Central California Coast Earthquake Hazards
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Quaternary Tectonic Setting of South-Central Coastal California

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The Quaternary tectonic setting of south-central California involves several distinct but interacting domains and tectonic structures. The Los Osos-Santa Maria (LOSM) domain is a triangular region consisting of northwest-striking reverse and thrust faults that border uplifted intervening blocks and subsiding basins. To the west, the LOSM domain is bordered by the more northerly trending Hosgri-San Simeon (HSS) fault system and Santa Maria Basin domain. The HSS is characterized by 1-3 mm/yr of right lateral slip, with the rate of slip increasing northward ultimately to 6 to 8 mm/yr on the San Gregorio fault. The LOSM domain is bordered on the south by the Western Transverse Ranges domain, and on the northeast by the more northerly trending Santa Lucia-San Rafael Range across the north-northwest trending Oceanic-West Huasna fault system. Tectonic deformation in the region appears to be driven by four distinct but interacting processes: (1) clockwise rotation of the western Transverse Range domain, which imparts northeast-directed stain in the LOSM domain; (2) northward left transfer of slip along the San Andreas fault system from the San Andreas fault to the Rinconada fault and Hosgri-San Simeon fault, which produces localized crustal shortening and uplift in the left-restraining stepover (*e.g.* San Rafael Range); (3) large left bends in the prominent strike-slip faults, which produce localized crustal shortening and uplift (*e.g.* Piedras Blancas antiform along the San Simeon left restraining bend); and (4) possible plate-normal convergence across the region. Any 3-D model of the region must accommodate the kinematic interaction of these processes as well as several fundamental field observations.

From Monterey to Maricopa: A Seamless Digital Geologic Map Database for the Central California Coast

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Our digital geologic map database (map) forms the foundation for the ongoing USGS/PG&E CRADA research project, which extends from Monterey Bay south to the Santa Ynez Mountains, and the San Andreas Fault west to the coast. This map is a critical data layer for other regional efforts, such as gravity/aeromagnetic analyses, association of hypocenters to faults, GPS studies, construction of cross sections, and development of 3D kinetic models.Typically, these other studies are based on an available single geologic map that uniformly covers the study area. In this case, the 1977 CGS Geologic Map of California (1:750,000 scale) is the only map that covers the entire study area. This map, because of its small scale, lacks stratigraphic and structural details, and does not include recent geologic mapping. Owing to the lack of a comprehensive single map, we are compiling a geologic map that incorporates the “best of ” various other geologic maps, mainly from the USGS and CGS, including previous work by PG&E. Most of the mapping is at scales of 1:24,000 and 1:62,500. Significant differences in stratigraphic nomenclature and mapping styles of various geologists present challenges in integrating the individual

maps used in our compilation.The nucleus of the map includes the detailed digital geologic maps of Monterey and San Luis Obispo Counties by Rosenberg. It also incorporates ongoing USGS mapping in the Cambria/Paso Robles region by Graymer and Rick Stanley, and along the San Andreas Fault as part of the USGS 3D/4D Mapping of the San Andreas Fault Zone Project.When complete, the map will consist of seamless GIS layers showing stratigraphic units, faults, folds, and structural attitudes for the study area. We anticipate that this digital geologic map database will be available through the USGS.

Constraints on 3-Dimensional Structure of the Central California Coast Ranges from Gravity and Magnetic Data

