8.0 SUMMARY AND CONCLUSIONS

In November 2008, Pacific Gas and Electric (PG&E) informed the U.S. Nuclear Regulatory Commission (NRC) that preliminary results from the Diablo Canyon Power Plant (DCPP) Long Term Seismic Program (LTSP) Update showed that there was an alignment of microseismicity indicating the presence of a previously unidentified fault located about 1 km offshore of DCPP. This previously unidentified fault was named the Shoreline fault zone.

The existence of an offshore fault zone between Point Buchon and Point San Luis had been discussed by NRC staff in 1989 in relation to the linear nature of the coastline in this area and the presence of bathymetric lineaments and escarpments parallel to the coast near Point Buchon. Prominent subsea escarpments that could be traced from Point Buchon to Point San Luis had been identified and interpreted as a series of closely spaced shoreline features that formed during previous low sea-level conditions. Although the general trend of the escarpment cuts obliquely across bathymetric contours, the individual slope breaks were subparallel to the bathymetric contours, sinuous and irregular, and thus were interpreted as submerged paleostrandlines and not as tectonically controlled features. NRC staff concluded that while the evidence presented by PG&E supported the absence of a coast-parallel fault, the presence of such a fault could not be completely ruled out (NRC, 1991, pp. 2-29 and 2-30).

As part of the notification to the NRC in 2008, PG&E conducted an initial sensitivity study to evaluate the potential impact of the Shoreline fault zone on the seismic safety of DCPP using a seismic margin approach (PG&E, 2008). A magnitude 6.5 strike-slip earthquake at a distance of 1 km from DCPP was considered, using conservative assumptions about the total length of the fault zone. The results of this sensitivity study demonstrated that the 84th percentile ground motion from the Shoreline fault zone was lower than the 1991 LTSP 84th percentile ground motion for which the plant had been evaluated and shown to have adequate margin (NRC, 1991). Therefore, PG&E concluded that the plant had adequate seismic margin to withstand the ground motions from the Shoreline fault zone. In early 2009, the NRC conducted an independent study of the potential impacts of the Shoreline fault zone on DCPP and also concluded that there was adequate seismic margin (NRC, 2009).

Although the initial seismic sensitivity studies showed that the plant has adequate margin to withstand ground motion from the potential Shoreline fault zone, both the NRC and PG&E recognized the need to better constrain the four main parameters of the Shoreline fault zone for a seismic hazard assessment: geometry (fault length, fault dip, downdip width), segmentation, distance offshore from DCPP, and slip rate. To address this need, PG&E conducted an extensive program in 2009 and 2010 to acquire and interpret new geological, geophysical, seismic, and bathymetric data as part of the PG&E LTSP Update. The following section summarizes the results of these investigations.

8.1 Shoreline Fault Zone Characterization

The 2009 and 2010 LTSP Update investigations have improved the understanding of the Shoreline fault zone, providing information on its location, geometry, segmentation, slip rate, and relationship to other structures, including the Hosgri and Southwestern Boundary faults.

8.1.1 Shoreline Seismicity Lineament

The Shoreline seismicity lineament was first identified by Hardebeck in 2008 (Hardebeck, 2010) and was subsequently verified through independent analysis by PG&E. The seismicity lineament is defined by microearthquakes ($1 \leq M < 3$) that have occurred during the period of instrumental recording (1970 to the present) along with one larger earthquake (M 3.5 on 10 August 2000). The seismicity lineament is divided into three distinct en echelon sublineaments referred to as the Northern, Central, and Southern seismicity sublineaments. The three Shoreline fault zone segments (discussed below) correspond spatially in both length and location to the three seismicity sublineaments, supporting the segmented nature of the fault zone. Two M ~5 events, on 20 October 1913 and 1 December 1916, are located in Avila Bay and could have been associated with the Southwestern Boundary zone or the South segment of the Shoreline fault zone.

8.1.2 Fault Length and Segmentation

The Shoreline fault zone is conservatively assumed to be up to 23 km long and has an overall strike of N60° W to N70° W. The Shoreline fault zone is divided into three segments based on differences in the geologic and geomorphic expression of surface and near-surface faulting, intersections with other mapped structures, features observed in the high-resolution magnetic field data, and variations in the continuity, trend, and depth of seismicity along the lineament. These segments of the Shoreline fault zone were named the North, Central, and South segments. The Shoreline fault zone appears to locally represent the reactivation of a preexisting Tertiary fault that is associated with distinct bathymetric lineaments and a pronounced series of magnetic anomalies that parallel the coast. This prior episode of faulting dates to either a mid-Miocene (~14 million years ago [Ma]) to early Pliocene (~4 Ma) period of transtensional deformation, or to a middle to late Pliocene (~3 Ma) episode of transpressional deformation.

