Seal Beach Wetlands: A Potential Paleoseismic and/or Tsunami Record for Southern California.

Report for SCEC Award # 14041
Submitted September 11, 2016

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I. Project Overview

A. Abstract

In the box below, describe the project objectives, methodology, and results obtained and their significance. If this work is a continuation of a multi-year SCEC-funded project, please include major research findings for all previous years in the abstract. (Maximum 250 words.)

The Seal Beach wetlands straddle the Newport-Inglewood fault zone within the perimeter of the U.S. Naval Weapons Station Seal Beach. A new paleoenvironmental study on 55 sediment cores collected throughout the wetlands reveals evidence for late Holocene coseismic subsidence events, representing previously unrecognized ecological and socioeconomical hazards along the southern California coastline. We present evidence for the coseismic subsidence events based on detailed sedimentological analyses in two vibracores with well-constrained radiocarbon chronostratigraphy. The cores reveal distinct and consistent changes in stratigraphy, percent total organic matter, grain size, magnetic susceptibility, and diatom and foraminiferal assemblages indicating repeated, rapid subsidence and filling of a small basin. Together, the core data indicate that three subsidence events occurred in the wetlands during the past 2000 calendar years. From these data we suggest a releasing step-over along the Newport-Inglewood fault zone results in the vertical displacement of an approximately 5-km^2 area, consistent with the footprint of an estuary identified in pre-development maps. This study identifies a new seismic hazard in coastal southern California and provides insight to coseismic deformation and earthquake controls on the evolution of the wetlands during the Holocene.

B. SCEC Annual Science Highlights

Each year, the Science Planning Committee reviews and summarizes SCEC research accomplishments, and presents the results to the SCEC community and funding agencies. Rank (in order of preference) the sections in which you would like your project results to appear. Choose up to 3 working groups from below and re-order them according to your preference ranking.

1. Earthquake Geology
2. Earthquake Forecasting and Predictability (EFP)
3. Tectonic Geodesy

C. Exemplary Figure

Select one figure from your project report that best exemplifies the significance of the results. The figure may be used in the SCEC Annual Science Highlights and chosen for the cover of the Annual Meeting Proceedings Volume. In the box below, enter the figure number from the project report, figure caption and figure credits.

Figure 3. Schematic diagram showing the chronological cycle in the Seal Beach wetlands of marine embayment followed by intertidal saltmarsh accretion, earthquake occurrence (coseismic subsidence) and basin formation, infilling with allochthonous sediment, and intertidal saltmarsh accretion.

D. SCEC Science Priorities

In the box below, please list (in rank order) the SCEC priorities this project has achieved. See *https://www.scec.org/research/priorities* for list of SCEC research priorities. *For example: 6a, 6b, 6c*

1a, 4a

E. Intellectual Merit

How does the project contribute to the overall intellectual merit of SCEC? *For example: How does the research contribute to advancing knowledge and understanding in the field and, more specifically, SCEC research objectives? To what extent has the activity developed creative and original concepts?*

This project is one of the first in southern California to evaluate the potential of coast wetland to record an earthquake chronology. We have found evidence that the Seal Beach Wetlands area was a marine embayment ~ 4,000 cal yrs BP. After formation of intertidal marsh, the wetlands abruptly subsided 3 times in the last 2000 years. After each subsidence event rapid infilling occurred and intertidal marsh formed. We have proposed that the wetlands subsided during large magnitude earthquakes on the NIFZ. This is the first concrete geologic record of earthquake activity on the Newport Inglewood Fault Zone, and provides additional constraints on the seismic hazards of southern California.

F. Broader Impacts

How does the project contribute to the broader impacts of SCEC as a whole? *For example: How well has the activity promoted or supported teaching, training, and learning at your institution or across SCEC? If your project included a SCEC intern, what was his/her contribution? How has your project broadened the participation of underrepresented groups? To what extent has the project enhanced the infrastructure for research and education (e.g., facilities, instrumentation, networks, and partnerships)? What are some possible benefits of the activity to society?*

1. Our data suggest that a significant hazard of sudden subsidence may exist for the Seal Beach Wetlands, and the Seal Beach Naval Weapons Station, which stores large numbers of naval weapons including nuclear warheads. Our data suggest that planning for sudden subsidence may be indicated for this installation.
2. Out project has a large educational component. SCEC helped fund 2 completed MS theses and 4 undergraduate theses. Additionally, over 10 additional undergraduate and graduate students assisted with field work and laboratory analyses. Most of these student were woman and/or minorities. Many are currently pursuing advanced degrees.

