Appendix F: Earthquake Catalogs

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LIST OF ABBREVIATIONS AND ACRONYMS

3D	three-dimensional
ANSS	Advanced National Seismic System
CCSN	Central Coast Seismic Network
CISN	California Integrated Seismic Network
DCPP	Diablo Canyon Power Plant
FGM	Fault Geometry Model
LTSP	Long Term Seismic Program
NCEDC	Northern California Earthquake Data Center
NSHMP	National Seismic Hazard Mapping Project
OADC	optimal anisotropic dynamic clustering
PG&E	Pacific Gas and Electric Company
SSC	seismic source characterization
TI	technical integration
UCERF	Uniform California Earthquake Rupture Forecast
USGS	U.S. Geological Survey

F.1.0 INTRODUCTION

Several earthquake catalogs were considered for different uses during development of the Diablo Canyon SSC model (Table F-1). We group these catalogs into three categories based on their application to the Diablo Canyon SSC. Catalogs providing event location information are described in *Section F.2.0* of this appendix. Catalogs of focal mechanisms used for kinematic information are described in *Section F.3.0*. Catalogs providing information about regional earthquake rates are described in *Section F.4.0*. Attachments to this appendix contain electronic files with catalogs that are not otherwise publicly accessible.

Table F-1. Earthquake Catalogs Considered in the Diablo Canyon SSC Model

Category	Catalog	Description	Catalog Duration and Magnitude Range	Application to the SSC Model
Event Location	Hardebeck (2010)	Earthquake relocations using tomoDD and hypoDD	10/1/1987 to 12/31/2008 $M \geq 0.0$	• Fault location and dip • Maximum depth of faulting • Extent of Local areal source zone
	Hardebeck (2014a)	Earthquake relocations using tomoDD and hypoDD (supersedes Hardebeck, 2010)	10/1/1987 to 12/31/2013 $M \geq 0.0$	• Fault location and dip • Maximum depth of faulting • Extent of Local areal source zone
	McLaren and Savage (2001) (their appendix)	DCPP subregion catalog of historical earthquakes	1830 to 1/31/1997 $M \geq 5$	• Location and magnitude of largest recorded earthquakes in the DCPP subregion for fault source characterization • Mmax assessment of areal source zones
Kinematic Information	Hardebeck (2010)	HASH single-event and composite focal mechanisms	10/1/1987 to 12/31/2008 $M > 0.0$	• Fault kinematics • Orientation of maximum principal stress and maximum shortening strain axes within the San Luis–Pismo block (SLPB)
	NCEDC (2013)	FPFIT single-event focal mechanisms	1/1/1968 to 6/3/2013 $M > 0.0$	• Fault kinematics • Orientation of maximum principal stress and maximum shortening strain axes within the SLPB

Category	Catalog	Description	Catalog Duration and Magnitude Range	Application to the SSC Model
Regional Earthquake Rates	PG&E catalog	Subregion catalog for DCPP seismic hazard evaluation	3/25/1806 to 2/6/2009† **M** ≥ 3	• Adjustments to the baseline seismicity rates for the Vicinity and Local areal source zones
	Felzer and Cao (2008)	Statewide catalog developed for Uniform California Earthquake Rupture Forecast, Version 2 (UCERF2)	1/1/1850* to 12/31/2006 *M* ≥ 5.5 (1850–1932) *M* ≥ 4.0 (after 1932)	• Development of the 2008 NSHMP gridded seismicity file (Petersen et al., 2008), the baseline rate model for the areal source zones
	Felzer (2013)	Statewide catalog developed for Uniform California Earthquake Rupture Forecast, Version 3 (UCERF3)	1/1/1850* to 12/31/2011 *M* ≥ 5.5 (1850–1932) *M* ≥ 4.0 (1932–1984) *M* ≥ 2.5 (after 1984)	• Adjustments to the baseline seismicity rates for the Vicinity and Local areal source zones
	Updated UCERF3	Updated UCERF3 catalog through January 2014	1/1/1850* to 1/31/2014 *M* ≥ 5.5 (1850–1932) *M* ≥ 4.0 (1932–1984) *M* ≥ 2.5 (after 1984)	• Adjustments to the baseline seismicity rates for the Vicinity and Local areal source zones

† This catalog was updated through December 31, 2013, for the Vicinity and Local areal source zones used in the Diablo Canyon SSC model.
* This catalog reflects an attempt at completeness at the stated magnitude thresholds from 1850 on; however, several pre-1850 earthquakes are included in the catalog.

F.2.0 CATALOGS USED FOR EARTHQUAKE LOCATION INFORMATION

Three catalogs were used by the TI Team for earthquake location information for the Diablo Canyon SSC model. Two of these catalogs—Hardebeck (2010) and Hardebeck (2014a)—are earthquake relocation catalogs of relatively well-instrumented events within the past few decades. The third catalog—McLaren and Savage (2001)—lists and describes historical earthquakes before 1997 of larger magnitude (~$M \geq 5$) from central coastal California, with the earliest recognized such earthquake occurring in 1830.

