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The Hayward fault

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OVERVIEW OF FIELD TRIP

This field guide consists of eleven stops at sites that illustrate the geological, geophysical, geographic, and engineering aspects of the Hayward fault in the East Bay. Section I (Stops 1–4) consists of stops that are part of the University of California at Berkeley (UC-Berkeley), including research facilities, retrofit of campus buildings, and geomorphic features along the fault. Section II (Stops 5 and 6) consists of stops along the Hayward fault north of the UC-Berkeley main campus, and Section III (stops 7–11) consists of stops related to the Hayward fault south of the UC-Berkeley main campus (Fig. 1). Stops are designed to illustrate geomorphic features of the fault, the effects of fault creep on structures sited on the fault, and retrofit design of structures to mitigate potential future deformation due to fault rupture.

Keywords: Hayward fault, seismic retrofit, fault creep, fault displacement, shake table, Seismic Simulator, paleoseismology.

SECTION I: THE HAYWARD FAULT AT UC-BERKELEY

The UC-Berkeley campus is located on the eastern alluvial plain rising from San Francisco Bay, at an elevation between 300 and 500 feet and abutting the Oakland-Berkeley Hills. The Hayward fault is located along the topographic interface between the gently sloping plain and the hills (Fig. 1), and poses a significant ground-rupture and seismic shaking hazard to the UC-Berkeley campus (Fig. 2).

The location of the Hayward fault across the Berkeley campus is known from interpretation of pre-development geomorphic features observed on topographic maps and photographs, from fault trenching studies, and from observations of fault creep-related deformation to man-made structures. Distinct right-lateral offsets of Hamilton, Blackberry, and Strawberry Creeks, and an ancient landslide in the area of the Greek Theater, indicate the general location of the fault. In addition, two former (and now dry, "beheaded") channels of Strawberry Creek cross the Berkeley

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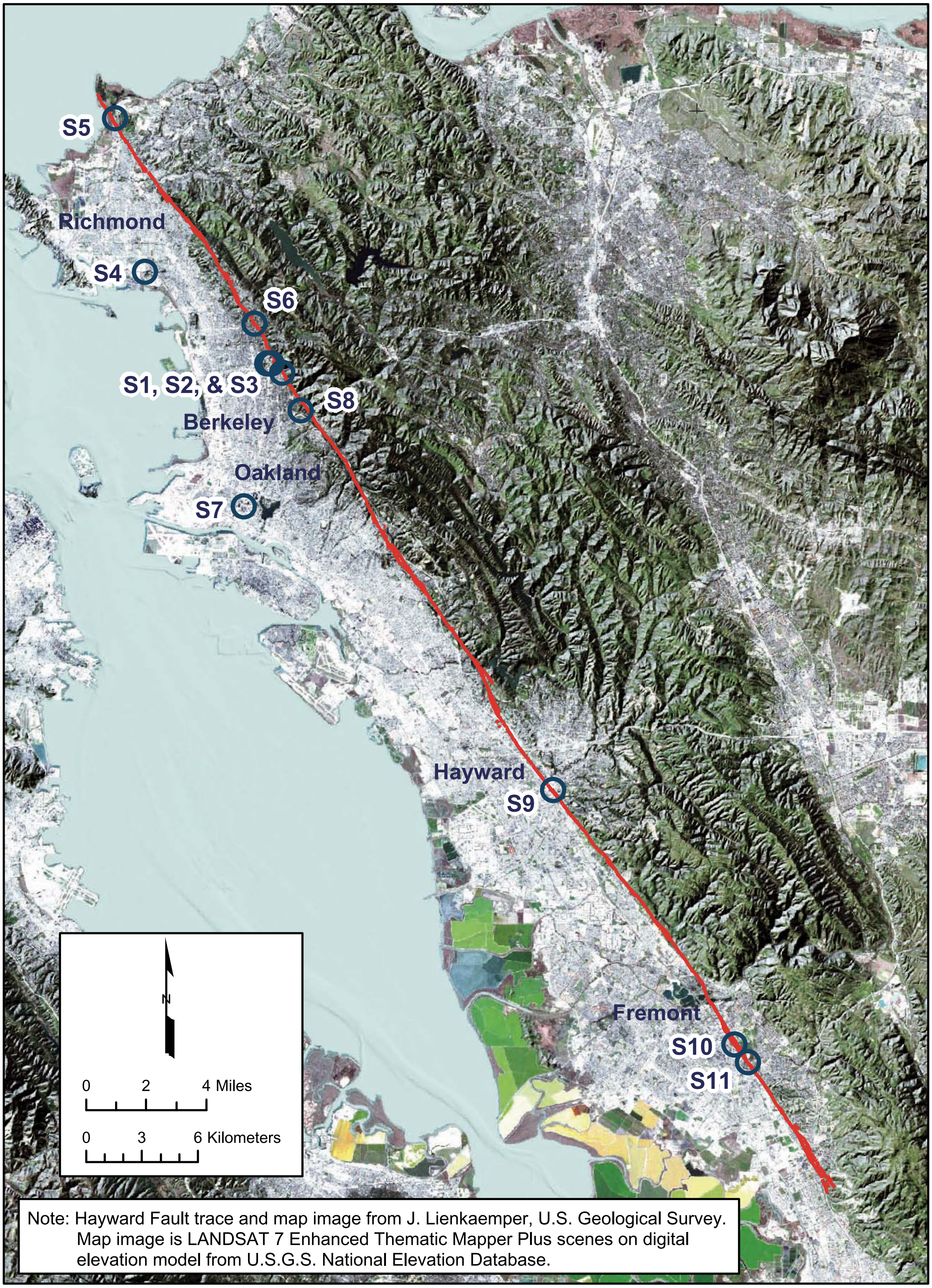
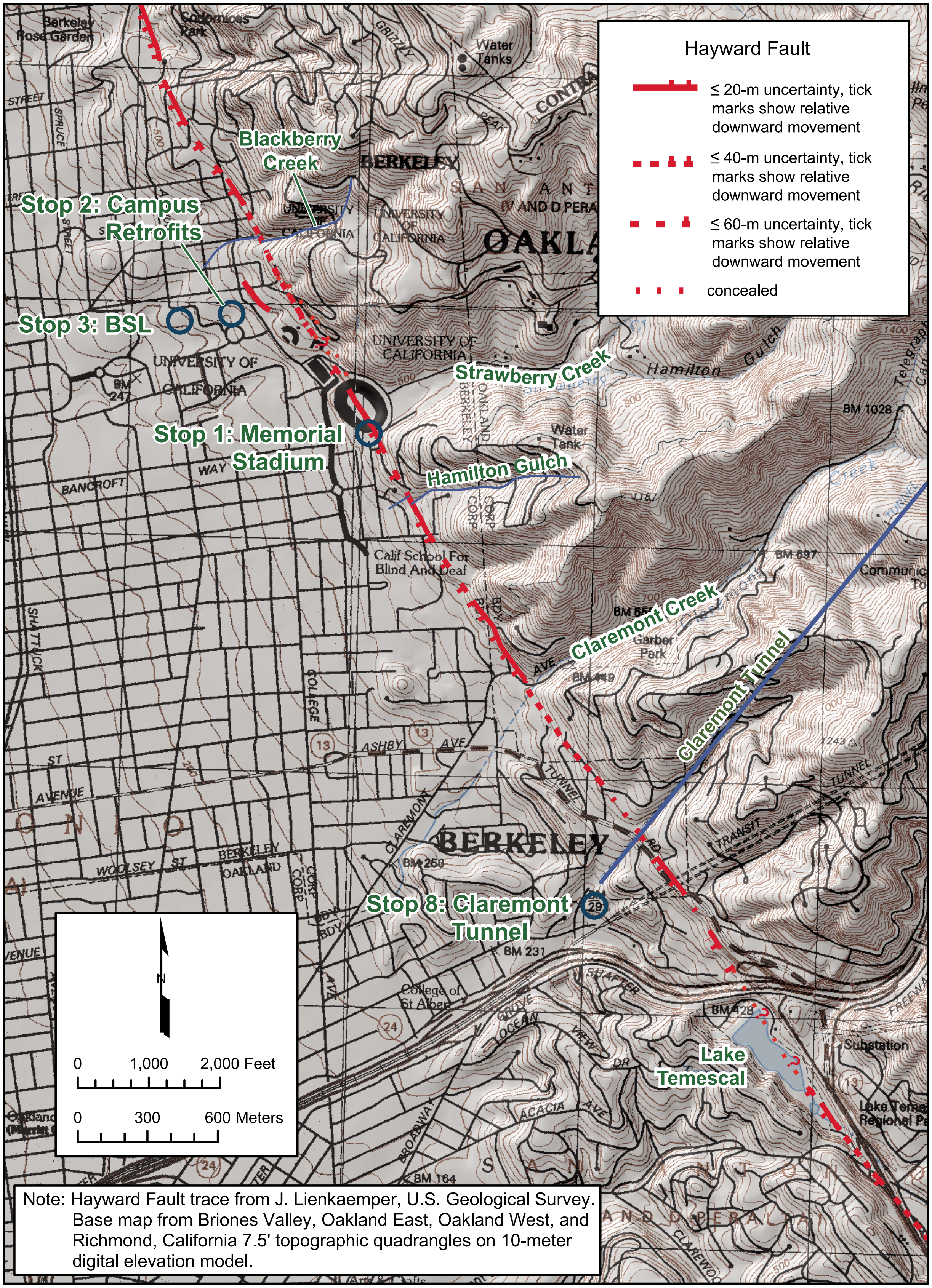


Figure 1. Map of the Hayward fault and stops.



Note: Hayward Fault trace from J. Lienkaemper, U.S. Geological Survey. Base map from Briones Valley, Oakland East, Oakland West, and Richmond, California 7.5' topographic quadrangles on 10-meter digital elevation model.

Figure 2. Stops and location of Hayward fault along the Berkeley–North Oakland Hills. The blue line shows the Claremont Water Tunnel (see Stop 8).

campus: one flowed through the East Gate and beneath the site of the Mining Circle (Fig. 3). An older channel flowed down Hearst Avenue. Fault trenching studies in the area of the Foothill Housing complex, Bowles Hall, Memorial Stadium, and the Smyth-Fernwald housing complex have identified primary and secondary traces of the Hayward fault. Right-lateral offsets of curbs, culverts, walkways, and buildings across the campus indicate the location of the creeping trace of the fault.

Stop 1: Memorial Stadium (Donald Wells, Nicholas Sitar, and David M. Doolin)

Significance of the site

Memorial Stadium (Fig. 4) was built in 1923 as a tribute to World War I heroes. It sits directly astride the creeping trace of the Hayward fault, at the base of Strawberry Canyon where Strawberry Creek exits the Berkeley Hills. The university is currently developing plans to renovate the stadium, including improvements to mitigate fault rupture hazard to the structure.

Accessibility

This is University of California at Berkeley property; restrooms are available, and there is limited parking in the surrounding neighborhood (very difficult when school is in session). Accessible from AC Transit Bus No. 51 and from downtown Berkeley Bay Area Rapid Transit (BART) station. From BART, walk east one block to campus.

GPS Coordinates

South Entrance to Stadium: 37.8700°N, 122.2504°W.

Directions

From San Francisco, take Highway 80 east (Bay Bridge) to Ashby Avenue exit (first Berkeley exit). Continue east 2 mi on Ashby Avenue to Telegraph Avenue, and turn left. Follow Telegraph Avenue north (0.6 mi) to Dwight Way and turn right. Continue east on Dwight Way to Piedmont Avenue (0.5 mi). Continue on Dwight Way one block to Prospect Street and turn left. Follow Prospect Street two blocks (0.25 mi) north to the south end of the stadium.

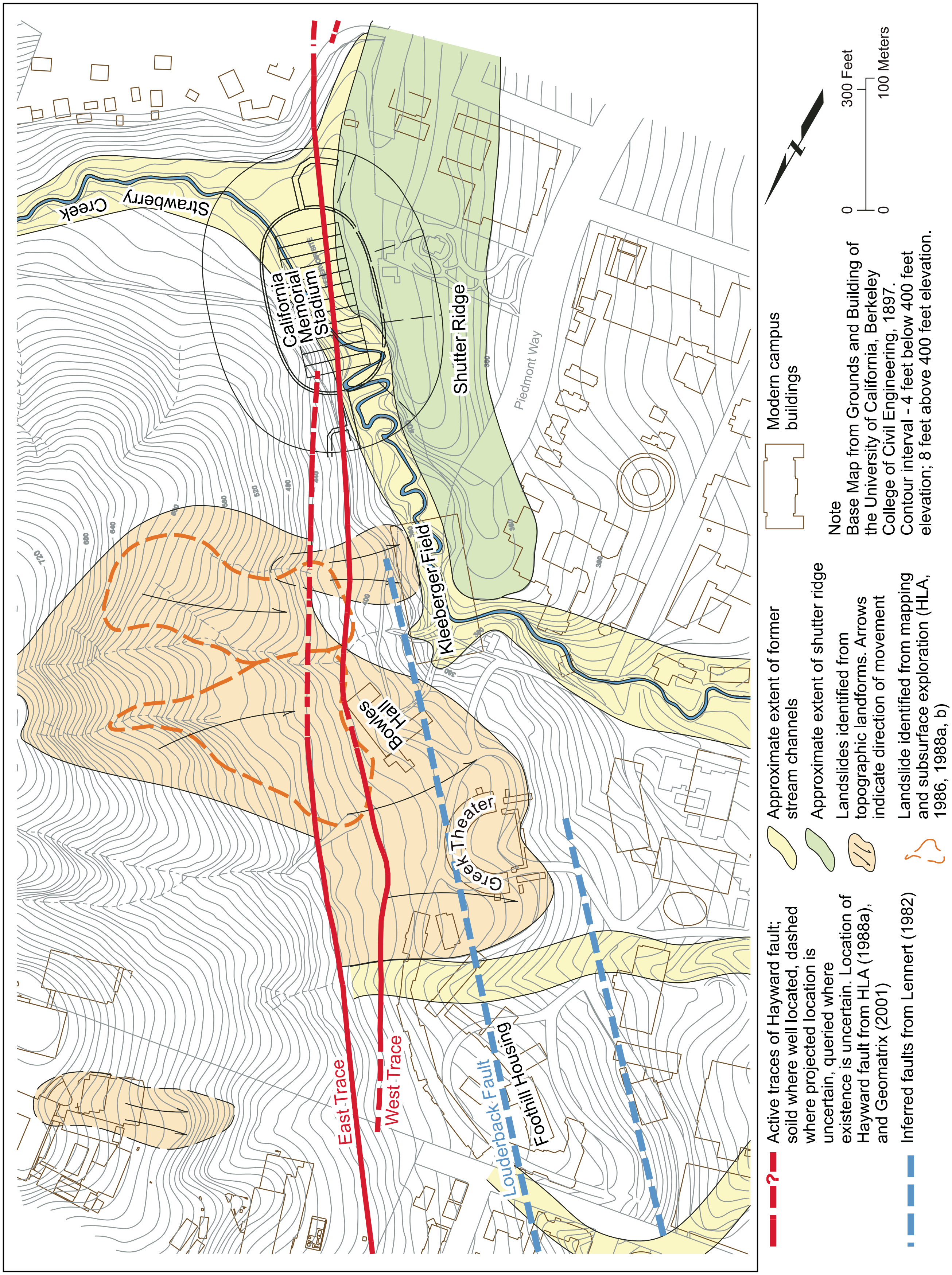
Stop Description

Memorial Stadium (Fig. 4) is an integral part of the UC-Berkeley campus. The stadium hosts football games, houses the athletic department offices, and is eligible for inclusion in the National Register of Historic Places. At the time of construction, the presence and youthful activity of the Hayward fault was known, but the earthquake hazard was not appreciated. Although the last major earthquake on the Hayward fault occurred in 1868, within the memory of residents still alive at the time Memorial Stadium was constructed, this earthquake did not produce surface rupture along the fault in Berkeley.

Prior to construction of the stadium, a faulted linear ridge, referred to as a shutter ridge, extended across the mouth of Strawberry Creek, forming a natural bowl at the mouth of the canyon. Strawberry Creek flowed westward to the mouth of the canyon, was deflected northward ~1100 ft along the shutter ridge, and resumed a westward flow around the end of the shutter ridge (Fig. 3). The stadium was constructed across the shutter ridge, natural bowl, and edge of the Berkeley Hills. The northeast side of the stadium is founded on a cut-slope in Cretaceous Great Valley Sequence sandstone; the west side is founded on dense alluvium-colluvium on the shutter ridge; and the north end, south end, and southeast side of the stadium are founded on fill placed in the creek channel and natural bowl. Strawberry Creek was buried in a culvert beneath the stadium and the area where Kleeberger Athletic Field was later constructed on the north side of the stadium. A second culvert was later constructed beneath Stadium Rim Way, crossing the hill north of the stadium and continuing beneath Kleeberger Field to carry excess flow from Strawberry Creek (Fig. 5). The creek now emerges from the culverts behind the Women's Faculty Club near the intersection of Centennial Drive and Gayley Road.

The position of the shutter ridge, location of changes in channel morphology of Strawberry Creek, and locations of fault creep in the area of the stadium show that the main creeping trace of the Hayward fault bisects the stadium from the south end through the north end (Fig. 3). The stadium structure has been deformed as a result of ongoing fault creep. As much as 15 inches (38 cm) of creep may have occurred beneath the stadium since it was built, assuming an average creep rate of ~4.7 mm/yr (Galehouse, 2002). Creep on the Hayward fault has resulted in cracking and separation of exterior and interior walls and joints, tilting of interior columns, and offset of expansion joints along the stadium's rim.

From the Prospect Court parking lot, climb the outside stairs along the south side of the stadium. Note the diagonal fractures extending along the south wall of the stadium. About halfway up the stairs, the fractures change orientation from down-to-the-west to down-to-the-east (Section LL, bottom profile on Fig. 6). This transition is consistent with the projected location of the creeping trace of the fault as identified inside the stadium. A similar inversion in the direction of fracturing occurs on the north exterior wall of the stadium, east of the north access tunnel (Section A, top profile on Fig. 6). Although there is extensive fill under the north and south ends of the stadium, the zone of extensive fracturing is localized and does not extend across the area where the thickest fill occurs below the stadium walls. Therefore, because of the orientation and localized nature, the zone of extensive fracturing does not appear to be the result of settlement of fill. In addition, and in contrast to the extensive fracturing in the exterior walls at the north and south ends of the stadium, only a few, short vertical fractures occur along the western exterior wall of the stadium (Section C on top profile, and Sections HH–K on lower profile of Fig. 6). Examples of the types of fractures and inferred mechanism for the origin of these fractures in the exterior stadium walls are shown on Figure 6 and in Doolin et al. (2005).



Note
Base Map from Grounds and Building of the University of California, Berkeley College of Civil Engineering, 1897. Contour interval - 4 feet below 400 feet elevation; 8 feet above 400 feet elevation.

Figure 3. Geomorphic features and location of Hayward fault at the University of California, Berkeley. Modified from Geomatrix Consultants (2001).

Figure 4. Memorial Stadium on the University of California–Berkeley campus. Kite photograph by Charles Beuton, University of California–Berkeley.

Return to the parking lot level. There is an expansion joint on the west side of the first entryway in the stadium. The stadium was originally built in two halves, to allow motion on the Hayward fault during a large earthquake. Apparently, it was thought that in such an event, the stadium structure would just gently separate along the junction. The walls of the stadium have tilted, forming about a 6-inch-wide gap at the top that is covered by a metal plate. The ~15 inches of fault creep occurring since construction of the stadium are accommodated in part by fracturing of the exterior wall along the stairs and by slip and rotation of the stadium walls along the expansion joint.

Enter the stadium through the archway at the base of the stairs. Note the tall interior columns supporting the stadium seating deck. The columns are progressively tilted around the south end of the stadium, from east (near the tunnel to the south end of the field) to west at the expansion joint (at the double columns). The creeping trace of the fault is constrained to pass between the first vertical column (on the east) and the first tilted column on the west, near the entrance of the tunnel to the field (Fig. 7). The tilting of the columns occurs because the stadium seating deck at the top of the columns is founded on fill east of the fault and is effectively cantilevered to the west across the creeping trace of the fault. Thus, the bases of the columns west of the fault are moving northwest, past the tops of the columns, which are attached to the stadium seating deck. The cantilevered deck section extends westward to the expansion joint. On the north side of the stadium, the orientation and locations of tilted columns indicate that the portion of the seating deck on the west (founded on the shutter ridge) is cantilevered eastward across the creeping trace of the fault.

Continue through the mezzanine level to the seats. Walk up the steps to the rim of the stadium to view the displacement at the top of the expansion joint (Sections K–KK). Walk down the steps to the field level to see deformation in the seating area. Note the separation of the stairs and the concrete footing for the seating decks and the minor cracking in the small wall around the field at the base of the steps (Sections KK–L-LL). Similar deformation is observed in Sections XX–X-WW at the north end of the stadium (Fig. 7). A series of fractures is also present on the east wall of the north access tunnel. Outside the north tunnel entrance, extensive fracturing occurs in the wall extending up the exterior stairs to the east (top profile on Fig. 6). The interior staircase up to the mezzanine level, which is accessed through the first entryway east of the tunnel, also is fractured due to fault creep (Fig. 7A). These features show that creep displacement on a narrow fault trace is accommodated across a wider zone within the stadium structure above the fault.

Logging of fault trenches extending from the curb at the parking lot and up the hill directly north of the exterior stairs revealed weakly defined shearing (attributed to creep in the soil) and several small faults in the young colluvium along the lower portion of the hill (Fig. 3). Fault creep deformation identified in the Strawberry Creek culverts (beneath the hillslope north of the trenches and beneath the stadium playing

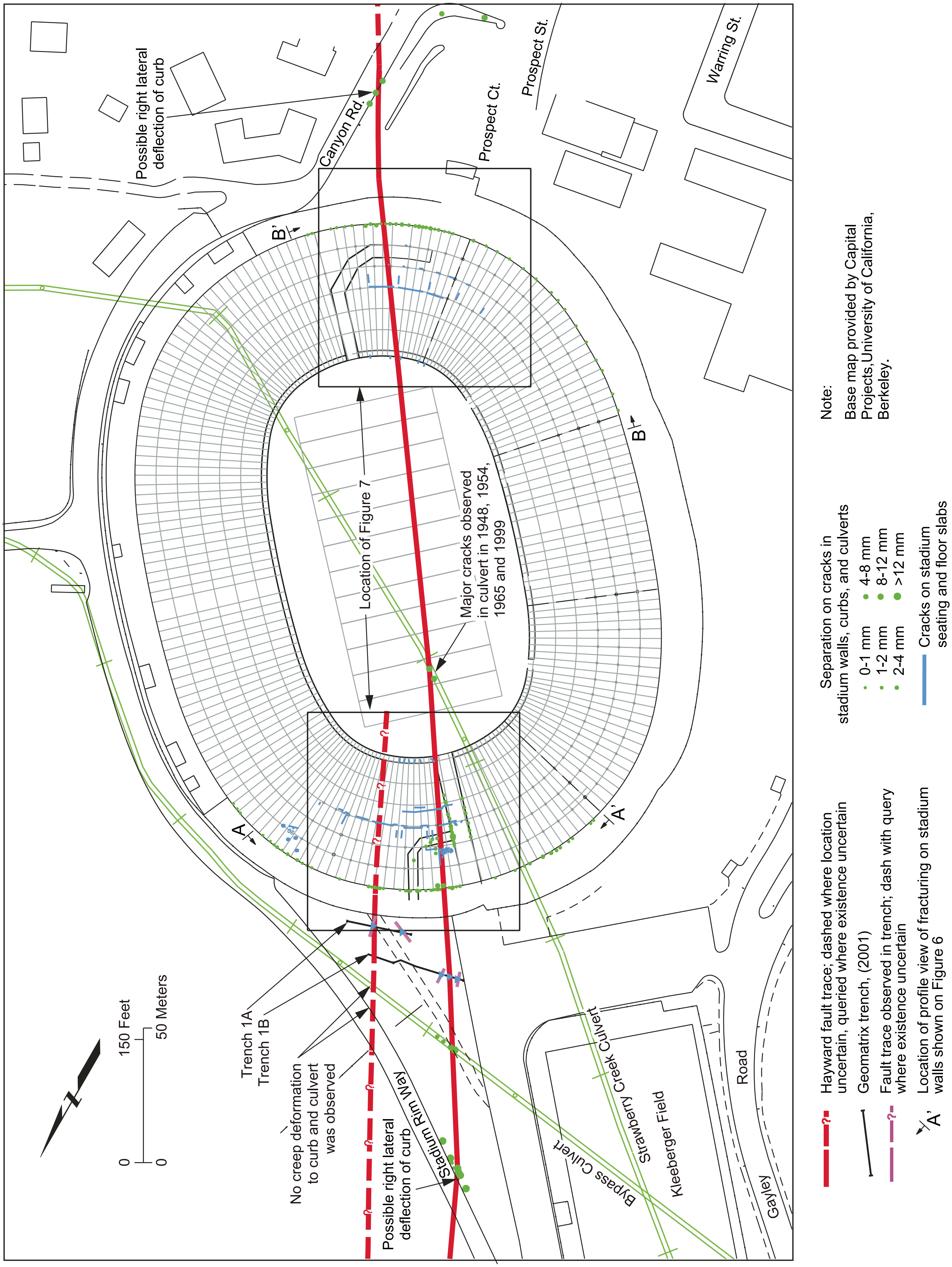


Figure 5. Plan map of Memorial Stadium area showing location of creep-related deformation. Modified from Geomatrix Consultants (2001).

