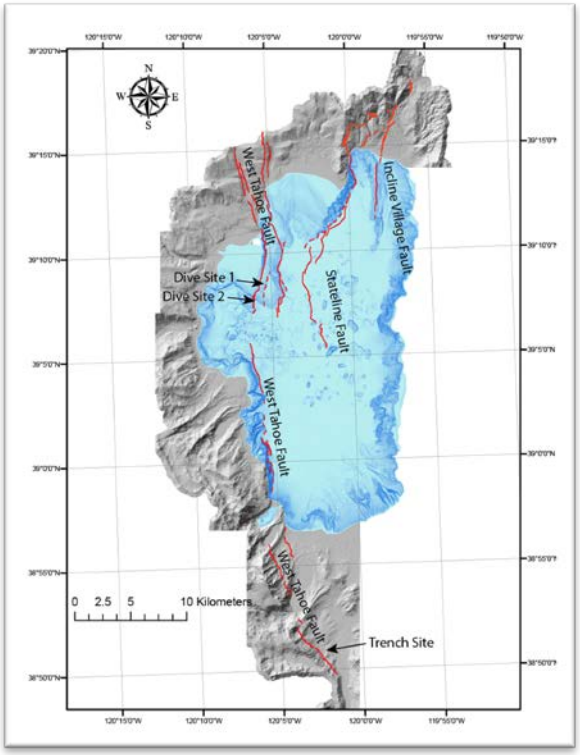
Alfred E. Alquist Seismic Safety Commission

Seismic Hazard Investigation of Lake Tahoe Using New Remote Operated Submarine: Dive Test in Support of Antarctic Subglacial Research (WISSARD) Project



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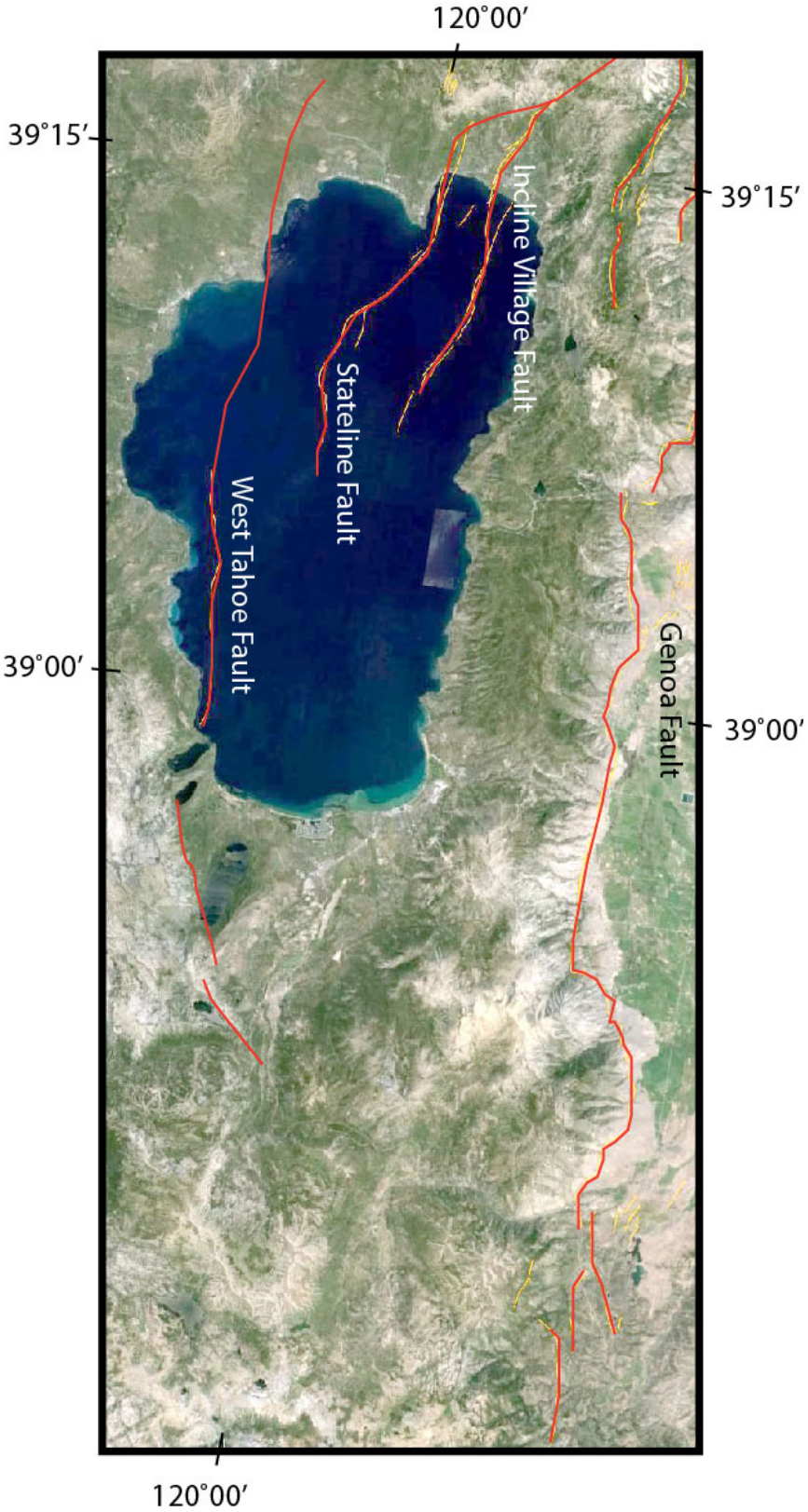


