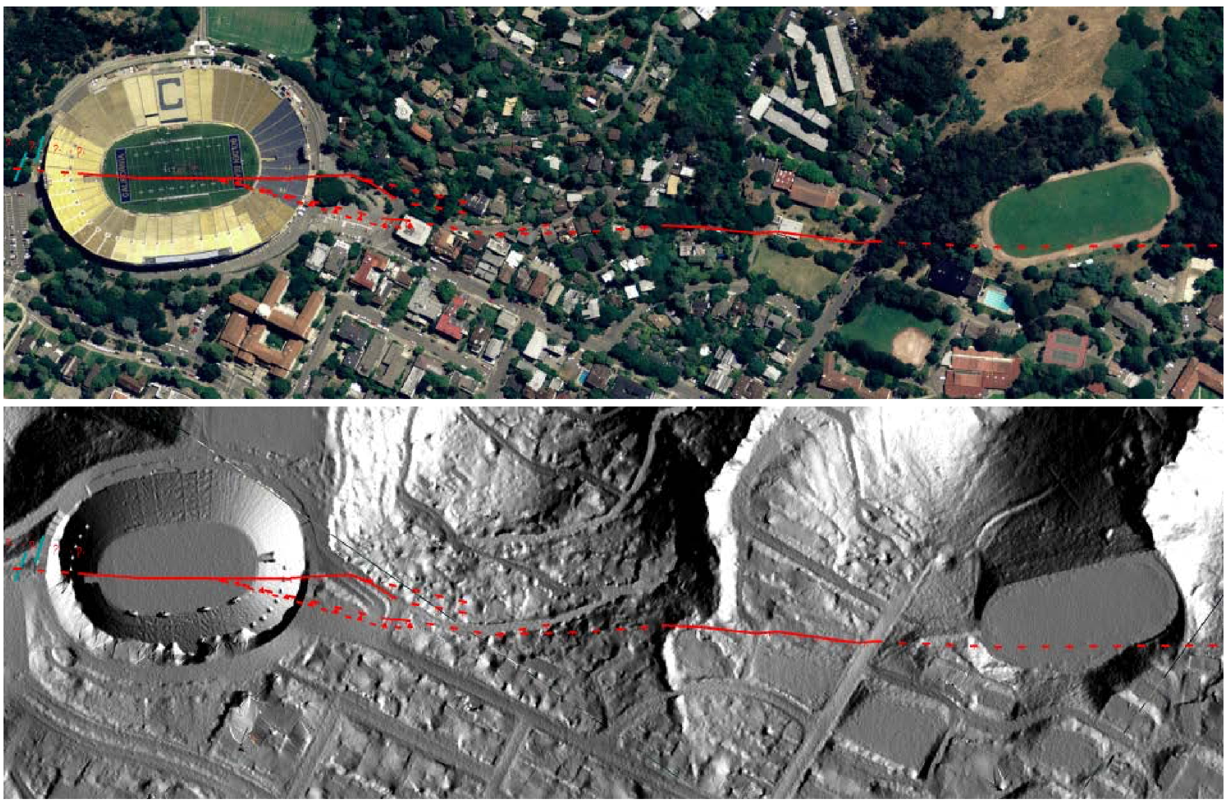
Horst Rademacher

The Hayward Fault
at the Campus of the
University of California, Berkeley

A Guide to a Brief Walking Tour



Content

Acknowledgements

Like everything else in Earth science this guide is the result of a cooperative effort. Numerous people in UC Berkeley's Department of Earth and Planetary Science have contributed bits and pieces of their knowledge about the Hayward Fault. Tim Teague prepared the thin section of Founders' Rock, Paul Renne evaluated it. Doris Sloan and Peggy Hellweg, who both have led countless tours along various sections of the fault, were always at my beck and call to find answers to whatever question I had when putting this guide together. Without the help of Samantha Teplitzky from UC Berkeley's Earth Sciences and Map Library I would not have found old maps and pictures. I thank all of them for their generosity.

Cover Picture

In urban areas it is sometimes difficult to perform geological research. The native landscape has been highly altered by human activity, like building roads, houses, sports facilities and many other structures. Geologic features are covered over by infrastructure or hidden inaccessibly on private property. Aerial or satellite photography sometimes helps to reveal the underlying landscape, but often enough such images show very little of interest to the Earth scientists, like in the top panel of our cover picture. A 3D-scanning technique called Lidar (Light detection and ranging) uses laser beams to scan a region mostly from aircraft. Using numerical calculations researchers can then strip such scans of buildings and vegetation to gain a detailed image of the hidden landscape. The lower panel of our cover shows such a Lidar image of the same area as the satellite picture above. The imagery covers the area of much of the tour described in this pamphlet, from the California Memorial Stadium on the left to the track field of Clark Kerr Campus on the right. The red line indicates the location of the Hayward Fault.

Introduction

The University of California, Berkeley is - according to the author's knowledge - the only major university in the world, whose campus is intersected by a dangerously active earthquake fault. The Hayward Fault, a branch of the San Andreas Fault system in the San Francisco Area of northern California, cuts through the eastern part of campus, most prominently through the playing field of the University's football arena, the California Memorial Stadium. Ranked by the latest probabilistic hazard analysis (UCERF-3) as the most dangerous earthquake fault in the greater San Francisco region, the Hayward Fault is thought to be able to generate magnitude 7.5 earthquakes, capable of causing significant damage. At the same time, some sections of the Hayward Fault are in constant motion. Across campus the fault creeps along aseismically by a few millimeters a year.

The fact that UC Berkeley is located on the Hayward Fault was not intentional. At the time the first students and faculty occupied the campus, in 1873, the science of seismology was in its infancy. Earth scientists were still oblivious to the causes of earthquakes, phrases like *earthquake fault* had not even been invented and the concept of plate tectonics would be almost a century away. Nevertheless, since the university's founding Berkeley faculty has played a major role in advancing the science of earthquakes and of seismic monitoring. In fact the first seismometer network in the western hemisphere was set up by Berkeley scientists in 1887. After adapting many times to advances in technology, it is still in operation today in northern California and southern Oregon as the Berkeley Digital Seismic Network. In addition, the Berkeley Seismological Laboratory (BSL) operates several local seismic networks.

Despite the fact that the Hayward Fault is one of the best studied earthquake faults in the world, it remains rather elusive. We are not talking about the lack of reliable earthquake prediction but instead about uncertainties in the exact location of the fault. Figure 1 shows a topographic map of the foothill area of East Berkeley with UC Berkeley's stadium prominently displayed. While many details in this map are not relevant for our tour, the important information is contained in the colored lines crossing the map. Each line represents the estimate made by one researcher or group of scholars as to the location of the fault. In some areas, these locations vary by more than 1000 ft. The reader may keep these uncertainties in mind, when looking at maps of the locations of our tour stops, as in figures 2 and 5.5. There we show the fault as a single straight line for reasons of simplicity.

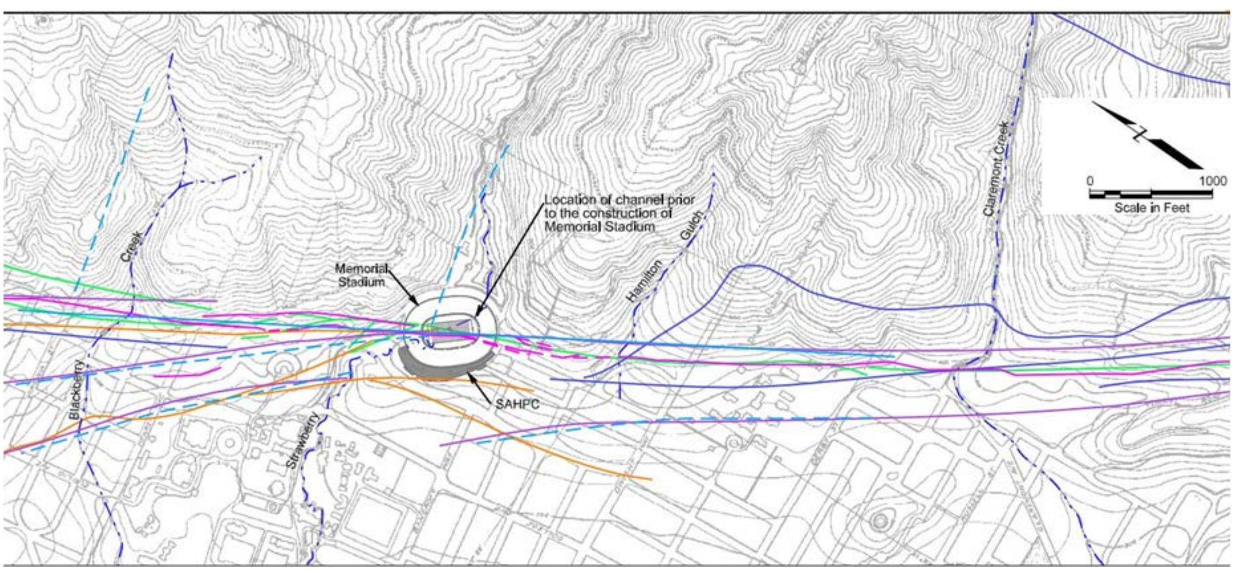


Fig. 1: Topographic map with locations of the Hayward Fault as different researchers see it. Each color represents a different geologic investigation. In some sections, the fault locations differ by 1000 ft.

