

**REPORT ON THE ANALYSIS  
OF THE SHORELINE FAULT ZONE,  
CENTRAL COASTAL CALIFORNIA**

**Report to the U.S. Nuclear Regulatory Commission  
January 2011**



# TABLE OF CONTENTS

	<b>Page</b>
LIST OF TABLES, FIGURES, AND APPENDICIES .....	iv
ACRONYMS AND TECHNICAL TERMS .....	x
EXECUTIVE SUMMARY .....	ES-1
1.0 INTRODUCTION .....	1-1
1.1 Organization of This Report .....	1-1
1.2 Background.....	1-2
1.3 Acknowledgments.....	1-4
2.0 DATA COLLECTION .....	2-1
2.1 Geology.....	2-1
2.1.1 Onshore Geologic Mapping.....	2-1
2.1.2 Offshore Geologic Mapping.....	2-1
2.2 Seismographic Station Coverage .....	2-2
2.3 Potential Field—Magnetic Surveys .....	2-2
2.4 Potential Field—Gravity Surveys.....	2-3
2.5 Multibeam Echo Sounding Surveys.....	2-3
2.6 LiDAR Survey .....	2-3
2.7 High-Resolution Seismic Reflection Profiling .....	2-4
3.0 REGIONAL TECTONIC AND SEISMIC SETTING .....	3-1
3.1 Regional Tectonic Setting.....	3-1
3.1.1 Los Osos Fault Zone .....	3-2
3.1.2 Southwestern Boundary Fault Zone.....	3-2
3.1.3 San Luis Bay Fault Zone.....	3-3
3.1.4 Hosgri Fault Zone .....	3-3
3.2 Regional Seismicity Setting.....	3-4
4.0 SHORELINE FAULT ZONE.....	4-1
4.1 Introduction.....	4-1
4.2 Shoreline Seismicity Lineament .....	4-2
4.2.1 Seismicity Lineament Data Statistics.....	4-3
4.2.2 Earthquake Location Uncertainties.....	4-3

4.2.3	Relation of the Shoreline Seismicity Lineament to Earthquakes Prior to 1988 .....	4-5
4.2.4	Data Interpretation .....	4-6
4.3	Geological and Geophysical Characterization of the Shoreline Fault Zone.....	4-10
4.3.1	Length and Segments .....	4-13
4.3.2	Faulting Style .....	4-15
4.3.3	Geometry and Downdip Width.....	4-15
4.4	Activity of the Shoreline Fault Zone .....	4-15
4.4.1	Offshore Wave-Cut Platforms and Strandlines.....	4-16
4.4.2	Evidence of Activity .....	4-17
4.4.3	Slip Rate.....	4-17
4.5	Relationship to Other Structures.....	4-21
4.5.1	Independent Shoreline Fault Zone Model.....	4-22
4.5.2	Linked Shoreline Fault Zone Model.....	4-23
4.6	Location of the Shoreline Fault Zone with Respect to DCPD .....	4-23
5.0	SEISMIC SOURCE CHARACTERIZATION.....	5-1
5.1	Shoreline Fault Zone Source Logic Tree .....	5-1
5.2	Logic Trees for Other Fault Sources.....	5-11
5.2.1	Hosgri Fault Zone Logic Tree.....	5-12
5.2.2	Los Osos Fault Logic Tree.....	5-12
5.2.3	San Luis Fault Logic Tree.....	5-13
6.0	SEISMIC HAZARD ANALYSIS .....	6-1
6.1	Introduction.....	6-1
6.2	Simplified Logic Trees .....	6-1
6.2.1	Shoreline Fault Source .....	6-2
6.2.2	San Luis Bay Fault Source.....	6-2
6.2.3	Los Osos Fault Source .....	6-3
6.2.4	Simplified Logic Tree for the Shoreline Fault Source.....	6-3
6.3	Mean Characteristic Magnitude Models.....	6-3
6.4	Magnitude Probability Density Function.....	6-4
6.5	Site Condition .....	6-5
6.6	Ground Motion Prediction Equations .....	6-5
6.6.1	Epistemic Uncertainty.....	6-6

