BUILDING ALONG THE HAYWARD FAULT: A CASE STUDY IN EARTHQUAKE HAZARD PERCEPTION

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ED 169A
November 16, 1999

Everyone who feels an intelligent interest in the future of our race must be concerned for the prospects of [the American west coast]. Soil, climate, mineral resources, relation to other great centres of population, alike promise that our children and children's children shall find here all the conditions of prosperity which these features can afford; but before we can say that the future is altogether bright, we must ascertain whether society can there find a stable footing on a firm-set earth, or whether this portion of our continent is as unfortunate as the similarly situated portion of its southern mate, the coasts of Peru and Chili (sp.).

N.S. Shaler, 1870
"California Earthquakes", in <u>Atlantic Monthly</u>, vol. 25, p. 352

As residents of the San Francisco Bay Area we are intimately aware of our geological setting. Earthquakes and faults are a matter of course in our lives. The presence of the San Andreas, Hayward, Calaveras, and other smaller (yet still active[1]) faults provide a dual reality: our geologic faults remind us of the instability of the earth as well as the source of landscape beauty. However, as informed as we are about the geologic setting of our region, we still live in a particularly hazardous region with regard to earthquakes. There are many buildings located on or adjacent to faults that are susceptible to damage. Damage to these and other buildings from earthquake rupture, shaking, liquefaction, and earthquake-induced landsliding will occur in the next big earthquake. These hazards are a relic of our previous lack of understanding about faults and earthquakes; they would not happen if we did not build in areas susceptible to these geologic phenomena. Despite the knowledge of what the next significant earthquake will do, our current knowledge of active Bay Area faults cannot save us from the hazards we have created.

In his review of cultural landscape axioms, Pierce Lewis (1979) suggests that landscape is a clue to culture and that "history matters". These axioms provide a basis for evaluating the development of the built environment, including that of the East Bay. I suggest that the evolution of the built environment is a function of: 1) the history of scientific knowledge about the Hayward fault, and 2) our perceptions of earthquake hazard.

The starting point for this investigation was to prove or disprove the claim I have heard made by local geologists: a surprising number of critical structures (hospitals, schools, etc.) in the East Bay are located along the Hayward fault. The Hayward fault is the closest active fault to UC Berkeley and is mapped along the eastern side of the campus (Lienkamper 1992). Local geologists have recently published probability estimates for Bay Area faults and determined that the Hayward-Rodgers Creek

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[1] The California Division of Mines and Geology defines an active fault has having ruptured in the past 11,000 years.

fault[2] has the highest probability of producing a magnitude 6.7 earthquake (32%) before 2030 (WGCEP 1999). I have chronicled the development of scientific knowledge of the Hayward fault and related it to the development of the built environment along the East Bay from 1900-1980. Even though geologists recognized the presence of a Hayward fault by the late 1800s, and first mapped the fault in 1908, development of the built environment along the East Bay has seemingly occurred with little regard for this knowledge. I focused my study on the area in the USGS Oakland East 7.5 minute quadrangle, for which there are relatively extensive historical maps. The following analysis describes the state of knowledge of earthquakes and the Hayward fault as well as the location of critical structures at five points during the 20th century: 1925, 1942, 1959, 1973, and 1980. This analysis is followed by suggestions regarding the relationship between hazard perception and our actions along the fault.

For the purposes of this investigation, I define critical structures as those that when damaged by an earthquake could significantly affect a large number of people. For example, I chose to map schools and hospitals because they might be the location of a large number of injuries and deaths due to the quantity of people they hold. I also chose structures such as freeways, power substations, and drinking water filtration plants because earthquake damage to these structures would severely inhibit our daily activities and the ability of the community or region to recover. As evidenced in the Nimitz freeway tragedy during the 1989 Loma Prieta earthquake, freeways may also be locations of heavy injuries and fatalities.

[2] Geologists suggest that the Rodgers Creek fault is an northward extension of the Hayward fault across San Pablo Bay.

Scientific knowledge and the built environment

1925

By the 20th century, Bay Area residents were already aware of the geologically unstable nature of the region in which they lived. Moderate and large earthquakes[3] shook the region in 1836 (Magnitude 6¾) and 1838 (Magnitude 7), both of which are believed to have originated from the San Andreas fault (Ellsworth 1990, Toppozada and Borchardt 1998). Numerous smaller earthquakes had occurred throughout the 18th century (Holden 1897?). The first confirmed historical account of a large earthquake along the Hayward fault occurred on Oct. 21, 1868 (then called the "Haywards" Rift, or fault) with a magnitude of 7. Until 1906, this event was known as the "great San Francisco earthquake" (Ellsworth 1990). The earthquake caused damage throughout the greater Bay Area region and was felt from Chico to Monterey, and as far east as Nevada. San Francisco officials suppressed the dissemination of a scientific study of the effects of the earthquake to "protect the city's reputation" and encourage redevelopment and continued growth (Lawson 1908).

