south of the trenches (Fig. 9). This trend is consistent with lineaments of the MFZ as mapped by Pampeyan and others (1981) and Upp (1989). The fault plane exposed in Trench 1 appears to dip to the southwest between approximately 32 degrees on the north wall and 42 degrees on the south wall.

Evaluation of Fault Offset

An examination of the north wall of Trench 1 (Fig. 10) reveals that the uppermost gravel of Unit 28 contains a distinct coarse gravel bed characterized by gray, subangular to subrounded clasts. However, this coarse gravel bed is not observed on the south side of the trench (Fig. 11), suggesting that even prior to faulting, the gravel bed on the north wall (Fig. 10) did not extend as far south as the width of the trench. Thus, if right-lateral displacement had occurred that was larger than the 1 m width of the trench, then the north trench wall (Fig. 10) would show the coarse gravel bed northeast of the fault break juxtaposed with finer deposits observed in the south trench wall (Fig. 11). Because this is not the case, it appears that coseismic near-surface fault motion was probably less than about 1 m, suggesting that only one earthquake ruptured datable sediments at the project site.

However, this estimate is not viewed as a maximum coseismic slip. During an investigation at Pallett Creek on the SAF, Verosub (1992) observed non-brittle, off-fault displacement of up to 350%. Possible off-fault displacement was not evaluated at Howell Creek. In addition, measured coseismic surface slip is typically about half of the maximum surface displacement for an event (Wells and Coopersmith, 1994). Using the estimate of 1 m of coseismic displacement and the relationship by Wells and Coopersmith (1994), a surface displacement of 2 m for the earthquake at Howell Creek is derived. This estimate is in agreement with the current 2.0 m estimate of coseismic slip for the MFZ by the Working Group (1996).

Radiocarbon Dating

The method of radiocarbon dating is based on the decay of the radioactive isotope ^{14}C , which forms in the Earth's upper atmosphere and is absorbed along with ^{12}C and ^{13}C by living organisms. Tissues within organisms typically maintain a relatively constant ratio of ^{14}C to ^{12}C until death, when unstable ^{14}C atoms begin to decay to ^{14}N . Over time, the ratio of stable ^{12}C to unstable ^{14}C contained in the organism increases exponentially. These carbon isotopes can be individually counted in a sample by accelerator mass spectrometry. The radiocarbon age of a sample is determined by using a known decay rate for ^{14}C , and assuming initial atmospheric concentrations of ^{14}C and ^{12}C . However, because the atmospheric carbon isotope ratio has not remained stable over time, radiocarbon ages reported by a laboratory must be calibrated to calendar ages. In recent years, radiocarbon dating of tree rings of known ages has been used to

develop calibration curves for prehistoric atmospheric carbon concentrations, providing a basis for converting radiocarbon ages to calendar years.

Radiocarbon ages were calculated using the international standard half-life of 5568 years established by Libby in 1963, with 1950 as the reference or zero age (Murphy and others, 1979). Lawrence Livermore National Laboratory (LLNL) and University of Arizona (UA) converted radiocarbon ages to calendar years (BC/AD) and years before present (BP) using software by Stuiver and Reimer (1993) (CALIB 3.0.3c and CALIB 2.0, respectively). Prehistoric concentration curves of ^{14}C were calculated by Stuiver and Reimer (1993) for the time interval AD 1950 through 6000 BC, using average results from Belfast and Seattle laboratories. Concentrations of ^{14}C for the AD 1950 through 5000 BC interval, spanning all laboratory dates reported in this investigation, are based on dendrochronologies obtained from Irish oak (Belfast) and German oak/Northwest Pacific sequoia or Douglas Fir (Seattle). In addition, because carbon isotope fractionation occurs in plants during photosynthesis, radiocarbon ages were normalized by both laboratories using the delta ^{13}C ($^{13}\text{C}/^{12}\text{C}$) values reported in Table 1. These values reflect the measured abundance of ^{13}C for samples analyzed at UA, and an assumed delta ^{13}C abundance of – 25 per mil for samples analyzed at LLNL. Converted radiocarbon ages were calculated by CALIB 3.0.3c using both “Intercept Method” and “Probability Method.” Probability method results calculate the likelihood that the actual age of a sample may fall within a reported range. Probability method results using 2-sigma probabilities, indicating a minimum 95 percent confidence level, are reported below in years BP. LLNL and UA laboratory reports are included

in Appendix B. Weighted averages of several statistically identical radiocarbon ages (where reported uncertainties overlap) were calculated by the author using CALIB 3.0.3c (Stuiver and Reimer, 1993).

This investigation utilized measurements made by accelerator mass spectrometers (AMS) located at LLNL, in Livermore, California and at UA, in Tucson, Arizona. Eight charcoal samples were selected for analysis by LLNL. Two of these samples were split into duplicate samples. These duplicate samples were sent with four additional samples for AMS analysis at UA. Duplicate radiocarbon analysis provides independent corroboration of radiocarbon results.

Radiocarbon dating was conducted first by preparing the samples in the laboratory and second by analyzing the radiocarbon ages derived by each laboratory. Sample preparation was a two-step process: first, the sample was cleaned of impurities and heated; second, the residual carbon in the form of CO₂ was converted to graphite for dating. The cleaning was conducted at LLNL on December 9, 1996. Laboratory employees conducted the cleaning process at UA and the graphite conversion at both laboratories. After cleaning 11 samples were large enough to analyze.

Radiocarbon ages derived from detrital charcoal have several inherent limitations. For example, the age of the charcoal can be significantly older than the timing of deposition. False older ages can be caused by deposition of charcoal long after combustion, bioturbation, which can

move datable detritus stratigraphically upwards into younger deposits, fluvial reworking, which can move older detritus into younger deposits, deposition of charcoal derived from the combustion of very old trees, or a combination of these mechanisms. Because of these uncertainties, the youngest reported age of a unit is sometimes considered to best represent the age of the unit. However, several mechanisms can also create false younger ages. False younger ages can be caused by bioturbation, which can displace charcoal downward into underlying sediment, sampling of burned or decayed root matter, unrecognized rootlets in a sample, or contamination by organic material in percolating water (Murphy and others, 1979).

RESULTS AND CONCLUSIONS

Radiocarbon Ages of Stratigraphic Units

Radiocarbon ages for samples are reported from oldest to youngest below; first, for the gravelly channel deposits of Units 20, 24, and 28 (referred to collectively as Unit 20 in the following section), and second, for the fine-grained overbank deposits of Unit 10. Because Unit 30 contained no datable material, it is not discussed in this section. Sample ages are presented below in Table 1; Plate 1 and Appendix A show sample locations; Appendix B contains laboratory reports and results from weighted average calculations.