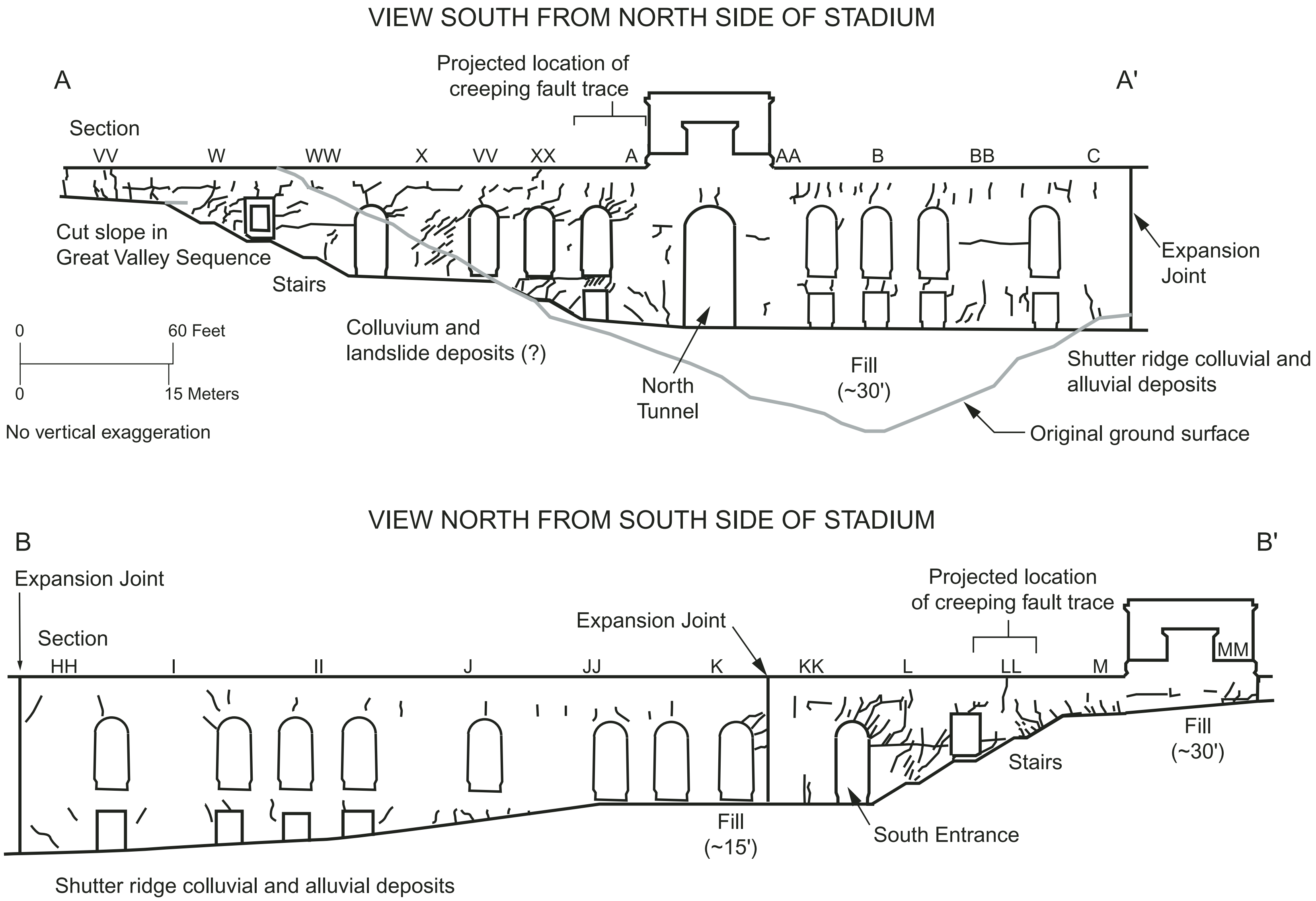
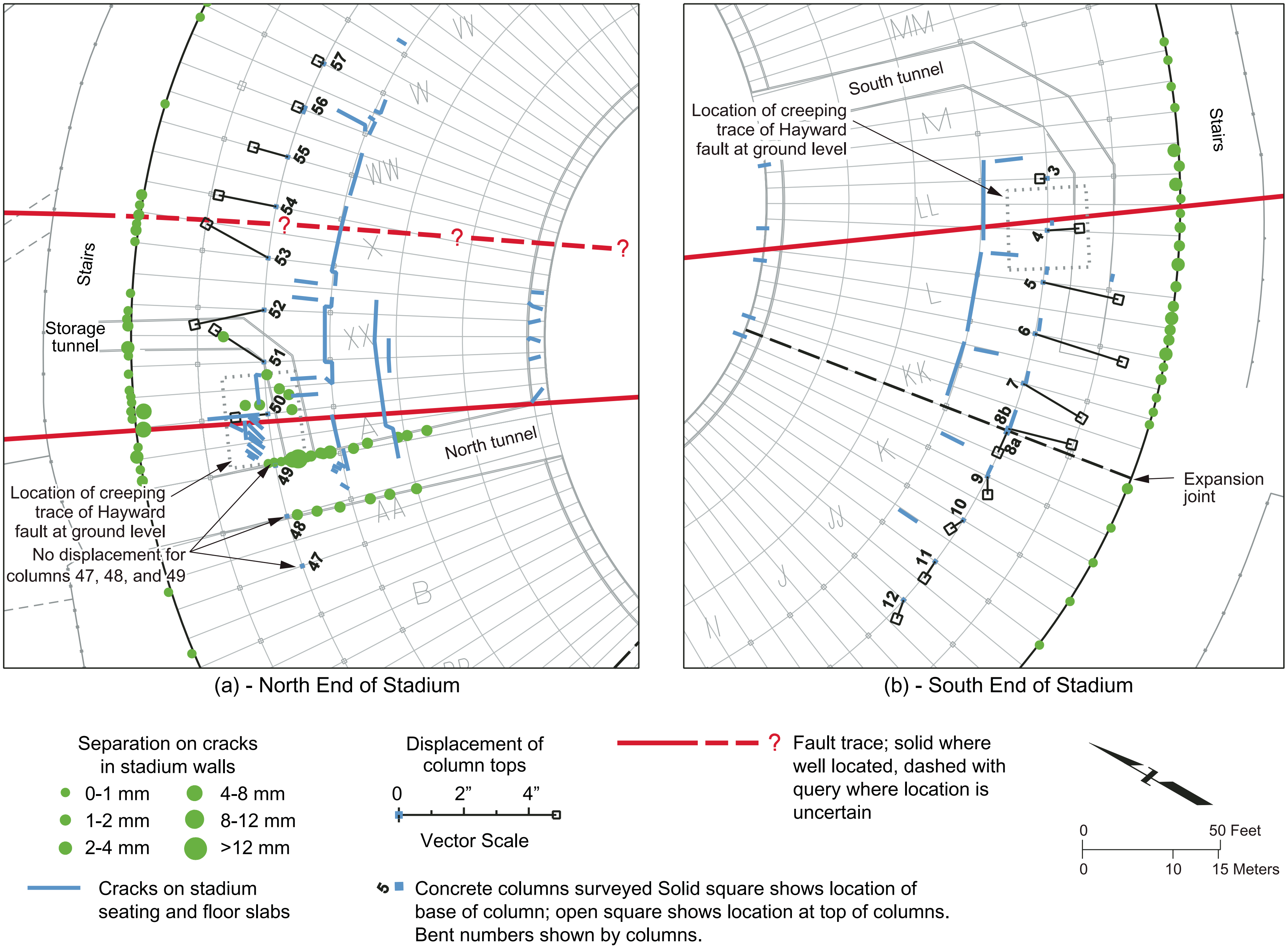


Figure 6. Elevation views of the northern (B, at bottom above) and southern (A, at top above) ends of Memorial Stadium. The diagonal, vertical, and horizontal fractures are interpreted as fault related, settlement induced, and construction induced, respectively. Modified from Geomatrix Consultants (2001).


(a) - North End of Stadium

(b) - South End of Stadium

Figure 7. Enlarged plan views of the northern (a, top left) and southern (b, top right) ends of the stadium. Modified from Geomatrix Consultants (2001).

field) and in the curb on Stadium Rim Way north of the stadium align with the zone of shearing observed in the trenches, and with the location of inversion of fracturing in the north and south stadium walls. The alignment of these features observed at or below ground level, along with the deformation to the columns inside the stadium, constrains the location of the creeping trace of the Hayward fault. The extent of shearing and faulting in the trenches and the width of fracturing in the stadium (attributed to fault creep) is used to infer a wider zone through the stadium where fault rupture may occur (Geomatrix Consultants, 2001).

The university and the athletic department are currently developing a plan to renovate the stadium. The plan is to preserve the historic character of the stadium while creating a first-rate facility that improves life safety, enhances the game-day experience for fans, and provides the football team and twelve other men's and women's intercollegiate teams with space for a state-of-the-art training and development and coaching center. The university and its consultants also are developing plans to improve the seismic safety of the stadium and to mitigate the surface rupture hazard. These plans are in the early stages of development but may involve reconstructing portions of the stadium above the fault zone on a mat foundation. The reconstructed sections would be connected to the eastern and western sections of the stadium across a series of seismic joints that would accommodate fault creep and fault displacement in the event of an earthquake. Specific considerations that may be addressed in mitigating the fault rupture hazard are the likely fault displacement during an earthquake on the Hayward fault, the amount of deformation that may propagate through the fill above the fault, and the width of the zone of deformation at the foundation level.

Additional information on Memorial Stadium, the Hayward fault, and the geology of the campus is found on "The Geology of Bear Territory" Web site at http://seismo.berkeley.edu/geotour/, and in Doolin et al. (2005), Borchardt et al. (2000), and Hirschfeld et al. (1999).

Stop 2: Seismic Retrofits on the UC-Berkeley Campus (Stephen Tobriner)

Significance of the Site

The Hayward fault cuts across the eastern end of the UC-Berkeley campus; this trip will examine seismic retrofits to buildings on the campus. The buildings illustrate different retrofit strategies, each designed to solve the specific seismic problem posed by the particular building. These buildings represent only a portion of the scores of buildings retrofitted on the UC-Berkeley campus. The retrofitted buildings on this tour include historic South Hall, built in 1870; the Hearst Mining Building, designed by John Gale Howard and completed in 1907; Hildebrand and Latimer Halls, designed by Ansen and Allen in 1960; and Wurster Hall, designed by Esherick, Olsen, DeMars and completed in 1964.

Accessibility

BART, Berkeley Station; AC Transit; public restrooms are available; parking on street or in the University Hall West Lot, Addison and Oxford Streets; Martin Luther King Jr. Student Union Garage, Bancroft below Telegraph.

GPS Coordinates

South Entrance to Memorial Stadium: 37.8700°N, 122.2504°W (WGS84/NAD83); Campanile 37.8720°N, 122.2578°W (WGS84/NAD83).

Directions

See the directions under Stop 1 to reach the UC-Berkeley campus. Walk to the grassy area west of the Campanile and look west at South Hall (see Fig. 8, map of campus).

Stop Description

Our tour of seismically retrofitted buildings on the UC-Berkeley campus (Fig. 8) begins southwest of the Campanile, facing west toward the façade of present-day South Hall (A, Fig. 8). Surrounding this area are campus buildings shaped and reshaped by seismic engineering. Chief among them are the oldest buildings of the group, South Hall (1870–1873) and the Campanile (1914–1916). These two buildings were designed from the outset to be earthquake-resistant: South Hall in reaction to the earthquake of 1868 and the Campanile in reaction to the earthquake of 1906. The retrofit programs of the university have also been prompted by earthquakes. The Santa Barbara earthquake of 1925 and the Long Beach earthquake of 1933 prompted a seismic retrofit for Stephen's Hall, the old student union, just to the left (southeast). The San Fernando earthquake of 1971 stimulated the university to reevaluate its building stock in relation to earthquake danger in 1978. Finally, the Loma Prieta earthquake of 1989 forced the university to confront the problems of seismic safety. With some retrofits already completed, university officials and California law makers saw what could happen as they witnessed tremendous losses in the 1994 Northridge earthquake in Southern California and the 1995 Kobe earthquake in Japan. The Hayward fault, as you shall see on this tour, runs through the campus, making UC-Berkeley one of the most seismically hazardous university campuses in the world.

After scattered retrofits, the university began in earnest to make the entire campus earthquake-resistant in one of the most ambitious programs, not only in California, but in the world. Usually, retrofits and seismic upgrades occur after a great disaster. UC-Berkeley's program is a mitigation program, confronting damage before it occurs. In the late 1990s, the university imaginatively combined a one-time grant from the Federal Emergency Management Agency (FEMA), funds for seismic upgrading from California Proposition 122, and university money into a single fund to support a new program called the Seismic Action Plan for Facilities Enhancement and Renewal (SAFER), committed to invest $20 million per

MAP OF CAMPUS

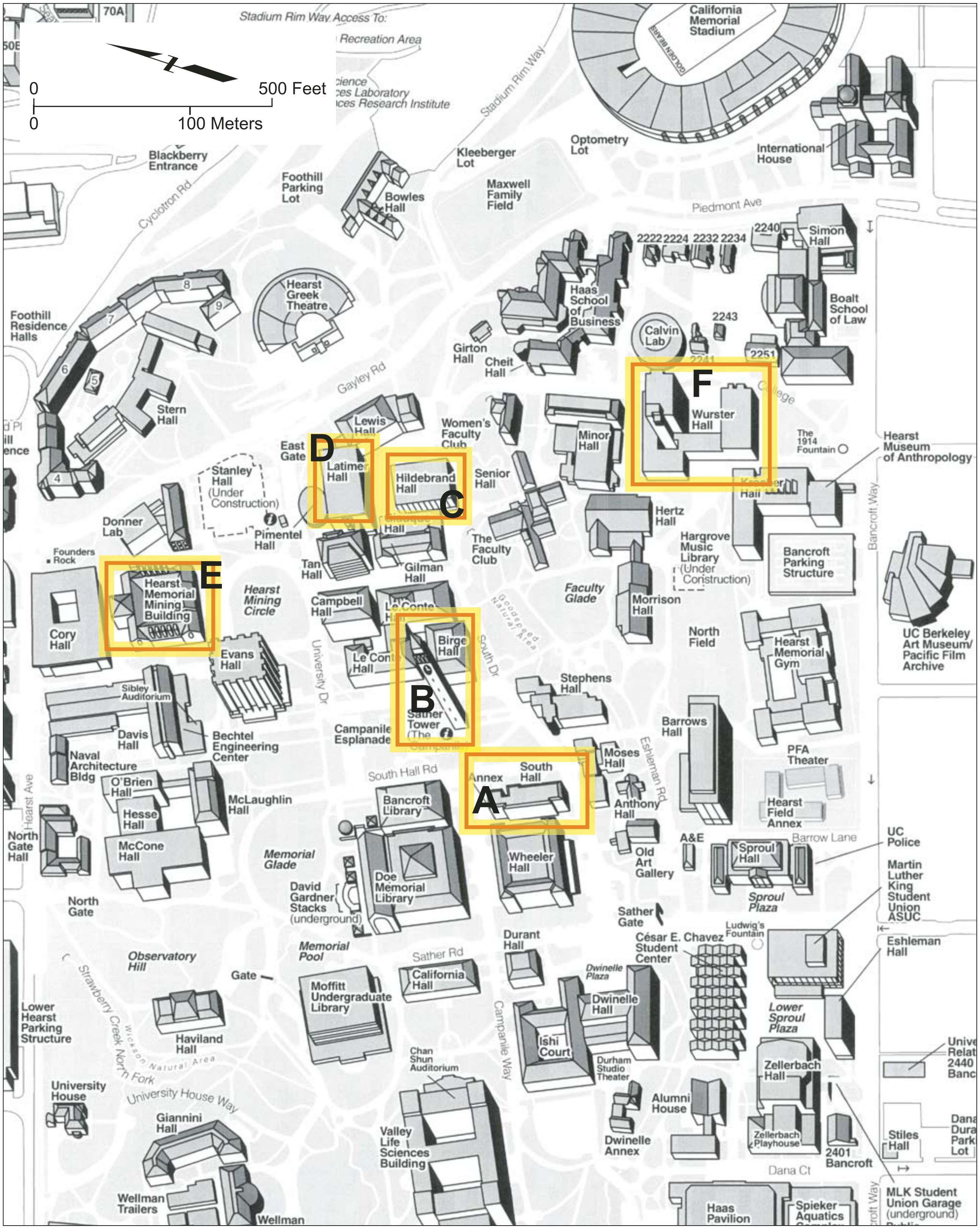


Figure 8. Map of the campus, showing retrofitted buildings described in the field guide. A—South Hall; B—The Campanile; C—Hildebrand Hall; D—Latimer Hall; E—Hearst Memorial Mining Building; F—Wurster Hall.

Figure 9. South Hall, 1873. Diagram of reinforcement in South Hall. A—bond iron courses through masonry; B—iron pilasters held in place by bond iron; C—the position of floor anchors in masonry; D—the position of internal iron girders.

year over 20 years to make the campus safe during earthquakes. The UC-Berkeley program is a model for seismic mitigation. Each building has been retrofitted using a system uniquely adapted to it, so each is different. Today we will examine just a few of the buildings that have been retrofitted on this campus.

On our tour we are going to see a strange phenomenon, best represented by South Hall: Even buildings originally constructed to be seismically resistant sometimes have to be retrofitted. Because seismic engineering has progressed since it was first built in the 1870s, South Hall was gutted and reinforced to be an even more effective earthquake-resistant building in the 1980s. Likewise, sometimes modern buildings, like Doe Library or the Bancroft Library (to your right), were not built strongly enough to resist earthquakes, so they have to be retrofitted. Unfortunately, the retrofits on campus will not make these buildings "earthquake-proof." Engineers never use that term because they cannot guarantee buildings they construct will be earthquake proof, but *earthquake-resistant*. These retrofits are designed primarily to save the lives of the students, staff, and professors.

South Hall

South Hall (Fig. 9), the oldest building on campus, was initially designed to be earthquake-resistant in 1870 because the university regents had seen building failures in San Francisco in the earthquakes of 1865 and 1868. The regents understood that wood buildings resisted seismic forces more effectively than brick masonry, and they considered having South Hall constructed of wood. The problem with wood is that it burns and is less monumental than brick. So they decided on brick, but they stipulated that the new building had to be earthquake-resistant.

Let us take a minute to try to understand the problems inherent in making a brick building earthquake resistant. Buildings are designed to support static or vertical loads. These include the weight of the materials in the walls, floors, and roof (dead loads), and whatever rests on the floors and can be moved, like people and furniture, as well as whatever falls on the roof, like snow (live loads). These loads are usually applied to the structure slowly and evenly, pressing down vertically.

However, the waves generated by an earthquake create dynamic forces that vibrate the structure and change rapidly. As the building vibrates in response to seismic ground motion, inertial forces are created within it. When it is pushed to one side, it rebounds, but because of inertial forces, it continues past its former resting position to bend in the opposite direction. Because buildings are primarily designed to resist vertical forces, sidewise (lateral) forces are the most dangerous in earthquakes.

Imagine South Hall in an earthquake. Think of it moving up and down and side to side in relation to ground shaking. Can you visualize what would happen if you pushed it strongly to the left or right? Lateral forces are transferred from the ground through walls to diaphragms, like floors and roofs, and then back to the ground again through the walls. The forces acting upon the walls are called shear forces. Shear forces, which tend to distort the shapes of walls, occur when lateral forces push a wall along its length. If a brick wall is pushed sideways by lateral forces, it will resist until the bond breaks between the bricks, or the bricks themselves break. A diagonal crack, called a shear crack, will appear, or sometimes an X-shaped crack. When you push against a wooden pencil, it can bend. Because stone and bricks are brittle, they can't bend, so they crack and eventually break.

Even in an extensive uninterrupted brick wall, bricks are problematic in earthquakes. The greater the mass—the heavier the wall—the greater the inertial forces an earthquake will create within it. In accordance with Newton's Second Law of Motion, $F = M \times A$, inertial force (F) is equal to the mass of the building (M, equivalent to its weight at ground level) times the acceleration (A). When shaken side to side, a properly braced, square, wooden, three-story structure on a sound foundation with well-tied diaphragms will bend because of wood's ductility and elasticity. A similar masonry building is heavier, stiffer, and more brittle, and instead of bending to dissipate energy, the brittle masonry will crack, or the walls may rupture and collapse.

Engineers and architects in the San Francisco of the 1860s were alarmed by this problem of brittle brick masonry, and they tried to solve it by designing buildings that included more flexible materials to hold them together. They also understood, as do modern engineers, that a building must be tied together to act as a unit in an earthquake.

South Hall as a Seismically Resistant Structure, 1870

South Hall was designed by David Farquharson (of Knitzer and Farquharson architects) probably using the ideas of the first design for the building by John Wright. Farquharson's seismic system was an architectural composite; it depended upon a building's brick walls, wood supports, wood diagonal sheathing, wood floors, iron tie-bars, iron anchors, and iron columns working together. He considered how every part of the structure, from its foundation to its chimneys, could be tied together. He believed that a building's structure, as well as its decoration, could aid in its seismic resistance. His use of seismically resistant ornament heralded a new style of architecture that was beautiful because of its frank expression of purpose.

South Hall is bound together by ribbons of iron called bond iron (Fig. 10), and the brickwork and lime mortar are exceptionally strong, even by modern standards. Pieces of bond iron measuring two and a half inches by three-eighths of an inch were worked through the brick above and below the apertures on each story and at the joist level. These pieces of iron were spliced together with two bolts at each joint to form a continuous belt around the whole structure. As each belt of bond iron approached an end wall of the structure, it was forged into a threaded rod. Depending upon their position, these rods either entered heavy corner impost blocks or went directly through the wall of the building to be bolted to iron pilasters on the exterior. This network was clearly intended to hold the whole structure together should the bricks begin to fail.

A second line of defense can be seen on the building's exterior, which is decorated with vertical ornamental panels made of cast iron. They appear at the corners and sides of the building, often with the threaded rods of the bond iron protruding through them. The rods are secured to the panels by decorative bolts that form a regular pattern, appearing even where no rods are present. Rather than securing the panels (which are held in place by special iron hooks), these bolts unite the bond iron from one side of the building to the other. This linking suggests that Farquharson hoped to form a sort of exoskeleton.

Farquharson seems to have taken great care to make sure the floors functioned as diaphragms, tying the exterior walls to them and thus helping the building move as a unit. South Hall is an I-shaped building with a corridor running down the middle. Farquharson lapped every other 4 × 16-inch joist over the top of the corridor, effectively tying the building together. Every joist in the structure was either nailed to a hanger or extended out into the brick walls. Large, round iron anchors are buried three widths into the brick exterior walls, bolted to the end of huge iron angles attached to the joists.

If the brickwork began to break up, vertical iron Ts implanted in the north and south walls of each the large lecture halls on the wings of South Hall would provide support (Fig. 11). Two great iron girders spanned the north and the south lecture halls, supporting 4 × 16-inch wooden joists. The vertical iron Ts supported the iron girders on each side of the room, creating a redundant brick and iron wall support; the iron would probably have buckled without brick around it. Farquharson's construction points to the significance of redundancy, another important idea in earthquake-resistant construction.

The Retrofit of South Hall, 1980s

When engineers examined South Hall in the 1980s, it was classed as an unreinforced masonry building (URM). The engineering firm of Rutherford and Chekene decided they could not depend on Farquharson's solutions because of certain design flaws in the building. There were notable weaknesses. For example, the horizontal planes in the building—floors and roofs—were intended to act as diaphragms, distributing loads to the exterior walls. But the roof structure was poorly con-

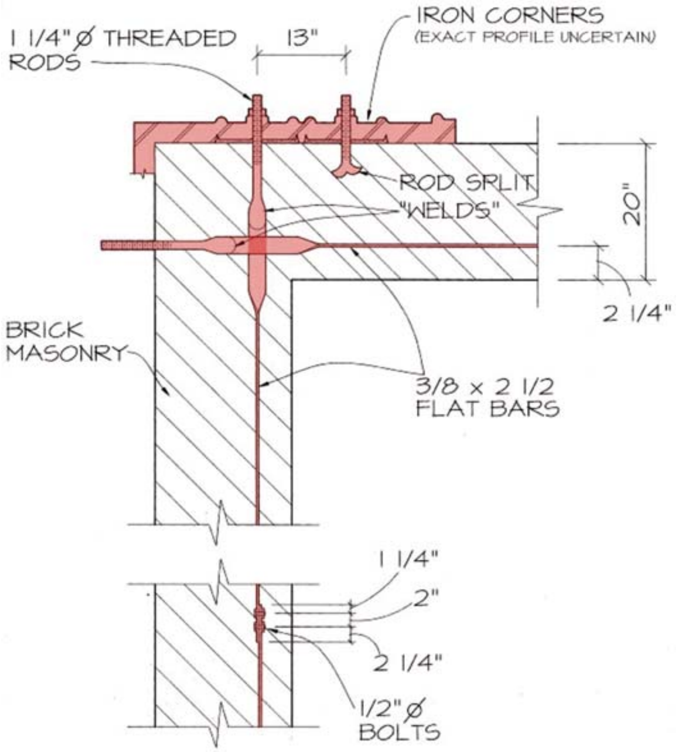


Figure 10. Diagram of bond iron in walls and attachment to external iron pilasters in South Hall.

ceived and badly built. The entire roof assembly needed to be rebuilt and many of its members replaced. The engineers also felt the many windows and fireplace flues in the façades weakened the wall planes to such an extent that they might fail in shear, that is, "in-plane." Because of these problems, they gutted the interior and tied the backs of the bricks to a reinforced concrete wall of sprayed shotcrete, which they built on the back side of the original wall. In order to do the work, they dismounted (and subsequently remounted) all the decorative woodwork and plaster on the walls. They also installed new floors to work more effectively as diaphragms, and tied the building together vertically by running reinforcement rods through its walls and the fireplace flues. When they were through with the interior, they removed the chimneys and substituted plastic replicas. The retrofit was done so carefully that both the interior and exterior of South Hall are remarkably similar in appearance to the original building.

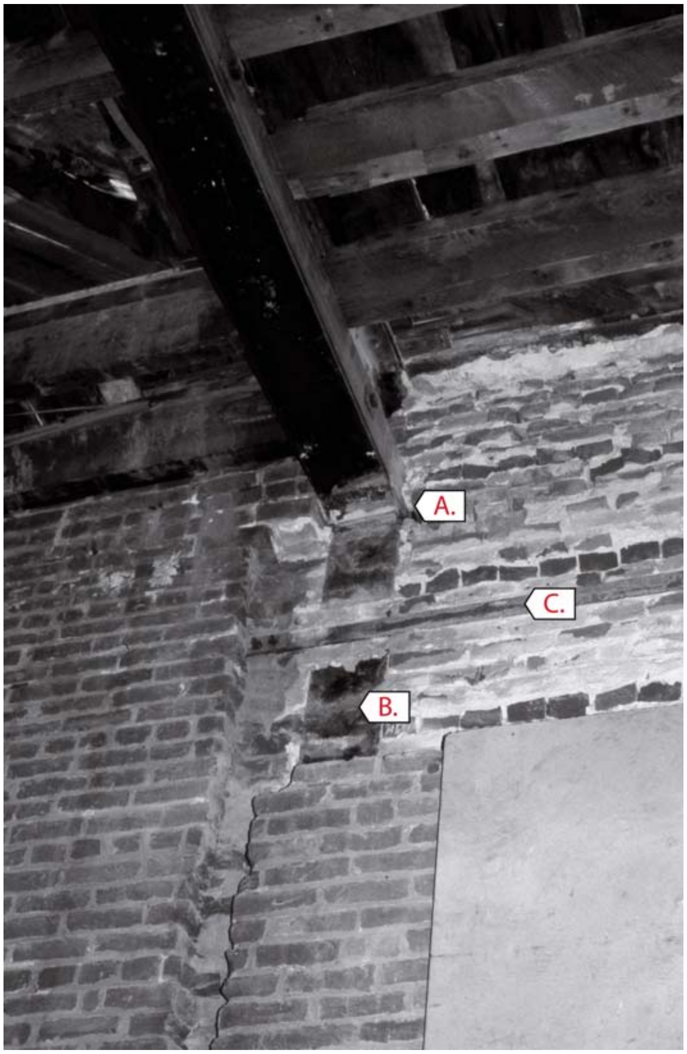


Figure 11. South Hall wall in demolition. Iron T-shaped columns (B) hold up girders (A) with bond iron in outside walls. Note one row of bricks has been removed.

The Jane K. Sather Campanile

To the right is the Campanile (B, Fig. 8), designed in 1914 by John Galen Howard, engineer Erle L. Cope, and consulting engineer Charles Derleth Jr. A professor of civil engineering, Derleth was the designer of the structural system that was intended to resist earthquakes. Walk up to the walls of the Campanile and look at the corners. Look at the sides of the tower and the canopy over the front door. Why do you suppose that there appear to be subtle barriers of plants and the canopy around the tower?

Derleth designed the tower to be both strong and flexible. He studied how towers failed in San Francisco in 1906 and decided his would never fail. One of the strategies he decided upon was to build a steel frame and use reinforced concrete as a backing for the granite veneer on the exterior. In order to make the tower strong and stiff, but also flexible enough to bend, he staggered the braced floors with unbraced floors. If you are here when the tower is open, go into the lobby and look at the plans. Then take the elevator to the top, not just to see the view, but to examine the structure of the tower, which is easy to see. Derleth made sure his tower would rock back and forth in an earthquake slowly enough as to be out of resonance with the earthquake. To be in resonance would be very dangerous. When we instinctively kick our feet while on a swing, we are attempting to put ourselves in resonance with the arc of the swing. When buildings are in resonance with earthquakes, as in the Mexico City earthquake of 1985, they can shake themselves to pieces.

Have you solved the problem of the planting? The corners tell the story. It wasn't shaking, but expansion and contraction caused by heat gain, combined with minute movements of the tower and decaying anchorage of the granite that contributed to its cracking. In the 1950s, while the problem was under investigation, the university erected the canopy to protect the entrance and the planting to keep us at a safe distance from the tower. In 1976, the granite was repaired and recaulked, but still the barriers remain. Unfortunately, seismic retrofits require more than planting and canopies.

Walk east on the road next to Strawberry Creek, passing Le Conte and Gilman Halls on our left, until we see a concrete and brick building hovering in front of us. Walk up to it and stand at the southeastern corner of its façade.

Hildebrand Hall

In the 1960s, the university began work on three buildings that would make up the core of its chemistry department, Latimer (1960–1963), Hildebrand Hall (1963–1966), and the huge, oval Pimentel Hall auditorium (1963–1964). The architects were Anshen and Allen, who in this case wanted to fashion handsome scientific buildings in the corporate mold of the day. The engineer of one of these buildings, Hildebrand Hall (C in Fig. 8; Fig. 12), was the famous T.Y. Lin (1912–2003). Although earthquake forces were specified in the building codes, no powerful earthquake had yet tested the engineering aesthetic of the day, which focused on economy and invention. T.Y. Lin was known internationally as the "father of pre-stressed concrete," a technology that fundamentally broadened the possibilities of architecture, engineering, and construction. Although pre-stressing technology was first invented in the 1940s, T.Y. Lin was the first to make it practical, economical, and popular. He enthusiastically recognized its enormous potential, not only for saving money but also for bringing a new freedom to architecture. Hildebrand Hall exemplifies the potentialities of pre-stressed concrete.

Reinforced concrete derives its strength from embedding steel, which is extremely strong in tension, in concrete, which is strong in compression but weak in tension. In a conventional reinforced concrete slab or beam, the normal bending forces put the bottom portion into tension, causing cracking at the bottom part of the beam. In a pre-stressed slab or beam, an initial tension is applied to the reinforcing steel prior to the pour. After the concrete cures, the steel tendons are released, causing the entire slab to go into compression, thus eliminating the tension stress at the bottom portion of the concrete and increasing the capacity of the slab. Pre-stressed slabs and beams can therefore be much thinner than conventional reinforced concrete, decreasing the weight and cost of each element and allowing for more innovative designs. The savings can approach 50% in concrete weight and 20% in steel weight.

Hildebrand Hall lies adjacent to the south side of Latimer Hall. A system of underground passageways connects the two buildings and other adjacent labs. Hildebrand Hall consists of two partially underground floors and a three-story tower that rises from the plaza level. You can actually walk underneath Hildebrand to a small courtyard and up two curving stairs to Latimer. (If this passage is closed, it is possible to walk around the left side of the Hildebrand façade and upstairs to the plaza.)