Figure 1. Location Map with Regional Faults. Note: the Genoa Fault (Ramelli et al., 1999) has a similar length, slip rate, and orientation to the West Tahoe Fault. The major difference is the West Tahoe Fault is submerged along its most active central portion. These faults both generate earthquakes in the magnitude 7+ range. Tsunamis are generated when the underwater portion of the West Tahoe Fault shifts during earthquakes.

Executive Summary

The purpose of this investigation has been to characterize the seismic hazard of Lake Tahoe using new ROV (Remote Operated Vehicle) technology. The innovations are the result of the development of an ROV designed and built in California, to explore below the 1000 m thick Ross Ice Shelf in Antarctica. The ambitious NSF-funded Whillans Ice Stream Subglacial Access Research Drilling (WISSARD) project aims to explore one of the most remote and difficult to access regions on the planet. The WISSARD project plans to drill a hole through the ice shelf, then lower a sophisticated sensor-equipped SIR (Sub Ice Rover), which expands in the water below. While Lake Tahoe is more accessible than Antarctica, it has important similarities to the Antarctic research site and many important seismic hazard related aspects of Lake Tahoe are largely unexplored.

Lake Tahoe was selected as a testing site for the Antarctica-bound ROV for the following reasons:

- Great water depth, required for a valid test of the ROV.
- Sediments similar to the targeted Antarctica dive site.
- Potential to make significant contributions to the understanding of seismic hazard in California leveraged by a public-private partnership.
- Access and proximity to the shipyard where the ROV is built.

Onshore and offshore studies have revealed that the most significant geologic hazard process in the Lake Tahoe basin is faulting; three active faults cross the basin and lake floor. These faults are among the most significant seismic sources in the region and appear to have their most active portions in the deeper portions of the lake. In addition to ground shaking and surface ruptures from earthquakes, the exceptional depth of Lake Tahoe creates the additional hazard of tsunamis. The hazard of even moderate earthquakes is greatly increased around Lake Tahoe because associated surface ruptures or triggered landslides may generate a tsunami wave that can impact the entire shoreline with inundation and permanent subsidence.

We make the following findings:

- Lake bottom visual observations are valuable because they reveal details in faulting and landsliding not obtainable by other methods.
- The lake bottom landscape promises a detailed record of past earthquake behavior, including vertical surface displacements, which may have occurred as a result of the most recent earthquake.
- These types of observations are needed to fill an important gap in our current overall assessment of seismic hazard. This data is needed as input for constructing realistic earthquake source scenarios and modeling tsunami waves.
- Although it is difficult to obtain observations at these water depths, fault and landslide scarps degrade much slower than those on land, and thus promise to provide valuable paleoseismic observations.
- Onshore paleoseismic research efforts complement this work.
- Preparation of California Geological Survey issued hazard planning and regulatory maps will be supported by this effort.

Recent onshore lidar surveys have made it possible to clearly map active faults in the Tahoe basin. Lidar is a remote sensing technology which uses lasers and provides the highest resolution topographic surveys. Our experience at Lake Tahoe has motivated us to seek higher resolution multibeam surveys of the active faults in the lake at resolutions comparable to on land lidar surveys. This is made possible by operating the multibeam sensor closer to the lake floor, which can be done from the SIR (Sub Ice Rover). By combining visual scarp observations with surveys from onboard sensors such as high-resolution seismic profilers CHIRP (Compressed High Intensity Radar Pulse) and the multibeam bathymetry, we expect to assess geologic hazards in the Lake Tahoe Basin with much greater confidence and accuracy.