G. Project Publications

All publications and presentations of the work funded must be entered in the SCEC Publications database. Log in at *http://www.scec.org/user/login* and select the Publications button to enter the SCEC Pubications System. Please either (a) update a publication record you previously submitted or (b) add new publication record(s) as needed. If you have any problems, please email *web@scec.org* for assistance.

Leeper, R.J., Rhodes, B.R., Kirby, M.E., Scharer, K.M., Starratt, S., Hemphill-Haley, E., Bonuso, N., Balmaki, B., Garcia, D., and Creager, D., 2014, Evidence of Coseismic Subsidence Along the Newport-Inglewood Fault Zone During the Late Holocene, presented Southern California Earthquake Center Annual Meeting, Palm Springs, California, September 7-10.

Leeper, R.J., Rhodes, B.R., Kirby, M.E., Scharer, K.M., Starratt, S., Hemphill-Haley, E., Bonuso, N., Balmaki, B., Garcia, D., and Creager, D., 2014, Evidence of Coseismic Subsidence Along the Newport-Inglewood Fault Zone During the Late Holocene, presented at 2014 Annual Meeting, GSA, Vancouver, BC, October 19-22.

Leeper, R.J., Rhodes, B.R., Kirby, M.E., Scharer, K.M., Starratt, S., Hemphill-Haley, E., Bonuso, N., Balmaki, B., Garcia, D., and Creager, D., 2014, Evidence of Coseismic Subsidence Along the Newport-Inglewood Fault Zone During the Late Holocene, presented at 2014 Annual Meeting, AGU, San Francisco, CA., December 15-19.

Leeper, Robert J., Rhodes, Brady P., Kirby, Matthew E., Scharer, Katherine M., Creager, Dlissa O., And Garcia, Dylan J., 2013, Does Evidence of Abrupt Coseismic Subsidence and Tsunami During the Late Holocene Existing Seal Beach Marsh Stratigraphy? Geological Society of America 2013 Annual Meeting, Denver, Co.

Cordova, J., Rhodes, B. P. Kirby, M. E., Bonuso, N, and Leeper, R. J., 2013, A Potential Paleotsunami Shell-Hash layer from the Los Penasquitos Marsh, San Diego County, California. Southern California Earthquake Center 2013 Annual Meeting.

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II. Technical Report

A. Introduction

The effects of coseismic subsidence in coastal wetlands along subduction zones are well known (e.g., Atwater, 1987; Kelsey et al., 2002; Cisternas et al., 2005), and evidence of similar changes in the elevation of coastal wetlands is documented along strike slip faults in northern California (e.g., Knudsen et al., 2002; Koehler et al., 2005). In coastal wetlands, abrupt changes in elevation due to coseismic subsidence are shown to drastically alter depositional environments and ecological communities. For example, depositional environments may shift from muddy organic-rich intertidal sediments to silty-to-sandy lagoonal, or marine sediments; ecological transitions are often reflected by abrupt changes in microfossil assemblages such as diatoms and foraminifera (e.g., Hemphill-Haley, 1995; Atwater and Hemphill-Haley, 1997; Nelson et al., 1996). If these depositional changes are followed by sustained submergence or rapid aggradation and shown to be laterally extensive and occur in zones of active strike-slip faulting, coseismic subsidence is considered the likely mechanism for the subsidence (e.g., Knudsen et al., 2002; Koehler et al., 2005). Here, we evaluate a coastal saltmarsh in southern California that contains multiple buried organic-rich layers, which are common in wetlands that subside coseismically, however, unique when compared to other southern California coastal wetlands (e.g., Scott et al., 2011; Rhodes et al., 2013; Wilson et al., 2014).