6.6.2	Hard-Rock Site Effects .....	6-8
6.6.3	Average Spectral Acceleration from 3 to 8.5 Hz.....	6-9
6.6.4	Single-Station Sigma and Site-Specific Site Effects .....	6-10
6.6.5	Directivity .....	6-13
6.6.6	Effects of New Ground Motion Models .....	6-14
6.7	Deterministic Ground Motions .....	6-15
6.7.1	Earthquake Magnitudes .....	6-15
6.7.2	Deterministic Ground Motions .....	6-16
6.8	Probabilistic Seismic Hazard Analysis .....	6-16
6.8.1	Additional Sources.....	6-16
6.8.2	Hazard Results .....	6-16
6.9	Seismic Hazard Conclusions.....	6-17
7.0	POTENTIAL FOR SECONDARY FAULT DEFORMATION .....	7-1
8.0	SUMMARY AND CONCLUSIONS .....	8-1
8.1	Shoreline Fault Zone Characterization .....	8-1
8.1.1	Shoreline Seismicity Lineament .....	8-2
8.1.2	Fault Length and Segmentation .....	8-2
8.1.3	Fault Dip .....	8-3
8.1.4	Downdip Width.....	8-3
8.1.5	Style of Faulting.....	8-3
8.1.6	Relationship to Other Structures.....	8-3
8.1.7	Slip Rate.....	8-4
8.1.8	Location of the Shoreline Fault Zone Offshore of DCPD.....	8-4
8.2	Earthquake Hazard Implications for DCPD .....	8-4
8.2.1	Ground Motion Results.....	8-5
8.2.2	Secondary Fault Deformation Results .....	8-5
8.3	Continued Studies .....	8-5
9.0	REFERENCES .....	9-1

## TABLES

Table 4-1	Comparison of characteristics of the Shoreline fault zone presented in the Progress Report (PG&E, 1988) with this report
Table 4-2a	Absolute and relative location uncertainty estimates for the Shoreline earthquakes
Table 4-2b	Average and median shifts in epicenters and depths between location methods for the Shoreline earthquakes
Table 5-1	Coordinates for the Shoreline, San Luis Bay, Hosgri, and Los Osos fault sources
Table 6-1a	Coordinates of fault sources
Table 6-1b	Coordinates of San Luis Bay west segment source models for the linked branch
Table 6-2a	Depth limits of the San Luis Bay fault sources
Table 6-2b	Depth limits of the San Luis Bay east segment source
Table 6-3	Magnitude-area scaling relations
Table 6-4	Computed $V_{S30}$ values (for 10 m embedment) for the power block and the ISFSI borehole sites
Table 6-5	smoothed coefficients for the amplification from $V_{S30}=760$ m/s to $V_{S30}=1200$ m/s
Table 6-6	Event terms for the 2004 Parkfield and 2003 San Simeon earthquakes
Table 6-7	Site-specific amplification terms and total variance reduction for the single-station sigma approach
Table 6-8	Selected deterministic earthquake scenarios
Table 6-9	Source parameters for other regional fault sources
Table 6-4	Source parameters for other regional faults
Table 6-5	Change in estimates of seismic core damage frequency
Table 7-1	Annual probability of secondary fault rupture at any of the eight Dresser couplings of the ASW in the $T_{ofc}$ unit

## FIGURES

Figure ES-1	Faults and earthquakes in the Shoreline fault zone study region
Figure 1-1	Map of Shoreline fault zone study area
Figure 2-1	Offshore samples obtained during the LTSP and in 2010 for this study overlain with the extent of the 2010 LIDAR survey
Figure 2-2	Map of seismographic station coverage of the California Central Coast region for selected years
Figure 2-3	Seismicity recorded by PG&E and USGS from 1987 through August 2010