On the plaza, turn to the southeast to look at Hildebrand (Fig. 13). The first level of the tower houses the chemistry library, whereas the two lower floors and the two upper floors contain labs, workshops, and storage spaces. The top two floors cantilever dramatically over the glazed library level. The building's site slopes equally dramatically to the south, exaggerating the effect of the cantilever. Designed to achieve architectural harmony with the adjacent buildings, the materials palette included concrete, glass, and terracotta.

Remember the problem of shear? Shear-resisting elements are absent here to a degree almost shocking by today's standards. The concrete stair and elevator enclosures provided the only lateral force resistance in the building. These enclosures shared the gravity loads with eight interior columns and a series of box and fin columns at the edge of the first floor. Precast panels were hung from the cantilevered second and third floors to create a façade. In earthquake country, this design was a disaster waiting to happen. As in South Hall, engineers and architects were innocent of how to design appropriately for earthquakes. But there is a difference: Farquharson had tried to use redundancy and multiple systems. T.Y. Lin was more intent on a single, light, cheap, beautiful system.

In 1997, Forell/Elsesser, Rutherford and Chekene and Degenkolb Engineers completed a joint seismic analysis of Hildebrand Hall. The analysis predicted that the interior columns would punch through the floor slabs, causing widespread structural collapse on all three floors of the tower. The precast panels' connections to the second and third floor slabs were expected to break due to lateral motion, and the library mezzanine was expected to collapse due to a lack of lateral resistance.

Anshen and Allen and Forell/Elsesser investigated numerous retrofit strategies for Hildebrand Hall and finally decided to use unbonded braces, which were a very new and promising addition to anti-seismic technology. You can see these braces on the plaza floor of the building (Fig. 14). Unbonded braces work in a simple and elegant manner. In a traditional steel cross brace, lateral forces are resisted axially by each cross-member. An applied lateral force will stretch one cross-member in tension and shorten the other in compression. Unbonded braces are made of both steel—which is strong in tension—and concrete—which is strong in compression, enabling the braces to exhibit nearly identical properties in both tension and compression. In addition to the braces, new concrete shear walls, providing lateral support, were added to the two lowest stories, and on the east and west side a portion of the shear walls extend up to the roof. The walls around the stair cores were strengthened and reinforcement was

Figure 12. Hildebrand Hall seen from the southwest.

added to the column-to-slab connections, mitigating the threat of punching shear by the columns. The connections between the precast panel hangers and the roof and floor slabs were strengthened as was the mezzanine level of the library.

Turn around; on the north side of the Plaza is Latimer Hall.

Latimer Hall

Architects Anshen and Allen also designed Latimer Hall (D in Fig. 8; Fig. 15). However, instead of T.Y. Lin, the engineer chosen for Latimer was Henry Degenkolb (1913–1989), a world-renowned expert in earthquake engineering. Despite the difference in the engineers' expertise, both buildings were found to be seismically unfit in a 1997 review and in 2001 both received extensive retrofits as part of the university's SAFER program. The fact that both buildings needed retrofits is a testament to the dramatic growth in the body of knowledge regarding earthquake engineering in the past four decades.

Henry Degenkolb graduated with a degree in civil engineering from UC-Berkeley in 1936. Special attention to seismic concerns comprised one of the major differences between the work of Degenkolb's firm and those of conventional offices. In professional practice, Degenkolb was one of the few offices in

Figure 13. Hildebrand Hall from the plaza.

Figure 14. Hildebrand Hall: unbonded braces.

Figure 15. Latimer Hall.

the country that set the standard for seismic safety. Although Degenkolb had been practicing for over two decades by 1960, when Latimer Hall was designed, the industry's knowledge of building performance in earthquakes was still nascent compared to what we know today. A string of earthquakes—in Alaska in 1964, Caracas in 1967, and San Fernando in 1971—spurred a period of intensive investigation of earthquakes and revision of building codes. When Degenkolb designed Latimer Hall, the code was a very thin document compared to today, but he recognized the threat of earthquakes and, like many engineers in California, designed beyond the code.

In addition to two basement stories, the 184,000-square-foot building has nine stories above ground in a rectangular tower that accommodates 831 laboratory stations and 213 fume hoods. The building's program required a floor plan that was unimpeded by walls and columns to allow for a flexible laboratory layout. The volume and complexity of the building program and needed services substantially influenced the design of the building. To develop an architectural solution that successfully addressed all of the project's challenges, Anshen and Allen worked closely with Degenkolb Engineers. To provide the main structure of the building, the project team used exterior concrete box columns. These large, hollow columns visibly line the exterior of the north and south sides of the building. They are like large, square donuts, 7 ft-3 inches wide, spaced 27 ft apart and constructed of 14-inch-thick walls of poured concrete heavily reinforced with steel rebar. These columns provide major structural support for the building and house the large ducts that drain the laboratory fume hoods, leaving each floor with an open plan that allows for easy rearrangement with nonstructural partitions. Openings in the columns at each floor made access for maintenance or modification relatively easy. The columns also provide a highly visible architectural expression of the building's structural and mechanical systems, announcing, as a series of exterior fume hoods would, the activities taking place within.

These concrete box columns, along with the floor diaphragms connecting them, provided the lateral force resistance in the longitudinal direction. Short shear walls at the stair and elevator cores also provided longitudinal shear strength. Lateral force resistance in a transverse direction was supplied by large concrete shear walls capping the east and west ends of the building, aided by the walls around the elevator core. Gravity loads were shared by the perimeter box columns, the elevator and stair cores, and 12 steel columns in the interior of the building.

In April of 1997, UC-Berkeley enlisted Degenkolb Engineers to do a preliminary seismic evaluation of Latimer Hall as part of its newly instituted SAFER program. This brief review of the building determined that in the case of a "rare" earthquake (one with a 10% chance of occurring within 50 years) the building would perform with a "poor," or near collapse, rating. This performance expectation was due mainly to deficiencies in the longitudinal lateral force resisting system. The box columns, and the floor slabs spanning the distance between them, were designed to act as moment frames that resisted applied shear force. However, the floor slabs were not continuous through the box columns, and their attachment to the columns was insufficient for the system to behave like a true frame in the event of a strong lateral load. The other longitudinal walls were too slender to add significant lateral support. Other deficiencies were also noted in the transverse direction; namely, that the stress in the transverse shear walls would exceed capacity and that openings at the first level of these walls weakened them.

The "poor" rating of the building and the chemistry department's size and importance to the university made Latimer Hall a high priority for a seismic retrofit. The university applied for and received a large grant from FEMA, nominally under the "Preventative Medicine Test Cases" program, and began the retrofit in 2000. Anshen and Allen once again acted as architects and Forell/Elsesser Engineers were hired as the structural engineers.

The architects and engineers worked together to find a retrofit solution that would not block light into the lab spaces. Rather than introducing a new structural system to the building, the selected strategy strengthened the building's existing system. This scheme essentially consisted of adding more reinforced concrete to the existing columns, beams, and walls at the building's exterior. You can see this by looking at the concrete balconies between the columns. Notice the different color of the concrete. These balconies were added along the longitudinal side of the building to strengthen it. Increased strength in the transverse direction was achieved by thickening and reconfiguring the shear walls at the east and west façades and improving their connections to the ground. The building continues to express its structural and mechanical systems on its exterior, now with a new layer that serves as a testament to the quickly changing field of earthquake engineering.

Now walk north again through Latimer Hall if it is open, or around it if not, passing the round to the Mining Circle and past the newly constructed Stanley Hall (the original Stanley Hall was demolished because it was a seismic hazard). In front and across the circle is the Hearst Memorial Mining Building.

The Hearst Memorial Mining Building

The Hearst Memorial Mining Building (E in Fig. 8; Fig. 16) was designed by John Galen Howard and completed in 1907. Phoebe Apperson Hearst, widow of Senator George R. Hearst,

Figure 16. Hearst Mining Building.

provided the funding for the building, which was to be a memorial to her late husband, who made his fortune in mining. The exterior is one of the most beautiful examples of the French Ecole des Beaux Arts style on campus. Step up to the façade and look at the detailing. Here the ideals of the Ecole, symmetry regularity and hierarchy, are married to an elegant Renaissance Revival–Mission style. As you walk inside, you are greeted by a magnificent open atrium (Fig. 17), the design for which was inspired by Henri Labrouste's reading room (1862–1868) of the Bibliotheque Nationale in Paris. Behind the vestibule was a tremendous open nave, which was designed to hold working mining machinery. Today, this space is occupied by classrooms and offices.

Walk in the door and admire the soaring atrium (Fig. 17). Read the bronze plaque with the dedication to George Hearst. Opposite the front door are double doors leading into the former nave which housed the mining machines. Facing the double doors are photographs of the building being retrofitted.

The building is a four-story steel and unreinforced masonry building with exterior cladding of granite masonry. The struc-

Figure 17. Hearst Mining Building interior.

tural system consists of brick bearing walls with a very thin steel skeleton that was found to be inadequate to support the high gravity loads. An unreinforced concrete and brick foundation supports the steel frame columns, the unreinforced brick masonry walls, and the concrete floors. Modifications were made in 1947 when the central nave was destroyed to create additional levels. In 1949 and 1959, other open galleries were closed in.

In a 1990 study conducted by the engineering firm Rutherford and Chekene and the architectural firm Esherick, Homsey, Dodge and Davis, several seismic construction deficiencies were found in the Hearst Memorial Mining Building. The masonry brick walls were overstressed in the shear; a number of the slabs were neither tied together nor tied to the masonry brick walls; the front façade did not adequately resist lateral loads; and chimneys, terra cotta, tile ceilings, and stone ornamentation were seen as falling hazards.

How could this building be made safe without destroying its beauty and historical character? After much discussion, it was decided by the engineers and the Chancellor's Seismic Review Committee that to bring the building from a "very poor" rating to a "good" rating, it would be necessary to use one the most expensive earthquake resistant systems: base isolation. In base isolation, a building's foundations are decoupled from the lateral motions of the earth. The Hearst Memorial Mining Building's base isolation system consists of 134 steel and rubber laminated composite columns, called base isolators, which can move 28 inches in any horizontal direction, allowing the building to safely ride out earthquakes. Because of the reinforcing steel plates, these bearings are very stiff in the vertical direction but are soft in the horizontal direction, so they can move sideways. The Hearst Memorial Mining Building's seismic retrofit not only strengthened the building, but it also allowed for significant upgrades. Additional space was created underground to house mechanical equipment, and two new three-story buildings were added at the north face. The scheme included the preservation of the building façades and restoration of many of its interior features.

Unfortunately, there are no pictures of the base isolators in the photographic display facing the double doors, and you can't see them inside the building without special permission. But if you walk out of the building, stand on the steps, and look down at its foundation, you will see that it is encircled by what appear to be dark gray paving blocks. These blocks cover the moat that runs around the entire building and are designed to move if the building pushes them. The stairs you are standing on and the entire building are supported by the base isolators.

Retrace your steps, walking south between Le Conte and Gilman Halls and crossing the footbridge over Strawberry Creek to lovely Faculty Glade. Walk up the hill, passing the music building. Before looking at the last retrofit on the tour, walk straight ahead to the new Jean Gray Hargrove Music Library by Mack Scogin Merrill Elam architects (2004). This is a steel building clad in panels of slate. Look at the doorway. You can see that part of the lateral resistant system for the building is being used as decorative feature. Have you seen a version of this system before? (Yes, in Hildebrand. This is an unbonded brace.)

If you turn around and look east, you'll see Wurster Hall. It is hard to miss.

Wurster Hall

William Wilson Wurster, the man who established the basic design parameters, picked the architects, and approved or vetoed their every decision, was pleased when he saw the nearly complete Wurster Hall (F in Fig. 8; Fig. 18) in 1964: "I wanted it to look like a ruin that no regent would like … It is absolutely unfinished, uncouth, and brilliantly strong. …This is the way architecture is best done. What I wanted was a rough building, not a sweet building. …The regents like cutie-pie and slick things…" Wurster succeeded in his wish that no regent would like the building. None did. William Wurster, the dean of the new College of Environmental Design, had a specific goal in mind when he chose the architects and interrupted their process time and time again. Like a proud father setting his sons to work, he continued to influence them. Don Olsen, one of Wurster Hall's architects, called him their "godfather"; when he was not present, he was "God hovering [over] the whole thing." Wurster wanted a particular look to the school. For him, the incomplete and the rough in architecture were physical manifestations of his philosophy of architectural education. He knew he was setting one architect against another to unleash "controlled chaos" when he chose architecture faculty members Vernon DeMars, Joseph Esherick, Donald Olsen, and Donald Hardison to design the future Wurster Hall. He wanted "strong people, each with a different slant."

After a series of attempts to create a combined design for the new College of Environmental Design (CED), Joe Esherick took over the decision-making process and set his office to work on the drawings, which did in fact incorporate some of the ideas of his partners. The building was to be as flexible in its floor plan as possible, a huge loft building, a giant concrete factory where architects, artists, craftspeople, city planners, and landscape architects would be free to explore new possibilities. The entire building is developed on the module of 4′8″, which was the area required for the surface of a drawing desk. It was to be environmentally sensitive, using special sun shades, "brise soliel," popularized by Le Corbusier. It was to be a product of the here and now, built of concrete, and as Wurster insisted, without any silly tile roofs (like those on every other UC building of the period). It was to be cheap and durable, made of reinforced concrete. Not only was reinforced concrete economically feasible, it also offered the sculptural quality that the designers desired.

The construction of the building included a combination of cast-in-place concrete with precast elements. The floors and roof were poured in place, while the exterior columns and sunshades were precast. The structural engineer, Isadore Thomp-

Figure 18. Wurster Hall, western façade.

son, invented the precast elements, which were sidewalls and brise soliel attached to mast-like fins poured elsewhere and lifted into place on the façade. If you look carefully at the façade, you can see how fins and their sidewalls are combined to create the façade. The interior of Wurster Hall was left unfinished to expose the various building systems (Fig. 19). All of the mechanical and electrical systems were suspended from the ceiling for the aesthetic effect and also because imbedding them in the concrete slab would render maintenance impossible.

UC-Berkeley architecture professors Mary Comerio and Stephen Tobriner became very concerned about the building in the 1990s. Tobriner examined the plans and found the building lacked sufficient lateral resistance systems. It would pancake in a major earthquake. As a member of the Seismic Review Committee, he asked the university to study the building. When the study was concluded, Wurster Hall, one of the largest and most heavily populated buildings on campus, was found to be a collapse hazard. In his analysis, engineer Ephriam Hirsch found that the 10-story tower had practically no bracing in the east-west direction, and that the tower's existing shear walls were discontinuous. As a result, the tower was likely to collapse during a major seismic event. Additionally, Wurster Hall's U-shaped plan with deep reentrant corners has the potential for high lateral stresses at the intersection of the north and south legs. During a major seismic event, severe damage was likely to occur at the corners where the north and south towers join the building. In order to strengthen the building, a building committee was convened in the fall of 1997 to review the retrofit process. The committee interviewed a number of potential teams to complete the retrofit project and selected the architectural firm of Esherick, Holmes, Dodge and Davis (EHDD) with the structural engineering firm of Rutherford and Chekene. Another committee was formed to work with the architect and engineer to develop a creative, cost-effective, and functional solution. Members of the CED wanted the retrofit not only to solve the poor seismic condition, but to enhance the existing structure as well.

Walk up to Wurster Hall and walk through and up the stairs to the courtyard. Look over to the tower for the most obvious retrofits (Fig. 20).

The project committee selected a design that involved adding a tube-like structure on the east of the tower and installing more continuous shearwalls on the west side of the tower, essentially creating two tubes. These tubes would brace the tower and provide lateral support. The tube scheme also included adding new shear walls and foundations to help resist lateral forces, minimizing potential displacement of the tower. Collector beams in the diaphragm were designed to tie the new

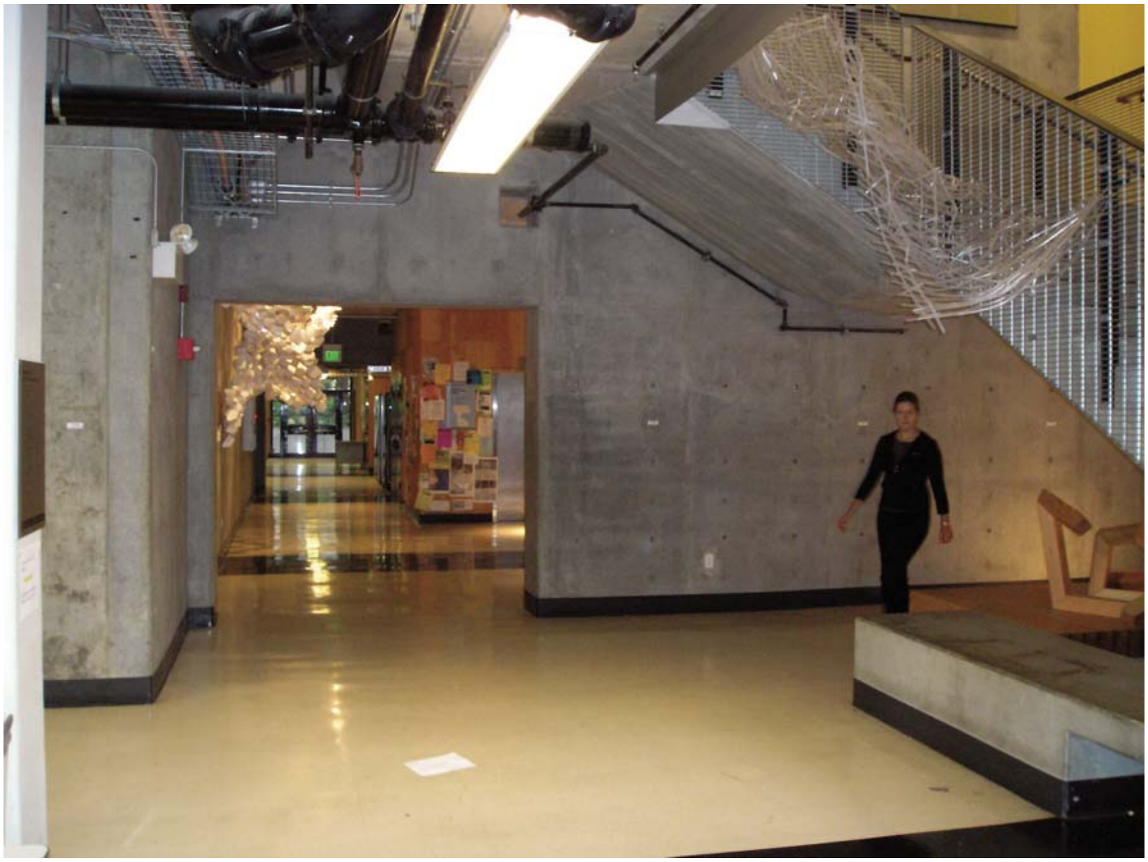


Figure 19. Wurster Hall interior.

shear walls together with the existing structure, and two new foundations supported by drilled piers were added under the tubes. One tube, to the east, is clearly visible from the court yard. Walk back into the building and peer in a few offices: notice the steel columns. To strengthen the fin columns, steel columns were added on the interior of the façade to transfer the vertical loads.

Walk over to the entrance of the Environmental Design Library. If you look inside, you can see a lovely two-story atrium in the reading room, the location of the former stacks, which were seismically hazardous. It is heartening that in the best of seismic retrofits, the functioning and the aesthetics of a building can be improved as well. Such was the case in Wurster Hall.

Stop 3: Berkeley Seismological Labs

(Lind S. Gee and Peggy Hellweg)

Significance of the Site

Seismology has a long tradition at UC-Berkeley. In 1887, seismometers were installed at the Student Observatory (on the knoll opposite the entrance to McCone Hall) and at Lick Observatory on Mount Hamilton by Edward S. Holden, professor of astronomy and president of the university. From these two observatories, the seismic network at UC-Berkeley has grown over the last century to include nearly 50 sites in California and southern Oregon. Today, the Berkeley Seismological Laboratory (BSL) is involved in a wide range of geophysical monitoring and research.

Accessibility

The BSL is open for tours by appointment only. Certain displays are accessible to the public during normal business hours. Restrooms are available in McCone Hall. Street parking is difficult, but the campus is easily accessible by BART and AC Transit. Parking is available on the street and on Level 2 of Lower Hearst Garage (entrance on Scenic Ave at Hearst Ave).

GPS Coordinates

Latitude: 37:52:27N (37.8742); Longitude 122:15:35W (–122.2598).

Directions

The BSL is located on the second floor of McCone Hall, on the north side of the UC-Berkeley campus. From the intersection of Euclid and Hearst, enter the campus at the North Gate. McCone Hall is the second building on your left, a five-story structure. Walk or take the elevator to the second floor; the BSL suite is located at the north end of the building.

Figure 20. Wurster Hall Tower from the courtyard looking north.

Stop Description

Visitors to the BSL will learn about the history of the lab and the role of the UC-Berkeley faculty and staff in studying the 1906 earthquake—now and then. Historical instrumentation, as well as current earthquake information, is on display. The tour includes examples of modern seismic sensors and information about the BSL's role in the California Integrated Seismic Network and earthquake monitoring.

Although much of the data collection now takes place invisibly on computers, several historical instruments are on display. A Wiechert seismometer with a 160 kg inverted pendulum stands in the ground floor lobby of McCone Hall. BSL acquired this seismometer in 1911 with funds donated by William Randolph Hearst after the 1906 earthquake to improve our capabilities to monitor seismicity in California. It and others like it were operated until the early 1970s, although new instruments were regularly added to stations as they were invented. Several examples of the Wood-Anderson seismometer are on display in the hall cases on the second floor near the entrance to BSL's suite. This small seismometer was fundamental to the development of the local or Richter magnitude scale in the late 1920s and early 1930s. Before, each seismograph station was likely to be equipped with a different instrument from others around it. Thus, each record of an earthquake was unique and could not be directly compared with those from other stations. This changed with the advent and installation of a standardized seismograph, the Wood-Anderson, at many locations in both northern and southern California. The hall displays also showcase maps of current seismicity, California faults and their associated hazards, as well as examples of current research directions at BSL. Within the BSL suite, the floors and doors are a reminder of the range of seismology. The floor shows a seismogram recorded at the BSL station CMB in Sonora, California, on 11 July 1995. It shows Rayleigh waves, a type of seismic surface wave, generated by a moment magnitude (M_W) 6.8 earthquake that occurred over 12,000 km away in the Myanmar-China Border Region. When an earthquake is strong enough, the waves will travel around the earth several times. The seismogram on the floor shows six such passages. The office doors display the seismogram of a local magnitude (M_L) 4.2 earthquake, which occurred on the Hayward fault at 1:24 a.m. local time on 26 June 1994, just 7 km away from here. This recording was made at BSL's station in the Berkeley Hills, BKS. Within the BSL suite computers display current seismicity, the digital data as it arrives from the seismometer stations of the network. A rotating drum recorder, called a helicorder, produces paper records using data from the station BKS.

Stop 4: Berkeley Laboratories of the Earthquake Simulator and Network for Earthquake Engineering Simulation at the University of California Richmond Field Station (Nicholas Sitar)

Significance of the Site

The earthquake simulator, or "shake table," was the first of its kind ever built in the world and is still the largest in the United States.

Accessibility

Restrooms are available on site; there free parking on site; no permit is required for entrance during regular business hours.

GPS Coordinates

37.9160°N, 122.3320°W.

Directions

From San Francisco or Oakland: Take I-80 East (toward Sacramento). Immediately following the Gilman Ave. exit, take the I-580 West exit (toward the San Rafael Bridge). Exit the freeway at the Bayview Ave. exit (the 2nd exit after merging onto I-580W). Turn left at the end of the off-ramp and continue straight onto Meade after stopping at the stop sign. Turn left at S. 47th St. (the 2nd street on the left), then immediately turn right (before entering the new Business Park) onto Seaver and enter the Richmond Field Station. Stop at the security kiosk. If a guard is on duty, tell him or her that you are visiting the Seismic Simulator in Building 420. At the first intersection, turn left and look for Building 420 on your left. You may park in the parking lot in front of the building.

Stop Description

The Seismic Simulator is located in Building 420, a separate, specially designed structure. The 40-ft-high, 60-ft-wide, 120-ft-long building is serviced by a 10-ton bridge crane and houses the earthquake simulator with its control and data acquisition facilities, an electronic maintenance room, and a suite of offices.

The central feature of the laboratory is the 20 × 20-foot shaking table. The table is configured to produce three translational components of motion: one vertical and two horizontal. These three degrees of freedom can be programmed to reproduce any wave forms within the capacities of force, velocity, displacement, and frequency of the system. It may be used to subject structures weighing up to 100,000 lbs to horizontal accelerations of 1.5 Gs. The concrete shaking table is heavily reinforced both with ordinary reinforcement and with post-tensioning tendons.

The University of California at Berkeley Network for Earthquake Engineering Simulation (NEES) site, known as nees@berkeley, features a 60 × 20-ft-strong floor, 40-ft clearance, a reconfigurable reaction wall, a 4-million-pound axial loading capacity, several large static and dynamic actuators, new instrumentation and a 128 channel high-speed data acquisition system, and advanced hybrid simulation capability that enables testing of large and complex structures. Real-time tests at actuator speeds up to 0.5 m/s are possible, and the digital controller can control up to eight independent degrees of freedom. The facility became operational on 30 September 2004.

SECTION II: THE NORTHERN HAYWARD FAULT

Stop 5: Hayward Fault Exposures at Point Pinole (Glenn Borchardt)

Significance of the Site

The northern end of the Hayward fault is at Point Pinole Regional Shoreline, a beautiful, relatively undeveloped 2000-acre oasis where tectonics, landslides, and global warming interact to form an earth scientist's dream (Fig. 21). Just outside the park lies a planner's nightmare: houses built in 1950 right on top of the fault without so much as a query about the strange white streak that appeared in aerial photos taken a decade earlier (Fig. 22). Within the park, two petroleum-laden pipelines lie buried along the railroad track near the entrance: one suspended in a 12-ft culvert designed to survive anything, and one built, like the railroad, without an inkling that the fault creeps 5.6 mm/yr below (Fig. 23). This field trip is a short introduction to a full-day trip that entails a 4-mi-hike (7-km) around the shoreline at Point Pinole (Borchardt and Seelig, 1991). In addition to the infrastructural items, we will examine the tectonic geomorphology of the Hayward fault, which includes a prominent fault scarp, benches, linear troughs, and an active, offset landslide. All this is on a backdrop of great crustal stability in which we can observe the effects of today's increasing sea level on top of evidence for the last time the bay was 20 feet higher than at present.

Accessibility

There are public restrooms available and ample parking.

GPS Coordinates

37.9915°N; –122.3553°W.

Directions

From San Francisco, cross the Bay Bridge and take I-80 east toward Vallejo/Sacramento. Exit at Richmond Parkway and turn left. Continue on Richmond Parkway, turn right at Atlas Road, turn left at Giant Highway, and turn right at Point Pinole Regional Shoreline.

Stop Description

Point Pinole Regional Shoreline is the park preserved by dynamite, having once been known as the "powder capitol of the west." Due to its relatively remote location, explosives were manufactured here from 1881 to 1960. Rare bricks found in the tidal marsh are said to be evidence of occasional mishaps. The park district bought the land from U.S. Steel in 1972 and has been "undeveloping" it ever since. Seismic

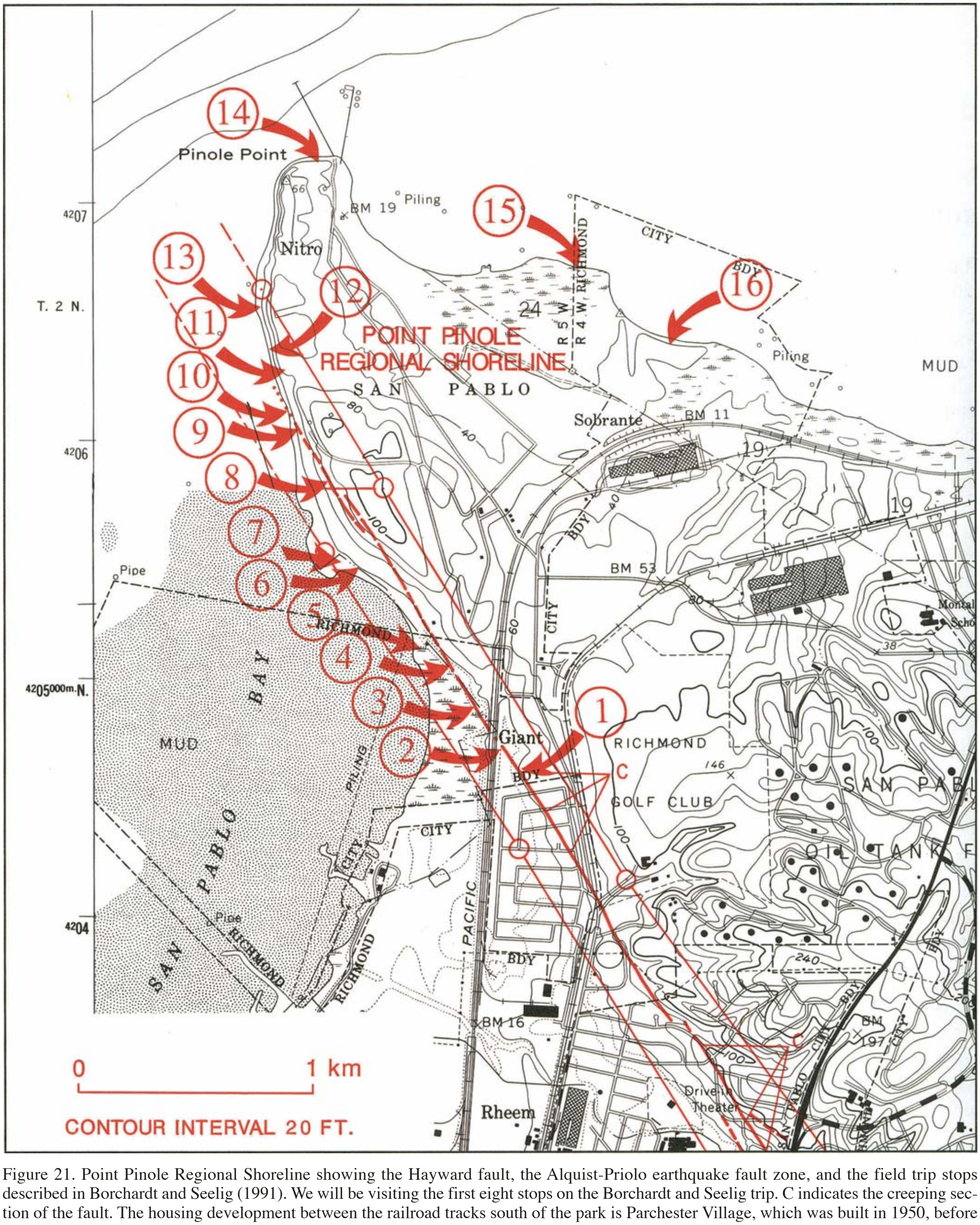


Figure 21. Point Pinole Regional Shoreline showing the Hayward fault, the Alquist-Priolo earthquake fault zone, and the field trip stops described in Borchardt and Seelig (1991). We will be visiting the first eight stops on the Borchardt and Seelig trip. C indicates the creeping section of the fault. The housing development between the railroad tracks south of the park is Parchester Village, which was built in 1950, before the fault-zoning act was passed.

