This manuscript is titled **A New Fault Model for the 1933 Long Beach Earthquake, Long Beach Area, Southern California**. The authors are Dan Gish (dgish@3dseismicsolutions.com) and Steve Boljen (sboljen@3dseismicsolutions.com). This manuscript has been submitted for review to *Seismica*.

The manuscript is undergoing peer review and has yet to be formally accepted for publication. Subsequent versions of this manuscript may have slightly different content.

If accepted, the final version of this manuscript will be available via the 'Peer-reviewed Publication DOI' link on the right-hand side of this webpage.

Please feel free to contact any of the authors; we welcome feedback.

A New Fault Model for the 1933 Long Beach Earthquake, Long Beach Area, Southern California

Dan Gish[1], Steve Boljen[2]

[1] 3D Seismic Solutions, 811 Birchwood Circle, Council Bluffs, IA 51503

[2] 3D Seismic Solutions, 316 Silver Creek Landing Road, Peletier, NC 28584

Corresponding Author: sboljen@3dseismicsolutions.com

Abstract

Newly identified thrust faults and their corresponding thrust sheets, combined with recent micro-earthquake epicenters, better explain anomalous rupture data observed during the 1933 Long Beach Earthquake than previous models based exclusively on Newport-Inglewood Fault Zone strike-slip faulting. A high-quality 45 km^2 3D seismic dataset was recorded in 2017, centered along the Seal Beach Anticline, providing direct confirmation of a much more complex system of previously unrecognized thrust faults and cross faults encompassing the east flank of Wilmington Anticline, Seal Beach Anticline, and Los Alamitos Anticline, extending onshore at least 6 miles into the Los Angeles Basin. Additionally, more than 1200 micro-earthquakes recorded by a dense seismic network during 2017 have been located several miles to either side of the NIFZ and correlate with the newly identified thrust sheets and areas of recent deformation, indicating the faults are active. Based on this new fault model, energy propagation from the 1933 Earthquake

appears to have transitioned from essentially pure horizontal strike-slip displacement along the NIFZ at its southern epicenter to high vertical-component transpressional displacement upon encountering the Garden Grove Fault – Coastal Fault thrust salient at the southern end of Seal Beach Anticline near Seal Beach Naval Weapons Station.

Non-Technical Summary

Newly identified thrust faults combined with recent micro-earthquake epicenters better explain the anomalous and extreme surface damage observed during the 1933 Long Beach Earthquake. Previous studies have attributed the earthquake's damage exclusively to the Newport-Inglewood Fault Zone strike-slip movement. A high-quality 45 km^2 3D seismic dataset that was recorded in 2017 provides confirmation of a much more complex system of previously unrecognized thrust faults and cross faults encompassing the Long Beach-Seal Beach area. Additionally, more than 1200 micro-earthquakes recorded by the dense seismic network, located several miles to either side of the Newport-Inglewood Fault Zone, have been incorporated into the database and correlate with the newly identified thrust sheets and areas of recent deformation, indicating the thrust faults are active. The Alquist-Priolo Act (enacted in 1972 and revised multiple times since) authorizes ongoing investigations to identify potential fault zones that may reactivate and harm existing urban centers. This study has identified the main faults responsible, not the Newport-Inglewood Fault Zone, for the widespread destruction resulting from the 1933 Long Beach earthquake and provides evidence that these newly discovered faults are currently active.

1. Introduction

The Magnitude 6.4 1933 Long Beach Earthquake, one of the most devastating earthquakes to hit coastal California in recorded history, historically has presented a conundrum to geoscientists, civil engineers, and legislators who have attempted to explain and model the extreme earthquake parameters, design appropriate infrastructure guidelines, and legislate future risk policies for expanding urban developments. The epicenter for the initial 1933 event has been determined to have initiated a few miles offshore from Huntington Beach as "pure dextral" strike slip displacement along a near vertical plane with a dip of 80 degrees, striking northwest at 315 degrees, which subsequently propagated northwest in at least two distinct sub-events along the Newport-Englewood Fault Zone (NIFZ) for approximately 8-10 miles (13-16 km), before terminating near Signal Hill Anticline (Haucksson and Gross,1991; Hough and Graves,2020). Interestingly, epicenters of the aftershock sequence were determined to lie within a region roughly 9-11 miles (15-18 km) wide, rather than being tightly focused along the NIFZ surface location as might be expected, most of which were located east of the NIFZ.

Unusually extreme surface damage occurred within the Long Beach area, famously evidenced by the collapse of 70 brick school buildings and damage to 50 others, ultimately resulting in 120 fatalities. Shortly thereafter, legislation was passed in the form of the Field Act to investigate the cause of the devastation and make recommendations to minimize future occurrences. Today, the Alquist-Priolo Act (enacted in 1972 and revised multiple times since) authorizes ongoing investigations to identify potential fault zones that may reactivate and harm existing urban centers. One of the primary goals of these studies has been to better identify and quantify the enigmatic NIFZ, assumed to be a right-lateral strike slip fault zone historically associated with the 1933 Long Beach Earthquake, and believed to extend for 47 miles (75.6 km) through the Los Angeles Basin (Haucksson and Gross,1991).

Primarily based on unconstrained log correlations from antique oil wells drilled along the Seal Beach Anticline (SBA), numerous investigators have assigned fault plane interpretations to the narrowly clustered well logs and to a few surface exposures also assumed to be NIFZ faults, and have extrapolated those correlations for miles along a NW-SE orientation and vertically nearly 14,000 feet from the surface into basement. When the fault correlations mandate, the NIFZ has been depicted as having as many as five fault splays at some locations along trend. Still today, modern fault maps of the Seal Beach segment depict the NIFZ fault zone as a questionable dotted line (California Geological Survey, California Department of Conservation, Seismic Hazards Program, Earthstar Geographics).

However, significant problems arise with NIFZ-focused, strike-slip interpretations along the SBA because of many conflicting observations, for example:

1. No surface rupture from the M6.4 event was observed along the SBA trend corresponding to the mapped NIFZ surface trace.

2. Aftershocks following the 1933 event occurred predominantly onshore east of SBA over a width of approximately 10 miles (17 km) and do not align along a linear, near-vertical NIFZ trend, nor do they align with the 1933 Long Beach Earthquake epicenter for the main event (Haucksson and Gross,1991).
3. During 2017, ~1200 micro-earthquake epicenters recorded by a dense seismometer array (Figure 1) were detected along northwest-southeast trending clusters on both flanks of the NIFZ, but not along the NIFZ itself (Yang and Clayton,2021).
4. Extensive deformation of low depositional energy Pleistocene sediments are apparent on 3D seismic data, on either side of SBA, miles away from the NIFZ. These deformation areas correspond to previously unrecognized thrust faults, and align with the micro-earthquake trends, but not with the NIFZ.
5. Large cross faults repeatedly offset the fold axis of the SBA, resulting in compartmentalized and rotated fault blocks along the SBA axial strike, as documented by well logs, production data, and 3D seismic data, and are analogous to adjacent cross-faults documented offshore at Wilmington Anticline (Ishutov,2013, Clark,1987, Wolfe, 2019). These large cross-faults which extend for miles into the offshore are not easily explained by pure strike-slip tectonics.
6. The strong motion sensor at Long Beach (LBPU) recorded abnormally high vertical acceleration with respect to the horizontal acceleration and are inconsistent with horizontally-dominant strike-slip displacements that would be expected from the NIFZ, and as predicted by recent NIFZ simulation models (Hough and Graves,2020).

7. Sediment cores taken within the Seal Beach Wetlands along the extrapolated NIFZ surface trace documented recurring changes of depositional environments and faunal communities associated with abrupt vertical elevation changes resulting from coseismic events (Lepper,2017). However, despite the proximity of the cores to the NIFZ, no analogous changes associated with the 1933 Long Beach Earthquake were observed.
8. Modern 3D seismic data along the Seal Beach Anticline (SBA) reveals that faults previously identified from oil well logs as NIFZ faults correlate to a complex sub-set of antithetic faults along the SBA related to the previously unrecognized Garden Grove Fault (GGF), which surfaces approximately 1-1 ½ miles (1.6 – 2.4 km) east of the NIFZ (Biondi,2023). The GGF, an east verging listric thrust fault, is the dominant fault creating and carrying the SBA.
9. The antithetic faults and SBA anticlinal folding terminate at a depth of approximately 5500 feet (1675 m) subsea at the GGF decollement, rather than continuing to basement as predicted by strike-slip theory, and terminate along strike in both directions.