Lake Tahoe is an ideal area to refine these methods as field deployments are much simpler and less costly than in true ocean settings and it is clear that Lake Tahoe has considerable seismic hazard and risk; however the methodologies that we develop here will clearly be used elsewhere. California has many hazardous offshore faults, essentially along its entire shoreline, which remain largely uncharacterized due to the lack of such methodology.

Purpose

The purpose of this investigation is to characterize the seismic hazard of Lake Tahoe using new ROV technology. The field investigation and dive sites were located along the west side of Lake Tahoe. At Lake Tahoe several active faults are located at great water depths, and coseismic surface displacements in deep water can generate tsunamis. Additionally, tsunamis can be generated by landslides, which can be induced by earthquakes. In order to assess the tsunami potential of Lake Tahoe one needs detailed paleoseismic observations of the amount of earthquake displacement at the lake floor. These direct observations currently do not exist. With these observations earthquake and tsunami scenarios suited for seismic safety policy issues can be formulated. New ROV technology presents a unique opportunity and perhaps the only method to make these critical observations. In the following report we present the first step in using significantly more sophisticated ROV technology than previously deployed at Lake Tahoe for this purpose. A broader objective is developing offshore research methodologies that can be used elsewhere such as the California coast.

Introduction

Lake Tahoe is a high Alpine lake that was created in an area that dropped down due to earthquake faulting. It was dammed on the north side by volcanic deposits. Ice-age glaciers and a mega-landslide shaped its shoreline (Fig. 1, 2). Onshore and offshore studies have revealed that of these processes, perhaps the most significant one, faulting, continues today with three active faults that cross the basin and lake floor. These faults are among the most significant seismic sources in the region and have their most active portions in the lake. In addition to ground shaking and surface ruptures from earthquakes, the exceptional depth of Lake Tahoe creates the additional hazard of tsunamis. The challenge of characterizing the current geological hazards of the Tahoe basin is that large portions of the faults are submerged. In general, the methodology for assessing seismic hazards offshore requires more advanced technology than the more established onshore fault investigation methods.

The hazard associated with even moderate earthquakes is greatly increased around Lake Tahoe because any submerged surface ruptures or triggered landslides may generate a tsunami wave that can impact the entire shoreline (Ichinose et al., 2000). An ancient 8-kilometer wide landslide caused a giant

tsunami wave (Ward, UCSC). The mega landslide, referred to as the McKinney Bay slide, appears to have been a relatively rare event compared to the much more frequent earthquakes, which also generate large tsunami waves. Additionally, earthquakes in Lake Tahoe shift fault blocks vertically, with the east side down, resulting in permanent shoreline subsidence and consequent inundation.

This project at Lake Tahoe is the result of serendipity. The Whillans Ice Stream Subglacial Access Research Drilling (WISSARD) project led by Northern Illinois University (NIU), designed to explore parts of Antarctica and funded by the National Science Foundation, needed a place to test its equipment. Lake Tahoe is ideally suited for this ROV testing because it is close to where the SIR is built. In addition, its great water depth, and its glacial history, which has resulted in the deposition of similar sediments as those expected in Antarctica. Meanwhile, the California Geological Survey (CGS) and the California Seismic Safety Commission (CSSC) were looking for an opportunity to explore the deeper parts of Lake Tahoe to assess seismic hazards. CGS offered the WISSARD team guidance in selecting targets for study in Lake Tahoe that would suit the purposes of both groups. The Seismic Safety Commission funded the CGS field work and helped NIU defray some of its expenses during field trials.