In the following, we highlight some of the major features of the Hayward Fault on campus. We will visit sites where the continuous aseismic creep along the fault is tearing at buildings, structures and roads, we will see examples of how the University mitigates some of the risk posed by the seismic hazard and we will look at methods to monitor the seismic activity of the fault.

This pamphlet is designed as a guide for a walking tour to the points of interest as they are shown on the maps in figures 2 and 5.5. The numbering of these points on the maps is consistent with their nomenclature in the text. *Paragraphs set in italic font and underlain in light grey explain how to get from one point of interest to the next.*

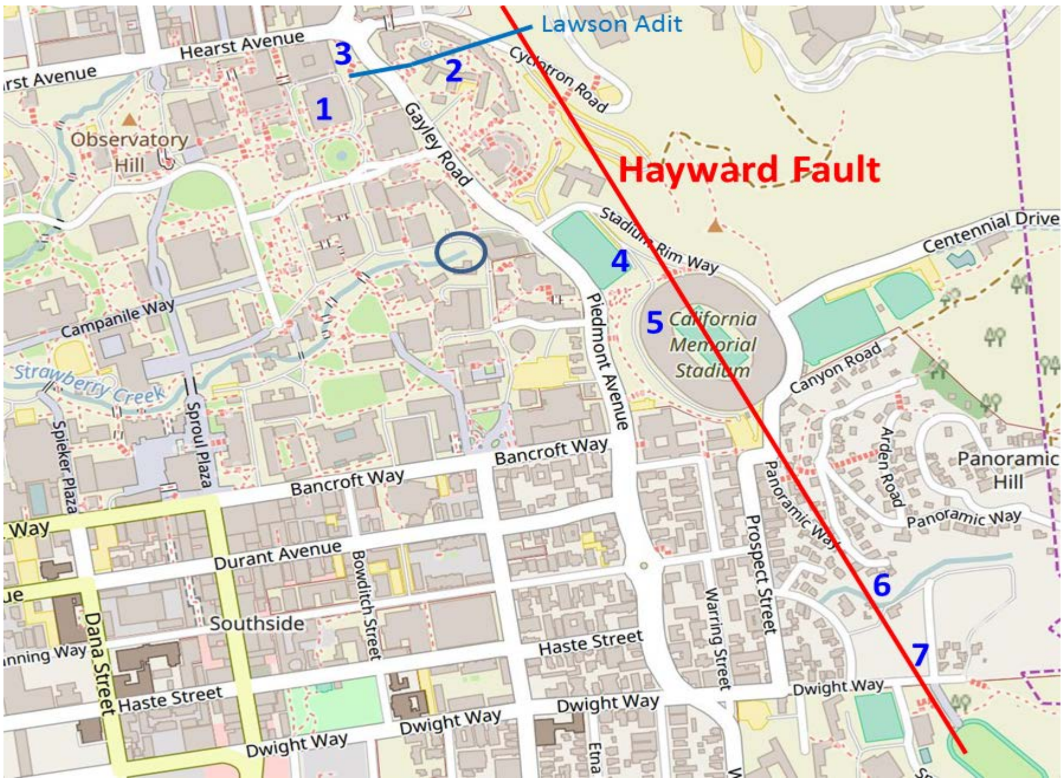


Fig. 2: Map of the eastern part of UC Berkeley's campus showing points of interest along the Hayward Fault

This tour is designed as a walking tour. Taken in its entirety the tour will take about 2.5 hours, depending, of course, how much time one spends at each stop. The tour can also be broken up in sections to be taken at different times. During our walk, we will mostly stay on UC Berkeley's property or on public roads. However at point 6 we will be looking at private property. Please respect the privacy of the owner and his neighbors and avoid loud noise. A word of caution: As the Hayward Fault runs along the foot of the Berkeley Hills, we will encounter several steep climbs and stairways during our walk. Be prepared by wearing sensible shoes and by carrying some drinking water and perhaps a snack. You are welcome to take as many pictures or videos as you want.

The tour starts on the north side of the Mining Circle at the base of the impressive stairs leading to the Hearst Memorial Mining Building, point 1 in figure 2. Walk into the building and stop in the grand lobby, the Memorial Gallery.

1. Hearst Memorial Mining Building

Because UC Berkeley was founded in a merger between the public *Agricultural, Mining, and Mechanical Arts College* and the private *College of California*, mining played an important role in the curriculum of the young university. After all, the California Gold Rush of 1849 had caused a mining boom in the state which lasted for many decades. In the early 1900's more than 15 percent of the 3000 students then enrolled in Berkeley majored in mining, making UC Berkeley's College of Mining the largest school of its kind in the world. However, in the beginning the UC miners did not have their own building on campus. That changed in 1907 when the Hearst Memorial Mining Building, designed by New York architect John Galen Howard, opened its doors. The building was financed and gifted to the university by the widow of George Hearst, a U.S. Senator who had made his vast fortune in silver mining in several western states. In all its Beaux Art splendor, particularly in its grand, three story lobby, the building has been called "the architectural gem of the entire UC system." But however beautiful, the building is located less than 800 ft away from the Hayward Fault and in its original state it constituted a major risk in a strong earthquake. Hence, between 1998 and 2003, it underwent a massive renovation and seismic retrofit. The College of Mining was integrated into the College of Engineering in 1942 and the building is now home to the Department of Materials Science and Engineering.

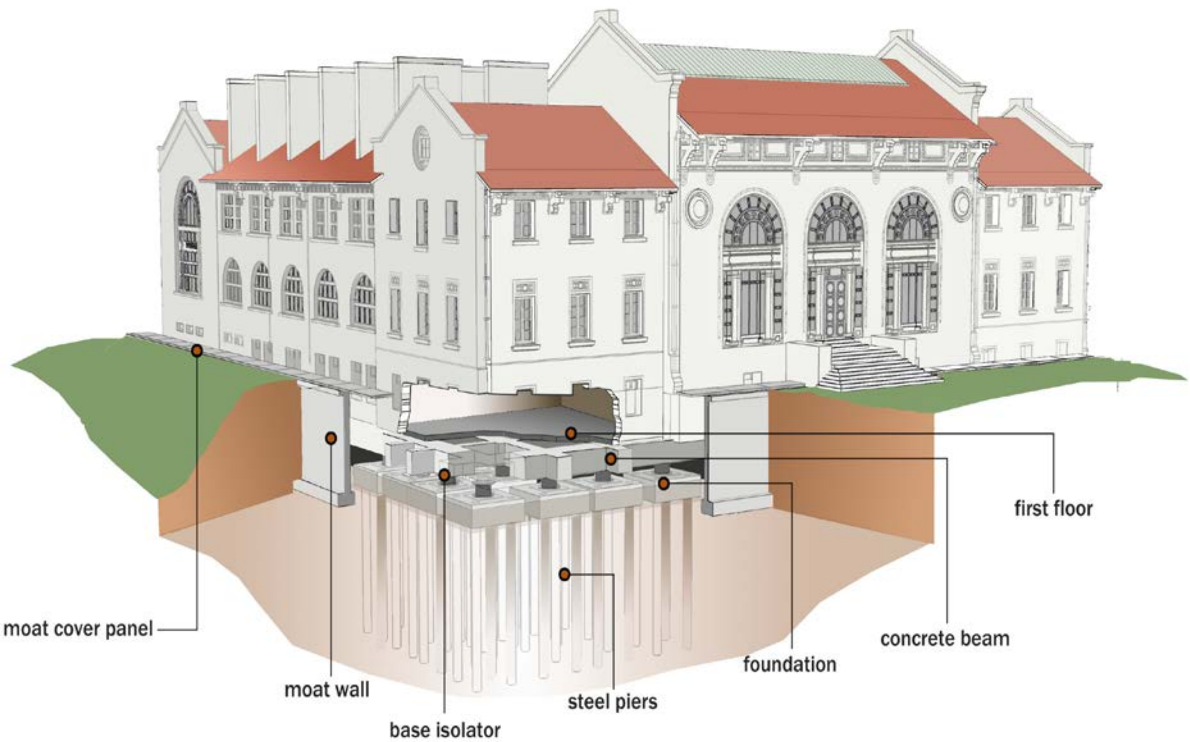


Fig. 1.1: The Hearst Memorial Mining Building and a cutaway of its new underpinnings after the major seismic retrofit. Note the moat surrounding the building

1.1 Memorial Gallery

At first glance this impressive, three story atrium style lobby seems like an earthquake nightmare. You are surrounded by brick walls accentuated by a vaulted tiled ceiling topped by beautiful glass domes. Every textbook on seismic engineering will tell you that unreinforced masonry, or brick, is the most vulnerable of all construction methods when shaken by seismic waves. Usually the thin layers of mortar holding the bricks together fail under vibrational load and the brick walls collapse. This was indeed the grave risk the building constituted until its retrofit.

Fig. 1.2: The impressive lobby of the Hearst Memorial Mining Building

In order to make the brick walls safe, they were reinforced with steel bars. The ceiling, however, posed a much greater challenge. Its tiles were produced more than 110 years ago by the “Guastavino Fire Proof Construction Company”. Their patented system allowed self-supporting vaulted ceilings to be built. The interlocking terracotta tiles were held together by layers of mortar. During the retrofit, much of the mortar was replaced by a mesh of fiberglass and wire. Nearly invisible polymer pins now connect every tile to the new backing. This is the only time such a Guastavino tile system was ever seismically strengthened. In addition, during the retrofit, the vinyl flooring added to the gallery in the 1960's was removed to reveal the original herringbone-pattern of yellow bricks.

