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EARTHQUAKE AND TSUNAMI SAFETY OF NUCLEAR POWER PLANTS – Case Study: The San Onofre Nuclear Plant in California, USA

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ABSTRACT

The present study addresses briefly the safety and design requirements of nuclear power plants from earthquakes and tsunamis that may affect the structure or cooling systems of their reactors, and which may result in additionally and longer term destructive impacts on nearby communities and marine life due to the additional release of radioctivity - as was the case with the 11 March 2011 Fukushima Daichi nuclear plant in Japan, as well as with the release of radioactivity by other nuclear power plants by tsunamigenic earthquakes in other parts of the world.

The vulnerability of nuclear power plants to earthquakes and tsunamis was specifically examined by the author in conducting a comprehensive study of historic earthquakes and tsunamis, as well as by an extensive air and land field survey of Southern California, undertaken under contract with the U.S. Nuclear Regulatory Agency (NRC), and the U. S. Army Coastal Engineering Research Center (CERC), in connection with the licencing of the San Onofre Nuclear Power Plant near San Clemente in California, and of subsequent attempts to licence the additional Units 2 and 3 of the same facility of the Southern California Edison Company (the licensee).

The present evaluation is also based on historical records extended back in time for determining earthquake and tsunami events when California was still under Spanish control under Gaspar de Portolá, the Spanish military officer from Catalonia in Spain, the first governor of Upper California, and founder of Monterey and San Diego, before California was annexed by the United States as a State of its Union. Also researched were archives in Seville, Spain.

Keywords: *Nuclear Power Plants safety; San Onofre power plant; Fukushima Daichi Nuclear plant Japan disaster; cooling system failure; licencing U.S. Nuclear Regulatory Agency (NRC)*

INTRODUCTION

As consultant to the U.S. Nuclear Regulatory Agency (NRC) for the licencing and construction of units 2 and 3 of the San Onofre Nuclear Plant (SONGS), the author of the present study undertook a thorough physical examination and mapping of major seismic faults in Southern California on the main San Andreas fault, and on other adjacent faults up to Baja California in northern Mexico. The main purpose of the conducted survey was to evaluate the impact of past Southern California earthquakes and possible tsunamis in this general region, their frequency of reccurrences, and the potential impact that future events on land and on offshore faults could have in the vicinity of the planned additional San Onofre nuclear plant construction site for units 2 and 3.

At the time of the investigation, there was also concern about the proximity of the additional nuclear power plant construction to the California residence of then U.S. President Richard Nixon in San Clemente (4 miles away from the nuclear plant), and its relative safety. Thus the field investigation was additionally extended by a helicopter survey of seicmic fault extensions on the offshore Island of Santa Catalina on the southern California coast – a survey which was subsequently intercepted, interrupted and aborted, following warnings by armed helicopters guarding the presidential house.

Although signicant destructive earthquakes occur frequently slong the San Andreas fault of California, most of them occur inland and involve strike-slip type of ground displacements. However some earthquakes which occur on extentions of faults into the sea, can and have generated destructive tsunami waves in the past. In general, and as mentioned and explained elsewhere in this present study, the relative tsunami threat for local tsunamis in California can be considered as being relatively low because of the low recurrence frequencies of such offshore California earthquakes.

A thorough and detailled study of historical earthquakes and tsunamis in California was published in a book by the author entitled "The Big One-The Next Great California Earthquake – Why, Where and When it will happen" (Pararas-Carayannis, 2000 Forbes Press). According to stated conclusions of this publication, large, locally-generated tsunamis in California are estimated to occur once every 100 years. Thirteen possible tsunamis have been observed or recorded from local earthquakes between 1812 and 1988. These tsunami events were poorly documented and some are very questionable. However, there is no doubt that earthquakes occurring along submarine faults off Santa Barbara, just North of Los Angeles, could generate large destructive local tsunamis. In fact, in December of 1812, local earthquakes occured, each capable of tsunami generation. Perhaps the size of the 1812 tsunami at Santa Barbara was exaggerated in the historical records, but one and possibly two large tsunami events did occur in the area that year according to substantiated accounts.

The following discussion provides summaries of such events along Southern California – events which were examined in relation to the licencing of units 2 and 3 of the San Onofre Nuclear Generating Station (SONGS). This station was granted a facility Operating License on January 1, 1968 and ceased operation on November 30, 1992. The licensee, Southern California Edison Company (SCE), completed defueling of the reactor on March 6, 1993, and the dismantlement and decommissioning of SONGS, Unit 1 by 15 December 1998.

Prior to the review of safety of the San Onofre Nuclear Plant based on the onsite inspections and findings (Parararas-Carayannis George, 1974), subsequent sections of this report document sequentially historical earthquake and tsunami events and evaluations of their occurences and reported impacts in Southern California, which could have had an impact until units 2 and 3 of the facility were completely decommissioned in June 2013, Unit 1 in 1998, and an 8-year dismantling plan of the entire facility was initiated in August 2022, at an estimated cost of 5 billion US dollars.

1. HISTORICAL EARTHQUAKES, TSUNAMIS AND OTHER DISASTERS IN SOUTHERN CALIFORNIA AND EVALUATION OF POTENTIAL IMPACTS

The following is a listing in chronological order of historical earthquakes and tsunamis that had impacts in Southern California, but particularly to those in close proximity to the San Onofre nuclear power plant. Also examined were potential failures of the reactor's cooling system from meteorological phaenomena causing sudden changes in atmospheric pressures and associated sudden sea level fluctuations. As stated, a thorough investigation of the literature of such events was undertaken by the author, initially in the early 1970's under contract as consultant to agencies funded by the the U.S. Nuclear Regulatory Agency (NRC), for the design, licencing and construction of units 2 and 3 of the San Onofre Nuclear Plant (SONGS) near San Clemente. The study was augmented later in a book for earthquakes of the entire state of California, and on the high probability of their reccurence along the San Andreas fault system and its adjacent seismic zones (Pararas-Carayannis, 2000).

This particular study includes a review of all available original records of the Fransican Missions of California established by the Spaniards, following Gaspar de Portolá y Rovira - the first governor of the "Californias" - and founder of Monterey and San Diego. The present review begins with the Santa Barbara Earthquake and tsunami(s) of 1812, and the controversies regarding local earthquakes in that year. These were the particular Santa Barbara earthquakes of December 1812. Also, all other historical earthquakes in Central and Southern California were particularly examined by the author, as consultant to the U.S. Nuclear Regulatory Commission in connection with the licencing of the San Onofre Nuclear Power Plant's Units 2 and 3 (Pararas-Carayannis, 1971), of the Crystal River (Florida) nuclear plant, and of proposed offshore nuclear plants - after reading all the impact statements that were filed by utilities, for evaluation of their adequacy and safety.

Parenthetically, for the Florida Crystal River nuclear plant – as well as for the San Onofre plant - the author also developed a mathematical model of a mega-hurricane - a hypothetical design hurricane striking the plant at a right angle. Based on this modeling study of the Crystal River plant, the Nuclear Regulatory Commission required the Utilities Company to redesign the cooling system, and build the cooling water pumps at a much higher elevation than Dames and Moore (the Engineering Consultants) were recommending.

The author was also present at the location of the San Onofre plant when the 1971 San Fernando earthquake occurred, and inspected the plant and its perimeter for possible damage. Subsequently, and under contract with the consulting firm "Marine Advisors", 'he undertook comprehensive studies of historical earthquakes and tsunamis in the Santa Barbara Channel, since he was particularly concerned about a possible repeat of the 1812 Santa Barbara earthquake and tsunami and the effects which they may have on the safety of the San Onofre plant (See also summary of author's subsequent book on "The Next Great California Earthquake" at http://www.forbesint.com/Book.htm . Chapter 15 of the book is devoted to the assessment of the California Tsunami hazard and includes maps of the faults in the Santa Barbara Channel that could generate earthquakes and potential tsunamis (Pararas-Carayannis, 1973).

Other specific references by the author refer to "Tsunami Guidelines at Power Reactor Sites", Guidelines For the Siting, Design. Construction, and Operation of Thermal Power Plants (Pararas-Carayannis, 1974), "Tsunami Hazard and Design of Coastal Structures" (Pararas-Carayannis, 1976), and "Guidelines For the Siting, Design. Construction, and Operation of Thermal Power Plants" (Pararas-Carayannis, 1979).

1A. The Santa Barbara Earthquakes and Tsunami(s) of 1812 - A Source of Controversy

There is great controversy regarding the generation of tsunamis from local earthquakes in California about events which occurred along the Santa Barbara coast region in December of 1812. These reported earthquakes and the accounts of resulting tsunami waves have been the subject of research by many scientists. Indeed, historical accounts reported large tsunami waves, but with no clear documentation on the chronology of such events.

There is no doubt that one and possibly two large tsunami events were generated by the December 1812 earthquakes in the Santa Barbara region. However, these tsunamis could not have been as large as they have been described in the historical accounts. Furthermore, tsunami events of such magnitude would place in different perspective the suseptibility of Southern California to the tsunami hazard (from local earthquakes).

Accounts of the 1812 Santa Barbara earthquakes and tsunami waves were found in numerous publications, including mission records (Padre José Señan, O.F.M., 1974; Carpenter, 1921; Sieh, EtAl, 1989; Iida, K. EtAl, 1967 a and b; Pararas-Carayannis, 1973)). Some of the existing historical descriptions of events which occurred in December of l8l2 in the Santa Barbara region are presented here to illustrate the difficulty of analyzing conflicting historical information and reaching definite conclusions as to their validity.

1B. Historical Accounts of the Effects of the December 1812 Santa Barbara Earthquakes on the Fransiscan Missions of Southern California

The intensity of the Santa Barbara earthquake described by Wood and Heck was given as 10 on the Rossi/Forel scale of 10 grades and the epicenter of the earthquake was stated to be in the offshore region in the vicinity of the Transverse Ranges (Wood and Heck, 1951.

In the same publication, the description of the earthquake effects of the 1812 events are as follows but without specific reference, beginning with events in Santa Barbara, Ventura and the Northern Los Angeles Counties, based prinarily on mission records.

"Damage to Santa Barbara, Ventura, and Northern Los Angeles Counties. The Church of Purissima Mission was destroye , together with many mission buildings. The strong fore-shock at about 10:30 am, which did alarming damage, caused the people to leave the building, and undoubtedly saved many lives when the main shock came. There were no deaths, but some injuries. At Santa Ynez Mission, a corner of the church fell and many new homes were destroyed. At Santa Barbara, old mission buildings were severely damaged, and the church was later rebuilt; some buildings were some buildings were ruined, and the remaining structures damaged at the Presidio. At Santa Buena Ventura Mission, the tower was wrecked and much of the facade of the church had to be rebuilt. At San Fernando Mission, thirty beams were used to keep the walls from falling. Strong aftershocks occurred until February, and lesser shocks continued until April, 1813."