South Segment

The South segment of the Shoreline fault zone extends from south of Point San Luis to the vicinity of Pecho Creek and Rattlesnake Creek and is approximately 7 km long. It follows a reactivated older fault that has a weak to moderate bathymetric expression, but does truncate bedding and is coincident with a strong linear magnetic anomaly.

Central Segment

The Central segment of the Shoreline fault zone extends from offshore of Pecho Creek, near the intersection with the Rattlesnake fault (the southern strand of the San Luis Bay fault zone), to Lion Rock, north of DCPP, and is approximately 8 km long. The Central segment is further subdivided into three en echelon subsegments (C-1, C-2, and C-3) based on discontinuities or steps in the bathymetric lineament. The Central segment is well expressed in the near-shore seafloor bathymetry as the result of differential erosion along the fault trace, and is associated with a series of distinct magnetic anomalies. These magnetic anomalies are spatially coincident with mapped Franciscan mélange that contain strongly magnetized metavolcanic rocks (greenstone) and serpentinite. The Central sublineament of the Shoreline seismicity lineament aligns with the preexisting Tertiary fault, within the resolution of the earthquake locations, indicating that the older fault has been reactivated in the current tectonic regime.

North Segment

The North segment of the Shoreline fault zone extends from Lion Rock, north of DCPP, to the Hosgri fault zone and is up to 8 km long, based on the extent of the Northern seismicity sublineament. While the preferred interpretation is that the North segment coincides with the location of the Northern seismicity sublineament, the bedrock surface is covered by sand sheets and marine deposits, and no faulting is visible at the seafloor. Analysis of the 2008 high-resolution seismic-reflection data indicates that the fault has produced only minor displacement in the buried Tertiary strata.

8.1.3 Fault Dip

The seismicity along the entire Shoreline lineament defines a nearly vertical zone. The magnetic anomalies along the Central segment of the Shoreline fault zone are consistent with a steeply dipping or vertical source that extends from the near-surface to a depth between approximately 0.5 and 4–5 km.

8.1.4 Downdip Width

The depth of seismicity along the Shoreline seismicity lineament is used to define the downdip width of the Shoreline fault zone. The seismicity along the Central and Southern sublineaments of the Shoreline seismicity lineament is between 2 and 10 km. Seismicity generally becomes more diffuse spatially and extends to greater depths (up to 15 km) along the Northern sublineament as it approaches the Hosgri fault zone.

8.1.5 Style of Faulting

The style of faulting is considered to be primarily right-lateral strike-slip based on the linear expression of the surface fault trace and earthquake focal mechanisms that indicate vertical right-lateral strike-slip motion.

8.1.6 Relationship to Other Structures

The Shoreline fault zone lies between the Southwestern Boundary fault zone on the south and east and the Hosgri fault zone on the west. Three alternatives are considered for the kinematic relationship of the Shoreline fault zone to these nearby structures.

In the first alternative, the Shoreline fault zone is part of a primarily strike-slip fault system that borders the southwestern margin of the uplifting San Luis Range. In this model, the Shoreline fault zone is kinematically linked to the San Luis Bay fault zone, and potentially other faults of the Southwestern Boundary fault zone (i.e., Wilmar Avenue, Los Berros, Oceano, and Nipomo faults) via left-restraining step-overs. Uplift of the San Luis range is accommodated primarily by reverse slip on the Los Osos fault zone and possibly transpressional oblique slip on the Southwestern Boundary fault zone.

In the second alternative, the Shoreline fault zone is an independent strike-slip fault within the San Luis–Pismo structural block. In this model, the Southwestern Boundary fault zone is a system of primarily reverse faults, and the Shoreline fault zone is a minor tear fault accommodating differential slip in the hanging wall of the fault zone. Uplift of the San Luis Range is accommodated by reverse slip on both the Los Osos and Southwestern Boundary fault zones.

In the third alternative, the Shoreline fault zone is an integral part of the Southwestern Boundary fault zone system of reverse-slip and oblique-slip faults. In this model, the Shoreline fault zone is kinematically linked to and may be, in part, the offshore continuation of the San Luis Bay fault zone. Uplift of the San Luis Range is accommodated by oblique slip on the Shoreline fault zone as part of the overall Southwestern Boundary fault zone.

All three alternatives are considered in the logic tree characterization of source parameters for the Shoreline fault zone. Alternatives one and two are given equal preference, assuming that the fundamental observation from seismicity that the fault zone is a near-vertical strike-slip fault. Alternative three is given a low preference, since the seismicity data and additional observations from offshore marine wave-cut platforms show little or no vertical separation across the Shoreline fault zone in the past 75,000 years.

Numerical models indicate that fault branching, where rupture begins on the Hosgri fault and then branches onto the Shoreline fault zone, would be inhibited under the current stress regime.