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New aeromagnetic and existing gravity data help define the geometry of faults and sedimentary basins in the central California Coast Ranges, extending from the Hosgri fault east to the San Andreas fault and from Monterey Bay south to Pt. Conception. Interpretation of these data provides constraints for seismic hazard studies. Potential-field data combined with geologic mapping, drillhole logs and other geophysical constraints indicate the faults in the central California Coast Ranges are not planar features. In the northern part of the study area, both the San Andreas and the Rinconada faults dip steeply southwestward and have an apparent reverse component of slip. Further south, where the Rinconada fault bounds the dense and magnetic La Panza block, the fault is essentially vertical. The San Andreas fault is nearly vertical in the study area, but changes to a southwest dip to the south, as the fault begins to bend eastward into the Big Bend, and to the north, where the fault begins to bend westward into the Santa Cruz Mountains. The San Gregorio-Hosgri fault zone also appears to change dip along strike. Modeling of magnetic data suggests an eastward dip of about 45-55 degrees for the San Gregorio-Hosgri fault zone in Monterey Bay, whereas preliminary analysis of magnetic data across the Hosgri fault 150 km to the south suggests a much steeper dip. The moderate dip in the northern part of the San Gregorio-Hosgri fault zone does not reflect a bend in the fault, but perhaps interaction and intersection with the Reliz-Rinconada and other faults. The magnetic data also suggest a shallow eastward dip along the Oceanic-West Huasna fault near its intersection with the Willmar Avenue fault zone in the Santa Maria basin. Fault and basin geometry will be important for estimating shaking potential of scenario earthquakes and for interpreting geodetic deformation.

Geophysical Characterization of the Hosgri Fault Zone, Central California

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High-resolution marine magnetic and seismic-reflection data collected offshore Point Buchon, California in June of 2008 are being combined with existing geologic, regional magnetic, industry multichannel seismic, and seismicity data to help define the geometry and geologic structure of the Hosgri and other nearshore faults. The magnetic anomaly pattern and distribution of seismicity is quite complex

north of Point Buchon as compared to the south. North of Point Buchon, a series of broad magnetic highs extends northwestward from Morro Rock and may signify the offshore extension of the Morro Rock-Islay Hill Complex. Short wavelength magnetic anomalies along the offshore Cambria Fault suggest the presence of meta-volcanic rocks and serpentinite in this fault zone. The southern part of the survey area is characterized by a northwest-trending linear magnetic anomaly that likely represents the presence of ophiolitic rocks in the subsurface. A linear trend of small earthquakes is located along the eastern edge of this anomaly, suggesting an active fault. Seismic reflection data show that the Hosgri Fault represents a complex zone of steeply dipping faults that varies significantly along strike. Alignments of horizontal gradient maxima in the marine magnetic data generally do not correspond to the location of the main surface trace of this fault. Between Cayucos and Point Buchon these maxima occur east of the Hosgri Fault, and further to the south the maxima occur along the eastern edges of broad magnetic highs corresponding to the western margin of the Hosgri Fault Zone. Continued interpretation and geophysical modeling of magnetic, seismic reflection, and seismicity data will help determine whether or not these magnetic boundaries are fault boundaries, and if so, how these structures relate to the Hosgri Fault Zone.

High Resolution, Seismic-Reflection Survey Offshore Central California Will Help Refine Regional Seismic Hazard Assessment

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The USGS recently (June, 2008) conducted a high-resolution, marine, seismicreflection survey between Cayucos and Pismo Beach, central California in order to better document regional seismic hazards. More than 550 km of single-channel seismic data were acquired aboard the USGS R/V Parke Snavely using a 500-joule mini-sparker source fired at a 1/2 second shot interval and recorded with a 15-meter streamer. The source signal frequency bandwidth was from about 200 to 1600 Hz. Most tracklines were run perpendicular to the coast at a dense 800 meter spacing, extending from the nearshore (~ 5 m water depth) to as far as 20 km offshore. Data quality varies with substrate, ranging from outstanding (100 to 150 m of penetration) in inferred Quaternary shallow marine deposits to poor (0 to 10 m) in the Mesozoic Franciscan Complex. Marine magnetic data were collected simultaneously on this survey, and both data sets are being integrated with new aeromagnetic data, publicly available industry seismic-reflection data, onshore geology, seismicity, and high-resolution bathymetry to improve characterization of the Hosgri, Los Osos, Pecho, Oceano, Wilmar Avenue, and other local faults. Specific goals are to refine fault location, length, segmentation, shallow geometry and structure, and to identify possible sampling targets for constraining fault slip rates, earthquake recurrence, and tsunami hazard potential. The anatomy of the >120-km-long Hosgri fault and its connections to northwest-trending inboard faults are a particular focus of this ongoing work. Notably, fifty-five crossings of a 44-km-long section of the north-northwest trending Hosgri fault reveal a vertical transpressional fault zone that extends upward to the seafloor, juxtaposes contrasting Quaternary stratigraphy, incorporates numerous growth folds and angular unconformities, and varies significantly along strike.