The following account of the effects of the the Santa Barbara, December 1812 earthquakes on the California Spanish Missions can be found also in Padre Señan's Biennial Report of 1811-1812 from Mission San Buenaventura (Padre José Señan, O.F.M., 1974, translated from Spanish by Maynard Geiger). Severe damage from the earthquake was also reported from Mission Santa Ines, Mission Santa Barbara, the Santa Barbara Presidio, Mission San Buenaventura (Ventura), and Mission San Fernando, covering a distance of over 100 miles. The report states:

“The already severe conditions have been rendered even more severe by the horrible temblors and earthquakes that have been experienced in this province and which will constitute a special epoch in it because of the great resulting damages. The violence of these occurrences have been extraordinary.

As a result of the ruinous events we have to build anew the churches of Missions San Fernando and Santa Barbara. ...... Mission San Gabriel suffered somewhat. At Missions Santa Ines (Santa Ynez, CA)and San Buenaventura (Ventura, CA) quite some time will be required to repair the damage which I consider annoying to describe in detail. Concerning the last named mission I will say only that the tower partially fell and that the wall of the sanctuary was cracked from top to bottom”

At Mission Purisima (Lompoc, CA) the bells rang out without the aid of a bell ringer and in a few minutes the mission was reduced to rubble and ruin presenting the picture of a destroyed Jerusalem. With the permission of the government the mission is to be rebuilt at a place about a league and a fourth distant called Los Berros which offers notable and known advantages” .

1C. Earthquake Effects at Mission La Purisima

The most serious damage from this earthquake was reported at Mission La Purisima, located at Lompoc Valley. On December 21, 1812, around 10:00 or 10:15 in the morning, a strong eartquake and ground motions frightened the mission's residents - - priests, Indians and soldiers - who rushed out of the mission buildings. This first shock turned out to be only a foreshock. Fifteen minutes later, a still stronger earthquake occurred. The shaking of this second earthquake was so intense that the mission's church bells rang out. The adobe walls of the mission buildings were shattered, and in some instances collapsed, reducing Mission La Purisima to "rubble (Fig. 1).

Fig. 1 Photograph(1935): Ruins of Mission La Purisima after the Santa Barbara Earthquakes of December 1812

Regarding specific earthquake effects of th 1812 Santa Barbara Earthquake at Mission La Purisima, Fathers Payéras and Ripoll reported:

"The extraordinary and horrible earthquake, which this Mission suffered on the memorable day of the glorious Apostle St. Thomas, entirely destroyed the church and vestry, buried under the walls the various images and paintings, and ruined the greater part of the furniture. ... Some of the work shops went down ... One hundred houses of neophyte Indians and the community kitchen, the walls of which were an adobe and a half thick, and roofed with tiles, have become inserviceable. The garden walls of adobe, covered with tiles, have collapsed or threaten to fall. ... Experience may teach us the best method of constructing other buildings".

In a letter to the Spanish governor of California, Father Payéras wrote:

"We have observed with sorrow that all of the structures are ruined from the foundations to the roof: that the church is demolished from the foundation up: and that neither Fathers, nor soldiers, nor neophytes will or can, without terror or risk, live in their habitations, which have partly fallen, are partly out of plumb, and are in many parts seriously cracked".

According to a report and letter from Mission La Concepcion Purisima de Maria Santisima, by Zeyphyrin Engelhardt, Mission Santa Barbara, Santa Barbara, CA, 1932.

"At the time of the disaster 999 Indians, two Padres, and ahandful of soldiers resided at Mission La Purisima. These missions were working ranches: at the time of the earthquake, Mission La Purisima had 4000 cattle,12000 sheep, 1150 horses, and grew wheat, corn, and beans. The Mission even had vineyards, from which the good Padres made wine".

1D. Earthquake Effects at Presidio Santa Barbara

The soldiers at the presidio in Santa Barbara were so disturbed by the earthquake that they abandoned the presidio, building thatched huts near the Santa Barbara Mission, where the shaking from the earthquakes was said to be more moderate. Strong earthquakes continued to rock the region through February of 1813. The Spanish soldiers from the presidio did not return to their former home until March, almost three months after the first earthquake.

Fig. 2 Photograph Santa Barbara Mission presently.

Repairs to the Missions made subsequently to the 1812 Earthquakes: The church at Mission Santa Barbara was rebuilt with thicker walls and was completed in 1820. The church was damaged again in the 1925 earthquake and repaired. The San Fernando Mission was repaired, but destroyed by the February 9, 1971, San Fernando earthquake. It has also been rebuilt (Fig. 2). Mission La Purisima was moved from its original site in Lompoc, California to a site a few miles away. This mission is now a California historical monument and is preserved roughly as it appeared around 1820 (see photo above). The earthquake damages at Mission San Gabriel could not have been too much of a surprise to the Spanish--the full name of that mission is Mission San Gabriel de los Temblores, or Saint Gabriel's Mission of the Earthquakes - a name quite appropriately given)

1E. Historical Accounts with Reference to the December 1812 Tsunami Waves

The following account of the 1812 tsunami is being quoted from a 1961 revised edition of the publication entitled "Earthquake History of the United States: Part II, Stronger Earthquakes of California and Western Nevada," by H.O. Wood and N.H. Heck, originally published in 1951.

"This earthquake was associated with by far the largest seismic sea wave ever reported for one originating in California. Descriptive accounts indicate that it may have reached elevations of 15 feet at Gaviota, 30 to 35 feet at Santa Barbara, and 15 feet or more in Ventura. It may have even shown visible effects in the San Francisco harbor. "

Reference to Bancroft's History of California, which has used original mission records, found in Holden's Catalog of Earthquakes, gives the following entry regarding the earthquake and tsunami of December 21, 1812, with the following item on the tsunami stated as follows:

"*P. Gil reported that there was a huge earthquake wave at sea. A stick with a pendant ball was set up at the mission (Santa Barbara), and that the ball vibrated continuously for eight days, and later at intervals for fifteen days. A ship at Refugio was carried up a canyon by the wave and returned to the sea. "*

According to Bancroft's History of California, P. Gill was in charge of Mission Santa Barbara until 1813, and according to the records, he was born on May 1, 1773 and died December 1833.

An item in a San Francisco newspaper stated that:

"*Senora Juana Priones relates that in 1812, the earthquakes were so severe as to cause tidal waves which covered the ground where the plaza now is. "*

Also, under the heading, "1812 September, October, or December ? Sunday? " appears a report credited to J.B. Trask's register of earthquakes in California from 1800 to 1863, stating :

"A Spanish ship anchored 38 miles from Santa Barbara was injured by the shock. "

1F. Tsunami Effects at Gaviota Canyon

Gaviota Canyon is not far from Lompoc, California. It is located at the northwestern end of the Santa Barbara Channel. At the time of the 1812 earthquakes, the coast along the northwestern shore of the Santa Barbara Channel was part of the Rancho del Refugio, a tract of ranch land that had been given to the first commandante of the Santa Barbara Presidio, upon the commandante's retirement. It was a favorite place for American smugglers to trade their goods for otter pelts. These American smuggling ships traveled between the Spanish-controlled coast of southern and central California, the Russian-controlled coasts of Alaska and northern California, and the Hawaiian Islands (then known as the Sandwich Islands).

There is a report of a tsunami at Gaviota Canyon (San Francisco Bulletin, March 16, 1864)

A Boston ship, the Thomas Newland, known before as the"Charon", commanded by Capt. Isaac Whittemore, was lying off anchorage, not far from the Gaviota Pass, Santa Barbara County, when the sea was seen to retire all at once and return in an immense wave, which came roaring and plunging back, tearing over the beach fit to crack everything to pieces. This wave penetrated the low lands of the gulches a mile from the shore, forming one of the most terrific sights possible to conceive. That old ship, then under the name "Charon", afterwards got 1,800 otter skins to the Sandwich Islands (Hawaiian Islands), and landed them, too; but a few days afterwards she was captured by the English man-o-war Cherub and taken as a prize to London".

1G. The 1812 Earthquake and Tsunami at Santa Rosa Island

One of the last outposts for the Chumash Indians was Santa Rosa Island which the Chumash called Mascui. At the time of the 1812 earthquakes, the Franciscan priests were trying to convince the remaining Chumash Indians to relocate to the missions on the mainland. When the 1812 tsunami at Santa Rosa caused the waters to recede several hundred yards from the island, the Indians became fearful that the island was about to be engulfed, so they abandoned totally their villages. They rowed out to in their oceangoing canoes to the mainland and settled in bands of three or four hundred at the several missions in the area. The Chumash Indians who moved to the missions did not fare well, many of them succumbing to European diseases. (H. W. Henshaw, quoted in Anthropological Records, California Linguistic Records, v. 15, no. 2)

1H. Conflicts of Historical Accounts on the 1812 Tsunami Event(s)

Obviously, there was some confusion in the literature about the dating of the 1812 earthquakes, but it is assumed that this account relates to the December 21, 1812, earthquake. Another interesting account of the 1812 tsunami appears in a 1921 paper entitled, "Early Records of Earthquakes in Southern California" by Ford A. Carpenter, which had been compiled from the records of the "mission fathers" and from Englehardt's Franciscans in California. This paper gives a lengthy account of the 1812 earthquakes in

Southern California with one item of interest, related to San Buenaventura, during the earthquake of 21 December 1812.

"The whole mission site appeared to settle, and the fear of being engulfed by the sea, drove all away to San Joaquin in Santa Anna, where they remained until April, 1813. "

Another account in a 1960 paper, "California Earthquakes" by Harry O. Wood states that;

"The sea wave at Refugio and the strong shock experienced by the ship 38 miles from Santa Barbara point emphatically to an earthquake of great energy having a submarine origin. "

There is also another item dated 1812, in the San Francisco papers relating to the origin of the earthquake and the tsunami. It reads:

"Severe shocks with tidal waves. Tidal waves from the great shock in the south entered San Francisco Bay, and washed over the sides of the plaza at Point Arena. The San Joaquin segment of the San Andreas Fault, or the Hayward Fault are the more probable places of origin for these earthquakes. Mention of tidal waves makes the San Andreas Fault the more probable source in this instance. "

If this is true or not, is not known, but it is doubtful that the earthquake that produced the largest tsunami in California had its origin on land where the Hayward Fault was. Suggestions have been made in the literature that this is a possibly mislocated report of December 21 waves at Santa Barbara, while others have claimed that the waves observed in 1812 in San Francisco originated from a different quake on a fault across the San Francisco Bay.

Review of additional references shows extensive descriptions of the earthquake of 1812 at Santa Barbara, but little information relating to the tsunami. Various references and accounts of these events can be found, but these descriptions are somewhat unclear as to the size of the tsunami in Southern California.