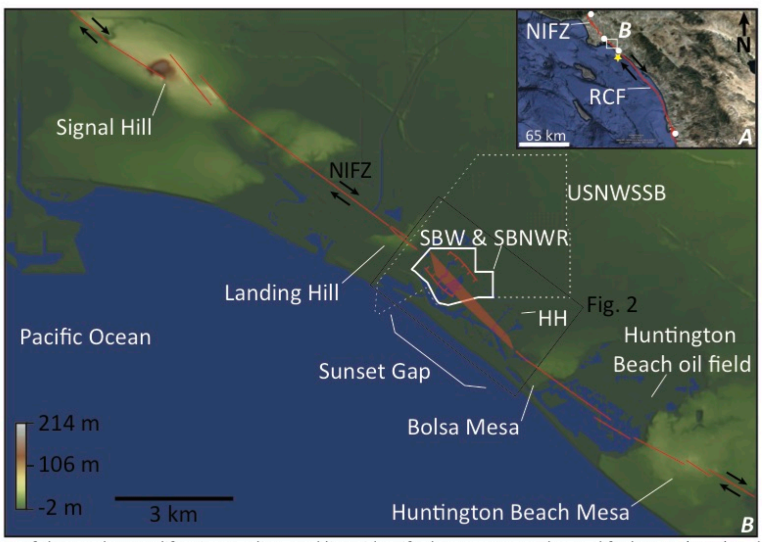


Figure 1. A. Google Earth base map of the southern California coastline. Red lines identify the Newport-Inglewood fault zone (NIFZ) and Rose Canyon Fault (RCF). Fault traces are from the USGS Quaternary Fault and Fold Database of the United States. From north to south, the white circles indicate the location of the cities of Beverly Hills, Long Beach, Newport Beach, and San Diego. Yellow star shows epicenter of the M_L6.3 1933 Long Beach earthquake. B. Location of the Seal Beach wetlands (SBW), Seal Beach National Wildlife Refuge (SBNWR), and the US Naval Weapons Station Seal Beach (USNWSSB) along the NIFZ. Base map is produced from 10 m NED data and shows the structural complexity of the NIFZ, key geographic features, and Huntington Harbor (HH). Arrows show sense of fault movement. Red lines are fault traces from State of California Special Studies Zones Seal Beach Quadrangle, 1986. Red polygon and red lines with hash marks illustrate right step in trace of fault and the zone and pattern of subsidence as discussed in the text.

B. Newport-Inglewood fault zone

The Newport-Inglewood fault zone (NIFZ) is a seismically active structurally complex right-lateral strike-slip fault comprised of en echelon fault strands, oil-bearing anticlines, and subsidiary fault segments exhibiting normal and reverse displacement (e.g., Poland and Piper, 1956; Barrows, 1974; Bryant, 1985; Wright, 1991). The NIFZ is located along the western margin of the Los Angeles basin and extends onshore for ~ 75 km from the City of Beverly Hills in the north to the City of Newport Beach in the south (Figure 1). South of Newport Beach, the fault zone continues offshore roughly parallel to the coastline for ~ 90 km into the San Diego region where it is known as the Rose Canyon Fault (e.g., Barrows, 1974; Treiman, 1999) (Figure 1). The NIFZ/Rose Canyon fault system is one of a series of major strike-slip faults likely kinematically linked along the 300-km long active Coastal Fault Zone, for which earthquake contemporaneity and magnitude is poorly known (Grant and Rockwell, 2002).

Limited data exist regarding the extent and magnitude of late Holocene seismicity on the NIFZ because dense urbanization and a high water table prohibit conventional paleoseismic methods (Grant et al., 1997). Thus, Grant et al. (1997) found evidence for three to five early to middle Holocene earthquakes in Huntington Beach using cone penetrometer testing. In this study, we examine a dense array of cores collected from the Seal Beach wetlands (SBW) and detail paleoenvironmental data on two vibracores.

C. Seal Beach wetlands

The SBW are the only remaining undeveloped part of an estuary known as the Anaheim Bay estuary (ABE), which once covered a large area in the Sunset Gap between Landing Hill and Bolsa Mesa Prior to development, the ABE had large fringing freshwater wetlands, salt flats, and alkali meadows (Chase, 1873; Stein et al., 2007; Grossinger et al., 2011). Reclaimed areas of the ABE proximal to the NIFZ are now occupied by military, municipal and industrial infrastructure including the U.S. Naval Weapons Station Seal Beach, Huntington Harbor, the 965-acre Seal Beach National Wildlife Refuge, and an active oil-extraction operation established in 1954. Consequently, understanding the earthquake history of the NIFZ in the SBW is critical for a large area of coastal southern California where coseismic subsidence could produce significant ecological and socioeconomical hazards.