After the 1906 San Francisco earthquake along the San Andreas fault, a team of prominent geologists published a classic report describing and explaining the earthquake. In addition, the team also reinvestigated anecdotal accounts and field evidence of the 1868 Hayward fault earthquake, and published a map showing the approximate trace of the rupture (Lawson 1908). This map is the first to show a location of the entire length of the Hayward fault. Subsequent maps by the leader of the 1906 team, Andrew Lawson (UC Berkeley professor of Geology), do not show the fault (Lawson 1913, 1914). Lawson did not show the Hayward trace on the 1914 map because he did not know the exact location of the fault (Graymer, Jones, and Brabb 1995). A 1922 fault map of California shows the Hayward fault, but at a scale (1"=8 miles) that reveals little detail (Bailey and Willis 1922).

By 1925, geologists knew the existence of the Hayward fault and had located the 1868 surface rupture. They understood that crustal stress caused earthquakes along faults (LeConte 1889, Lawson 1910, Reid 1911), but they had not yet discovered the source of that stress. Armed with this knowledge, geologists called for changes in building construction practices in earthquake-prone regions (Science 1923). Studies of earthquake damage to buildings and recommendations to prevent such damage were published as early as 1886 (Milne). With the publication of the fault map of California, the co-author declared that "engineers should no longer build in ignorance of the existence of dangerous rifts" (Willis and Wood 1924).

Given the state of knowledge of earthquakes and the Hayward fault in 1925, what did the built environment look like (Fig. 1)? The analysis for the built environment in 1925 is based on Lawson's 1908 map, which is the only resource that shows the Hayward fault at this time, and a Thomas Brothers map (1925). The only critical structure on the fault was the new California Memorial Stadium on the UC campus. The fault is mapped as passing southward through Lake Temescal and a pond in Oakland. This area of the East Bay was sparsely populated at the time: the southeast portion of Berkeley was largely residential and the land east of Oakland only had a few roads that presumably connect small clusters of houses and ranches to the city. The California School for the Blind and Deaf, Mills College, Dingee Reservior, Reservoir No. 1, and an unidentified school were the closest critical structures to the fault and were located up to 1/3 mile west of the mapped fault.

1942

The primary advances between 1925 and 1942 in knowledge about earthquakes and the Hayward fault included advances in seismological instrumentation (Wood 1934) and more detailed descriptions of the geomorphology and geologic history along the fault. Building on observations made by Lawson (1914) of deflected streams along the Hayward fault in the Berkeley Hills, Russell (1926) and Buwalda (1926, 1929) saw evidence of right-lateral displacement[4] in many of the deflected streams along the fault. Buwalda (1926, 1929) also observed evidence of vertical displacement along the fault during an earlier phase of the fault's history. At the time, Buwalda's

[3] Moderate earthquakes are defined as having a magnitude between 6.0 and 7.0. Large earthquakes are those with a magnitude between 7.0 and 8.0.
[4] Right-lateral displacement refers to a particular direction of horizontal movement along a fault. If you stand on one side of the fault during an earthquake, the other side of the fault appears to move to the right.

(1929) description of geomorphological features along the fault in the vicinity of the Oakland East quadrangle was probably the most detailed account of the Hayward fault. However, despite more thorough verbal descriptions of the fault, geologists did not produce any new detailed maps showing the fault. Unfortunately, Lawson's 1908 map remained the most detailed. Knowledge, publication, and education of the location of the Hayward fault was limited and probably could not have prevented the siting of critical structures along the fault.

During the pre-WWII period, the city of Oakland extended eastward. Residents of Oakland built new houses and the facilities needed to support this eastward growth. Additions to the built environment along the Hayward fault between 1925 and 1942 (Fig. 2) included a power substation adjacent to Lake Temescal and four schools (Luther Burbank School, Castlemont High School, and 2 unidentified schools). One of the unidentified schools (as of 1980 the site of the Terrace Avenue Playground in Oakland) appears to have been located on or immediately adjacent to the mapped fault.