Bancroft's History of California documents the 1812 - 1813 and the 1956 translation of the manuscript of Angustias De Li Guerra Ord, entitled "Occurrences in Hispanic California as related by Mrs. James L. Ord to Thomas Savage for the H. Bancroft Collection in 1878." Mrs. Ord was the daughter of Don Jose De La Guerray Norieja, who replaced Jose Arguello as Commandant of Santa Barbara Presidio in the autumn of 1815. She had been borne on the 11th of June of the same year. In this account she relates:

"When I went to the north in 1833, several of the northern missions were in charge of Fernandinos namely, San Louis Obisbo and Padre Louis Gil Taboada (a Mexican by birth, but very Spanish in sentiments). In speaking to Padre Louis Gil Toboada, he told me that in 1812 there had been very strong earthquakes at Santa Barbara while he was there. That on the eighth of December while at the Presidio, there occurred an earthquake so violent that the sea receded and rose like a high mountain. He, with all the people of the Presidio, went running to the mission chanting supplications to the virgin. I asked him humorously, why he had not gone to see if there was a ship at the foot of the mountain of water. He also

assured me that they had placed a pole with the ball to it. It was fastened to the ground where the air would not move it, and it was in continuous motion for eight days. After eight days the ball was still for two or three hours and then started to move again, and this lasted for about 15 days. "

Obviously, this account throws more confusion because the date is given as 8 December. This account would indicate that two major earthquakes occurred on 8 and 21 December, both producing large tsunamis.

John Boardman Trask, a medical doctor, who was appointed President of the California Academy of Sciences in 1864, gave the following description of the tsunami at Santa Barbara in a paper he presented on the history of the 1812 earthquake as obtained from accounts of native inhabitants of the coast.

" The sea was observed to recede from the shore during the continuance of the shocks, and left the latter dry for a considerable distance, when it returned in five or six heavy rollers, which overflowed the plain on which Santa Barbara is built. Inhabitants saw the recession of the sea and, being aware of the danger on its return, fled to the adjoining hills near the town to escape the probable deluge. The sea on its return flowed inland a little more than a half of a mile, and reached the lower part of town, doing but trifling damage destroying three small adobe buildings."

In the same paper, Trask, making reference to a writer unknown to him, quotes him and adds this account.

" The sea was seen to retire all at once, and return in an immense wave, which came roaring and plunging back over the beach. This wave penetrated the lowlands and gulches a mile from the shore, forming one of the most terrific sights possible to conceive. "

2. SEISMIC FAULTS IN THE LOS ANGELES AREA

In the vicinity northeast of Los Angeles, along the Transverse ranges, there are a number of other faults, such as the Garlock and Big Pine, and other east-west trending faults that seem to extend into the ocean in the Santa Barbara channel. Both the Garlock and Big Pine faults intersect the San Andreas fault system. Seismic activity on these two faults has been very low within 40 to 50 km of the San Andreas. However, small clusters of earthquake epicenters can be found on either side of their junction with the San Andreas, suggesting higher seismicity.

Closer to Los Angeles, dozens of smaller faults stem from beneath this great metropolis, faults we have already discussed such as the San Jacinto, Cucamonga, and Garlock. Of these faults, the San Jacinto fault has been the most active branch of the San Andreas Fault System with several moderate earthquakes in recent times. Another potentially dangerous fault is the Newport-Inglewood fault. This is a major fault traversing beneath Los Angeles, along which strain is building up. This fault starts in Whittier and continues west, cutting directly below the downtown Los Angeles area.

The existence of about two dozen other “blind” faults in the Los Angeles area is suspected. These faults are characterized as “blind” faults because they have no surface expression or are buried by sediments. A number of such faults may be low-angle thrust faults, running beneath some of the most heavily developed and densely populated neighborhoods of the Los Angeles Metropolitan Area. One of them for example, the Elysian Park fault, is 11 miles long and about 10 miles deep and runs through downtown Los Angeles. Even earthquakes of relatively small magnitude occurring along such blind faults can be extremely destructive because of their proximity to highly populated areas. Geologists search for blind thrust faults throughout southern California by modeling the system of folds and uplifts believed to be produced by slip on these faults.

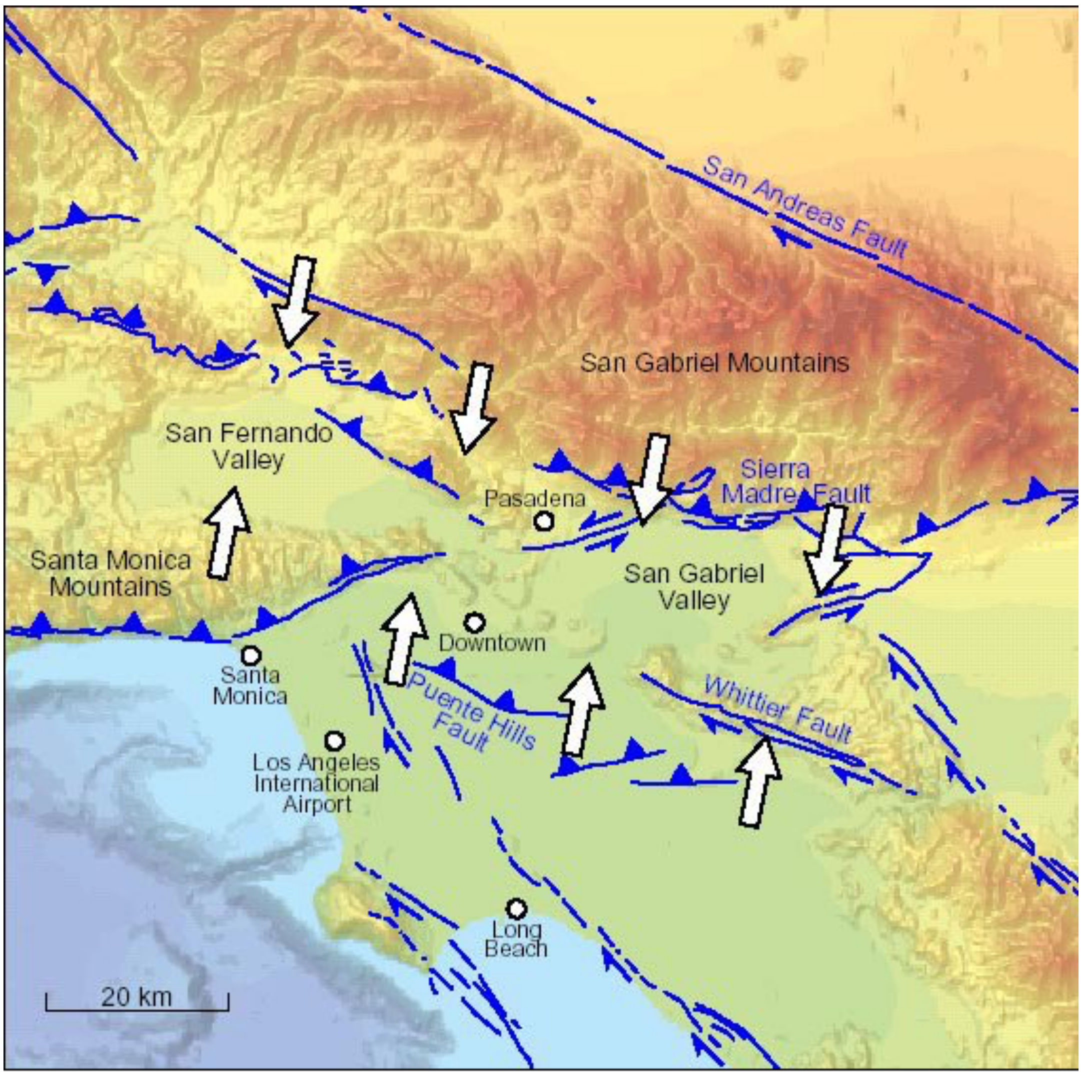

Fig. 3 Map of the Greater Los Angeles area, showing the location of selected major faults and directions of seismic stresses.

2.1 Newport-Inglewood Fault Zone

As we mentioned above, the Newport-Inglewood fault is a major fault traversing beneath Los Angeles. It parallels the San Andreas Fault system and is considered active. It begins a little north of Culver City, continues through the Baldwin Hills, Inglewood, the Dominquez Hills and Signal Hill, reaching the coast along Seal Beach, Sunset Beach, Huntington Beach, and entering the ocean near Newport Beach. Then the fault continues under the ocean and may extend as far south as San Diego.

This fault has been responsible for a number of earthquakes in Southern California, including the destructive Long Beach earthquake of March 10, 1933. There is a strong possibility that an earthquake of moderate size could occur along this fault, which could be even more destructive to Los Angeles than earthquakes occurring along the San Andreas Fault system. Seismic waves from such an earthquake could be quite damaging to structures sitting on top of fairly recent and unconsolidated alluvial soil in the area, most of which is only 3,000 years old.

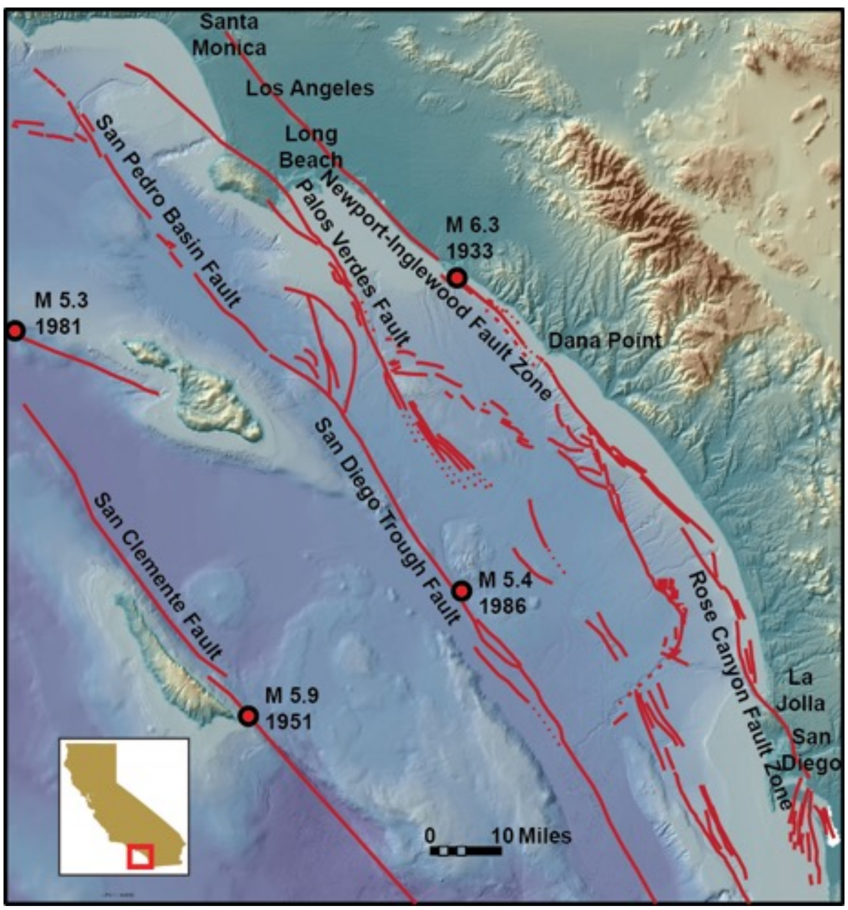

Fig. 4 Offshore faults in Southern California and epicenter of a 1986 earthquake on the San Diego Trough fault and of a 1951 earthquake on the San-Clemente fault (Pacific Coastal and Marine Center, 2022).