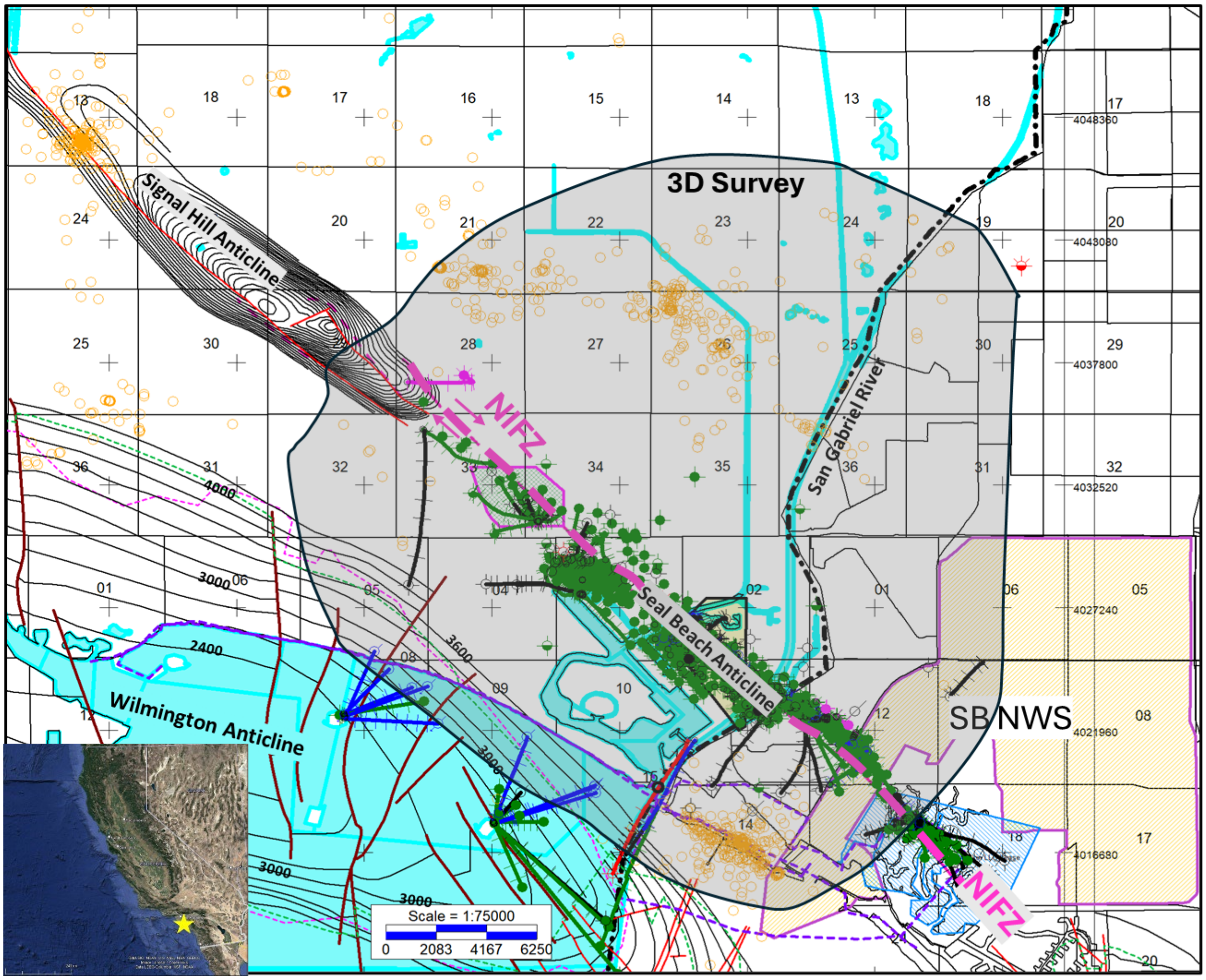

Figure 1. Published structural contours and key faults associated with Wilmington Anticline and Signal Hill Anticline, and oil wells associated with Seal Beach oil fields (green dots). Dotted pink line indicates the currently mapped surface position of the NIFZ. Gold circles represent micro-earthquakes recorded by dense seismic networks. Area encompassed by 2017 3D survey highlighted in gray. Seal Beach Naval Weapons Station (SB NWS) is shown in lower right corner (yellow highlight). Yellow star on inset map indicates study location.

2. Method: Integration of New Datasets

In 2017, a proprietary high resolution 28 square mile (45 square km) 3D survey was acquired centered along the NIFZ and the Seal Beach Anticline, covering the area along strike between the southern end of Signal Hill Anticline and the Seal Beach Naval Weapons

Station, and extending in the dip direction about 1 mile (1.6 km) offshore along the east flank of Wilmington Anticline to approximately six miles (9.7 km) onshore (Figure 1). This high-resolution 3D dataset provides some of the most detailed subsurface information presently available for direct analysis of faults and corresponding deformation, as well as quantifying tectonically related stratigraphic features throughout the Seal Beach trend, and for providing chronostratigraphic control for well log correlations.

Integration of multiple 3D seismic attribute volumes assisted in providing data redundancy and clarity to the interpretations. These multiple attribute volumes included multiple PSTM datasets, enhanced impedance volumes, animated horizontal timeslice volumes, integration of hundreds of oilfield well logs using proprietary log correlations and formation tops tied to the 3D data, historical production data, logs from two new proprietary oil wells, new proprietary check shot velocity surveys, correlations with published structural and subsurface data from Wilmington Field tied along the western edge of the 3D dataset, and with selected subsurface well data associated with the Long Beach oil field. Regional 3D depth conversions were further assisted by proprietary correlations between seismic inversion data and public and proprietary well logs, providing a greater density of lateral and vertical control points to calibrate extensive velocity anisotropy throughout the survey.

The passive 3D seismic dataset, analyzed by Caltech using autocorrelation techniques to identify micro-earthquakes which occurred during the survey acquisition (Figure 1), resulted in identifying more than 1200 high confidence nighttime events (Yang and Clayton,2021). None of the 2017 micro-events registered on the Southern California

Seismic Network (SCSN) because the events occurred below the SCSN detection threshold of M2.5. Geo-located coordinates (X-Y-Z) of the micro-earthquake epicenters using independent velocity models developed by Caltech were incorporated into the depth converted 3D seismic dataset. Epicenter locations were subsequently correlated with faults interpreted on 3D seismic data.

3. Results/Observations

The SBA is carried by the GGF thrust sheet, including dozens of antithetic faults related to recurring deformation of this structure, which terminates immediately north of Recreation Park and along strike to the south near the western edge of the Seal Beach Wetlands, as a doubly terminated anticline (Figures 2 and 3).