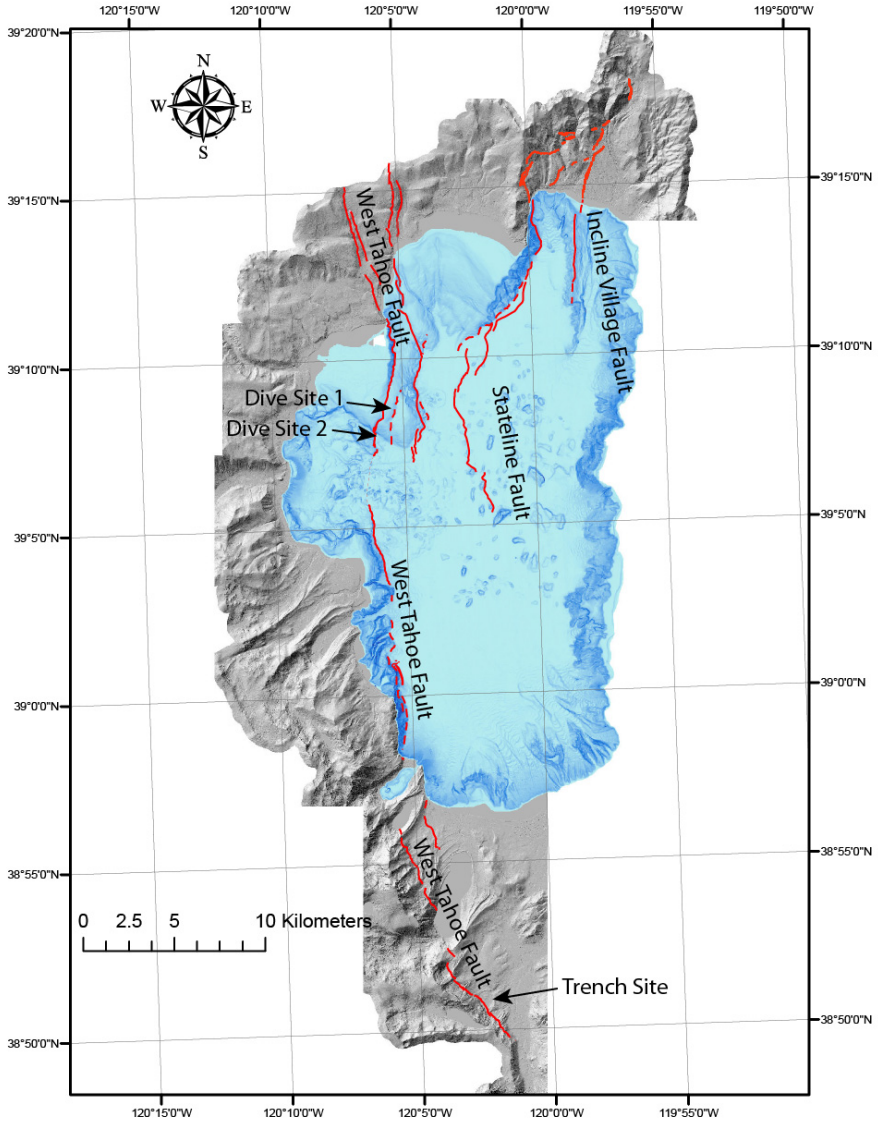


Figure 2. Tahoe Basin Fault Map. Highest-resolution elevation data maps with faults. The West Tahoe Fault investigation sites are shown. The dives were conducted in 2012, the trenching in 2013. The lake bathymetry multibeam data have a resolution of 10 m and is displayed as a slopeshade; darker shades are steeper slopes. The onshore data consists of lidar processed as a bare earth model displayed as a hillshade (illuminated from one direction) essentially removing all vegetation, and the resolution is 0.5m. The faults at the dive sites 1 and 2 are considered to be part of the West Tahoe Fault.

In the Antarctic, this equipment (Fig. 3) will be used to probe some of the last unexplored aquatic environments on Earth. In addition to the California Seismic Safety Commission and National Science Foundation, the National Oceanic and Atmospheric Administration and the Gordon and Betty Moore Foundation have provided funds for instrument design, construction and testing.