D. Stratigraphic evidence for coseismic subsidence

In most southern California coastal saltmarshes, the typical deposits consist of thick basal sand overlain by interlayered fine lagoonal sand, silt, and mud, topped by a single, uppermost layer of organic-rich marsh sediment (e.g., Scott et al., 2011; Rhodes et al., 2013; Wilson et al., 2014). This type of stratigraphic sequence is consistent with salt marsh accretion during marine transgressions (e.g., Van Straaten, 1961, Bouma, 1963, Cole and Wahl, 2000). However, in the SBW, Wilson et al. (2014) and Leeper (2016) observed a different stratigraphic sequence; multiple buried organic-rich layers, which are not expected if sea level change were gradual.

Therefore, we examined 55 cores throughout the SBW to investigate the origin or the buried organic-rich layers and reconstruct the paleoenvironmental history of the estuary. In 45 cores along the trend of the NIFZ we observed sharp sedimentological changes from brown-to-gray organic-rich silt to overlying brown organic-poor mica-rich silty sand. To understand the ecological changes associated with the distinct sedimentological transitions observed at similar depths, we paired detailed microfossil analyses with sedimentological data in two vibracores, 02VC and 18VC, which are separated in the wetlands by ~ 650 m.

In 02VC, ecological and sedimentological changes occur at 320 cm, 228-222 cm, and 40 cm depth. For example, a change in the diatom and foraminiferal assemblages is recorded at 228 cm depth where a subtle sedimentological change occurs (Figure 2A). Below 228 cm, intertidal diatoms and foraminifera are preserved in high concentration (Figure 2A). At 227 cm, intertidal diatoms decrease by an order of magnitude, intertidal foraminifera decrease in concentration by nearly 45%, and sparse, mostly poorly preserved fresh-to-fresh brackish (f-fb) diatoms appear suggesting freshwater mixing at the site (Figure 2A). We interpret that at 229 cm, the relatively high organic content determined through loss on ignition (LOI), low magnetic susceptibility (MS), and dominance of intertidal diatoms and foraminifera indicate a salt marsh environment where the sedimentation rate is relatively low and autochthonous intertidal material is accumulating. At 227 cm, the decrease in LOI, increase in silt and MS, and first appearance of f-fb diatoms commensurate with a reduction in intertidal diatoms and foraminifera suggest a shift to an environment where autochthonous and freshwater allochthonous sediment is accumulating (Figure 2A).

This change in depositional environment persists up the core. By 225 cm, f-fb diatoms become more abundant than intertidal diatoms and no intertidal foraminifera are present, LOI and MS are intermediate, and silt concentration continues to increase (Figure 2A). At 222.5 cm there is a distinct depositional contact where the underlying organic-rich silt is buried by a 122.5 cm thick deposit of mica-rich silty sand (Figure 2A). At 222 cm, mostly limited intertidal and f-fb diatoms are present. Further up the core, only sparse f-fb diatoms occur until disappearing from the silty sand completely. Although the thicknesses of the deposits observed in 02VC differ, this sequence from intertidal sediment to sediment that contains mostly poorly preserved f-fb diatoms is also found in 02VC at 320 cm and 40 cm depth.

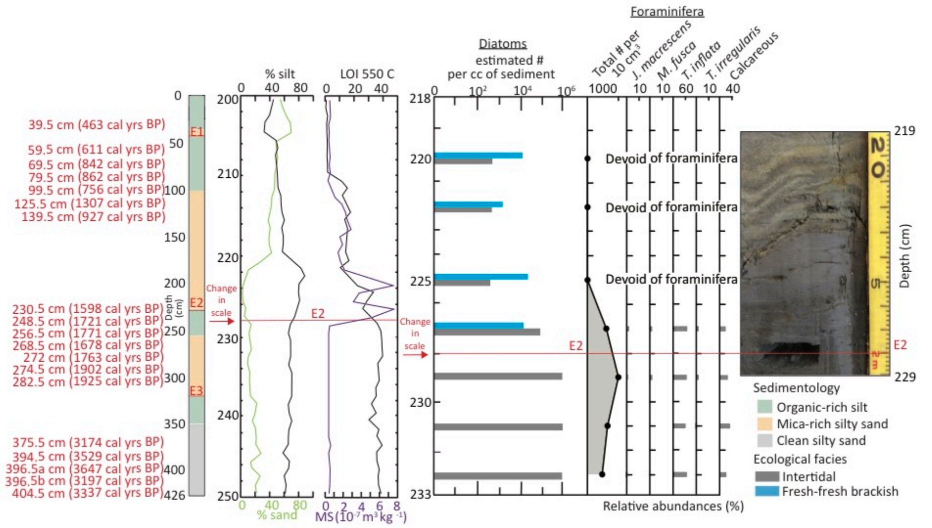


Figure 2. Core log of 02VC with panels on right showing zoom view at different scales of grain size (% silt and % sand), loss-on-ignition @ 550°C (% total organic content), magnetic susceptibility, and microfossil assemblage data. In red are the calibrated radiocarbon ages (median) of samples used in OxCal age model and events E1 - E3 with the E2 horizon shown in detail at 228 cm. Photo on the right shows the sharp depositional contact between the organic-rich silt and overlying organic-poor mica-rich silty sand at 222.5 cm.