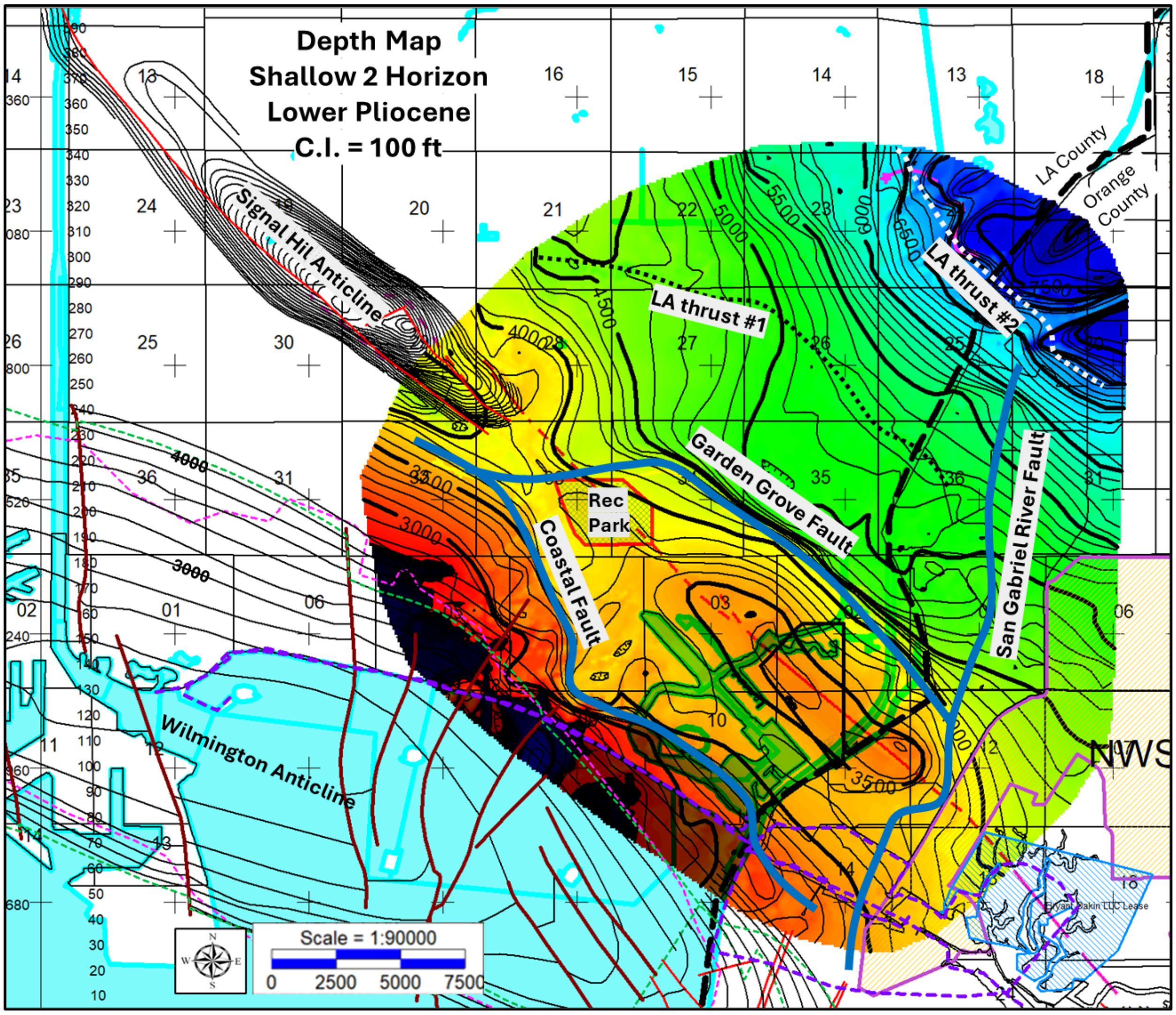

Figure 2. Mapped Lower Pliocene horizon (Shallow2, green horizon in Figure 4) is ~1400 ft above the Ranger Fm (Wilmington contours). Dashed red line shows the USGS surface trace of NIFZ (Calif. Geol. Survey, 2024).

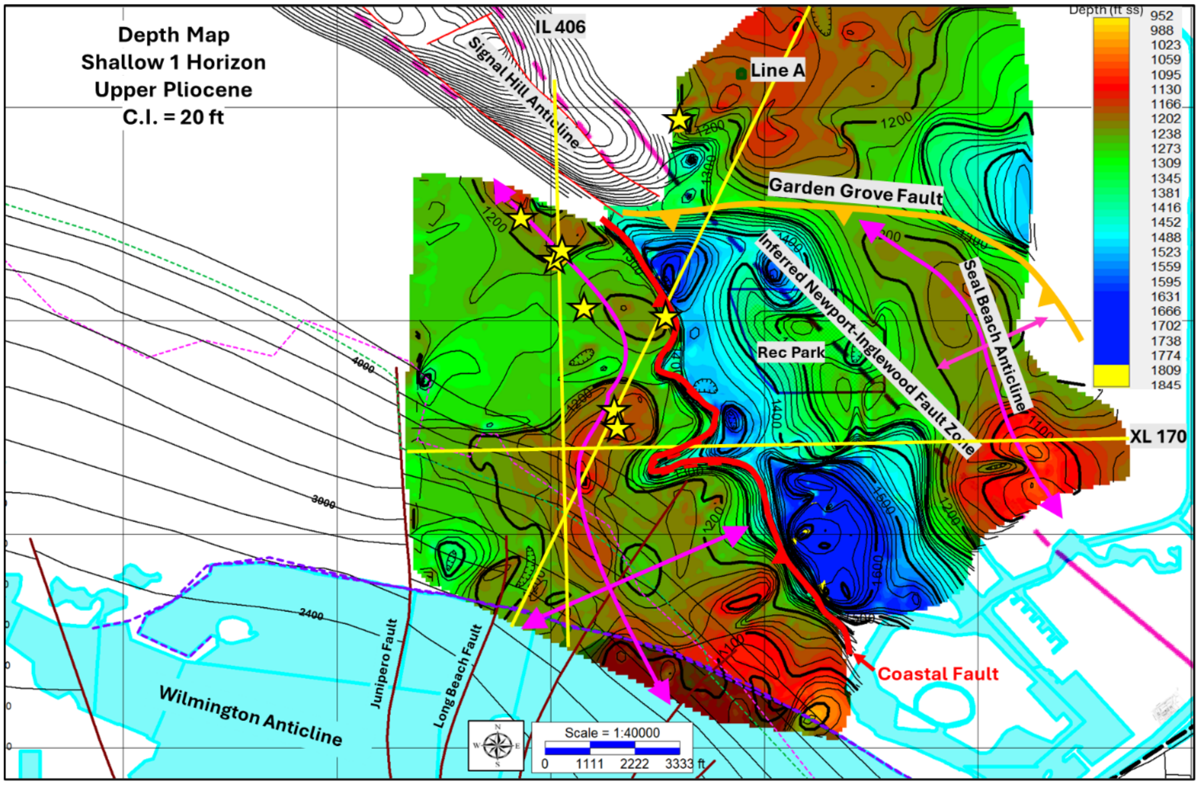

Figure 3. Structure map on the Upper Pliocene Shallow1 (pink) reflector shown in Figure 4. Seismic x-section lines in Figure 4 are shown as solid yellow lines. Pink arrows indicate strike and dip of anticlinal folding of Coastal Fault and Garden Grove thrust plates. Micro-earthquakes at the north end of the Coastal Plate (yellow stars) correlate with the leading edge of the Coastal Fault (solid red line). GGF shown by solid gold line. Note offset of SBA with respect to Signal Hill Anticline at shallow horizons. Lower left structural contours are mapped on the deeper Ranger Formation in Wilmington Field. Brown lines are named cross faults at Wilmington Oil Field. Signal Hill and Wilmington Anticline contours are from published maps.

Additionally, the SBA fold and its antithetic faults are truncated by the GGF décollement at depths of approximately 5500 ft (1675 m) (Figures 6 and 7). The southern terminus of the SBA is offset by a series of closely spaced NE-SW trending faults, the San Gabriel River Fault and the Leisure World Fault, resulting in right-lateral offset of the SBA structural axis (Figure 5a).

The GGF is a listric fault (Figures 4, 6, and 7) which surfaces approximately 1 to 1.5 miles (1.6 to 2.4 km) northeast (Figure 5) of the NIFZ surface trace (Biondi,2023) and carries the SBA as a ramp anticline within the leading edge of the GGF salient.