Seismotectonics and Fault Structure of the California Central Coast

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I present and interpret new earthquake relocations and focal mechanisms for earthquakes occurring along the central California coast. These relocations improve upon catalog locations by using 3D seismic velocity models to account for lateral variations in structure, and by using relative arrival times from waveform cross-correlation and double-difference methods to image seismicity features more sharply. Single-event and composite focal mechanisms are computed using ray-tracing in the 3D velocity models. The new relocations and focal mechanisms for aftershocks of the 2003 M6.5 San Simeon and 2004 M6.0 Parkfield earthquakes are similar to those found in previous aftershock studies. The most noticeable improvement is the sharpening of seismicity features in the offshore region near San Luis Obispo. Seismicity alignments along parts of the Hosgri Fault confirm that the Hosgri is a vertical fault down to 12 km depth. The Hosgri Fault focal mechanisms are also consistent with right-lateral strike-slip motion on a vertical fault. A prominent newly-observed feature is a 25 km long linear trend of seismicity running just offshore and parallel to the coast-line in the region of Point Bouchon. This seismicity trend is accompanied by a linear magnetic anomaly, and both the seismicity and the magnetic anomaly are truncated where they obliquely meet the Hosgri Fault. Focal mechanisms indicate that this feature is a vertical strike-slip fault. Several seismicity lineations with vertical strike-slip mechanisms are also observed in Estero Bay, trending sub-parallel to the Hosgri Fault. Events greater than about 10 km depth in Estero Bay, however, form a diffuse cluster and exhibit thrust-faulting mechanisms. The predominately strike-slip mechanisms offshore transition to predominately thrust faulting onshore, with complex fault geometry dominating the whole central coast.

Construction of a Three-Dimensional Geologic, Tectonic, Kinematic Crustal Model of Coastal Central California

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We are constructing a 3D geologic, tectonic, and kinematic crustal model of coastal central California in support of hazard assessments and tectonic analyses. The model encompasses the region between the San Andreas and San Gregorio-Hosgri Fault Zones, extends roughly from Monterey Bay to the Santa Barbara Channel, and includes the whole crust and uppermost mantle. The model volume is divided by 19 faults into completely enclosed fault blocks, each having a distinct lithostratigraphic makeup. Faults included in the model are selected based on some subset of the following criteria: recognized as important in San Andreas system quaternary activity great length (>100 km) aligned faults with consistent structural style linked into a longer fault large total offset (>1 km vertical, >5 km horizontal) profound physical property boundary3D geometry of the faults is defined by geologic maps and cross sections, catalogues of microseismicity, analyses of gravity and magnetic data, seismic profiles, drillhole information, and analysis of seismic tomography. Few of the faults are vertical and none are simple planes. Some faults (for example Oceanic, Reliz-Rinconada) may require alternative representations (deeply penetrating vs lystric).The primary purpose of the 3D model is to support a new Probabilistic Seismic Hazard Assessment of coastal central California. The model is also designed to support realistic, quantitative, predictive, computer-based simulations of a wide range of geologic processes, such as seismic wave propagation and ground shaking from scenario earthquakes, definition of the total slip budget

and partitioning within the region, analyses of tectonic strain accumulation and localization, investigation of factors controlling fault segmentation and rupture scenarios, and examination of the influence of geologic materials on tectonic processes.