As seen in Fig. , the epicenter of the 1933, magnitude 6.3 earthquake was in the offshore underwater segment of the Newport-Inglewood Fault Zone and occurred prior to the construction of the San Onofre nuclear plant, thus the author concluded that a recurrence of such an event on this fault could have had an adverse effect on either the structure or the cooling system of its reactor facility – something which was not adequately considered when the nuclear station was licensed (Parararas-Carayannis, 1974).

2.2 Norwalk Fault

The Norwalk fault is another small, but active fault, situated in a densely populated area southeast of Los Angeles. The fault extends for only about five miles from the general area of Norwalk, Cerritos, and Artesia, through La Mirada and Buena Park to Fullerton. Numerous small earthquakes have occurred along the Norwalk fault. The most notable is a magnitude 4.7 event, which caused damage in the Whittier area.

2.3 Whittier Fault

The Whittier fault is considered to be the northern extension of the much longer Elsinore fault. The fault extends along the base of the Puente Hills, beginning in the vicinity of Whittier through the area of La Habra, Brea, Fullerton, Placentia, and Yorba Linda. Because of its proximity to the Norwalk fault, a number of earthquakes in the area have been confused as having occurred on the Whittier. The Whittier fault is composed of a web of faults crossing numerous towns in the area, and there is a strong possibility of a damaging earthquake in the future.

2.4 San Fernando Valley Faults

The Sierra Madre fault zone, and a number of smaller faults listed below, transverse the heavily populated area of the San Fernando Valley and adjacent foothills presenting a significant risk to the area. The San Fernando fault which transverses the valley has two major segments. The Sylmar segment which crosses the heavily populated Sylmar - San Fernando area, and the Tujunga portion which consists of only one or two parallel breaks and extends along the foothills of the San Gabriel Mountains, the Tujunga Valley to the east of San Fernando.

The Northridge Hills Fault is considered to be the most potentially dangerous fault in the area. It extends through the populated region of the valley from the vicinity of Chatsworth to Northridge where it changes into an eastward direction to the east central valley from where it disappears beneath deep alluvium deposits.

Many of these smaller faults in the San Fernando Valley are deeply buried; blind thrust faults that have produced very destructive earthquakes in the past. The 1971 San Fernando and the 1994 Northridge earthquakes are the most recent examples. Both of these destructive earthquakes occurred beneath the San Fernando Valley on a deeply buried blind thrust fault that may be eastern extensions of the Oak Ridge fault system.

2.5 Sierra Madre Fault Zone

The Sierra Madre Fault Zone is one of the major geologic features of the Los Angeles Basin, extending from the base of the San Gabriel Mountains to the northern edge of the San Fernando Valley. The fault zone starts in the vicinity northwest of Altadena, through the foothills of the San Gabriel Mountains and Sierra Madre to Monrovia, Duarte, Azusa, and Glendora. It is believed that the first recorded earthquake of 1769, in California, occurred along this fault.

2.6 San Fernando Fault (Sylmar and Tujunga segments)

The San Fernando fault can be divided into two segments: The Sylmar segment crosses the heavily populated Sylmar - San Fernando area, as a zone of ground breaks up to one mile wide. The Tujunga portion of the San Fernando fault, consists of only one or two parallel breaks and extends along the foothills of the San Gabriel Mountains, the Tujunga Valley to the east of San Fernando. Since 1971, this fault has become the focus of extensive studies because of its location across a major metropolitan region of California.

2.7 Raymond Hill Fault

This is a short fault traversing the area between South Pasadena and Monrovia where it joins the Sierra Madre fault. It extends eastward from the vicinity of South Pasadena in close proximity to San Marino, Temple City, Sierra Madre, and Arcadia. The fault is considered active and potentially dangerous.

2.8 Northridge Hills Fault

The Northridge Hills Fault is considered to be an active and potentially dangerous fault in the San Fernando Valley. It extends through the populated area of the valley from the] vicinity of Chatsworth to Northridge where it changes into an eastward direction to the east central valley, disappearing beneath deep alluvium deposits.

2.9 Elsinore Fault

The Elsinore fault, one of the longest in Southern California, parallels the San Jacinto fault some 20 to 25 miles west, and extends for approximately 150 miles from where the Whittier fault ends in the vicinity of Yorba Linda, through Lake Elsinore, Wildman, Murrieta, Temecula, Palomar Mountain, and Santa Isabel, crossing the Borrego Desert and the Coyote Mountains towards Mexico. A secondary branch of the fault runs through Aguanga, Oak Grove, and Warner's Hot Springs. Few significant earthquakes have occurred on this fault. The Elsinore fault is considered active.

2.10 Imperial Fault

One of the most active faults of the San Jacinto fault system is the Imperial. The fault was first identified by the major earthquake of May 18, 1940, in El Centro (Imperial Valley). Other smaller earthquakes have occurred in recent times, causing little damage, but small displacements along the fault.

2.11 Submarine Faults

A number of earthquakes have been observed in the past, with epicenters in the Santa Barbara channel where water depths can range from up to 2,000 meters. The Santa Barbara channel is one of the more seismic active regions of California, and several major and moderate earthquakes have caused considerable damage to coastal communities in California. A number of destructive earthquakes have occurred, some of them having epicenters offshore. The most important historical earthquakes in the area were those of December 1812, which also produced a destructive local tsunami.

It is difficult to study the existence of these submarine faults with conventional means as only on-shore extensions of submarine faults can be observed. A number of such offshore faults are considered to be active and could pose a potential threat in the future for destructive earthquakes and locally damaging tsunamis.

3. LARGER EARTHQUAKES IN CALIFORNIA FROM 1769 to 2000

Numerous early large earthquakes which occured from 1769 to the year 2000 have been documented in a publication entitled, "Early Records of Earthquakes in Southern California", which is a paper compiled from the records of the "mission fathers" and from Englehardt's Franciscans in California (Carpenter Ford, 1921). Also, stronger earthquakes in California have been documented in publications entitled "Earthquake History of the United Sates from 1882 to 1953 part I, and in part II entitled "Stronger Eartquakes of California and western Nevada" by Heck (Heck/Nicholas Hunter, 1947) and by (Iida EtAl, 1967 a and b). Several other Central California earthquakes of the 1830's were documented (Louderback, 1947), but these would not have been expected to have an impact on the San Onofre nuclear plant because they were distant and not of sufficient magnitude.

3.1 Earthquake of 28 July 1769

The first strong earthquake listed in Spanish records, is an earthquake of great intensity (VII-IX), which affected the Los Angeles region on 28 July 1769, probably near the San Andreas Fault. No real details on this event exist.

3.2 Earthquake of 8 December 1812

This was the first of a series of earthquakes that struck Southern California in December 1812. The Gaspar de Portola Expedition, in camp about 30 miles southeast of Los Angeles center, recorded four violent shocks. Particularly affected was the Santa Barbara region, with extensive damage to San Buena Ventura and Santa Barbara Missions. The strong earthquake that destroyed the church killed forty persons attending church at San Juan Capistrano on December 8, 1812. Many mission buildings were severely damaged there and at San Gabriel. The mission records are not very clear on exact dates. Most authorities speculate, even though the record is very incomplete, that this was a major earthquake and that subsequent earthquakes were strong aftershocks. Based on damage reports, the intensity of the first of the series of earthquakes of December 1812 must have been approximately VIII to IX. The quake probably centered on a submarine fault in the offshore area of Santa Barbara.

3.3 Earthquake of 21 December 1812

This was another of the reported December 1812 earthquakes. It occurred near the Santa Inez fault zone and other related faults of the Santa Barbara region. According to mission records, the quake destroyed the Santa Barbara Mission and the Mission Purisima Concepcion, the latter being located about 10 miles northeast of Point Arguello. An earlier foreshock that occurred at 10:30 a.m., on 21 December caused considerable damage and served as a warning to people who evacuated outdoors. This saved their lives when the main earthquake struck.

Fig. 5 Photograph (1935): Ruins of Mission La Purisima

In addition to the Santa Barbara Mission and the Mission Purissima Concepcion, which were extensively destroyed, the other missions in the region were heavily damaged. At

Santa Ynez Mission, a corner of the church fell and many new homes were destroyed. All roofs were ruined and walls cracked. A new church had to be built. At San Ventura Mission, the tower was wrecked and much of the facade of the church had to be rebuilt. At San Fernando Mission, thirty beams were used to keep the walls from falling. Strong aftershocks continued until February, and aftershocks of lesser magnitude, until April 1813. According to mission records, the earthquake generated a large tsunami along the north coast of the Santa Barbara Channel. Eyewitness accounts on the effects of the earthquake and resulting tsunami, are discussed in detail in a subsequent chapter on tsunamis and the California coast.

3.4 Earthquake of 19 January 1857 - The Great Fort Tejon Earthquake

One of the largest earthquakes to have occurred in the recorded history of California, and the largest in Southern California, was the Fort Tejon earthquake of 1857. In fact, there were two major earthquakes on that day. The first occurred at approximately 6:30 a.m. on Friday, January 19 (Wood, 1955, 1951; Sieh EtAl, 1989). The second, and most powerful shock occurred at 8:33 a.m. (Spall, 1977). It was felt throughout California, from San Francisco and Sacramento in the north, to Fort Yuma in the South. However its intensity was greater in the Fort Tejon area. The violent shock threw down buildings and large trees at the military Fort. It was also severe in Los Angeles, San Francisco, and Sacramento (Agnew, and Sieh, 1978; Earthquake Information Bulletin, 1981).

A total of four other foreshocks occurred earlier with estimated magnitude between five and six near the northwestern extent of the fault rupture of the main shock, in the Parkfield/Cholame area. The main earthquake, with an estimated magnitude of over 8 on the Richter Scale, occurred along a 225-mile segment of the San Andreas fault, that extends from the vicinity of Cholame near Parkville, in Central California, southwards to San Gorgonio Pass, north of Palm Springs. In some locations, the earthquake's surface-fault rupture had a strike slip displacement of as much as 28 feet. The epicenter was in the vicinity of Fort Tejon, on the Tejon Pass through the Tehapachi Mountains (Sieh, 1978a and b).

3.5 Earthquake of 26 March 1872 - The Great Owens Valley Earthquake

This earthquake occurred in Owens Valley, east of the Central Sierra, along the Owens Valley fault of the Sierra - Nevada Fault system on March 26, 1872. This quake is considered to be one of the largest that ever occurred in California, if not the largest. Its felt area and the maximum fault displacements were comparable to the 1857 Fort Tejon and the 1906 San Francisco earthquakes on the San Andreas fault (.

The US Geological Survey assigned it a magnitude of 7.8, but invariably in the literature the magnitude has been estimated to be about 8.3 to 8.4 on the Richter scale. Its effects were felt throughout California, Nevada and several western states. According to reports, the quake stopped clocks and awakened people as far away as San Diego to the south, Red Bluff to the north, and Elko, Nevada, to the east. Intensities of VIII or greater on the Modified Mercalli scale were assigned over an area of about 25,000 square kilometers.