Now walk a few steps through the glass doors opposite the entrance to the Memorial Gallery and look at the wall of pictures. They show the various phases of the original construction and of the seismic retrofit.

1.2 Seismic Base Isolation

The entire building was raised from its original foundation by several feet and a new foundation system was constructed underneath, including the steel piers shown in figure 1.1. A new platform was constructed as the base of the building. A total of 134 circular columns made of a rubber and steel composite were placed between the platform and the foundation in order to mechanically separate the building above from the ground below (see figures 1.3 and 1.4). Each of these circular columns is called a seismic base isolator and is approximately 4 ft in diameter and 2 ft high. The composite is compressed between two round steel plates and it acts - in simple terms - like a shock absorber. While the ground underneath moves in an earthquake, the base isolators mostly absorb these horizontal vibrations and thereby minimize the seismic forces acting on the building. Such passive structural vibration isolation technique is common for big buildings in earthquake prone areas. For example, the City Halls in San Francisco, Oakland and Los Angeles were similarly retrofit and now rest on base isolators.

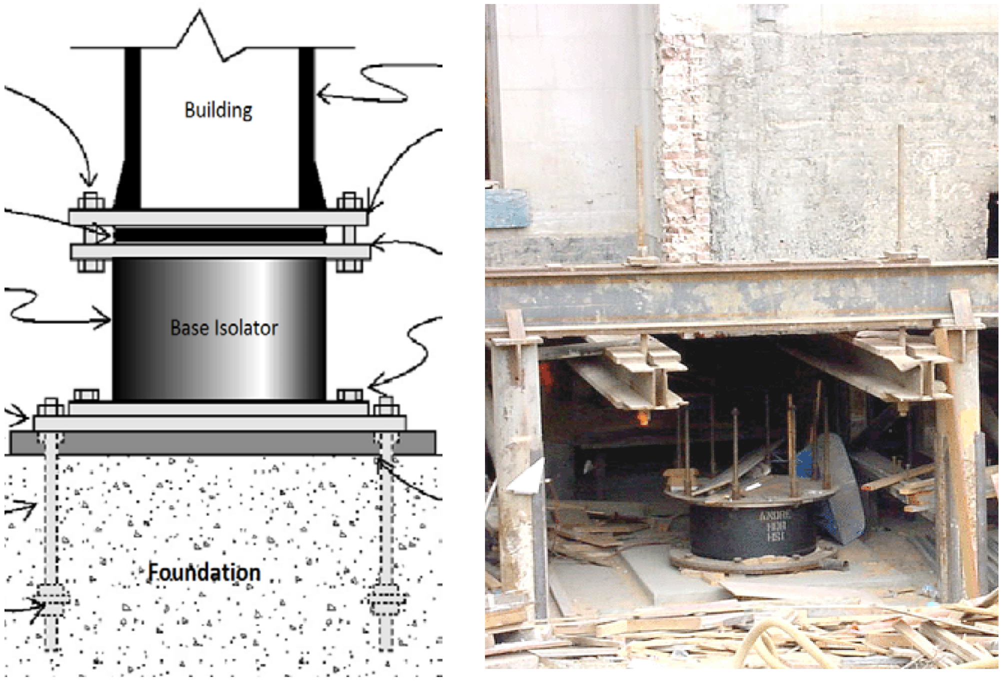


Fig. 1.3: The left panel shows in a sketch how seismic base isolation works. A base isolator mechanically separates a building from its foundation anchored in the ground. When the ground vibrates in an earthquake, the rubber and steel laminate absorbs much of the movement and prevents the building from shaking. The right panel shows a base isolator underneath the raised Hearst Memorial Mining Building during its installation in 2000.

Fig. 1.4: A total of 134 base isolators in the subbasement of the Hearst Memorial Mining Building, like the two shown here, keep the floor of the building (above) seismically separated from the ground (below).

Leave the building through the main entrance and walk down the stairs in front of the building. Turn right and walk a short distance downhill. Then turn right again around the corner and walk about 100 ft along the west side of the building until you reach the walkway leading to the side entrance. Turn right and walk until you almost reach the door and stop directly under the "underpass". You are now standing on the moat.

1.3 The Moat

The seismic base isolators protecting the Hearst Memorial Mining Building from underneath are designed to absorb horizontal ground movement of up to 28 inches in any direction. When the ground moves by that amount, the building will essentially not move at all and stays in place. But that applies only to forces underneath the building. What would happen if the outer walls of the building were still directly connected to the ground as in any ordinary building? The ground shaking would still affect the building despite the base isolators, because the ground vibrations would excite the outer walls from the sides. The best way to prevent the walls from being shaken is to separate them entirely from direct contact with the ground - and the easiest way to achieve that is to dig a deep trench around the structure, in short, to protect the building with a moat like a medieval fortress. That is exactly what the engineers have done with the Hearst Memorial Mining Building. It is completely surrounded by such a trench, which, unlike the classic moats, is dry and not filled with water. All around the building the trench is covered by dark grey concrete slabs, except at the western side entrance, where one can look into the moat through the iron bars at the underpass.

Retrace your steps to the stairs in front of the building and continue uphill for a short distance. Turn left around the corner of the building, walk about 100 ft on the street along its east side. Walk until you reach a heavily secured steel gate on the right (eastern) side of the street. This is the Lawson Adit, point 2 in figure 2.

2. Lawson Adit

In order to prepare its graduates for their professional lives in and around mines, UC Berkeley's College of Mining could not just rely on teaching theory. The students had to learn how to lay out and construct a mine, how to blast their way into rocks, how to shore up the hollows they created. Perhaps most importantly they had to learn how to adapt to hours of hard work underground in dark, wet and poorly ventilated conditions. Hence in 1916 Frank Probert, a newly appointed Professor of Mining, started his students in digging a demonstration and teaching mine on campus. He did not have to venture far from the Hearst Memorial Mining Building, because the foot of the Berkeley Hills lies just a few a dozen feet to the east. The mine entrance - where you are standing now - is right across from the northeastern door of the building.

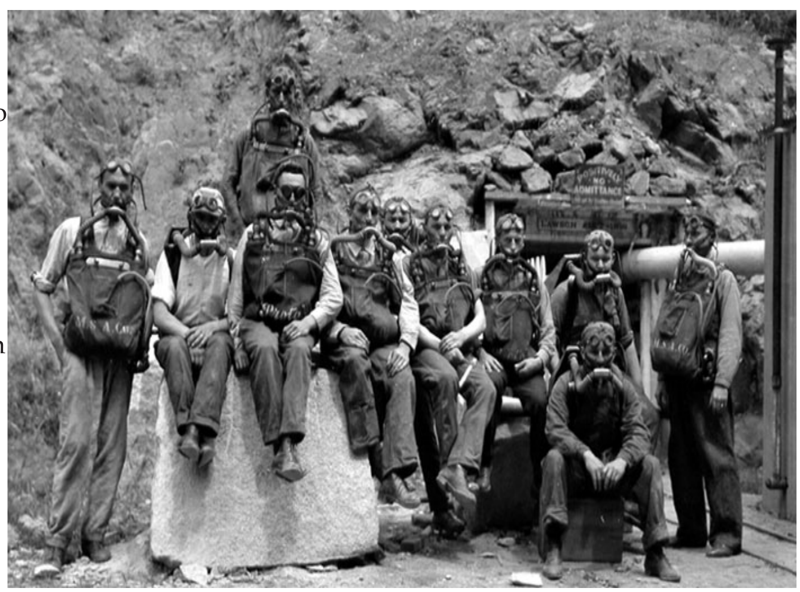


Fig. 2.1: Students in front of the Lawson Adit before a mine rescue exercise.

Over the years, classes of the students dug a 200 ft long horizontal adit eastward into the hills to provide "sound, practical training in drilling, drifting, blasting, timbering, and mine surveying" as the classes were advertised in the catalogue.

Students also had to become familiar with the technical language miners use. The word "adit" describes a horizontal passage leading into a mine - in contrast to a "shaft", which is a vertical passage. Adit is also different from a "tunnel", which has both an entrance and an exit. The adit here was named after Andrew Lawson, a Berkeley geologist who lead the team of eminent scientists studying the aftermath of the Great San Francisco Earthquake of 1906. Starting in 1914 Lawson was also the Dean of the College of Mining for four years.

In the late 1930's when new campus buildings were planned east of Gayley Road, questions were raised about the stability of the slopes - after all, the Hayward Fault was only a few yards away from the proposed building sites. In order to investigate the geologic conditions, UC Berkeley geologist George Louderback had the adit extended by 700 ft until it reached the Hayward Fault. He was surprised by what he found:
- near what is now Stern Hall and Foothill Student Housing the fault was split into at least two branches,
- the traces were defined by a peculiar mix of serpentine and metamorphic rocks.