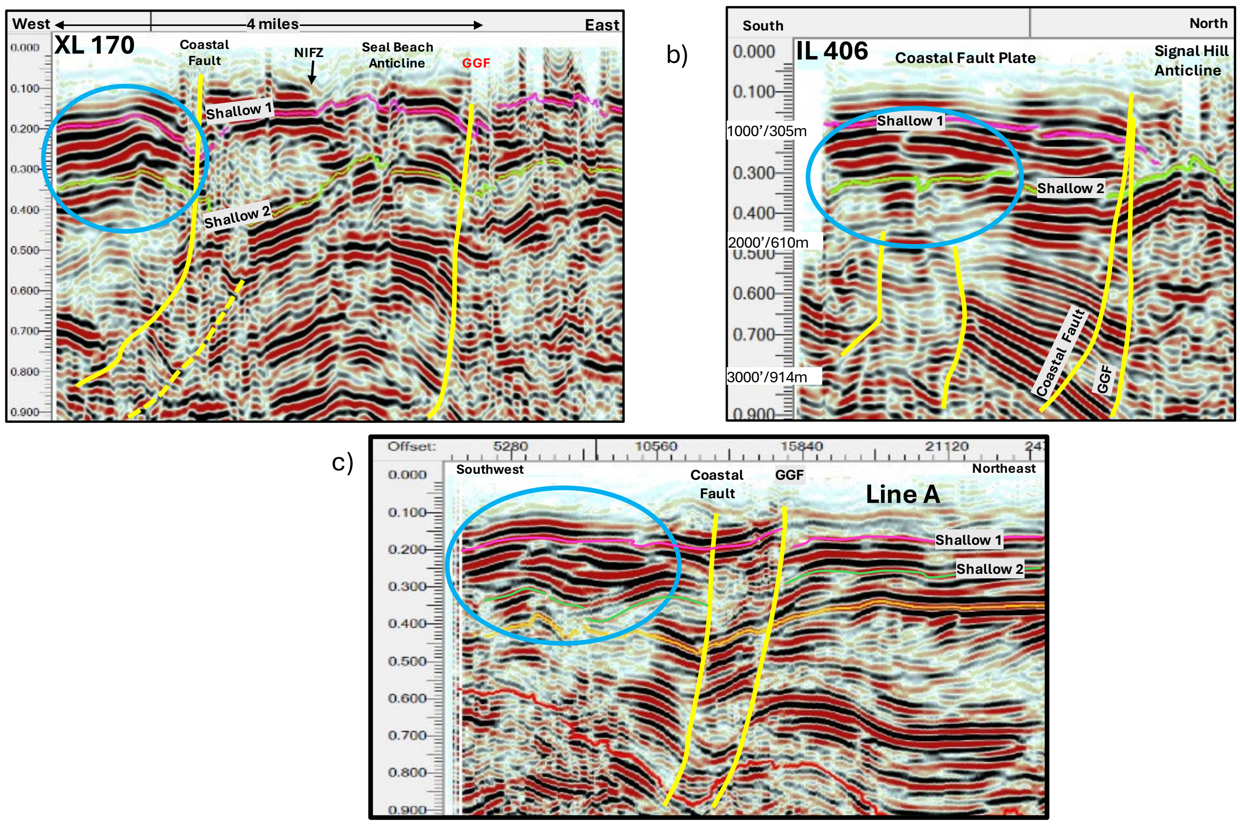

Figure 4. Coastal Fault with folding along leading edge of the thrust plate. Mapped horizons in Figures 2 & 3 are shown in green and pink respectively; areas within blue circles show more intense shallow thrusting than on other thrust plates.

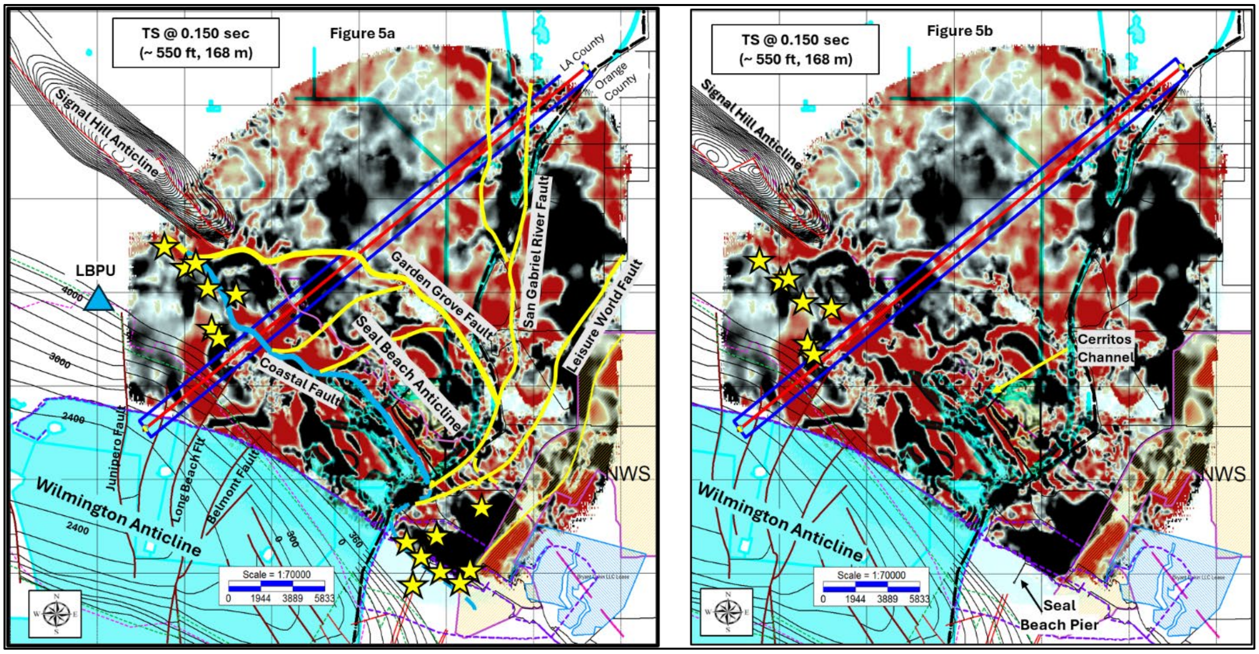

Figure 5. **5a**: Interpreted seismic amplitude timeslice at approximately 550 ft ss (168 m) Upper Pliocene, showing arcuate trace of the GGF (yellow line) cutting obliquely between Signal Hill Anticline and Seal Beach Anticline. Blue line is the Coastal Fault. Pink line is the NIFZ. **5b:** Uninterpreted timeslice. Seismic x-section (red line) is shown in Figure 6. Yellow stars are select micro-earthquakes recorded during 2017.

Below the GGF décollement, a previously unrecognized system of generally NW-SE oriented thrusts extend basinward as blind thrusts from nearly 1 mile (1.6 km) offshore along the east flank of Wilmington Anticline to at least six miles into the Los Angeles Basin, and are named the Los Alamitos Fault #1 (LAF #1), and the Los Alamitos Fault #2 (LAF #2), (Figures 2, 6, and 7).

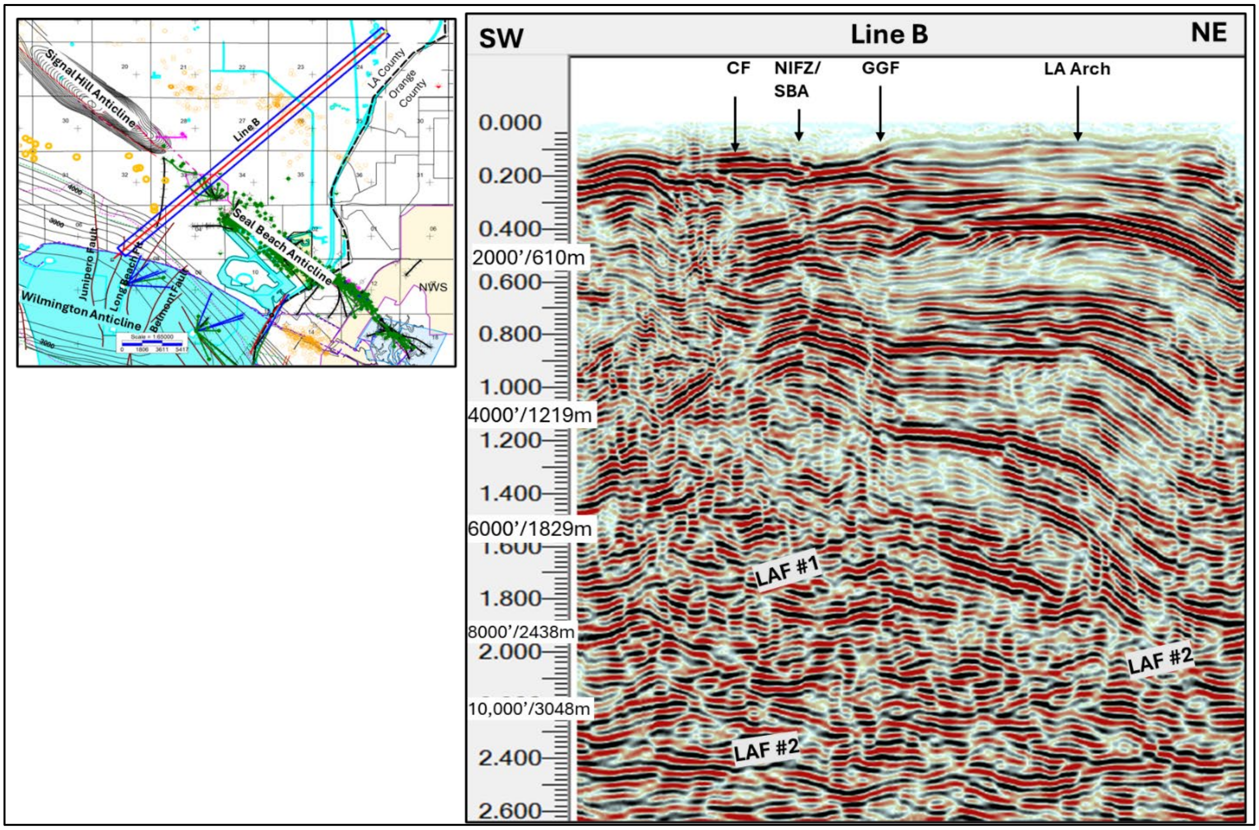

Figure 6. Uninterpreted diagonal seismic line through Recreation Park, with surface locations of major faults labeled. SBA does not exist below ~5500 ft (1675m), consistent with a thrust anticline. NIFZ neither extends to basement, nor dips eastward into the basin. The Coastal Fault (CF), plate (upper left corner) is tightly folded with a steeply dipping east flank. Underlying blind thrust faults occur at ~1.80 sec (LAF#1) and at ~2.4 sec (LAF#2) which steeply folds the northeast limb of the Los Alamitos Arch.