Unit 20: A total of five detrital charcoal samples was analyzed from Unit 20 channel deposits, including three samples from Trench 1 and two samples from Trench 2. T1-96-15DS-20A, collected from near the base of Unit 28 in Trench 1, and T2-96-7CS-20A, collected from near the top of Unit 20 in Trench 2, provided statistically equivalent radiocarbon ages. However, T1-96-15DS-20A, analyzed at both laboratories, provided two similar but not statistically equivalent radiocarbon ages. Because it is not clear which reported radiocarbon age most accurately represents the age of the split sample, both radiocarbon ages from T1-96-15DS-20A as well as the third radiocarbon age from T2-96-7CS-20A were used to calculate a weighted average age of $5,170 \pm 130$ years BP. T2-96-7CS-20B, collected from near the top of Unit 20 in

Trench 2 (adjacent to T2-96-7CS-20A), or about 1.5 m below ground surface, provided an age of $6,285 \pm 185$ years BP.

T1-96-8DS-20A, collected from near the bottom of Unit 20 in Trench 1, provided the youngest reported age, of 155 ± 155 years BP. As mentioned above, false younger ages can be caused by a number of factors. Of the possible modes of error, bioturbation may be the least likely, due to nearly 1 m of gravelly channel deposits overlying the sampled location. In addition, no evidence of bioturbation was identified in this unit. Because each sample was carefully screened in the field and at the laboratory prior to analysis, it also is unlikely that the sample contained a significant amount of rootlets or that a root was sampled. Contamination by organic material in percolating water, also seems unlikely, as none of the other samples at similar depths appear to be impacted by young organics. For these reasons, the youngest reported age of 310 years BP is considered to most accurately represent the age of the channel deposits of Unit 20.

The minimum age of a surface-rupture earthquake can be obtained by the dating of unfaulted sediments overlying faulted sediments. However, because the youngest radiocarbon age of this investigation is associated with the lowermost datable unit, this investigation cannot provide a minimum age to further constrain the timing of this event.

Unit 10: A total of six detrital charcoal samples was analyzed from Unit 10 overbank deposits, including five samples from Trench 1 (T1-96-19BS-10A was split for analysis by both

laboratories) and one sample from Trench 2. T1-96-13AN-10A, collected approximately 0.5 m below surface grade in Trench 1, provided an age of $1,345 \pm 75$ years BP. However, because this sample was collected from a depth of active bioturbation in Trench 2, this age is probably not credible. T1-96-11CS-10A, T1-96-12CN-10A, and T1-96-19BS-10A provided four radiocarbon ages that were statistically equivalent to the within a 1-sigma confidence level. These radiocarbon ages provided a weighted average age of $5,090 \pm 90$ years BP. T2-96-5CS-10A, also collected from the base of the overbank deposits or about 1 m below ground surface, provided a calibrated age of $5,715 \pm 225$ years BP. As mentioned above, false older ages can be caused by a number of mechanisms. Regardless of the mechanism, the lack of soil development near the surface in Unit 10 suggests that sediment was probably deposited more recently than the calculated average age of $5,090 \pm 90$ years BP.

Because the overbank deposits of Unit 10 are certainly younger than the underlying channel deposits of Unit 20, the youngest reported age of 310 years BP is considered the favored age for Unit 10 as well as Unit 20. Because of the lack of corroborating young dates and the possibility of contamination of the sample by young organics or bioturbation ancient deposition is also a possible interpretation for the project site. Therefore, implications regarding both of these scenarios are examined below.

Table 1. Radiocarbon Laboratory Results.

Table 1 RADIOCARBON LABORATORY RESULTS Howell Creek Paleoseismic Investigation Talmage, California						
SAMPLE NO.	Laboratory ¹	Radiocarbon (14C) Yrs BP ²	Delta 13C (‰) ³	+ 1 Sigma	Years Before Present (BP) ^{4,5}	Calendar Date Range (AD/BC) ⁵
UNIT 10						
T2-96-5CS-10A	LLNL	5000	-25.0	100	5715 ± 225	3990 - 3540 BC
T1-96-11CS-10A*	UA	4575	-24.7	70	5225 ± 235	3510 - 3040 BC
T1-96-12CN-10A*	UA	4510	-25.8	65	5100 ± 220	3370 - 2980 BC
T1-96-13AN-10A	LLNL	1450	-25.0	50	1345 ± 75	530 - 680 AD
T1-96-19BS-10A*	LLNL	4370	-25.0	50	5025 ± 185	3260 - 2890 BC
T1-96-19BS-10A*	UA	4520	-25.2	70	5160 ± 280	3490 - 2980 BC
UNIT 10 AVERAGE ⁶	-	4472	-	32	5090 ± 190	3330 - 2950 BC
UNIT 20						
T2-96-7CS-20A*	LLNL	4440	-25.0	60	5075 ± 205	3330 - 2920 BC
T2-96-7CS-20B	LLNL	5510	-25.0	80	6285 ± 185	4520 - 4150 BC
T1-96-8DS-20A	UA	175	-26.8	45	155 ± 155	1640 - 1950 AD
T1-96-15DS-20A*	LLNL	4490	-25.0	50	5095 ± 205	3350 - 2940 BC
T1-96-15DS-20A*	UA	4660	-26.4	55	5365 ± 205	3620 - 3210 BC
UNIT 20 AVERAGE ⁶	-	4531	-	32	5170 ± 140	3360 - 3080 BC

Notes:

- 1 - Laboratories UA and LLNL are University of Arizona and Lawrence Livermore National Laboratory, respectively.
- 2 - Radiocarbon years Before Present (BP).
- 3 - Delta 13C values provided by UA. LLNL assumes a delta C13 of -25.0 ‰.
- 4 - Calendar years before present (BP) equals years before 1950. Dates rounded to nearest 10 years (Stuiver and Reimer, 1993).
- 5 - Calculated using CALIB software by Stuiver and Reimer (1993). Calendar date ranges include 100% of the 2-sigma probability.
- 6 - Average of *** marked samples (Long and Rippeteau, (1974).

The sample naming convention used for all samples includes the trench number (T1 or T2) - year sampled (1996) - panel, section, wall-of-trench (north-"N", south-"S") - and unit number (samples taken from the same sample section were differentiated using "A" and "B" designations). Sample locations are indicated on trench logs in Plate 1 and Appendix A.