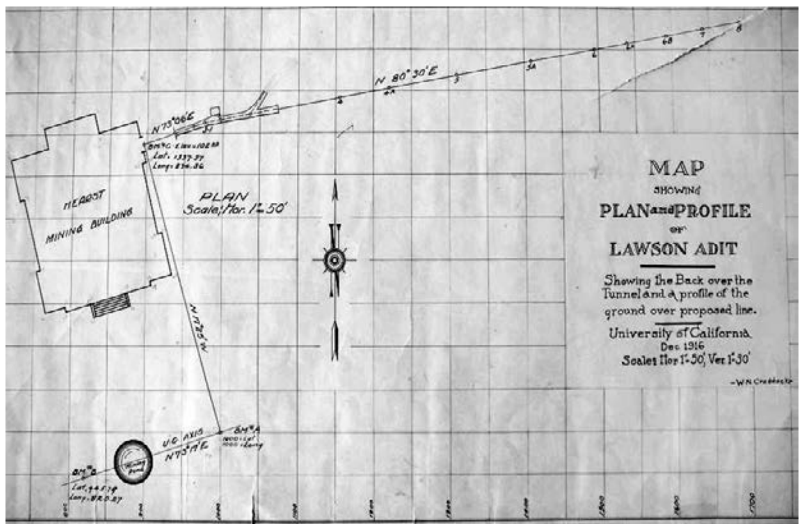


Fig. 2.2: Original plan for the Lawson Adit from 1916

He also discovered several accumulations of rounded cobbles similar to those found in Strawberry Canyon further to the southeast. Louderback interpreted these as exposures of the offset of Strawberry Creek, indicating a displacement of more than 600 ft north along the Hayward Fault (see also section 5).

After Louderback's extension, the adit was eventually abandoned. Today much of it has collapsed and it is deemed unsafe to enter the mine. However, the Berkeley Seismological Laboratory (BSL) has plans to place a seismic monitoring station into the adit.

Walk back to the Mining Circle and take a very sharp, almost 180 degree turn to the left. Then walk across the parking lot of Donner Laboratory until you reach a stairway. Climb the stairs to the top and turn left. After about 20 yds, Founders' Rock is on your right.

3. Founders' Rock

UC Berkeley's lore has it that the campus and by default the entire University of California system was founded on April 16th, 1860, at this unique rock outcrop now hidden under trees and behind bushes at the corner of Hearst Avenue and Gayley Road. Never mind that the actual founding of the University happened on March 23rd, 1868, when then Governor Henry Haight signed into law the Charter Act, which the State Assembly had passed a few weeks earlier. And also ignore that the commemorative plaque inserted into the rock does not mention UC Berkeley at all but one of its predecessors, the College of California. Nevertheless, this location is special to the University, being the highest point above sea level in the northeast corner of the original campus. The view across campus and over the San Francisco Bay must have been spectacular before Cory Hall was built in 1950 obstructing the overlook. And the oddly shaped outcrop itself is definitely worthy of being called Founders' Rock.

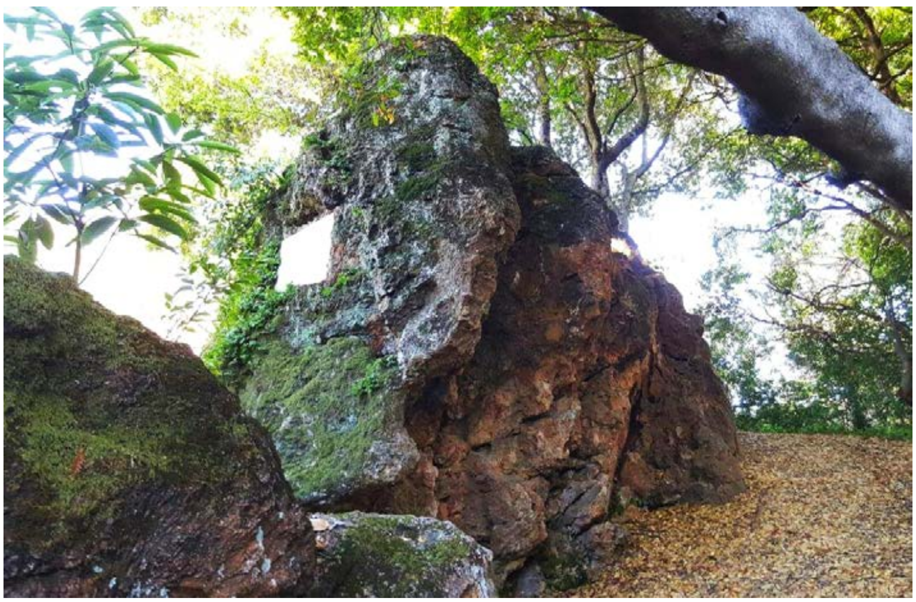


Fig. 3.1: Founders' Rock at the corner of Hearst Avenue and Gayley Road.

While its north and east sides are thickly covered with moss and lichen, the west side reveals the rock's origin. It is a reddish volcanic rock very rich in silica. Such rocks with high silica content are called rhyolite. Looking at it from up close it seems to be volcanic ash baked together with small fragments of other volcanic material. These two observations make Founders' Rock a "volcanoclastic welded tuff" with rhyolitic composition.

But where does this strange outcrop come from, when there is no volcano in sight anywhere on campus? One plausible hypothesis is based on the fact that Founders' Rock is very similar to a rock type from the Jurassic period, which was quarried for decades in the Leona Quarry at the upper end of Hegenberger Road in Oakland, the so-called Leona rhyolite. The tectonic movement of the Hayward Fault, so the hypothesis goes, carried the rock to its current location almost 10 miles northwest of the quarry. It this is true, then Founders' Rock formed when dinosaurs still roamed the planet, which predates the founding of the University by a mere 150 million years.

Confirming this hypothesis, however, is not that easy. Figure 3.2 shows what geologists call a "thin section" of a small piece of Founders' Rock. It is less than a tenth of an inch thick and molded into clear plastic, so that light can shine through it. The section reveals the reddish color of the rock, but also shows clear veins which are filled with mineral called calcite. When the author of this guide asked Paul Renne, the Director of the Berkeley Geochronolgy Center, to determine the age of this rock, he responded: "This rock has a tortured history. It is completely recrystallized and metasomatized, to the point that I can’t tell what kind of rock it was originally. It may have undergone major deformation and brittle shear but the texture is so heavily overprinted with carbonate and other secondary minerals that even this is hard to say." It seems that for right now Founders' Rock shall remain an enigma.

Fig. 3.2: Thin section of a small piece of Founders' Rock

Walk southeast on Gayley Road until you reach the intersection with Stadium Rim Way, where you turn left. Walk uphill to the end of the parking garage under the Maxwell Family Field across from Bowles Hall. Turn right at the stop sign there and walk towards the stadium. At the end of the parking row on your left an asphalted walkway leads gently uphill. Get on this walkway. Just before you reach to top of the walkway, you'll see a concrete box with a steel lid on your right. This is our stop 4 in figure 2.

4. Seismic Borehole Station CMSB

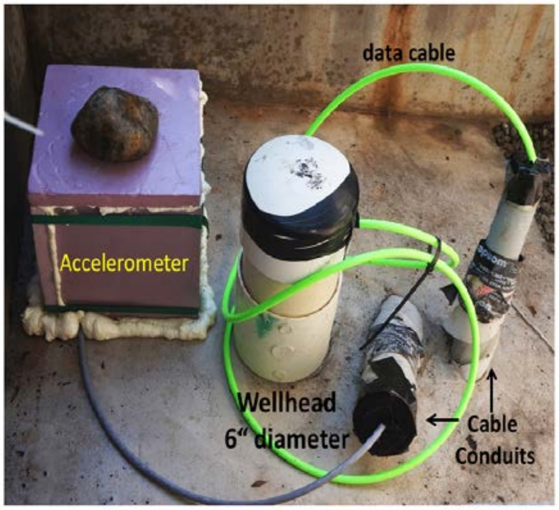
A key element to understanding and classifying the behavior of an earthquake fault is to monitor its seismic activity. The BSL operates several extensive networks of seismometers in Northern California. One of these networks covers the Hayward Fault. Currently, you are standing in front of one of the most important components of this network, where a seismometer is sunk into a borehole, which penetrates directly into the active fault. This borehole is almost 600 ft deep, which its bottom is about 150 ft below sea level. The seismometer is one of the few seismic sensors in the world deployed directly into an active fault. The station is named "CMSB" after the California Memorial Stadium.

Fig. 4.1: Borehole Seismometer

Typically seismometers are placed in small concrete vaults directly on or at a maximum of a few feet below the ground. There are however special seismometers which can be placed deep into water filled boreholes. They are of a slim, cylindrical design capable of withstanding several thousand pounds of water pressure. The latest seismometer sunk into this borehole is shown inside the red ellipse in figure 4.1 during its deployment in August 2016.
There are two reasons why seismologists deploy seismometers in deep boreholes. At depth the seismic noise (ground vibrations) generated by the footsteps of thousands of football

fans or by cars and trucks driving by is greatly reduced, which makes for clearer recordings of even the smallest earthquakes (see figure 4.3). A deep deployment also brings the seismometer closer to the earthquake sources, which further increases its detection capability.

Like any other seismometer, such borehole sensors can be overwhelmed, when a strong earthquake occurs close by. They clip and the data they collect become useless to seismologists. In order to still be able to "catch" strong local earthquakes, BSL engineers have placed an additional sensor into the concrete vault built around the wellhead of the borehole. Such accelerometers (see figure 4.2) are also called strong motion sensors, because they are designed to record strong earthquakes with a high fidelity.



Together, the highly sensitive borehole sensor and the accelerometer at the surface are able to record the full spectrum of the earthquakes which are expected in the Berkeley section of the Hayward Fault.

Fig. 4.2: A view into the concrete vault at the wellhead.

An example of a recording of a very small earthquake is shown in figure 4.3. The epicenter of this quake with a magnitude of 1 was about 900 yards north of the borehole at the westernmost edge of the Lawrence Berkeley National Laboratory. The quake occured on the Hayward Fault at a depth of more than 5 miles.