Tectonic deformation of shallow sediments is not restricted to just along the SBA trend. Seismic data shows intensely deformed shallow reflectors, characterized by tightly folded, thrusted, and steeply dipping beds occurring several miles west of SBA along the coast, corresponding with a recently identified large thrust plate, the Coastal Fault (Figure 4).

Within the study area, thousands of feet of sediments were continuously deposited within relatively low energy fluvial-deltaic-lagoonal environments as essentially horizontal sediments. However, 3D seismic data shows multiple high stand systems tracts (HST's) stacked along the eastern, downthrown side of the Garden Grove Fault (Figures 4c, 6, and 7), indicating repeated uplift of the GGF fault block creating corresponding updip accommodation spaces; yet no similar HST's were observed along the NIFZ. Sequence stratigraphy analysis of these parasequences record up to 1000 feet (305 m) of recurring vertical displacements of the GGF during the Upper Pliocene through Upper Pleistocene, based on the combined vertical separation between "topset" and "toeset" reflections.

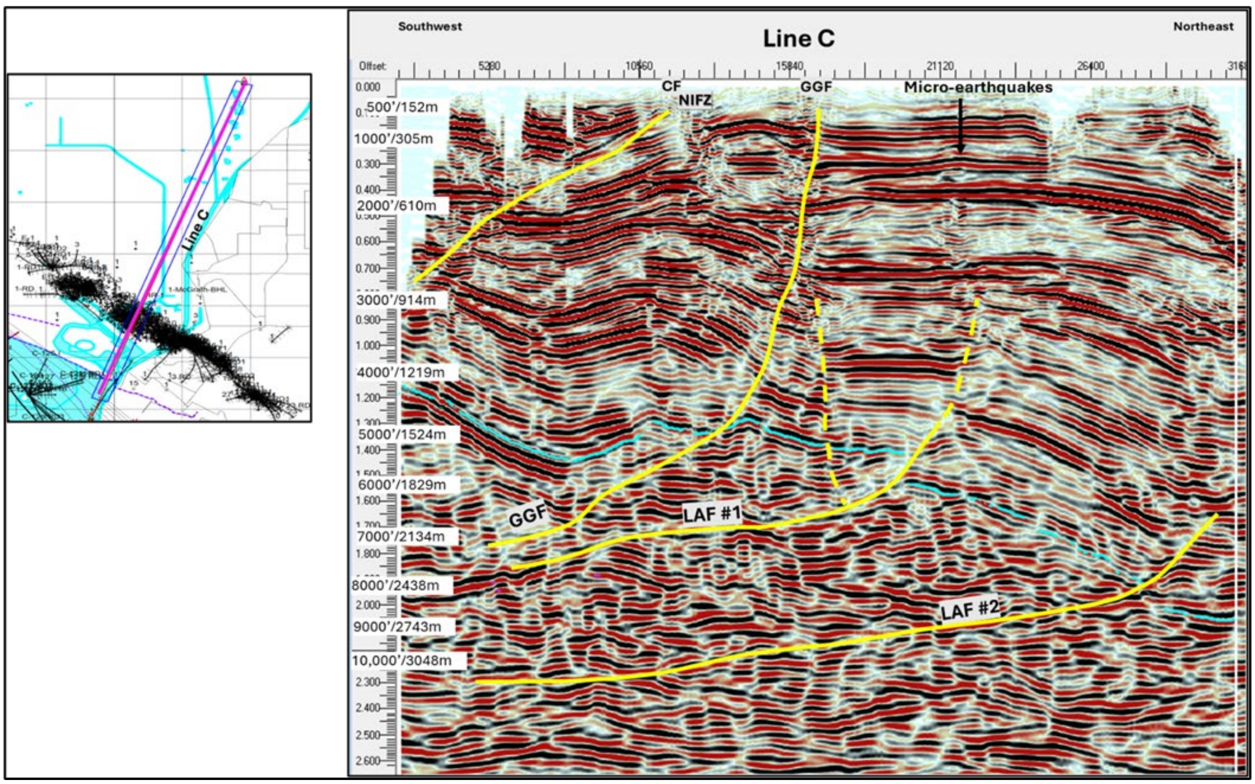

Figure 7. Garden Grove Fault carries the Seal Beach Anticline as a ramp anticline, which disappears below ~5500 feet (~1,680 m) at 1.50 sec. The NIFZ neither extends to basement nor dips eastward into the basin. Basement is interpreted to occur below 2.6 seconds. Horizontal scale (feet) shown across top of section.

Hundreds of micro-earthquakes recorded in 2017 (Figure 1) by a dense seismic network have been directly tied to the Coastal Fault, and to the Los Alamitos #1 blind thrust, indicating these faults remain active today. The widely spaced occurrence of these micro-earthquakes are consistent with the widely spaced aftershocks following the 1933 Long Beach Earthquake. Virtually all the recent micro-earthquakes recorded south of Signal Hill occurred along the flanks of the Seal Beach Anticline rather than along the projected NIFZ trace (Yang and Clayton,2021).

3.1 Coastal Fault newly discovered

Steeply east-dipping sediments paralleling the coastline between the coast and Seal Beach Anticline are folded and carried by an east-vergent thrust fault, herein called the Coastal Fault (Figure 2 and 3). The Coastal Fault (CF) flattens offshore toward the west, based on observations that i) hanging wall structures exhibit listric anticlinal folding along the leading edge (Figures 4, 6 and 7), ii) steeply dipping horizons along the eastern flank of the thrust sheet terminate abruptly against flatter footwall horizons (Figures 4 and 6), and iii) cutoff positions of hanging wall horizons move progressively westward with increasing depth, at least down to mid Miocene horizons. Seismic data along the Coastal Fault thrust sheet reveals thrust faulting of even very shallow sediments (Figure 4) and pronounced folding along the leading edge of the Coastal Thrust plate on the east flank of Wilmington Anticline, consistent with the transpressive thrust structure proposed for Wilmington Anticline (Ishutov,2013). The Coastal Fault exhibits up to 200 – 250 feet (61 – 76 m) of vertical displacement (Figure 3) of Upper Pliocene sediments west of Recreation Park and extends southward sub-parallel to the coastline, passing under the Marina area. Near the

Seal Beach Pier, the CF also correlates with a fault segment about 1 mile (1.6 km) southwest of the NIFZ which is associated with recent micro-seismic activity (Clayton and Yang,2021, Yang and Clayton,2021), proving it remains active.

The Coastal Fault and the Garden Grove Fault appear to merge south of Signal Hill representing a large northeast-vergent thrust salient (Figure 5) carrying the SBA between Signal Hill and the western edge of the Seal Beach Wetlands. Where the two faults merge west of Recreation Park (Figures 2, 3), the combined Garden Grove Thrust and the Coastal Thrust are interpreted to have east-west oriented, left-lateral transpression relative to the northern block carrying the Signal Hill Anticline, consistent with oblique thrusting, rather than NW-SE oriented right-lateral strike slip displacement.

3.2 Micro-earthquakes reveal new fault zones

The dense 3D geophone network installed during the 3D seismic acquisition period continuously recorded data over a three (3) month period, resulting in two distinct datasets, one which recorded dynamic reflection energies, and a second passive dataset which recorded only ambient energies. The passive dataset was delivered to Caltech who identified more than 1200 high-confidence micro-earthquakes having magnitudes less than M2.5, none of which registered on the Southern California Seismic Network because they were below the networks' detection threshold (Clayton and Yang,2021). These micro-earthquakes aligned in distinct patterns across the survey, revealing new clues as to locations of previously unrecognized faults, and of current seismic activity levels (Yang and Clayton,2021). Significantly, none of the recent micro-earthquake epicenters aligned with the NIFZ south of Signal Hill (Figure 1). Most events were oriented along a NW-SE trend located approximately 2 miles (3.2 km) north of NIFZ, correlated with the leading edge of the Los Alamitos #1 Thrust, a blind thrust. A second dense cluster of events occurred at the shoreline near the Seal Beach pier (Yang and Clayton, 2021) more than a mile from NIFZ. No events were detected along the NIFZ.