Figure 22. 1939 aerial photo showing the white linear feature that marks the location of the Hayward fault through what became Parchester Village in 1950. The white streak is the result of cultivation and erosion of an "E" soil horizon, which formed as a result of the water barrier produced by the fault. Most of the buildings seen here have been removed from the park.

Figure 23. 1978 aerial photo of the Hayward fault as it passes through Parchester Village, offsets two pipelines and the Union Pacific railroad tracks, and then forms the linear scarp along the tidal marsh.

studies within the park have continued since the first U.S. Geological Survey (USGS) alignment array was emplaced in 1968. (Note: creep rates in the following are given in millimeters per year [mm/yr]. One mm = 0.039 inches; 3 mm = ~1/8 inch.)

Location 1 (0 mi [0 km])—USGS Alignment Array and Creep Meter

After bisecting several houses, streets, and curbs (Fig. 24) in Parchester Village at 5.6 mm/yr since 1950 (Lienkaemper, Borchardt, and Lisowski, 1991), the Hayward fault crosses the southern boundary of the park (Fig. 23). The fault is delineated here by a small SW-facing scarp associated with a prominent white linear feature on 1939 air photos (Fig. 22). A series of benchmarks placed perpendicular to the fault by the USGS in 1968 underwent ~2.5″ (65 mm) of aseismic displacement between 1968 and 1980 (5.3 mm/yr; Harsh and Burford, 1982). A real-time creep station was installed across the fault in 1996, yielding steady creep measurements of 4.8 mm/yr in a 50-ft-wide (15-m) zone from 1996 to 2004 (Bilham, 2005).

Location 2 (~325 ft [0.10 km])—Offset Wave-Cut Platform

The Hayward fault generally forms the boundary between the East Bay Hills and the alluvial plain formed along San Francisco Bay, but at this site, the fault is up to ~650 ft (200 m) from the range front (Figs. 21 and 22). This area is nearly flat because bay waters reached elevations up to 13 ft (4 m) higher than this location the last time global warming caused sea level to be higher than at present—~122,000 yr ago (Edwards et al., 1987). Wave action leveled the surface of the fault into a feature called a wave-cut platform. Despite the fan-shaped landform on the other side of the railroad tracks, none of the seismic trenches dug here in 1987 and 1994 uncovered stream alluvium that would provide a geologic slip rate for the fault. The nearest stream crosses the fault 2260 ft (690 m) to the south, so the geologic slip rate here appears to be <6 mm/yr since the bay waters receded ~114,000 yr ago.

The strong linear feature on 1939 aerial photos (Fig. 22) was shown during seismic trenching to be a light gray "E" horizon (a soil horizon depleted of organic matter and iron oxides) formed in response to the water barrier formed by the fault (compare Figs. 25 and 26) (Borchardt, 1988a). The shallow water table helped to preserve spectacular slickensides at the 13-ft (4-m) depth (Fig. 27). The area is still nearly level today because vertical slip along the fault diminishes as it steps over to the Rodgers Creek fault to the northwest.

An earthquake on the northern Hayward fault probably would impact the Union Pacific railroad and the fuel lines lying just northwest of here (Steinbrugge et al., 1987). The U-shaped parallel lines east of the tracks (arrows, Fig. 28) are the result of fill settlement on either side of a 300-ft-long 12-ft culvert buried in 1975 (Fig. 28). A 16″ pipeline suspended within the culvert will provide an uninterruptible fuel supply from the Chevron refinery on the west side of the fault to power plants on the east side of the fault. Unfortunately, an older 12″ fuel line lies buried alongside the tracks and could rupture at any time due to the stresses already introduced by creep along the fault.

Figure 24. Right-lateral curb offset at 704 Phanor Drive due to aseismic slip in Parchester Village that was 150 mm (6 inches) by 21 March 1985. More precise techniques found 214 mm of offset in a wider span of the northwestern curb on Banks Drive in 1988 (Lienkaemper et al., 1991). By now, the offset should be about twice as much as shown here. Gene Kelley, Colorado State University, for scale.

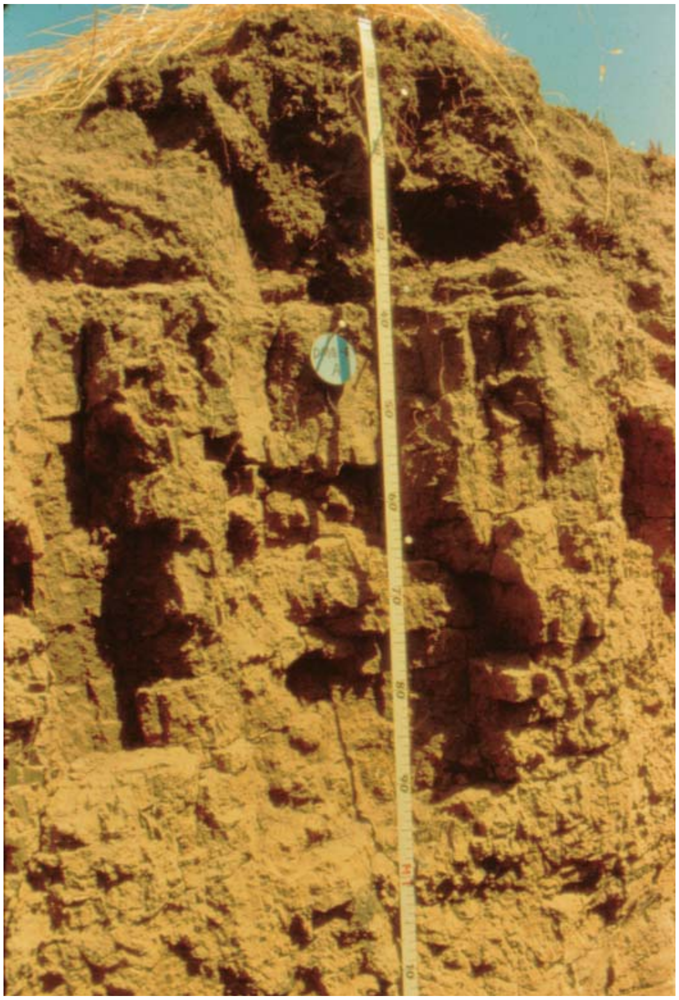


Figure 25. Moderately strong soil developed on the SW side of the Hayward fault in Trench DMG-E (Borchardt, 1988a).

Location 3 (~1000 ft [0.30 km])—Tidal Marsh and Fault Scarp

A prominent SW-facing scarp forms an abrupt boundary between the tidal marsh and the uplands north of the railroad tracks. This linear scarp strikes N30W—on trend with the Hayward fault seen on air photos and in seismic excavations to the SE. We studied a small embayment here that contains late Holocene surficial estuarine deposits overlying the projection of the fault. The white patches in this area (Fig. 28) were studied for evidence of paleoliquefaction—there was none (Borchardt, 1988b). No evidence for catastrophic ground rupture was found in the park.

Figure 26. Light gray "E" horizon developed on the NE side of the Hayward fault in Trench DMG-E, a few meters from the soil profile in Figure 25 (Borchardt, 1988a).

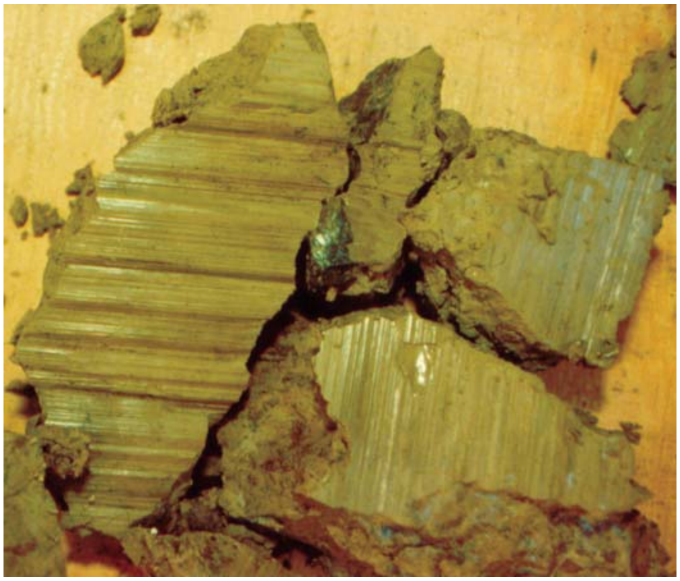


Figure 27. Slickensides from Trench DMG-E excavated across the Hayward fault in 1987 (Borchardt, 1988a).

Location 4 (~1300 ft [0.40 km])—Peat and Crustal Stability

A 1300-yr-old black sedimentary peat containing sand-size flakes of vermiculite (flakes of weathered biotite mica sometimes mistaken for gold in Sierra streams) lies buried in the tidal marsh southwest of the fault (Figs. 29 and 30). Examination of the salt marsh cliff and probings throughout the marsh revealed that the base of this distinctive peat layer exists at depths between 14″ and 30″ (36 and 75 cm) and that it varies in thickness from 4″ to 11″ (10–27 cm). Its depth and age are what would be expected in a crustally stable part of the world such as Micronesia (Bloom, 1970). Global sea level rise has been ~0.4 mm/yr during the past 4000 years, but measurements at the

Figure 28. 1978 aerial photo showing a close-up of the point at which the fault crosses the railroad track. White arrows show the location of two parallel fill-settlement lines that mark the location of a special 12-ft culvert offset containing a suspended petroleum line built in 1975. The beginning and end of the installation is marked by two white squares that are 500 ft apart (Borchardt, 1988a).

Golden Gate show a rise of 2 mm/yr between 1857 and 1975. In addition, this implies that the 6.5-ft-high (2-m) scarp is a result of uplift on the NE rather than subsidence on the SW. No definite offsets were observed in boring transects and trenches across the fault projection (Fig. 29).

Location 5 (0.3 mi [0.55 km])—Bay Mud Cliff

Modern plant remains of the type found in the dated peat layer may be seen here mixed with vermiculite particles at the edge of the mud flat (Fig. 30). At low tide, the peat layer is exposed within the bay mud deposits along the full length of the salt marsh cliff. Bay mud is of mixed clay mineralogy and normally contains only clay and silt. Sand, if any, is brought in locally from nearby upland drainages.

Location 6 (0.6 mi [1.00 km])—Paleosol Section P2

This paleosol (fossil soil) section, like most of the others along the shoreline, was exposed as a result of erosion produced by rising sea level in San Pablo Bay (Figs. 31 and 32). Note that the young trees at the shoreline are being rapidly undermined. The modern soil has traces of gravel and a moderately developed B horizon (a soil horizon in which clay and iron oxides have accumulated) overlying a zone of mangan (black manganese oxide coatings) development.

The development in the lower paleosol here is particularly striking (Fig. 31). This paleosol has a 35″-thick (88-cm) B horizon with strong blocky structure and clay films that extend into the BC horizon (a transitional soil horizon less weathered than the B horizon) for at least another 18″ (45 cm). At a depth of 131–140″ (333–355 cm), the base of the paleosol contains moderately dense, 2″-diameter (5-cm) calcite (calcium carbonate) nodules. The mechanism by which these nodules could form in soils and paleosols of the Bay Area is not well understood. In California, most calcareous soil horizons are found in the semiarid and arid regions. Calcium carbonate nodules, however, have been reported in borings in east-west cross sections across the southern San Francisco Bay. ^{230}Th-^{234}U analysis of two of these nodules resulted in an age of 26,000 yr. This was confirmed by a ^{14}C date of 21,000 yr B.P. (yr B.P. of 1950), coral-corrected to 26,000 calendar years. The modern

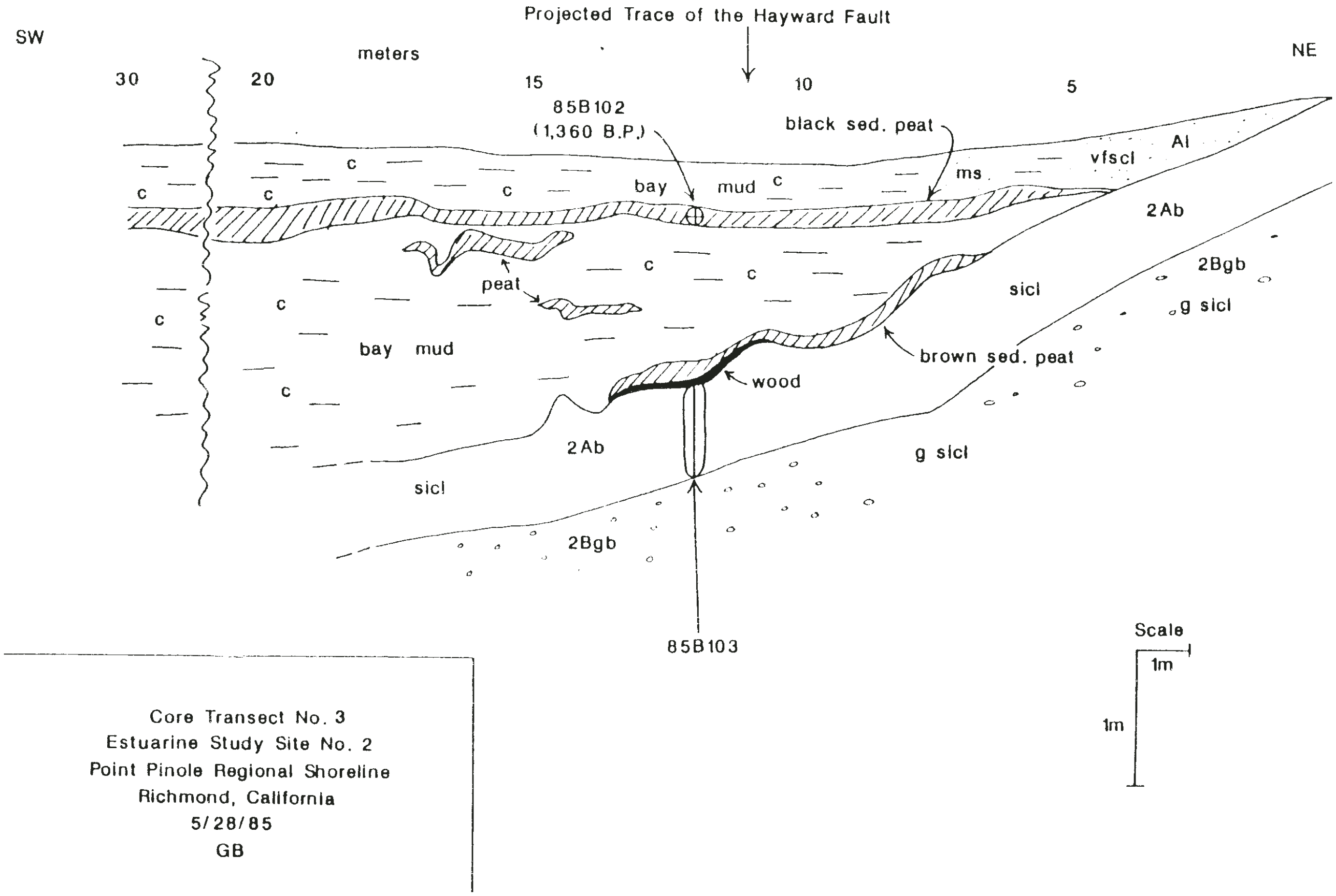


Figure 29. Cross section prepared from a core transect at Location 4 of Stop 5 showing the peat, bay mud deposits, and the paleosol overlying the projected trace of the Hayward fault (from Borchardt, 1988a).

Figure 30. Bay mud cliff showing the younger bay mud and the pervasive sedimentary peat at the base that was dated at 1300 calendar years old.

wave-cut platform ~328 ft (100 m) northwest of this site is presently cutting through an arcuate zone of calcite nodules that dips SW.

Location 7 (0.7 mi [1.10 km])—Landslide Toe

Modern as well as ancient landslides exist along the Hayward fault as it crosses the SW side of the ridgeline (Fig. 32). A water pipeline has been displaced ~30 ft (10 m) downslope by a major landslide that crosses the Hayward fault. Landslide deposits "rumple" the landscape, producing closed depressions as well as raised topography. The soils within such deposits are typically multicolored, having both oxidized and reduced zones that are indicated by changes in iron mineralogy. The slides are triggered by extremely active erosion at the bay cliff, where there are excellent exposures of the toes and slide planes.

Location 8 (0.8 mi [1.35 km])—Landslide–Fault Complex

Heading uphill, cross a series of benches and linear depressions that are parallel to the Hayward fault (Fig. 32). It is likely that some of the downslope depressions are the oldest and were produced during early Holocene earthquakes. These may contain "faults" that are no longer active. A trench at this site was dug across this prominent linear depression in a bench along the mapped trace of the fault. The trench exposed a cross section through a block of NE-dipping Tertiary bedrock that had slid across the fault and was subsequently displaced. The soil SW of the fault is only 3.3 ft thick (1 m), whereas the soil NE of the fault is up to 13 ft (4 m) thick. The lower 3.3 ft (1 m) of the deep soil was devoid of modern rootlets and yielded a soil carbon age of 4200 yr.

Figure 31. Paleosol (fossil soil) at the base of soil profile P2 at Point Pinole Regional Shoreline. The white nodules are calcium carbonate dated at 26,000 yr old (Borchardt et al., 1988; Borchardt and Seelig, 1991).

Stop 6: Fault-Related Landslide at Cragmont School (Alan Kropp)

Significance of the Site

An elementary school has recently been reconstructed in an area of active landsliding as well as adjacent to the active Hayward fault. Extensive studies were required to meet safety requirements for the new buildings.

Accessibility

This is a public site, but there are no restrooms and only on-street parking.

GPS Coordinates

37.89349°N, 122.26785°W.

Directions

From the University of California Memorial Stadium, head north on Gayley Road. Turn left (west) on Hearst Avenue and proceed five blocks to Spruce Street. Turn right (north) on Spruce

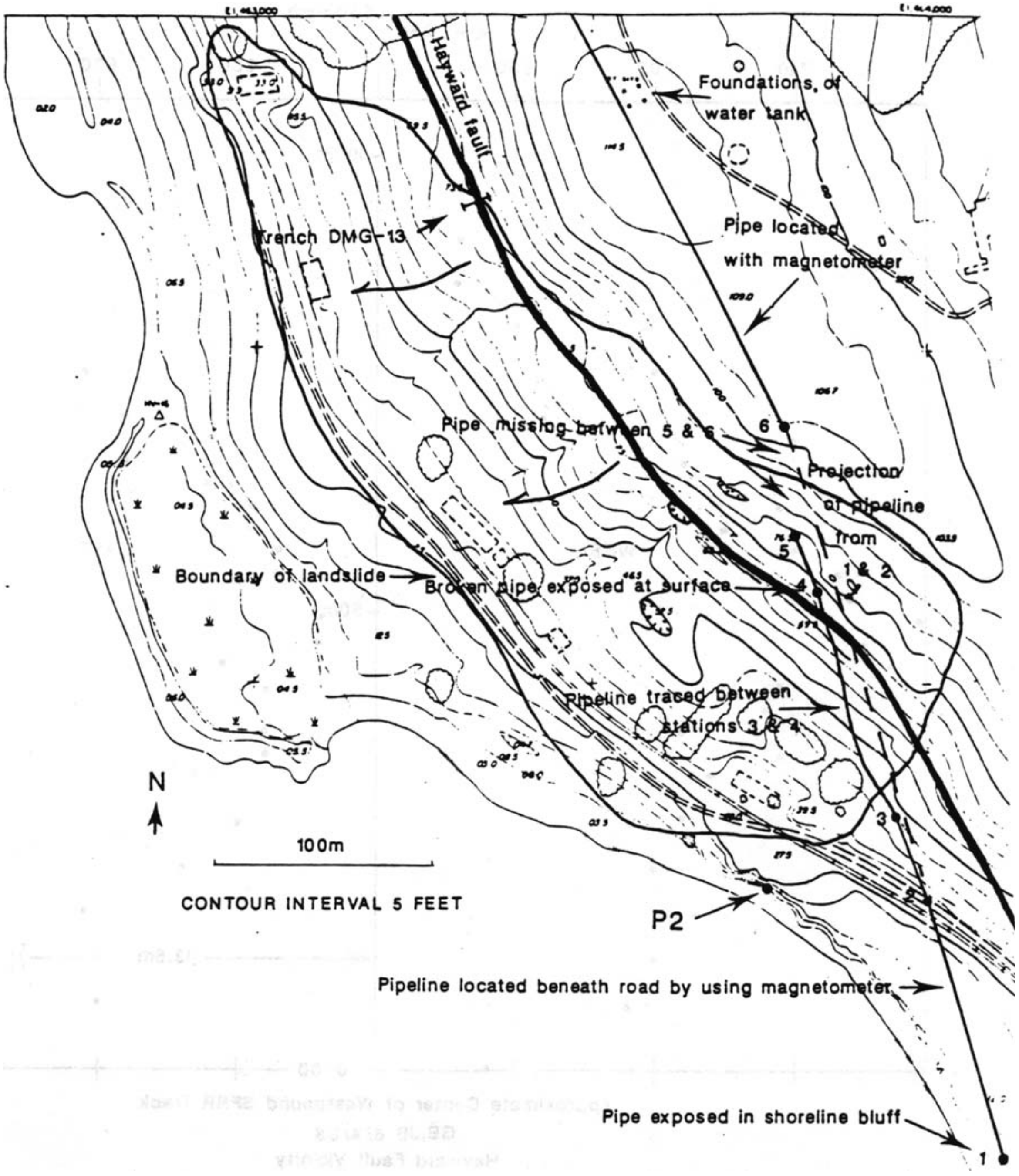


Figure 32. Active landslide along the Hayward fault at Point Pinole Regional Shoreline, showing a survey of a water pipeline offset 30 ft by landsliding since 1920. P2 is the location of a soil profile having two paleosols “fossil soils” in addition to the modern surface soil.

Street and proceed ~10 blocks. After passing Santa Barbara Road, look for parking along the street. Get out of your vehicle and walk to the intersection of Spruce Street and Marin Avenue.

Stop Description

The Cragmont School site is located on the northern corner of Spruce Street and Marin Avenue (Fig. 33). This parcel lies about halfway up a southwest-facing hill slope along the northwest-trending Berkeley Hills. The site is at an elevation of ~600 ft and is bounded along its southeast border by Marin Avenue; this street extends linearly up the hillside at an average inclination of ~5:1 (horizontal to vertical).

The oldest widespread rocks in this region are highly deformed sedimentary and volcanic rocks of the Mesozoic-age Franciscan Complex. These materials are in fault contact with the somewhat younger Mesozoic-age Great Valley Complex (which

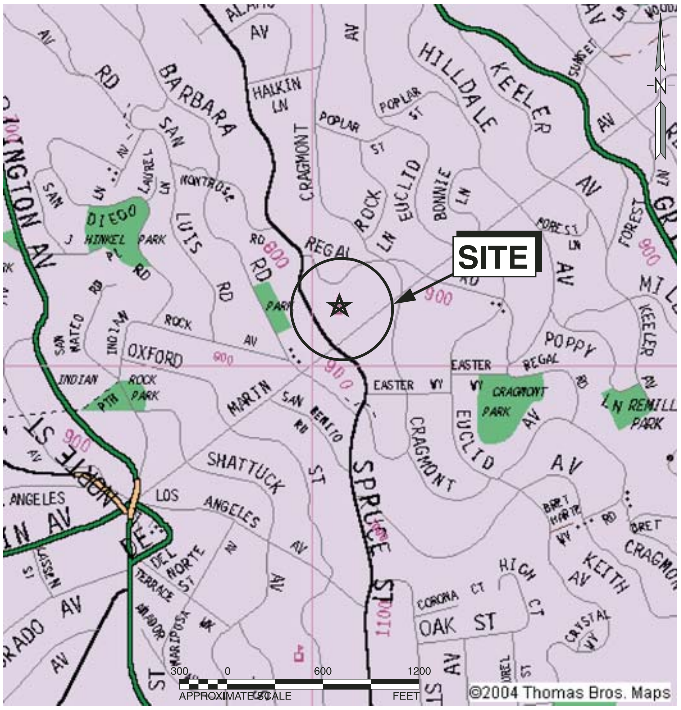


Figure 33. Site location map.

includes both the Coast Range Ophiolite and the Great Valley Sequence). These materials are, in turn, overlain by a diverse sequence of Tertiary sedimentary and volcanic rocks. Since deposition, the Mesozoic and Tertiary rocks have been extensively deformed by repeated episodes of folding and faulting.

The general geologic setting of the area is illustrated on Figure 34 (taken from the Stop 5 field trip guide notes in Ponce et al. [2003]). The caption from the Ponce field trip guide has been included with this figure because it illustrates a geologic understanding that has undergone a number of shifts over the past 20 yr. The Northbrae Rhyolite has recently been determined to be a deformed Miocene volcanic rock, whereas an earlier understanding indicated the rhyolite was part of the Jurassic silicic volcanics within the Coast Range Ophiolite (Jones and Curtis, 1991) (although before that, they were believed to be Miocene in age). A large extruded exposure of the rhyolite is present on the northeast side of Santa Barbara Avenue ~100 ft northwest of Marin Avenue. This exposure is also visible in the historic photograph (Fig. 35).

Historically, published maps of this area have shown several traces of the Hayward fault (Bishop, 1973; Case, 1963; Radbruch-Hall, 1974). The 1982 Alquist-Priolo Fault Map (California Division of Mines and Geology, 1982) indicated the primary trace passed ~300 ft southwest of the site, approximately at the intersection of Santa Barbara Road and Marin Avenue. However, other traces are truncated ~1500 ft to the southeast and 1000 ft to the northwest, which, if extended, might pass through the school site. Lienkaemper (1992) mapped the recent active traces of the Hayward fault and indicated the active trace passed along the northeast side of Spruce Street, at the school's southwest border.

Offset from the Hayward fault in the area is obscured by landslide movements and various repeated construction activities. However, right-lateral offset due to the Hayward fault can generally be seen in the curb lines on both sides of Marin Avenue, just uphill of Spruce Street (these features are cited by Lienkaemper, 1992). While looking up Marin Ave. from Spruce Street (and avoiding the traffic on this heavily-traveled road), a broad left-lateral offset can be seen near Cragmont Avenue due to landslide displacement of the roadway.

Landsliding in this area is well known, and an historic photograph of the area shows the hummocky topography that existed before most construction occurred (Fig. 35). Published maps have varied widely in interpretations of the extent of the landslides, however. In fact, in his mapping of the Quaternary faulting of the Hayward fault, Herd (1978) indicated the entire hillside area from just north of the University of California campus to the southern portion of El Cerrito was one massive landslide complex. Other maps, such as Nilsen (1975) and Dibblee (1980), showed discreet landslides, especially in the area of Cragmont School, but these maps varied widely in their interpretation regarding landslide limits. As a result, starting in 1985, the author began preparing maps of deep-seated, slow moving "active" and "potentially active" landslides for local distribution. (Active landslides were defined as landslides that moved recently enough to damage cultural features, whereas potentially active landslides were slide deposits that were very young but did not significantly damage cultural features.) An example of a 1995 version of this map is presented as Figure 36. More recent delineation of the boundaries of these landslides based on InSAR data has been presented in Hilley et al. (2004).

