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SEAFLOOR MAPPING
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Seafloor Mapping for Earthquake, Tsunami Hazard Assessments

Geophysical and Seismic Surveys Conducted Offshore A California Nuclear Power Plant for Preventive Safety

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The global dialogue on the safety and reliability of nuclear power plants has changed since the 2011 magnitude-9 earthquake and tsunami in Tohoku, Japan. While coastal central California is tectonically different than eastern Japan (a strike-slip versus subduction plate margin), critical facilities located near active fault zones in coastal environments, like Pacific Gas and Electric's (PG&E) Diablo Canyon Power Plant (DCPP), have been the focus of increased attention regarding earthquake and tsunami hazards. Extensive geological and geophysical investigations underway at DCPP are designed to improve hazard assessments. DCPP geosciences staff monitors regional earthquakes and studies global seismic events as part of the plant's safety program. Earthquake hazard information from the program is used to confirm that DCPP can withstand all credible ground motions from nearby faults.

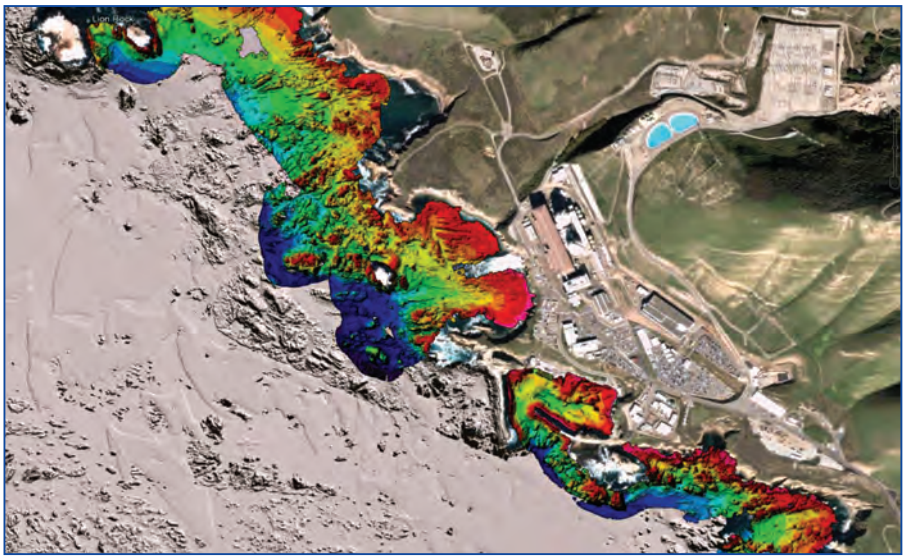
After the 2003 magnitude-6.5 San Simeon, California, earthquake, PG&E began a multiyear geological and geophysical evaluation of earthquake and tsunami hazards for the south central coastal area. PG&E funded U.S. Geological Survey (USGS) research that reevaluated more than 20 years of earthquake data, which led to the 2008 discovery of the Shoreline fault offshore DCPP. The Central Coastal California Seismic Imaging Project (CCCSIP) now conducts multibeam echosounding (MBES) mapping, potential field (gravity and high-resolution marine and aeromagnetic) mapping, high-resolution high and low energy 2D and 3D seismic-reflection profiling, and ocean-bottom seismic monitoring.