Intensities of IX or larger were assigned to an area of about 5,500 square kilometers. In some areas estimated intensities were reported to be as much as X and XI. Thousands of aftershocks followed the main event, some severe. The largest ground displacements of up to 20 feet in the horizontal direction and up to 23 feet in the vertical direction occurred between Lone Pine and Independence.

The observed faulting involved both dip-slip and right-lateral components of movement. Surface escarpments extended for at least a distance of 160 kilometers - from Haiwee Reservoir, south of Olancha, to Big Pine. Near Owens Lake, numerous depressions formed between fissures in the earth. One area 200 to 300 feet wide sank from 20 to 30 feet forming several long, narrow ponds. Ground cracks were reported from as far north as Bishop. The vertical offsets were smaller, averaging about 1 meter with the downthrown crustal block on the east. The rupture of the 1872 earthquake along the Owens Valley fault was not as great as those caused by the 1857 Fort Tejon (300 kms) or by the 1906 San Francisco (430 kms) earthquakes on the San Andreas fault.

Although the region was sparsely populated at that time, the death toll was considerably high. A total of 60 people lost their lives primarily from the collapse of adobe buildings. 27 of the deaths occurred at Lone Pine, the rest in other parts of Owens Valley. Property damage at Lone Pine was most severe. Of the 59 adobe or stone houses, 52 were completely destroyed. According to reports, all the main buildings in almost every town in Inyo County were leveled by the shock. Even as far away as Indian Wells, 100 kilometers south of Lone Pine, adobe houses sustained cracks. Property loss was estimated at $250,000 (in1872 dollars).

3.6 Earthquake of 11 April 1885

A major earthquake of undetermined magnitude caused property damage in San Luis Obispo and to a lesser extent to Visalia and Monterey.

3.7 Earthquake of May 1889

A quake in May 1889 caused damage at Antioch and Collinsville.

3.8 Earthquake of 24 February 1892

This was a very large earthquake in the Imperial Valley. Its magnitude was estimated at 7.8. It was felt throughout the area, as far east as Yuma, Arizona, as far north as the coastal area of Santa Barbara and as far south as San Quintin, in Baja California. According to one report the shock was felt at Visalia, Tulare County, about 700 kilometers north of San Quintin. During a 12-hour period following the main shock about 155 aftershocks were felt at Campo. Observers reported that 135 aftershocks were felt as far away as National City, on San Diego Bay. The aftershocks continued to April 1892.

This quake caused extensive damage at the old Carrizo station in San Diego County, where all adobe buildings were destroyed. Chimneys and plaster were reported broken in San Diego. In Paradise Valley, a church and schoolhouse were destroyed. Ground fissures were reported at McCain Valley and Jewel Valley. Rockslides were reported between Campo and Carrizo and at Dulzura and Jewel Valley.

3.9 Earthquake of 19 April 1892

A strong earthquake, centered north of Santa Rosa in the Healdsburg Fault area, destroyed nearly all the brick structures and damaged many frame buildings in Vacaville. Similar damage occurred at Winters and Dixon, two small towns nearby. Ground cracks were reported in the area.

3.10 Earthquake of 30 March 1898

An earthquake along the Calaveras fault with a magnitude of about 6, known as the Mare Island earthquake, caused considerable damage at Vallejo.

3.11 Earthquake of 22 July 1899

A strong earthquake with its epicenter near Cajon Pass shook San Bernardino County with great intensity (up to IX) causing extensive damage in San Bernardino, Highland, and Patton, and some damage in Riverside, Pomona, Pasadena, Redlands, and Los Angeles. Many landslides blocked the roads in Lytel Creek Canyon in Cajon Pass.

3.12 Earthquake of 25 December 1899

On Christmas Day of 1899, a strong earthquake with a magnitude estimated to be between 6.2 and 7 on the Richter scale, occurred on the San Jacinto Fault in the vicinity of Hemet and San Jacinto. This shock caused considerable damage in the area. At nearby Hemet, nearly all the brick buildings were severely damaged, with only two chimneys remaining upright. Six persons lost their lives and several more were injured at Saboba, near San Jacinto. The quake was felt as far south as San Diego. The intensity of this earthquake and has been compared to that which occurred later, on April 1918 (magnitude 6.8) in the same region.

3.13 Earthquake of July 1902

An earthquake in northern Santa Barbara County was responsible for extensive property damage at Lompoc and Los Alamos, the latter being nearer to the epicenter. All houses and chimneys in the area were damaged, according newspaper accounts in the San Francisco Chronicle.

3.14 Earthquake of 29 June 1925

This was one of the better-known earthquakes to affect Santa Barbara in more recent times. The quake occurred in the Santa Barbara Channel, on an extension of the Mesa Fault or the Santa Ynez fault system. It had a magnitude of 6.3 and was particularly damaging in the Santa Barbara business district, which the Mesa fault crosses. On State Street, the principal business section, most buildings sustained significant damage, while several collapsed. One building located on marshy ground withstood the shaking well, but its foundation sank 19 feet. The quake killed 13 people and caused about $8 million damage in Santa Barbara. Deaths and injuries would have been much greater but, fortunately, the quake occurred at 6:42 in the morning when people had not reported for work and when the streets were still not crowded.

3.15 Earthquake of 4 November 1927

A large earthquake with a magnitude of 7.5 struck the southwestern corner of Santa Barbara County. Its epicenter was offshore, near Point Arguello, but it was particularly damaging at Surf and inland communities, in the towns of Honda, Santa Maria, Los Alamos and Lompoc (Gawthrop, 1978, 1981; Hanks, 1979, 1981). Earlier, shortly after midnight on the 4th of November, a small earthquake foreshock awakened residents of the coastal community of Casmalia. Another strong foreshock occurred at 3:10, which awakened most of the inhabitants of Lompoc. This foreshock was followed by three other smaller foreshocks within half an hour. At 5:51 in the morning, the main earthquake struck. Damage from the quake was substantial at Lompoc and other communities. The shock wrecked chimneys, shifted a house off its foundation and caused heavy earth and rock slides on steep slopes. Water was reported to spurt from the ground in many places and sand craters formed.

A small tsunami was generated and observed along the coast at the western end of Santa Barbara County. The tsunami was estimated at six feet near Pismo and five feet at Port San Luis. No tsunami damage was reported. Small tsunami waves of a few inches were recorded on tide gauge records at San Francisco, La Jolla, Honolulu, and Hilo, Hawaii.

3.16 Earthquake of 20 August 1927

This particular earthquake had its epicenter 30 miles off the coast, northwest of Eureka. It caused little damage in Eureka and Ferndale. Although its magnitude is not known, it had a maximum intensity of VIII on the Modified Mercalli scale.

3.17 Earthquake of 6 June 1932

An earthquake with a magnitude of 6.4 shook Humboldt County and was felt as far north as Coos Bay, Oregon, and south, to San Jose. The earthquake triggered numerous landslides around Humboldt Bay and caused sever damage in Eureka.

3.18 Earthquake of 10 March 1933 - The Long Beach Earthquake

The Long Beach earthquake, as this event became known, was the second most destructive earthquake to strike Southern California up to that time. The quake's epicenter was offshore, southeast of Long Beach near Newport Beach, on the Newport - Inglewood Fault. It occurred at 5:55 p.m. Although its magnitude was relatively small, 6.25 to 6.3, and there was no surface faulting, maximum intensities of VIII to IX were experienced and major damage occurred in the densely populated district from Long Beach to the industrial section south of Los Angeles, where unfavorable geological conditions exist. The quake was destructive at all the coastal cities, particularly at Long Beach. Compton was practically leveled (US. Geological Survey, 1933; Binder, 1952).

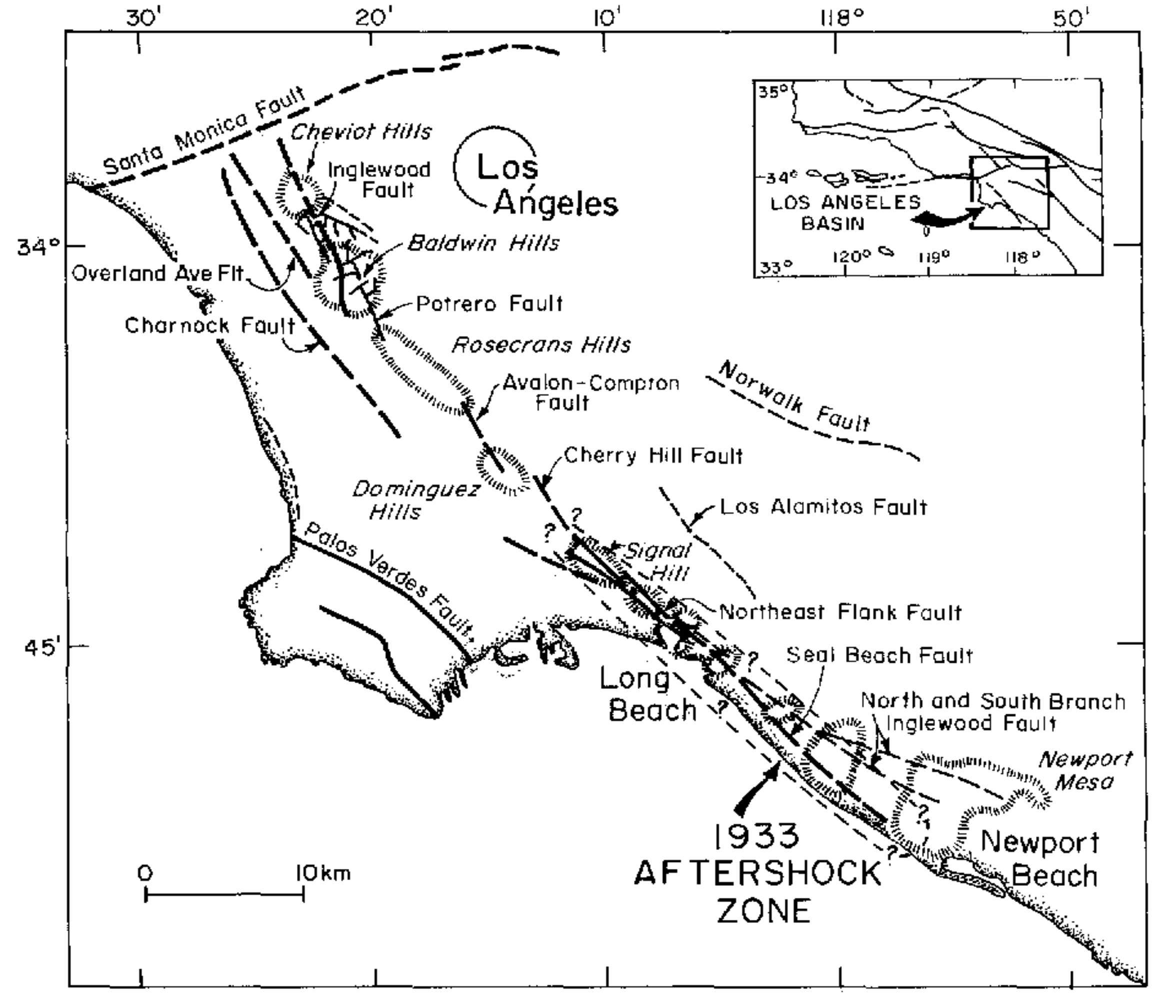

Fig. 6 The Newport-Inglewood fault which runs 47 mikes underneath Los Angeles

About 120 people were killed. largely from the collapse of houses, small buildings or from falling debris. Property damage was extensive and estimated at more than 50 million (in 1933 dollars). Approximately 20,000 dwellings and 2,000 apartments and office buildings, stores, warehouses, factories, churches, and theaters were damaged ranging from cracks to complete destruction. Reinforced concrete buildings fared quite well and sustained little or no structural damage. Most of the damage occurred to brick buildings with unreinforced masonry walls.