8.1.7 Slip Rate

The Shoreline fault zone lies entirely offshore and thus it is difficult to develop direct evidence of recent fault displacement or slip rate. The MBES bathymetric data were extensively examined to identify piercing points (i.e., potentially datable geomorphic features such as paleostrandlines or channels on both sides of the fault zone) that could be used to constrain cumulative slip and, from that, estimate slip rate. No late Quaternary piercing points have been identified to directly constrain horizontal slip across the Shoreline fault zone. In the absence of more direct information, constraints on slip rate are provided by several qualitative and indirect quantitative estimates of slip rate. These include (1) comparison of the geomorphic and structural features to the Hosgri–San Simeon fault system; (2) estimates of vertical separation based on the evaluation of submerged late-Pleistocene wave-cut platforms and paleostrandlines; (3) estimates of cumulative right-lateral strike slip based on offset of magnetic anomalies; (4) estimates of right slip on the Rattlesnake fault; and (5) seismicity rates. Based on these five estimates, the maximum horizontal slip rate on the Shoreline fault zone potentially ranges from 0.05 to possibly 1 mm/yr, with a preferred value of 0.2 to 0.3 mm/yr.

8.1.8 Location of the Shoreline Fault Zone Offshore of DCPP

The mapping based on high-resolution MBES bathymetric data clearly shows a sharp, well-defined lineament that lies offshore and west of the DCPP. This lineament is interpreted as the surface expression of the Central segment of the Shoreline fault zone. Immediately offshore of DCPP, the Central segment is located 300 m southwest of the intake structure and 600 m southwest of the power block.

8.2 Earthquake Hazard Implications for DCPP

Inclusion of the Shoreline fault zone in the seismic hazard analysis for the DCPP follows the methodology used in the original LTSP (PG&E, 1988) and uses both deterministic and probabilistic seismic hazard analyses (DSHA and PSHA, respectively). The source characterization used to model ground motions at the power block is represented in terms of a logic tree that captures the range of values that characterize each fault source. In addition to using new ground motion prediction equations (GMPEs) and the new Shoreline fault zone source, logic trees for the Hosgri, Los Osos, and San Luis Bay fault sources are based on the current understanding of those faults and the regional tectonic setting.

8.2.1 Ground Motion Results

For the deterministic analysis, the new estimates of the 84th percentile ground motion fall below the 1991 LTSP 84th percentile deterministic spectrum, indicating that the deterministic seismic margins for the new estimates of the ground motion are at least as large as those found in the LTSP.

Probabilistic hazard calculations show that the primary contribution to the total hazard at DCPP is from the Hosgri fault zone, and that both the Los Osos and Shoreline fault zones represent similar, but secondary, contributions to the hazard. The inclusion of new GMPEs and using updated source characterization, that includes the Shoreline fault zone, to the DCPP hazard model has resulted in changes to both the level and slope of the hazard curve. The hazard for 3–8.5 Hz spectral acceleration is lower than the LTSP hazard for spectral acceleration less than 3.0 g and is greater than the LTSP for spectral accelerations greater than 3.0 g. This change in the hazard curve is primarily due to the change in the ground motion models. The NGA models result in lower median ground motions for sites close to large earthquakes, but with an increased standard deviation. The flattening of the new hazard compared to the LTSP hazard curves is due to the larger standard deviation. Because the updated hazard curve is not enveloped by the 1988 LTSP hazard curve, the seismic core damage frequency (CDF) has been reevaluated. The seismic CDF estimated during the 1988 LTSP is 3.8E-5. Using the revised source characterization and ground motion models decreases the seismic CDF to 2.1 E-5. The reduction is mainly due to the use the NGA ground motion models with the single-station sigma approach incorporating the site-specific amplification.

8.2.2 Secondary Fault Deformation Results

The analysis presented in this report addresses the potential for secondary fault deformation associated with rupture of the Shoreline fault zone using a deterministic approach and concludes that secondary deformation does not affect the safety of the DCPP. The deterministic assessment of the geology at the DCPP site and vicinity documented the absence of late Quaternary primary or secondary surface faulting or other forms of late Quaternary tectonic deformation (e.g., tilting, folding, and subsidence) within the DCPP site that may be associated with a conservative maximum M 6.5 earthquake on the nearby Shoreline fault zone. These investigations encompassed the entire 750 m wide control zone east of the Shoreline fault zone, including the entire DCPP site, and included detailed mapping of onshore marine terraces, detailed geologic mapping of the sea cliffs directly west of the DCPP site, and review of the initial site investigations that were conducted for the FSAR.

8.3 Continued Studies

The original completion date of 2011 for the LTSP Update, as stated in the Action Plan and Revised Action Plan (Appendix A-1 and A-3), has been extended to allow completion of additional studies to further refine the models presented in this report. These studies include three-dimensional (3-D) marine and two-dimensional (2-D) onshore seismic reflection profiling, additional potential field mapping, GPS monitoring, and the feasibility of installing an ocean bottom seismograph network. These activities will further refine the characterization of those seismic sources and ground motions most important to the DCPP: the Hosgri, Shoreline, Los Osos, and San Luis Bay fault zones and other faults within the Southwestern Boundary zone.