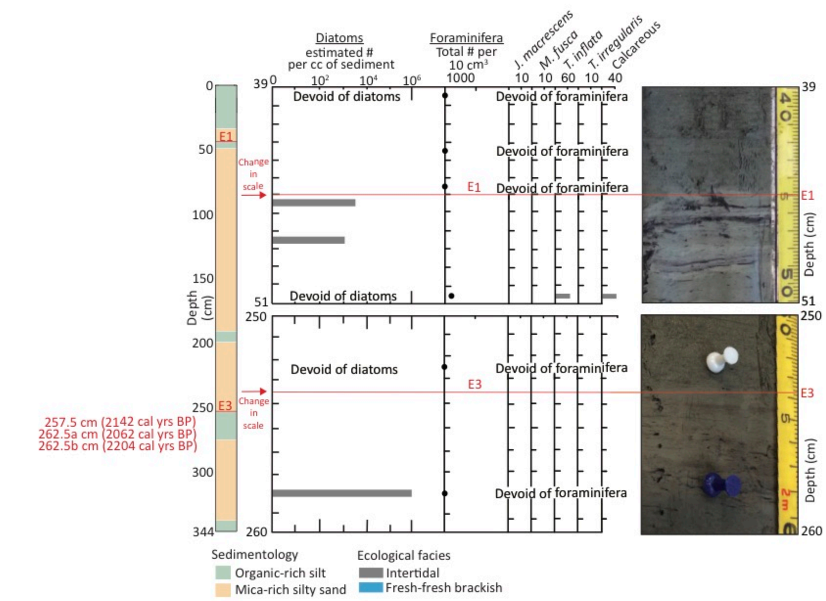


Figure 2a. Core log of 18VC with panels on right showing zoom view at different scale of microfossil assemblage data. In red are the calibrated radiocarbon ages (median) of samples used in OxCal age model and events E1 - E3 with the E1 horizon at 45 cm and E3 horizon at 253.5 cm shown in detail. Photos on the right show the sharp depositional contacts between the organic-rich silt and overlying organic-poor mica-rich silty sand.

Similar ecological and sedimentological transitions occur in vibracore 18VC at 253.5 cm, 190 cm, and 45 cm depth (Figure 2B). For example, at 258 cm depth in organic-rich silt, intertidal diatoms occur in high concentration and no foraminifera are present (Figure 2B). Just above, at 253 cm depth in mica-rich silty sand, no intertidal diatoms or foraminifera are present (Figure 2B). Similarly, from 50.5 cm to 45.5 cm there is a mix of intertidal diatoms and foraminifera preserved in organic-rich silt. This changes at 45 cm to mica-rich silty sand in which no diatoms or foraminifera occur.

In both 02VC and 18VC, we identify three separate events (E1, E2, and E3) where ecological and sedimentological changes occur from organic-rich intertidal silt to overlying allochthonous organic-poor mica-rich silty sand. We interpret that the three events observed in the vibracores are the same based on similar depths of occurrence, and correlate them to similar sharp sedimentological changes observed by Leeper (2016) in 43 other sediment cores collected across the SBW. The three events are observed at comparable depths and correlate over horizontal distances that exceed 1 kmTo determine the timing of the events, we obtained radiocarbon ages on macrophytes, charcoal, and shells from deposits with similar characteristics at comparable depths in vibracores 02VC and 18VC. Calibrated radiocarbon dates indicate that the events occurred 2045-1947 cal BP (E3), 1554-1355 cal BP (E2), and 590-477 cal BP (E1).