- Figure 2-4 Comparison of 1989 LTSP residual magnetic intensity with 2009 helicopter total magnetic intensity anomaly map
- Figure 2-5 Comparison of 1989 LTSP gravity anomaly map with the 2009 USGS gravity anomaly map
- Figure 2-6 Comparison of 1989 LTSP bathymetry with the 2009 MBES bathymetry—offshore DCPD area
- Figure 2-7 Comparison of 1989 LTSP bathymetry with the 2009 MBES bathymetry—offshore Olson Hill area
- Figure 3-1 Los Osos domain
- Figure 3-2 (a) Regional seismicity patterns and (b) focal mechanisms, 1987–2008
- Figure 4-1 Comparison of nomenclature for (a) the Shoreline fault zone in this report and (b) the 2010 Progress Report
- Figure 4-2 Comparison of Shoreline seismicity relocations in (a,b,c) map and (d,e,f) cross section views.
- Figure 4-3 Shoreline seismicity lineament statistics 1987–2008
- Figure 4-4 Magnitude 5 and greater pre-1987 historical earthquakes
- Figure 4-5 Comparison of 1970–1987 earthquake locations: (a) 1-D USGS absolute locations and (b) Hardebeck relocations
- Figure 4-6 Comparison of (a) 1-D USGS catalog, (b) 3-D, and (c) tomoDD earthquake locations
- Figure 4-7 P-wave first-motion focal mechanisms, 1987 through August 2008
- Figure 4-8 (a) Seismicity map and (b) cross sections AA' across the east and west traces of the Hosgri fault zone (HFZ), and BB' across the Shoreline Northern seismicity sublineament
- Figure 4-9 Comparison of (a) MBES bathymetric image with (b) the interpreted geology and (c) paleostrandlines across the N40W fault
- Figure 4-10 Comparison of (a) MBES image with (b) the interpreted geology and (c) paleostrandlines across the Central segment (C-1) of the Shoreline fault zone west of DCPD
- Figure 4-11 Comparison of (a) MBES image with (b) the interpreted geology and (c) paleostrandlines across the Central segment (C-2) of the Shoreline fault zone southwest of DCPD entrance
- Figure 4-12 Migration of sandsheet along the Central segment (C-2) of the Shoreline fault zone between (a) the 2009 and (b) 2010 MBES surveys northwest of Olson Hill
- Figure 4-13 Comparison of (a) MBES image with (b) the interpreted geology and (c) paleostrandlines across the Central segment (C-2) of the Shoreline fault zone west of Olson Hill

- Figure 4-14 Comparison of (a) MBES image with (b) the interpreted geology and (c) paleostrandlines (c) across the Central segment (C-3) of the Shoreline fault zone west of Rattlesnake Creek
- Figure 4-15 Comparison of (a) MBES image with (b) the interpreted geology and (c) paleostrandlines (c) across the South segment of the Shoreline fault zone southwest of Point San Luis
- Figure 4-16 Earthquake epicenters with isostatic gravity field data
- Figure 4-17 Earthquake epicenters with residual marine and coastal helicopter magnetic field data
- Figure 4-18 Generalized area of (a) Franciscan mélangé offshore compared to (b) RTP magnetic field anomalies
- Figure 4-19 COMAP seismic reflection profiles (a) CM-21 and (b) CM-23 across the Hosgri fault zone, North Segment of the Shoreline fault zone and the N40W fault
- Figure 4-20 Cross section of geology, magnetic inversion and gravity through Olson Hill
- Figure 4-21 Faults and paleoshorelines in the Shoreline fault zone study area
- Figure 4-22 Comparison of (a) the geology with (b) the RTP magnetic-field anomalies in DCPD area
- Figure 4-23 Apparent offset of Cretaceous sandstone beds across the Rattlesnake fault, San Luis Bay fault zone
- Figure 4-24 Map of submerged MIS 5a wave-cut platforms west of San Luis Hill
- Figure 4-25 Profiles on MIS 5a wave-cut platforms west of San Luis Hill
- Figure 4-26 Distance to DCPD power block and intake structure from Shoreline fault zone
- Figure 5-1 Map of seismic sources for Shoreline, San Luis Bay, and Los Osos fault zones
- Figure 5-2 Shoreline fault zone logic tree, nodes 1–5
- Figure 5-3 Shoreline fault zone logic tree, nodes 6–12
- Figure 5-4 Shoreline fault zone logic tree, not linked to San Luis Bay fault branch, nodes 13–16
- Figure 5-5 Shoreline fault zone logic tree, linked with San Luis Bay fault branch, nodes 17–23
- Figure 5-6 Shoreline fault zone logic tree, linked with San Luis Bay fault branch, nodes 24–30
- Figure 5-7 Empirical rupture length versus width data for strike-slip earthquakes
- Figure 5-8 Seismic source model, map traces of sources Hosgri, Los Osos, San Luis Bay, and Shoreline seismic sources
- Figure 5-9 Hosgri fault zone logic tree, modified form LTSP final Report (PG&E, 1988)
- Figure 5-10 Los Osos fault zone logic tree, modified form LTSP final Report (PG&E, 1988)