Since there are both an active fault and active landslide deposits in this area, a number of studies have been performed in an attempt to separate movements from these two sources. The most prominent of these studies are Hoexter et al. (1982, 1992), Lennert (1982), and Waterhouse (1992). Lennert focused on the offset between sections of concrete pavement in Spruce Street just southeast of Marin Avenue to help understand the mechanism. These slab sections were offset in a right-lateral sense and he attributed this movement to creep of the Hayward fault (unfortunately, these slabs were recently covered by asphaltic concrete when Spruce Street was repaved). In the Hoexter studies, surveys were extended along the southeast curbline of Marin Avenue from "the Circle" at Arlington Avenue up the hill past the school to Grizzly Peak Boulevard. Several feet of right lateral offset was recorded between Santa Barbara Road and Spruce Street, much of which was attributed to fault creep but a portion of which was attributed to landslide movement. An additional left lateral offset of ~5 ft over a very broad zone between Spruce Street and Cragmont Avenue was also recorded; this was attributed to the oblique component of the active landslide movement. Hoexter also attributed most of the concrete slab offset in Spruce Street to landslide movement.

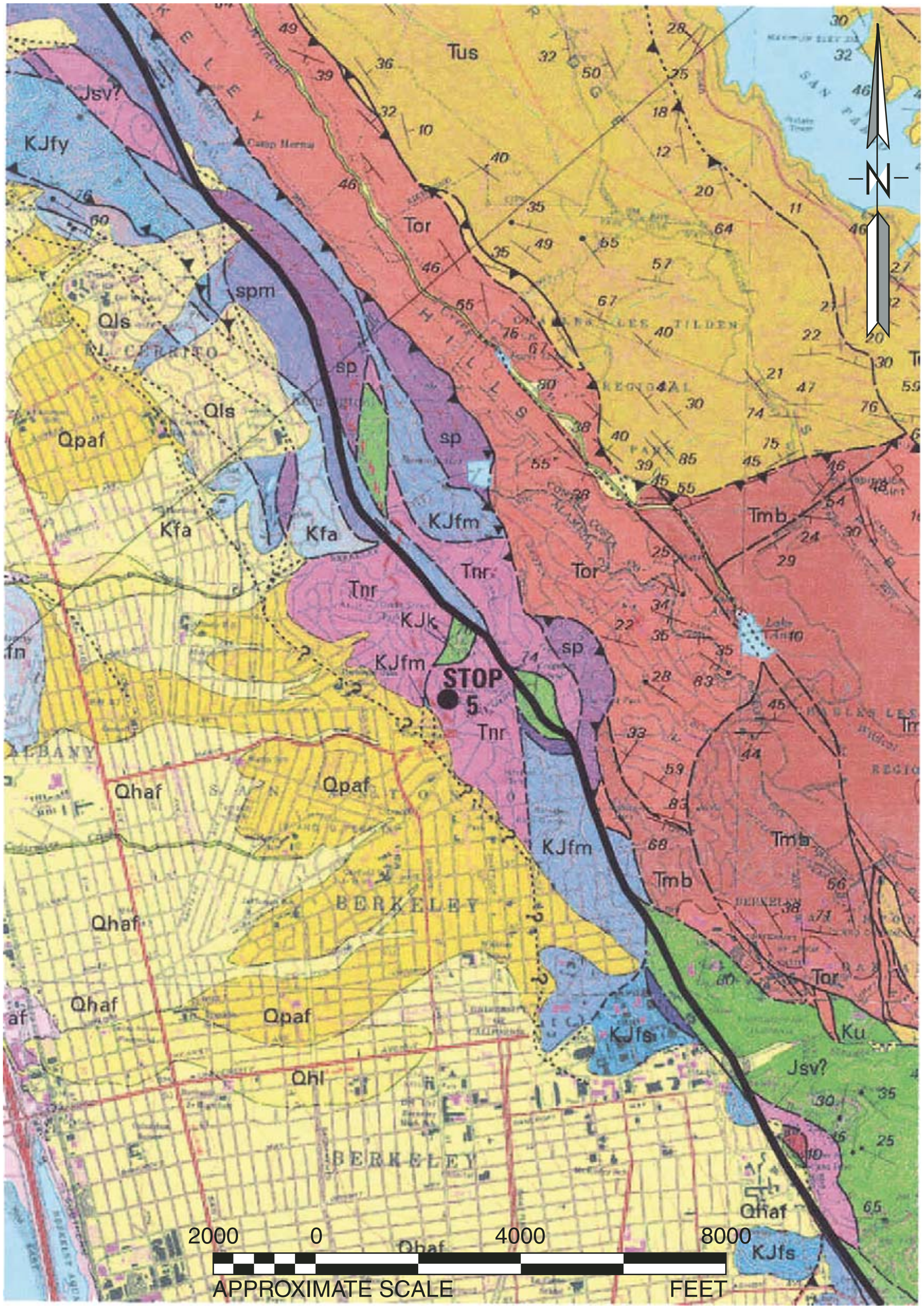


Figure 34. "Geologic map of the Berkeley area (modified from Graymer, 2000) showing the distribution of the Northbrae rhyolite (Tnr). The through-going mapped active strand of the Hayward fault is shown as a thick black line; the field trip stop location is shown as a black dot. Note that the Northbrae rhyolite has no apparent offset along the mapped active strand of the Hayward fault, although the outcrops of questionably identified silicic volcanics of the Coast Range Ophiolite (Jsv?) could be correlative with the Northbrae rhyolite, which would indicate an ~4 km offset" (figure and caption from Ponce et al., 2003, their Stop 5, Figure 5-1).

Figure 35. Photograph taken in late 1800s from Los Angeles and Mariposa Avenues. Marin Avenue was later built immediately beyond (northwest) the creek channel. Farm and saloon buildings in approximate area where Cragmont School later constructed (Berkeley Historical Society).

The subject site at the northern corner of Marin Avenue and Spruce Street has been in use for a lengthy period as a public elementary school location. Portable school buildings were placed on the Cragmont school site early in the twentieth century, and the first permanent buildings were built as the entire site was developed in 1927. "Modern" concrete buildings replaced the earlier structures in 1966, and additional buildings were constructed in 1975. Unfortunately, structural evaluations after the 1989 Loma Prieta earthquake indicated concerns about the seismic performance of the "modern" concrete buildings and these structures were closed. In light of the active fault and active landslide concerns, extensive studies were performed by Harding Lawson Associates and William Cotton and Associates in the early 1990s (Harding Lawson Associates, 1991; Cotton, W., and Associates 1993, 1995) to help characterize the site-specific geologic framework present and indicate whether new school buildings could be built that would avoid the landslide and fault concerns.

The investigations by William Cotton and Associates concluded the entire school site was located within landslide deposits of various ages (1993). The active landslide materials were shown to encompass the southeastern portion of the site (roughly parallel to Marin Avenue), with a dormant lobe of the same landslide encroaching further into the site. The remainder of the site was underlain by sheared and fractured bedrock units, which were believed to possess a low potential for reactivation; these materials were classified as a static (ancient) landslide. In relation to the Hayward fault, no subsurface exploration on the site encountered evidence of active faulting, and it was concluded no active trace of the fault was within the school site, but an active trace might be present immediately downhill based on a preponderance of other data. Therefore, as shown on Figure 37, William Cotton and Associates (1995) recommended new buildings be constrained by setbacks beyond the active and dormant portions of the landslide, as well as a projection of the nearest possible active fault trace. The new school campus has subsequently been reconstructed using these setback requirements.

SECTION III: THE SOUTHERN HAYWARD FAULT

The Hayward fault lies along a narrow rift valley along Highway 13 (Warren Freeway) that extends over a distance of 5 mi from the Berkeley-Oakland border at Lake Temescal, south to the intersection of Highway 13 with Highway 580. At the north end of the rift valley, the fault apparently passes along the east bank of Lake Temescal, through the dam, and beneath Highway 24, as described in Borchardt et al. (2000). The fault continues through a residential area to Tunnel Road, and along Tunnel Road toward the Claremont Resort in Berkeley. The fault passes

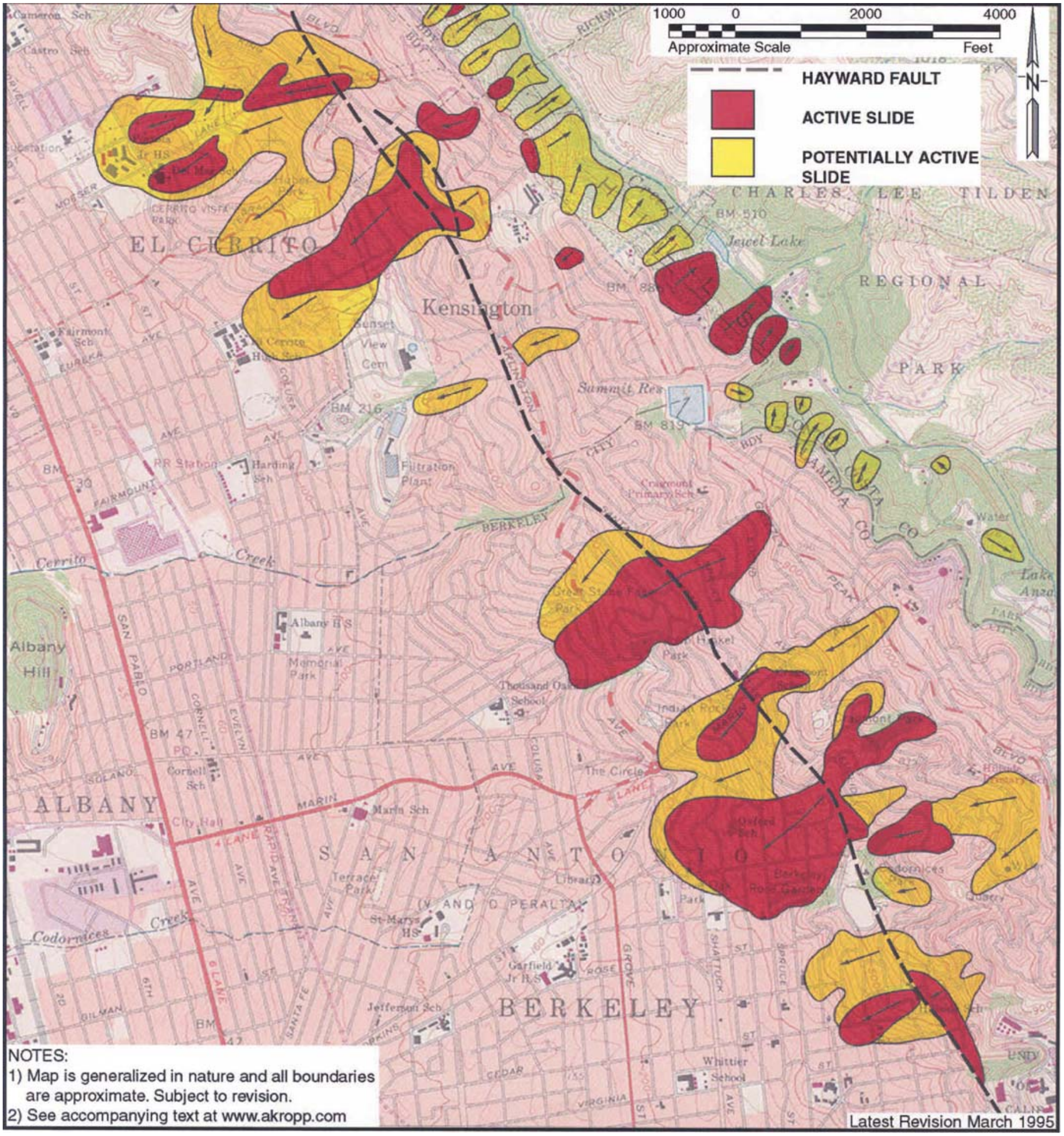


Figure 36. Berkeley Hills landslide map (Kropp, 1995).

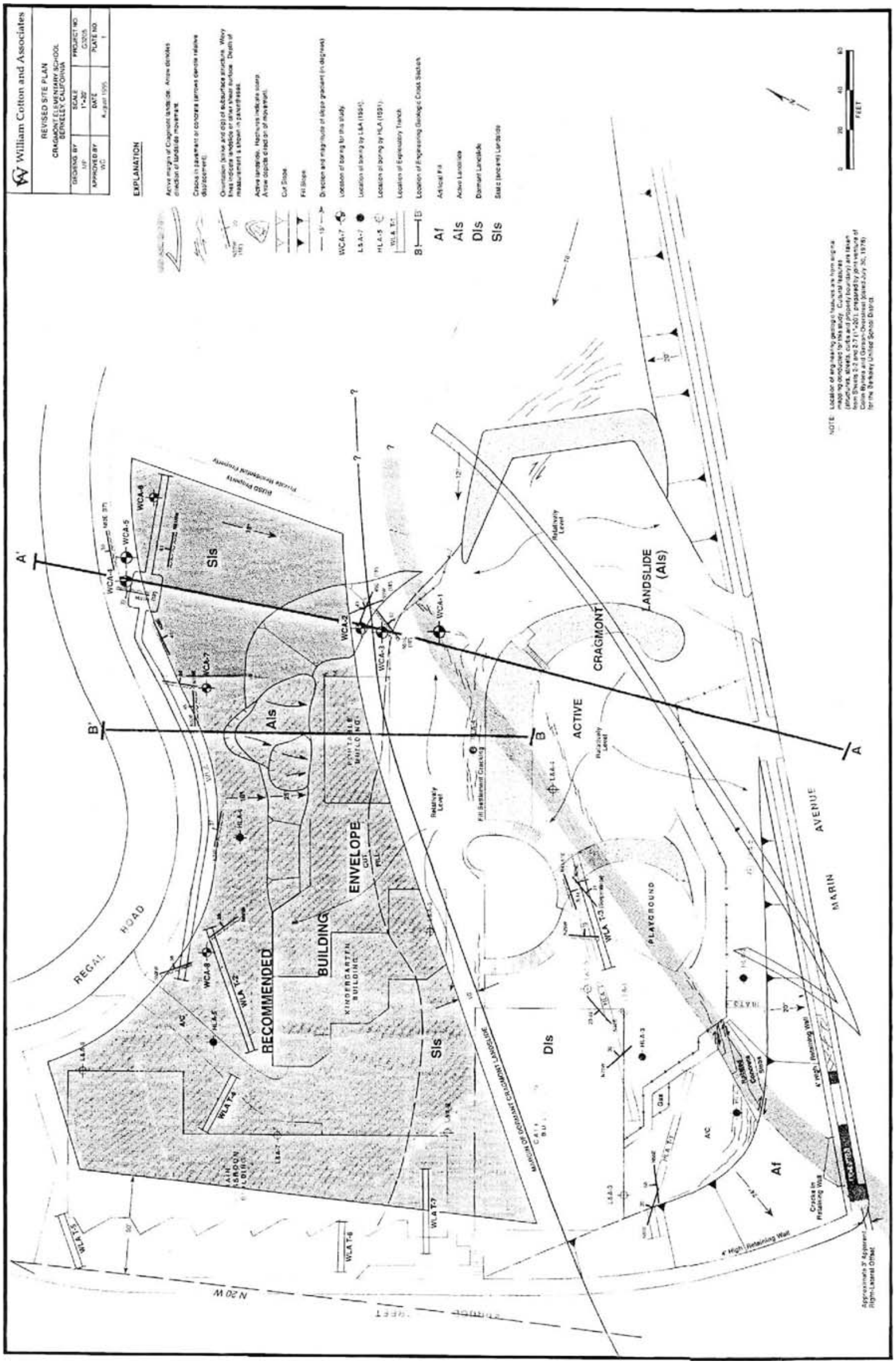


Figure 37. Site map that guided school reconstruction (Cotton and Associates, 1995).

through the East Bay Municipal Utility District's (EBMUD's) Claremont Water Tunnel and Bay Area Rapid Transit (BART) tunnel in the area directly north of Highway 24 (Fig. 2).

Stop 7: Oakland City Hall Base Isolation (Charles Rabamad and Donald Wells)

Significance of the Site

Constructed in 1914 in the Beaux Art style, and currently registered as a National Historic Landmark, this building is 18 stories tall. It consists of a 3-story podium, a 10-story office tower, and a 2-story clock tower base that supports a 91-ft ornamental clock tower (Fig. 38). The total height of the building is 324 feet, and the total square footage is 153,000 sq. ft. The structural system is a riveted steel frame with unreinforced masonry perimeter in-fill walls clad with granite veneer and terra cotta ornamentation (DIS Inc., 2005).

The Oakland City Hall, which was severely damaged in the 1989 Loma Prieta earthquake, was retrofitted (1992–1994) to withstand earthquake ground shaking through the installation of a seismic base isolation system. The first high-rise building in California to be base isolated, it served as a model for design-

Figure 38. Photograph of Oakland City Hall (from Steiner and Elsesser, 2004).

ers and resulted in the acceptance of base isolation as a cost-beneficial method of seismic risk reduction for historic buildings. The successful installation of the base isolation system led the way for funding for seismic isolation of other public buildings damaged by the Loma Prieta earthquake.

GPS Coordinates

37.8052°N, 122.2725°W.

Accessibility

This site is not accessible to the public. Parking: Nearby parking is available at the following locations: Dalziel Building (250 Frank H. Ogawa Plaza) Parking Garage (entrance on 16th Street at Clay Street); Clay Street Garage (entrance on Clay Street between 14th and 15th Streets, behind City Hall); City Center Garage (entrance on 11th Street between Clay Street and Broadway; also entrance on 14th Street).

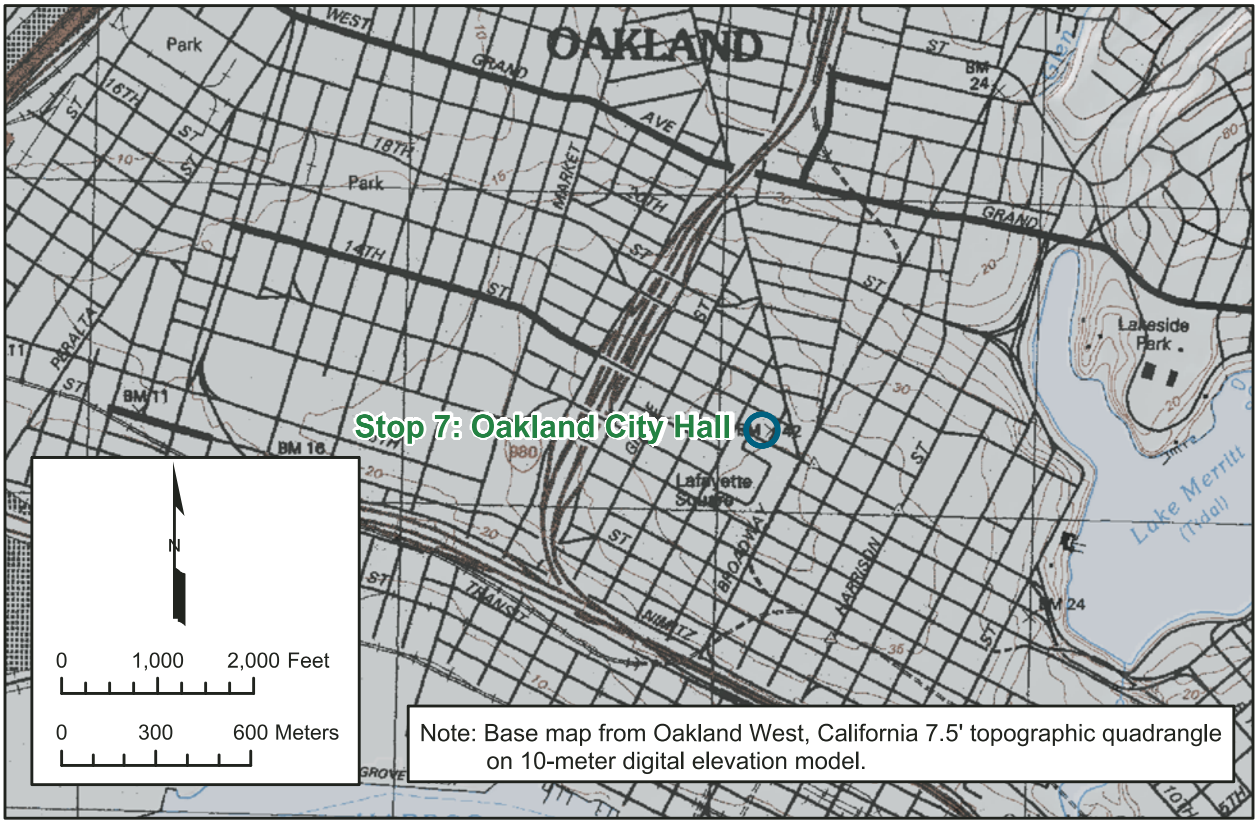
Directions

From San Francisco: Take I-80 East toward the Bay Bridge. Take the I-580 East/Downtown Oakland (CA-24) exit toward Hayward/Stockton. Merge onto I-580 East. Take the MacArthur Blvd/San Pablo Ave exit. Continue on W. MacArthur Blvd. Turn Right on San Pablo Avenue, and bear right on City Hall Plaza/Frank H. Ogawa Plaza (Fig. 39).

Stop Description

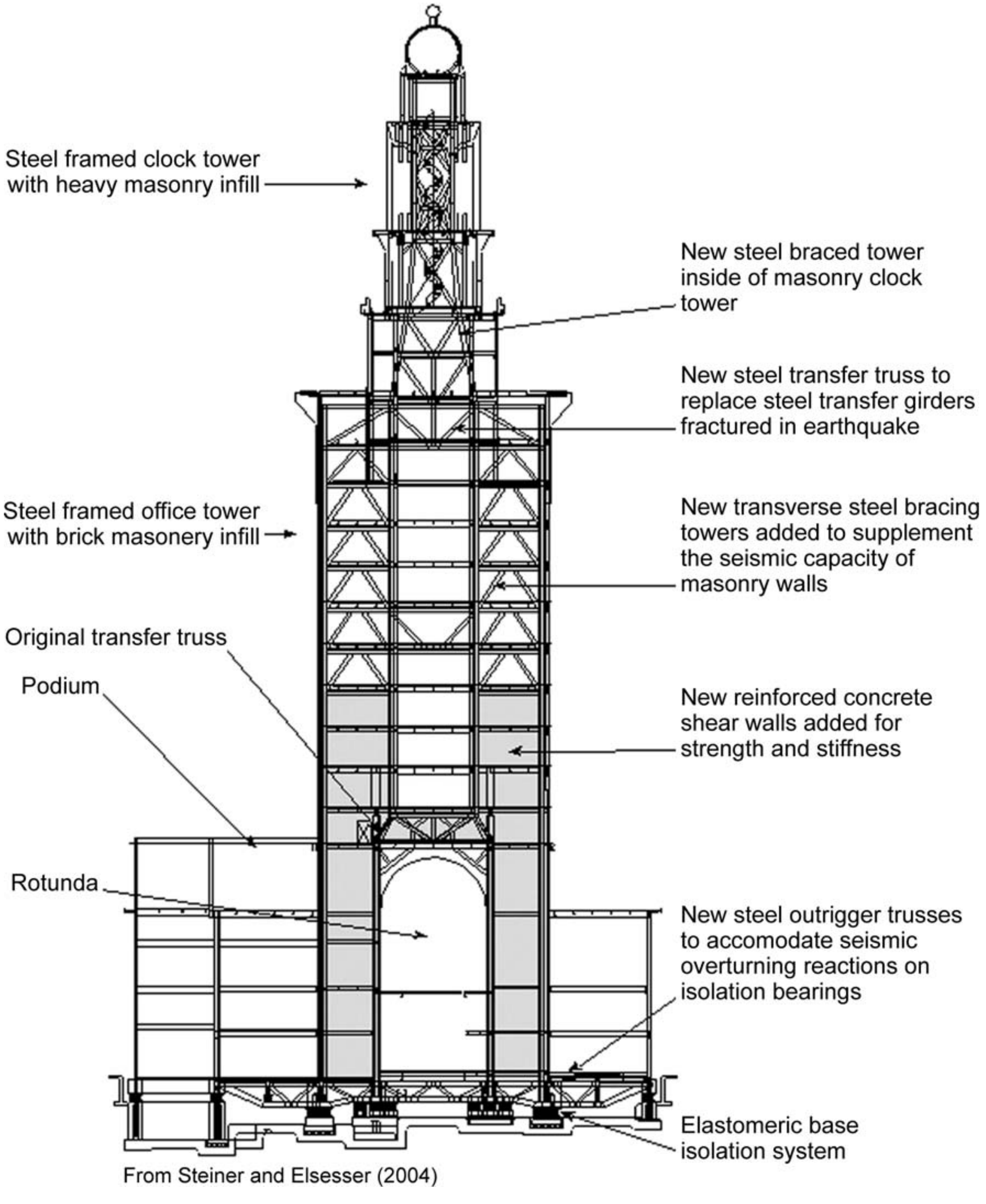
The Oakland City Hall (Fig. 38) suffered significant damage in the October 1989 Loma Prieta earthquake, forcing the city to move all operations out of the building. The city hired a project team, headed by VBN Architects, to undertake a detailed feasibility study to quantify the building's lateral capacity and to examine alternative repair and strengthening schemes. The decision to install a seismic base isolation system as the most cost-effective solution was reached after eight alternative repair systems were compared and analyzed. A significant factor in the selection of base isolation as the most cost-effective approach was the limited strength of the building as constructed. To minimize the amount of new construction, the existing structure was given credit for the strength it exhibited during the Loma Prieta earthquake. This performance-based approach required less strengthening than conventional, code-based design, which ignores the existing capacity of the building.

A total of 42 lead-rubber and 69 rubber base isolators were placed under the building columns during 1992–1994 (Fig. 40). The isolators are 29–39 inches in diameter and 19 inches high. The columns supporting the office tower portion of the building carry extremely high loads (3000 kips dead load and more than 4100 kips for combined live and dead loads), requiring two to four isolators for each of these columns (Steiner and Elsesser, 2004). The foundation thickness above the seismic isolators



Note: Base map from Oakland West, California 7.5' topographic quadrangle on 10-meter digital elevation model.

Figure 39. Stop location for Oakland City Hall.



From Steiner and Elsesser (2004)

Figure 40. Diagram of seismic retrofit components at Oakland City Hall.

was increased by adding new concrete around the perimeter of all footings. The interaction between old and new concrete was improved by installation of special tendons (32 mm DYWIDAG Transverse Bar Tendons [THREADBAR®]) that passed through holes cored through the concrete.

Strengthening to the building included installation of a new steel-braced tower inside the masonry clock tower, a new steel transfer truss at the base of the clock tower to replace steel transfer girders cracked during the earthquake, new traverse steel bracing in the office tower to supplement the seismic capacity of the masonry walls, addition of reinforced concrete shear walls at the base of the office tower and through the core of the podium, and new steel trusses to accommodate overturning reactions on the isolation bearings (Steiner and Elsesser, 2004).

At the time of the retrofit work, it was the tallest seismically isolated building in the world.

Stop 8: Claremont Water Tunnel Portal (Donald Wells, John Caulfield, and David Tsztoo)

Significance of the Site

The Claremont Water tunnel, which is owned by the East Bay Municipal Utility District (EBMUD), is a critical lifeline facility that supplies water to more than 800,000 customers west of the Oakland-Berkeley Hills. The tunnel crosses the Hayward fault ~850 ft in from the west portal. EBMUD is constructing a bypass tunnel that incorporates several innovative design measures to mitigate the potential for service loss due to fault rupture through the tunnel during a major earthquake on the Hayward fault. The BART tunnel also crosses the Hayward fault, ~900 feet south of the Claremont Tunnel. Information on the fault crossing and construction issues for BART is described in Borchardt et al. (2000).

Accessibility

There is limited parking at the Rock La Fleche School or on Chabot Road. The Claremont Tunnel Portal is visible through the chain link fence on the north side of the parking lot at the school. Entrance to EBMUD property is not allowed except by prior permission.

GPS Coordinates

37.8519°N, 122.2390°W.

Directions

From Oakland City Hall, follow San Pablo Avenue 0.3 mi northeast, turn left onto 19th Street, and continue on to 18th Street 0.2 mi to intersection of Castro Street at Highway 980. Turn right onto the ramp for Highway 980 then continue on to Highway 24 east toward Walnut Creek for 3.2 mi. Exit right onto Keith Avenue toward Broadway Avenue (0.2 mi), keep right on Broadway under the highway (0.1 mi), and keep left on Patton Street. Continue 0.2 mi and turn right onto Chabot Avenue. Continue 0.3 mi to the intersection with Golden Gate Avenue. Follow Golden Gate Avenue ~250 ft, and turn right up the hill into the parking lot for Rock La Fleche School. The Claremont Center Tunnel Portal is located directly north of the driveway and parking lot for the school.