In order to understand the transition from intertidal silt to the silty sand containing sparse allochthonous f-fb diatoms we consider in detail 02VC, where we conducted the highest resolution analyses. On both sides of the sharp depositional contact at 222.5 cm, the diatom assemblage consists of a mixture of intertidal and f-fb taxa, and foraminifera no longer occur. Up the core intertidal diatoms disappear and only f-fb diatoms are present. A few of the f-fb diatom valves are well preserved, but most are fractured or broken suggesting that the diatoms were transported into the wetlands after originating nearby. The absence of foraminifera suggests a freshwater source of the sediment. The f-fb diatom taxa that occur are consistent with aerophile and shallow freshwater and alkali environments, possibly similar to those historically mapped fringing the ABE. Thus, the microfossil results suggest that silty sand deposits could be allochthonous freshwater material transported into the site.

We considered if the thick silty sand units could be river deposits from major flooding events preserved above the relic wetland surface as there is historical evidence of major flooding that resulted in >1-m thick deposits of silty sand across the low gradient coastal plains of southern California (e.g., CADWR, 1968; Stein et al., 2007; Grossinger et al., 2011). However, radiocarbon dating indicates that the sediment accumulated in ~300-670 years at an average rate of 2.5 mm/yr, not a single event. This rate is much faster than the late Holocene relative sea level rise determined for southern California (0.8 +/-0.3 mm/yr, Reynolds and Simms, 2015), and requires that subsidence occurred in order to preserve the 122 cm of silty sand and eventually return to intertidal conditions by 100 cm depth. One mechanism for preserving the sediment is to deposit it below sea level, as would occur if the wetland surface rapidly subsided, providing accommodation space and producing a subaqueous environment where the sediment would be preserved (e.g., Knudsen et al., 2002, Koehler et al., 2005).

E. NIFZ structure in the Sunset Gap

The geometry of the NIFZ within the Sunset Gap provides a mechanism that would produce the proposed subsidence events (Figure 1). Extensive oil and water well data in the region show that within Sunset Gap primary aquifers 100-200 m deep are folded into a broad structural low on the northeast side of the fault between Landing Hill and Bolsa Mesa (CADWR, 1968). Upper Miocene and early Pliocene units also step down on the northeast side of the fault at the SBW (Wright, 1991), providing evidence that at a broad scale, both older and more recent deposits show persistent vertical motion along the NIFZ that would isolate the landward side of the fault from sea level during tectonic activity. The fault-zone structure of the NIFZ itself would also tend to accentuate subsidence in center of the SBW due to a small (5°) right step in the fault between Bolsa Mesa and Landing Hill. This step would be resolved as a small pull-apart basin at least 1-km wide in the SBW, similar in scale to a graben northwest of Huntington Beach Mesa where paleoearthquakes are documented (Grant et al., 1997) and a small push-up ridge at Signal Hill located to the NW (Figure 1).

Thus, the three paleo-environmental transitions we observe from intertidal organic-rich silt to overlying allochthonous organic-poor silty sand are consistent with the hypothesis that earthquakes along the NIFZ resulted in coseismic subsidence of the wetlands (e.g., Knudsen et al., 2002; Koehler et al, 2005).

Evidence of a past marine embayment and three coseismic subsidence events

The deepest sedimentary deposit we cored in the SBW (4.26 m depth) is comprised of clean gray organic-poor silty sand, sparse mica, and scattered and clustered shell fragments, and the diatom assemblages consist of taxa that suggest a marine origin (Sup File 1). Most of the diatoms are broken and show erosion or abrasion at the edges, and shells that occur are fragmented and abraded. A bivalve, *Chione californiensis,* preserved in core 02VC, is commonly recognized living in mud flats, estuarine environments and shallow marine settings (e.g., Fitch, 1953). The fragmented and abraded diatoms and shells indicate that the organisms were living in an environment exposed to wave energy. The grain size, presence of marine organisms, and radiocarbon dating indicate that around 3500 cal yrs BP the SBW area was a shallow marine embayment; as sedimentation exceeded sea level rise, the bay became an intertidal marsh approximately 2700 cal yrs BP.

Following formation of the intertidal marsh over the marine embayment, we suggest that coseismic subsidence episodically lowered the wetlands along and NE of the fault zone (Figures 1 and 3). This would instantly provide accommodation space, creating a subaqueous depositional environment with an increased tidal prism and fetch in a newly formed, larger and deeper low-energy basin (e.g., Davis and Fitz-Gerald, 2004). The area would be immediately filled by seawater, and the fringing perennial freshwater wetlands and alkali meadows would be exposed to tidal and wave energy and erosion of the inland area would occur. Mostly intertidal diatoms and foraminifera, but some f-fb diatoms, would accumulate in organic-rich silt preserved above the subsided wetlands surface. Subsequent infilling with organic-poor mica-rich silty sand would occur basin wide through erosion of the fringing freshwater wetland habitats. Foraminifera would be absent, intertidal diatoms would be rare, and mostly broken and poorly preserved f-fb diatoms would become more prevalent as non-marine sediments become dominant. During local fluvial flooding events the basin would accumulate sediment rapidly and no diatoms or foraminifera would be preserved. As the accommodation space created by the coseismic subsidence is filled, the tidal prism is reduced, the subaqueous environment disappears and the system returns to a similar pre-earthquake saltmarsh, and intertidal diatoms and foraminifera would return to prominence.

