Independent Peer Review Panel

A multi-agency panel of seismic hazard specialists
established by the California Public Utilities Commission

CALIFORNIA GEOLOGICAL SURVEY, CALIFORNIA COASTAL COMMISSION
CALIFORNIA PUBLIC UTILITIES COMMISSION, CALIFORNIA ENERGY COMMISSION
CALIFORNIA SEISMIC SAFETY COMMISSION, COUNTY OF SAN LUIS OBISPO

IPRP Report No. 7, November 21, 2014

Comments on PG&E's Central Coastal California Seismic Imaging Project Report part 1: offshore seismic studies intended to reduce the uncertainty in seismic hazard at Diablo Canyon Power Plant

BACKGROUND

In 2006, the California Legislature enacted Assembly Bill (AB) 1632, which was codified as Public Resources Code Section 25303. AB 1632 directed the California Energy Commission (CEC) to assess the potential vulnerability of California's largest baseload power plants, which includes Diablo Canyon Power Plant (DCPP), to a major disruption due to a major seismic event and other issues. In response to AB 1632, in November 2008 the CEC issued its findings and recommendations in its AB 1632 Report, which was part of its 2008 Integrated Energy Policy Report Update.

In Pacific Gas and Electric Company's (PG&E) 2007 General Rate Case decision D.07-03-044, the California Public Utilities Commission (CPUC) directed PG&E to address and incorporate the recommendations from the AB 1632 Report into its feasibility study to extend the operating licenses of its Diablo Canyon Units 1 and 2 for an additional 20 years.

In November 2009, PG&E submitted its formal application with the Nuclear Regulatory Commission (NRC) to extend the licenses of DCPP Units 1 and 2. In 2010 PG&E filed for cost recovery with the CPUC for expenditures associated with the enhanced seismic studies recommended by the CEC's AB 1632 Report. The motions for cost recovery were subsequently approved in 2010 and 2011. CPUC Decision D.10-08-003, issued on August 16, 2010, established that the CPUC would convene its own Independent Peer Review Panel (IPRP) and invite the CEC, the California Geological Survey (CGS), the California Coastal Commission, and the California Seismic Safety Commission to participate on the panel. Under the auspices of the CPUC, the IPRP is conducting an independent review of PG&E's seismic studies including independently reviewing and commenting on PG&E's study plans and the findings of the studies.

The comprehensiveness, completeness, and timeliness of these studies will be critical to the CPUC's ability to assess the cost-effectiveness of Diablo Canyon's proposed license renewal. As noted in the CEC's AB 1632 Report, a major disruption because of an earthquake or plant aging could result in a shutdown of several months or even cause the retirement of one or more of the plants' reactors. A long-term plant shutdown would have economic, environmental and reliability implications for California ratepayers.

This report by the IPRP responds to reports released by PG&E on September 10, 2014. Those reports are collectively referred to as the Central Coastal California Seismic Imaging Project (CCCSIP) report. The CCCSIP report is divided into 14 chapters focused on individual studies. This review, and subsequent reviews of the CCSIP, are divided into sections based on factors that are important to seismic hazard analysis and the studies intended to help constrain those factors. In this organization and emphasis, these reports by the IPRP follow the format of IPRP reports 2 and 3 and refer to investigation "targets" described in a memo report "Response to IPRP Request for Hazard Sensitivity for Targets for the DCPP Geophysical Surveys," that was prepared by the PG&E Geosciences Department and dated August 8, 2011. Due to the large volume of information in the CCCSIP report, the IPRP chose to review it in three parts. The first part includes offshore seismic studies and the hazard parameters that they are designed to study. These studies, Chapters 2 and 3 of the CCCSIP report, were the subject of a public meeting on October 23, 2014 and of this report.

At the IPRP meeting on October 23, 2014, PG&E project manager Stuart Nishenko presented an update of the "tornado diagram" from the 8/11/2011 memo report. In the updated "tornado diagram" (Figure 1), the distance between points related to a hazard parameter is based on uncertainty in seismic hazard resulting from that parameter. In this type of diagram, parameters that are poorly constrained and have a large effect on hazard

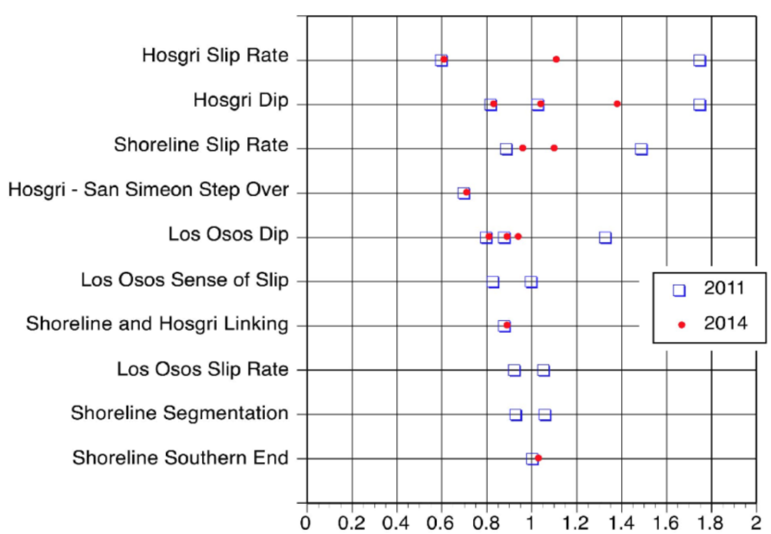

Figure 1. "Tornado diagram" from CCCSIP report, chapter 14, showing seismic hazard parameters and related uncertainty in seismic hazard. Values depicting state of knowledge in 2011 and 2014 show reduction in uncertainty related, in part, to CCCSIP studies.

are shown as widely separated points at the top of the diagram. Closely spaced points shown near the base of the diagram can be either parameters that are well-constrained or parameters that are poorly-constrained but have slight effect on hazard. As stated by Dr. Nishenko, reducing the uncertainty in the parameters near the top of the “tornado” will have the greatest effect in reducing the uncertainty in hazard. The depiction of uncertainty in 2011 and 2014, particularly the lower uncertainty for the parameters at the top of the “tornado” show how much studies described in the CCCSIP report have decreased the uncertainty in seismic hazard. Due to the limited time between the issuing of the CCCSIP report and this review, the IPRP has not independently calculated the uncertainty in hazard related to these parameters, but finds that the pattern of reduction in uncertainty is consistent with the updated data and its expected impact on seismic hazard calculations. The IPRP notes that the parameters shown on the “tornado diagram” are all “seismic source characterization” parameters, other parameters, especially “site conditions” or “site amplification” parameters can have equal or greater impact on seismic hazard calculations as any shown on Figure 1. Site conditions and seismic amplification factors were the subject of IPRP Report #6 and sections of the CCCSIP report. Those factors will be addressed in a subsequent IPRP report.