A third cluster of micro-events were recorded along a NW-SE trend ½ mile (0.8 km) south of Signal Hill Anticline and are clearly offset from the NIFZ (Figures 1, 3, and 5). The location and orientation of these micro-events correlate with the northern extent of the Coastal Fault plate along its leading edge. The micro-earthquake cluster south of Signal Hill Anticline and the cluster near Seal Beach pier, as well as shallow deformation documented by 3D seismic data, confirm that the Coastal Fault is presently active. This deformation is characterized by extensive shallow thrusting, and tightly folded, steeply dipping Pliocene sediments offsetting the Seal Beach Anticline and the NIFZ by 1.5 - 2 miles (2.4 – 3.2 km) (Figures 4, and 6).

3.3 Newport-Inglewood Fault Zone

Detailed mapping of NIFZ faults along Seal Beach Anticline indicates NIFZ faults have frequently been correlated to numerous relatively minor en-echelon antithetic faults related to the Garden Grove thrust. These en-echelon fault segments lack significant displacement, neither vertically nor horizontally, and do not follow the strike of the NIFZ surface maps but have been locally rotated clockwise due to cross faulting, resulting in local north-south orientations (Gish and Boljen,2015).

It is worth repeating that the Seal Beach Anticline, historically interpreted as a major structural anticline related to dextral strike slip faulting along the NIFZ, and as a southern continuation of the Signal Hill Anticline, in this 3D seismic dataset: i) is carried by the GGF thrust salient, ii) disappears entirely below the Garden Grove decollement at ~5500 feet ss (-1524 m), iii) folding along the SBA terminates in both directions along strike resulting in a doubly plunging anticline approximately 4 miles (6.4 m) long, iv) the asymmetrical SBA fold axis is displaced to the east of Signal Hill Anticline by left lateral faulting at shallow Pliocene horizons but aligns with it at deeper Lower Pliocene horizons (Figures 2 and 3), v) the fold axis of the anticline dips westward as the anticline deepens, vi) the SBA fold axis is repeatedly offset by cross-faults which can be correlated to well documented cross faults at Wilmington Anticline, vii) the mapped surface location of the NIFZ at Recreation Park occurs significantly off-structure along the west flank of the SBA at Upper Pliocene reflectors (Figure 3, and 4c), and viii) none of the ~1200 high confidence micro-earthquakes recorded in 2017 correlate to NIFZ faults along SBA (Figure 1). These facts do not support the classic definition of the NIFZ as a regionally extensive, narrow-width, near vertical, basement-related, strike-slip fault.

4. Discussion

The 2017 micro-seismic activity which is correlated to a widely spaced system of thrust faults on both sides of the SBA suggests these faults are linked at depth, complexly interacting via a displacement mechanism which is distinctly different from that of the NIFZ strike slip focal mechanism solution recorded at its Huntington Beach epicenter, which has historically been associated with the 1933 Long Beach Earthquake and subsequently extrapolated along the inferred NIFZ trace.

This paper does not take issue with the interpretation of the fault plane solution assigned to the 1933 Long Beach Earthquake near Huntington Beach (Hauksson and Gross,1991), but rather with the manner in which subsequent rupture has been assumed to propagate exclusively along a narrow fault zone, the NIFZ, as essentially pure strike-slip displacement throughout the Seal Beach area and into Long Beach. It is not necessarily true that subsequent propagation of the rupture process can or should be associated with a single unique fault. Continued efforts to extrapolate focal mechanism results obtained at the Huntington Beach epicenter to deformation observed at Long Beach have proven to be less than satisfactory. Considerable conflicting evidence indicating that a different tectonic regime is active within the Seal Beach area has been largely ignored and discarded in favor of traditional NIFZ models. The 2017 micro-earthquake results, recognition of the GGF thrust plate carrying SBA, extensive shallow deformation observed on 3D seismic data throughout the study area, atypical displacement parameters recorded by the LBPU instrument during the 1933 Long Beach Earthquake, and active thrust faults extending into the Los Angeles Basin under SBA are consistent with the nearly 10 miles wide (17 km) onshore aftershock pattern which occurred during the 1933 Long Beach Earthquake (Hauksson and Gross 1991), and with the compressional tectonic system and significant cross-faulting described at Wilmington Anticline (Ishutov,2013), Clark, 1987, Wolfe 2019, Wright 1991, Ponti 2007).

Micro-earthquake activity throughout Seal Beach is associated with a system of thrust sheets extending eastward from the Wilmington Anticline, that have been subsequently displaced by well documented cross faults cutting the Wilmington Anticline which can be extended onshore at least to the leading edge of GGF. The SBA cross faults are primarily concentrated near the change of strike of the thrust salient immediately south of the Signal Hill Anticline, near Recreation Park, but also cut SBA ½ mile (0.8 km) north of Cerritos Channel as a very apparent offset likely associated with the Belmont Fault cross fault (Figure 5). Evidence of recent deformation is particularly evident west of Recreation Park, along the Coastal Fault plate where the GGF merges with the Coastal Fault, coinciding with the area of extreme deformation and anomalous intensities observed during the 1933 Long Beach Earthquake (Figures 3 and 4).

These newly identified structural details imply that a wide transpressional tectonic system has been prevalent from Mid Pliocene to Recent times within the study area, in contrast to long-held beliefs of dextral strike slip displacement focused along a narrow, near-vertically oriented fault (NIFZ) along the Seal Beach Anticline. SBA is not simply a continuation of Signal Hill faulting and folding extending to basement and striking southeastward into the Wetlands areas, but rather is restricted to the GGF thrust plate. Within the study area, new seismic evidence shows the NIFZ does not exist as a meaningful, competent fault system, and that other major faults and pre-existing structural elements are transferring and propagating unique energy wavefields, resulting in atypical intensity distributions and localized ground motion amplification.

Detailed measurements of large rupture events in Ecuador (Chalumeau, C.,2024) using highly sensitive dense arrays, and in California (Lee, J.,2024), have shown that regional displacement transfer is not necessarily restricted to a single fault type, nor to a single fault zone or geometry type, but can occur between different fault blocks due to deep-seated structural linkage and pre-existing fault networks, resulting in considerable variations of local dispersion kinematics as energy propagates along strike.

The apparent change in displacement transfer mechanism from pure strike-slip near the Huntington Beach epicenter to transpressional displacements along an active thrust fault trend at Seal Beach helps to explain the unusually extreme vertical acceleration values recorded by LBPU miles away from the NIFZ, and why efforts to model that data based solely on NIFZ strike-slip models have consistently under-predicted observed results.

This paper proposes that a complex system of linked east-vergent thrust faults may have transformed initial NW-SE oriented dextral strike-slip displacements recorded at the Huntington Beach epicenter into transpressional displacements between Signal Hill Anticline and Seal Beach Wetlands, primarily accommodated by the Coastal Fault, Garden Grove Fault, and Los Alamitos Thrust #1. The point at which this change in displacement mechanism occurs may coincide with an enigmatic NE-SW trending fault zone, the San Gabriel River and Leisure World faults zone (SGR/LWF) (Figures 2 and 5). These large, extensive faults displace the SBA with dextral offset near the western edge of the Seal Beach Wetlands and extend northward beyond the 3D dataset with generally down-to-the-east displacement. North-south oriented folding of recent sediments along the SGR/LWF zone indicates the faults are currently active.

During the 1933 Long Beach Earthquake, the strong motion instrument, LBPU, recorded ground acceleration values of 0.20g, 0.16g and 0.29g for north-south horizontal, east-west horizontal, and vertical displacement components, respectively. While there may have been some instrument saturation of the horizontal components at peak ground acceleration rates, the vertical acceleration component is deemed reliable (Hough and Blair, 2023). One of the most striking observations from these data is that the vertical displacement component at LBPU exceeds the maximum horizontal component by a ratio of 1:1.45. These results are in surprising contrast to the expected response from “pure dextral strike-slip” as determined by Haucksson and Gross (1991) for the epicentral rupture mechanism near Huntington Beach. The extreme ground acceleration and anomalous vertical displacement values recorded by LBPU are not easily explained by efforts to assign the 1933 Long Beach response parameters exclusively to the NIFZ, located about 3 miles (5 km) away. Additionally, a more complex rupture scenario supporting two distinct propagation sub-events (“asperities”) near Long Beach was noted by Haucksson and Gross (1991). The northernmost of the two asperities was calculated to be about 3.7 – 4.3 miles (6 – 7 km) in length, a distance and location that agrees very well with the width of the Coastal Fault-GGF salient.