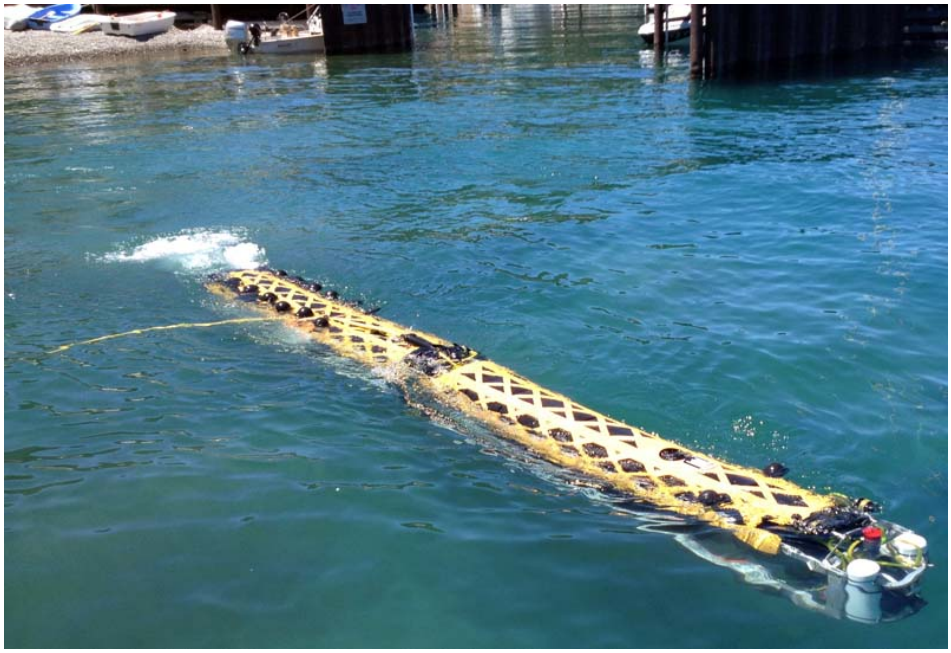


Figure 3. Sub Ice Rover-SIR. First water launch, 2013. CSSC report No. 13-04 describes the ROV engineering.

Method

Although several studies have focused on faults and landsliding in Lake Tahoe (Fig. 2,12,13), there remain significant gaps in information due to the difficulty in making direct observations at the lake bottom. Most of the previous lake research used remote sensors towed behind ships to image the lake bottom either with seismic profiling or multibeam sensors. With ROV (remote operated vehicle) technology (Fig. 3, 4, 5, 6) one moves closer to land-based geologic hazard investigation methods that have much higher resolutions. This means one is able to observe much greater detail and thus greatly improve the assessment of faulting and landsliding. In particular the observations that are most valuable are those that indicate the activity of the most recent event. Because single event displacements are smaller than the more commonly observed cumulative displacements, higher resolution observations are needed. In turn, these detailed observations are more useful for seismic hazard assessments. In the past, none of the ROV dives at Lake Tahoe observed the faults at depths greater than approximately 30 meters. With our investigation we took advantage of the ROV capabilities to observe the West Tahoe Fault at depths ranging up to 400 meters. We specifically targeted the West Tahoe Fault at these locations because the fault appears to be most active i.e. has a higher slip rate there.

Previous ROV Dives at Lake Tahoe

Various researchers have deployed ROVs and AUVs (autonomous underwater vehicles) at Lake Tahoe. In general these efforts involved relatively small ROVs that are limited to shallow water and also do not have sensors other than video with limited lighting. Additionally, the deployed ROVs often had limited navigation capabilities. For example, Kent and Seitz (2002) included an ROV dive in Meeks Bay targeting submerged lake levels and possible glacial moraines. The ROV was provided by the Department of Mechanical Engineering University of Santa Clara. In 2004 (Seitz and Kent) deployed another small ROV to visually inspect the Incline Village Fault at depths up to approximately 30 m. Moore et al. 2006 report the use of the University of Santa Clara ROV to observe the shallow Tahoe City shelf. In general these ROV efforts provided qualitative complements to other investigations by providing visual data. For example our previous Incline Village Fault dives (2003, 2004) were combined with CHIRP seismic profiling to provide a fuller characterization of the fault scarp under water, which we later integrated with onshore observations.

AUVs have also been deployed at Lake Tahoe (TERC, 2009) with a focus on invasive species. Because AUVs require the dive route to be programmed in advance, direct interactions from the researchers in real time are not possible. Hence the nature of investigations is very different, with an emphasis on surveying.