Parameters addressed in Chapters 2 and 3 of the CCCSIP report and discussed here are:

- Hosgri slip rate
- Shoreline slip rate and southern extent
- Shoreline - Hosgri Intersection

For each of these parameters, the previous review comments and recommendations of the IPRP will be briefly summarized, followed by current review comments on the CCCSIP report and PG&E presentations.

HOSGRI –SLIP RATE

Background

The slip rate of the Hosgri fault was identified as the most significant hazard parameter on the PG&E tornado diagram. IPRP Report No. 2 recognized this and recommended further studies to decrease the uncertainty in the seismic hazard at Diablo Canyon by better constraining the slip rate on the Hosgri fault. At that time PG&E had not yet presented specific plans to better constrain the Hosgri fault slip rate. In IPRP Report No. 3 the IPRP repeated the recommendation of further studies to better constrain the Hosgri fault slip rate. Specifically, the IPRP stated that the high energy seismic surveys then being planned would not be useful for imaging younger offset features and low energy methods should be considered. The IPRP summarized the state of knowledge of the Hosgri slip rate in IPRP Report No. 5. At that time (March 2013) slip rate estimates in the vicinity of DCPP were based on studies on land near San Simeon, or from regional geodetic studies. A summary of the slip rate data suggested a slip rate in the 2 mm/yr range, with an upper bound of about 4 mm/yr, less than the previous upper bound estimate of 6 mm/yr. At the IPRP meeting on February 25, 2013 PG&E recognized that offshore slip rate determinations promised the possibility of reducing uncertainties and described areas where they planned slip rate studies. Several offshore slip rate targets were discussed, including the three studies that are reviewed here.

Point Estero Cross-Hosgri Slope

In addition to the studies by PG&E described in the CCCSIP report, a study of the slip-rate on the Hosgri fault was conducted by Johnson et al. (2014) of the USGS with support from PG&E. This study investigated a distinct, 1700 m long, linear slope that crosses the Hosgri fault at a fairly high angle about 5 km northwest of Point Estero. This feature was discovered and investigated by Johnson et al. (2014). It is interpreted to be the shoreface of a late Pleistocene sand spit and is referred to as the cross-Hosgri slope (CHS). High-resolution bathymetric data were collected by the California State University Monterey Bay Seafloor Mapping Lab (CSMP, 2009, 2010). These data were the first high-resolution imagery of tectonic landforms of the Hosgri fault (Johnson and Watt, 2012). In 2012, the USGS (Hartwell et al., 2013) conducted an additional survey optimized to image the CHS. The resolution of this data is typically 1 m in water depths less than 50 m, and 2 m at greater depths, with vertical uncertainties in the 10-40 cm range. The CHS is 250 – 280 m wide, 7-9 m high and is located at a water depth of 63-77 m. The CHS slope face dips 1.6º-2.0º, whereas the surrounding terrain is flatter, in the 0.4º-0.6º range. The lateral offset of the CHS was estimated as 30.3 m from the USGS survey and 44.8 m from the CSMP survey. Johnson et al. (2014) prefer the lower USGS survey result because the survey was specifically designed to image this feature, but the difference between the two surveys has not been fully reconciled. The age estimate of the CHS is based on the elevation at which this feature formed and the paleo sea-level curves. With this approach the estimated age of the feature is 12 thousand years (ka). Considering uncertainties in the age estimate and lateral offset, Johnson et al. (2014) estimate a slip rate of 2.6 $\pm$0.9 mm/yr using the preferred USGS survey. Using the alternative CSMP survey yields a slip rate of 3.7 $\pm$1.0 mm/yr.

This slip rate estimate has undergone multiple internal USGS reviews and was peer reviewed for publication. The composition of this feature and exact water depth of formation are somewhat uncertain, however, the stated uncertainties appear reasonable given the current data. The strength of this slip rate determination lies in the certain correlation of the feature across the fault, the simple fault zone structure with a well imaged single strand, and the age range of the feature which is appropriate for seismic hazard assessments.

CCCSIP Slip Rate Studies

Slip rate investigations of the Hosgri fault by PG&E are described in Chapter 3 of PG&E's Central Coastal Seismic Imaging Project report, and were summarized by Dr. Gary Greene (MBML) at the IPRP meeting on October 23, 2014. Two sites were investigated, in Estero Bay about 5 miles north of DCPP and Point Sal about 20 miles south of DCPP.

Estero Bay Study Area

For the Estero Bay area, PG&E examined previous 2D seismic surveys of the region by USGS (Sliter et al., 2009) to develop a stratigraphic model that provides age estimates for sedimentary layers and to identify potential channels for more detailed investigation. PG&E then conducted 2D and 3D seismic surveys of the Estero Bay area over 3 years (2010, 2011, 2012) to image channels that may be offset by the Hosgri fault. The 2D survey covered a large area. The much higher-resolution 3D survey only covered an area 3.5 by 0.6 km (plate 3 of the CCCSIP report) including the eastern Hosgri fault strand but not the western Hosgri fault strand. As described by Dr. Greene in the IPRP meeting on October 23, 2014, the channels crossing the entire fault zone were originally planned to be imaged with a 3D seismic survey, however based on the anticipation of the arrival of the HESS survey ship, the area was instead investigated with a lesser resolution 2D survey, and only the eastern portion of the planned 3D LESS survey was accomplished.

The Estero Bay study area is located at the edge of the continental shelf and on the adjacent slope. The area is entirely below the elevation that was exposed in any late Quaternary sea level low stands, so all features and potententially fault-crossing channels in this area were formed below sea level. The combined 2D and 3D seismic imaging in the Estero Bay study area identified paleo channels that were considered potential piercing points for determining offsets across the Hosgri fault. Although many channels were identified in the Estero Bay study area, only seven were well enough constrained to be considered for use as piercing points, with three located east of the of the eastern fault strand (11006), one on the central block, and three west of the most active western fault strand (10001). Of all these channels, only one set of channels from east to west De-Ee1-DBw was interpreted to be correlated across the entire fault zone. Presented as a type section seismic profile PBS-T2, located 2.8 km west of the most active Hosgri fault strand (10001) shows the candidate channels including channel DBw with a thalweg depth of 270-350 m or a stratigraphic depth of 130 m. The seismic stratigraphy and key horizons described in PG&E (2013) were used as age control, and correlated to the Estero Bay study area channels.