Timing of the Most Recent Earthquake Event

As mentioned previously, radiocarbon data from this investigation provide two possible interpretations for the timing of the most recent earthquake occurring on the MFZ. Either the earthquake occurred sometime after about 310 years BP, as indicated by the youngest reported radiocarbon age collected from channel deposits, or sometime after about 5,280 years BP, as indicated by the average age of several charcoal samples collected from Howell Creek overbank deposits. Although this investigation favors an scenario of recent deposition, this section discusses both possible scenarios.

Stratigraphy exposed in Trench 1 suggests that at least one and possibly two surface-rupture earthquakes occurred across a narrow fault trace in Unit 30 (Figs. 10 and 11). Because no datable material was found in sediments of Unit 30, the timing of the possible older earthquake is unknown. The most recent earthquake also faulted overlying Units 28, 24, and 20 (Figs. 10 and 11). Overlying the faulted coarse sediments of Unit 20 are the overbank deposits of Unit 10. The contact between Unit 10 and Unit 20 does not appear to be fault offset (Figs. 10 and 11). In addition, overbank deposits above the contact do not display evidence of fault displacement. Based on these observations, it seems likely that Unit 10 was deposited sometime after the most recent surface-rupture earthquake at Howell Creek.

At the time of this writing, the only previous paleoseismic investigation conducted on the central segment of the MFZ (Working Group, 1996) is the investigation at Talmage (Galehouse

and others, 1992). Conclusions from the Talmage investigation (Galehouse and others, 1992) that identified a surface-folding earthquake occurring sometime after about 1500 AD (450 years BP) are consistent with the interpretation of a recent earthquake at the Howell Creek site. If Howell Creek sediments were in fact recently deposited, the timing of the most recent earthquake can be better constrained from sometime after 450 years BP (Galehouse and others, 1992) to sometime after about 310 years BP. In addition, a possible recent earthquake at the Howell Creek site is consistent with the current recurrence estimate of 220 years for the MFZ (Working Group, 1996). As mentioned previously, because the charcoal found in sediments overlying the fault zone in Unit 10 was older than the youngest sample found in Unit 20, this investigation cannot provide a minimum age for this earthquake event.

Although this investigation favors an interpretation of a recent earthquake, the sediments at Howell Creek may have been deposited sometime after about 5,280 years BP. This relatively old age is consistent with the investigation that Upp (1989) conducted on the northern segment of the MFZ. Upp's investigation also suggests fault rupture of ancient sediments. As mentioned previously, the Upp investigation concluded that one earthquake apparently occurred sometime after about 8,300 years BP. At the time of this writing, there have been too few investigations conducted on the MFZ to conclusively determine whether these radiocarbon ages are false ages caused by the recent deposition of ancient charcoal. Therefore, if these radiocarbon ages are not false, then this investigation at Howell Creek constrains the timing of the most recent earthquake from sometime after about 8,300 years ago to sometime after about 5,280 years BP.

Calculation of MFZ Recurrence Interval

The most recent estimate of earthquake recurrence interval for the MFZ reflects slip rate and slip per event (coseismic slip) estimates from the Hayward and Rodgers Creek fault zones (Working Group, 1996). Recurrence interval estimates for these fault zones, as reported by the Working Group, are 210 years for the HFZ (north and south segments), 230 years for the RCFZ, and 220 years for all three segments of the MFZ. However, only one investigation (Upp, 1989) can be used to calculate a recurrence interval for the MFZ. The following analysis outlines the methodology for calculating a recurrence interval, then utilizes data from Upp (1989) to calculate a possible long recurrence interval for the northern segment of the MFZ. Because ancient charcoal can be deposited in young geologic features, this estimate is considered preliminary. Additional data will most likely constrain and possibly replace this estimate. Unfortunately, because this investigation at Howell Creek as well as the previous investigation by Galehouse and others (1992) identified only a single faulting event in datable sediments, a possible short recurrence interval cannot be calculated for the MFZ.

Calculation Methodology

Earthquake recurrence intervals can be calculated either by dividing the coseismic slip by the slip rate or by dividing a time interval by the number of earthquakes that occurred during that time interval (Budding and others, 1991). The following discussion summarizes the latter method

used to calculate a recurrence interval. Using this method, a recurrence interval is calculated for the northern segment of the MFZ (see *Calculation of a Long Recurrence Interval*).

Paleoseismic investigations often provide poorly resolved estimates for the timing of seismic events. Large uncertainties can be caused by poorly defined stratigraphy, little or no datable organic material, errors inherent in using detrital charcoal, or all of the above.

Uncertainties are most pronounced when there are few earthquakes and when adjacent datable units differ in age by a significant portion of the recurrence interval. As reported by Budding and others (1991), the calculation of a recurrence interval depends on when the earthquakes are presumed to have occurred relative to the deposition of sediments. The calculation of a recurrence interval often assumes that earthquake events are evenly distributed throughout a time period and that each event is separated by an equal time interval, as shown in diagram (a) below.

The recurrence interval for diagram a) is equal to $t/2$, calculated by dividing the time (t) (representing the difference in the age of datable deposits) by two time intervals.

However, fault displacement occurring either immediately prior to or following deposition of dated sediment packages can cause significant errors in the calculated recurrence interval. For example, if an earthquake event occurred immediately prior to the deposition of datable sediments (diagram b), the calculated recurrence interval of $t/2$ will be overestimated.

The recurrence interval for diagram b) is approximately equal to $t/3$ (calculated by dividing the time (t) by 3 time intervals) instead of the recurrence interval estimate of $t/2$ (diagram a).

Conversely, if an earthquake event occurred immediately after the deposition of datable sediments (diagram c), the recurrence estimate (missing an interval) will be underestimated.

The recurrence interval for diagram c) is approximately equal to t , (calculated by dividing the time (t) by one time interval) instead of the recurrence interval estimate $t/2$ (diagram a).

Calculation of a Long Recurrence Interval

Logs from exploratory trenches at the Laughlin site (Upp, 1989) indicate that the older of two or possibly three faulting events ruptured a unit of silty clay containing a charcoal sample that was radiocarbon dated as 16,200 years BP. The charcoal sample was located about 2 m below the surface. In addition, the oldest event ruptured two units of undated sandy clay overlying the silty clay that contained the charcoal. The uppermost unit was not faulted, and continued deposition mantled the fault rupture. The accumulation of approximately 1 m of sediment above the fault may indicate that a significant period of time elapsed following the deposition of the charcoal sample. Thus, the oldest identified earthquake could be much younger than the reported age of the charcoal sample. In addition, two undeformed soil horizons were identified above the fault zone, suggesting that a significant amount of time elapsed following the last fault rupture event.