- Figure 5-11 San Luis Bay fault zone logic tree, modified form LTSP final Report (PG&E, 1988)
- Figure 6-1 Simplified logic tree for the Shoreline fault source
- Figure 6-2 Logic Tree for ruptures for Shoreline and San Luis Bay fault sources
- Figure 6-3 Magnitude probability density function for different percentages of the seismic moment being released in characteristic earthquakes
- Figure 6-4a Standard deviation of the median ground motion from the NGA models for representative earthquakes for the four nearby fault sources
- Figure 6-4b Standard deviation of the additional epistemic uncertainty for the NGA models
- Figure 6-5 Logic tree for ground motion models for crustal earthquakes
- Figure 6-6 Smoothed model of the coefficient for the amplification from  $V_{S30}=760$  m/s to  $V_{S30}=1200$  m/s
- Figure 6-7 Comparison of the average horizontal response spectrum at 5% damping for the free-field recording with the expected California rock site spectrum from a moment magnitude 3.4 earthquake at a distance of 7.8 km with a stress-drop of 120 bars and kappa of 0.042 sec based on the stochastic point source model (red curve).
- Figure 6-8 Example of effect of the site-specific hard-rock approach (solid lines) versus extrapolating the  $V_{S30}$  scaling (dashed lines) for the five NGA models.
- Figure 6-9 Distribution of distances and site conditions for the 2003 San Simeon and 2004 Parkfield earthquakes.
- Figure 6-10a Residuals from the 2003 San Simeon earthquake for 5 Hz spectral acceleration. The rupture distance to DCPD is 35 km.
- Figure 6-10b Residuals from the 2003 San Simeon earthquake for 1 Hz spectral acceleration. The rupture distance to DCPD is 35 km.
- Figure 6-11a Residuals from the 2004 Parkfield earthquake for 5 Hz spectral acceleration. The rupture distance to DCPD is 85 km.
- Figure 6-11b Residuals from the 2004 Parkfield earthquake for 1 Hz spectral acceleration. The rupture distance to DCPD is 85 km.
- Figure 6-12 Comparison of the event-term adjusted medians from the NGA models with the observed ground motions from the 2003 San Simeon earthquake.
- Figure 6-13 Comparison of the event-term adjusted medians from the NGA models with the observed ground motions from the 2004 Parkfield earthquake
- Figure 6-14 Site-specific site amplification terms for DCPD.
- Figure 6-15 Effect of the NGA ground motion models and the site-specific single-station approach for estimating hard-rock motions for nearby strike-slip as compared to the HE design spectrum and the LTSP/SSER spectrum.