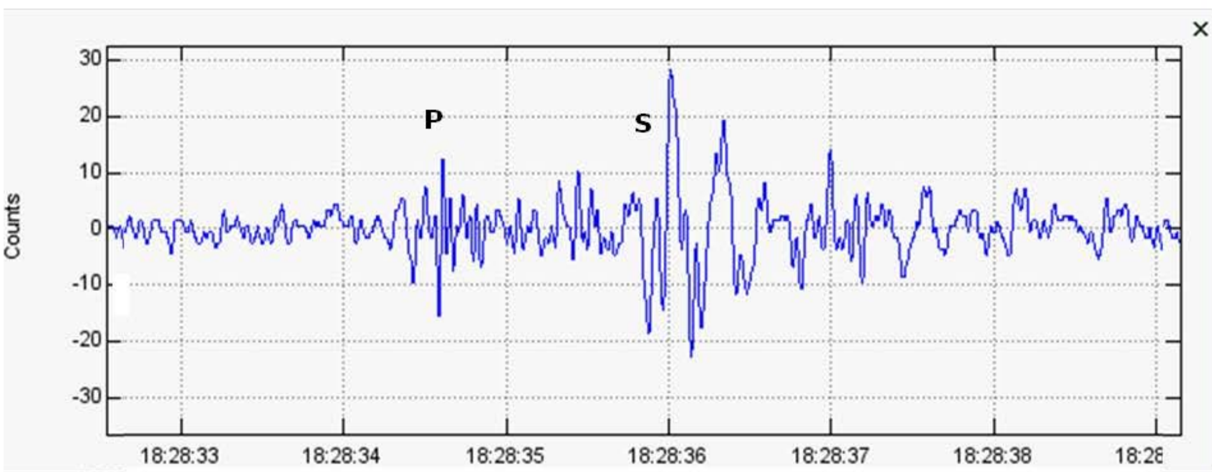


Fig. 4.3: Recording of a micro-earthquake with magnitude 1 by the borehole seismometer at CMSB. The time marks along the horizontal axis are in seconds. The P-waves arrives between 18:28:34 and 18:28:35, the S-waves follow a second later.

5. The California Memorial Stadium

The California Memorial Stadium, like the Hearst Memorial Mining Building (see section 1), was designed by John Galen Howard. It is a tribute to UC Berkeley alumni who died in World War I. It is located at the base of the Berkeley Hills directly at the mouth of Strawberry Canyon. This spot on the easternmost part of the campus was chosen after a more convenient location in downtown Berkeley was rejected by local merchants. When construction of the sports arena commenced in December 1922 the University's administration was fully aware that the future stadium would straddle the Hayward Fault.

Fig. 5.1: A view upstream of Strawberry Canyon around 1870 along what is now Centennial Drive. Panoramic Hill occupies the right side of this photograph.

How did the landscape in this area look, before the first dirt was excavated? Strawberry Canyon was still largely undeveloped, except for a dairy farm where the Botanical Garden is located today. On Panoramic Hill to the south of the creek, Fredrick Law Olmsted, the landscape architect of Golden Gate Park and New York's Central Park fame, had - at the University's request - laid out a gracious residential neighborhood. At the base of the Berkeley Hills where Strawberry Creek encountered the Hayward Fault its straight downhill flow was blocked by a shutter ridge, transported there by the right lateral movement of the Hayward Fault. As a consequence, the creek turned sharply to the northwest for about 1100 ft, before it resumed its westward downhill flow. As with many other creeks on the west side of the East Bay Hills the bed of Strawberry Creek is an offset stream channel.

Howard managed to squeeze the large stadium with its more than 72,000 seats right into the depression caused by the erosion of Strawberry Creek where its bed bends to the northwest. This was exactly the spot for which Frank Soulé, who would later become the first dean of UC Berkeley's College of Civil Engineering, had in 1875 proposed to dam Strawberry Creek into a reservoir to secure the drinking and irrigation water supply for the growing campus (see figure 5.2). The plan for the reservoir, however, never came to fruition.

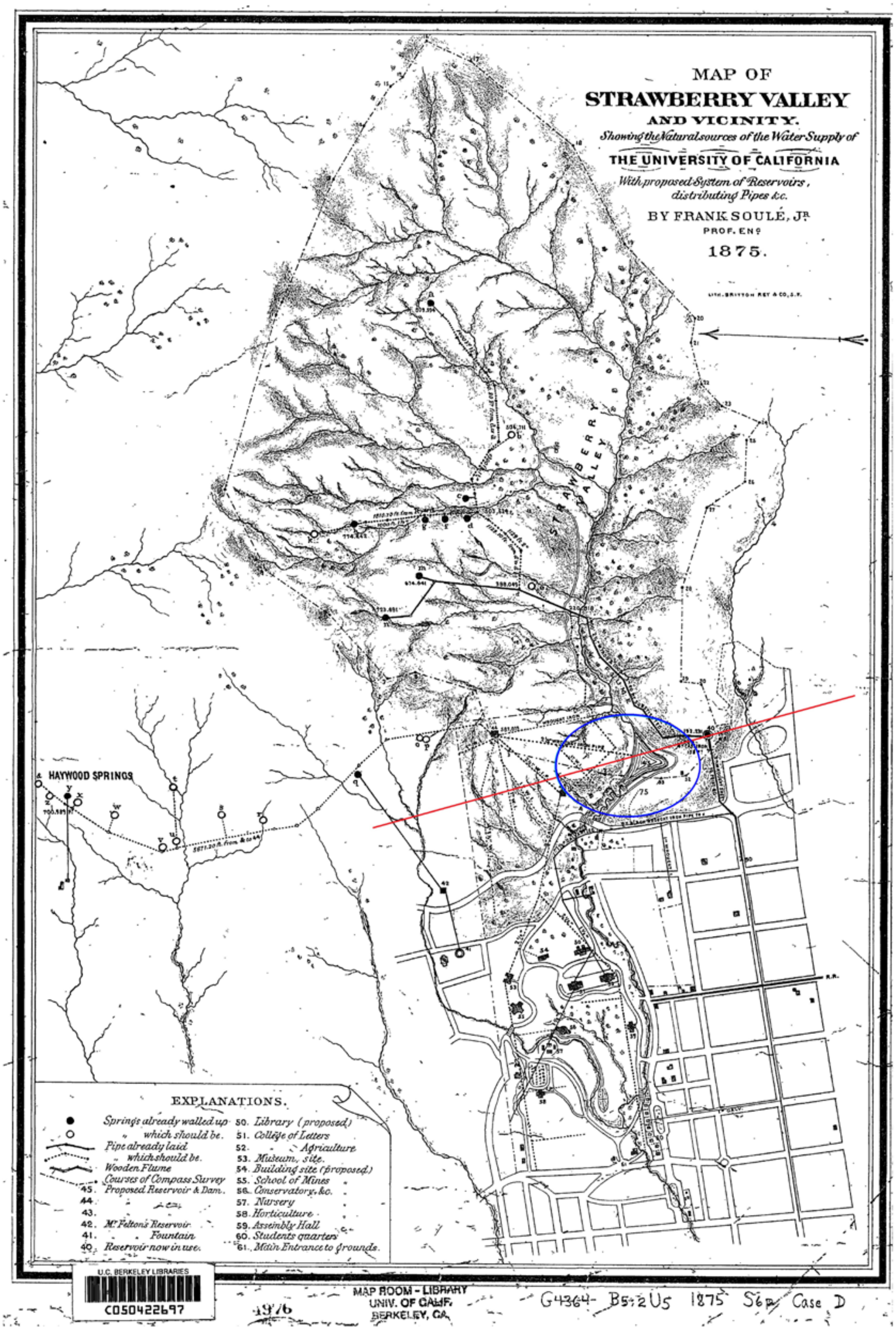


Fig. 5.2: Map of the Strawberry Creek area by Frank Soulé from 1875. The fault is highlighted in red. The area where Soulé proposed a drinking water reservoir is marked in blue. This is exactly the spot where the stadium was built 48 years after this map was drawn

To build the stadium Howard made use of the natural bowl shape. In addition he cut away a section of what is now Tightwad Hill at the base of the Berkeley Hills. It consists of sandstone from the Great Valley Sequence of the Cretaceous period. For their work the engineers used hydraulic mining techniques similar to those developed during the Californian Gold Rush. The newly created slope was turned into the foundation for the bleachers on the east side of the field. At the same time Strawberry Creek was diverted into a 4 ft diameter culvert. It initially runs under the stadium and then turns west (downhill) where the parking garage below Maxwell Family Field is today. After a total length of 1450 ft the culvert daylights near the Women's Faculty Club (blue circle in figure 2). From there Strawberry Creek runs through campus as a lovely gurgling brook. Because the capacity of the culvert proved insufficient during the Christmas Floods of 1964, a larger bypass was constructed under Stadium Way.