Using the system by Budding and others (1991) summarized above, a maximum recurrence interval of 14,200 years is generated by assuming that two earthquake events (Upp, 1989) occurred over one time interval of approximately 14,200 years (or 16,200 years less 2,000 years of soil development). This scenario is presented graphically as diagram c in *Calculation Methodology* above.

However, because of the apparent age represented by accumulation of sediments overlying the dated charcoal sample, and to the time represented by the undeformed soil mantle overlying the fault zone, a more likely scenario may be that two events occurred over two time intervals (shown graphically in diagram a in *Calculation Methodology* above). This assumption generates a favored maximum recurrence interval of 8,100 years (16,200 years divided by two time intervals). Two events occurring over three time intervals is also a possible scenario (shown graphically in diagram b above). This scenario generates a recurrence of 5,400 years (three time intervals in 16,200 years).

As reported by Upp (1989), three events could also have occurred, presumably over two, three, or four time intervals. The assumption that three earthquakes were distributed over two time intervals generates a recurrence of 8,100 years (16,200 years divided by two time intervals). Three events distributed over four time intervals produces a recurrence of 4,050 years (16,200 years divided by four intervals). Because it is unclear whether two or three ground-rupture events occurred at the Laughlin Range site, a recurrence interval of 4,050 to 8,100 years is calculated for the northern section of the MFZ using data from the Upp investigation.

Discussion of a Possible Long Recurrence Interval on the MFZ

By assuming a coseismic slip of 2 m (Working Group, 1996) and a minimum recurrence interval of 4,050 years, calculated in the previous discussion, a strain release rate of about 0.5 mm/yr is generated for the MFZ. Currently, the slip-rate estimate for the MFZ is 9 mm/yr

(Working Group, 1996). It seems likely that false older ages associated with the radiocarbon age dating of detrital charcoal are responsible for at least part of the apparent discordance between the published recurrence estimate and the recurrence estimate calculated above. However, several geologic factors that could also reduce the calculated recurrence interval include unrecognized earthquakes in trench investigations or slip (occurring by fault rupture or aseismic creep) occurring adjacent to investigated sites.

Unidentified rupture events in sediments at the Laughlin Range site (Upp, 1989) would lower the recurrence interval calculated in this investigation. However, even if several unrecognized earthquakes occurred at the site, the calculated recurrence interval would not be in agreement with the currently accepted estimate. The possible ancient deposition of Howell Creek sediments would also imply a long recurrence interval. However, more than one faulting episode through these sediments seems unlikely due to the small lateral motion (apparently less than about 1 meter) interpreted from bedding in Trench 1 (see *Evaluation of Fault Offset* above in this report).

An examination of the fault trace map by Upp (1989) in addition to aerial photographs (Fig. 8) indicates that a short fault segment is apparently located to the southeast of the Howell Creek site. In addition, several short fault segments are apparently located adjacent to the Laughlin Range site (Upp, 1989). Because they have not been investigated, the amount of strain released across these apparent fault breaks is unknown. Aseismic creep occurring adjacent to

investigated sites could also lower the recurrence interval in investigated areas. However, at the time of this writing, aseismic creep has been recognized on the MFZ only in Willits and Ukiah (Galehouse, personal communication, 1998). The following discussion examines the implications of aseismic creep on the MFZ and explores the possibility that creep or possibly elastic deformation (released during fault rupture) may be occurring in previously unidentified areas of the MFZ.

Possible Mechanism for Creep on the MFZ

Only two creeping sites on the MFZ, one located in Ukiah and one in Willits, have been recognized and examined in detail (Galehouse, personal communication, 1998). Although it is unclear how much of the length of the MFZ is currently displaying aseismic creep, the occurrence of fault creep in these areas has several implications. First, rock strength along the creeping segments is probably very weak. Second, rocks of similar lithologies adjacent to the main trace of the MFZ may also be very weak. The following discussion examines the strength and mineralogy of the melange present on the west side of the Central belt of the Franciscan Complex.

As noted previously, the MFZ displaces rocks along the west side of the Central belt (and possibly Coastal belt rocks at depth). The western Central belt consists of melange (McLaughlin, personal communication, 1998). To the east, the melange becomes more broken, less penetratively deformed (McLaughlin, personal communication, 1998), and contains a larger percentage of exotic blocks (Blake and others, 1995). Cowan and Mansfield (1970) compared the

relative strength of sheared scaly serpentinite and massive serpentinite. The authors concluded that the scaly serpentinite exhibited an oriented shear strength “orders of magnitude lower than the massive serpentinite.” (p. 458) Cowan (1985) suggests that this also may be the case with scaly mudstone of the Type III melange which is “a comparably weak, readily deformable material.”(p. 458) The melange most common to the western Central belt is the Type III melange (McLaughlin, personal communication, 1998).

Related work was conducted in early studies investigating the fault strength of SAF. Results of these investigations indicated that the shear strength of poorly oriented clay minerals was higher than required for motion on the fault (Morrow and others, 1992). However, in a study by Wintsch and others (1995), the authors conclude that phyllosilicate mineral assemblages that are oriented favorably and contiguous can allow deformation under the low stress conditions exhibited by mature faults such as the SAF. Wintsch and others (1995) suggest that the shear strength of well-oriented phyllosilicate mineral assemblages can approach that of a single crystal. These investigations indicate that the rock strength of melange is dependent on the direction of applied shear with respect to the orientation of the scaly petrologic fabric, as described by Cowan (1985).

According to Wakabayashi (1992, p. 34), “Franciscan melanges formed as shear zones as part of internal imbrication of coherent nappes and separating coherent nappes...”. In addition, according to Blake (personal communication, 1998), the Central belt melange is characterized by a steep, north-trending fabric that is superimposed by a northwesterly fabric of Cenozoic fault-related activity. The north-trending fabric of the Central belt melange may reflect a regional orientation of the scaly fabric investigated by Cowan (1985) and Cowan and Mansfield (1970). If this is the case, then it seems possible that aseismic creep on the MFZ occurs as a result of the favorable alignment of a regional petrologic fabric with the northwesterly tectonic motion of the San Andreas fault system.

If true, the above hypothesis has several implications. First, creep may be occurring in areas not previously identified that display a petrologic fabric that is aligned favorably with a northwesterly shear direction. Second, zones of weakness located off the main fault trace of the MFZ may be accommodating regional motion. Displacement across these zones of weakness (occurring either by aseismic creep or elastic deformation during earthquakes) may explain at least part of the possible long recurrence interval calculated in this investigation. Finally, if a significant component of strain is released by creep as opposed to elastic rupture, the seismic hazard posed by regional slip on the MFZ may be less than the Rodgers Creek or Hayward fault zones.