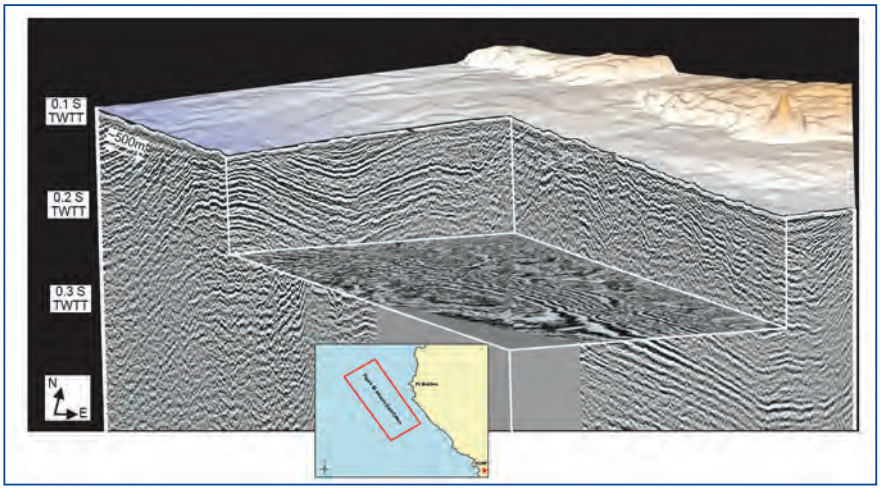
Transition Zone Mapping

For much of its length along the coast, the Shoreline fault zone is located in the transition zone (also known as the white zone) in water less than 25 meters deep, with intervening kelp beds, wash rocks and pinnacles. Combined with steep coastal bluffs, the transition zone around DCPP presented a challenge for geophysical data collection.

PG&E sponsored an MBES survey offshore DCPP in 2009 to document possible surface expression of the Shoreline fault. The survey was conducted by the California State University, Monterey Bay (CSUMB), Seafloor Mapping Lab as part of the California Seafloor Mapping Project, a statewide

The RV Kelpfly*, a modified jet-ski powered by an airboat engine and equipped with swath bathymetry echosounding and lidar systems. (Photo courtesy of Rikk Kvitek, CSUMB Seafloor Mapping Lab)*





(Top) Google Earth image. The RV Kelpfly can operate and map in most shallow coastal and estuarine areas off limits to conventional mapping platforms, including airborne bathymetric lidar often limited by kelp cover, fog and water clarity along the California coast.

(Bottom) The 3D cube image illustrates structural relationships in deformed sedimentary rock both in cross section and plan view (time slices), allowing for identification of folds and faults represented by the seismic reflections.

initiative to map all state waters out to the 3-mile territorial sea boundary. The CSUMB 34-foot aluminum RV *Ven Tresca* was used to map much of this area using RESON A/S (Slangerup, Denmark) 8101 and 7125 MBES systems. MBES data clearly identified a series of linear seafloor features offshore DCPP coinciding with the earthquake epicenter lineations.

Areas within the shallow subtidal and intertidal zones that could not be safely mapped with the vessel required a new approach. Rikk Kvitek developed the RV *Kelpfly*, an armored airboat/jet-ski rigid inflatable boat hybrid equipped with fully integrated hydrographic and topographic mapping instrumentation, including an Applanix Corp. (Richmond Hill, Canada) POS MV Wavemaster for recording sensor position and attitude at 100 hertz, a SEA (Beckington, England) SWATH*plus* 468-kilohertz interferometric side scan sonar for ultrawide (15:1) swath bathymetry, a backscatter Riegl USA (Orlando, Florida) LMS-Z420i topographic lidar used in line scan mode for intertidal and shoreline mapping to port or starboard, and a YSI Inc. (Yellow Springs, Ohio) Castaway CTD sound velocity profiler for bathymetry refraction correction.

The ability to work in the surf zone, bounce off rocks in as little as 50 centimeters of water and skim the sea surface over eel grass and kelp beds allows the *Kelpfly* to operate and map in most shallow coastal and estuarine areas off-limits to conventional mapping platforms, including airborne bathymetric lidar often limited by kelp cover, fog and water clarity along the California coast.

3D Subsurface Mapping

Marine seismic reflection surveys were conducted using a nested survey strategy. High-resolution single-channel data were collected at 800-meter intervals perpendicular to the coast aboard the 34-foot aluminum RV *Parke Snavely* by the USGS Pacific Coastal and Marine Science Center in Menlo Park and Santa Cruz, California in 2008 and 2009, using a SIG 2 Mille mini-sparker. Using these data, specific target areas were identified for higher-resolution multichannel 2D and 3D surveys. These studies were conducted beyond the Transition Zone, in waters more than 20 meters deep outside the kelp canopy, where there was less risk of fouling or snagging equipment.

The 2010 and 2011 surveys focused on the northern end of the Shoreline fault zone, offshore Point Buchon, where it projects towards the larger Hosgri fault zone. Mobile sand sheets of variable thickness obscure seafloor basement features that may be related to the fault zone in this northern area. PG&E contracted Fugro Consultants Inc. (Ventura, California) to conduct a series of low-energy (less than 2 kilojoules, the power limit in California state waters) high-resolution 2D and 3D seismic-reflection surveys.