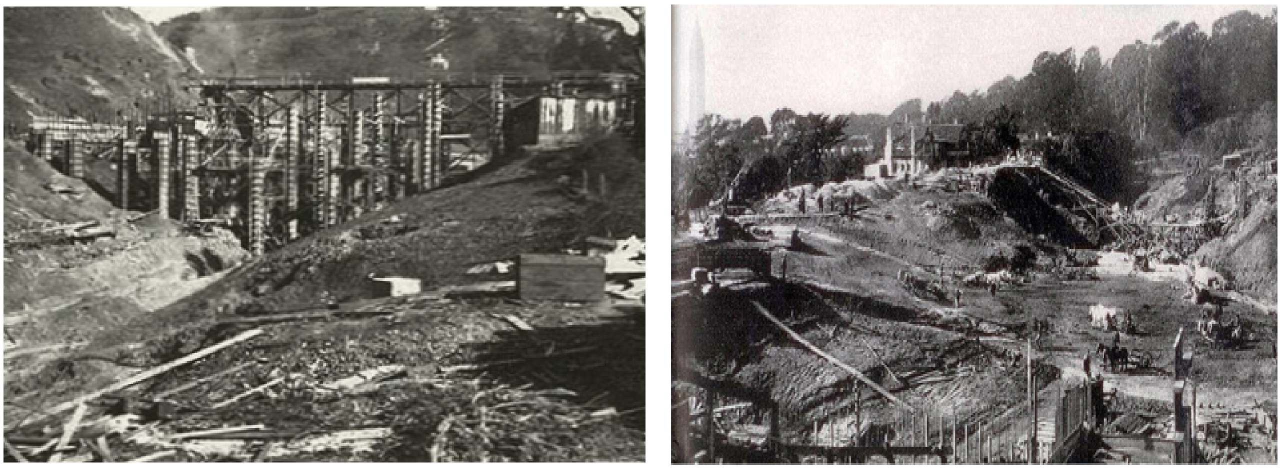


Fig. 5.3, left panel: A view from the northwest of the construction site in early 1923. The ditch seen in the lower left is the offset bed of Strawberry Creek, which also marks the fault line of the Hayward Fault. Right panel: opposite view to the northwest in an earlier phase of the construction. Horse drawn carriages were used to remove excess excavation material. The Campanile can be seen faintly in the upper left.

Because the approximate location of the Hayward Fault, its potential for significant earthquakes were known at the time of construction, Howard adapted the design of the stadium accordingly. He placed expansion joints in the stadium exterior walls mainly at the points where the wall intersected the fault. We will see examples at points 5.2 and 5.4 on this tour. Despite the enormous engineering challenges, the construction of the stadium was finished in only 11 months. The arena opened on November 24th, 1923, just in time for the Big Game against Stanford, which, by the way, the Bears won 9-0.

Over the next eight decades the Beaux Art façade of the exterior wall of the football arena became one of UC Berkeley's iconic symbols. In 2006 the stadium was even placed as a landmark on the National Register of Historic Places (ref# 06001086). In the meantime the tectonic movement along the Hayward Fault tugged relentlessly on the structure - with dire consequences. Columns in the interior had bent and bulged, façades had cracked and during a seismic safety study the stadium received a rating of "poor", which means that the building had become an "appreciable life hazard" during an earthquake. Hence in early 2010 the University's Board of Regents approved the retrofit and the complete renovation of the stadium.

During this reconstruction, which cost an estimated $445 million, the stadium was entirely gutted. Only the exterior wall had to be left untouched because of the stadium's status as a protected landmark (see figure 5.4). The bleachers and all athletic and spectator facilities were completely rebuilt according to the latest seismic mitigation techniques. The old press box was demolished and a new structure built in its place, independent of the rest of the stadium.

Fig. 5.4: During the renovation from 2010 to 2012 the stadium was entirely gutted except for the exterior wall. This areal view from the east is looking over the stadium towards campus. When this picture was taken the construction of the new press box had not yet commenced.

The newly renovated stadium, as we see it today, opened on September 1st, 2012 when the Cal Bears hosted the University of Nevada's Wolf Pack team as the season opener. This time, the Bears lost 31-24.

As of this writing not even five years have passed since the reopening of the stadium, but the Hayward Fault has already been tirelessly at work. At the following stops we will see some of the effects which the fault creep of a few millimeters per year has already had on the rebuilt stadium. Some signs are still rather subtle, but given the unstoppable movement of the tectonic plates under northern California, the small cracks and movements visible today will grow larger with each passing year.

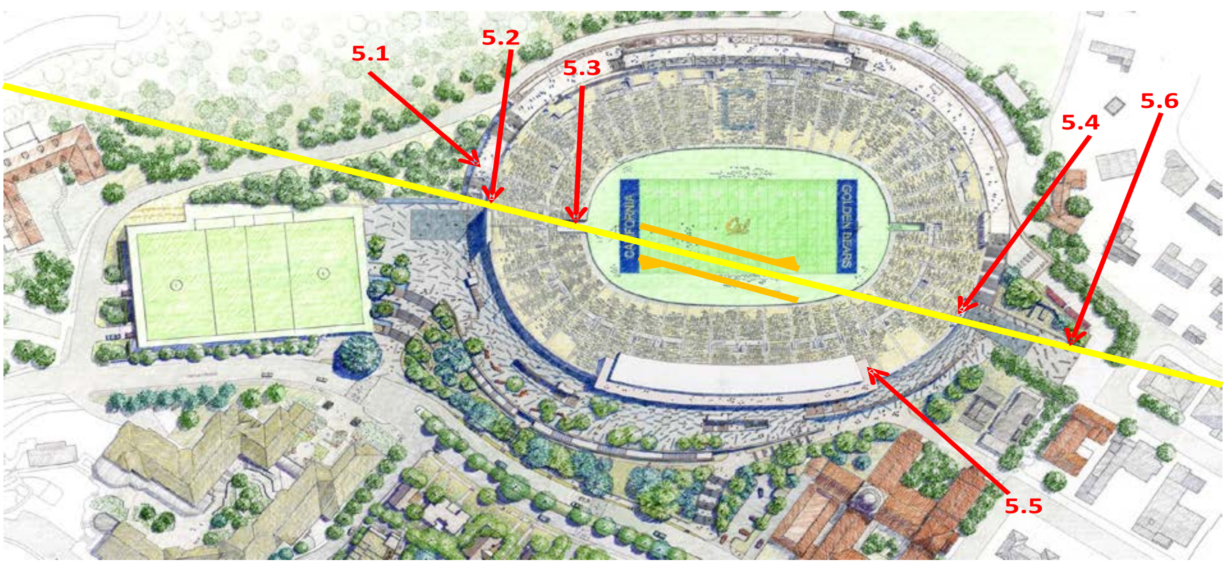


Fig. 5.5: The Hayward Fault crosses the stadium and its surroundings along the yellow line. The orange arrows indicate the right lateral character of the fault movement. The numbered red arrows point to stops during the stadium tour.

From the borehole continue the walkway uphill for a few steps until you reach a flight of concrete stairs. Walk down a few of these stairs, but not farther than the first platform. Stop there. This is our initial point of interest in the stadium.

5.1 Stairway on North Side of Stadium

The stairway on which you are standing was built during the stadium's renovation in 2012. If you walked the whole length of the stairway, you would not find any cracks in the concrete steps or in the wall holding the hand rail, except here on the first platform from the bottom. There are several subtle, cracks crossing the base of the platform. Much more noticeable, however, are the cracks where at least three handrail supports are set into the concrete wall (see figure 5.6). The reason for these cracks is not shoddy workmanship during construction. Instead the cracks are caused by the aseismic creep of the Hayward Fault, which crosses the stairway exactly at the platform on which you are standing.

Fig. 5.6: Cracks in the handrail support

Continue down the stairs. Go through the gate at the bottom of the stairway. Immediately turn left and walk to the exterior stadium wall on the left side of the north tunnel. Walk for a few yards in a clockwise (left) direction along the wall until you reach a corner. To the left is a joint between two sections of the wall, which is filled with sealant.

5.2 Exterior Wall - North Side of Stadium

When Howard designed the stadium in the early 1920's he was aware of the fault's location. Hence he separated the exterior wall into several sections, which were supposed to move independently during an earthquake. Currently, you are standing at one of these separations - we will see another one at stop 5.4. Because no significant earthquake has happened along the Berkeley section of the Hayward Fault during the existence of the stadium, Howard's concept was never tested. However here at the northern expansion joint, the two sections of the stadium's exterior wall have slid by about 1.5 inches due to the aseismic creep along the fault (see figure 5.7). During the renovation, this expansion joint was filled with a flexible sealant. Note how the sealant is cracking as a result of the fault's movement.

Fig. 5.7: Here two sections of the exterior stadium wall meet. The fault creep has moved the sections about 1.5 inches apart. During the renovation, the expansion joint was filled with flexible sealant.

When you look back from your current location to the stairway and to the borehole (stop 4) you will notice that our last stops lie on a straight line facing northwest. This is the fault line.

Walk back to the tunnel entrance and enter it. Don't walk all the way to the playing field but stop at the point where the tunnel daylights.

5.3 North Tunnel

Fig. 5.8: En-échelon-cracks

Where the tunnel daylights, the smooth concrete floor gives way to a softer asphalt with a rougher surface, which looks like roofing material. On the east side of the ground are a dozen or so cracks in this material. The cracks of various lengths are aligned in a parallel fashion and are all pointing in the same direction, northeast-southwest (see figure 5.8). Again, this cracking is not the result of shoddy workmanship during the reconstruction of the stadium, but a consequence of the aseismic creep along the Hayward Fault. Such cracks are rather common along faults. Geologists call them by their French name *en échelon-cracks*. The same word is also used in military terms, where an "echelon formation" describes a staggered set-up of naval vessels or aircraft, in which each element is positioned somewhat behind and to the side of the one in front. How such cracks form is indicated by the red arrows in figure 5.8, which show the right lateral movement of the Hayward Fault. When the two sides of the fault creep in the direction of the arrows, they exert a shear force on the ground. Under such shear somewhat pliable materials, like asphalt, break at 45^{O} angles to the fault, generating a set of parallel cracks. Hence the orientation of the cracks allows geologists to exactly pinpoint the location of the fault by connecting the center of each crack with a straight line.