At Long Beach, buildings collapsed, tanks fell through roofs, and houses displaced on foundations. School buildings were among those structures most generally and severely damaged. Many school buildings in Long Beach and surrounding areas, built of brick with no reinforcement for lateral forces, were totally destroyed. However, reinforced concrete school buildings survived the quake with no structural damage. Fortunately the earthquake struck when school was not in session, otherwise the loss of life would have been much greater.

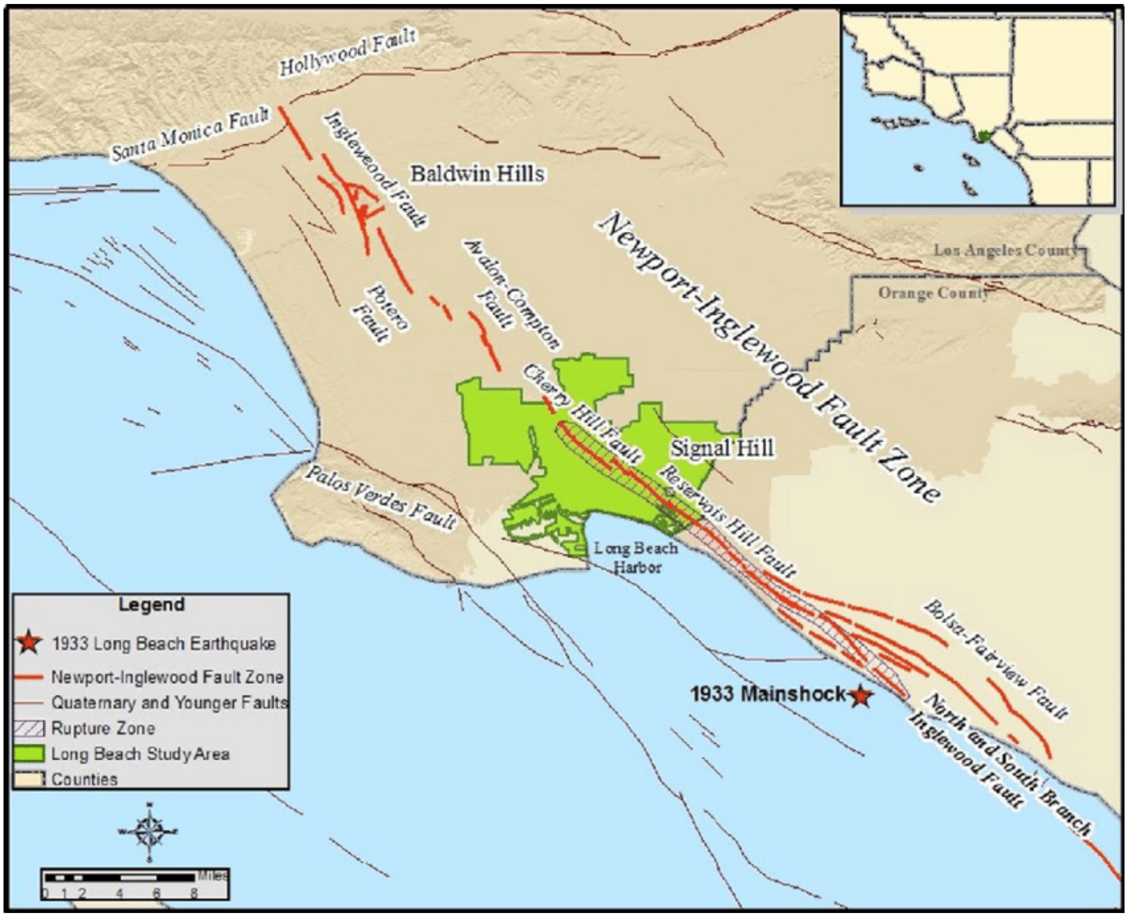

Fig. 7 Epicenter of the 1933 earthquake near the Newport-Inglewood fault

Fig. shows the 1933 earthquake's main epicenter on the Newport-Inglewood fault, as well as its proximity to Long Beach and Los Angeles, and to other faults on land and at sea close to the San Onofre nuclear plant. The reason for the 1933 quake's extreme and disproportionate destruction is attributed to the density of population and to the development of the area without proper earthquake disaster planning. As a direct result of the structural failures of unreinforced masonry schools, a law known as the Field Act was passed on April 10, 1933, requiring earthquake-resistant design and construction for all public schools.

Fig. below is a photograph of destruction of a building by the Long Beach earthquake of 10 March 1933,

Fig. 8 Destruction of building by the Long Beach earthquake of 10 March 1933 (photo; U.S. Geological Survey

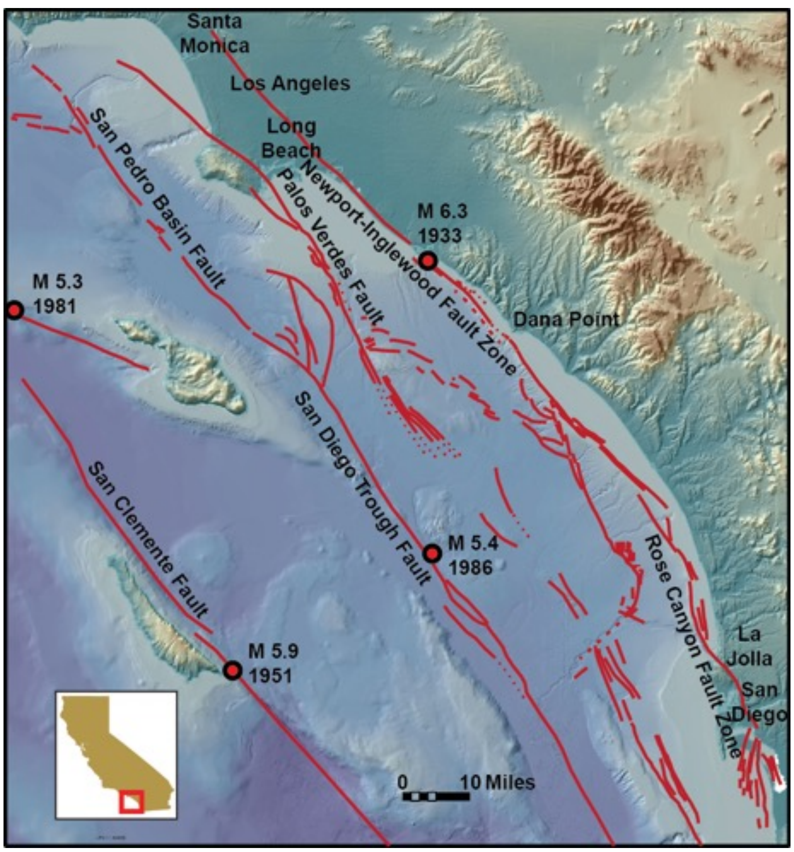

Fig. 9 Offshore Southern California map showing active faults and earthquakes since 1933 with magnitudes 5 or larger.

As shown in Fig, above, detailed views of the seafloor have greatly enhanced the understanding of active faults off Southern California, and have improved hazard assessments for the region. For example, this information contributed to an update of the seismic hazard assessment of the San Onofre Nuclear Generating Station in 2014, and the 2014 National Seismic Hazard Mapping Project, which included faults located entirely offshore for the first time.

3.19 Earthquake of 16 May 1933

This large earthquake along the Hayward fault caused extensive damage to dwellings in Niles and Irvington (Wood. 1933).

3.20 Earthquake of 2 October 1934

A moderate earthquake, with its epicenter near Colma, was responsible for considerable damage in Colma, Daly City, South San Francisco, and the Portola district of San Francisco.

3.21 Earthquake of 18 May 1940

A large earthquake with a magnitude of 7.1 on the Richter scale struck the Imperial Valley. Its epicenter was in the vicinity of El Centro, on the Imperial fault, which is part of the San Andreas Fault system in southern California. The fault rupture was about five miles east of the towns of El Centro, Imperial, and Calexico but overall the shock caused about 40 miles of surface faulting along the Imperial Fault (Trifunac abd Brunem 1970). Damage in all the towns in the area was heavy, and the irrigation system of the Imperial Valley was practically destroyed by displacements of up to 19 feet. At Imperial, 80 percent of the buildings were damaged to some degree. In the business district of Brawley, all structures were damaged, and about 50 percent had to be condemned. This earthquake was the first test of public schools designed to be earthquake resistant after the 1933 Long Beach earthquake. Fifteen such public schools in the area had no apparent damage. The earthquake killed a total of nine people and property damage was estimated at about $6 million.

3.22 Earthquake of 30 June 1941

This earthquake had its epicenter in the Santa Barbara Channel, approximately five miles south of the coast between Santa Barbara and Carpinteria. It was particularly damaging in Santa Barbara.

3.23 Earthquake of 14 November 1941

Another earthquake on the Newport-Inglewood fault zone caused about one million dollars in damage to the towns of Gardena and Torrance.

3.24 Earthquake of 4 December 1948

A major earthquake with a magnitude of about 6.5 occurred in the vicinity of Desert Hot Springs. Maximum intensities of this quake were felt in the Desert Hot Springs-Mecca area. Light damage was reported from the towns of Twenty-Nine Palms and Indio. However, the area was sparsely populated there.

3.25 Earthquake of 21 July 1952 - The Kern County Earthquake

This was the largest earthquake in Southern California since the great earthquakes of 1857 and 1906. Its magnitude was 7.7 on the Richter scale. It occurred along the White Wolf fault in Kern County. Six major aftershocks with magnitude 5.0 or greater occurred on the same day. In the following days and weeks, through September 26, the California Institute of Technology recorded 188 aftershocks of magnitude 4.0 or greater.

The main shock was felt over most of California and in parts of western Arizona and western Nevada at such distant points as Stirling City, California, Phoenix, Arizona, and Gerlach, Nevada. Long-period surface waves from the main shock caused water to splash from swimming pools as far away as Los Angeles, and from pressure tanks on tops of buildings in San Francisco.

Maximum intensity of XI on the Modified Mercalli scale was assigned to a small area southeast of Bealville where the earthquake cracked reinforced concrete tunnels with walls almost half a meter in thickness. In the same area, the shock reduced by about 2.5 meters the distance between the entries to two tunnels and bent the steel rails on both sides. Elsewhere, maximum intensity did not exceed VIII. At Owens Lake, about 160 kilometers from the epicenter, there were reports of shifted salt beds and of brine lines bent into irregular curves shapes.