Determining the slip rate involves measuring the distance along the fault required to restore the original shape of the channel in seismic imagery. Channel DBw can be restored to match up with central block channel Ee1, with 700 m to 1000 m of displacement on the western fault strand 10001 (stated total range possible: 450 m to 1650 m, fig. 6-16). Channel Ee1 can then be restored to match up with the east block channel De with 260±60 m of displacement on the eastern strand 11006. If these channels once were a continuous single channel across the fault, as described in the report, they have been offset horizontally about 1000 m to 1300 m. The channel restorations also require vertical motions down to the west of about 150 m. The most significant uncertainty in this interpretation is that the three channel fragments correlated across the fault may not have ever been parts of a single channel. Although the cross-sectional shapes of the channels present permissible matches, they do not allow a unique match with a high level of confidence. As observed in the fault parallel seismic profiles, many other candidates for matching channels can be envisioned. The IPRP was not convinced that the proposed channel correlation is sufficiently well defined that any slip rate calculation was justified with sufficient certainty to be relevant for seismic hazard assessments.

In order to calculate a slip rate for the interpreted offset, an age for the channel west of the fault was estimated based on its stratigraphic position or depth. Channel DBw is buried deeply between two unconformities, below T05 and above ELP. These key stratigraphic markers are not dated directly but rather inferred from regional sequence stratigraphic correlations that include considerable uncertainty. The reported age estimate for the channel is 840 +690/-25 ka. Using the reported age range and offset directly results in a slip rate range for this feature of 0.44 - 3.3 mm/yr. This slip rate range, shown in figure 2, would be valid only if the proposed channel restoration is correct. The IPRP regards this channel restoration as possible, but far from a well-constrained, unique interpretation. In the absence of other data to more conclusively demonstrate the proposed channel restoration, the IPRP regards the Estero Bay slip rate study as inconclusive, and would not use results of this study to constrain slip rate on the Hosgri fault. The CCCSIP report, in Synthesis sub section 8.1.1.3, titled “Age Constraints and Slip Rates”, lists a preferred slip-rate estimate of 1.75-1.90 mm/yr within a range of 1.61-2.05 mm/yr for the entire HFZ in the Estero Bay study area. This slip rate is based on a channel Fe3/Fw3 in the Point Sal area described below. Hence, it appears that the slip rate from the Estero Bay study area is not being used directly in estimating seismic hazard.

In summary, the CCCSIP describes deeply buried submarine channels in the Estero Bay study area. Although the fault zone is relatively well imaged, especially within the east and central block 3D seismic volume, the lack of 3D coverage across to the west block greatly limits the value of this survey. The physical match of the channels across the two active fault strands is very uncertain, although possible. Combined with a very broad age range estimate, and compounded by the fact that this age range is of less certain applicability to seismic hazards, because fault slip rate, and fault zone structure may change significantly in such a long time span, this slip rate estimate does not significantly constrain the slip rate on the Hosgri fault in the context of other existing estimates.

Point Sal Study Area

The Point Sal study area is located along the Hosgri fault about 20 miles south of DCPP. An estimate of slip rate at this site could corroborate slip rate estimates along the fault farther north, or could support tectonic models in which some long-term slip diverges from the Hosgri fault onto other faults, such as the Shoreline fault, that branch from the Hosgri fault. Results from the Point Sal site that are similar to results from sites farther north would support the hypothesis that the Hosgri fault is the dominant seismic source through the region, while slip rates significantly lower would support the hypothesis that other faults are significant. At the Point Sal site, Fugro collected a 3D volume of boomer seismic data to image buried submarine paleochannels which have the potential to be used as fault piercing points. The new seismic data reported in the CCCSIP report enables more precise mapping of the Hosgri fault, which includes three main active faults strands: a western bounding strand, a through-going central strand and an eastern bounding strand. Overall, the broad paired fault bend forms an anticlinal structure with multiple narrow slivers formed by short more northerly trending faults which slice the central block. The northwest striking Lions Head fault converges into the Hosgri fault from the east into the northern end of the paired-fault structure. Within the 3D seismic imaging volume, the Lions Head fault is vertical to steeply dipping with substantial vertical displacements. The observed structure is typical of actively deforming transpressive fault bends.

The Point Sal study area is located at the edge of the continental shelf and on the adjacent slope. The area is entirely below the elevation that was exposed in any late Quaternary sea level low stands, so all features in this area were formed below sea level. Seven buried paleochannel complexes A-G were identified in the seismic reflection 3D volume and 2D seismic reflection profiles in the Point Sal study area. The term channel complexes refers to multiple channel features that may at some point in the past been related, having been formed by the same drainage system, and hence have the potential to be restored and used to measure fault displacements. Within the paired-fault bend structure only one channel, complex F, was identified as crossing the entire Hosgri fault zone, which is required to measure a fully representative slip rate. The Channel Complex F thalwegs and margins are well imaged in the 3D volume to the west and east of the Hosgri fault zone as pronounced angular unconformities. The top width of channel Fw3 is about 600 m, whereas the potential match Fe3 is much narrower at about 200 m. However, given the overlying unconformity capping Fe3 the overall channel shape is very similar in cross-section and provides a reasonable match. The nested channel structure of the western Fw channels and the eastern Fe channels provide a convincing case for correlation (figures 6-43 and 6-47). Two other channel complexes A and B were identified as crossing the western and eastern bounding faults, respectively. These channels, A and B were investigated to help validate offsets measured on channels F. Channel Complex A (figure 6-39) is limited to a correlation across the western HFZ main fault splay. Because the channel thalwegs are broad and hence poorly defined, the correlation confidence level was reported as low. This seems at odds with the rather low uncertainty in the offset measurement of 95 $\pm$ 20 m and is interpreted to reflect a general low confidence level in whether the feature actually matches across the fault. Channel Complex B is limited to crossing the eastern fault splay of the HFZ, the correlations are challenged by an absence of part of the channel on the central block, nevertheless, an offset was measured at 356 m with a minimum of 193 m and a maximum of 510 m. Although this offset range is quite large, especially compared to Channel Complex A, the confidence level was reported as medium. The confidence levels reported refer to whether the features being correlated were actually once continuous rather than the uncertainty in offset measurements.

In contrast to the relatively convincing correlation of channels of Channel Complex F across the fault zone, age estimates of these channels are poorly constrained. The depths of the potentially matching Fe1 and Fc1 thalwegs are approximately 160 m and 200 m, respectively. Because these depths are significantly greater than the glacial maximum sea level low stands, these channels could be of marine origin, or fluvial channels that subsided tectonically since they were formed. Given the similarity to other marine channels, the CCCSIP report favors this origin. Channel Complex F is deeply buried below unconformities that are correlated with regional unconformities H30 and H40. Because the absolute depth of the channels is significantly lower than reported sea level low stands at depths of 120 m, and the most likely origin of these channels is marine, there is no clear process to correlate these channels to sea level low stand age estimates. One concept suggested by Dr. Greene is that submarine channels on the continental slope are more likely to form at sea level low stands because sediment is transported by streams closer to the shelf break, producing submarine gravity flows that form submarine channels. Although, this concept appears physically reasonable, it does not provide a confident and unique correlation with any particular sea-level low stand. The preferred model described in the CCCSIP report is based on the correlation of the Channel F complex with the MIS (marine isotope stage) 10 at 342 ka. This correlation is possible, but correlation with other low stands, or with other ages not associated with low stands, are also possible because the correlation of submarine channels with low stands is not required. The overall age range reported for Channel F Complex, between 138 ka (MIS 6b) and 1.4 million years (Ma) (MIS 45) appears to be an appropriate wide range considering the uncertainties. The CCCSIP report lists a preferred age range near 342 ka which appears to be based on the stratigraphic position of the channel and an interpolated sedimentation rate. Channel Complex B is located at a depth coincident with the sea level low stands and the reported age estimate range is MIS 6b at 138 ka to MIS 45 at 1.4 Ma. The preferred age MIS 8b at 250 ka is not clearly justified. Channel Complex A age control is poorly defined and the total age range reported is between MIS 2 at 20 ka to MIS 45 at 1.4 Ma, and they have linked it in a general fashion to 100 ka sea-level cycles, which is difficult to reconcile with any preferred age estimate.