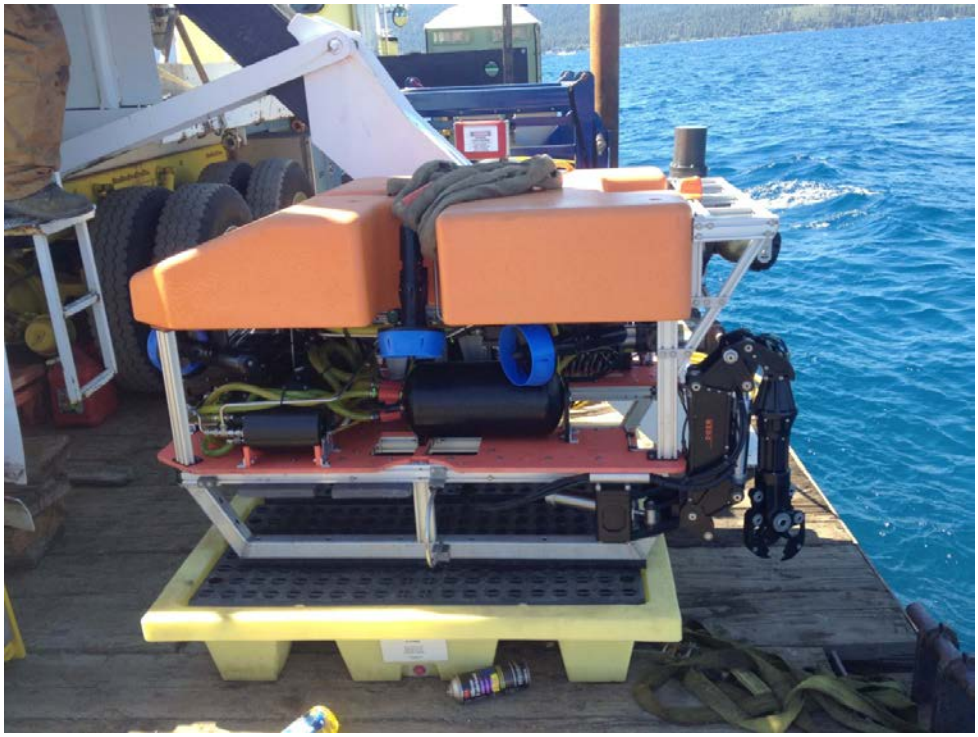


Figure 4. Conventional ROV. This DOER Marine built ROV operated by Scripps Institute of Oceanography was used in the 2012 investigation. Thrusters with blue guides, grab arm on right side.

Figure 5. ROV Grab Arm. Camera, lights, yellow tether and winch.

Figure 6. ROV Control Center. Multiple monitors and control joysticks.

Faulting and Earthquakes

On and offshore studies in the Tahoe basin (Kent et al., 2002, Seitz et al., 2004, Kent et. al, 2005, Seitz et al., 2006, Dingler et al., 2009, Brothers et al., 2009, Smith et al., 2013), have revealed three active normal faults that are significant seismic sources (Fig. 2). Using high-resolution seismic CHIRP (Compressed High Intensity Radar Pulse) profiles, combined with age dating of sediment cores using radiocarbon (C-14) and optically stimulated luminescence (OSL) techniques, have allowed estimates for slip rates for the West Tahoe (WTF), Stateline (SF) and Incline Village (IVF) faults (Fig. 2). Offset submerged paleolake terraces and a catastrophic slide debris deposit provide markers for vertical slip rates of 0.6 mm/yr (0.44-1.1), 0.45 mm/yr (0.35-0.6) and 0.2 mm/yr (0.12-0.3) on the West Tahoe, Stateline and Incline Village faults, respectively (Kent et al., 2005; Dingler et al., 2009). Total extension across all three basin forming faults is estimated to be 0.84 mm/yr (0.53-1.15), or more than 30% of east-west extension observed along Sierra Frontal faults through geodetic measurements spanning the Walker Lane (Hammond and Thatcher, 2004). The Walker Lane as used here is a tectonic system consisting of many faults that accommodate right-lateral shear between the North American and Pacific plates. Large fault scarps seen both on land, and on the lake floor (Gardner et al., 2000), combined with the stratigraphic offsets observed in both offshore seismics and in a trench (IVF) suggest that these basin faults behave much like other Basin and Range range bounding normal faults and release strain in M7+ range earthquakes (Wells and Coppersmith, 1994, Wesnousky, 2008).