F.2.1 Hardebeck (2010) Catalog

The Hardebeck (2010) catalog contains earthquakes from two seismic networks: (1) the California Integrated Seismic Network (CISN), which is operated by the U.S. Geological Survey, Caltech, and University of California, Berkeley, and (2) the Central Coast Seismic Network (CCSN), which is operated by PG&E. The catalog includes earthquakes that occurred from October 1, 1987, through the December 31, 2008. Depending on the earthquake location, hypocenters of catalog events are relocated using one of two double-difference codes. Catalog events that occurred near the DCPP—referred to as the San Luis Obispo subregion (Figure F-1)—are relocated using the double-difference tomography program known as tomoDD (Zhang and Thurber, 2003). TomoDD is a computationally intensive tomography code that incorporates ray tracing in a 3D velocity model, which improves absolute earthquake locations, and differential travel-time data, which improves relative locations of nearby earthquakes (Hardebeck, 2010). Outside the San Luis Obispo subregion, catalog events are first relocated using 3D velocity models for the region (developed in Hardebeck, 2010) and the San Simeon aftershock zone (McLaren et al., 2008). The earthquakes are then relocated again using the hypoDD code (Waldhauser and Ellsworth, 2000) to refine the relative locations. To improve relative arrival-time information and earthquake relocations, Hardebeck (2010) implements waveform cross-correlation (e.g., Schaff et al., 2004). The absolute earthquake location uncertainty is constrained to be ≤1.2 km horizontally and ≤1.3 km vertically based on shot relocations in the 3D model (Hardebeck, 2010). In addition to the earthquake relocations, Hardebeck (2010) calculates single-event and composite focal mechanisms using the HASH algorithm (Hardebeck and Shearer, 2002). These focal mechanisms are described in more detail in *Section F.3.0*.

The uncertainties and robustness of the Hardebeck (2010) offshore earthquake relocations between the latitudes of 35.1°N to 35.3°N were evaluated by Thurber (2011) and Waldhauser (2011). In assessing the Hardebeck (2010) tomography results through waveform cross-correlation analysis and re-running of the tomoDD analysis, Thurber (2011) concludes that a coarser velocity model grid would have been more appropriate; however, the tomography results are stable because of the heavy smoothing that Hardebeck applies. Thurber also finds the uncertainties reasonably small enough to warrant confidence in the Hardebeck (2010) offshore earthquake locations. Waldhauser (2011) performs a similar test of the robustness and uncertainty of the Hardebeck (2010) offshore earthquake locations through double-difference relocations using hypoDD. Waldhauser finds that, on average, the resolution in relative hypocenter locations is ≤0.2 km in horizontal directions and ≤0.7 km in vertical directions.

F.2.2 Hardebeck (2014a) Catalog

The Hardebeck (2014a) catalog is an update of the Hardebeck (2010) dataset and was provided to PG&E and the SSC TI Team in early 2014 (Attachment F-1). The catalog includes earthquakes through the end of 2013. The events in this catalog occurring outside the San Luis Obispo subregion are relocated using the same methodology as in Hardebeck (2010). Within the

San Luis Obispo area, Hardebeck attempts to update the 3D velocity model using the new (post-2008) data and quarry blast data. However, the new model is effectively identical to the 3D model in Hardebeck (2010), and the majority of earthquakes present in both catalogs have only minor shifts in location. On Figure F-2, we compare epicenter locations for the 975 events that are common to both the 2010 and 2014 catalogs within the San Luis Obispo subregion. The horizontal position change is less than 1 km for 84% of the events, and fewer than 5% of the events are moved more than 2 km (Figure F-2a); the mean and median horizontal position changes are 0.67 km and 0.49 km, respectively. Figure F-2b shows the distribution of the change in depth between the 2010 and 2014 catalog, where negative values imply that the depth in 2014 was shallower than in 2010, and positive values imply that the 2010 depth was shallower. Although the median of the distribution is 0 km depth change between catalogs, the mean and mode 2010 depths are 0.10 km and 0.54 km, respectively, which is deeper than reported in the 2014 catalog. The 2014 catalog is considered the most accurate catalog in terms of depth and location of hypocenters; however, the horizontal position and depth change distributions on Figure F-2 highlight the similarities of the two Hardebeck catalogs. Both the 2010 and 2014 catalogs were developed and used for location information and not for earthquake rates in the Diablo Canyon SSC model. Declustering and magnitude conversion to a uniform magnitude scale were not performed on either catalog.

The Hardebeck (2010, 2014a) catalogs have several applications in the Diablo Canyon SSC, as follows:

- Constraining the geometry of the Hosgri and Shoreline faults (*Chapter 7*).
- Evaluating the maximum depth of faulting (D90 and D95 analysis; *Chapter 7*).
- Defining the Local areal source zone extent and the orientation of virtual faults within the source zone (*Chapter 13*).
- Defining the optimal anisotropic dynamic clustering (OADC) planes published in Hardebeck (2013) and the OADC-FM planes presented at Workshop 3 by Hardebeck (2014b), which were considered in the development of the Fault Geometry Models (FGMs; *Chapter 7*) and virtual faults (*Chapter 13*).