Slip rates for the Channel Complex F across the entire HFZ range from 0.39 mm/yr to 4.71 mm/yr. In the reported slip rates (table 6-7), the preferred age model results in a slip rate range of 1.61 mm/yr to 2.05 mm/yr based on an MIS 10 age. As a minimum age estimate MIS 6b was reported, however, it appears equally feasible that the MIS 8 age is possible which would result in a slip rate of about 2.5 mm/yr. In summary, although the F Channel Complex provides a fairly compelling match of a nested channel, with very similar channel cross sectional shapes and matching channel fill seismic signatures, the contribution of this feature as a slip rate value is greatly diminished by the lack of precise age control. It is difficult to reconcile the reported age estimate preferences with the overall observed uncertainties in correlated seismic stratigraphy. In other words, no convincing basis is provided for preferring one age model over others.

Summary

Two studies described in the CCCSIP report and one by USGS add to our knowledge of the Hosgri fault slip rate. Each of these studies includes estimates of the age and amount of offset of a feature that crosses the fault. The offset of the cross-Hosgri slope reported by Johnson et al. (2014) has significant uncertainties, as does the age estimate, which are considered in the estimate of slip rate. The resulting slip rate is an average over the past 12 ka, a period that is considered clearly applicable to current seismic hazard estimates. The studies for the CCCSIP rely on correlations of submarine channels across the fault. This correlation is relatively convincing at Pt Sal, but less so in Estero Bay. Age estimates of the channels depend on regional correlations of unconformities and age estimates based on correlation of the unconformities with global sea-level curves. The CCCSIP reports slip rates from Estero Bay and Point Sal based on interpreted channel offsets and preferred age estimates based on correlations with dates of global sea-level low stands. Uncertainties in these values and alternative models for correlation with sea-level curves are described in the text, but are not reflected in a final “preferred” slip rate value. We do not see a strong reason to prefer correlation of the channels with the age of one sea level low stand over the others, or even a strong reason for correlation with any sea level low stand, so would summarize the slip rate determined from the Point Sal study as 2.2 ± 1.8 mm/yr, rather than the reported 1.8 ± 0.4 mm/yr. The large uncertainty in the slip rate is a consequence of large uncertainties in age estimates. In addition, estimated ages of the offset channels at both sites are in the range of about a half million years. Because slip rates may change over time, slip rates averaged over long times may not be as applicable to seismic hazard estimates. A summary of slip rate studies on the Hosgri fault, updated from the figure in IPRP report #5, is shown as Figure 2. The net result of studies reported in the CCCSIP report and by Johnson et al. (2014) is that uncertainty in the slip-rate on the Hosgri fault has been decreased and uncertainty in seismic hazard has decreased. This decrease is largely the result of the previous upper-bound slip rate being incompatible with newer geodetic and geologic data, including the results of the CCCSIP studies.