Alternate Directions

From Memorial Stadium on the Berkeley campus, drive south on Prospect Street (0.25 mi), turn right on Dwight Way, and make an immediate left turn to continue south on Waring Road (past the Clark Kerr Campus). Turn left on Derby and right on Belrose, continuing on Claremont Blvd. to Ashby Avenue (0.8 mi from Dwight Way). Turn left (east) on Ashby Avenue, which becomes Tunnel Road, passing the Claremont Resort on the left. Continue on Tunnel Road to the divided section of road (0.4 mi), and turn right on The Uplands. Follow The Uplands for 0.3 mi (around to the right to a large intersection), and continue left 0.2 mi down the hill (south) on Roanoke Road to the bottom at Chabot Elementary School. Turn left on Chabot Road and continue 0.2 mi to the intersection with Golden Gate Avenue. Follow Golden Gate Avenue ~250 ft, and turn right up the hill into the parking lot for Rock La Fleche School. The Claremont Center Tunnel Portal is located directly north of the driveway and parking lot for the school.

Stop Description

The Claremont Water Tunnel was excavated and constructed between 1926 and 1929, is 9 ft in diameter, and extends 3.4 mi from the Claremont Center Portal through the Oakland-Berkeley Hills to the Orinda Water Treatment Plant. The tunnel routinely carries 110 million to 175 million gallons per day (mgd). Most of the tunnel is constructed of unreinforced concrete. Inspection of the tunnel showed that the tunnel is cracked and deformed due to creep on the Hayward fault and that voids are present between the existing concrete liner and the surrounding rock throughout the tunnel. Prior to retrofitting, the primary concern for operation of the tunnel was the potential for fault offset during a major earthquake on the Hayward fault, which could have effectively blocked the tunnel, resulting in loss of service for up to six months, a reduction in fire-fighting capacity, and associated economic losses for East Bay communities.

As part of a system-wide seismic improvement program, EBMUD and its consultants developed a solution to retrofit the tunnel that will allow for sustained operation following a major earthquake on the Hayward fault. The seismic retrofit includes constructing a 1570-ft bypass tunnel across the fault zone, with a 480-ft access tunnel driven parallel to the existing tunnel (Fig. 41A and 41B). Use of the access tunnel allows construction of the bypass tunnel without interruption in service of the existing tunnel. When completed, the bypass tunnel will tie into the existing tunnel on both sides of the Hayward fault zone, and the existing tunnel between the tie-ins will be backfilled with cellular grout and abandoned. Elsewhere in the existing tunnel, structural repairs will be completed where needed, and the concrete walls will be strengthened with grout injected into gaps between the walls and the rock around them. The contact grouting is necessary to improve interaction between the ground and liner, and will significantly reduce the potential for damage to the liner due to ground shaking. A major constraint on the bypass tunnel construction and repairs to the existing tunnel is that shutdown of the water flow and retrofit work in the existing tunnel is constrained to a three-month window between December and February due to water system demands. Specific concerns for construction of the bypass tunnel include areas of squeezing ground, groundwater flow, and the presence of naturally occurring methane gas and petroleum.

Three major types of geologic conditions have been identified along the existing tunnel near the Hayward fault zone and west portal. Franciscan Complex mélange, including sheared shale, sandstone, altered volcanic rocks, serpentinite, silica carbonate, and some blocks of chert and blueschist, occur west of the Hayward fault zone (extending ~800 ft east from the west portal). Silica carbonate rock and serpentinite, with some

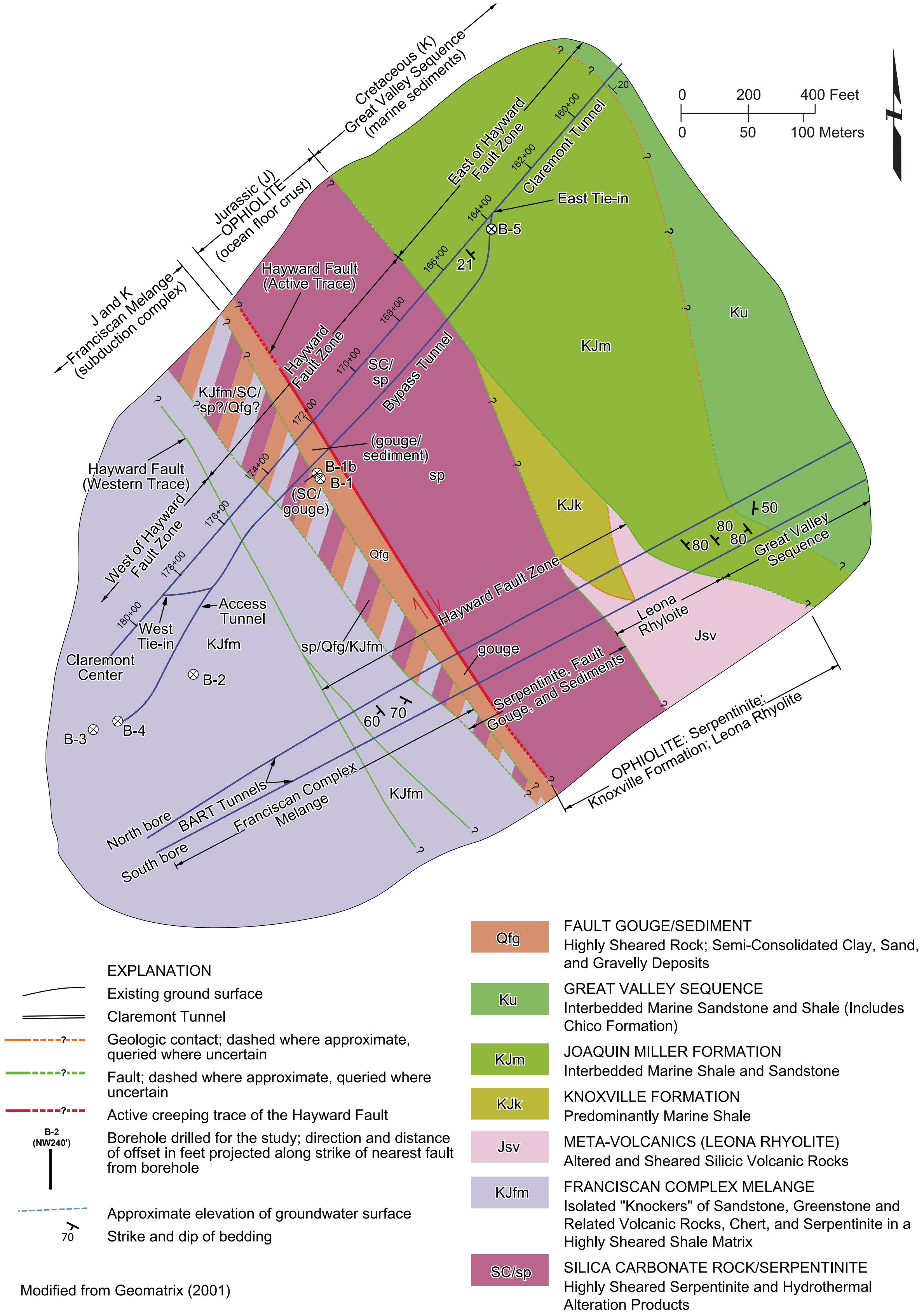


Figure 41. (*this and following page*) (A) Geologic map at the elevation of the Claremont tunnel and Bay Area Rapid Transit (BART) tunnel alignment.

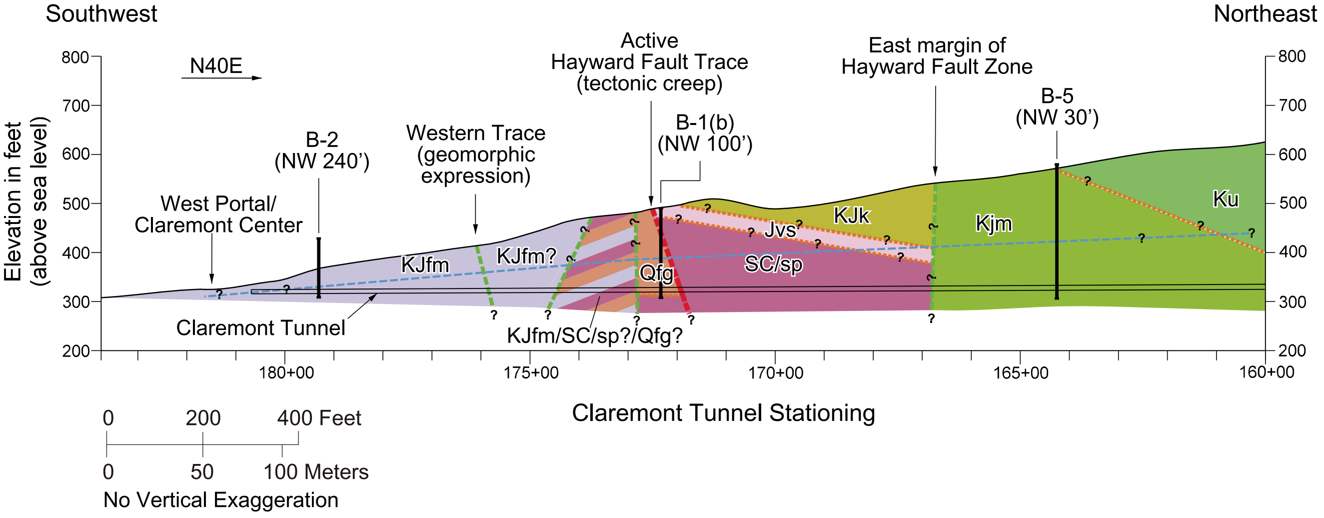


Figure 41. (*continued*) (B) Geologic profile along the Claremont tunnel alignment.

clayey gouge, and Great Valley Sequence sandstone with interbedded shale and siltstone occur east of the Hayward fault zone (Fig. 41A).

In the bypass tunnel, the Hayward fault zone includes two distinct zones: (1) the primary fault zone, which is composed of ~6 inches to 1 ft of dark gray to black, stiff, highly plastic clay (gouge) with sand-size to fine gravel-size inclusions of light-green crushed serpentine; and (2) the clay gouge associated with fault parallel zones of pervasively sheared and crushed serpentinite up to several feet wide. Immediately east of the fault zone, bedrock is serpentinite with inclusions of metabasalt. The serpentinite becomes blocky and less deformed away from the fault zone.

Immediately west of the fault zone, bedrock includes Mesozoic (~200 million to 65 million yr B.P.) Franciscan mélange (serpentinite and sheared greenstone) and silica carbonate rock. Semi-consolidated middle to late Quaternary age (~750,000 yr to 10,000 yr B.P.) alluvial and colluvial sediments also are exposed in the tunnel west of the Hayward fault (Fig. 41A and 41B). The alluvial and colluvial materials are stratified, are gravelly to clayey, and contain rounded pebbles and cobbles and large wood fragments. These materials were deposited on an erosional surface developed on the Franciscan mélange and silica carbonate rock. The alluvial and colluvial materials are interpreted to have been deposited in a depression along the fault, such as in the area of a possible extensional bend in the fault at Lake Temescal to the south (Geomatrix Consultants, 2001). Sediments accumulated in the depression along the fault; as the fault moved by creep and by sudden slip during earthquakes, these sediments were transported northward along the west side of the fault to the area of the Claremont Tunnel.

The location, width, and potential amount of fault displacement are critical factors for the design of the bypass tunnel. Geologic investigations performed for the project identified a design-level primary fault displacement of 7.5 ft horizontally and 9 inches vertically, which was estimated to occur within a 60-ft reach to be identified during tunnel inspections and excavation of the bypass tunnel (Geomatrix Consultants, 2001). Galehouse (2002) notes that in this area, the fault creeps at ~0.18–0.25 inch per year. The primary fault zone is located within a wider secondary faulting zone extending for 920 ft, where additional fault displacement of up to 2.25 ft (30% of the slip in the primary zone) may occur.

The performance goal of the seismic improvements to the Claremont Tunnel includes maintaining a minimum flow of 130 mgd without significant decrease in water quality for a period of 60–90 days following a major earthquake on the Hayward fault. Inspection of and any necessary repairs to the tunnel would be initiated following the post-earthquake period of high water demand and following repairs to other critical components of the water system. The tunnel also is designed to accommodate fault creep of up to 0.25 inch/yr over a design lifetime of 50 yr.

The seismic design measures used in construction of the bypass tunnel include the following:

- Construction of an enlarged tunnel structure through the entire zone of potential fault offset to accommodate potential fault displacement without blockage of the tunnel;
- Construction of backfill concrete side drifts surrounding the tunnel through the zone of primary fault displacement (Fig. 42);
- Installation of a structural steel carrier pipe within the tunnel across the zone of primary faulting (Fig. 43); and
- Construction of gaps in the final concrete lining reinforcement through the zone of primary fault displacement to permit shear failure between adjacent liner segments.

The enlarged tunnel section has a 2.25-ft-thick concrete liner, which will serve to accommodate any secondary fault displacement. In the area where primary fault rupture of up to

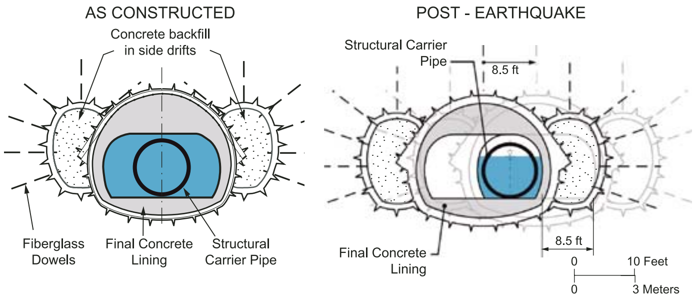


Figure 42. Cross section of oversized tunnel section before and after 8.5 ft (2.6 m) of discrete fault offset. Modified from Kieffer et al., 2004.

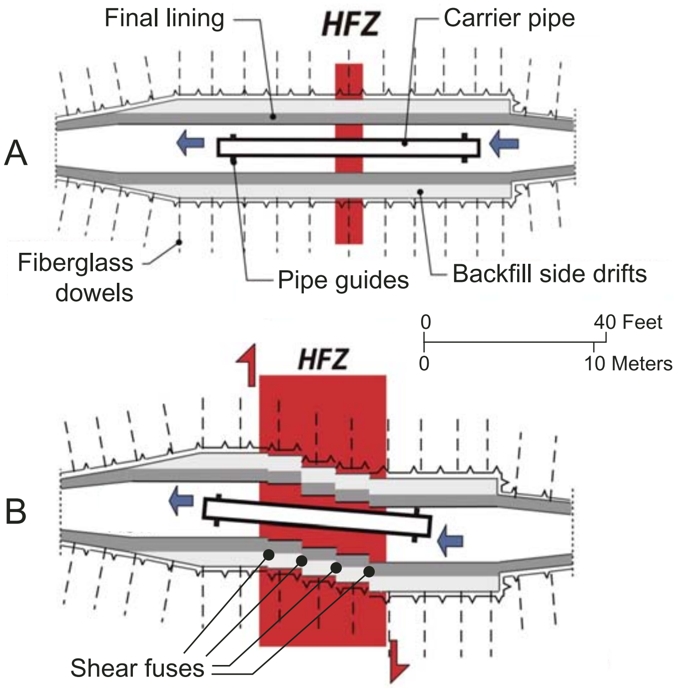


Figure 43. Plan view showing structural carrier pipe before and after 8.5 feet (2.6 m) of distributed fault offset (HFZ—Hayward fault zone). Modified from Kieffer et al., 2004.

7.5 ft is expected to occur, the concrete side drifts will mitigate the potential for faulted ground entering the tunnel and polluting the water supply (Fig. 42). The structural carrier pipe will prevent blockage of and will allow for the required minimum flow through the tunnel should the tunnel crown collapse due to fault rupture. The steel carrier pipe is lightly restrained within the surrounding tunnel so that it is essentially free to rotate and shift as fault displacement occurs (Fig. 43A). The gaps (referred to as shear fuses) in the liner consist of isolated locations without longitudinal steel reinforcement to permit the liner to displace segments while minimizing the potential for significant collapse of the lining (Fig. 43B). Additional details on the measures to mitigate the potential for loss of service due to fault rupture are presented in Kieffer et al. (2004).

Stop 9: City of Hayward Fault Creep
(Russell W. Graymer)

Significance of the Site

Here we can see evidence of creeping and non-creeping strands of the Hayward fault. We will look at the effect of fault creep on various structures, including the old City Hall. We will look at the effect of the fault on San Lorenzo Creek, and the possibility that the creeping strand is only one of the active strands of the fault here.

Accessibility

This is a public site; public restrooms are nearby, and there is easy on-street parking

GPS Coordinates

36.67079°N, 122.08117°W.

Directions

From the Claremont Tunnel Portal, get on Highway 13 South. Merge onto Interstate 580 East. Exit at Hayward–Foothill Blvd. Go straight ahead onto Foothill Blvd. Turn right onto C Street. Go two blocks to Mission Blvd. and park near the old City Hall (see map, Fig. 44).

Stop Description

Start by looking through the glass doors on the old Hayward City Hall (now unused). Note the large cracks and other evidence of structural distress. This building was unfortunately built directly on the creeping strand of the Hayward fault. A creeping fault strand is one that slowly but continuously moves at the surface in response to the same forces that generate earthquakes. This creeping strand moves right (if you look across the fault, the other side is moving to the right) at ~6 mm/yr (Lienkaemper et al., 2001). That is only 0.0000000004 (4 ten-billionths) miles per hour, so don't try to see it go. However, over years and decades that continuous sliding adds up.

From City Hall, walk northwest along Mission Blvd, parallel to the creeping strand. Note that there is a little hill to the east. In addition to sliding right, the Hayward fault is also pushing its east side up ~0.5–1 mm/yr (Gilmore, 1992; Kelson and Simpson, 1995; Lienkaemper and Borchardt, 1996). Half a block past B Street, turn right into the City of Hayward parking lot. Here look for evidence of the creeping strand on the pavement, curbs, and nearby buildings (Fig. 45).

Does surface creep mean that the fault is not building up the stress to generate a future earthquake? Unfortunately, probably not. Because the rate of surface creep is less than the long-term rate of fault offset, geologists believe that deep in the earth where large earthquakes are generated the fault is stuck tight and building up stress (Simpson et al., 2001). The last time this fault released that stress was in 1868, when it produced a severe earthquake that caused major regional damage (Fig. 46).

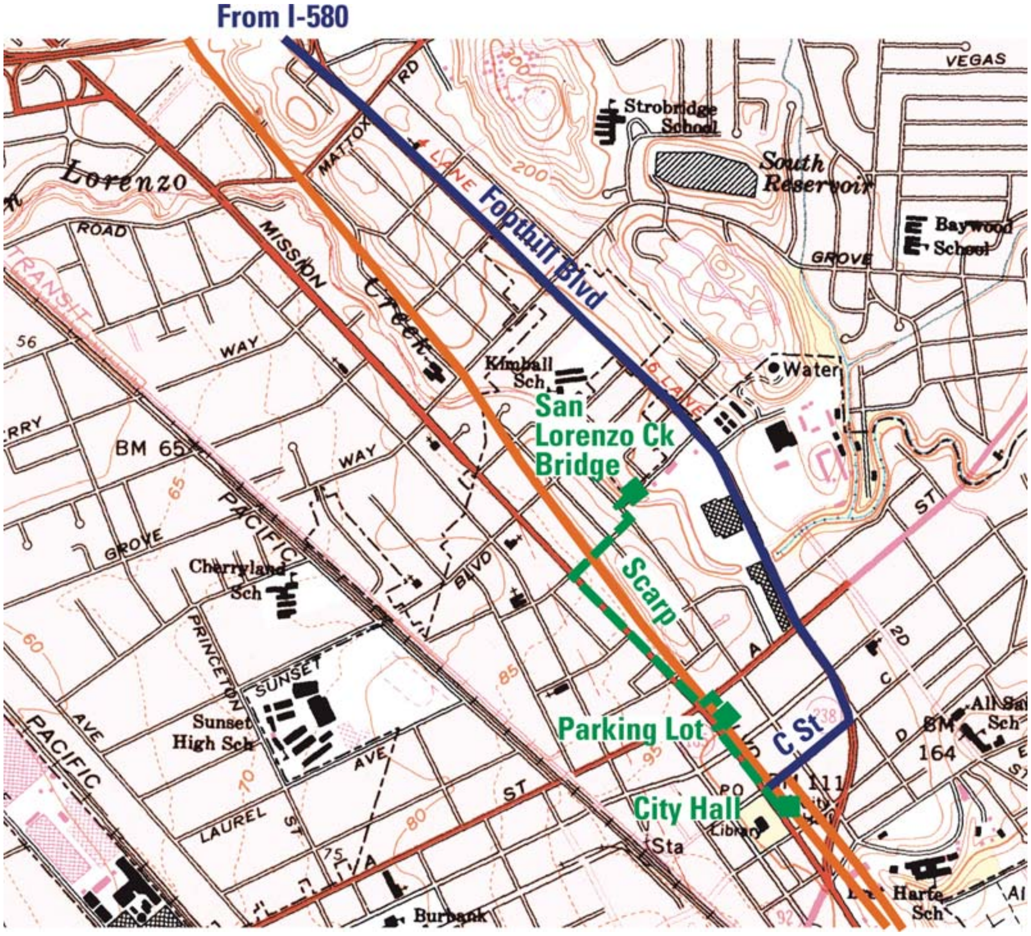
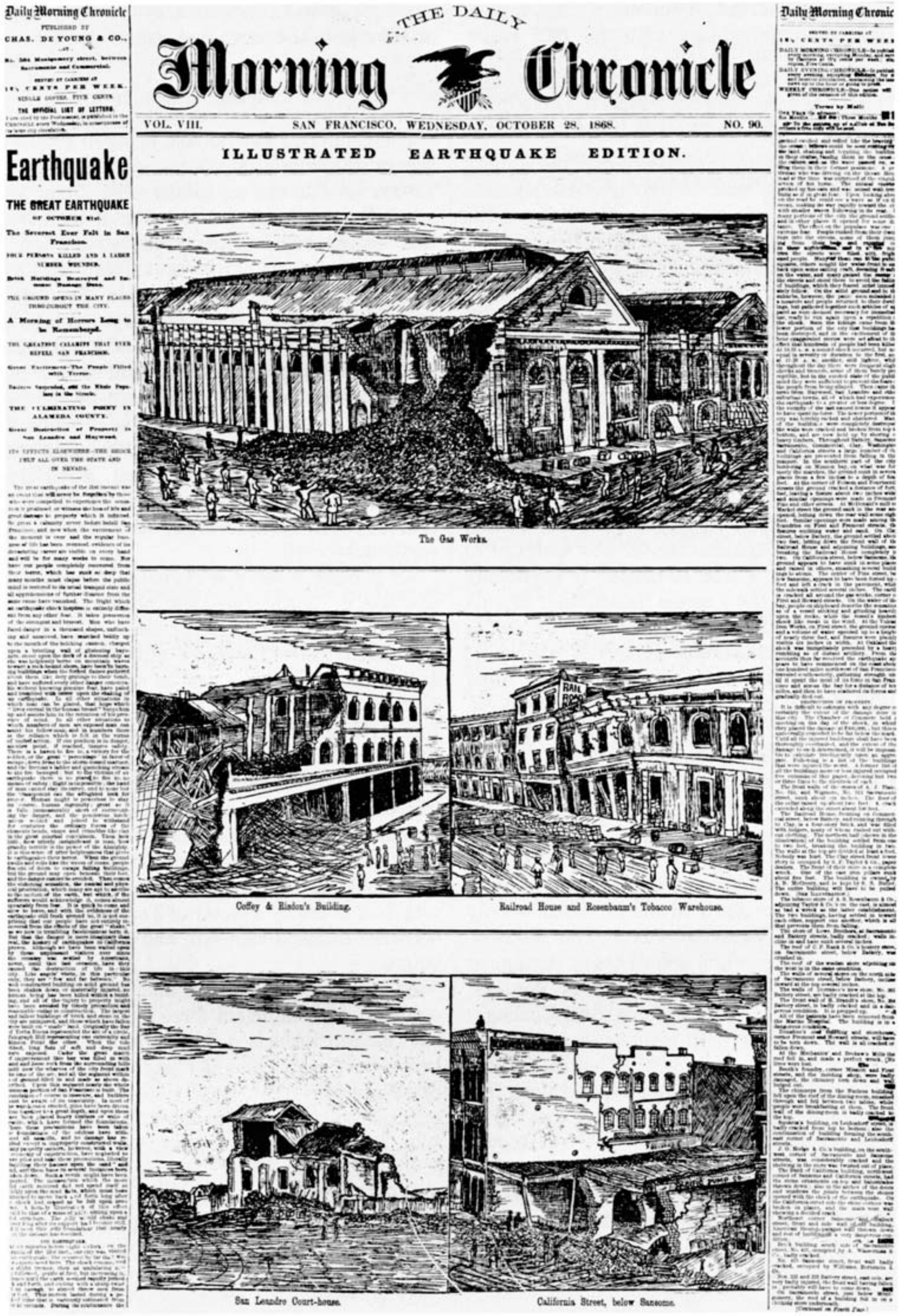


Figure 44. Topographic map of downtown Hayward and north. The driving route is shown in blue; the walking route and the features mentioned in text are shown in green. The creeping strands of the Hayward fault are shown in orange.

From the parking lot, continue northwest on Mission Blvd two blocks past A Street to Simon Street. Turn right and climb up the steep hill pushed up by the Hayward fault. A steep hillside like this is called a scarp. Just over the top of the hill, turn briefly left on Main Street, then immediately right onto Hazel Street and go to the bridge over San Lorenzo Creek. Note that the creek here is running northwest, parallel to the creeping strand (Fig. 44). Where creeks and streams cross active faults, they are frequently deflected by the long-term offset of the fault (Wallace, 1990). Looking at the map of San Lorenzo Creek, you can see that it is deflected to the right in two places, here and on the other side of the hill to the northwest, although neither of those deflections is directly along the creeping strand (Lienkaemper, 1992). That means that there are probably two more strands of the Hayward fault in this area that pulled the stream into its current shape (Fig. 47). Are these strands part of the active Hayward fault? Geologists do not know. Unfortunately, scientific studies that were undertaken after the 1868 earthquake have been lost, so we don't now know if either of the strands that offset the creek broke the

Figure 45. Photograph of evidence of right lateral creep on the mapped active strand of the Hayward fault. This offset curb is in the parking lot between A and B streets in downtown Hayward.

ground during that quake. However, geologists do know that long-term offset on the Hayward fault has taken place on several strands and that here the creeping strand has taken up at most 5% of the total offset over the fault's geologic history (Graymer et al., 1995; Graymer, 1999). Radiometric dating of offset rocks suggest that the fault has a total offset of ~100 km or 60 mi in the past 12 million years (Graymer et al., 2002), but only at most 3 mi (5 km) can have occurred on the creeping strand because that strand runs right through an only slightly offset rock body. Perhaps the creek-deflecting strands are now-abandoned old strands, or perhaps they are still-active strands that aren't creeping. We are still learning about how the complicated Hayward fault works.



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THE DAILY
Morning Chronicle

VOL. VIII. SAN FRANCISCO, WEDNESDAY, OCTOBER 28, 1868. NO. 90.

ILLUSTRATED EARTHQUAKE EDITION.

Earthquake

THE GREAT EARTHQUAKE
OF OCTOBER 21st.

The Severest Ever Felt in San Francisco.

FOUR PERSONS KILLED AND A LARGE NUMBER WOUNDED.

Brick Buildings Destroyed and Immense Damage Done.

THE GROUND OPENS IN MANY PLACES THROUGHOUT THE CITY.

A Morning of Horrors Long to be Remembered.

THE GREATEST CALAMITY THAT EVER BEFELL SAN FRANCISCO.

Great Excitement—The People Filled with Terror.

Business Suspended, and the Whole Population in the Streets.

THE CULMINATING POINT IN ALAMEDA COUNTY.

Great Destruction of Property in San Leandro and Hayward.

ITS EFFECTS ELSEWHERE—THE SHOCK FELT ALL OVER THE STATE AND IN NEVADA.

The Gas Works.

Coffey & Risdon's Building.

Railroad House and Rosenbaum's Tobacco Warehouse.

San Leandro Court-house.

California Street, below Sansome.

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(Continued on Fourth Page.)

Figure 46. Front page of the *San Francisco Daily Morning Chronicle* from October 1868, showing the widespread damage from the earthquake generated by rupture of the Hayward fault. This earthquake was known as the Great San Francisco Earthquake until 1906.