F.2.3 McLaren and Savage (2001) Catalog

A listing and evaluation of historical earthquakes of approximately $M \geq 5$ was published by McLaren and Savage (2001), based in large part on the work conducted by PG&E for the Long Term Seismic Program (LTSP; PG&E, 1988, 1991). The historical earthquakes are discussed briefly in an appendix to McLaren and Savage (2001), along with the best estimates of their locations. The application of this catalog to the Diablo Canyon SSC was in documenting that Primary faults in the SSC model have no evidence for historical large ($M \geq 6$) earthquakes (*Chapter 5*). This information was used for documenting the following:

- The lack of constraint for fault geometry from historical large ruptures for the Fault Geometry Models (*Chapter 7*).
- The lack of historical constraints on the characteristic or maximum earthquakes for the Magnitude Distribution Model (*Chapter 10*).

- The constraint on the time since the most recent “resetting” earthquake for the Time Dependency Model (*Chapter 11*).

The McLaren and Savage (2001) historical catalog is also used in the Diablo Canyon SSC to locate the 1927 Lompoc earthquake and identify a regional fault source associated with that earthquake (*Chapter 12*).

F.3.0 CATALOGS USED FOR KINEMATIC INFORMATION

Three focal mechanism catalogs provide kinematic information to help inform the Diablo Canyon SSC model: the Hardebeck (2010) single-event and composite focal mechanism catalogs and the NCEDC (2013) focal mechanism catalog.

F.3.1 Hardebeck (2010) Single-Event and Composite Focal Mechanism Catalogs

Hardebeck (2010) provides two of these catalogs: a single-event catalog and a composite focal mechanism catalog. These catalogs include earthquakes that occurred between October 1, 1987, and December 31, 2008. The focal mechanisms were calculated using the HASH algorithm of Hardebeck and Shearer (2002) and were derived using machine phase and hand picks and a 3D velocity model. The focal mechanisms were assigned a quality rating of “A” through “D.” The quality ratings of “A” through “C” were based on criteria presented in Hardebeck and Shearer (2002): percent misfit of polarities, root-mean-square difference between acceptable mechanisms and the preferred mechanism, station distribution ratio, and probability that the given solution is better than any other solution. Lower-quality events that did not meet one or more of the Hardebeck and Shearer (2002) criteria for quality “A” through “C” were either assigned a rating of “D,” based on examination of polarity data and visual inspection of the solutions by Dr. Hardebeck, or they were removed from the catalogs. All acceptable solution earthquakes $M > 0$ are included. Hardebeck (2010) calculated composite focal mechanisms in areas that were judged poorly sampled (offshore and the southern end of the 2010 study area). The composite focal mechanisms are made up of earthquakes that appear spatially clustered or are interpreted as forming seismicity lineaments.

F.3.2 NCEDC (2013) Catalog

The NCEDC (2013) catalog contains network mechanisms calculated automatically using the FPFIT algorithm (Reasenberg and Oppenheimer, 1985) from machine phase and hand picks (Attachment F-2). This catalog was downloaded from the Northern California Earthquake Data Center (NCEDC) website and cleaned as part of an evaluation in 2013 of the contemporary stress and strain fields of central coastal California (PG&E, 2015). The catalog includes earthquakes that occurred from January 1, 1968, through June 3, 2013, in the area of 34°N to 35.75°N and 121.5°W to 120.5°W. All earthquakes $M > 0$ are included.

The focal mechanism catalogs had the following applications in the Diablo Canyon SSC:

- Used to constrain the principal stress and strain orientations and possible styles of deformation in the Diablo Canyon region (PG&E, 2015; *Chapter 5*).

- Considered in the development of the FGMs (*Chapter 7*).
- Considered in the development of the Local and Vicinity areal source zones (*Chapter 13*).

F.4.0 CATALOGS USED FOR EARTHQUAKE RATE INFORMATION

Four catalogs provide information about magnitude and regional earthquake rates for the Diablo Canyon SSC model: the PG&E catalog (Attachment F-3), the Felzer and Cao (2008) catalog, the Felzer (2013) catalog, and the updated UCERF3 catalog (Attachment F-4).

F.4.1 PG&E Catalog

The PG&E catalog was compiled for DCPP seismic hazard evaluation. This catalog is included as Attachment F-3 and contains earthquakes $M \geq 3$ that have occurred between March 25, 1806, and February 6, 2009, within a rectangular area 34° to 36.75° latitude and –123° to –119° longitude approximately centered on the DCPP. A portion of this catalog was updated through December 2013 for the Vicinity areal source zone (35° to 35.5° latitude and –121.1° to –120.6° longitude; *Chapter 13*). Note that no earthquakes $M \geq 3$ have occurred within the Vicinity areal source zone since February 6, 2009. Figure F-3 shows the portion of the catalog from 1984 through February 6, 2009, within the DCPP subregion. Earthquakes of magnitude $M \geq 5$ are labeled with the year they occurred. We refer to McLaren and Savage (2001) for location and magnitude information about historical $M \geq 5$ earthquakes. All magnitudes in the PG&E catalog are converted to moment magnitude (**M**). Aftershocks and foreshocks are identified using the CLUSTER2000 algorithm (Reasenberg, 1985).