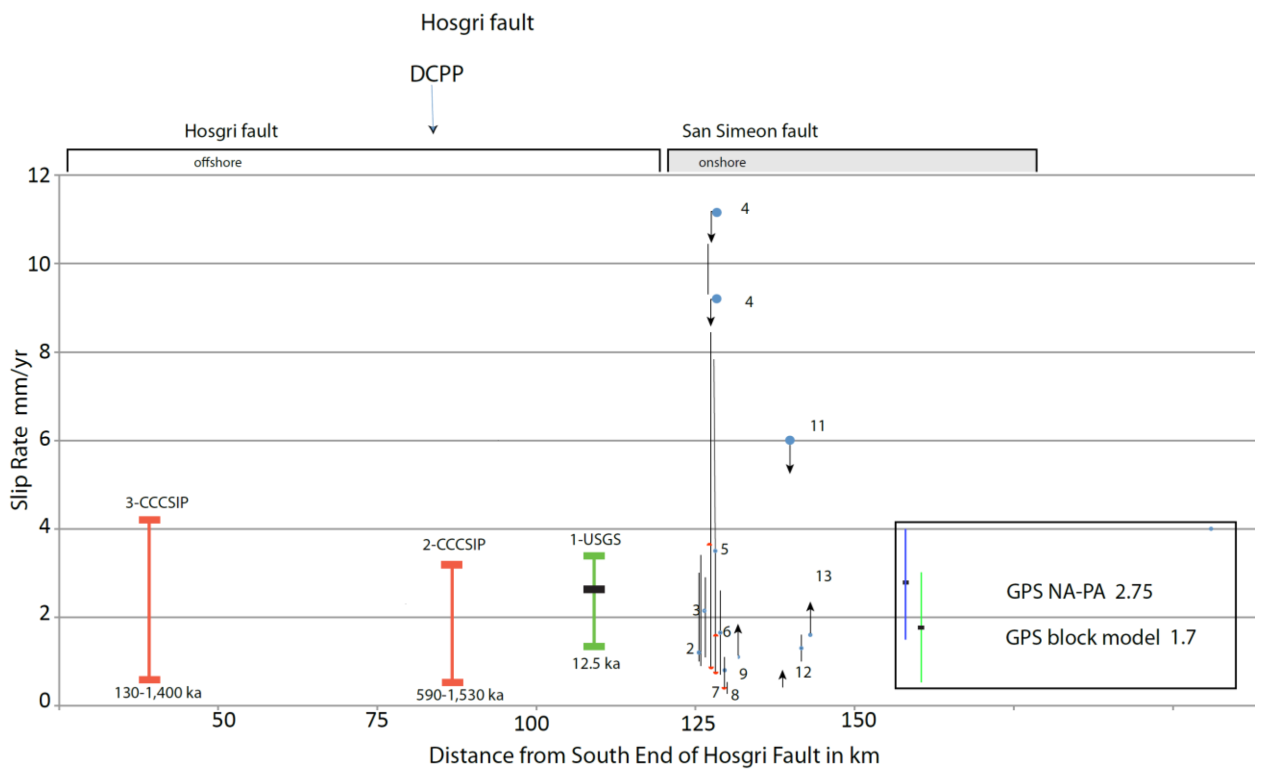

Figure 2, Hosgri – Fault Slip Rates. Geologic fault slip rates are shown with vertical bars. The three new offshore slip rate estimates are shown on the left side of the figure with red and green vertical bars. For the new offshore rate estimates the green indicates a highly suitable age range for seismic hazard assessments, whereas the red indicates a less suitable age range due to the increasing uncertainty of fault zone evolution and behavior changes over time. Modes are indicated by a tick mark, when absent no basis for a preferred choice was recognized, blue dots and associated errors. Downward pointing black arrows indicate a maximum rate whereas upward pointing black arrows indicate minimum rates. Red half dots indicate offset terrace slip rates inferred from vertical separations and slickensides from a fault exposure. The geodetic slip rates are representative of a region, and are indicated with broad color bands spanning the ranges, with central point estimate and error bars. GPS NA-PA: 2.75 mm/yr; geodetic slip rate constraint west of the West Huasna fault (DeMets, 2012). GPS block model: 1.7 mm/yr (Murray et al. 2012).

An unstated limitation in all the LESS studies is that they were designed to image sediments at shallow to intermediate depth to complement the proposed HESS studies. Because of this, the technologies used in the 2D and 3D LESS studies all have significant limitations when imaging the shallowest sediments. Since the shallowest sediments are the youngest, they record evidence for most recent fault displacement. Higher resolution seismic studies designed for imaging of the shallowest sediments, such as CHIRP seismic profiling, would be more likely to detect younger features offset by smaller amounts than those studied in the CCCSIP. Uncertainty in slip rates because of uncertainty in the ages of offset channels could also be reduced with a well-executed shallow coring program. Very high resolution profiling of the youngest sediments with sampling to determine ages of those sediments offers the best chance to constrain slip rates representative of seismic hazard at the DCNPP, particularly along the relatively fast-slipping Hosgri fault. If older deposits are targeted, such as those recorded by the LESS studies, then significant improvements in age control are needed in order to reduce to uncertainties associated with the slip rates. The acquisition of more absolute dating control may decrease the slip rate uncertainties both in terms of age control, and possibly feature correlation.

SAN LUIS OBISPO BAY SLIP RATE STUDIES AND EXTENT OF THE SHORELINE FAULT ZONE

Background

The slip rate of the Shoreline fault was identified as the third most important hazard significant parameter on the PG&E tornado diagram. In IPRP Report No. 2, the IPRP noted that the slip rate of the Shoreline fault was poorly constrained and that PG&E should conduct further studies in order to better characterize the slip rate of the Shoreline fault zone. In IPRP Report No. 3, the IPRP noted that the slip rate could be developed from marine bathymetric surveys and seismic surveys that imaged the shallow subsurface beneath the sea floor.

IPRP Report No. 2 also recommended that seismic surveys could also help constrain the location and extent of the Shoreline fault zone, and possibly show connections with other faults mapped on land, such as the Oceano fault. On PG&E’s tornado diagram, the southern end of the Shoreline fault ranked low (item ten of ten), as a hazard significant parameter. However, the IPRP noted that the planned seismic studies would help constrain the location and extent of faulting, and that if a connection could be shown between faults offshore and onshore, then onshore slip rate and recurrence studies could be relevant to the Shoreline fault zone.

Data Collection and Analysis

As part of PG&E's Low Energy Seismic Surveys (LESS) studies for DCPP, PG&E collected 3D data in San Luis Obispo Bay in 2011 and 2012. The selection of the 3D study area was partly informed by previously collected multibeam echosounder (MBES) surveys, as well as 2D seismic reflection data collected by the USGS in 2008 and 2009, and PG&E legacy archive data. The LESS 2D and 3D studies were undertaken to refine the location and patterns of faulting and folding, and determine fault slip rates from offset of geologic features. Within San Luis Obispo Bay, the total 3D LESS area is about 27.6 km^2. The results of these studies are presented in Chapter 3 of PG&E's Central Coastal Seismic Imaging Project report, and were summarized by Dr. Gary Greene (MBML) at the IPRP meeting on October 23, 2014.

Results

Fault locations: The San Luis Obispo Bay 3D study area is located entirely on the continental shelf. Due to a relatively thin cover of sediments, the LESS was able to image down to the top of bedrock throughout the survey area. Faults were mapped based on cross-sections, as well as in map view time slices from the 3D volume. Generally the faults are clearly distinguished in the seismic survey images cutting the bedrock surface. Faults mapped within the 3D survey area include the Shoreline fault, the Oceano fault, the Los Berros fault, and strands of the Pecho fault zone. The Shoreline fault, Oceano fault and Los Berros faults all appear to merge in the northwestern part of the study area in the vicinity of Souza Rock. Outside of the 3D survey area, faults were mapped using the 2D data. Based results of the CCCSIP, the Oceano fault can be mapped from near Souza Rock southeast to the coast over a distance of about 10.7 km, to where the offshore shore strand of the fault connects with the mapped onshore traces of the Oceano and Santa Maria River fault zones. The Shoreline fault can be mapped from the 3D survey area, southeast for about 13.7 km, to where it connects with an onshore fault mapped in the Guadalupe Oil field, for a total fault length of about 45 km. A southern extension of the Pecho fault has been mapped about 500 meters west of the Shoreline fault and parallels the Shoreline for about 12 km south of the 3D study area.

Offset features: In general, Holocene deposits are found on top of bedrock in the northern and central parts of the survey area. Holocene deposits overlie late Pleistocene deposits in the southeastern part of the study area and these late Pleistocene deposits overlie bedrock. The 3D LESS data was able to image 12 paleochannels buried by these deposits. The paleochannels are interpreted to have formed during sea-level low stands and are incised into the bedrock and filled with younger, unfaulted deposits. Each of these channels were evaluated by the CCCSIP interpretation team for potential fault offset. Within the resolution of the data, only Channel A appears to be offset by the Shoreline fault, by about 20 – 50 meters (30 meters, preferred), in a right lateral sense. The offset measurements are based on measurements of both the channel thalweg and the channel margins, with the channel thalweg being the preferred offset. In the same general area, the Oceano fault appears to vertically offset the Channel A margin by about 3 ± 2 meters. Other channels within the survey area do not appear offset within the resolution of the data, which is about 6 meters horizontal and 2 meters vertical.

The 3D LESS data was also able to image two buried paleostrandlines, located in the southeastern part of the survey area that are interpreted to be offset by the Shoreline fault. The paleostrandlines, located at -84 meters and -92 meters elevation, are offset the same amount: 9.4 ± 6 meters, right laterally. Both paleostrandlines are well-imaged, giving a reasonably high confidence that the offset can be precisely measured and that the individual features can be correlated across the fault.