INSAR Deformation Patterns for the 22 December 2003 Moment Magnitude (Mw) 6.5 San Simeon Earthquake, Central California

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The 22-December-2003 moment magnitude (MW) 6.5 San Simeon earthquake was located in the California Central Coast region about10 km east-northeast of the town of San Simeon. The earthquake nucleated 10-km beneath the Santa Lucia range, initiating nearly pure reverse motion along a northeast-dipping rupture surface that unilaterally ruptured to the southeast. The primary thrust plane is approximately 30 km long with two back thrust faults about 10 km in length along the northwestern and southeastern thirds of the primary thrust fault as resolved in the aftershock patterns (McLaren et al, 2008). Coseismic and postseismic ERS (July 2003-April 2004; Dec. 2003-Feb. 2004) and RADARSAT 1 (Jan. 2004-April 2004) satellite Interferometric Synthetic Aperture Radar (InSAR) imagery reveal broad-scale deformation patterns consistent with the back thrust fault planes inferred from the aftershock patterns as well as very localized faulting in the hanging wall of the mainshock rupture plane with left-stepping en echelon fault segments. The coseismic interferogram, which spans the postseismic period shows greater than 425 mm of decreased range; decorrelation in the interferogram masks the full deformation pattern. The postseismic interferogram shows about72 mm of postseismic uplift in the vicinity of maximum coseismic slip in the central section of the rupture, and about48 mm and 45 mm at the northwest and southeast end of the aftershock zone, respectively during the period 9–44 days after the mainshock. Motion along the two back thrust faults uplifted the northwest and southwest regions by more than 20 and 45 mm, respectively. The postseismic deformation continued from Jan. 20-April 20, 2004, but was limited primarily to the region of the main thrust.

Complex Rupture during and after the 2003 San Simeon Earthquake Determined from Multiple SAR Interferograms

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Aftershocks following the 2003 M6.5 San Simeon earthquake delineated both the main rupture plane, as well as at least one other sub-conjugate structure. An analysis by McLaren *et al.* (BSSA, 2008) relies on relocated aftershocks to identify three separate backthrust structures. They also argue that shallow postseismic slip occurred on some of the backthrusts, based on an interferogram spanning the postseismic period. We use McLaren *et al.*'s structures as a starting point and constrain the geometry and slip on the San Simeon earthquake's main plane, as well as two backthrust structures, using four interferograms and GPS data. The InSAR dataset consists of two interferograms spanning the coseismic rupture and two with only postseismic deformation and is inverted simultaneously for co- and post-seismic slip. The GPS data is a mix of campaign and continuous and is used to help constrain the coseismic slip only. We find that the rupture is complex both in space and

time. Postseismic and possibly coseismic slip occurred on at least two backthrust structures, as well as the main plane. Also, the four interferograms cannot be fit well by assuming a single decay function, and there is an indication that one backthrust slipped as a triggered slow earthquake. The complex faulting is consistent with a not-fully-established fault system, which could be expected given the low strain rates determined across the region by GPS data (1.5 mm/yr of contraction). The complexity of the San Simeon earthquake could therefore be characteristic of Central Coast earthquakes.

Probabilistic Tsunami Inundation Maps for California

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Tsunami hazard in California comes from a variety of sources including distant and local earthquake sources as well as local offshore submarine landslides. Over the last few years we have developed methods for a probabilistic analysis for tsunami hazard, both in terms of nearshore waveheight hazard as well as inundation hazard. This analysis, similar in character to modern seismic hazard analysis, includes both probabilistic recurrence models of earthquake sources and their uncertainties as well as well as an extensive uncertainty model for the propagation and inundation effects. We have used a hybrid approach, using a full probabilistic analysis for the offshore waveheight hazard with more targeted (in terms of sources and magnitudes) computation of inundation hazard based on the offshore hazard and its disaggregation. We have included large subduction zones sources from around the Pacific Rim, as well as local offshore faults, that may contribute to localized tsunami hazard. As expected, the tsunami hazard in Northern California is dominated by the Cascadia subduction zone. However, this hazard tapers off rapidly south of Cape Mendocino, where distant subduction sources become more significant, in particular the Alaska subduction zone, the Kurile-Kamchatka subduction zone and Chile. We will present inundation maps for several return periods of interest We will present maps of probabilistic tsunami inundation hazard for the entire state of California showing the areas of inundation for different average return periods (ARP) and discuss how geological information and geological uncertainties are used and expressed in inundation mapping. This work presents a major advance in probabilistic inundation mapping. Compared to the offshore waveheights it is more complicated due to the highly non-linear nature of tsunami inundation, especially when considering local as well as distant sources as in the case of the Cascadia coast.