F. Earthquake magnitude and sequencing

The largest historic earthquake on the NIFZ is the 1933 ($M_L = 6.3$) Long Beach Earthquake, which ruptured a 13-16 km long section of the fault zone between the cities of Newport Beach and Long Beach and resulted in extensive structural damage in the Los Angeles region and 120 deaths (Wood, 1933; Hauksson and Gross, 1991) (Figure 1). There was no surface rupture mapped during field investigations following the 1933 earthquake, although liquefaction and lateral spreading were observed (Wood, 1933; Barrows, 1974; Bryant, 1988). Cracking was reported "along and near the structural [fault] zone" in the SBW (Wright, 1991) but we observe no evidence of the 1933 earthquake in the cores, consistent with minimal land-level changes during this moderate sized earthquake. Hauksson and Gross (1991) estimate that horizontal displacements for this event were 85-120 cm at seismogenic depths.

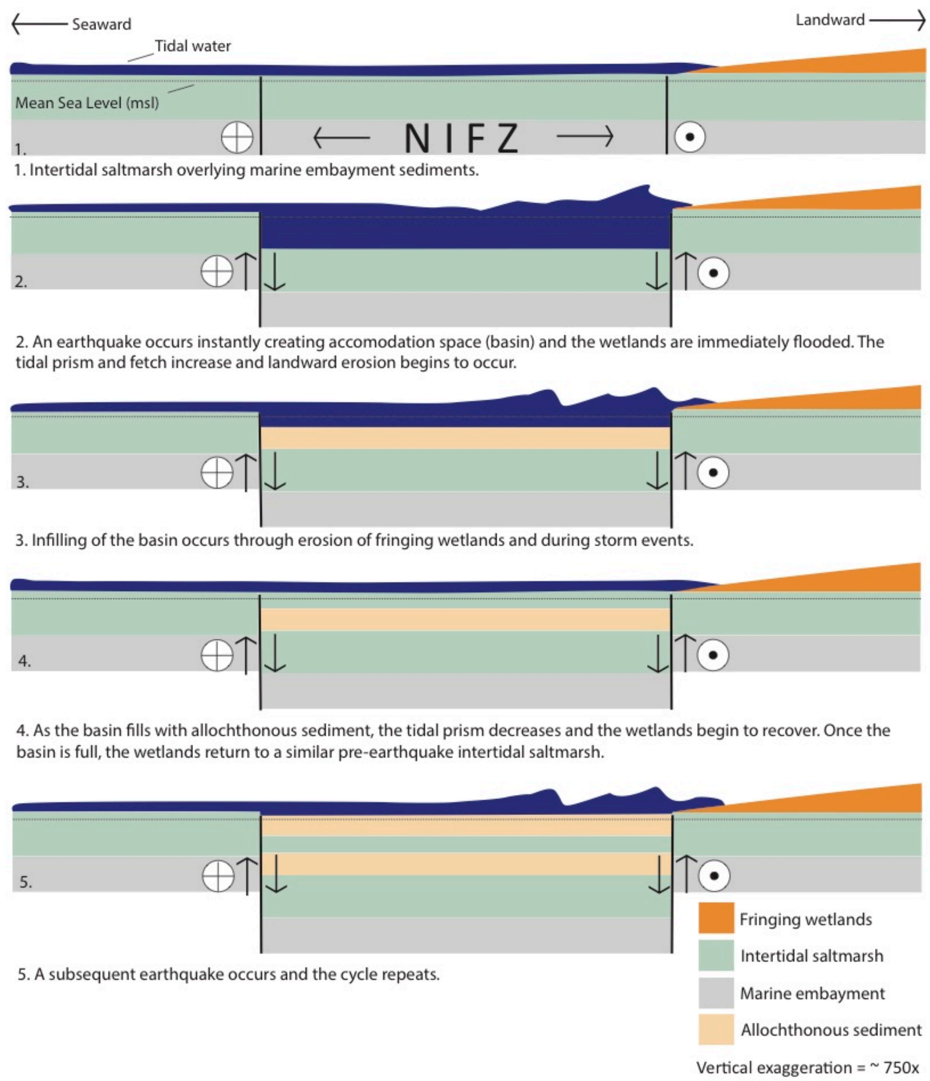
The thicknesses of the silty sand deposits above the event horizons in 02VC and 18VC suggests that the average subsidence during these paleoearthquakes is ~62 cm (Figures 2A and B) and is deepest in the center of the wetlands (Leeper, 2016). We do not have an estimate for the horizontal displacement of the paleoearthquakes, but can use the M_L6.3 historic earthquake as a minimum estimate, since that earthquake was not associated with any subsidence. Sahakian (2015) improved characterization of step overs along the Rose Canyon Fault, showing that the fault system could rupture in single events between the regions of San Diego and Newport Beach, yielding large magnitude (M7.5) earthquakes. The most recent (E1) and penultimate (E2) earthquakes identified in the SBW are contemporaneous with two surface-rupturing earthquakes documented along the Rose Canyon Fault (e.g., Rockwell and Murbach, 1999; Grant and Rockwell, 2002; SCE, 2012). Rockwell and Murbach (1999) determine that about 3 m of slip occurred during the earthquake along the Rose Canyon Fault dated to 491-241 cal BP. Using empirical scaling relationships of Wesnousky (2008) and assuming that 3 m was the average displacement, this earthquake could have produced a 225-km long rupture that could have extended north to the SBW exceeding M_w7.6. Alternatively, considering dating limitations and Coulomb modeling by Sahakian (2015), E1 and E2 could represent the northernmost ruptures of a sequence of intermediate sized earthquakes that sequentially ruptured up the coast (Grant and Rockwell. 2002).