1959

A revolution of our understanding of the earth began in the late 1950s – plate tectonics. Plate tectonics suggests that the earth is made up of distinct and separate crustal plates whose movement is driven by heat convection in the mantle. However, the implication of plate tectonics for Bay Area geology probably was not realized until the 1960s. As the plate tectonics revolution began, few geologists were publishing work that refined the location of
the Hayward fault. Radbruch (1957) published a geologic map of the Oakland West quadrangle, but geologists did not publish any work regarding the Oakland East quadrangle. Lawson's 1908 map of the Hayward fault remained the only detailed map of the entire length of the fault. With a continued "drought" of additional published mapping, there was little knowledge available to the public about the location of the Hayward fault.

By 1959, the post-war housing boom had long since begun. In Oakland, people continued to build further from the city center, especially in the southeast (Fig. 3). The California School for the Blind and Deaf had expanded it facilities eastward across the fault trace. About half of the Warren Freeway had been constructed along a convenient linear valley caused by active fault movement. Montclair School, Joaquin Miller Junior High School, Holy Names College, Golden Gate Academy, Redwood Heights School, Sweet School, Burckhalter School, Parker School, Holy Redeemer College, Toler Heights School, and an unidentified school had been built on the fault or within 1/3 mile of the fault since 1942. Mills College expanded eastward toward the fault. Two reservoirs (including Seneca Reservoir) and the Upper San Leandro Filtration Plant were built within 1/3 mile of the fault. The Oak Knoll Naval Hospital was built a little more than ½ mile to the east of the fault trace. In essence, extensive suburban development without the aid of an up-to-date, detailed fault map resulted in the siting of numerous critical structures along the Hayward fault.

1973

By 1973, Bay Area geologists had recognized the role of the San Andreas fault system, which includes the Hayward fault, in plate tectonics. Geologists characterized this fault system as a strike-slip, transform plate boundary[5] between the North American and Pacific plates. More detailed maps of the Hayward fault in the vicinity of the study area were finally published in the late 1960s (Radbruch 1968a, 1968b, 1969). Radbruch augmented Lawson's (1908) 1868 rupture data with fault creep evidence and geomorphological interpretation. Her research revealed a more complex fault zone rather than a single fault trace as was previously mapped.

According to Radbruch's 1969 map, the reinterpretation of the fault trace(s) changed how close certain critical structures were mapped to the fault (Fig. 4). As of 1973, two fault traces were mapped through the California School for the Blind and Deaf. The Warren Freeway went through to Highway 580 and follows the fault zone for its entire length. The Laurel School, Sweet School, Luther Burbank School, Mills College, Burckhalter School, Castlemont High School, and the Upper San Leandro Filtration Plant are facilities that were not previously mapped on the fault by Lawson (1908). But as of 1973, fault traces were mapped through these sites. The Oak Knoll Naval Hospital,

[5] A strike-slip fault is a localized boundary between any two blocks of crust moving horizontally past each other. A transform plate boundary is a regional boundary between two crustal plates defined by strike-slip fault(s).

which in 1959 was located over ½ mile from the fault, is now located adjacent to a fault trace. The construction of a few new schools (including Kaiser School and King Estate Junior High School, among other unidentified schools) since 1959 added to the list of critical facilities located along the fault trace.

The faults had not moved, nor had the structures. The difference in 1973 was that there was more detailed information about the location of the fault. Suddenly, with additional research and a new map, earthquake hazard risk to facilities now mapped closer to or actually on the fault was greater.

1980

The 1971 San Fernando Earthquake in southern California was an important catalyst to increased legislation regarding land use along California faults. The Alquist-Priolo Special Studies Zone Act of 1973 established special studies zones along active faults. The legislation required real estate sellers to notify potential buyers if the prospective site was in a special studies zone and it prohibited the construction of structures for human occupancy within 50 feet of a mapped active fault trace (Lundgren 1986).

Radbruch refined her 1969 map of the Hayward fault in a map published in 1974. Her revisions were located along the northern half of the Warren Freeway, in the vicinity of Mills College, and between Luther Burbank and Toler Heights Schools (Fig. 5). Only the Luther Burbank and Toler Heights Schools benefited from these revisions, which placed a fault trace shown in Radbruch's 1969 map further away from the schools. There were no critical facilities built between 1973 and 1980; therefore I cannot make any conclusions regarding the utility of the Alquist-Priolo Act other than the possibility that the act prevented the construction of critical facilities that made it on the map.

Hazard perception, public knowledge, and public behavior

The preceding analysis of the development of the built environment over time reveals that Californians built critical structures on and along the Hayward fault into the 1970s. Throughout most of the 1960s, published scientific knowledge of the location of the fault in the study area was based on surface rupture evidence published in 1908. Is this lack of updated scientific knowledge to blame for the poor or non-existent land use planning that allowed the siting of critical structures on and along the fault? Up-to-date mapping showing current knowledge of the fault location is important, but there are other factors. Based on research and suggestions from the field of hazard perception, I suggest that the large amount of time since the last Hayward fault earthquake is also an important factor in our attitude and behavior regarding earthquake hazards.