<u>Feature ages and slip rates</u>: As with the other LESS study areas, Chapter 3 notes that due to the lack of radiometric ages, biostratigraphy, or magneto-stratigraphic data, the ages of features in the San Luis Bay study area are poorly constrained. Age control relies on correlations of stratigraphic horizons (mapped unconformities) to worldwide sea level curves and stratigraphic models. In the case of the San Luis Obispo Bay study area, additional uncertainty is added due to the relatively thin cover of sediment above bedrock, making it difficult to correlate key unconformities (e.g., H30, H40) into parts of the study area.

In the case of Channel A, the initial age of incision into the bedrock platform is poorly constrained. Based on stratigraphic and cross cutting relationships, other channels associated with the same channel complex (Channels B, C, E) are thought to be younger than Channel A, and are therefore associated with younger sea-level low stands. Also, due to the presence of unfaulted channel fill, Channel A is thought to be older than MIS 2 and "likely older" than MIS 6. Two alternative preferred age estimates are considered: An older age estimate where Channel A was incised during MIS 12 (430 – 450 ka), and a younger age estimate where Channel A was incised during MIS 10 (335 – 350 ka). A maximum limiting age for Channel A is 1.4 Ma. These ages are used in conjunction with the reported offsets to calculate a slip rate of 0.07 or 0.12 mm/yr (alternative preferred age models), with a reported range of 0.01 – 0.37 mm/yr. Based on the age models and the 3 ± 2 meter vertical offset of the Channel A margin across the Oceano fault, the CCCSIP reports a preferred slip rate of either 0.007 or 0.012 mm/yr, with a range of 0.001 – 0.2 mm/yr.

The ages of the paleostrandlines are estimated by correlating the paleostrandline elevations to the global sea-level curves. Based on elevation, the paleostrandlines likely formed during an intermediate sea-level stand, possibly MIS 4, 6, or 8. An additional constraint is that the paleostrandlines appear to be buried by deposits below the H30 unconformity. Based on this, the paleostrandlines are interpreted to have been cut between 185 ka and 155 ka. The report leaves open the possibility that the features could be as young as MIS 3 - 4 (28 – 70 ka) and as old, or older, than MIS 8 (~250 ka or older). The calculated slip rate for this location on the Shoreline fault is 0.06 mm/yr (0.01 – 0.51 mm/yr range).

Chapter 3 also reports slip rates for other channels in the 3D study area. However, it should be noted that offsets were not observed on these features, but rather, the slip rates are derived from the inferred age of the features from the age models and an assumed maximum offset based on the resolution of the data (typically 6 meters horizontal and 2 meters vertical). Therefore, these other slip rates are considered maximum rates based on the resolution of the data, and not conventional slip rates that are typically used in fault slip rate assessments.

Summary

With the 2D and 3D data acquired for this study, PG&E has addressed the issue of the southeastern extent of the Shoreline fault zone and they are able to connect both the Shoreline fault and the Oceano fault to their onshore equivalents. Although this was not identified as an issue with great significance to the seismic hazard at DCPP, this is a significant contribution to the understanding of fault geometry and tectonic framework within the region. Based on the new mapping presented in Chapters 2 and 3, it appears the Shoreline fault is essentially a continuous feature from its intersection with the Hosgri fault, for a distance of 45 km. The Shoreline fault comes onshore near the Camarillo Oil field and is mapped to within a few kilometers of the Casmalia fault zone. The new mapping also shows that the Oceano fault connects with the Shoreline fault near Souza Rock, and likely connects with the Oceano fault as mapped onshore.

The slip rate of the Shoreline fault was identified as a key parameter with respect to the seismic hazard at DCPP and the San Luis Obispo Bay 2D and 3D LESS studies were targeted to identify potential offset features and obtain slip rate data for this fault. Within the study area, the LESS study was able to identify multiple features that crossed the mapped trace of the Shoreline fault and these were evaluated as potential piercing lines. Of these features, one channel and two paleostrandlines were identified as being faulted by the Shoreline fault and offsets measurements obtained. Based on PG&E's work, Channel A and the paleoshorelines appear to be excellent features from which to obtain offset measurements. In the case of Channel A, both the thalweg of the channel, as well as the margins are offset, and were measured. While the total range of the measured offset is large (10 – 50 meters), this is typical of the uncertainty of offset measurements along active faults. The preferred offset of 30 meters on the channel thalweg appears to be reasonable and is better constrained than measurements taken on the margins of the channel. The paleostrandlines, mapped within the 3D volume appear to be distinct features that are offset about the same amount (~10 m). From this data, there is a high degree of confidence that the strandlines can be measured precisely and that the features can be correlated across the fault. In summary, the authors of the report have high confidence regarding their measurement of the Channel A and paleostrandline offsets, and based on the data presented in the report, their preferred values and ranges appear to be reasonable estimates that are supported by data.

In contrast to the fairly well-constrained offset measurements, the CCCSIP report notes that the age of the channels and paleostrandlines are poorly constrained due to limitations in the ability to directly date the features using radiometric dating, paleontological techniques, or other more absolute methods. For this reason, the CCCSIP report relies on correlations to global sea-level curves and stratigraphic models to assign ages to the offset features in the San Luis Obispo Bay study area. These types of age estimates are highly model dependent and have large uncertainties. The report attempts to account for age dating uncertainty by incorporating alternative age estimates into the slip rate calculations. The approach taken synthesizes the available data and geologic relations in order to provide minimum, preferred, and maximum age models that typically span a wide age range. While the age estimates presented are all viable models, and likely represent the range of ages for other possible models, one issue to consider is how the calculate slip rates are to be weighted in a seismic hazard model. Given the large uncertainties in the age estimates, it may be difficult to select a “preferred” slip rate from the spectrum of possible slip rates, and multiple slip rate estimates may need to be weighted more or less equally, unless better age estimates are obtained, or a strong case for a particular stratigraphic model can be made.

In summary, the 2D/3D LESS study in San Luis Obispo Bay has resulted in a better understanding of the location, extent, and relationship between the Shoreline, Oceano, and associated faults. The 3D LESS study was designed to target offset features within San Luis Obispo Bay and obtain a slip rate for the Shoreline fault. Based on the results of this study, PG&E was successful in identifying offset features and assigning age estimates to these features in order to calculate a slip rate for both the Shoreline and Oceano faults in San Luis Obispo Bay. However, it should be noted that, although it is likely the true slip rate of the Shoreline and Oceano faults lies within the reported range and may be close to the reported preferred values, age control on the offset features remains the largest contributor to the uncertainty in the calculated slip rates. These slip rate estimates could be improved with the acquisition of absolute dating control and such work should be considered for follow up studies in the future.