F.4.2 Felzer and Cao (2008) Catalog

The Felzer and Cao (2008) catalog was compiled for UCERF2 and was the input catalog to develop the gridded seismicity rate file used for the 2008 National Seismic Hazard Mapping Project (NSHMP; Petersen et al., 2008). The Felzer and Cao (2008) catalog was extended to develop the later UCERF3 catalog (Felzer, 2013) and the updated UCERF3 catalog (Attachment F-4). Covering the area 31° to 43° latitude and –126° to –114° longitude, the Felzer and Cao (2008) catalog extends approximately 100 km beyond the California border (offshore and onshore) to include earthquakes $M \geq 5.5$ that could potentially cause damage within California. The catalog contains all known $M \geq 5.5$ earthquakes that occurred from 1850 to 1932 and all known $M \geq 4.0$ earthquakes that occurred from 1932 to 2006, although some $4.0 \leq M \leq 5.5$ earthquakes that occurred before 1932 are included. Felzer and Cao (2008) state that a goal of the catalog was completeness from 1850 on at these magnitude thresholds, but several pre-1850 earthquakes are included in the catalog. The magnitudes of events that occurred between 1850 and 1932 were solved for from intensity estimates from felt reports, which are often subjective and lack sufficient intensity data. These events were derived from several catalogs, including those of Toppozada and Branum (2002) and Bakun (1999, 2000, 2006). Given the uncertainty in these data, Felzer and Cao (2008) compare the Toppozada and Branum catalog to the Bakun catalogs and their respective methods, describing the advantages of each.

Within central coastal California and the subregion surrounding the DCPP, there are few differences between the Felzer and Cao (2008) and McLaren and Savage (2001) catalogs for the historical $M \geq 5$ earthquakes. One difference of note is the location of the 1927 Lompoc earthquake, which was the subject of much investigation during the LTSP (PG&E, 1988, 1991). The location of this earthquake is discussed in *Chapter 12*.

Aftershocks and foreshocks were classified in the Felzer and Cao (2008) catalog using the Gardner and Knopoff (1974) declustering algorithm. In addition, the catalog includes magnitude error (one standard deviation) and magnitude rounding estimates. Earthquake magnitudes are not converted to a uniform magnitude scale.

F.4.3 Felzer (2013) Catalog

The Felzer (2013) catalog was compiled for UCERF3 and extends the Felzer and Cao (2008) catalog through the end of 2011. Earthquakes that occurred before 1932 are identical to those in the Felzer and Cao (2008) catalog; however, between 1932 and 1984, only earthquakes $M \geq 4.0$ are included. Between 1984, the year the statewide seismic network was updated and catalog completeness improved, and 2011, earthquakes $M \geq 2.5$ are included (Felzer, 2013). Declustering, magnitude error, and magnitude rounding estimates followed procedures identical to those of Felzer and Cao (2008).

F.4.4 Updated UCERF3 Catalog

An update to the UCERF3 catalog for the Diablo Canyon SSC study was compiled by PG&E. This catalog, which is provided as Attachment F-4, lists the same earthquakes contained in the Felzer (2013) catalog through the end of 2011, with the addition of earthquakes $M \geq 2.5$ downloaded from the Advanced National Seismic System (ANSS) catalog through the end of 2014 that occurred within approximately 320 km (200 mi.) of the DCPP. Figure F-4 shows the portion of this catalog from 1984 through January 2014, within the same subregion surrounding the DCPP as Figure F-3, which is complete for magnitude $M \geq 2.5$. Similar to Figure F-3, earthquakes of magnitude $M \geq 5$ on Figure F-4 are labeled with the year they occurred. The earthquakes added by PG&E to this catalog do not contain a description of magnitude type or source. As with the Felzer and Cao (2008) and Felzer (2013) catalogs, Karen Felzer declustered these additional earthquakes using the Gardner and Knopoff (1974) routine.

In the Diablo Canyon SSC model, the PG&E catalog and the updated UCERF3 catalog were used to evaluate and adjust the baseline 2008 NSHMP gridded seismicity rate file for the Vicinity and Local areal source zones (*Chapter 13*).