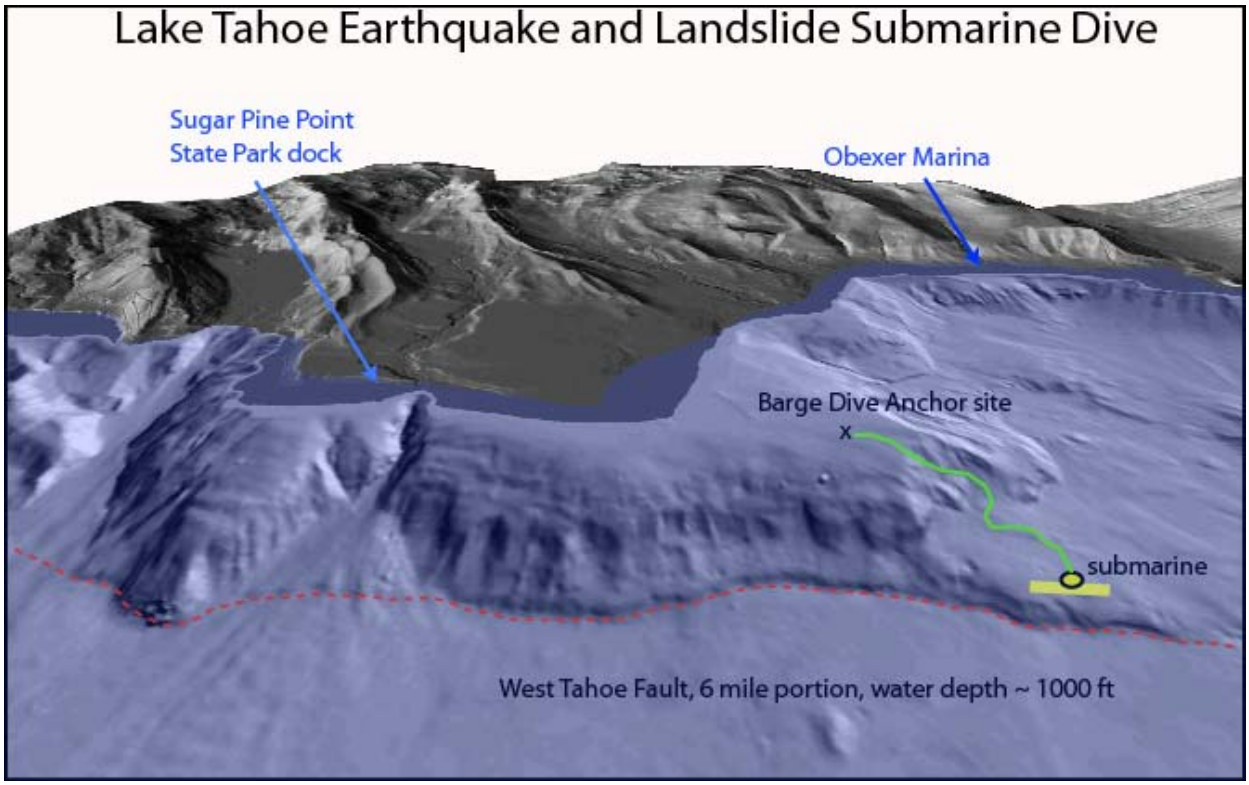


Figure 7. West Tahoe Fault Underwater Map. 2013 dive plan schematic along the best expressed 10 kilometer portion of the West Tahoe Fault (dashed red line) at a water depth of about 300 m. On the left side of the image the fault crosses a glacial-age submarine fan with a scarp height of about 10-12 m (shown in detail in Fig.10).

The West Tahoe fault has a mapped length of 45 km (Fig. 2), and its vertical slip rate is estimated at 0.6-1.0 mm year. It is the range bounding, east dipping normal fault along the west margin of the basin, and is largely located along the western base of Lake Tahoe at a water depth of 400-500 m. In the lake the fault has clearly defined scarps that offset submarine fans (Fig. 7,10), lake-bottom sediments, and the McKinney Bay slide deposits (Hyne et al, 1972; Gardner et al, 2000; Kent et al, 2005; Dingler et al. 2009). Fault kinematic considerations based on the geometry of the lake basin faults, with the West Tahoe fault being the only mapped fault in the southern half of the basin, combined with across the lake displacement measurements (Dingler et al., 2009) result in interpreting this portion of the fault to have the highest slip rate. Recent work analyzing sediment cores from the lake bottom has clearly shown that earthquakes on the local faults trigger landslides in the lake (Smith et al., 2013). These triggered landslides in turn stir up the lake sediments which form distinct wide spread sediment deposits termed turbidites. The sediment cores provide a long-term record of strong earthquake shaking frequency, and between 14 to 17 events were recognized in the past 12 thousand years.

The most recent offshore studies conducted in Fallen Leaf Lake, Cascade Lake and Lake Tahoe (Brothers et al. 2009, Maloney et al., 2013) further refine the paleoseismic chronology of the West Tahoe fault and show an event at about 4 thousand years before present.

A’ **A**

Figure 8. West Tahoe Fault Trench Log Image Mosaic. Clear evidence for two earthquakes was identified during this 2013 USGS NEHRP funded project conducted by Gordon Seitz, California Geologic Survey. Radiocarbon dating of these events is pending. The main fault is the sharp left sloping contact between gray glacial sediments and brown alluvial and scarp derived colluvial sediments. The trench exposure is about 4 meters deep, image tiles are1 meter horizontal by 0.5 meter vertical. The excavation was benched, the upper bench is the separate top mosaic. The uppermost slope is the ground surface. The surface soils and colluvium thicken on the left down-faulted block. Fault trench location is indicated in Fig. 2 and 9.