SUMMARY OF FINDINGS

The main objectives of this investigation were: (1) to identify and estimate the timing of paleo-earthquake events on the MFZ, and (2) to provide estimates of the average recurrence interval and slip rate for the MFZ. This investigation provided two possible interpretations for the timing of the most recent earthquake event on the central segment of the MFZ. Radiocarbon analyses of detrital charcoal suggest that the event occurred either sometime after about 310 years BP or sometime after about 5,280 years BP. The younger of these dates is consistent with a previous investigation in Talmage that concluded that the most recent large earthquake occurred sometime after 450 years BP (Galehouse and others, 1992). By utilizing the younger radiocarbon age from this investigation, the maximum age of the most recent surface-rupture earthquake is significantly constrained from 450 years BP to about 310 years BP. Because the youngest radiocarbon age is associated with the lowermost datable unit, there is no minimum age to further constrain the timing of this event. Although a scenario that includes ancient deposition of Howell Creek sediments (after 5,280 years BP) is possible, it appears more likely that the older dates are a result of ancient charcoal in young sediments at Howell Creek. Thus, a young earthquake occurring sometime after about 310 years BP is considered the favored interpretation for this investigation.

Using data from Upp (1989), this investigation included the calculation of a preliminary recurrence interval of 4,050 to 8,100 years for the north segment of the MFZ. However, due to ambiguities associated with interpreting radiocarbon dates from detrital charcoal, this result is considered speculative. Because only one event was recognized in Howell Creek sediments, this investigation cannot provide an independent recurrence interval.

This investigation utilized stratigraphic relationships across the width of Trench 1 to provide a preliminary estimate of coseismic slip of 1 m. Because conclusions from a recent study by Wells and Coopersmith (1994) suggest that surface slip is typically equal to about half the coseismic slip at depth, this is considered consistent with the current coseismic slip estimate of 2.0 m for the MFZ (Working Group, 1996).

This investigation proposes a tentative mechanism for aseismic creep; that the petrologic fabric of the Central belt melange may be favorably aligned with the northwesterly tectonic motion of the SAFS. In addition, if a large component of displacement across the MFZ (and possibly in areas outside of the fault zone) occurs by aseismic creep, then the seismic hazard associated with the MFZ may be less than previously assumed.

RECOMMENDATIONS FOR FUTURE PALEOSEISMIC INVESTIGATIONS

Although this investigation provided a preliminary coseismic surface slip of approximately 1 m, the direct measurement of coseismic slip was not possible. Future investigations that include excavation and detailed logging of fault-parallel trenches could allow the direct measurement of coseismic slip for the latest earthquake or possibly for several earthquake events on the MFZ.

The long recurrence interval calculated as one possibility in this investigation may, be caused, at least in part, by strain release accommodated by fault strands adjacent to investigated sites. Future paleoseismic investigations should identify fault splays located adjacent to investigated sites and evaluate them for possible trenching.

In a previous section, it was speculated that a possible mechanism for fault strength reduction that may help to explain the occurrence of aseismic slip on the MFZ. The author's hypothesis is that fault-strength reduction may occur because of a petrologic fabric in the Franciscan Central belt melange that is aligned favorably with the orientation of fault motion on the MFZ. A detailed study of Franciscan rocks near creeping segments of the MFZ could indicate whether the melange minerals display any dominant fabric oriented parallel to the creep direction.

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APPENDIX A
TRENCH 2 LOGS

Trench 2 South Wall (Image Reversed)

Trench 2 North Wall

Explanation of symbols on trench logs:

- Contact between units
- Fault surface
- Location of charcoal sample
- K = krotovina; B = burrow

Notes for Trench 2 logs:

Section designations (A-F) are left and right of the logs, panel designations are above the logs.

Vertical rectangles are where shores obscured logging.

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APPENDIX B
LABORATORY ANALYTICAL REPORTS

UNIVERSITY OF WASHINGTON
QUATERNARY ISOTOPE LAB
RADIOCARBON CALIBRATION PROGRAM REV 3.0.3c
Stuiver, M. and Reimer, P.J., 1993, Radiocarbon, 35, p. 215-230.

Calibration file(s): INTCAL93.14C
Listing file: C14FIL.TXT

T1-96-13AN-10A

14399

Radiocarbon Age BP	1450 ± 50	Reference(s)
Calibrated age(s)	cal AD 628	(Stuiver and Pearson, 1993)
	cal BP 1322	

cal AD/BC (cal BP) age ranges obtained from intercepts (Method A):
one Sigma** cal AD 595 - 654 (1355 - 1296)
two Sigma** cal AD 540 - 669 (1410 - 1281)

Summary of above:

minimum of cal age ranges (cal ages)	maximum of cal age ranges:
1 sigma cal AD 595 (628) 654	
cal BP 1355 (1322) 1296	
2 sigma cal AD 540 (628) 669	
cal BP 1410 (1322) 1281	

cal AD/BC & cal BP age ranges (cal ages as above)
from probability distribution (Method B):

% area enclosed	cal AD (cal BP) age ranges	relative contribution to probabilities
68.3 (1 sigma)	cal AD 567 - 577 (1383 - 1373)	.09
	593 - 656 (1357 - 1294)	.91
95.4 (2 sigma)	cal AD 465 - 473 (1485 - 1477)	.00
	532 - 680 (1418 - 1270)	1.00

T1-96-1985 -10A

14400

Radiocarbon Age BP	4370 ± 50	Reference(s)
Calibrated age(s)	cal BC 2924	(Stuiver and Pearson, 1993)
	cal BP 4873	

cal AD/BC (cal BP) age ranges obtained from intercepts (Method A):
one Sigma** cal BC 3037 - 2913 (4987 - 4863)
two Sigma** cal BC 3256 - 3247 (5206 - 5197)
cal BC 3099 - 2887 (5049 - 4837)

Summary of above:

minimum of cal age ranges (cal ages)	maximum of cal age ranges:
1 sigma cal BC 3037 (2924) 2913	
cal BP 4986 (4873) 4862	
2 sigma cal BC 3256 (2924) 2887	
cal BP 5205 (4873) 4836	

cal AD/BC & cal BP age ranges (cal ages as above)
from probability distribution (Method B):

% area enclosed	cal BC (cal BP) age ranges	relative contribution to probabilities
68.3 (1 sigma)	cal BC 3031 - 2916 (4981 - 4866)	1.00

95.4 (2 sigma) cal BC 3260 - 3244 (5210 - 5194) .01
 3101 - 2886 (5051 - 4836) .99