Central California Coast Tsunami Hazards

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The Pacific Gas and Electric Company recently completed an extensive reanalysis of marine data along the continental margin from Point Conception to Point Sur (34.5° to 36.5°N) to identify potential local tsunami sources. The primary objectives of the study were to: a) construct digital elevation models (DEMs) at the

highest possible resolution by re-processing individual surveys that comprise the NGDC/NOAA coastal relief model and other sources; b) use these combined data sets in a GIS environment to aid in the identification and characterization of local tsunami sources and to provide a reference sea floor surface to be used for modeling tsunami effects; and c) develop a probabilistic framework to evaluate hazard from distant, regional, and local tsunami sources. A geomorphic seafloor classification map was developed based on the DEMs, published maps, available single channel and multibeam bathymetric data as well as known/inferred relationships between landforms, modes of sediment transport and erosion, and underlying geologic structure. Fault source and potential slope failure parameters were then used in a nested-grid, non-linear tsunami wave propagation model to estimate the median tsunami wave heights along the central California coast. The standard deviation of the wave height was estimated from comparison of observed and predicted wave heights along the California coast from the 1952 Kamchatka and 1964 Alaska tsunamis. The recurrence intervals of large earthquakes and submarine landslides were then combined with the computed probability distribution of the wave heights to compute probabilistic hazard curves for the tsunami wave height. As with ground motion hazard, we show that the inclusion of the standard deviation of the tsunami wave heights from the numerical simulations has a strong impact on the hazard at long return periods.

Site-Specific Seismic Hazard Analyses for the Monterey Peninsula

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We develop seismic design ground motions for sites on and near the Monterey Peninsula. The 2008 USGS National Hazard Maps use a relatively simple fault model in its characterization for the area, which lies between the San Andreas fault on the east and the San Gregorio fault on the west. We incorporate several potentially seismogenic faults in our probabilistic analyses that are not part of the USGS model, including the Cypress, Chupines, Hatton Canyon, and Sylvan Thrust faults. The most significant fault on the Peninsula in a deterministic framework is the 84-km-long Monterey Bay-Tularcitos fault, which has a maximum earthquake of M 7.1 ± 0.3, although little is known about its segmentation, and a slip rate estimated to be 0.5 ± 0.4 mm/yr. To characterize the attenuation of ground motions in the probabilistic and deterministic analyses, we use the recently developed NGA relationships, and to account for the epistemic uncertainty in Vs30 of the sites, we use a range of values for each site and envelope the ground motions as expressed by Uniform Hazard Spectra (UHS). At a 2,475-year return period, the hazard is dominated by events in the magnitude range of M 6.5 to 7.0 at distances less than 15 km, coming from the San Gregorio and Monterey Bay-Tularcitos faults. The shorter faults we added to the model contribute to the hazard at return periods longer than a few hundred years. The calculated 2,475-year return period PGA for a site in Pacific Grove is 0.69 g for a soft rock site condition, approximately 15% higher than the firm rock National Hazard Map value. A M 7.1 earthquake on the Monterey Bay-Tularcitos fault is used in the deterministic evaluation for this same site, and an 84thpercentile PGA of 0.78 g is yielded. For the Pacific Grove site, the UHS is lower than the deterministic spectrum, so it forms the basis for the design ground motions.