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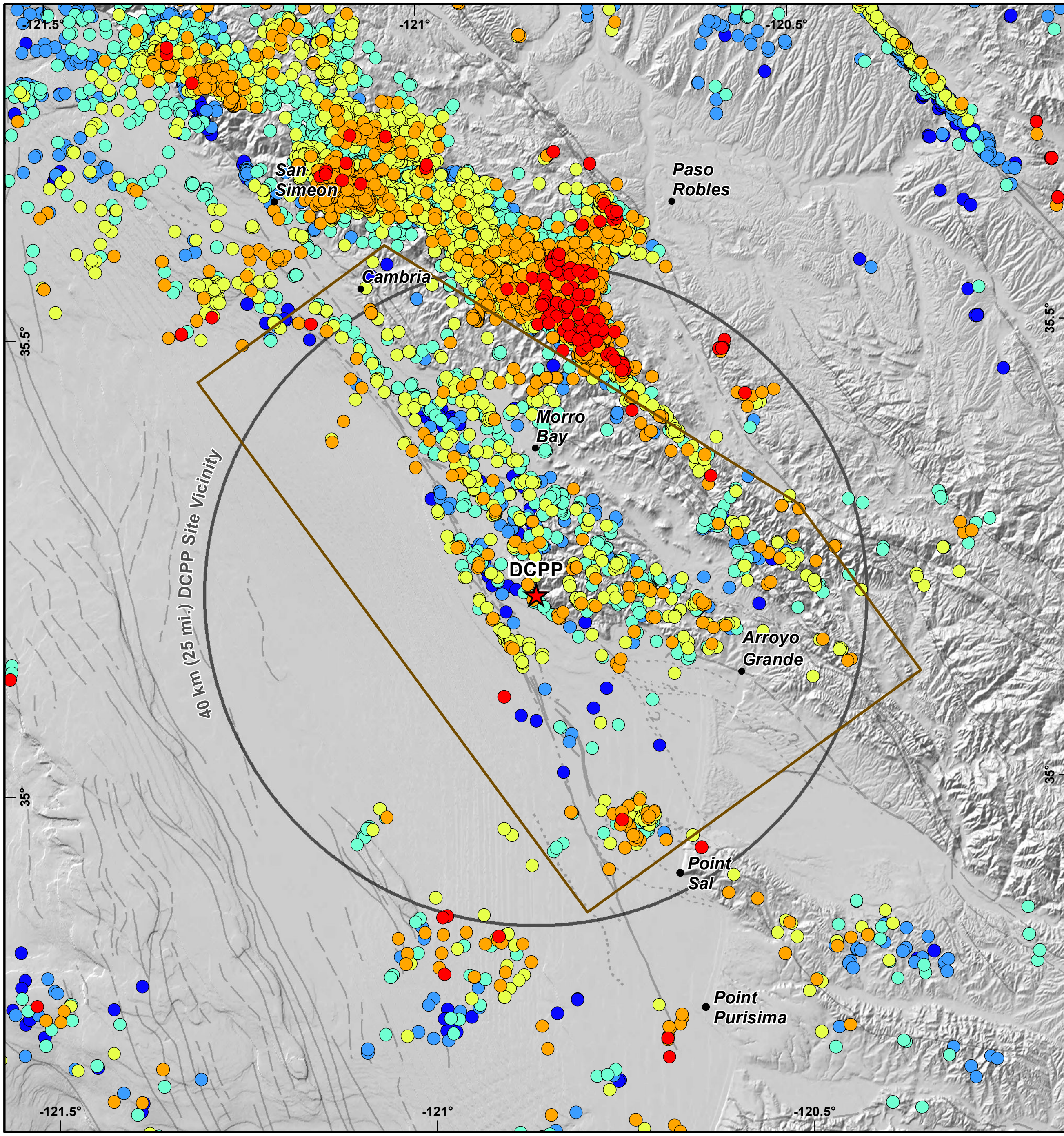

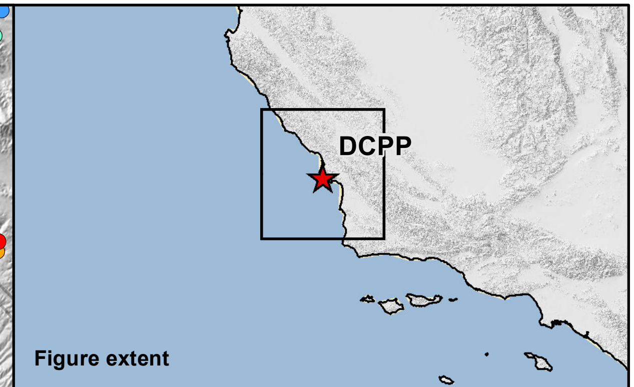

EXPLANATION

★ DCPP

Quaternary fault trace; solid where well located, dashed where approximately located, dotted where buried, short dashed where inferred, queried where existence is uncertain.

San Luis Obispo subregion bounding box

Seismicity
depth (km)

- 0 - 2
- 2 - 4
- 4 - 6
- 6 - 9
- 9 - 12
- > 12

Note: Events within the brown box were relocated using tomoDD. Events outside of the box were relocated using 3D models and hypoDD.

Source: Hardebeck (2014a).

N

0 10 20 mi.