The asphalt ground cover was applied during the final phase of the reconstruction in the summer of 2012. The cracks have formed in the years since and as of April 2017 they varied in length between one and seven inches. Because of the continuing fault creep, the cracks will grow. It is expected, however, that the stadium grounds keepers will repair them eventually. After that it may take a few years for new cracks to show up.

Another anomaly caused by the fault creep at this location cannot be corrected so easily. When you look up to the concrete tunnel arch right above the ground cracks you will see that the arch is separated vertically into two sections. When the concrete was poured during the reconstruction, the two sections were flush with each other. But as of this writing the fault creep has moved them an inch or so past each other. The same creep has also put the metal plate covering the separation into the odd angle shown in figure 5.9.

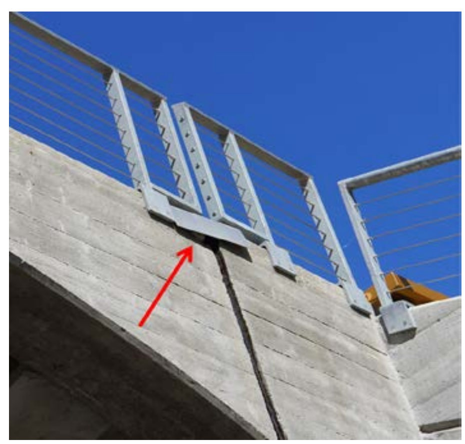


Fig. 5.9: Movement due to fault creep in the arch of the north tunnel

Leave the tunnel entrance by entering the spectators area of the stadium along the the walkway on the west side of the tunnel. This is the side toward the press box. Walk almost halfway around the playing field in a counterclockwise manner. Then make your way up the bleachers until you reach the uppermost benches of section KK. Catch your breath by taking a seat and enjoying the view across the playing field and up Strawberry Canyon to your east.

5.4 Section KK

As the reconstruction of the stadium was meant to significantly increase its seismic safety, nearly all traces that the creep of the Hayward Fault had imposed on the structure in the more than eighty years of its existence were erased. However, the stadium's status as a historic landmark did not allow for the alteration of the exterior wall during the remodelling. Hence all of Galen's original separation joints had to be left exactly as they were when the reconstruction began, no matter how severely they had been affected by the movement of the Hayward Fault. We already saw one example of such a joint on the north side of the stadium at stop 5.2 . But nowhere else has the fault left a clearer mark than at the rim of the exterior wall in section KK. Since the original opening of the stadium the two sections of the wall here have separated and rotated significantly, leaving a 6-7 inch wide gap at the top. This gap is still clearly visible today. The landmark rules for non-altering the appearance of the stadium were so strict, that engineers even had to leave in place the weather beaten, rusty metal plate, which had been covering the gap for decades.

Fig. 5.10: The famous gap in the exterior wall at section KK as seen from outside the stadium in April 2017. Note the rusty metal cap, a relic from long before the reconstruction of the stadium.

Fig. 5.11: The gap seen from the bleachers in section KK as it appeared in December 2008, almost two years before reconstruction began. Today, the gap is still there but the benches and the signage have been replaced.

When comparing the gap in the wall here on the south side of stadium with the movement at the corresponding expansion joint on the north side near section XX at stop 5.2, one notices a significant difference. There the separation was 1.5 inches at best while the gap in section KK is at least 7 inches wide. Why is there such a difference? There is no clear answer, but several factors may come into play. One possibility is that the foundation of the stadium in these two sections reached down to different depths and hence into different rock types. They in turn may respond differently to the shear exerted by the creep. It is more likely, however, that the Hayward Fault does not creep at the same rate everywhere in this area and that the creep is not uniformly distributed along the fault. While the creep is clearly noticeable in and around the stadium and further south on Dwight Way (stop 7), there are no traces that the fault is currently creeping between these two locations.

From the rim walk straight down and leave the bleachers area through the exit immediately below section KK. Once through the exit you have reached the concourse level. Turn right and walk along the concourse until you reach the walls of the new press box. This is our stop 5.5.

5.5 Concourse Level

While walking along the concourse level, compare today's solid concrete construction and the size of the columns with the columns before reconstruction as shown in figure 5.12. Then each column had a footprint of approximately one square foot. Today's supports are much bigger and contain the appropriate rebar layout for maximum seismic resilience.

Fig. 5.12: This picture was taken on the concourse level below section KK in December 2008. It shows typical support columns before reconstruction. Due to fault creep the two neighboring columns are tilted with respect to each other and hence misaligned. Note that the water and electric lines are fixed and not flexible.

While looking up at the "ceiling" of the concourse you will notice several places where the lifelines (power, water, waste water, communication) are put in flexible conduits. This was done to give the pipes and cables enough flexibility to prevent them from rupturing during earthquake induced shaking. Such flexible conduits did not exist in the "old" stadium.

Where ever you see these flexible conduits "dangling" from the ceiling, you will also notice a flexible plastic cover between the concrete. This plastic has no structural role. Instead it was installed to cover the space between two separate sections of the stadium support structure. Similar to Galen's original concept, the "new" stadium was also build in sections, each of which can move independently during an earthquake. This is supposed to make the stadium less rigid and more flexible, which will help mitigate damage due to seismic shaking.

Fig. 5.13: Flexible conduits were installed to reduce the chance that lifelines rupture during an earthquake. Note the plastic cover separating two separate sections of the stadium.

For the same reason the new pressbox is structurally completely separated from the rest of the stadium. It can move independently during earthquake shaking. To reduce the overall level of shaking a total of 16 massive hydraulic dampers have been installed between the various sections of the stadium and also between the press box and the rest of the stadium. They act like shock absorbers in a car. Each damper contains a silicone fluid which reaches its best damping when the shaking velocity is highest.

Fig. 5.14: In order to reduce the overall level of shaking between the various sections of the stadium and the press box, they are connected by massive hydraulic dampers.

From the concourse level walk straight out Gate 6 (south gate) onto the parking lot at Prospect Court. Just before you walk through the gate, stop for a moment and look back at the exterior wall of the stadium. Under the proper viewing angle, you will see the sky through the gap at section KK, as shown in figure 5.10.

5.6 Prospect Court Parking Lot

In preparation for the reconstruction geologists dug several trenches along and across the Hayward Fault in the vicinity of the stadium. One 80 ft long and about 20 ft deep trench was excavated perpendicular to the fault at the southern end of this parking lot near today's pedestrian crosswalk. The goal of the trenching was to pinpoint the exact location of the active fault trace and to study its most recent seismic history. During the excavation the researchers encountered several areas in this trench, similar to the one pictured in figure 5.15. It shows how an active fault trace looks underground: The greyish material is what geologists call *fault gouge.* It is essentially a rock which is ground into a fine powder by the constant movement of the two flanks of the fault. In addition, the arrow in the picture points to striations in the rock. These are also caused by fault creep, like the grooves left behind when one uses rough sandpaper on a shiny piece of metal.

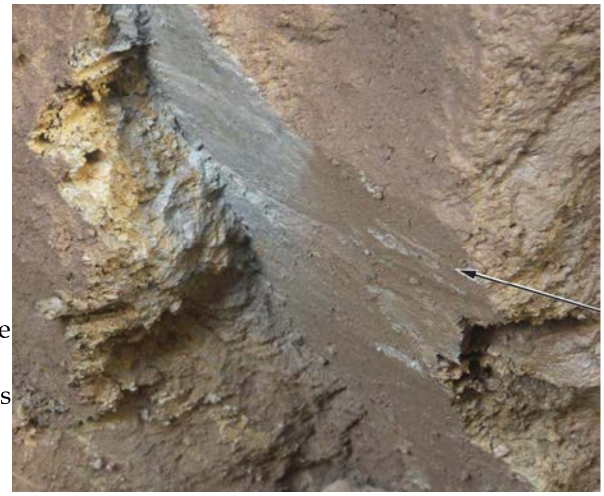


Fig. 5.15: A picture of the actual fault trace

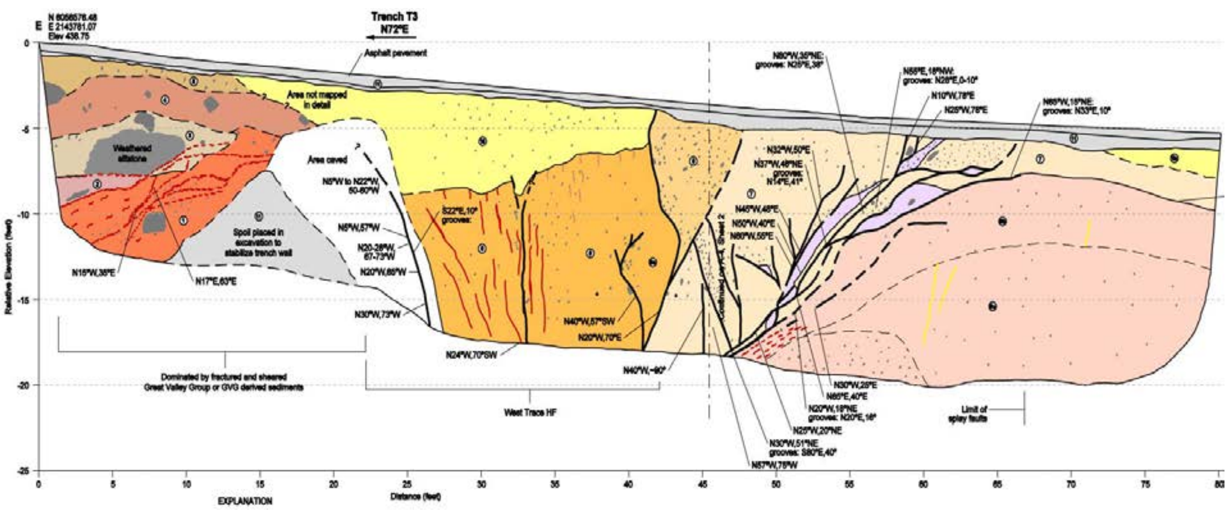


Fig. 5.16: Map of the southern wall of the trench at Prospect Court.