The only long-term estimate of paleoearthquake recurrence for the NIFZ is from near the Huntington Beach oil field, where Grant et al. (1997) used continuous cone penetrometer borings to locate offsets in stratigraphic units in a small graben on the NIFZ (Figure 1). They interpret five early to middle Holocene earthquakes and weak evidence of a sixth, late Holocene earthquake. Of this record, only the youngest earthquake near the Huntington Beach oil field could be correlative with the events in SBW. The absence of the SBW paleoearthquakes in the study near the Huntington Beach oil field is likely explained by low sedimentation rates in the late Holocene, which would limit preservation of any offsets and/or lateral variations in the youngest units, preventing detailed correlation required to identify faulting events (Grant et al., 1997). In combination, the SBW and Huntington Beach oil field events suggest that about 8 large earthquakes have occurred on the NIFZ since 11.7 ka, for an average interval of 1600 years.

G. A new understanding of SBW evolution, coseismic deformation, and earthquake hazards for southern California

We present paleoenvironmental evidence that the SBW area was a marine embayment ~ 4,000 cal yrs BP. After formation of intertidal marsh, the wetlands abruptly subsided three times in the last 2000 years. After each subsidence event rapid infilling occurred and intertidal marsh formed. We propose that the wetlands subsided during large magnitude earthquakes on the NIFZ. The NIFZ has a small extensional step in the area of the SBW and has long-term, down on the northeast displacement, consistent with recurring coseismic subsidence of the wetlands. It is possible that the entire reclaimed area of the ABE is related to coseismic deformation along the NIFZ. Coseismic subsidence of 13 cm and up to as much as 122 cm may only occur during large-magnitude (>M 7) earthquakes.

Two of three large magnitude earthquakes recorded in the SBW are contemporaneous with two large magnitude earthquakes that occurred along the Rose Canyon Fault in San Diego (e.g., Rockwell and Murbach, 1999; Grant and Rockwell, 2002; SCE, 2012). Thus, it is possible that the earthquakes recorded in the SBW may be the northern extent of a M7.6+ rupture involving the Rose Canyon Fault. If the two paleoearthquakes recorded in the SBW and along the Rose Canyon Fault are the same, the average interval for large magnitude surface-rupturing earthquakes along the Newport-Inglewood/Rose Canyon Fault system is ~750 years. Future earthquakes that result in abrupt subsidence of the SBW may present serious hazards to the U.S. Naval Weapons Station Seal Beach, Seal Beach National Wildlife Refuge, Huntington Harbor, and southern California coastal communities.



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