0 20 40 km

Map projection and scale: WGS 84 / UTM 10N, 1:750,000

Hardebeck (2014a) Seismicity Catalog, 1987 through 2013

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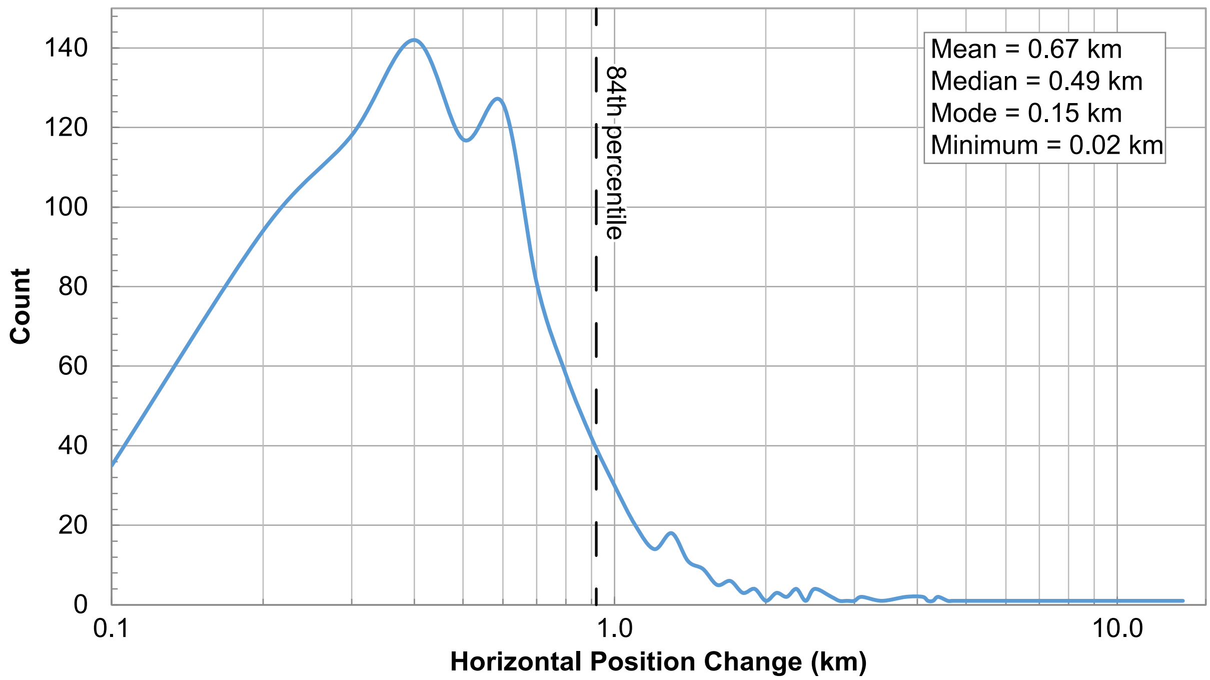
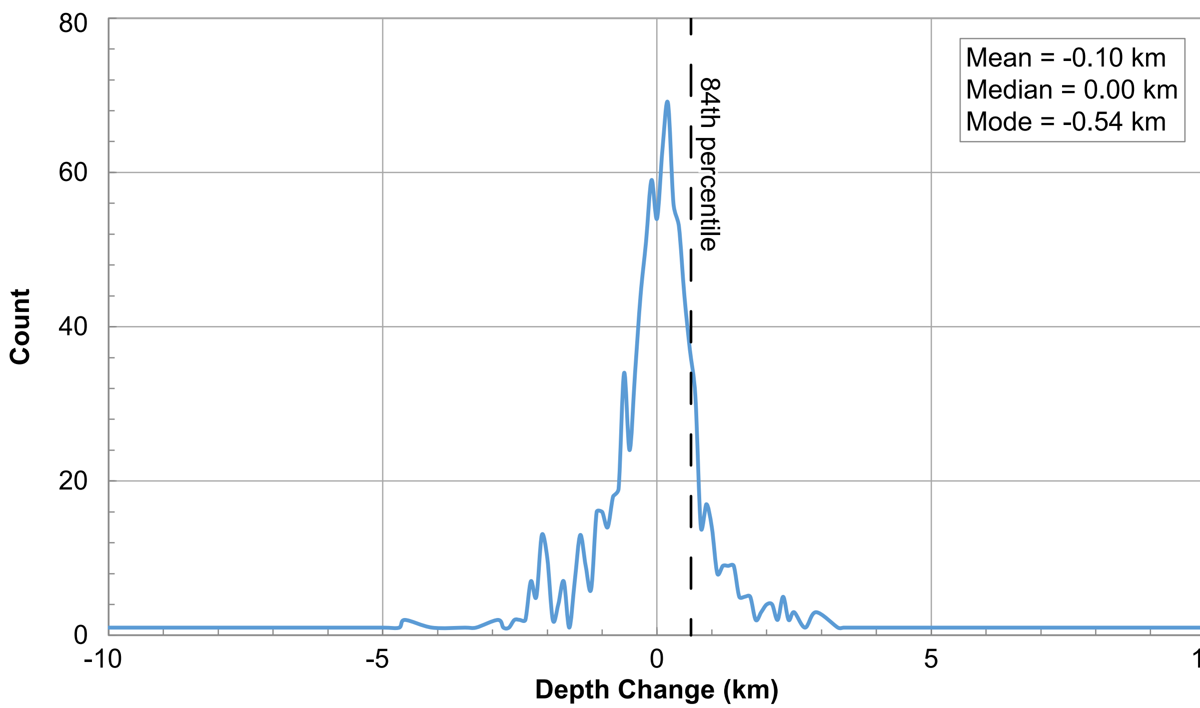
(a) Distribution of 2010 to 2014 Horizontal Position Changes



(b) Distribution of 2010 to 2014 Depth Changes



Note: The location of 975 events within the San Luis Obispo subregion that were common to both the 2010 and 2014 catalogs were compared.

Sources:
- Hardebeck (2010) seismicity catalog.
- Hardebeck (2014a) seismicity catalog.