T1-96-1505 - 20A

14401

Radiocarbon Age BP 4490 $\pm$ 50 Reference(s)
 Calibrated age(s) cal BC 3292, 3283, 3266 (Stuiver and Pearson, 1993)
 3241, 3104
 cal BP 5241, 5232, 5215
 5190, 5053

cal AD/BC (cal BP) age ranges obtained from intercepts (Method A):
 one Sigma** cal BC 3336 - 3083 (5286 - 5033)
 cal BC 3062 - 3043 (5012 - 4993)
 two Sigma** cal BC 3354 - 3019 (5304 - 4969)
 cal BC 2988 - 2927 (4938 - 4877)

Summary of above:

minimum of cal age ranges (cal ages) maximum of cal age ranges:
 1 sigma cal BC 3336 (3292, 3283, 3266, 3241, 3104) 3043
 cal BP 5285 (5241, 5232, 5215, 5190, 5053) 4992
 2 sigma cal BC 3354 (3292, 3283, 3266, 3241, 3104) 2927
 cal BP 5303 (5241, 5232, 5215, 5190, 5053) 4876

cal AD/BC & cal BP age ranges (cal ages as above)
 from probability distribution (Method B):

% area enclosed	cal BC (cal BP) age ranges	relative contribution to probabilities
68.3 (1 sigma)	cal BC 3332 - 3216 (5282 - 5166)	.56
	3197 - 3155 (5147 - 5105)	.20
	3137 - 3092 (5087 - 5042)	.21
	3054 - 3047 (5004 - 4997)	.03
95.4 (2 sigma)	cal BC 3349 - 3030 (5299 - 4980)	.96
	2973 - 2936 (4923 - 4886)	.04

T2-96-5CS- 10A

14402

Radiocarbon Age BP 5000 $\pm$ 100 Reference(s)
 Calibrated age(s) cal BC 3782 (Stuiver and Pearson, 1993)
 cal BP 5731

cal AD/BC (cal BP) age ranges obtained from intercepts (Method A):
 one Sigma** cal BC 3946 - 3831 (5896 - 5781)
 cal BC 3829 - 3691 (5779 - 5641)
 cal BC 3673 - 3669 (5623 - 5619)
 two Sigma** cal BC 3986 - 3630 (5936 - 5580)
 cal BC 3555 - 3547 (5505 - 5497)

Summary of above:

minimum of cal age ranges (cal ages) maximum of cal age ranges:
 1 sigma cal BC 3946 (3782) 3669
 cal BP 5896 (5731) 5619
 2 sigma cal BC 3986 (3782) 3547
 cal BP 5936 (5731) 5497

cal AD/BC & cal BP age ranges (cal ages as above)
 from probability distribution (Method B):

% area enclosed	cal BC (cal BP) age ranges	relative contribution to probabilities
68.3 (1 sigma)	cal BC 3940 - 3852 (5890 - 5802) 3820 - 3697 (5770 - 5647)	.39 .61
95.4 (2 sigma)	cal BC 3990 - 3628 (5940 - 5578) 3563 - 3543 (5513 - 5493)	.99 .01

T2-96-7CS-20A

14403

Radiocarbon Age BP 4440 $\pm$ 60
 Calibrated age(s) cal BC 3085, 3061, 3043
 cal BP 5034, 5010, 4992

Reference(s)
(Stuiver and Pearson, 1993)

cal AD/BC (cal BP) age ranges obtained from intercepts (Method A):

one Sigma** cal BC 3298 - 3236 (5248 - 5186)
 cal BC 3174 - 3167 (5124 - 5117)
 cal BC 3108 - 3014 (5058 - 4964)
 cal BC 3000 - 2925 (4950 - 4875)
 two Sigma** cal BC 3343 - 2913 (5293 - 4863)

Summary of above:

minimum of cal age ranges (cal ages) maximum of cal age ranges:

1 sigma cal BC 3298 (3085, 3061, 3043) 2925
 cal BP 5248 (5034, 5010, 4992) 4875
 2 sigma cal BC 3343 (3085, 3061, 3043) 2913
 cal BP 5293 (5034, 5010, 4992) 4863

cal AD/BC & cal BP age ranges (cal ages as above)
 from probability distribution (Method B):

% area enclosed	cal BC (cal BP) age ranges	relative contribution to probabilities
68.3 (1 sigma)	cal BC 3297 - 3237 (5247 - 5187) 3172 - 3168 (5122 - 5118) 3107 - 3015 (5057 - 4965) 2997 - 2926 (4947 - 4876)	.24 .01 .44 .30
95.4 (2 sigma)	cal BC 3333 - 3212 (5283 - 5162) 3206 - 3153 (5156 - 5103) 3141 - 2919 (5091 - 4869)	.27 .09 .64

T2-96-7CS-20B

0

14404

Radiocarbon Age BP 5510 $\pm$ 80
 Calibrated age(s) cal BC 4348
 cal BP 6297

Reference(s)
(Stuiver and Pearson, 1993)

cal AD/BC (cal BP) age ranges obtained from intercepts (Method A):

one Sigma** cal BC 4453 - 4415 (6403 - 6365)
 cal BC 4403 - 4322 (6353 - 6272)
 cal BC 4282 - 4262 (6232 - 6212)
 two Sigma** cal BC 4499 - 4226 (6449 - 6176)
 cal BC 4181 - 4163 (6131 - 6113)

Summary of above:

minimum of cal age ranges (cal ages) maximum of cal age ranges:

1 sigma cal BC 4453 (4348) 4262
 cal BP 6403 (6297) 6212

2 sigma cal BC 4499 (4348) 4163
cal BP 6449 (6297) 6113

cal AD/BC & cal BP age ranges (cal ages as above)
from probability distribution (Method B):

% area enclosed	cal BC (cal BP) age ranges	relative contribution to probabilities
68.3 (1 sigma)	cal BC 4455 - 4412 (6405 - 6362)	.26
	4407 - 4320 (6357 - 6270)	.58
	4287 - 4259 (6237 - 6209)	.16
95.4 (2 sigma)	cal BC 4517 - 4222 (6467 - 6172)	.97
	4192 - 4155 (6142 - 6105)	.03

References for datasets used:

Stuiver, M and Pearson, GW, 1993, Radiocarbon, 35, 1-23.
Stuiver, M and Pearson, GW, 1993, Radiocarbon, 35, 1-23.

Comments:

†This standard deviation (error) includes a lab error multiplier.

** 1 sigma = square root of (sample std. dev.^2+ curve std. dev.^2)

2 sigma = 2 x square root of (sample std. dev.^2+ curve std. dev.^2)

[ ] = calibrated with linear extension to calibration curve

0* represents a "negative" age BP

1955* denotes influence of bomb C-14

For cal yrs between 5500-5190 BC an offset of 25 years is possible.