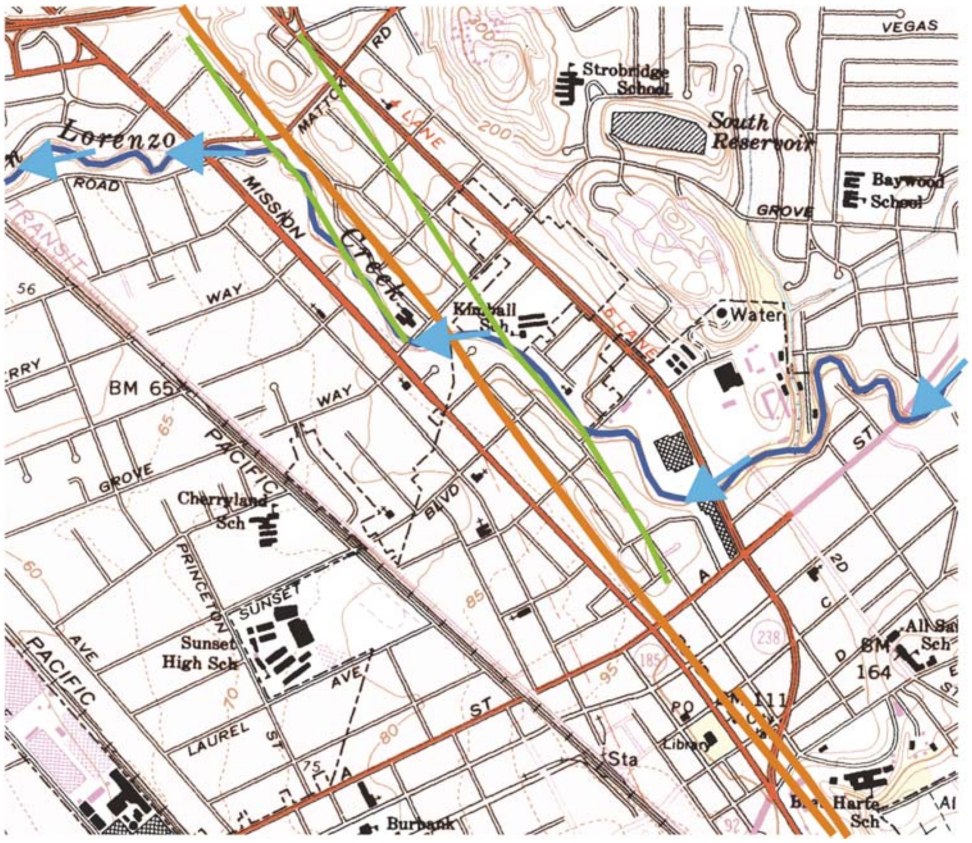

Figure 47. Topographic map of downtown Hayward and north. The mapped active trace of the Hayward fault is shown as a thick orange line, San Lorenzo Creek is shown by the blue line, and the double right-step in San Lorenzo Creek is illustrated by the blue arrows. The non-creeping strands of the Hayward fault that probably caused the double right-step are shown in green.

Stop 10: Fault Trench Exhibit at Fremont Central Park (Heidi Stenner, Jim Lienkaemper, and Mary Lou Zoback)

Significance of the Site

The Hayward fault has been studied and trenched extensively in Fremont's Central Park to help locate new civic structures away from active fault traces and to evaluate the safety of existing structures in and near the fault. The 1868 earthquake on the Hayward fault broke the earth's surface at this location. A trench excavated in 1987 represented a particularly clear example of the active Hayward fault trace. This trench will be reopened for two months in 2006 as an exhibit to show the public what an active fault looks like beneath the surface (to depths of 10–15 ft) and to explain how it produces earthquakes.

Accessibility

This exhibit is on City of Fremont property and has ample parking and public restrooms nearby. Wheelchairs can access the site.

GPS Coordinates

37.549205°N, 121.968917°W.

Directions

From the City of Hayward, take I-880 South. Exit to the Northeast onto Stephenson Boulevard. You will be heading toward the East Bay hills. Turn right onto Paseo Padre Parkway. Turn left onto Sailway Road into Central Park. The Trench Exhibit will be northwest of the parking area. Signs will guide you.

Stop Description

Do earthquakes tend to repeat at regular intervals? If so, knowing when they have happened in the past may tell us when to expect the next one. Many earthquakes happened long before people were recording history, so how can we discover what happened so long ago?

Geologists look for evidence by digging into the ground to study the layers of earth that accumulate, one on top of the other, over time. Like the pages of a history book, each layer records what was happening at that time. A layer of round rocks can indicate an ancient river, whereas a layer of mud can be from an ancient flood. Layers also record earthquakes. The ground can shift several feet or much more during an earthquake, disrupting the layers (and "tearing" the pages of Earth's history book). In the years after an earthquake, new layers of rock and soil may blanket the area and bury the broken layers below.

To go back in time, geologists dig trenches up to 20 ft deep and 10 ft wide and then walk in to observe the layers. If there has been a large quake, the sediment will be disrupted along the fault. Any layers that are not disturbed and that rest on top of the faulted layers were laid down after the earthquake. Then, if we can figure out when the layers formed, we can date the earthquake. Geologists look for plant or animal remains, like sticks or shells, in the buried layers and date them using the same tools used by archaeologists.

With the information gathered in the trenches, geologists can tell how often earthquakes occur and even how large past quakes were. The more scientists know about a fault's past, the better they are able to suggest what may happen in the future.

This fault trench exhibit in Fremont's Central Park (Fig. 48) consists of an open pit that exposes the Hayward fault in a locality where the steep fault ruptured in 1868 and is easily observed in the different types of sediment (Fig. 49). The Fig. 49 photo comes from a trench located where the exhibit is today, ~150 feet north of the front of the former library (now the teen center). The public can observe the fault from the ground surface as well as walk down into the pit for a closer look. Visitors can also see where slow and constant creep along the fault is deforming the parking lot. A series of explanatory posters and exhibit material and brochures cover what happened during the earthquake here in 1868, a description of the City of Fremont's response to dealing with the hazard posed by the Hayward fault, as well as general information on earthquake preparedness and mitigation.

The exhibit is open for two months, beginning in April 2006 and concluding in May 2006, and is open both during the week (by appointment, primarily for school groups) as well as on the weekend for individuals and families. Volunteer docents will staff the exhibit during operating hours. The exhibit includes a rectangular open pit roughly 10–15 ft deep with gently sloped sides and stair access to the bottom. The fault trace is exposed on two walls of the pit and is highlighted with surface markers to help explain it.

Stop 11: Bay Division Pipeline Crossing, Fremont (Donald Wells and John Eidinger)

Significance of the Site

The Bay Division Pipelines Nos. 1 and 2 are owned by the San Francisco Public Utilities Commission (SFPUC) and supply drinking water from the Sierra Nevada Mountains and local watersheds to customers in four Bay Area counties. These

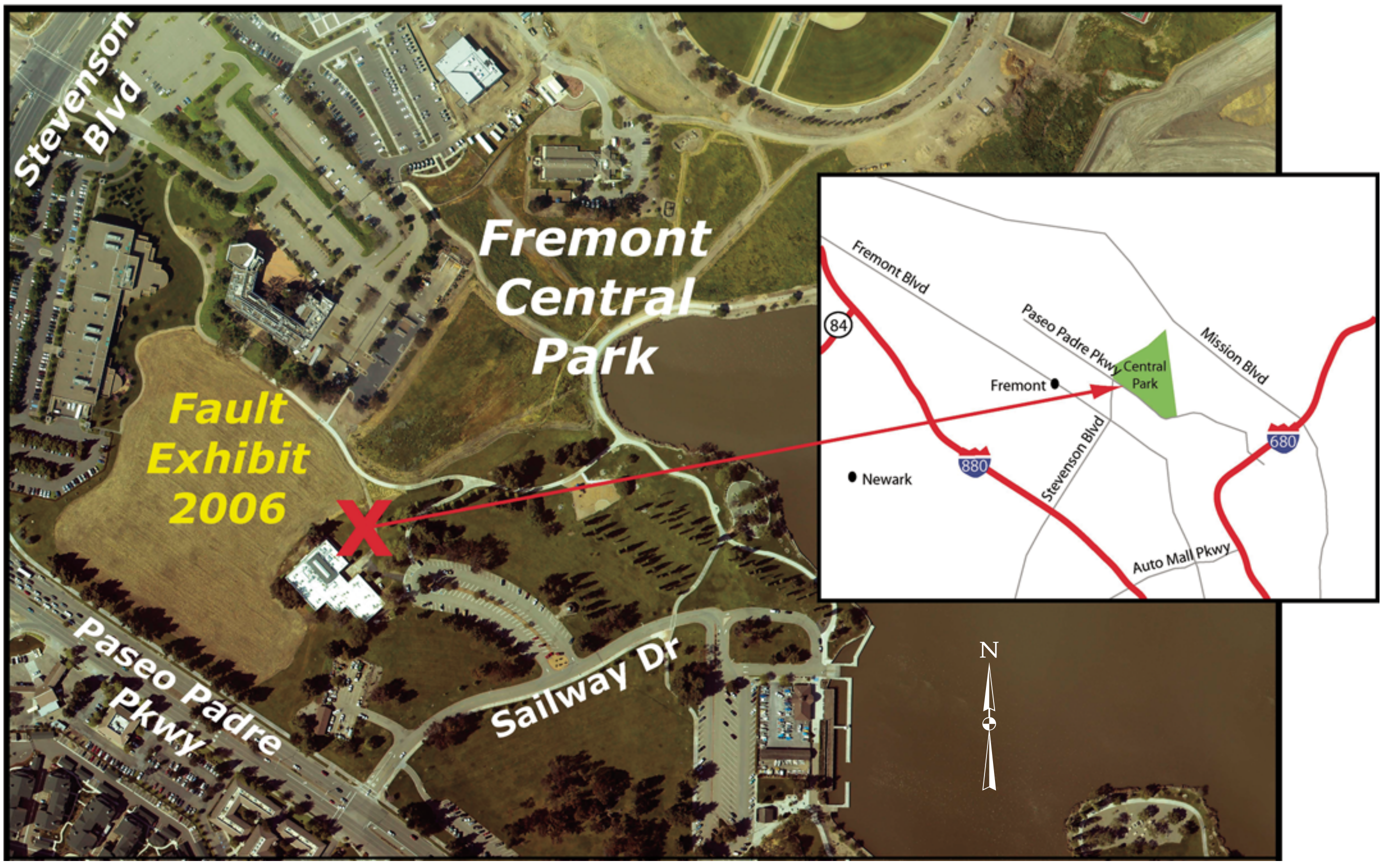

Figure 48. An aerial view of Central Park in Fremont with an inset of a road map showing its location.

pipelines, along with Bay Division Pipelines Nos. 3 and 4 located ~4 mi south, are a critical lifeline facility that supplies most of the water to the 2.4 million people in San Francisco, San Mateo, Santa Clara, and Alameda counties either directly or through wholesale customers. These four pipelines all cross the southern reach of the Hayward fault. The San Francisco Public Utilities Commission and its consultants have evaluated the fault rupture hazard and have developed and implemented mitigation measures to minimize the potential for damage and loss of service to the pipelines due to surface fault rupture along the Hayward fault.

Accessibility

There is parking along north side of Grimmer Boulevard at the intersection of Paseo Padre Parkway. The Bay Division Pipelines 1 and 2 cross beneath Paseo Padre Parkway ~400 ft southeast of the intersection with Grimmer Boulevard, continuing west beneath Grimmer Boulevard ~500 ft west of the intersection with Paseo Padre Parkway.

GPS Coordinates

37.5408°N, 121.9050°W.

Directions

From the parking lot at Fremont Civic Center–Lake Elizabeth, return to Paseo Padre Parkway, and turn left. Continue 1.0 mi south to intersection with Grimmer Boulevard. Turn right on Grimmer Boulevard, and park in the dirt area on right side of road. Walk across Grimmer Boulevard to the sidewalk and dirt area at the corner of Paseo Padre Parkway and Grimmer Boulevard.

Stop Description

The Bay Division Pipelines (BDPL) Nos. 1 and 2 extend ~21 mi from the Irvington Tunnel in Fremont westward under San Francisco Bay to the Pulgas Tunnel near Redwood City. BDPL No. 1 is a 60-inch, riveted steel pipeline constructed in 1925. BDPL No. 2 is a 66-inch, welded steel pipeline constructed in 1935. The pipelines run parallel in an 80-ft-wide right-of-way and cross the Hayward fault in the vicinity of Paseo Padre Parkway and Grimmer Boulevard in Fremont (Fig. 50). The pipelines are buried in the area of the Hayward fault, except for a 200-ft-long above-ground, pedestal-supported reach located west of the fault.

In the Central Park area of Fremont, the Hayward fault is characterized by a well-located creeping fault, designated as the western trace, and a discontinuous eastern trace that bound a low knoll at the Fremont Civic Center and a depression at Tule Pond north of Lake Elizabeth (Fig. 51). The average horizontal creep rate on the western fault trace over the past ~20 years is ~5 mm/yr in the area of Lake Elizabeth (Galehouse, 2002). At Lake Elizabeth, the western trace of the Hayward fault bounds a series of low, rounded hills on the west from a low-lying area on the east (Fig. 51). The low-lying area was formerly called Stivers Lagoon; this lagoon was modified by the City of Fremont to develop Central Park and the Lake Elizabeth recreation area. Borchardt et al. (2000) present a summary of the development history of the Fremont Civic Center site. The extent of the eastern trace south from the Civic Center knoll along Lake Elizabeth is uncertain.

Figure 49. (*this and following page*) (A) Photograph of the Hayward fault exposure in a trench opened in 1987 on City of Fremont property (photo courtesy of San Jose Mercury News). The fault is a sharp boundary between fine-grained gray silt and light-colored sandy gravels.

Inspection of the BDPL 1 and 2 in the early 1990s by the SFPUC revealed that the pipes were distressed due to fault creep and that expansion couplings originally outfitted on both sides of the fault had accommodated some of the slip due to fault creep (Eidinger, 2001). The SFPUC determined that these pipelines, as well as BDPL 3 and 4 (located 4 mi south of BDPL 1 and 2), could fail due to ongoing fault creep or rupture of the Hayward fault. Although the SFPUC has raw water storage facilities along the peninsula, the system is dependent upon a steady of flow of drinking water through the Bay Division Pipelines to service their customers, particularly during peak demand. Thus, failure of these pipelines would result in significant reduction in water service to the South Bay and Peninsula customers. The SFPUC initiated a program to evaluate and mitigate the potential for loss of service to these four pipelines.

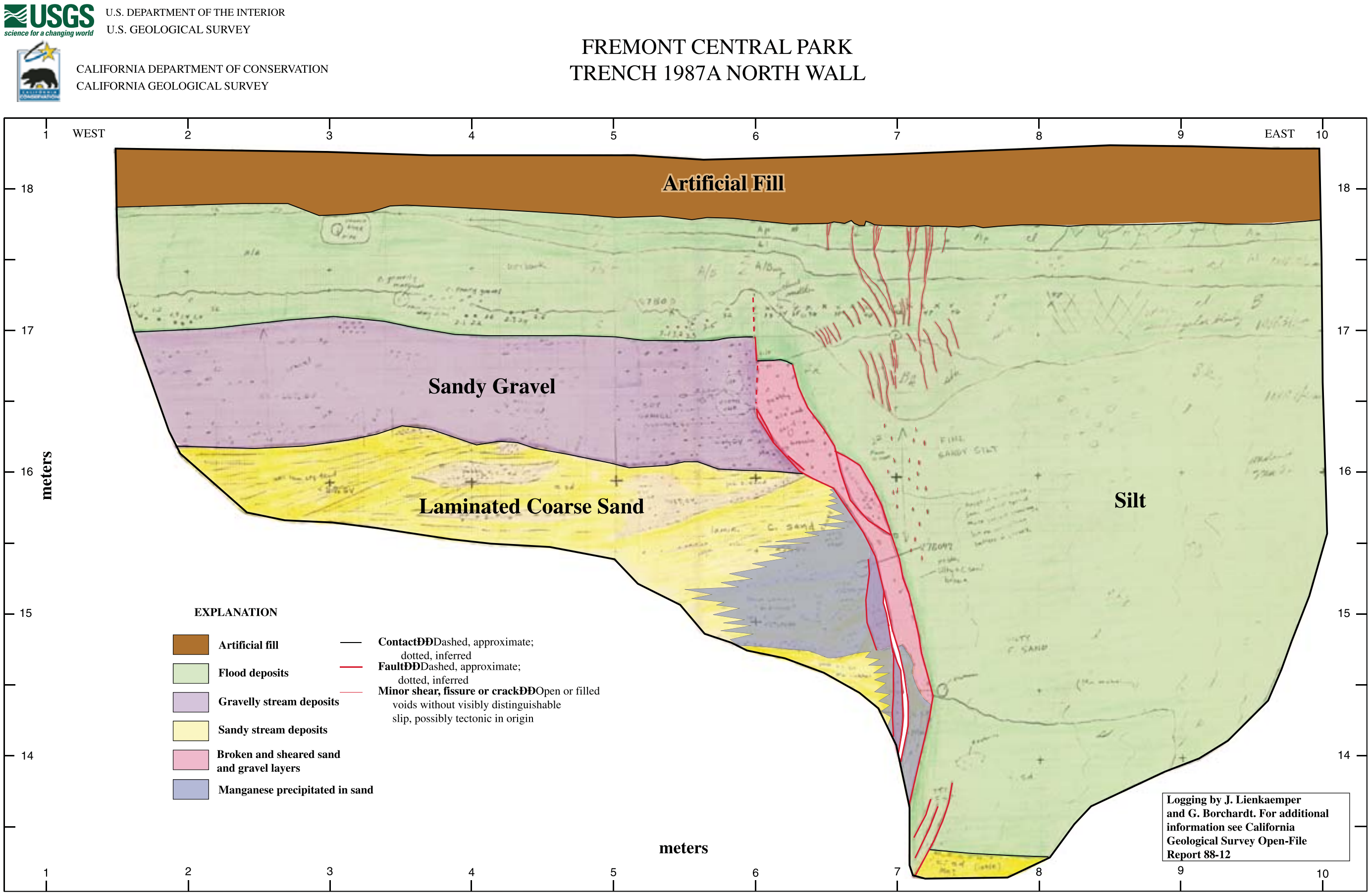

Figure 49. (*continued*) (B) Geologic log of the opposite wall of the trench with a 2-ft grid superimposed.

Geomatrix Consultants (1999) conducted detailed investigations at the BDPL 1 and 2 to locate the western (creeping) trace of the Hayward fault, to assess the evidence for an eastern trace of the Hayward fault, and to define the width of the fault zone and the expected displacement during future earthquakes. Fault trenching showed that the pipelines traverse the main active trace of the Hayward fault along the projected location of the main creeping trace of the fault. The zone of active creep and major deformation is ~20 ft wide, and zones of subsidiary faulting and folding extend 15–30 ft on each side of the primary zone of creep and faulting (Fig. 52). The eastern fault trace observed to the north at the Civic Center knoll was not observed in the fault trenches and does not extend to the BDPL. The trenching investigation also showed that the expansion couplings installed during construction of the pipeline to span the fault zone were mislocated to the east of the main creeping trace of the fault.

The SFPUC design team considered two levels of fault displacement for the design of retrofit measures for BDPL 1 and 2. The displacements were based on a probabilistic distribution of maximum magnitudes for rupture of the Hayward fault and empirical relationships between magnitude and fault displacement (Geomatrix, 1999). The “probable earthquake” was selected at the 84th percentile nonexceedance level, corresponding to a horizontal displacement of 5 ft; a “maximum earthquake” displacement of 10 ft also was considered, which corresponds to about a 95th percentile nonexceedance level.

BDPL 1 and 2 intersect the Hayward fault at an angle of ~70°, such that right-lateral movement on the fault produces net tension in the pipes (Fig. 53). Detailed surveying of the pipelines also showed that fault creep was accommodated by slip only out of the westernmost expansion joint and that continued creep could result in failure of the pipeline by about the year 2010 or sooner. The design team considered several design options to replace the pipelines at the fault crossing. These options were based on a nonlinear structural model of the pipeline developed using three-dimensional nonlinear pipeline elements and suitable nonlinear soil springs (Eidinger, 2001).

The selected mitigation was the “rapid anchorage” design, which used new, thick, welded pipes set in pea gravel for 90 ft across the fault zone and in controlled low-strength material (CLSM) beyond the fault zone extending to Grimmer Boulevard and Paseo Padre Parkway (Fig. 54). Native soil was com-

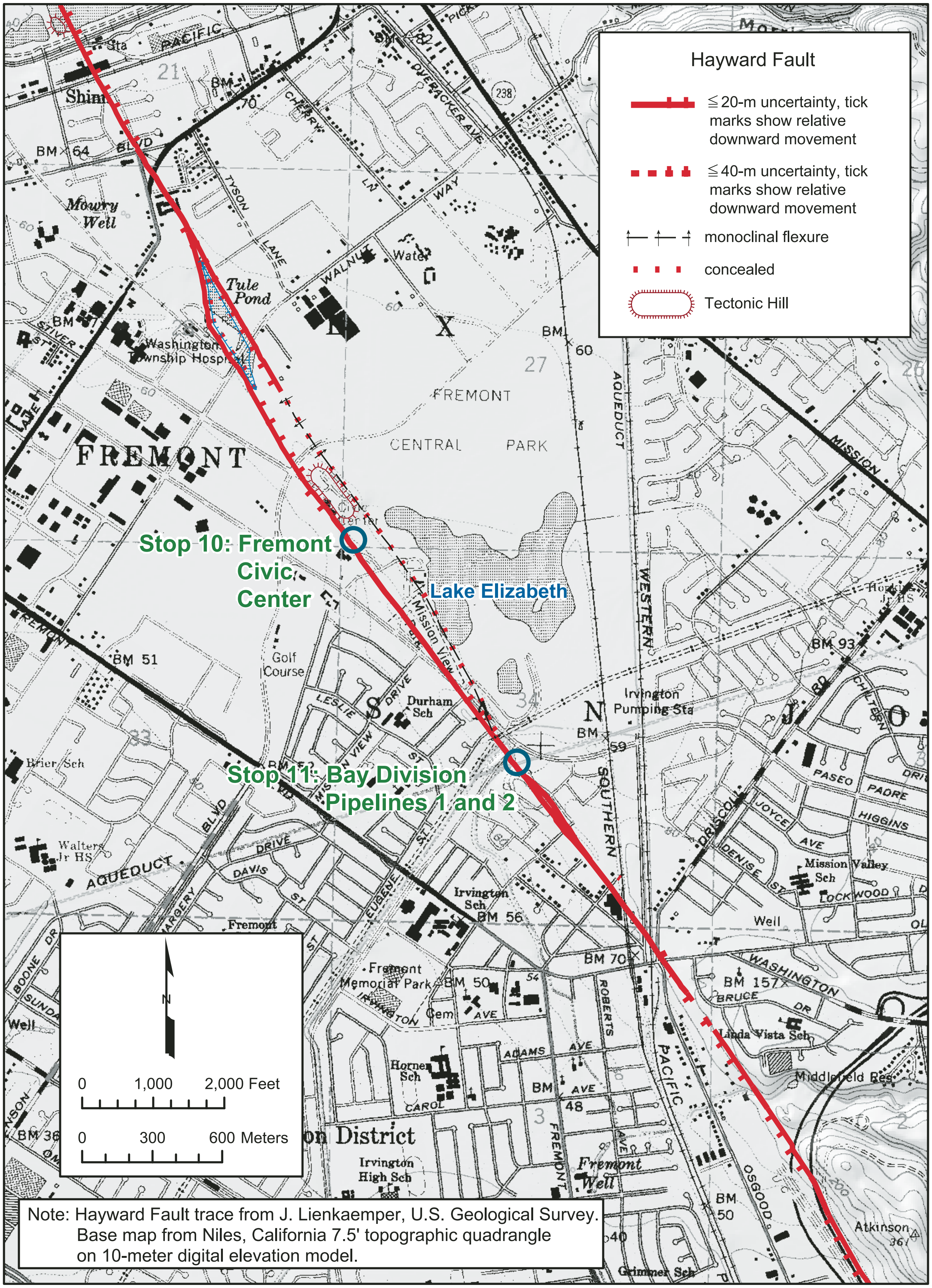

Figure 50. Stop location for Bay Division pipelines.

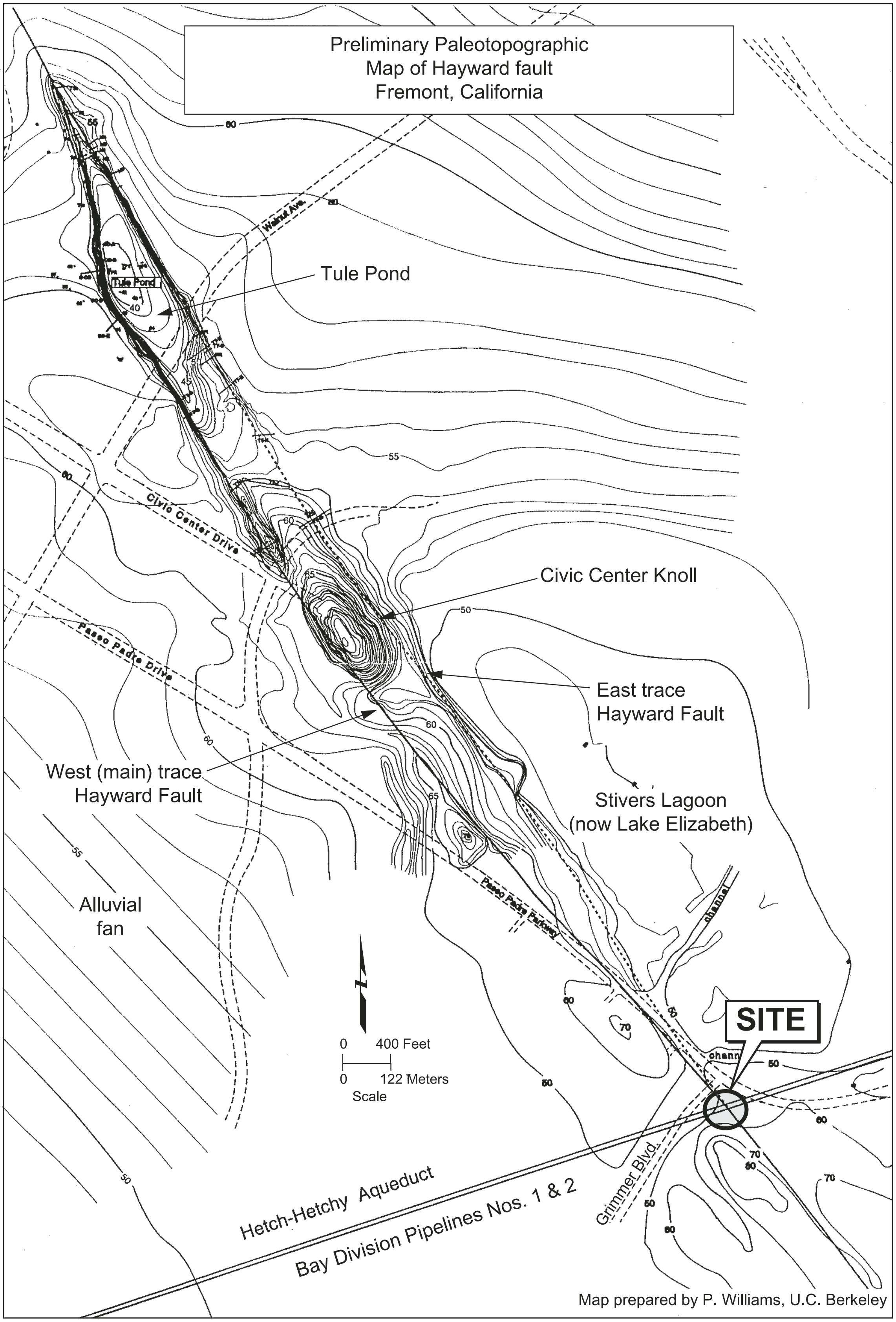

Figure 51. Predevelopment topographic map of the Hayward fault zone in Fremont.