Earthquake Location Difference Statistics Between Hardebeck (2010) and Hardebeck (2014a) in the San Luis Obispo Subregion

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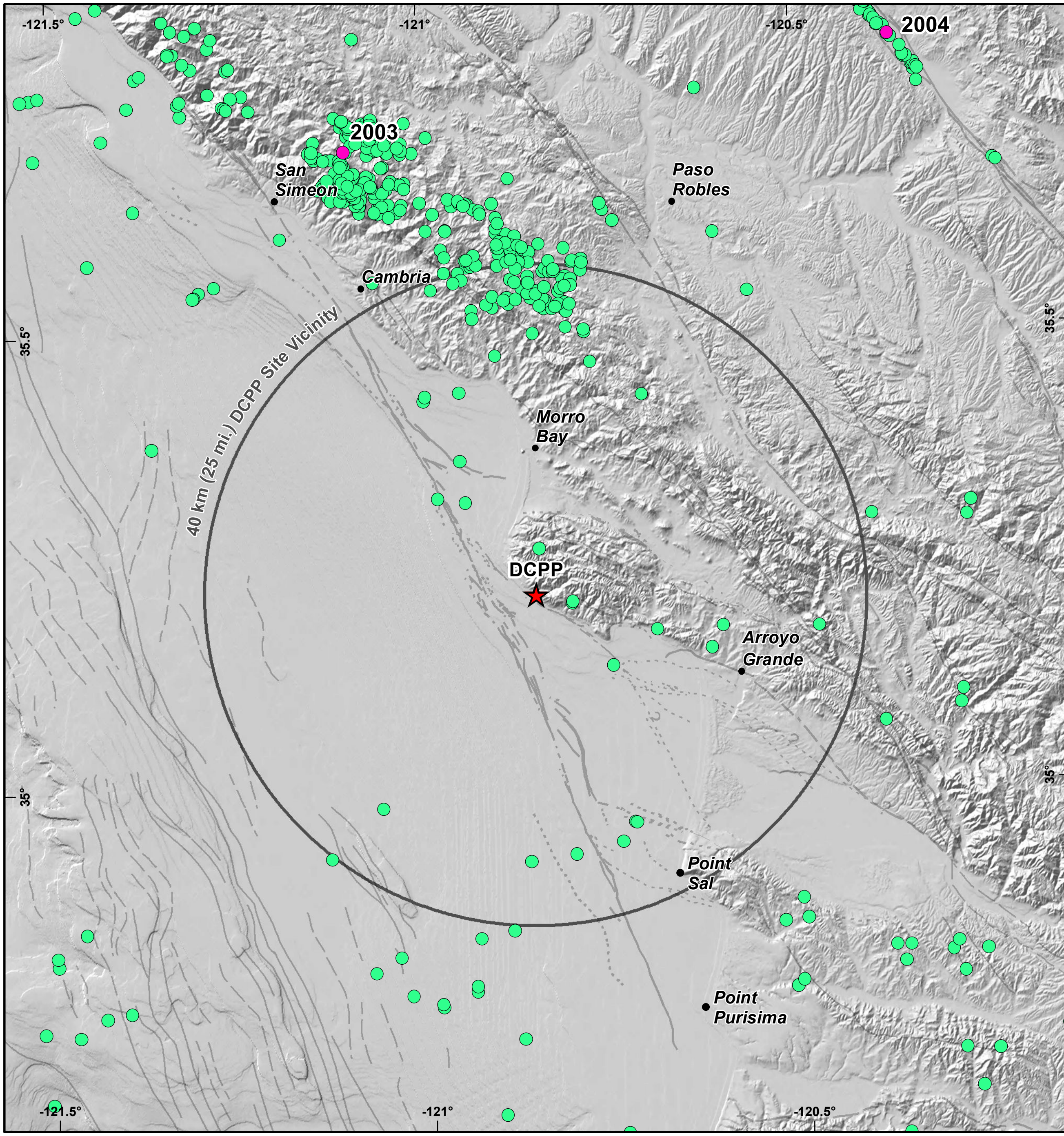
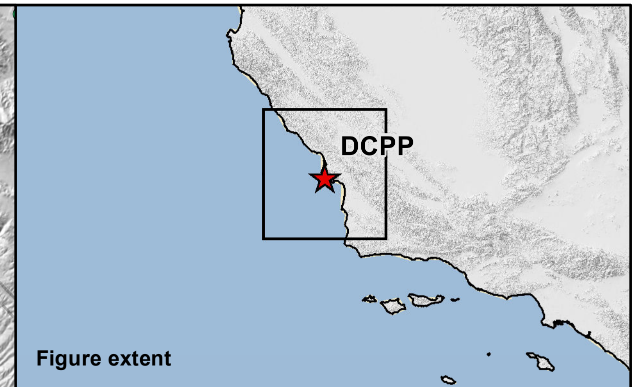
Figure **F-2**





EXPLANATION

★ DCPP

Quaternary fault trace; solid where well located, dashed where approximately located, dotted where buried, short dashed where inferred, queried where existence is uncertain.

Seismicity
(magnitude)

- 3.00 - 4.99
- 5.00 - 6.55

Note: Seismicity was binned by magnitude according to the minimum magnitude defining areal source zones (M≥3) and the minimum magnitude of engineering. significance (M≥5).

Source: Attachment F-3.

N

0 10 20 mi.