Recent earthquake simulations using an extended length NIFZ rupture model resulted in predicted maximum horizontal acceleration of 0.35g and vertical acceleration of 0.09g, less than 1/3 the observed vertical acceleration value recorded at LBPU, and a relative vertical:horizontal ratio of just 0.26 (Hough and Blair,2023). While the modeled displacement ratio is consistent with nearly pure strike-slip displacement mechanisms as expected, it vastly under-predicts the observed vertical displacement ratio of 1:1.45 which was recorded by the LBPU strong motion instrument. While it is possible the horizontal components of LBPU were saturated at the highest acceleration rates and that greater horizontal displacement values may have resulted in a lower vertical:horizontal displacement ratio for the 1933 earthquake, achieving the vertical:horizontal displacement ratio of 0.26 predicted by extended rupture simulations would require the horizontal displacement at LBPU to have reached a maximum value of 1.1g, in contrast to the actual recorded LBPU value of 0.20g, or even the modeled maximum horizontal value of 0.35g. Considering that no surface ruptures were observed at Long Beach nor along the NIFZ, this possibility seems unlikely. Instead, it is more likely that the anomalous 1933 Long Beach rupture kinematics observed near Long Beach occurred in response to a different tectonic mechanism than that of the strike-slip event recorded at Huntington Beach.

Locations of well documented collapsed school buildings and of the LBPU strong motion instrument from the 1933 Earthquake, and micro-earthquake locations recorded during the 2017 survey have been superimposed on an Upper Pliocene 3D seismic structure map (Figure 8). Although the 3D Seal Beach survey does not extend far enough west to fully image the entire area of Long Beach damage, a strong correlation can be made between recent deformation along the Coastal Plate and documented evidence from the 1933 Long Beach Earthquake.

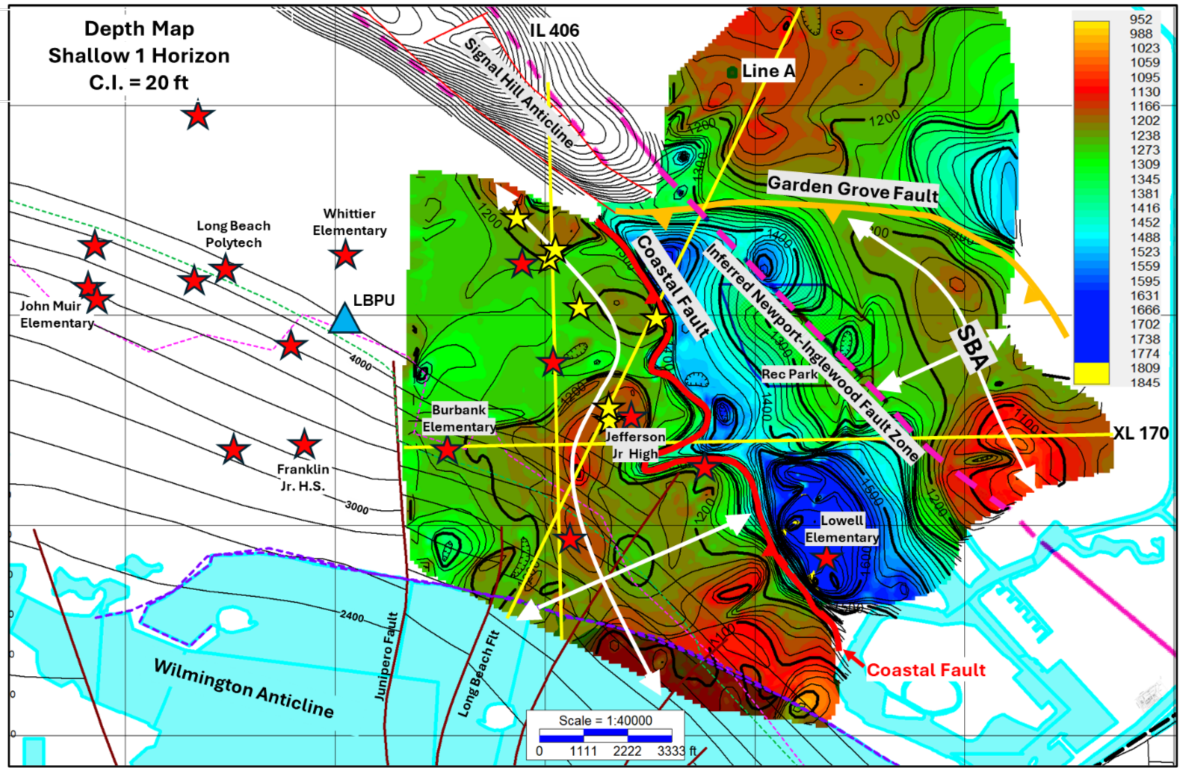

Figure 8. Map shown in Figure 3 with superimposed locations of Long Beach collapsed school buildings (red stars) and seismometer LBPU (blue triangle). Yellow stars show select 2017 micro-earthquake locations. Brown lines are known cross faults at Wilmington Field. Yellow lines are seismic lines shown in Figure 4.

The lack of sedimentary response to the 1933 Long Beach Earthquake documented by shallow core data within the Seal Beach Wetlands (Lepper,2017) implies that the NIFZ was not involved in the 1933 rupture mechanics at least at this location, and that perhaps displacement transfer from the NIFZ to the Coastal Fault, and to the underlying thrusts occurred upon encountering the San Gabriel/Leisure World Fault zone, the second "asperity" reported by Haucksson and Groves (1991).

This new tectonic model proposes that displacements from the 1933 Earthquake which originated at an epicenter 15 miles (25 km) to the south and offshore from

Huntington Beach as pure strike slip rupture along the NIFZ, may have been subsequently transferred to the pre-existing Coastal/Garden Grove/Los Alamitos thrust sheets during northwest propagation. The location of the suggested transfer zone is proposed to occur along the San Gabriel/Leisure World Fault zone (Figure 5). Transpressional displacement of the Coastal Fault plate, perhaps amplified by contributions from the GGF rather than strike-slip displacement along the NIFZ, was most likely responsible for the anomalously high ground acceleration values, high vertical displacement ratios, and extreme intensities experienced at Long Beach during the 1933 Long Beach Earthquake event. Such a modified rupture mechanism is consistent with the two-stage propagation scenario discussed by Haucksson and Groves (1991).

5. Conclusions

High resolution 3D seismic data has revealed previously unrecognized thrust faults within the Seal Beach area, associated with intense near-surface deformation and with micro-earthquake patterns recorded by dense seismic networks during 2017 along both flanks of the SBA, but not along the NIFZ. Within the greater Seal Beach area there is little evidence supporting the concept of a large regional strike-slip fault system corresponding to assumed NIFZ models. Faults previously described as NIFZ faults are identified as numerous antithetic fault segments associated with leading edge deformation. The doubly-plunging Seal Beach Anticline is carried as a ramp anticline by the Garden Grove Fault, a previously unknown thrust fault which outcrops ~1.5 miles (2.4 km) east of the NIFZ. SBA is separated from Wilmington Anticline on its west flank by the Coastal Fault, another previously unrecognized thrust fault. Both faults are listric and flatten toward the west. These distinctive thrust faults indicate that a transpressive tectonic regime rather than a simple strike-slip tectonic system prevails within the Seal Beach region, identical to the transpressional system described for the adjacent Wilmington Anticline. Dozens of micro-earthquakes clustered along the Coastal Fault indicate the fault remains active, whereas no corresponding events were detected along the NIFZ.

Previous researchers have reported that the 1933 Long Beach Earthquake propagated toward the northwest from the Huntington Beach epicenter in at least two discrete sub-events, or asperities, lending support to the concept presented in this paper that propagation of the 1933 Long Beach Earthquake event may have begun as pure dextral displacement at the initial source location near Huntington Beach, but transformed into more complex transpressional displacements as the stress field encountered and reactivated pre-existing thrust faults bracketing the Seal Beach Anticline area. One of these previously unknown thrust faults, the Coastal Fault, closely parallels the coastline, transforming the eastern flank of the Wilmington Anticline from simple east dip separated from the SBA into a more complex structure crossing multiple thrust sheets. 3D seismic data shows more intensive recent deformation along the Coastal Fault plate than along the GGF plate or elsewhere, characterized by tight shallow folds and thrusts and hundreds of recent microearthquakes, indicating that within the Seal Beach area, the CF is a dominant fault more active than either the NIFZ or the GGF. The Coastal Fault merges with the Garden Grove Fault immediately northwest of Recreation Park, effectively separating Signal Hill Anticline from Seal Beach Anticline by west-east oriented, predominantly left lateral faults corresponding to the edge of the CF/GGF salient. The combined displacements of the merged faults may have been responsible for the amplified intensities and anomalous accelerations observed at Long Beach. Abnormally high vertical accelerations recorded by the LBPU instrument during the 1933 Long Beach Earthquake supports the interpretation of transpressional displacement of the Coast Fault, resulting in larger vertical components than would be expected from strike-slip rupture along the NIFZ. Similar dramatic changes in rupture mechanics during large earthquakes have been documented by dense network recordings in Ecuador.