When trenching across active faults researchers usually put together their findings in maps of the walls of the trench, like the one shown in figure 5.16 for the south wall of the trench at Prospect Court. The various colors depict different kinds of sediments and soil found in the trench. The information relevant to this tour are the many black lines in the map, which look somewhat like roots growing underground. These lines mark active traces of the Hayward Fault like the one shown in figure 5.15. This again is proof that an active earthquake fault is not just a single straight line, but a complex zone of cracks and fault planes, which can extend over a large area. Hence, it is not surprising that different researchers found different strands of the Hayward Fault as depicted in figure 1 on page 3.

After it yielded its results, the trench was backfilled, paved over and is no more visible.

We are now leaving the stadium area by walking south along Prospect Street. After about 750 ft turn left into Hillside Avenue which gently curves to the south. After about 150 ft the road narrows and you will reach an old stone arch bridge, where the street crosses Hamilton Creek. Stand on the bridge and look to the east (upstream). This is our stop 6 in figure 2.

6. Hamilton Creek

Looking up the creek bed, you will see that it bends sharply to the right about 100 ft uphill from the bridge. This is the spot, where the Hayward Fault meets the creek (star in figure 6.1). On the right (south) side of the creek bed is a Tibetan Retreat which is built on a hill. This hill is a shutter ridge, carried to this location by the movement of the Hayward Fault. The ridge prevented Hamilton Creek from flowing straight downhill. Instead the water was deflected to the northwest, following the trace of the Hayward Fault. At the bend, which you can see from the bridge, the Creek resumes its downhill flow. This is another example of an offset stream channel, like Strawberry Creek further to the northwest. But while the actual offset of Strawberry Creek is covered by the stadium, it is more obvious here at Hamilton Creek.

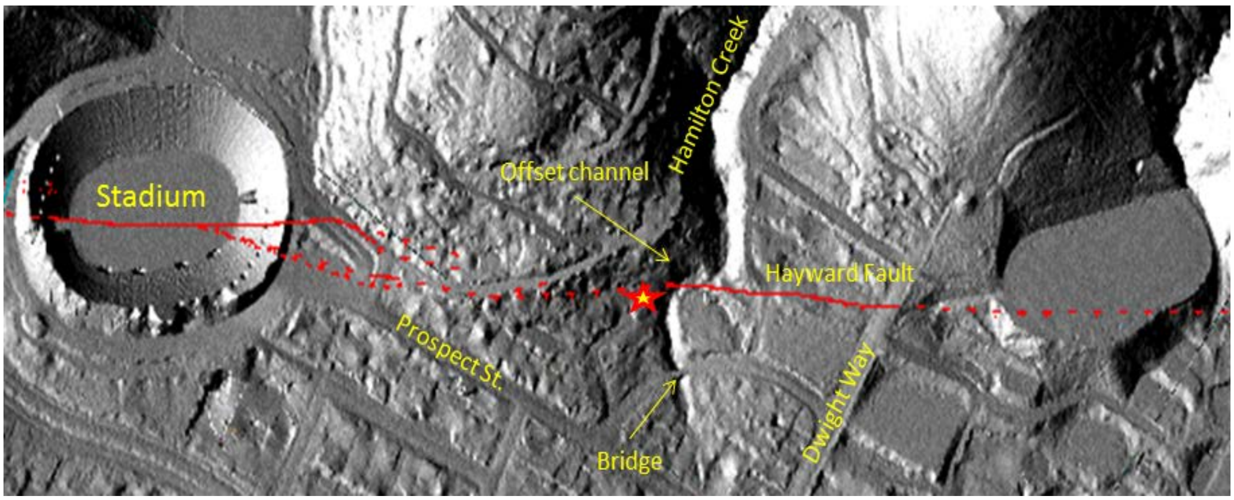


Fig. 6.1: The offset of Hamilton Creek can be seen in this Lidar image. See also front cover.

There seems to be some confusion about the name for this very short creek. On a topographic map dated approximately 1923 this Creek is called *Hamilton Creek*. Buwalda (1929) seems to be the first person to assign it the name *Hamilton Gulch.* He probably uses the word gulch because of the steepness of the creek's upper reaches on the south slope of Panoramic Hill. Starting with the 1947 edition, however, the Oakland East map of the official 7.5 minute quadrangle topographic maps series assigns the name *Hamilton Gulch* to the upper headwaters of Strawberry Creek, above what is now the Botanical Garden. In their *Creek & Watershed Map of Oakland & Berkeley* Sowers and Richard (1993) make this creek one of the headwaters of *Derby Creek*. In his guide to the Hayward Fault Stoffer (2008) calls this creek *Hamilton Creek*. We are using the name *Hamilton Creek* and not *Hamilton Gulch*, in order not cause a mix-up with the Hamilton Gulch identified on the topo maps.

Trace your way back to the stone arch bridge. At the gate, turn left and continue on Hillside Avenue until you reach Dwight Way. Turn left and walk uphill to the intersection with Fernwald Road. The turn around and look down Dwight Way. This is stop 7 on figure 2, the last stop on our tour.

7. Dwight Way

For the first time during this tour you are not standing on either the west side of the Hayward Fault or directly on it, but on its east side. Can you pinpoint the spot where you crossed the fault? While looking for the crossing point keep in mind that the fault shows an appreciable level of aseismic creep in this area. Because the mechanics of the Hayward Fault is right lateral, and you are looking across the fault, the creep should have moved items on the other side of the fault to your right. Well, if you guessed you crossed the fault where the curbs of Dwight Way are offset, then you are correct. Sometimes parked cars make these offsets difficult to see. The best viewing point is looking downhill to the west from the south side of Dwight Way. The crooked curb near the power pole is exactly where the active trace of the fault crosses the street (see figure 5.18).

Fig. 7.1: Street curb offset by aseismic creep looking west down Dwight Way.

On a clear day, when the Bay is not shrouded in fog you might spot from this view point another feature important to our local geotectonics. Far beyond the Golden Gate Bridge you may see the Farallon Islands, several dozen rocks of solid granite which rise up to 360 ft above sea level. Because granite is not a very common rock anywhere in the Bay Area, how did it get to this spot about 30 miles offshore from San Francisco? The granite of the Farallons is actually very similar to the granite of the southern extensions of the Sierra Nevada. The same forces, which tug on the stadium walls and make the curbs on the street in front of you bulge, were also instrumental in transporting the granite to its current location. The Farallon Islands are actually part of the Pacific Plate, which slides with a speed of about 2 inches per year in a northwesterly direction past the North American Plate. Together with the San Andreas Fault to the west of us and the Calaveras Fault further east, the Hayward Fault here at the foot of the East Bay Hills marks the active boundary zone between these two plates. Everything fault related you have seen on this tour is part of the bigger picture of *Plate Tectonics*, the eternal movement of the puzzle pieces of the outer shell of the Earth as they drift over the semi-molten Earth's mantle deep below our feet.

Fig. 7.2: View of Golden Gate Bridge at sunset from the upper end of Dwight Way.

Illustration sources

Cover:	Jim Lienkamper, USGS
Fig. 1:	adapted from figure 5 in Final Report of "Fault Rupture Hazard Investigation" by Geomatrix Consultants Inc., Project 10766003, Oakland 2006.
Fig. 2:	Modified from *Open Street Map*
Fig. 1.1&1.2:	UC Berkeley
Fig. 1.3	left panel courtesy of Don Eng, Department of Public Works, City of San Francisco right panel: UC Berkeley
Fig. 1.4	Horst Rademacher
Fig. 2.1&2.2:	Bancroft collection, UC Berkeley
Fig. 3.1:	Horst Rademacher
Fig. 4.1&4.3:	Peggy Hellweg
Fig. 4.2:	Horst Rademacher
Fig. 5.1:	Berkeley Architectural Heritage Association, http://berkeleyheritage.com/berkeley_landmarks/strawbcanyon.html
Fig. 5.2:	Earth Science Library, UC Berkeley
Fig. 5.3:	left panel: Berkeley Architectural Heritage Association, http://berkeleyheritage.com/berkeley_observed/berkeleyobserved90203.html right panel: http://www.californiagoldenblogs.com/2010/12/15/1865216/the-house-that-andy-built-the-making-of-memorial-stadium
Fig. 5.4:	Webcor Builders http://205.186.162.57/projects/all-projects/government/cal-memorial-stadium/
Fig. 5.5:	modified from drawing provided by UC Berkeley Athletics Department
Fig. 5.6-5.14:	Horst Rademacher
Fig. 5.15&5.16:	from Final Report of "Fault Rupture Hazard Investigation" by Geomatrix Consultants Inc., Project 10766003, Oakland 2006.
Fig. 6.1:	modified from Jim Lienkamper, USGS
Fig. 7.1&7.2:	Horst Rademacher

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Revision History

Version 1.0	05/09/17	New document
Version 1.1	06/06/17	Figure 1.4 added