Other comments

Comment regarding age model of paleostrandlines: The preferred age model for the paleostrandlines during MIS 6 time appears overly constrained on the young end. In the preferred age model, the CCCSIP report lists a preferred age range where the paleostrandlines are cut sometime between 155 ka and 185 ka. However, this appears to be done without accounting for the uncertainties shown on Figure 7-44 (blue shaded area). If the uncertainties are accounted for, then the 6c high stand is also a time when one of the paleostrandlines could be cut, making the offsets about 10,000 years younger. In some ways, this is a more satisfying correlation that accounts for the excellent preservation of the features. If the higher of the paleostrandlines was cut at about 155 ka, sea-level then drops, preserving the higher strandline. At about 145 ka (6c time), sea-level comes back up and cuts the lower strandline, which then is isolated and preserved during the 6b lowstand. In the correlaton presented in the CCCSIP, one of the paleostrandlines must survive a transgressional erosive episode, while in the alternative model, both are cut as sea-level drops, and then are buried by prograding shelf of deltaic deposits during 6b time.

Comment regarding Channel A preferred age: The CCCSIP report appears to rely on duration of sea-level low stands as criteria for selecting preferred channel ages. For example, the “highest preferred age model” for Channel A is MIS 12, partly because, of all the sea-level low stands, this was of the longest duration (about 45,000 years), while other low stands were much shorter (as little as 20,000 years). Little, if any, data are presented to support a relationship between sea-level low stand duration and channel incision morphology, leaving the question open as to whether or not there is a difference between a 20 kyr-long or 45 kyr-long low stand in the morphology or development of an incised channel. If this is a criteria used in assigning channel ages, then this should be supported by additional data, because as written, it appears somewhat speculative.

The report also notes that the MIS 12 low stand was lower than MIS 10, therefore a MIS 12 age is preferred for the incision of Channel A. It should be pointed out that within the uncertainties of MIS 10 sea level, it is the same (or lower) than MIS 12. Furthermore, MIS 12 does not appear to have any uncertainty associated with it (Figure 7-45). Is the MIS 12 sea-level elevation that well-constrained, or are formal uncertainties not available? If the latter case is true, then it is hard to make a case that there is a distinct difference between the elevations between MIS 10 and MIS 12, making it difficult to prefer MIS 12 over the MIS 10 age.

Comment 2 regarding Channel A preferred age: The report appears to dismiss a possible MIS 6 age for Channel A. For example, the text notes “Channel A is likely…older than MIS 6”. However, there is very little additional discussion regarding why this MIS 6 is rejected as a viable age model, leaving it to the reader to piece together the bits of information in order to follow this interpretation. Additional discussion of why this age range is not considered would help the reader follow the rationale behind rejecting this age for the channel.

Editorial comment: The text describing the preferred Channel A age (Chapter 3, page 127) is confusing. The text refers to “The highest preferred age model for Channel A,…” and “The lowest preferred age model for Channel A” and it is not clear what this means. This text refers to Figure 7-45, where both age models are plotted, but referred to as “A (lowest preferred) (initial bedrock incision)” plotted under MIS 8b, and “A (lowest preferred)” under MIS 12. Consistency between the text and figures in this section would make this less confusing. Also, the qualifiers “highest” and “lowest” seem more appropriate to a description of stratigraphic position, rather than age. Perhaps these models could be referred to as alternative preferred age models, with an older preferred model (MIS 12) and a younger preferred model (MIS 8).

HOSGRI – SHORELINE INTERSECTION

The intersection between the Hosgri fault zone and the Shoreline fault zone was identified as a moderately important hazard significant parameter (number seven of ten items on the “Tornado” diagrams PG&E presented at several IPRP meetings). IPRP Report No. 2 discussed the significance of this fault intersection, noting that a “direct connection” between the two fault zones would potentially lower the hazard in a probabilistic seismic hazard model because a direct connection would mean fewer earthquakes on the Shoreline fault, and thus less hazard. Alternatively, in a deterministic framework, a connected Hosgri-Shoreline fault system results in larger earthquakes near the plant, and higher hazard than earthquakes on the Shoreline alone.

PG&E originally proposed to address this issue through the High Energy Seismic Surveys (HESS) component of the CCCSIP. The goal of this study was to image the Hosgri and Shoreline faults, ideally to seismogenic depths, and be able to connect structures imaged at depth to the seismicity associated with the Shoreline fault zone. However, plans for the HESS study were canceled with the denial of a permit by the California Coastal Commission in November 2012.

With the HESS effectively tabled, PG&E continued with the plans for 2D and 3D Low Energy Seismic Surveys (LESS) in several target areas, including the area in the vicinity of the Hosgri – Shoreline fault zone intersection off of Point Buchon. The goal of this study was to image the shallow structure of the northern Shoreline fault zone and a possible Hosgri – Shoreline fault zone intersection. Although portions of the Point Buchon fault (previously called the N40W fault by PG&E (2011)) were mapped in this area based on multibeam echosounder (MBES) surveys, the presence of young sand sheets obscured the bedrock geology and evidence for recent faulting along much of the extent between the central section of the Shoreline fault and the projection of this zone to the Hosgri fault zone. The 2D and 3D studies were undertaken with the goals of providing the location and patterns of faulting and folding, as well as constraints on dip of the faults, and identification of possible piercing points for slip rate studies. The other goal of this study was to investigate the nature of the intersection between the Hosgri and Shoreline fault zones. The results of these studies are presented in Chapter 2 of PG&E's Central Coastal Seismic Imaging Project report, and were summarized by Dr. Gary Greene (MBML) at an IPRP meeting held on October 23, 2014 in San Francisco.

Data Collection and Analysis

High resolution LESS 2D and 3D data were collected in late 2010 and early 2011. The 2D data was collected with ~100 meter line spacing over an approximately northwest trending rectangular area that is about 4 km wide and 12 km long. The 3D survey area is a "T-shaped" polygon, located entirely within the 2D survey area and is approximately 18 km^2 in area. The survey area is narrower where it follows the trend of the Point Buchon fault, with the wider "T" designed to encompass the strands of the Hosgri fault zone as well as strands of the Point Buchon fault zone. In general, the data was processed to about 0.5 seconds depth (two way travel time), with interpretable geologic structure imaged to about 0.35 seconds, or about 280 meters depth, or less. The processed data was interpreted by a team of geologists from MLML, Fugro Consultants, and LCI, who looked at both the 2D seismic lines, as well as the 3D data, both in cross section, as well as in map-view time-slices. The interpretation included mapping of selected stratigraphic layers and structural features such as faults and folds. The interpretation team also attempted to distinguish areas of good and poor data interpretability. Areas of "poor interpretability" were typically not the focus of detailed mapping, or mapped features in those area were inferred or projected from areas of "good interpretability". The spatial accuracy between the prior MBES data and 2D/3D LESS survey was also examined and shown to be well-correlated, indicating that the two datasets could be used to map geologic features seen on the ocean bottom and extended into areas covered by young sand sheets.