Although East Bay residents probably did not have the information they needed to make foresightful decisions regarding the siting of critical facilities, Jackson and Burton (1978) concluded that scientific knowledge does not decrease the potential for earthquake loss. Turner, Nigg, and Paz (1986) found that people tend to receive earthquake hazard information from non-technical sources such as news media and informal social networks. If there is little scientific knowledge, and the information people receive tend to be from non-technical sources, people are probably receiving limited, incomplete, and inaccurate information regarding earthquake hazards.

Even if people are receiving adequate and accurate information regarding earthquakes and fault location, how do people process this information and how does this information influence their behavior? People can take a range of precautions and mitigation measures in response to earthquake hazards, including but not limited to: securing the building to the foundation; storing food, flashlights and other items useful after an earthquake; and arranging a reunion with family members after an earthquake. In several studies, researchers have found that Americans in earthquake hazard-prone areas tend to have a high awareness of earthquake hazard, but that only a few people take limited measures to reduce these hazards (Jackson and Mukerjee 1974, Jackson 1981, Palm and Hodgson 1992, Palm and Carroll 1998). A survey respondent in Jackson's (1981) study put it this way: “An earthquake, it’s not a tangible thing . . . . You can’t see it coming, you don’t know when it’s going to come . . . . So my philosophy is: Forget it.” Palm and Hodgson (1992) found that few people adopted new hazard mitigation measures even after the 1989 Loma Prieta earthquake, and those who did change their attitude and behavior about earthquake hazards were those who had experienced damage. Jackson (1981) and Palm and Hodgson (1992) found some level of correlation between past experience and the adoption of precautions. However, research by Palm and Carroll (1998) does not support such a correlation and that those with personal experience were only slightly more apt to adopt mitigation measures.

Some researchers suggest that the perception of minimal future damages from an earthquake and a lack of the adoption of mitigation measures may be related to how long it has been since the last big earthquake (Jackson and Mukerjee 1974, Jackson 1981, Simpson-Housley and de Man 1987). If a community has not experienced a large earthquake in some time, people tend to forget about what happened and perceive less intense damage potential. Ellsworth (1990) alludes to the failure of the collective memory after the 1868 Hayward fault earthquake:

> Sadly, many of the engineering lessons learned from this earthquake and openly discussed at the time, such as the hazards of building on ‘made ground’ reclaimed from the San Francisco Bay or the admonition to ‘build no more cornices’ were long forgotten by the time of the 1906 earthquake.

Considering how quickly it took people to forget about the 1868 earthquake, it is not surprising that they built many critical structures on or along the fault through much of this century. People tend to have short term memories when it comes to natural hazards, including earthquakes. Until the Alquist-Priolo Act, development in the East Bay with respect to the Hayward fault was based on a series of individual decisions unregulated by the community or government. Collectively, these individual decisions reflect a communal perception of the fault and its associated hazards. People believe that the last earthquake was not that bad, or that it will not happen again during their lifetime. Coupled with little scientific information, such a collective perception of earthquake hazards is reflected in the built environment of the East Bay.

The last major earthquake on the Hayward fault was over 130 years ago. Recent efforts by local geologists to estimate the probability of the next magnitude 6.7 earthquake has received a lot of press (WGCEP 1990, 1999). Their results have been published in the newspaper and on the internet. The next question might be whether, and to what degree, this type of public outreach refreshes our collective memory and influences our attitude and behavior regarding earthquake hazards before the next Big One.