NOTE: Cal ages and ranges are rounded to the nearest year which may be too precise in many instances. Users are advised to round results to the nearest 10 yr for samples with standard deviation in the radiocarbon age greater than 50 yr.

Preilice data summary - 25 Sep 98 (reported previously in 1997)

	AA#	material	sample ID	$\delta^{13}\text{C}(\text{‰})$	14C age (BP)	$\pm 1\sigma$	2 σ calendar age range*
1	22994	charcoal	T1-96-8DS-20A	-26.8	175	45	1645 - 1955 AD
2	22995	charcoal	T1-96-15DS-20A	-26A	4,660	55	3622 - 3208 BC
3	22996	charcoal	T1-96-18CS-20A		insufficient sample		
4	22997	charcoal	T1-96-19BS-10A	-25.2	4,520	70	3494 - 2929 BC
5	22998	charcoal	T1-96-11CS-10A	-24.7	4,575	70	3510 - 3043 BC
6	22999	charcoal	T1-96-12CN-10A	-25.8	4,510	65	3370 - 2929 BC

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Calibration file(s): INTCAL93.14C
Listing file: avg_U_10.TXT

U_10avg

U_10avg

Average of Unit 10 (11cs-10a, 12cn-10a, 19bs-10a)

Radiocarbon Age BP 4472 ± 32

Reference(s)

Calibrated age(s) cal BC 3255, 3247, 3098

(Stuiver and Pearson, 1993)

cal BP 5204, 5196, 5047

cal AD/BC (cal BP) age ranges obtained from intercepts (Method A):

one Sigma** cal BC 3301 - 3235 (5250 - 5184)

3177 - 3165 (5126 - 5114)

3109 - 3082 (5058 - 5031)

3062 - 3043 (5011 - 4992)

two Sigma** cal BC 3335 - 3030 (5284 - 4979)

2973 - 2943 (4922 - 4892)

Summary of above:

minimum of cal age ranges (cal ages) maximum of cal age ranges:

1σ cal BC 3301 (3255, 3247, 3098) 3043

cal BP 5250 (5204, 5196, 5047) 4992

2σ cal BC 3335 (3255, 3247, 3098) 2943

cal BP 5284 (5204, 5196, 5047) 4892

cal AD/BC & cal BP age ranges (cal ages as above)
from probability distribution (Method B):

% area enclosed	cal BC (cal BP) age ranges	relative area under probability distribution
68.3 (1σ)	cal BC 3305 - 3232 (5254 - 5181)	.51
	3181 - 3162 (5130 - 5111)	.10
	3116 - 3077 (5065 - 5026)	.24
	3066 - 3040 (5015 - 4989)	.15
95.4 (2σ)	cal BC 3335 - 3150 (5284 - 5099)	.60
	3150 - 3031 (5099 - 4980)	.38
	2970 - 2969 (4919 - 4918)	.00
	2964 - 2950 (4913 - 4899)	.01

References for datasets used:

Stuiver, M and Pearson, GW, 1993, Radiocarbon, 35, 1-23.

Comments:

†This standard deviation (error) includes a lab error multiplier.

** 1 sigma = square root of (sample std. dev.² + curve std. dev.²)

2 sigma = 2 x square root of (sample std. dev.² + curve std. dev.²)

[ ] = calibrated with linear extension to calibration curve

0* represents a "negative" age BP

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Calibration file(s): UWTEN93.14C
Listing file: ave_U_20.TXT

U_20avg

U_20avg

Average of Unit 20 (7cs-20a, 15ds-20a (LLNL), 15ds-20a (UA))

Radiocarbon Age BP 4531 $\pm$ 32 Reference(s)

Calibrated age(s) cal BC 3335, 3315, 3315
3210, 3197, 3178
3174, 3152, 3136
cal BP 5284, 5264, 5264
5159, 5146, 5127
5123, 5101, 5085

cal AD/BC (cal BP) age ranges obtained from intercepts (Method A):

one Sigma** cal BC 3350 - 3297 (5299 - 5246)
3284 - 3261 (5233 - 5210)
3234 - 3166 (5183 - 5115)
3163 - 3100 (5112 - 5049)
two Sigma** cal BC 3364 - 3083 (5313 - 5032)
3067 - 3055 (5016 - 5004)

Summary of above:

minimum of cal age ranges (cal ages) maximum of cal age ranges:

1 σ cal BC 3350 (3335, 3315, 3315, 3210, 3197, 3178,
3174, 3152, 3136) 3100
cal BP 5299 (5284, 5264, 5264, 5159, 5146, 5127,
5123, 5101, 5085) 5049
2 σ cal BC 3364 (3335, 3315, 3315, 3210, 3197, 3178,
3174, 3152, 3136) 3055
cal BP 5313 (5284, 5264, 5264, 5159, 5146, 5127,
5123, 5101, 5085) 5004

cal AD/BC & cal BP age ranges (cal ages as above)
from probability distribution (Method B):

% area enclosed	cal BC (cal BP) age ranges	relative area under probability distribution
68.3 (1 σ)	cal BC 3347 - 3326 (5296 - 5275)	.13
	3324 - 3306 (5273 - 5255)	.11
	3275 - 3271 (5224 - 5220)	.02
	3228 - 3168 (5177 - 5117)	.40
	3160 - 3146 (5109 - 5095)	.08
	3144 - 3116 (5093 - 5065)	.18
	3114 - 3102 (5063 - 5051)	.07
95.4 (2 σ)	cal BC 3360 - 3247 (5309 - 5196)	.38
	3244 - 3097 (5193 - 5046)	.61
	3086 - 3085 (5035 - 5034)	.00

References for datasets used:

Comments:

+This standard deviation (error) includes a lab error multiplier.

** 1 sigma = square root of (sample std. dev.² + curve std. dev.²)

2 sigma = 2 x square root of (sample std. dev.² + curve std. dev.²)

0* represents a "negative" age BP

1955* denotes influence of bomb C-14

For cal yrs between 5500-5190 BC an offset of 25 years is possible.

NOTE: Cal ages and ranges are rounded to the nearest year which may be too precise in many instances. Users are advised to round results to the nearest 10 yr for samples with standard deviation in the radiocarbon age greater than 50 yr.

NOTE TO USERS

Oversize maps and charts are microfilmed in sections in the following manner:

LEFT TO RIGHT, TOP TO BOTTOM, WITH SMALL OVERLAPS

The following map or chart has been microfilmed in its entirety at the end of this manuscript (not available on microfiche). A xerographic reproduction has been provided for paper copies and is inserted into the inside of the back cover.