- Figure 6-16 Effect of the NGA ground motion models for the Los Osos fault source for the traditional ergodic approach.
- Figure 6-17 Magnitude fractiles from the logic trees for four fault sources
- Figure 6-18a Sensitivity of the deterministic ground motions to the dip of the Hosgri fault source.
- Figure 6-18b Sensitivity of the deterministic ground motions to the dip of the Los Osos fault source.
- Figure 6-18c Sensitivity of the deterministic ground motions to the dip of the San Luis Bay fault source.
- Figure 6-19 84th percentile ground motion from the four nearby fault sources using the site-specific single-station sigma approach (solid lines) and the traditional ergodic approach (dashed lines).
- Figure 6-20a Hazard by fault sources for PGA; the Other source includes regional sources listed on Table 6-9.
- Figure 6-20b Hazard by source for 5 Hz spectral acceleration
- Figure 6-20c Hazard by source for 1 Hz spectral acceleration.
- Figure 6-21 Uniform hazard spectra for four hazard levels. The peak at 2.5 Hz reflects the site-specific amplification at DCP.
- Figure 6-22a Deaggregation for PGA for a hazard level of 1E-4.
- Figure 6-22b Deaggregation for 5 Hz for a hazard level of 1E-4.
- Figure 6-22c Deaggregation for 1 Hz for a hazard level of 1E-4.
- Figure 6-23 Hazard for spectral acceleration average over 3–8.5 Hz showing the contribution from the Shoreline fault source to the total hazard.
- Figure 6-24 Fractiles of the hazard for 3-8.5 Hz.
- Figure 6-25 Comparison of the mean hazard for 3-8.5 Hz with the mean hazard from the 1988 LTSP (PG&E, 1988) and with the mean hazard using the traditional ergodic assumption.
- Figure 6-26 Comparison of the 3-8.5 Hz hazard fractiles from the 1988 LTSP (PG&E, 1988) (black) with the updated results (blue).
- Figure 7-1 Detailed geology in the vicinity of the ASW pipe (this study).

**PLATE**

- Plate 1 Geologic map of the Shoreline fault zone study area, with inset

**APPENDICES**

- Appendix A Action Plans and 2009 Progress Report.....1
- Appendix B Onshore-Offshore Geologic Map .....1
- Appendix C Seismicity Reviews.....1

Appendix D	Potential Field Data—Magnetic Surveys.....	1
Appendix E	Potential Field Data—Gravity Surveys .....	1
Appendix F	Multibeam Echo Sounding Surveys.....	1
Appendix G	Coastal LiDAR Survey .....	1
Appendix H	High Resolution Marine Seismic Reflection Surveys .....	1
Appendix I	Identification and Correlation of Offshore Wave-Cut Platforms and Strandlines...	1
Appendix J	2-D Rupture with Splay Faults .....	1
Appendix K	New Directivity Models.....	1
Appendix L	Regional Earthquakes .....	1

## **GLOSSARY OF ACRONYMS AND TECHNICAL TERMS**

### **ACRONYMS**

ASW	auxiliary salt water
CCSN	Central Coast Seismic Network
CDF	core damage frequency
CRADA	Cooperative Research and Development Agreement
DCPP	Diablo Canyon Power Plant
DSHA	deterministic seismic hazard analysis
FSAR	final safety analysis report
GMPE	ground motion prediction equation
GPS	global positioning system
ISFSI	independent spent fuel storage installation
LGM	Last Glacial Maximum
LiDAR	light detection and ranging
LOSM	Los Osos–Santa Maria
LTSP	Long Term Seismic Program
MBES	multibeam echo sounding
MIS	marine oxygen isotope stage
MLLW	mean lower low water
NEHRP	National Earthquake Hazards Reduction Program
NGA	Next Generation Attenuation
NRC	U. S. Nuclear Regulatory Commission
OBS	ocean bottom seismometer
PG&E	Pacific Gas and Electric Company
PSHA	probabilistic seismic hazard analysis
RMS	root mean square
USGS	U. S. Geological Survey

## TECHNICAL TERMS

Coastline – A broad region in the vicinity of a shoreline that includes coastal landforms, such as beaches, wave-cut platforms, sea cliffs, marine terraces, and seaward-facing hill slopes.