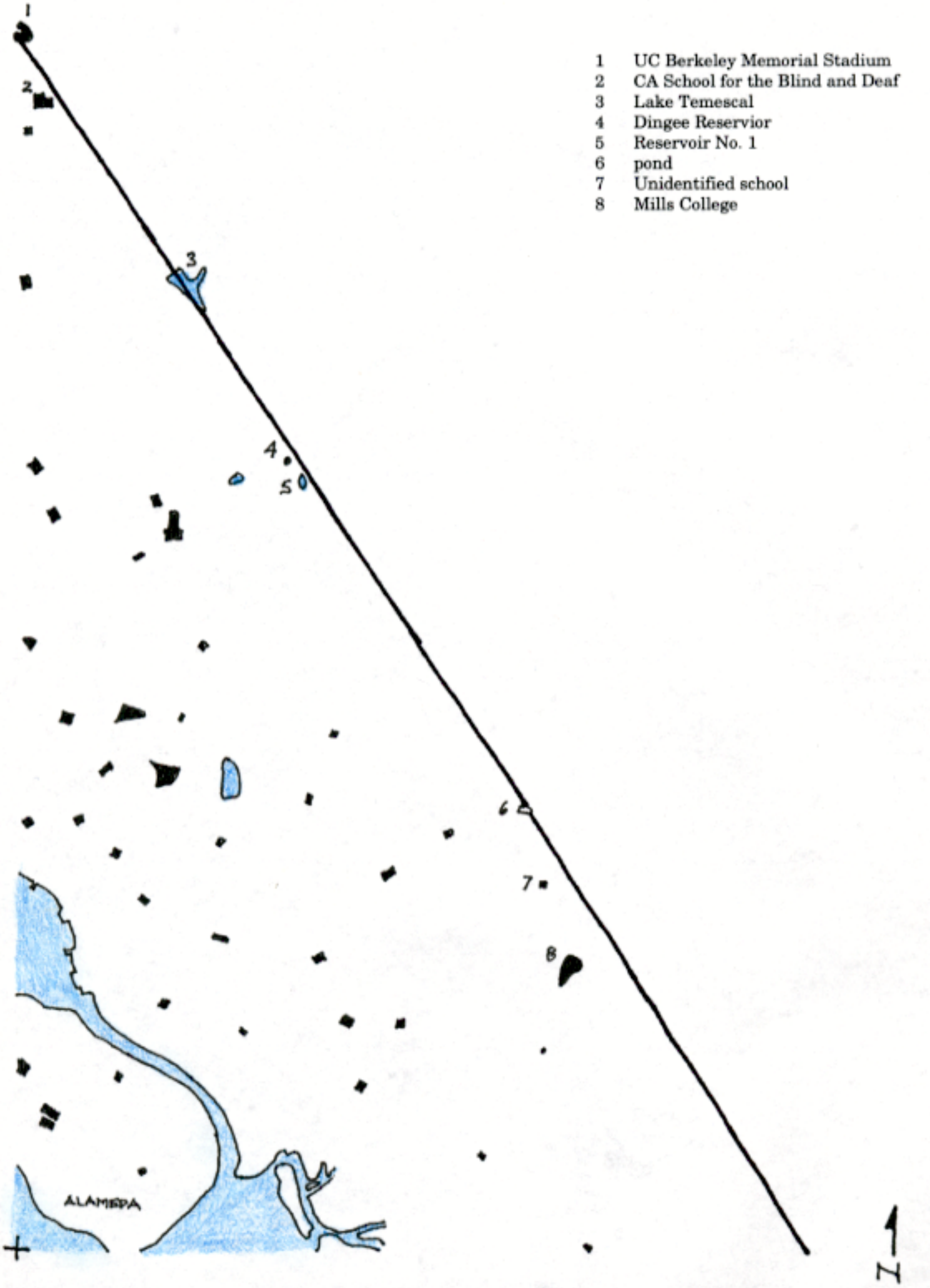

Figure 1 Map showing locations of critical structures and the mapped trace of the Hayward fault in 1925. Critical structure locations taken from Thomas Brothers (1925); fault trace approximated from Lawson (1908). Fault trace is shown as a heavy black line. All critical structures shown in black. Scale is approximately 1"=5500'.