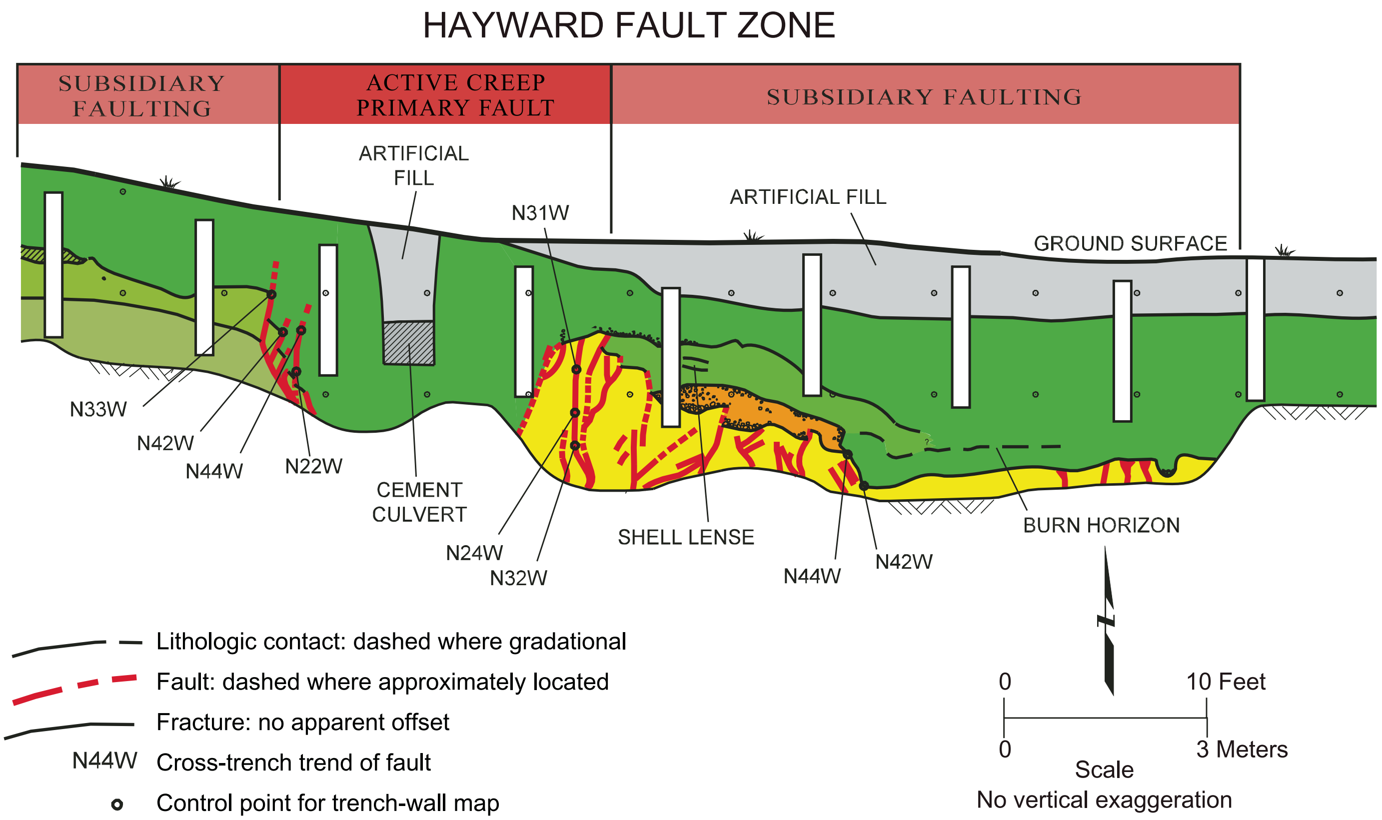

Figure 52. Trench log of the Hayward fault zone at Bay Division Pipelines (BDPL) 1 and 2 crossing. From Geomatrix Consultants (1999).

pacted to grade overlying the pea gravel and CLSM. The pea gravel was designed to permit flexure of the pipeline in the event of rupture on the Hayward fault. New welded steel pipelines were slip-lined and grouted in place through the existing pipelines beneath Grimmer Boulevard and Paseo Padre Parkway; the slip-line pipe reaches were connected to the existing pipe beyond the roads using a butt strap joint. This option was selected in part because this method would not require trenching across the city streets adjacent to the site. Other considerations in this design option included:

- Selecting a hard, epoxy-type corrosion protection to promote transfer of strain into the pipeline section anchored in the CLSM;
- Adding straps (lugs) to the pipeline to improve anchorage in the CLSM and to minimize transfer of strain to the adjacent original pipeline sections;
- Installing new seismic isolation valves ~650 ft away from the fault;
- Installing 24″ bypass pipelines with a manifolds designed for use with six 12″ flexible hoses; and
- Constructing a retaining wall to stabilize sloping ground adjacent to the pipelines.

The hydraulically actuated isolation valves can be closed remotely without the need for an additional power source. Bypass pipeline manifolds are located on both sides of the fault zone, such that flex hoses could be installed across the fault to restore water flow in the unlikely event of failure of the pipelines between the valves. The performance objective of the bypass pipeline is to restore most of the water supply across the Hayward fault within 24 hours in the event of pipeline failure.

Mitigation options for BDPL 3 and 4 were developed using a cost-benefit analysis (discussed in Eidinger, 2001), and implementation of the selected option(s) has recently been initiated.

ACKNOWLEDGMENTS

The authors wish to thank the following organizations for permission to visit the sites and facilities described in this guidebook: The University of California at Berkeley, East Bay Municipal Utility District, San Francisco Public Utilities Commission, and the cities of Pinole, Berkeley, Oakland, Hayward, and Fremont. The support of Geomatrix Consultants for Donald Wells and the extensive work by Javier Chalini, David O’Shea, and Steve Wessels of the Graphics Design Group of Geomatrix Consultants in preparing illustrations for several of the stops is greatly appreciated. We also appreciate the use of several original illustrations provided by the Earthquake Engineering Research Institute, Oakland, California.

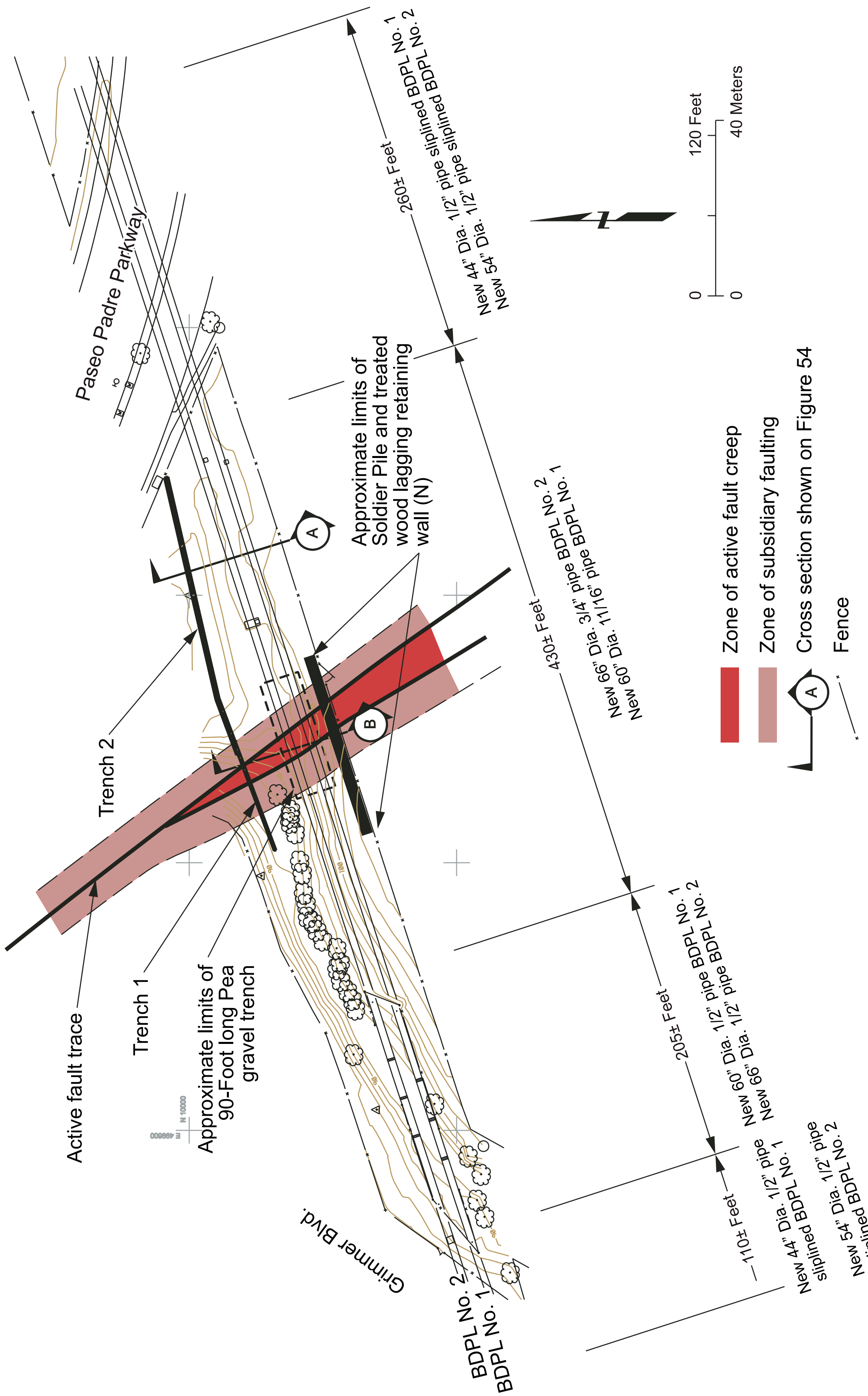

Figure 53. Site plan showing pipeline retrofit design. BDPL—Bay Division Pipelines. Modified from Geomatrix Consultants (1999).

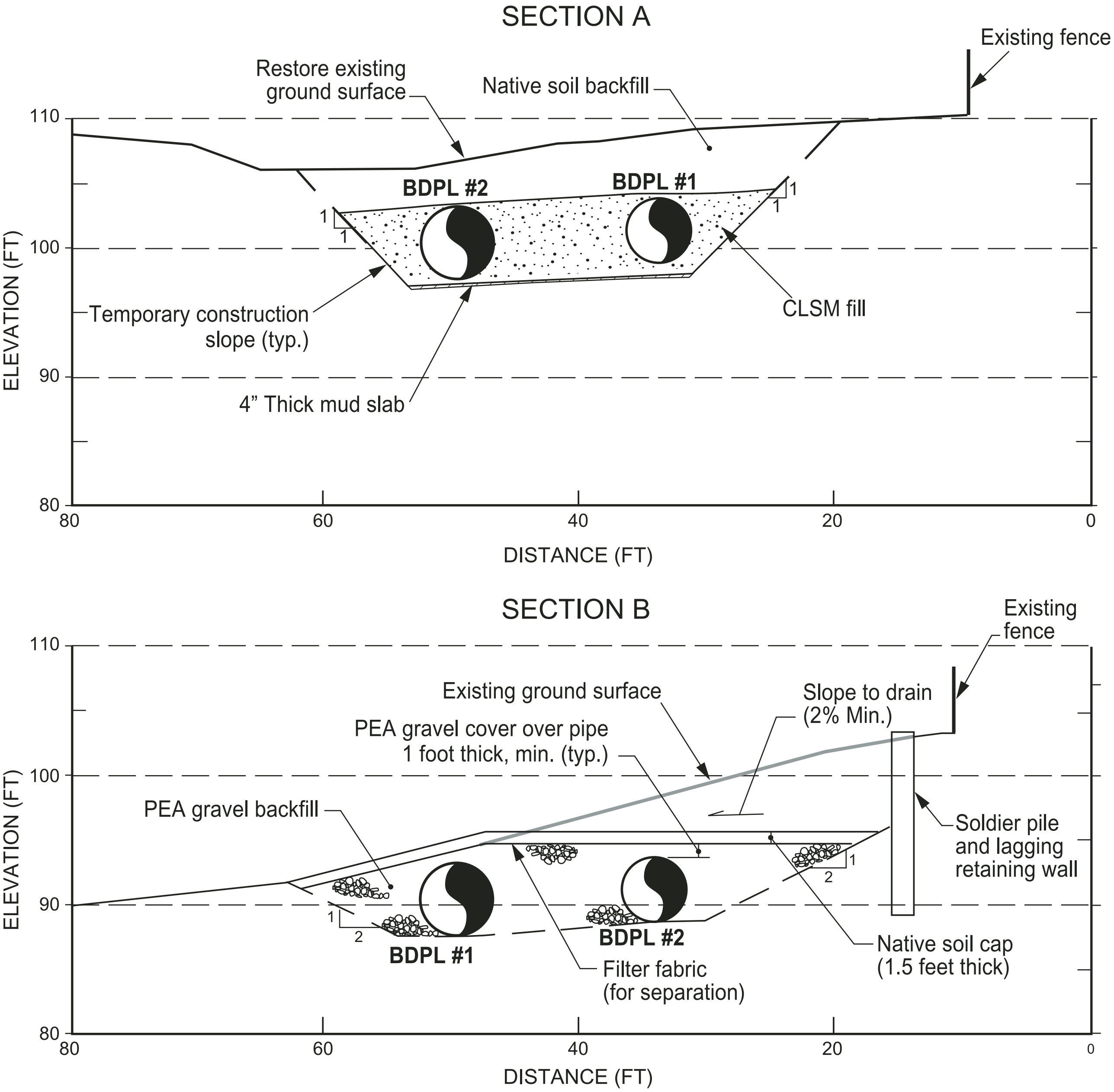

Figure 54. Cross sections showing pipeline retrofit design. (A) Cross section through fault zone reach. (B) Cross section outside fault zone reach. BDPL—Bay Division Pipelines. From Geomatrix Consultants (1999).

REFERENCES CITED

General References for the Hayward Fault

Ponce, D.A., Bürgmann, R., Graymer, R.W., Lienkaemper, J.J., Moore, D.E., and Schwartz, D.P., 2003, Proceedings of the Hayward Fault Workshop, Eastern San Francisco Bay Area, California, September 19–20, 2003: U.S. Geological Survey Open-File Report 2003-485, 71 p. URL: http://pubs.usgs.gov/of/2003/of03-485/.

U.S. Geological Survey, "Browse the Hayward fault map": http://quake.wr.usgs.gov/research/geology/hf_map/HF_index.html.

Stop 1: Memorial Stadium

Borchardt, G., Taylor, C.L., Rogers, J.D., Wells, D.L., Shastid, T., Yiadom, A., Ortiz, J., and Williams, P.L., 2000, Engineering for surface ground rupture on the Hayward fault: *in* Alvarez, L., ed., AEG-GRA 2000 Field Trip Guidebook, From the Pacific Ocean to the Sierra Nevada: Taming Shaky Ground: Association of Engineering Geologists and Groundwater Resources Association, Chap. 6, 25 p.

Doolin, D.M., Wells, D.L., and Williams, P.L., 2005, Assessment of fault-creep deformation at Memorial Stadium, University of California, Berkeley, California: Environmental & Engineering Geoscience, v. 11, no. 2, p. 125–139, doi: 10.2113/11.2.125.

Galehouse, J.S., 2002, Data from theodolite measurements of creep rates on San Francisco Bay region faults, California: 1979–2001: U.S. Geological Survey Open-File Report 02-225, http://geopubs.wr.usgs.gov/open-file/of02-225/.

Geomatrix Consultants, Inc., 2001, Fault rupture hazard evaluation, California Memorial Stadium: Report prepared for Capitol Projects, University of California, Berkeley, October.

Harding Lawson Associates, 1986, Geologic and Fault Hazard Investigation Phase I, Foothill Student Housing, University of California, Berkeley: Report Prepared for O'Brien-Kreitzberg and Associates, San Francisco, 13 November, 3 p., 28 plates.

Harding Lawson Associates, 1988a, Geologic and Fault Hazard Investigation Phase II, Foothill Student Housing, University of California, Berkeley: Report Prepared for O'Brien-Kreitzberg and Associates, San Francisco, 12 January, 31 p., 48 plates.

Harding Lawson Associates, 1988b, Supplemental Fault Hazard Investigation, "Louderback Trace," Foothill Student Housing Project, University of California, Berkeley: Report Prepared for O'Brien-Kreitzberg and Associates, San Francisco, 22 June.

Hirschfeld, S.E., Borchardt, G., Kelson, K.I., Lienkaemper, J.J., and Williams, P.L., 1999, The Hayward Fault—Source of the next big Quake? *in* Wagner, D.L., and Graham, S.A., eds., Geologic Field Trips in Northern California: California Geological Survey Special Publication 119, p. 150–159.

Lennert, B.J., 1982, Accurate location of the active trace of the Hayward fault between Ashby and Marin Avenues in Berkeley, with proposed models of stress-strain conditions from creep and rapid offset, *in* Hart, E.W., Hirschfeld, S.E., and Schulz, S.S., eds., Proceedings, Conference on Earthquake Hazards in the Eastern San Francisco Bay Area: California Division of Mines and Geology Special Publication 62, p. 45–54.

Stop 4: UC Richmond Field Station

George E. Brown Jr. Network for Earthquake Engineering Simulation (NEES): University of California at Berkeley, http://nees.berkeley.edu

Pacific Earthquake Engineering Research Center (PEER): University of California at Berkeley Richmond Field Annex maps: http://peer.berkeley.edu/PEERCenter/Contact/maps.html.

Stop 5: Point Pinole

Bilham, R., 2005, Creepmeters on the San Andreas fault system: http://cires.colorado.edu/~bilham/creepmeter.file/creepmeters.htm.

Bloom, A.L., 1970, Paludal stratigraphy of Truk, Ponape; and Kusaie, Eastern Caroline Islands: Geological Society of America Bulletin, v. 81, p. 1895–1904.

Borchardt, G., 1988a, Soil development and displacement along the Hayward fault, Point Pinole Regional Shoreline, Richmond, California, *in* Borchardt, Glenn, ed., Soil development and displacement along the Hayward fault (Volume II): Point Pinole, California, California Division of Mines and Geology Open-File Report DMG OFR 88-13, p. 95–161.

Borchardt, G., 1988b, Estuarine deposition and its relationship to the Hayward fault, Point Pinole Regional Shoreline, Richmond, California, *in* Borchardt, Glenn, ed., Soil development and displacement along the Hayward fault (Volume II): Point Pinole, California, California Division of Mines and Geology Open-File Report DMG OFR 88-13, p. 163–220.

Borchardt, G., and Seelig, K.A., 1991, Soils, paleosols, and Quaternary sediments offset along the Hayward fault at Point Pinole Regional Shoreline, Richmond, California, *in* Sloan, Doris, and Wagner, D. L., eds., Geologic excursions in northern California: San Francisco to the Sierra Nevada, California Department of Conservation, Division of Mines and Geology Special Publication 109, p. 75–83.

Borchardt, G., Seelig, K.A., and Wagner, D.L., 1988, Geology, paleosols, and crustal stability at Point Pinole Regional Shoreline, Contra Costa County, California, *in* Borchardt, G., ed., Soil development and displacement along the Hayward fault (Volume II): Point Pinole, California, California Division of Mines and Geology Open-File Report DMG OFR 88-13, p. 3–94.

Edwards, R.L., Chen, R.H., Ku, T.-L., and Wasserburg, G.J., 1987, Precise timing of the last interglacial period from mass spectrometric determination of Thorium-230 in corals: Science, v. 236, p. 1547–1553.

Harsh, P.W., and Burford, R.O., 1982, Alinement-array measurements of fault slip in the eastern San Francisco Bay area, California, *in* Hart, E.W., Hirschfeld, S. E., and Schulz, S.S., eds., Proceedings of the Conference on Earthquake Hazards in the Eastern San Francisco Bay Area, California Division of Mines and Geology Special Publication 62, p. 251–260.

Lienkaemper, J.J., Borchardt, G.R., and Lisowski, M., 1991, Historic creep rate and potential for seismic slip along the Hayward fault, California: Journal of Geophysical Research, v. 96, no. B11, p. 18,261–18,283.

Steinbrugge, K.V., Bennett, J.H., Lagorio, H.J., Davis, J.F., Borchardt, G.R., Toppozada, T., Degenkolb, H.J., Laverty, G.L., and McCarty, J.E., 1987, Earthquake planning scenario for a magnitude 7.5 earthquake on the Hayward fault in the San Francisco Bay area, California Department of Conservation, Division of Mines and Geology Special Publication 78, 243 p.

Stop 6: Cragmont School

Bishop, C.C., 1973, Geological and geophysical investigations for tri-cities seismic safety and environmental resources study: California Division of Mines and Geology Preliminary Report 19, 44 p.

California Division of Mines and Geology, 1982, Special Study Zones, Richmond 7.5-minute Quadrangle, 1:24,000.

Case, J.E., 1963, Geology of a portion of the Berkeley and San Leandro Hills, California [PhD. dissertation]: Berkeley, University of California, 216 p.

Cotton, W, and Associates, June 1993, Engineering Geologic and Geotechnical Engineering Investigation, Cragmont Elementary School, Berkeley, California, AP#2602.

Cotton, W., and Associates, September 1995, Supplemental Fault Investigation, Cragmont Elementary School: Berkeley, California, AP#2602.

Dibblee, T.W., Jr., 1980, Preliminary geologic map of the Richmond quadrangle, Alameda and Contra Costa Counties, California: U.S. Geological Survey Open-File Report 80-1100, scale 1:24,000.

Graymer, R.W., Jones, D.L., and Brabb, E.E., 1995, Geologic map of the Hayward fault zone, Contra Costa, Alameda, and Santa Clara Counties, California: A digital database: U.S. Geological Survey Open-File Report 95-597, http://wrgis.wr.usgs.gov/open-file/of95-597/.

Graymer, R.W., 2000, Geologic map and map database of the Oakland metropolitan area, Alameda, Contra Costa and San Francisco Counties, California: U.S. Geological Survey Miscellaneous Field Studies MF-2342, http://geopubs.wr.usgs.gov/map-mf/mf2342/.

Harding Lawson Associates, 1991, Fault and Landslide Hazard Evaluation, Cragmont School, Berkeley, California: unpublished consultant report no. 3874,034.03 to the Berkeley Unified School District, 20 p.

Herd, D.G., 1978, Map of Quaternary faulting along the northern Hayward Fault Zone; Mare Island, Richmond, Briones Valley, Oakland West, Oakland East, San Leandro, Hayward, and Newark 7–1/2′ Quadrangles, California: U.S. Geological Survey Open-File Report 78-308, scale 1:24,000.

Hilley, G.E., Burgman, R., Ferretti, A., Novali, F., and Rocca, F., 2004, Dynamics of slow-moving landslides from permanent scatter analysis: Science, v. 304, p. 1952–1955, doi: 10.1126/science.1098821.

Hoexter, D.F., Knudsen, K., Hecht, B., Laduzinsky, D., and Fielder, G., 1992, Creep and downslope movements in the Hayward fault zone in North Berkeley: Ten years later, *in* Second Conference, Earthquake Hazards in the Eastern San Francisco Bay Area: California Division of Mines and Geology Special Publication 113, p. 121–127.

Hoexter, D.F., Levine, C.R., Hecht, B., and Collier, G., 1982, Deformation along the Hayward fault zone, North Berkeley: Fault creep and landsliding, *in* Hart, E.W., Hirschfeld, S.E., and Schulz, S.S., eds., Proceedings, Conference on Earthquake Hazards in the Eastern San Francisco Bay Area: California Division of Mines and Geology Special Publication 62, p. 1–10.

Jones, D.L., and Curtis, G.H., 1991, Guide to the geology of the Berkeley Hills, central Coast Ranges, California, *in* Sloan, D., and Wagner, D.L., eds., Geologic Excursions in Northern California: San Francisco to the Sierra Nevada: California Division of Mines and Geology Special Publication 109, p. 63–74.

Kropp, A., and Associates, 1995, Landslides of the Berkeley Hills: Berkeley, Alan Kropp and Associates, unpublished consultant's map, scale 1:24,000.

Lennert, B.J., 1982, Accurate location of the active trace of the Hayward fault between Ashby and Marin Avenues in Berkeley, with proposed models of stress-strain conditions for creep and rapid offset: California Division of Mines and Geology Special Publication, v. 62, p. 45–54.

Lienkaemper, J.J., 1992, Map of recently active traces of the Hayward fault, Alameda and Contra Costa Counties, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-2196, 13 p., 1 sheet, scale 1:24,000.

Nilsen, T.H., 1975, Preliminary photointerpretive map of landslide and other surficial deposits of the Richmond 7.5-minute quadrangle, Contra Costa and Alameda Counties, California: U.S. Geological Survey Open-File Report 75-227-47, scale 1:24,000.

Ponce, D.A., Burgmann, R., Graymer, R.W., Lienkaemper, J.J., Moore, D.E., and Schwartz, D.P., 2003, Proceedings of the Hayward Fault Workshop, Eastern San Francisco Bay Area, California, September 19–20, 2003: U.S. Geological Survey Open File Report 03-485, 71 p.

Radbruch-Hall, D.H., 1974, Map showing recently active breaks along the Hayward fault zone and the southern part of the Calaveras fault zone, California: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-813, scale 1:24,000.

Waterhouse, G.V., 1992, The Hayward fault and deep-seated landsliding in the Northern Berkeley Hills, *in* Hart, E.W., Hirschfeld, S.E., and Schulz, S.S., eds., Proceedings, Conference on Earthquake Hazards in the Eastern San Francisco Bay Area: California Division of Mines and Geology Special Publication 62, p. 1–10.

Stop 7: Oakland City Hall

DIS, Inc., 2005, Oakland City Hall project brief: http://www.dis-inc.com/oakbrief.htm.

Steiner, F., and Elsesser, E., 2004, Design decision, methods, and procedures: Oakland City Hall repair and upgrades: Earthquake Engineering Research Institute Report DS-4, 29 p.

Stop 8: Claremont Water Tunnel Portal

Borchardt, G., Taylor, C.L., Rogers, J.D., Wells, D.L., Shastid, T., Yiadom, A., Ortiz, J., and Williams, P.L., 2000, Engineering for surface ground rupture on the Hayward fault, *in* Alvarez, L., ed., AEG-GRA 2000 Field Trip Guidebook, from the Pacific Ocean to the Sierra Nevada: Taming shaky ground: Association of Engineering Geologists and Groundwater Resources Association, Chap. 6, 25 p.

Galehouse, J.S., 2002, Data from theodolite measurements of creep rates on San Francisco Bay region faults, California: 1979–2001: U.S. Geological Survey Open-File Report 02-225, http://geopubs.wr.usgs.gov/open-file/of02-225/.

Geomatrix Consultants, 2001, Preliminary geologic interpretive report for the Claremont Tunnel Seismic Upgrade Project: Report for East Bay Municipal Utility District, Oakland, California, 54 p.

Kieffer, D.S., Caulfield, R.J., and Tsztoo, D.F., 2004, Seismic retrofit of the Claremont Tunnel, Proceedings of the EUROCK 2004 and 53rd Geomechanics Colloquium: International Society of Rock Mechanics Regional Symposium, Salzburg, Austria, October 7–9, 6 p.

Stop 9: City of Hayward Fault Creep

Gilmore, T.D., 1992, Historical uplift measured across the eastern San Francisco Bay region, *in* Borchardt, G., et al., eds., Proceedings of the Second Conference on Earthquake Hazards in the Eastern San Francisco Bay Area: California Division of Mines and Geology Special Publication 113, p. 55–62.

Graymer, R.W., 1999, Offset history of the Hayward fault zone, San Francisco Bay region, California: Geological Society of America Abstracts with Programs, v. 31, no. 6, p. 59.

Graymer, R.W., Jones, D.L., and Brabb, E.E., 1995, Geologic map of the Hayward fault zone, Contra Costa, Alameda, and Santa Clara Counties, California: A digital database: U.S. Geological Survey Open-File Report 95-597, http://wrgis.wr.usgs.gov/open-file/of95-597/.

Graymer, R.W., Sarna-Wojcicki, A.M., Walker, J.P., McLaughlin, R.J., and Fleck, R.J., 2002, Controls on timing and amount of right-lateral offset on the East Bay fault system, San Francisco Bay region, California: Geological Society of America Bulletin, v. 114, p. 1471–1479, doi: 10.1130/0016-7606(2002)114<1471:COTAAO>2.0.CO;2.

Kelson, K.I., and Simpson, G.D., 1995, Late Quaternary deformation of the southern East Bay Hills, Alameda County, California: American Association of Petroleum Geologists Bulletin, v. 79, p. 590.

Lienkaemper, J.J., 1992, Map of recently active traces of the Hayward Fault, Alameda and Contra Costa Counties, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-2196, scale 1:24,000, 1 sheet, 13 p.

Lienkaemper, J.J., and Borchardt, G., 1996, Holocene slip rate of the Hayward Fault at Union City, California: Journal of Geophysical Research, v. 101, p. 6099–6108, doi: 10.1029/95JB01378.

Lienkaemper, J.J., Galehouse, J.S., and Simpson, R.W., 2001, Long-term monitoring of creep rate along the Hayward fault and evidence for a lasting creep response to 1989 Loma Prieta earthquake: Geophysical Research Letters, v. 28, p. 2265–2268, doi: 10.1029/2000GL012776.

Simpson, R.W., Lienkaemper, J.J., and Galehouse, J.S., 2001, Variations in creep rate along the Hayward fault, California, interpreted as change in depth of creep: Geophysical Research Letters, v. 28, p. 2269–2272, doi: 10.1029/2001GL012979.

Wallace, R.E., 1990, Geomorphic expression, *in* Wallace, R.E., ed., The San Andreas fault system, California: U.S. Geological Survey Professional Paper 1515, p. 15–58.

Stop 11: Fremont Pipeline Crossing

Borchardt, G., Taylor, C.L., Rogers, J.D., Wells, D.L., Shastid, T., Yiadom, A., Ortiz, J., and Williams, P.L., 2000, Engineering for surface ground rupture on the Hayward fault: *in* Alvarez, L., ed., AEG-GRA 2000 Field Trip Guidebook, From the Pacific Ocean to the Sierra Nevada: Taming shaky ground: Association of Engineering Geologists and Groundwater Resources Association, Chap. 6, 25 p.

Eidinger, J.M., 2001, Seismic retrofit of the Hetch Hetchy Aqueduct at the Hayward fault: *in* Castronova, J.P., ed., Pipeline 2001: Advances in Pipelines Engineering & Construction, American Society of Civil Engineers Conference, San Diego, California, July 15–18, 2001, 10 p.

Galehouse, J.S., 2002, Data from theodolite measurements of creep rates on San Francisco Bay region faults, California: 1979–2001: U.S. Geological Survey Open-File Report 02-225, http://geopubs.wr.usgs.gov/open-file/of02-225.

Geomatrix Consultants, Inc., 1999, Phase III Engineering Report on Geotechnical and other Specialized Engineering Services, Seismic Upgrade for Bay Division Pipeline Nos. 1 and 2: Report prepared for San Francisco Utilities Engineering Bureau, UEB Contract No. CS-458, May 1999.

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