The 100-foot MV *Michael Uhl*, from Morro Bay, was used as the survey vessel. For the 2010 and 2011 surveys, Fugro employed four parallel, 16-channel, 50-meter-long, liquid-filled GeoEel streamers manufactured by Geometrics (San Jose, California), with GeoEel hydrophones grouped at intervals of 3.125 meters. Trackline spacing was 12.5 meters, with a subsurface swath width of 18.75 meters, and the data were binned at 3.125 meters by 1.56 meters. The seismic source was an AP3000 Triple Plate Boomer (less than 2 kilojoules) manufactured by Subsea Systems Inc. (Ventura, California). Fugro and NCS Subsea (Stafford, Texas) provided DGPS navigation utilizing a GPS unit located on the Boomer sled and at the head of each streamer.

Data and Imagery Analysis

The use of multibeam bathymetry, 2D seismic reflection profiles and 3D seismic volumes allowed peeling the ocean's subsurface away like the layers of an onion. The shallow nearshore and white zone can be accurately imaged using these new surveying techniques, revealing a seafloor primarily

composed of bedrock exposures. Deeper water areas have a cover of mobile sand sheets of variable thickness that require high-resolution seismic reflection profiling to image the buried irregular bedrock surface and deeper strata. To assist in examining the subsurface, a 3D seismic volume, or cube, was produced in IHS Inc.'s (Englewood, Colorado) SMT Kingdom Software. The 3D cube can be viewed in various orientations, similar to a medical CT scan, to show both user-selected cross sections and surfaces or planes (horizontal time slices) within an area of interest. The 3D cube image illustrates structural relationships in deformed sedimentary rock both in cross section and plan view (time slice), allowing for identification of folds and faults represented by the seismic reflections.

"The 3D seismic volume image allows for identification of folds and faults represented by the seismic reflections."

PG&E is constructing high-resolution maps and cross sections using these techniques to better constrain fault parameters, such as type, length, connectivity and displacement, needed for the DCPP seismic hazard analyses. High-resolution bathymetry and seismic profiling can be used to identify fault offsets of recent geomorphic features as well as earthquake-related landslide and debris flow deposits. Measurements of offset paleostream channels can constrain rates of fault motion. Mapping and dating of successive debris flows can be used to develop a paleoearthquake chronology.

A Second 3D Survey

In December 2011, Fugro Consultants conducted a second 3D survey to image the southern end of the Shoreline fault zone in San Luis Bay using the new Geometrics P-Cable array. The survey area included a buried paleostream channel that crossed the projected trace of the Shoreline fault. Identified offsets of that channel by the Shoreline fault could provide a key constraint on the rate of fault slip. The Geometrics P-Cable system represents a significant upgrade in equipment technology with a wider swath width, solid digital streamers and compasses embedded in the streamers, allowing faster survey time with improved data quality.

Fugro used a larger vessel, the 164-foot MV *Bluefin* from Seattle, Washington, and employed 14 parallel, eight-channel, 50-meter-long, solid-filled Geometrics GeoEel streamers, with hydrophones grouped at intervals of 6.25 meters. The subsurface swath width was approximately 80 meters and the data were binned at 3.125 by 3.125 meters. The seismic source was the same AP3000 Triple Plate Boomer used for the Point Buchon survey. NCS Subsea provided navigation control using new software specifically developed for the Geometrics P-Cable system. Data from this 3D survey are now being processed at Fugro Seismic Imaging Inc. (Houston, Texas) and will be interpreted later this year.

Summary and Conclusions

Application of new technologies to the geophysical investigation of the area offshore DCPP is producing a clearer view of the complex geologic structure that exists in this strike-slip tectonic regime and illustrates how marine sciences can support public safety. Filling in the white zone with the RV *Kelpfly* has provided detailed bathymetry that will be useful in accurately correlating onshore and offshore geologic structures.

"Filling in the white zone with the RV **Kelpfly** *has provided detailed bathymetry that will be useful in accurately correlating onshore and offshore geologic structures."*

The marine 3D seismic reflection data cubes or volumes provide a modern method to view subsurface deformation in a manner that will assist in comprehensively interpreting complex geology.

The interpretations will eventually be merged with additional geologic and geophysical data to be collected and interpreted in the near future as part of the plant's long-term seismic program.

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