Results

Based on the LESS 2D and 3D data, the interpretation team was able to better map strands of the Hosgri fault zone, Point Buchon fault zone and associated structures such as folding and fault-bounded grabens. The principal new conclusion with respect to the Hosgri fault zone is that the fault appears to shift from a transpressional regime in the south to a transtensional regime in the northern part of the study area as demonstrated by the mapping of “Graben A” on the Hosgri fault zone.

On the Point Buchon fault zone, the interpretation team was able to better map strands of the fault using the 2D and 3D LESS data. Within the study area, two principal strands of the Point Buchon fault were mapped: The east branch of the fault generally follows the contact between bedrock exposed on the sea floor to the east and the sand sheet to the west. This fault was formerly called the N40W fault in previous PG&E reports (PG&E, 2011) but is now referred to as the “Eastern Branch of the Point Buchon fault zone” in the CCCSIP report. Another, previously unidentified, strand of the Point Buchon fault was imaged under the sand sheet, trends towards the Hosgri fault zone. The interpretation is that this is the primary strand of the Point Buchon fault. This strand appears to terminate in a fault-bounded graben (“Graben B”), which is located about 500 meters east of the main trace of the Hosgri fault zone. The western bounding fault of this graben is associated with the Hosgri fault zone, effectively making this graben the intersection between the Hosgri fault zone and the Point Buchon fault zone. South of “Graben B”, other west, northwest trending minor faults appear to splay off of the Point Buchon fault, although these strands appear to die out within folds, located 1–2 km east of the Hosgri fault.

The interpretation team also examined structures overlying the Shoreline fault zone seismicity lineament. This seismicity lineament (referred to as the northern segment of the Shoreline fault zone in previous reports by PG&E) is located west of the Point Buchon fault and east of the Hosgri fault zone. With the exception of the minor west-northwest trending faults that splay off of the Point Buchon fault zone, no distinct, continuous faults could be mapped on the vertical projection of the Shoreline seismicity lineament. The authors of Chapter 3 note that they cannot confidently extrapolate the seismicity at depth to features mapped in the shallow subsurface.

Summary

Based on the new data provided by the 2D and 3D LESS study off of Point Buchon, a better understanding of the surface and near-subsurface geometry of the Hosgri – Point Buchon fault zones has been developed. With respect to seismic hazard, this investigation has shown that effectively, there is a direct connection between the two fault zones, with the intersection located at a graben that is structurally controlled by the Hosgri and Point Buchon fault zones. Furthermore, this graben is located about 500 meters east of the main trace of the Hosgri fault zone, which is well within the upper limit of 5 km that is typically viewed as the maximum distance that earthquake ruptures can jump from fault to fault (e.g. Wesnousky, 2008). Based on this work, it appears that this study has provided the data necessary to address the question regarding if and how the two fault zones are connected, at least in the near surface. Although the canceled HESS study may have provided additional details regarding deeper structure and connections of fault at depth, it appears that the LESS study has provided the needed data for the purposes of seismic source characterization being conducted for DCPP.

No offset features such as buried channels were identified in the LESS data for use in slip rate studies. However, the two grabens that were mapped should be considered as targets for estimating relative rates of deformation (vertical subsidence as a proxy for fault slip rate) and as a target for coring and dating in future studies, perhaps as part of the LTSP.

One minor recommendation the IPRP has is that PG&E simplify the naming nomenclature for the zone of faults currently referred to as the Point Buchon and Shoreline fault zones. Based on this work, it is apparent the Shoreline fault zone, the Point Buchon fault zone, and possibly the Shoreline seismicity lineaments are related structures. Although the authors of Chapter 3 note that they could not map a direct connection between the Point Buchon fault zone and the central section of the Shoreline fault, the gap is small (~2 km), and occurs in an area described as one of low interpretability, which possibly limits the ability to map a through-going fault. Given that both named faults are on trend with each other, and the size of the gap in mapping is small, it is reasonable to assume the faults are part of the same fault zone. Condensing this down to a single named fault zone would help prevent confusion, both within the text and for future users of these data and results.

CONCLUSIONS

Parameters addressed in Chapters 2 and 3 of the CCCSIP report are:

- Hosgri slip rate
- Shoreline slip rate and southern extent
- Shoreline - Hosgri Intersection

Two studies described in the CCCSIP report and one by USGS add to our knowledge of the Hosgri fault slip rate. Each of these studies includes estimates of the age and amount of offset of a feature that crosses the fault. The offset of the cross-Hosgri slope (CHS) reported by Johnson et al. (2014) has significant uncertainties, as does the age estimate, which are considered in the estimate of slip rate. Correlation of the CHS across the fault is certain, while channel correlations reported in the CCCSIP studies are not, meaning that this study has one less source of uncertainty than the CCCSIP studies. The resulting slip rate is an average over the past 12 ka, a period that is considered clearly applicable to current seismic hazard estimates. The studies for the CCCSIP study rely on correlations of submarine channels across the fault. This correlation is relatively convincing at Pt Sal, but less so in Estero Bay. Age estimates of the channels depend on regional correlations of unconformities and age estimates based on correlation of the unconformities with global sea-level curves. The large uncertainties in the age estimates result in large uncertainties in the resulting slip rates. Age estimates of the offset channels at both sites are in the range of about a half million years. Because slip rates may change over time, slip rates averaged over long times may not be as applicable to seismic hazard estimate. The net result of studies reported in the CCCSIP report and by Johnson et al. (2014) is that uncertainty in the slip-rate on the Hosgri fault has been decreased and uncertainty in seismic hazard has decreased.

Studies described in the CCCSIP report add to our knowledge of the Shoreline fault slip rate. Previous seismic hazard studies used very poorly constrained slip rates. Estimated slip rate of the Shoreline fault based on the paleostrandline imaged in the 3D seismic survey slip rates are based on a clearly offset feature, although the age estimate of this feature is not as well constrained. Even considering the remaining uncertainty in slip rate, the uncertainty in the slip-rate on the Shoreline fault has been substantially reduced and the resulting uncertainty in seismic hazard has also been reduced.

As part of the CCCSIP studies of the Shoreline fault, the connections of that fault with the Los Berros, Oceano, and Pecho faults have been mapped. Although these connections and extensions of mapped faults do not have a large impact on seismic hazard at DCPP, the improved mapping allows for improved interpretation of these faults.

The 3D seismic survey near Pt Buchon reported in the CCCSIP report documents strands of the Pt Buchon fault that extend from near the Shoreline fault to within a kilometer of the Hosgri fault. This new mapping shows that the Hosgri and Shoreline faults are essentially connected in the near-surface. As a result, seismic hazard models that do not consider the possibility of these faults linking no longer need to be considered and the uncertainty in seismic hazard is reduced.