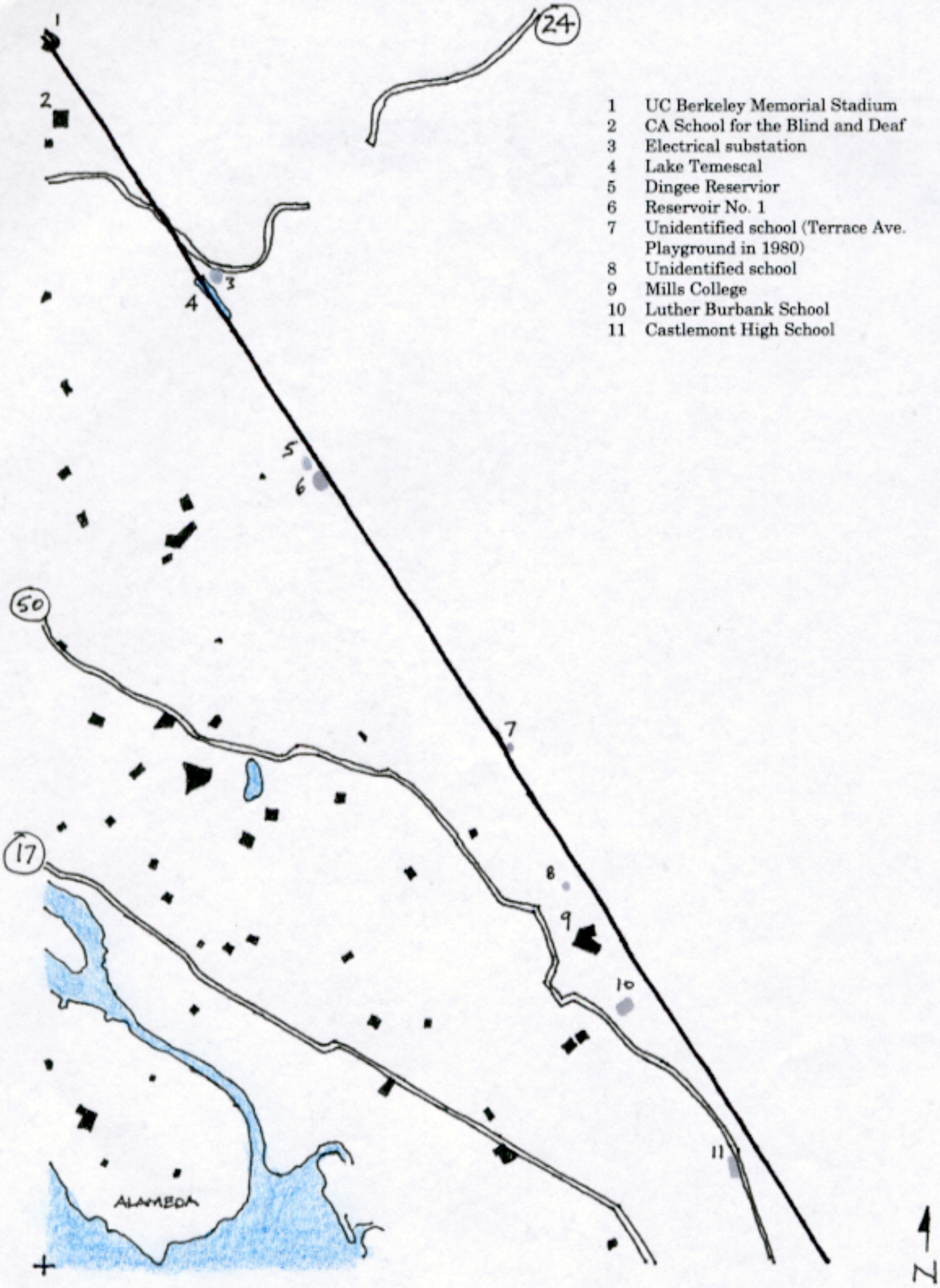

Figure 2 Map showing locations of critical structures and the mapped trace of the Hayward fault in 1942. Critical structure locations taken from Army Corps of Engineers Oakland East 7.5 minute quadrangle (1942); fault trace approximated from Lawson (1908). Fault trace is shown as a heavy black line. Structures built since 1925 shown in gray, structures existing prior to 1925 shown in black. Scale is approximately 1"=5500'.

(only those along the fault)

<u>Figure 3</u> Map showing locations of critical structures and the mapped trace of the Hayward fault in 1959. Critical structure locations taken from USGS Oakland East 7.5 minute quadrangle (1959); fault trace approximated from Lawson (1908). Fault trace is shown as a heavy black line. Structures built since 1942 shown in gray, structures existing prior to 1942 shown in black. Scale is approximately 1"=5500'.

^ (only those along the fault)