Black and white photographic prints (17"x 23") are available for an additional charge.

UMI

TRENCH 1 SOUTH WALL

Image Reversed

SW

SW

TRENCH 1 NORTH WALL

SW

SW

Panel 12 Panel 11 Panel 10 Panel 9 Panel 8 Panel 7 Panel 6 Panel 5 Panel 4 Panel 3

Panel 12 Panel 11 Panel 10 Panel 9 Panel 8 Panel 7 Panel 6 Panel 5 Panel 4 Panel 3

Panel 12 Panel 11 Panel 10 Panel 9 Panel 8 Panel 7 Panel 6 Panel 5 Panel 4 Panel 3

UNIT DESCRIPTIONS

UNIT 10:

Light brown, medium- to fine-grained sand and silt with scattered roots. This unit is moderately well indurated and massive with no evidence of bedding. Abundant roots and rootlets occur in the uppermost 1/2 of the unit. As Krotovina were encountered in Trench 2 to approximately 1 m below the surface. This unit was apparently deposited during flooding events of Hov...

UNIT 20:

Brown to gray, poorly sorted, sandy gravel. Gravel clasts are subangular to subrounded, well indurated and include metasedimentary, siltstone, sandstone, and chert. Typically, gravel clasts include red and green chert, and actinolite schist of Franciscan origin. The unit matrix typically consists of brown to gray (10YR 5/1) medium-grained sand (similar in texture and lithology to overlying Unit 10). This unit was deposited in a high-energy fluvial environment.

UNIT 24:

Brown to gray, medium to coarse sand interbedded with rounded gravel clasts (see the north wall), bedding includes pebbly laminae traceable over several meters. Deposits are typically finer in texture than deposits of Units 20 and 28. This unit is brown to gray moderately well indurated silt to medium-grained sandstone. This unit was deposited in a moderate-energy fluvial environment.

UNIT 28:

Brown to gray, poorly sorted, sandy gravel. Gravel clasts typically are subangular and apparently rotated near the fault zone. Clasts include sandstone, and conglomerate lithologies. Less typically, gravel clasts include actinolite schist interpreted to be of Franciscan origin. The unit matrix consists of brown to gray moderately well indurated sandstone. This unit was deposited in a high-energy fluvial environment.

UNIT 30

Olive-green silty gravel. Gravel clasts are typically poorly indurated and include sandstone. Interclast matrix consists of olive-green silt to clayey silt.

DESCRIPTIONS

medium- to fine-grained sand and silt with scattered pebble- to cobble-sized clasts. This is very well indurated and massive with no evidence of bedding, soil development or soil roots. Plant roots and rootlets occur in the uppermost 1/2 meter. Several open burrows as well as small rootlets were encountered in Trench 2 to approximately 1 meter below ground (see Appendix A). This unit is apparently deposited during flooding events of Howell Creek.

poorly sorted, sandy gravel. Gravel clasts are subrounded to 35 cm in cross section, and include metasedimentary, siltstone, sandstone and conglomerate lithologies. Less typical clasts include red and green chert, and actinolite schist interpreted to be of Franciscan origin. The matrix typically consists of brown to gray (10YR 5-3) moderately well indurated silt to medium sand (similar in texture and lithology to overlying floodplain deposits of Unit 10). This unit was deposited in a high-energy fluvial environment.

medium to coarse sand interbedded with rounded to subrounded, pebbly gravel. In the north wall, bedding includes pebbly laminae traceable across the fault break. These are typically finer in texture than deposits of Units 20 and 28. The unit matrix consists of moderately well indurated silt to medium-grained sand, similar in texture and lithology to Units 20 and 28. This unit was deposited in a moderate- to high-energy fluvial environment.

poorly sorted, sandy gravel. Gravel clasts typically subrounded but angular to subangular, apparently rotated near the fault zone. Clasts include metasedimentary, siltstone, sandstone and conglomerate lithologies. Less typically, gravel clasts include red and green chert and actinolite schist interpreted to be of Franciscan origin. The unit matrix is similar in texture to overlying units and consists of brown to gray moderately well indurated silt to medium-grained sand. This unit was deposited in a high-energy fluvial environment.

fine to medium sand and silt. Gravel clasts are typically poorly indurated, subrounded siltstone and fine sandstone. The matrix consists of olive-green silt to clayey silt. Blue discoloration of the fine sand is commonly encountered around roots and rootlets below the ground water table (approximately 2 meters below ground surface). This unit may be Irish beds.

TRENCH 1 NORTH WALL

SW

SW

E

NE

B

C

D

NE

Figure 1 consists of five panels labeled A through E, showing histological sections of the rat brain. Panels A, B, C, and D are arranged vertically on the left, showing different regions of the brain. Panel E is a higher magnification view of a specific area, likely the hippocampus, showing detailed cellular structure and the distribution of ^3H -THC. The sections are stained to show the presence of the tracer, with darker areas indicating higher concentrations.

D

E

0

Scale (1

Horizontal = $\dot{v}$

Gravel clasts include red and green chert, and actinolite schist interpreted to be of Franciscan origin. The unit matrix typically consists of brown to gray (10YR 5-3) moderately well indurated silt to medium-grained sand (similar in texture and lithology to overlying floodplain deposits of Unit 10). This unit was deposited in a high-energy fluvial environment.

Gray, medium to coarse sand interbedded with rounded to subrounded, pebbly gravel. In the north wall, bedding includes pebbly laminae traceable across the fault break. These are typically finer in texture than deposits of Units 20 and 28. The unit matrix consists of gray moderately well indurated silt to medium-grained sand, similar in texture and lithology to units 20 and 28. This unit was deposited in a moderate- to high-energy fluvial environment.

Gray, poorly sorted, sandy gravel. Gravel clasts typically subrounded but angular to rounded and apparently rotated near the fault zone. Clasts include metasedimentary, siltstone, sandstone, and conglomerate lithologies. Less typically, gravel clasts include red and green chert and actinolite schist interpreted to be of Franciscan origin. The unit matrix is similar in texture to overlying units. This unit typically consists of brown to gray moderately well indurated silt to medium-grained sand. This unit was deposited in a high-energy fluvial environment.

Gray silty gravel. Gravel clasts are typically poorly indurated, subrounded siltstone and fine sandstone. Interclast matrix consists of olive-green silt to clayey silt. Blue discoloration of the fine sandstone is commonly encountered around roots and rootlets below the ground water table (approximately 2 meters below ground surface). This unit may be Ukiah beds.

Rectangles are where shores obscured logging. Dotted and dashed lines are inferred contacts. Letters (A - E) are Section designations. Panel designations are above the logs and numbers.

Sample