More than 1200 high-confidence micro-earthquakes recorded in 2017 along distinct trends flanking the SBA support the interpretation of an active, linked, widely dispersed thrust system within the Seal Beach area of investigation. Linear swarms of shallow micro-earthquakes recorded near the Seal Beach Pier and micro-events directly under Long Beach corresponding to the Coastal Fault, combined with 3D seismic evidence of intense shallow deformation, indicate the Coastal Fault has been and remains highly active. A larger cluster of NW-SE trending micro-earthquakes located about 2 – 2.5 miles (~3.2 - 4 km) northeast of the GGF correlates with a near vertical fault zone along the leading edge of a deep seated, previously unrecognized blind thrust, the Los Alamitos Thrust #1. An even deeper blind thrust also correlated to deep micro-earthquakes, the Los Alamitos Thrust #2, disappears into the basin beyond the northern limit of the 3D dataset. Los Alamitos Thrust #2 is also uplifting and steeply folding the east flank of the Los Alamitos Arch. The compelling evidence for widespread on-going activity over a width of nearly 6 miles (9.7 km) strongly suggests the thrusts may be linked in the subsurface.

The NIFZ is located approximately 1.5 - 2 miles (2.4 – 3.2 km) east of the area of the most intense Long Beach ground shaking where more than 70 buildings were seriously damaged and the LBPU strong motion instrument recorded extreme vertical acceleration components that have not been satisfactorily explained by NIFZ model simulations. Recent modeling of extended NIFZ rupture scenarios continue to under-predict the observed vertical accelerations documented by the LBPU strong motion instrument by a factor of more than three and does not explain recent micro-earthquake activity located miles away on either side of NIFZ, but lacking along the NIFZ. Multiple antithetic faults previously assumed to be NIFZ faults are spatially confined to the GGF thrust plate, are highly compartmentalized by cross faults, and are not continuous either vertically or horizontally. Structural and sedimentological data show that the GGF is a more dominant fault than any of the antithetic faults associated with the SBA.

This study using integrated subsurface data proposes that anomalous Long Beach surface damages and unusual ground motion parameters recorded by the LBPU strong motion instrument can be better explained by transpressional rupture along the Coastal Fault thrust plate, and perhaps the GGF plate, than by large strike slip movements along the NIFZ.

Exactly where and how the transition from dextral strike-slip displacement along the NIFZ near Huntington Beach to wide-spread transpressional fault system across a 6 mile wide thrust zone (Coastal Fault, Garden Grove Fault, Los Alamitos Faults #1 and #2) is not entirely clear; however, 3D seismic data shows that a dramatic change in tectonic style occurs along a NE-SW trending fault zone, the SGR/LW fault zone, oriented perpendicular to the NIFZ approximately along the western boundary of the Seal Beach Wetlands which may indicate a deep-seated transform boundary and correlate with the northernmost asperity of the 1933 Earthquake. This enigmatic fault zone truncates the SBA at its southern terminus, cuts and folds sediments less than 300 feet below the surface at the Los Alamitos Arch and may also be associated with a right-stepping shear zone extending into the offshore.

Acknowledgements

The Authors wish to provide thanks to Synergy Oil & Gas for permission to publish these results, and to LA Seismic for acquiring and permitting the challenging field operations. Thanks also go to continuing cooperation and constructive technical discussions with Dr R. Clayton at Caltech.

Data Availability

The strong-motion data from three stations can be downloaded from: https://www.strongmotioncenter.org/cgi-bin/CESMD/iqr_dist_DM2.pl?IQRID=LongBeach_10Mar1933&SFlag=0&Flag=3. Micro-seismic data from the Long Beach-Seal Beach relocated nighttime seismicity catalog can be found in the following Caltech repository: https://data.caltech.edu/records/5ws5e-ddh43. All websites were last accessed in November 2024.

Seismic reflection data was designed and collected for specific commercial purposes, is considered proprietary data and is currently under corporate non-disclosure agreement. 3D Seismic Solutions has received permission to publicly display illustrations of the data but may not make the actual digital data available.

Competing Interests

The authors declare there are no competing interests.

References

Biondi, E., Castellanos, J., Clayton, R., (2024) Imaging Urban Hidden Faults with Ambient Noise Recorded by Dense Seismic Arrays, Seismological Research Letters https://doi.org/10.1785/0220230408

California Geological Survey, California Department of Conservation, Seismic Hazards Program, Earthstar Geographics, accessed January 16, 2024, https://maps.conservation.ca.gov/cgs/EQZApp/app/

Clayton, R., and Yang, Y., Hollis, D., Gish, D., Boljen S. Campbell, E. and Stanford, B. (2021) Results From 2017-18 High-Density Seismic Hazard Survey. *http://laseismic.com/2017-18_High-Density_Seismic_Hazard_Survey.ppsx*

Chalumeau, C. Agurto-Detzel, H., Rietbrock, A., Frietsch, M., Oncken, O., Segovia, M., Galve, A., (2024) Seismological Evidence for a multifault network at the subduction interface, Nature, Vol 628. https://doi.org/10.1038/s41586-024-07245-y

Gish, D., and Boljen, S. (2021) Newly Identified Fault in Seal Beach, CA, Quietly Rattles Beneath the City, TK, *Temblor*, *https://temblor.net/earthquake-insights/newly-identified-fault-in-seal-beach-ca-quietly-rattles-beneath-the-city-13477/ http://doi.org/10.32858/temblor.219*

Hauksson, E., Gross, S. (1991) Source Parameters of the 1933 Long Beach Earthquake *Bulletin of the Seismological Society of America* 81 (1): 81–98. *https://doi.org/10.1785/BSSA0810010081*

Hough, S. E., L. Blair, S. Ellison, R. W. Graves, S. Haefner, E. M. Thompson, N. van der Elst, M. Page, and D. J. Wald (2023) Modern Products for a Vintage Event: An Update on the 1933 Long Beach, California, Earthquake, *The Seismic Record*. 3(2), 171–181, doi: 10.1785/0320230015.

Hough, S. E., and Graves, R. W. (2020) The 1933 Long Beach Earthquake (California, USA): Ground Motions and Rupture Scenario, *Scientific Reports*, *10*(1), 10017, 2020. *https://doi.org/10.1038/s41598-020-66299*

Ishutov, S.(2013) Tectonic Characterization of the THUMS-Huntington Beach Fault, Offshore Southern California, *SPE Western Regional/Pacific Section AAPG Conference*.

Lee, J., Tsai, V., Hirth, G., Chatterjee, A., Trugman, D.T. (2024) Fault-network geometry influences earthquake frictional behaviour, *Nature*. *DOI: 10.1038/s41586-024-07518-6*

Lepper, R., B. Rhodes, M. Kirby, K. Scherer, J. Carlin, E. Hemphill-Haley, S. Avnaim-Katav, G. MacDonald, S. Aranda, and A. Aranda, (2017), Evidence for coseismic subsidence events in a southern California coastal saltmarsh, *Sci Rep* **7** 44615. https://doi.org/10.1038/srep44615

Ponti, D.J., Ehman, K.D., Edwards, B. D., Tinsley III, J.C., Hildenbrand, T., Hillhouse, J.W., Hanson, R.T., McDougall, K., Powell, C.L., II, Wan, E., Land, M., Mahan, S., Sarna-Wojcicki**,** A.M. (2007) A 3- Dimensional Model of Water-Bearing Sequences in the Dominguez Gap Region, Long Beach, California, *U.S. Geological Survey Open-File Report 2007–1013, U.S. Department of the Interior U.S. Geological Survey*. *https://doi.org/10.3133/ofr20071013*

Yang, Yan and R. Clayton (2021), Shallow Seismicity in the Long Beach-Seal Beach, CA Area, early publication, *Seismological Research Letters*, https://doi.org/10.1785/0220220358.