0 20 40 km

Map projection and scale: WGS 84 / UTM 10N,1:750,000

PG&E Seismicity Catalog Developed for Seismic Hazard Evaluation of the DCPP, 1984 through February, 2009

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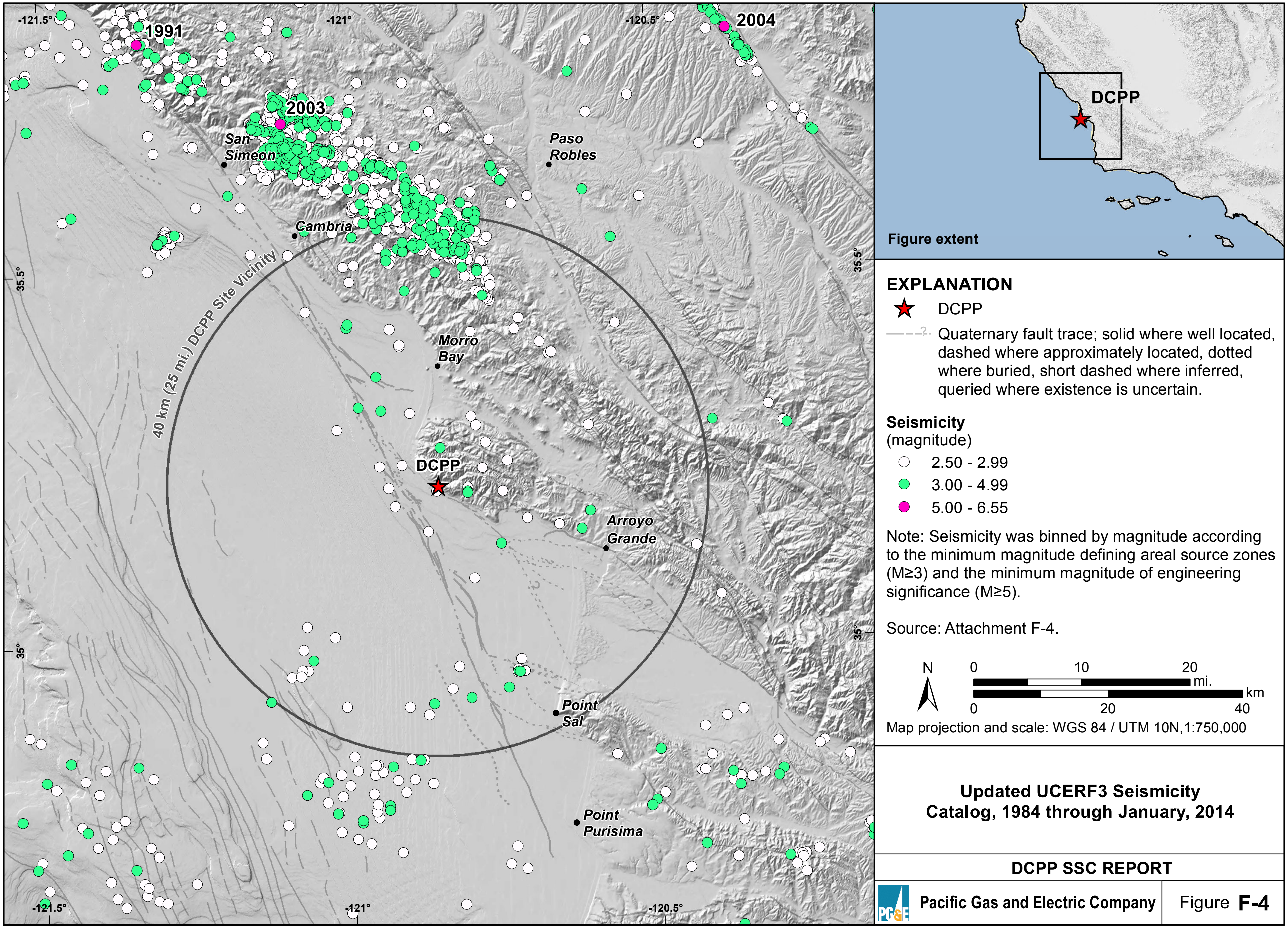
Pacific Gas and Electric Company | Figure **F-3**

File path: S:\1005\005\Final_Report_Figures\Appendices_Figures\EQ_Catalog\Figure_F-3.mxd; Date: 02/27/2015; User: Alex Remar, LCI; Rev.1

File path: S:\1005\005\Final_Report_Figures\Appendices_Figures\EQ_Catalog\Figure_F-4.mxd; Date: 02/26/2015; User: Alex Remar, LCI; Rev.1



EXPLANATION

DCPP

Quaternary fault trace; solid where well located, dashed where approximately located, dotted where buried, short dashed where inferred, queried where existence is uncertain.

Seismicity
(magnitude)

- 2.50 - 2.99
- 3.00 - 4.99
- 5.00 - 6.55

Note: Seismicity was binned by magnitude according to the minimum magnitude defining areal source zones (M≥3) and the minimum magnitude of engineering significance (M≥5).

Source: Attachment F-4.

N

0 10 20 mi.

0 20 40 km

Map projection and scale: WGS 84 / UTM 10N,1:750,000

Updated UCERF3 Seismicity Catalog, 1984 through January, 2014

DCPP SSC REPORT

Pacific Gas and Electric Company | Figure **F-4**