Ground displacements of up to two feet in a horizontal direction, and up to four feet in a vertical direction occurred for many miles along the White Wolf fault zone. Surface ruptures were reported along the lower slopes of Bear Mountain and in the valley below. The movement indicated that the mountain itself moved upward and to the north. Brick and adobe structures were primarily damaged and to a lesser extent wood-frame buildings. Multistory steel and concrete structures sustained minor damage with the exception of the Kern General Hospital where damage was extensive. Reinforced tunnels with walls 18 inches thick near Bealville were cracked, twisted, and caved in; rails were shifted and bent into S-shaped curves. Near Caliente, reinforced concrete railroad tunnels were demolished. At Tehachapi, Bakersfield, and Arvin, old and poorly built masonry and abode buildings were cracked, and some collapsed. In Los Angeles extensive damage occurred on the nonstructural components of tall buildings. At least one building was damaged in San Diego. Even as far as Las Vegas, Nevada, a building under construction was damaged and required realignment of its structural steel frame. Finally, on August 22, an aftershock Near Bakersfield with magnitude 5.8 killed two people and caused extensive damage to many already weakened buildings and structures.

The death toll was relatively low. A total of twelve people lost their lives, 9 in Tehachapi and three more in other towns. Property damage estimated at $60 million, occurred in much of Southern California but it was particularly concentrated in the Bakersfield area. Although severe, property damage was not nearly as extensive as that of the 1933 Long Beach earthquake. Fig. shows the collapse of a school building in Kern County, California from the 1933 Long Beach strike-slip earhquake on the White Wolf fault.

Fig. 10 Collapse of school building in Kern County, California from the 1933 Long Beach earhquake

3.26 Earthquake of 9 February 1971

This earthquake, with a magnitude of 6.6, was the most destructive event to affect the greater Los Angeles Metropolitan area since the magnitude 6.3 Long Beach Earthquake of 1933 (Heaton, 1982). It struck the populated San Fernando Valley and surrounding areas, causing extremely heavy destruction. Earthquake intensities varied from VII to XI. The quake occurred in the lightly inhabited area in the middle of the San Gabriel (USGS, 1971. In the mountains along the San Fernando fault where most of the energy was released at least 10 miles of surface rupture was observed. Strong ground shaking occurred only at the northeastern end of the valley. The quake was responsible for extensive destruction at the Sylmar Veterans Hospital, where two older buildings completely collapsed, killing 45 people in that locality along. A total of 58 fatalities and approximately 2,000 injuries were reported. A major overpass at the interchange of Interstate 5 and State Route 14 collapsed. Direct damage to buildings and other structures in this suburban Los Angeles area was estimated at more than half a billion dollars (1971 dollars). Because of extensive earthquake damage there was extensive reevaluation and revision of the building codes in the area.

3.27 Earthquake of 1 August 1975

An earthquake measuring 6.0 in magnitude occurred in the vicinity of Palermo, a small community south of Oroville. The quake was felt as far as Fresno, 380 kilometers south of the epicenter. In the immediate area, the quake was reported to have caused about a dozen injuries and approximately six million dollars in damage. This was the largest earthquake to strike California since the disastrous San Fernando earthquake (6.6) of February 9, 1971. The main earthquake shock was preceded by two smaller quakes earlier on that day. Several strong aftershocks with magnitudes greater than 4.0 followed the main shock, and two exceeded magnitude 5.0.

3.28 Imperial Valley Earthquake of 15 October 1979

An earthquake occured earlier on 6 August 1979 in the area of Coyote Lake in California by a larger earthquake on 15 October 1979 - the largest earthquake in California in the past decade, and which occurred on the Imperial fault and northern Baja California, 5 km south of United States-Mexican border, and was felt from Las Vegas, Nevada, to Northern Mexico. The moment-magnitude (M) 6.5 event damaged structures in and near the town of El Centro, in California, was felt from Las Vegas, Nevada to the Pacific Ocean, and was accompanied by surface movement on four other fault zones. The main quake and its aftershocks were distributed primarily along the Imperial and Brawley faults. Extensive surface movement was measured along a 19.3-mile (30 km) segment of the northern section of the Imperial fault and along eight miles of the Brawley fault. Maximum horizontal displacements were measured to be 31 inches near the southern end of the surface rupture, decreasing to 0.6 inches in the northern end (Heaton, 1982).

Fig. 11 Imperial Valley, California Earthquake of October 15, 1979 (USGS)

The earthquake damage was extremely heavy at El Centro. Overall, it caused an estimated $21.1 million in damage and injured 73 people, but no deaths were reported in the United States. The small number of injuries is indeed fortunate, and is no doubt related to the fact that the areas of greatest population and number of manmade structures were not situated in the most strongly shaken area.

The earthquake and its aftershocks occurred in a region that has undergone several similar-size earthquakes in the recent historical past, including the well-known M=7.0 earthquake near El Centro on May 18, 1940. Because of the frequent recurrence of moderately strong earthquakes, this region has been under intensive study for many years by seismologists, geologists, and engineers of the U.S. Geological Survey and other research institutions. Their efforts have included the design and installation of numerous types of seismologic, strong-motion, geodetic, and other earth quake-monitoring instruments, as well as in depth studies of various earthquake-related topics. As a consequence of this preparatory work, the 1979 earthquake provided the seismologic and geologic sciences and the field of earthquake engineering with a wealth of important information, much of it unprecedented.

3.29 Earthquake of 2 May 1983

An earthquake measuring 6.5 on the Richter scale was particularly damaging at Coalinga in Southern California where damage was estimated at approximately thirty-one million dollars (Rymer and Ellsworth, 1990; Stein and King, 1984). This was the most damaging earthquake in California since the San Fernando earthquake of 1971. Damage was most severe to older, unreinforced masonry and older wood-framed structures.

The earthquake was felt as far away as Sacramento, Los Angeles, Carson City, and Las Vegas. At least 6,000 aftershocks were measured in the Coalinga region during the following days and weeks. Six of those had magnitudes greater than 5.0 Surface rupture of about 2 miles with vertical displacement of over 23 inches were measured along the Nunez fault following an aftershock of magnitude 5.2, which occurred, subsequently, on June 11.

3.30 Earthquake of 24 April 1984

A moderate earthquake of magnitude 6.1 occurred along the Calaveras fault east of San Jose. Earthquake damage estimated at seven-point-five million dollars occurred primarily in the southern Santa Clara Valley area near the town of Morgan Hill and the south end of Anderson Reservoir (Bakun EtAl, 1984; Hartzell, and Heaton, 1986).

3.31 Earthquake of 1 October 1987

A strong earthquake, followed by fifteen aftershocks, struck Southern California at 7:42 a.m., killing three people, injuring dozens more, collapsing buildings, touching off fires from ruptured gas lines, toppling walls, and closing freeways. The magnitude of the quake was 6.1 on the Richter scale, and its epicenter was nine miles south-southeast of Pasadena, in the Montebello-South Gate-Downey area on the north end of the Whittier-Elsimore fault.

In Los Angeles, there were at least 24 injuries and two deaths. Forty-six fires were reported from natural gas leaks, 26 structural fires, 36 heart attacks, 14 traffic accidents, and 21 elevators with people stuck in them. In Pasadena, one vacant brick building collapsed. One of the worst hit areas was downtown Whittier, where several buildings collapsed, and cars were crushed by bricks. In Bellflower, 15 miles southeast of downtown Los Angeles, the roof collapsed at Kaiser Permanente Hospital. The quake set off a fire at a small shopping center.

3.32 Earthquake of 10 June 1988

An earthquake of magnitude 5.2 was felt widely across Southern California at 4:06 in the afternoon. The quake had its epicenter on the Garlock fault in a sparsely populated area northwest of Los Angeles. The Garlock fault extends from the south end of Death Valley to an intersection with the San Andreas fault in the general vicinity of Lebec, about 70 miles northeast of Los Angeles. The quake was felt strongly in Lebec and nearby Gozman. It was felt mildly in downtown Los Angeles, and as far north as the San Joaquin Valley. No injuries or damage was reported, but the California Aqueduct was shut down over its entire 440 miles as a result of a power failure at two pumping stations.

3.33 Earthquake of 17 October 1989 - The Loma Prieta Earthquake

This was the strongest earthquake to strike the San Francisco Bay region since the great earthquake of 1906 (Ward and Page, 1989). It was felt over an area of approximately 400,000 square miles, from the California-Oregon border on the north to Los Angeles on the south and to Western Nevada on the east. It occurred at 5:04 in the afternoon (October 18 0004 UTC) and had a magnitude of 7.1. Its epicenter was about 10 miles northeast of the city of Santa Cruz and 60 miles southeast of San Francisco at 37 2.19 North and 121 52.98 West. It was named as the Loma Prieta earthquake, after the highest peak of the Santa Cruz Mountains. The earthquake ruptured a large segment of the San Andreas Fault beneath the Santa Cruz Mountains.

The quake was particularly damaging in the Marina District of San Francisco. Also, severe damage occurred south of San Francisco. Throughout the region homes were shattered. Hardest hit were towns like Watsonville, Los Gatos, Aptos and Davenport, where thousands were left homeless the historic downtown district in Santa Cruz was virtually devastated.

The earthquake resulted in 67 known deaths, 3,757 injuries and left more than 12,000 people homeless. It destroyed 1,018 homes and damaged 23,408 others. Among businesses, 366 were destroyed and 3,530 damaged. The earthquake disrupted transportation, utilities, and communications. It caused over $6 billion in property damage in 10 northern California counties. Since this is one of the most recent of destructive earthquakes to strike California in recent times. Because of the great distance, no potential impact on the San Onofre nuclear plant would be expected.

3.34 Earthquake of 28 June 1991

A strong earthquake rocked Southern California, at 7:43 in the morning, killing one person, injuring 46 and damaging buildings and homes in suburbs east of Los Angeles. The magnitude of the earthquake was 6 on the Richter scale and its epicenter was 7 miles north of suburban Monrovia, beneath the San Gabriel Mountains, on the long-dormant Sierra Madre fault. The tremors were felt 100 miles northwest in Santa Barbara, 225 miles to the east in Las Vegas, and south to the Mexican border. Damage was relatively light because the quake had a shallow depth of about 7 miles beneath the mountains.

The greatest damage confined to the San Gabriel Mountain foothill communities 10 to 20 miles northeast of downtown Los Angeles. Store windows crashed down in Pasadena and part of the facade of a four-story brick apartment building fell onto Colorado Boulevard. In the small town of Sierra Madre at least150 homes and buildings suffered structural damage. In Monrovia 125 homes, buildings and other structures were damaged and 331 chimneys were destroyed. In Arcadia, at least 100 homes sustained some damage. Damage was reported at the Pasadena City Hall and the historic Pasadena Playhouse.