DCPP – Diablo Canyon Power Plant The area includes the power block where the reactors and generators are located, and the adjacent support facilities.

High Stand – a still stand of sea level caused when glaciers reach temporary equilibrium between accumulating snow/ice and melting snow/ice causing rising sea level to stop before falling.

Islay shelf – The rocky portion of the inner continental shelf that lies offshore of Point Buchon. It extends from the coastline to the continental slope on the west and from Estero Bay on the north to the general latitude of the DCP on the south. It is generally characterized by wide, gently sloping subsea exposures of rock, but also includes limited areas of thin late Quaternary marine deposits and mobile sand sheet deposits.

Low Stand – a still stand of sea level caused when glaciers reach temporary equilibrium between melting snow/ice and accumulating snow/ice causing falling sea level to stop before rising.

Mean sea level (MSL) – Sea level measured at the mean of all tides in the region. This is approximately coincident with NAVD 88, the reference datum for project topographic surveys. In this study we reference all maps to NAD 83\_1983\_UTM Zone \_10N.

Mean lower-low water (MLLW) – Sea level measured at the mean of the low tides, 2.6 feet (0.8 m) below MSL in the DCP area.

Mean higher-high water (MHHW) – Sea level measured at the mean of the high tides, 2.5 feet (0.77 m) above MSL in the DCP area.

Paleoshoreline – A preserved remnant of an ancient shoreline. In the DCP area, these are discontinuous features related to sea-level highstands onshore and high- and lowstands offshore. Paleoshorelines are typically associated with wave-cut platforms and paleosea cliffs and/or paleobeaches. In the DCP area, about 10 paleoshorelines of different ages are preserved onshore and at least 10 offshore; locally, multiple closely spaced strandlines are grouped with a single paleoshoreline.

San Luis Bay fault zone – The northern group of faults in the Southwest Boundary fault zone. These consist of the San Luis Bay, Rattlesnake, and Olson faults.

Santa Rosa Reef shelf – The rocky portion of the inner continental shelf that lies offshore of Point San Luis. It extends from the coastline to the continental slope on the west and from the general latitude of the DCP on the north to the limit of bedrock outcrops south and southeast of Point San Luis. It is generally characterized by the wide, gently sloping and flat subsea exposures of rock, but also includes limited areas of thin late Quaternary marine deposits and mobile sand sheet deposits.

Shoreline – The location where the sea surface meets the land. It includes the entire tidal range.

Shoreline angle – The point (typically in profile) where a wave-cut platform meets a sea cliff. Because of natural variation in wave-cut platform surfaces, shoreline angles can be formed at a variety of elevations with respect to the tidal range, ranging from as low as MSL (approximately elevation 0 relative to NAVD 88) to a few meters above MSL. In the DCPD area, the most common elevation of shoreline angles on the modern coastline is 2 m, approximately coincident with MHHW. An ancient shoreline angle provides an approximate record of the relative sea level at the time the paleoshoreline formed.

Shoreline fault zone – The geologic structure interpreted to have produced the seismicity lineament as recognized by Hardebeck (2010).

Still Stand – Sea level remains at a constant elevation (level) for a period of a few thousand or more years during the Quaternary Period. This occurs when glacier melt and snow accumulation maintain equilibrium.

Strandline – The two-dimensional geomorphic record of sea level. On an erosional coastline (such as the Irish Hills coastline), it is marked by the intersection of a sea cliff and wave-cut platform. On a depositional coastline, it is marked (less precisely) by a beach berm. As with shoreline angles, modern strandlines in the DCPD area typically occur about 2 m above MSL, but may range from MSL to a few meters above MSL. An ancient strandline provides an approximate record of the relative sea level at the time the paleoshoreline formed.

Wave-cut platform – A broad bedrock platform that slopes gently seaward from a sea cliff. Wave-cut platforms are carved predominantly by wave erosion; however, other processes may contribute to their genesis, such as chemical and salt weathering, bio-erosion, and expansion-contraction of clays and ice.