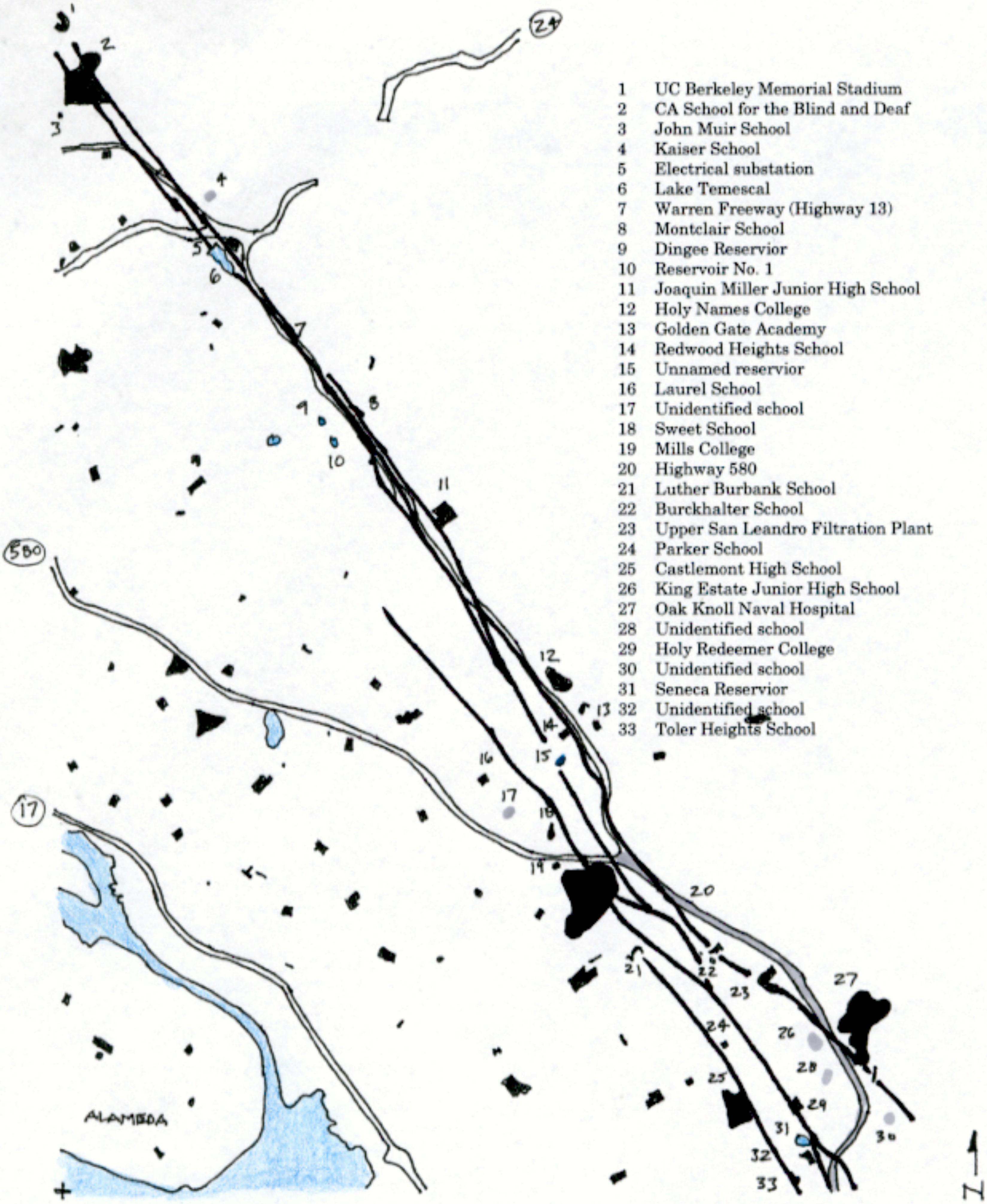

Figure 4 Map showing locations of critical structures and the mapped trace of the Hayward fault in 1973. Critical structure locations taken from USGS Oakland East 7.5 minute quadrangle (1973). Fault traces shown as heavy black lines and are simplified from Radbruch (1969) - each fault trace on Radbruch's map is expressed with a level of certainty that for scale reasons is not preserved in this figure. Structures built since 1959 shown in gray, structures existing prior to 1959 shown in black. Scale is approximately 1"=5500'.

(only those along the fault)