In downtown Los Angeles high rise buildings swayed but no damage was reported. There were about 20 to 30 small aftershocks in the first 90 minutes with many more later. Estimates of damage from the quake were in excess of $20 million. A total of 380 buildings and homes suffered some damage to varying degree from this earthquake, which was the most strongly felt quake in the Los Angeles area since the October l, 1987 earthquake.

3.35 Earthquake of 28 June 1992

A large, 7.3 earthquake struck the Landers area at 11:57:34 UTC. It caused damage in excess of 92 million dollars in the Landers - Yucca Valley area. One person was killed as a result of the earthquake and two others died of heart attacks. More than 400 people were reported injured. The maximum earthquake intensity was IX. The shock was felt throughout southern California, southern Nevada, southern Utah, and Western Arizona and as far east as Denver, Colorado and Albuquerque, New Mexico, and as far north as Boise, Idaho.

Extensive surface rupturing was observed for a distance of 70 kms from Joshua Tree to near Barstow. Horizontal ground displacements were as much as 5.5 meters while vertical displacement were as much as 1.8 meters. Extensive seiching action was reported in lakes as far east as Aurora, Colorado, and Corpus Christi, Texas and as far north as Lake Union, Washington. A strong aftershock with a magnitude of 6.7 struck the same area at 15:05 UTC on the same day.

3.36 Earthquake of 17 January 1994 - The Northridge Earthquake

A moderate earthquake struck the densely populated San Fernando Valley, about 32 km northwest of downtown Los Angeles at 4:30 A.M., Pacific Standard Time (1230 UTC) on Monday, January 17. Its epicenter was located near Northridge along the San Fernando thrust fault at the northern edge of the valley, approximately 100 km to the west and south of the San Andreas. Although the earthquake had a moment magnitude (Mw) of only 6.7, it was very damaging because it struck a well-developed area within the San Fernando Valley with a population of nearly 3 million. Thousands of aftershocks occurred in the next few weeks, some with magnitudes of 4.0 to 5.0, causing additional damage.

This region has been frequently struck by moderate to large earthquakes. The last major, magnitude 6.6, earthquake had struck about 32 km to the northeast on February 9, 1971. However this 1994 quake resulted in far greater damage than the 1971 event, which had released most of its energy in the San Gabriel Mountains. Extremely strong ground motions - among the strongest ever recorded - were responsible for most of this damage. Accelerations in the range of 1.0 g were recorded over a large area. Fortunately, because the earthquake occurred in the early morning and on a holiday, its effects were not as bad as they could have been. The number of fatalities was about the same as in the 1971 quake. A total of 57 people lost their lives and more than 1,500 people were seriously injured.

In terms of financial losses and property damage, this earthquake was one of the worst natural disasters in U.S. history. The quake's intense shaking caused extensive ground liquefaction and triggered many fires. Most of the severe destruction occurred within 16 km of the epicenter area, however significant damage to structures was reported as far away as 77 km. There was extensive damage in Santa Monica, located directly south of the epicenter area; however building damage was widespread throughout the Valley. About 12,500 structures were moderately to severely damaged and thousands of people were left temporarily homeless. Major freeway damage occurred up to 32 km from the epicenter region. Collapses and other severe damage forced closing portions of 11 major roads to downtown Los Angeles. The Santa Monica Freeway (Interstate 10) was badly damaged. As with the 1971 earthquake, the interchange (Interstate 5 and State Route 14) sustained heavy damage. Damage to utilities was significant. For several days after the earthquake, more than 48,500 homes had little or no water, while 9,000 homes and businesses were without electricity and 20,000 more were without gas.

3.37 Earthquake of 1 September 1994

Another earthquake struck the offshore area of Northern California in the vicinity of the Mendocino Fracture zone. This event had and magnitude of 6.9. Its epicenter was close to where earthquakes had struck in 1991 and 1992, thus indicating a continuation of seismic activity and crustal movement along the Mendocino Fracture Zone. The quake occurred at 15:15, on September 1. There were no reports of damage.

3.38 Earthquake of 19 February 1995

The same offshore area of Northern California, west of Eureka was struck again by another earthquake. This event had and magnitude of 6.6. Its epicenter was very close to where earthquakes had struck in 1991, 1992 and as recently as 1 September 1994, thus indicating a continuation of seismic activity and crustal movement along the Mendocino Fracture Zone. The quake occurred at 04:03, on February 19 (UTC). There were no reports of damage.

Following are two tables listing all the California earthquakes with Richter magnitudes of 6 and above and intensity VII and above from 1769 through 1995.

DESTRUCTIVE EARTHQUAKES IN CALIFORNIA

1769 THROUGH 1995 (Based on USGS data)
(MAGNITUDE 6 AND ABOVE - INTENSITY VII AND ABOVE)

Date	Region	Modified Mercalli Intensity	Richter Magnitude
July 28, 1769	Los Angeles Region	(VIII-IX)	
October, 1800	San Juan Bautista Region	VIII	
December 8, 1812	Southern California	VIII-IX	
December 21, 1812	Off Coast of Southern California	X	
June 10, 1836	San Francisco Bay	IX-X	
June, 1838	San Francisco Region	X	
July 10 or 11, 1855	Los Angeles County	XIII	
January 9, 1857	Near Fort Tejon	X-XI	Possibly 8
November 26, 1858	San Jose	VIII	
November 12, 1860	Humboldt Bay	VIII	
July 3, 1861	Near Livermore	VIII	
October 1, 1865	Fort Humboldt-Eureka Area	VII-IX	
October 8, 1865	Santa Cruz Mountains	VII-IX	
October 21, 1868	Hayward	IX-X	
March 26, 1872	Near Lone Pine	X-XI	Possibly 8
April 19, 1892	Vacaville	IX	
April 21, 1892	Winters	X	
April 4, 1893	Northwest of Los Angeles	VIII-IX	
June 20, 1897	Near Hollister	VIII	
March 30, 1898	Vallejo Region		
April 14, 1898	Mendocino Area	VIII-IX	
July 22, 1899	San Bernardino County	VIII	
December 25, 1899	San Jacinto-Hemet Area	IX	
July 27 & 31, 1902	Santa Barbara County	VIII	
April 18, 1906	San Francisco Region	XI	8.25
April 18, 1906	Brawley, Imperial Valley	VIII	6 to 6.9
October 28, 1909	Humboldt County	VIII	6+
January 11, 1915	Los Alamos	VIII	
June 22, 1915	El Centro-Calexico-Mexicali	VIII	6.25
October 7, 1915	Piedmond		
April 21, 1918	San Jacinto-Hemet Area	IX	6.8

Fig Magnitudes, Intensities and Locations of the Large Destructive Earthquakes in California

June 21, 1920	Inglewood	VIII	
March 10, 1922	Cholame Valley	IX	6.5
June 29, 1925	Santa Barbara Area	VIII-IX	6.3
October 22, 1926	Monterey Bay	VIII	6 to 6.9
August 20, 1927	Humboldt Bay	VIII	
November 4, 1927	West of Point Arguello	IX-X	7.5
February 25, 1930	Westmorland	VIII	5.0
March 1, 1930	Brawley	VIII	4.5
June 6, 1932	Humboldt County	VIII	6.4
March 10, 1933	Near Long Beach	IX	6.3
May 16, 1933	Niles-Irvington		
June 7, 1934	Parkfield	VIII	6.0
May 18, 1940	Imperial Valley	X	7.1
June 30, 1941	Gardena-Torrance		
March 15, 1946	North of Walker Pass	VIII	6.25
July 29, 1950	Imperial Valley	VIII	5.5
July 21, 1952	Kern County	XI	7.7
August 22, 1952	Bakersfield	VIII	5.8
April 25, 1954	East of Watsonville	VIII	5.25
December 21, 1954	Eureka	VII	6.6
October 23, 1955	Marinez		
April 8, 1968	Northeast San Diego County	VII	6.5
October 1, 1969	Santa Rosa	VII-VIII	5.7
February 9, 1971	San Fernando	VIII-XI	6.6
August 4, 1975	Oroville		6.0
October 15, 1979	El Centro		6.6
May 2, 1983	Coalinga		6.5
April 24, 1984	East of San Jose		6.1
October 1, 1987	Near Pasadena		6.1
June 10, 1988	Lebec		5.2
June 27, 1988	San Jose		5.0
October 17, 1989	Santa Cruz	VIII-X	7.1
August 16,1991	W. of Crescent City		6.3
August 17, 1991	Punta Gorda		6.2
August 17, 1991	W. of Crescent City		7.1
April 23, 1992	Joshua Tree		6.1
April 25, 1992	Cape Mendocino		7.2
April 16, 1992	Cape Mendocino		6.5
April 26, 1992	Cape Mendocino		6.6
June 28, 1992	Landers		7.3
June 28, 1992	Big Bear		6.2
May 17, 1993	Big Pine		6.1
January 17,1994	Northridge		6.7
September 1,1994	Mendocino Fracture Zone		6.9
February 19, 1995	W. of Eureka		6.6
October 16, 1999	Mojave Desert		7.1

Fig. Magnitudes, Intensities and Locations of the Large Destructive Earthquakes in California

Fig. 12 The San Onofre Nuclear Plant, including units 2 and 3 before completed defueling of the reactor on March 6, 1993, and the dismantlement and decommissioning of SONGS, Unit 1 by 15 December 1998.

CONCLUSIONS

An early study of historic earthquakes and tsunamis, as well as of an extensive air and land field survey of Southern California, was undertaken under contract with the U.S. Nuclear Regulatory Agency (NRC), and the U. S. Army Coastal Engineering Research Center (CERC), primarily in connection with the licencing for the additional Units 2 and 3 added to the original Unit 1 of the San Onofre Nuclear Power Plant near San Clemente in Southern California. During this initial study and subsequently, and in preparation of a book by the author, the study of earthquakes and tsunamis in California was extended for all major faults of the San Andreas fault zone which, although capable of strong earthquakes, cannot generate significant tsunamis. Only earthquakes in the Transverse Ranges, specifically along the seaward extensions in the Santa Barbara Channel and in the offshore area from Point Arguello, can and have generated local tsunamis of any significance, a recurrence of which could have had an impact on the San Onofre plant were considered. The reason for this may be that earthquakes occurring in these regions result in significant vertical displacements of the crust along these faults. Such tectonic displacements are necessary for tsunami generation.

The area offshore of Point Arguello in Southern California has sea-floor features which suggest such displacements, so local tsunamis from this area as well as from the Santa Barbara region, can be expected in the future. It is obvious from the historical accounts that one, and possibly two large tsunamis were generated from two major earthquakes in the Santa Barbara region in December of 1812. The size of these tsunamis may never be known with certainty, and the estimates of 15 feet at Gaviota, 30-35 feet at Santa Barbara, and 15 feet or more at Ventura, seem somewhat exaggerated. Which of the two earthquakes produced the bigger tsunami, or whether indeed there were two separate events, may never be known with certainty, as all the historical accounts are sketchy and ambiguous. Tsunamigenic earthquakes from the Santa Barbara were regarded as being the more significant sources that could have had an adverse impact in Los Angeles and the San Onofre nuclear plant, although the danger to San Onofre no longer exists, with the recent total decommisioning and total dismantling of the facility.

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