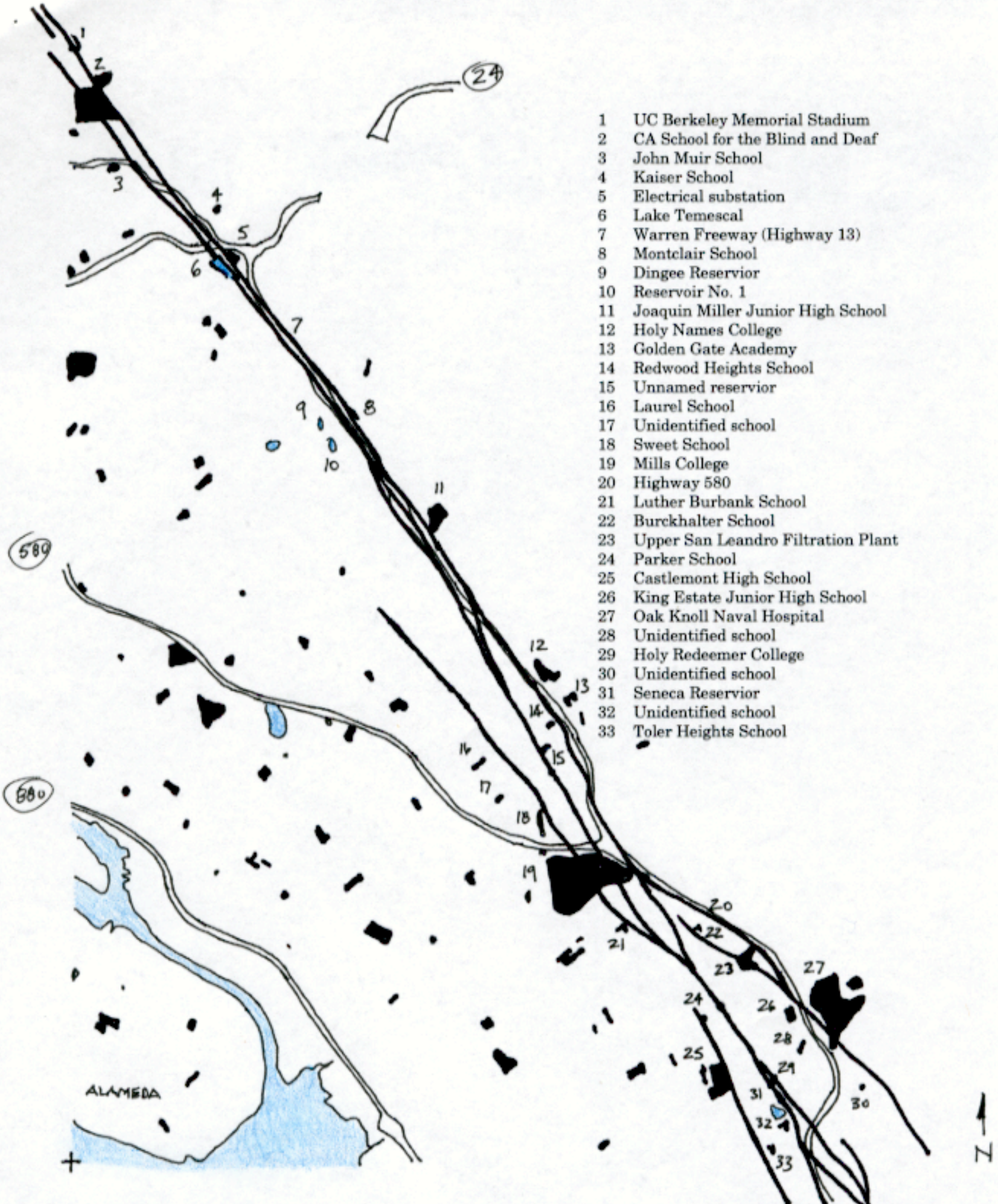

Figure 5 Map showing locations of critical structures and the mapped trace of the Hayward fault in 1980. Critical structure locations taken from USGS Oakland East 7.5 minute quadrangle (1980). Fault traces shown as heavy black lines and simplified from Radbruch (1974) - each fault trace on Radbruch's map is expressed with a level of certainty that for scale reasons is not preserved in this figure. Structures built since 1973 shown in gray, structures existing prior to 1973 shown in black. Scale is approximately 1"=5500'.

SOURCE LIST

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A curious feature of all earthquakes is the sinister aspect of the landscape after the shock. A cyclone tears through the country, leaving a trail of wreckage behind it. Here a house is unroofed, and there a tree is uprooted; fences are down, and the scene is one of disorder. But the tornado has freshened the atmosphere; the sun shines brightly, a zephyr is perchance wafted across the cheek, and the spectacle contains nothing terrifying beyond the remembrance of the whirlwind itself. But the visitation of an earthquake produces quite a different sensation. The landscape is twisted out of shape and looks drunk. The roofs of buildings are littered with bricks and mortar from dismantled chimneys, and the buildings themselves are awry. This house has been wrenched about so that it looks as if some monstrous giant of a fairy-tale had given it a vicious twist; the corner of yonder farm-house has been jammed down so that the hitherto smiling home has the aspect of a vulgar bully with his hat down over his eye. Nature has a peculiar, surly air, like that of a spider lurking in his web in a dark cellar, and seems to be meditating more mischief in the same direction. This appearance is heightened by the heaviness of the atmosphere, which hangs down over the earth like a pall and depresses the spirits. An occasional trembling of the ground sends the heart up into the throat in apprehension of another shock, for the earthquake, unlike the cyclone, gives no warning of its approach. The barometer does not herald it, and the Weather Bureau knows nothing whatever about it until it is all over. This is why earthquakes are so feared. They come like a thief in the night, when least expected.

Frederick H. Dewey, 1899
"How an Earthquake Looks and Feels", in Lippincott's Monthly Magazine,
vol. 63, January-June, 1899, p. 529-530.