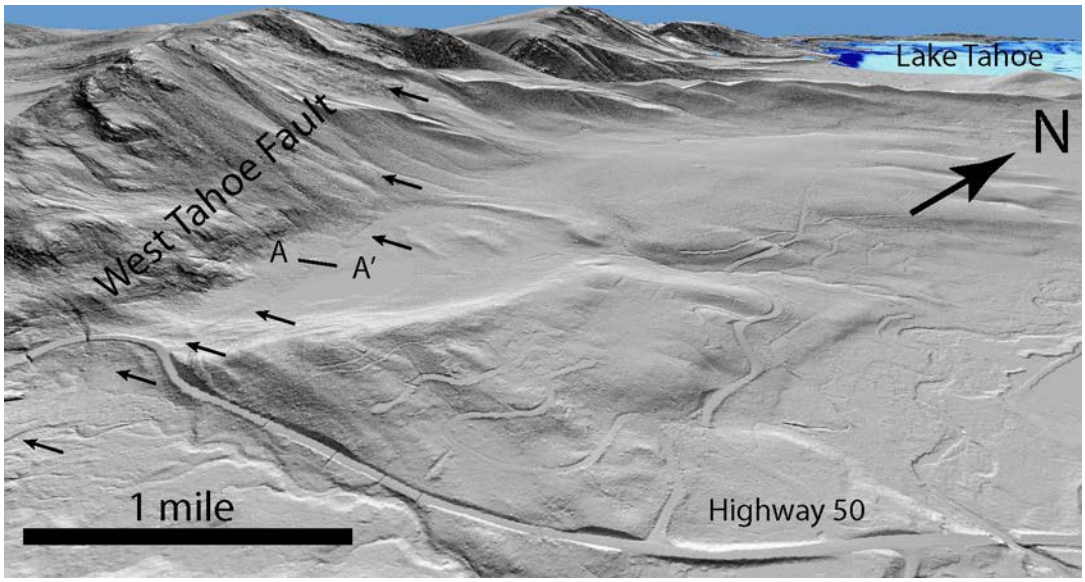


Figure 9. Oblique Lidar Hillshade Image of Southernmost West Tahoe Fault. The arrows point to the fault scarp, The A-A' line indicate the location of a profile and this is also the location of the fault trench shown in figure 8. The fault scarp is about 3.5 meters in height at A-A'. Scale 1 mile = 1.6 kilometer.

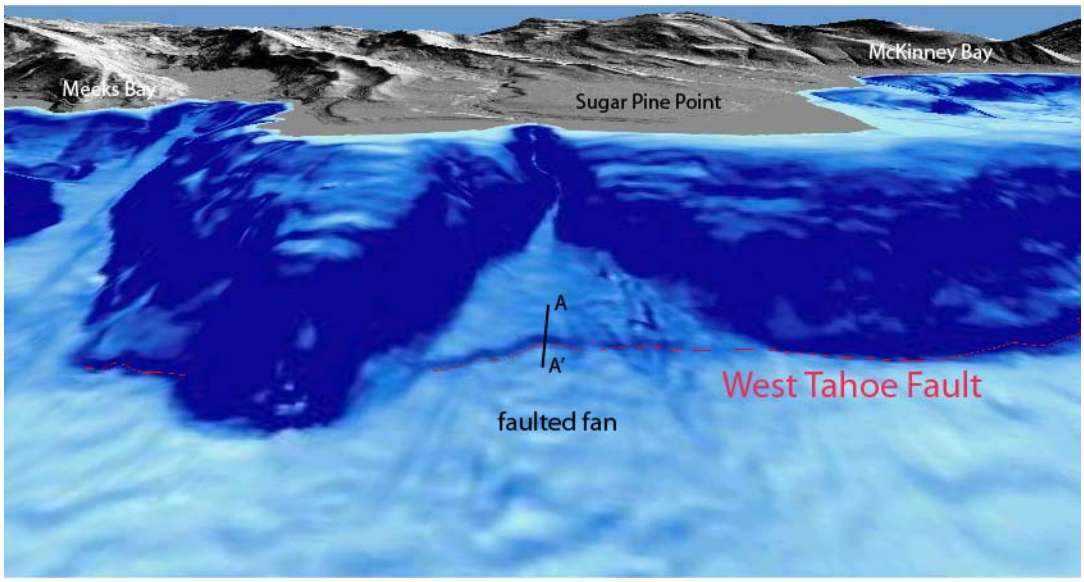
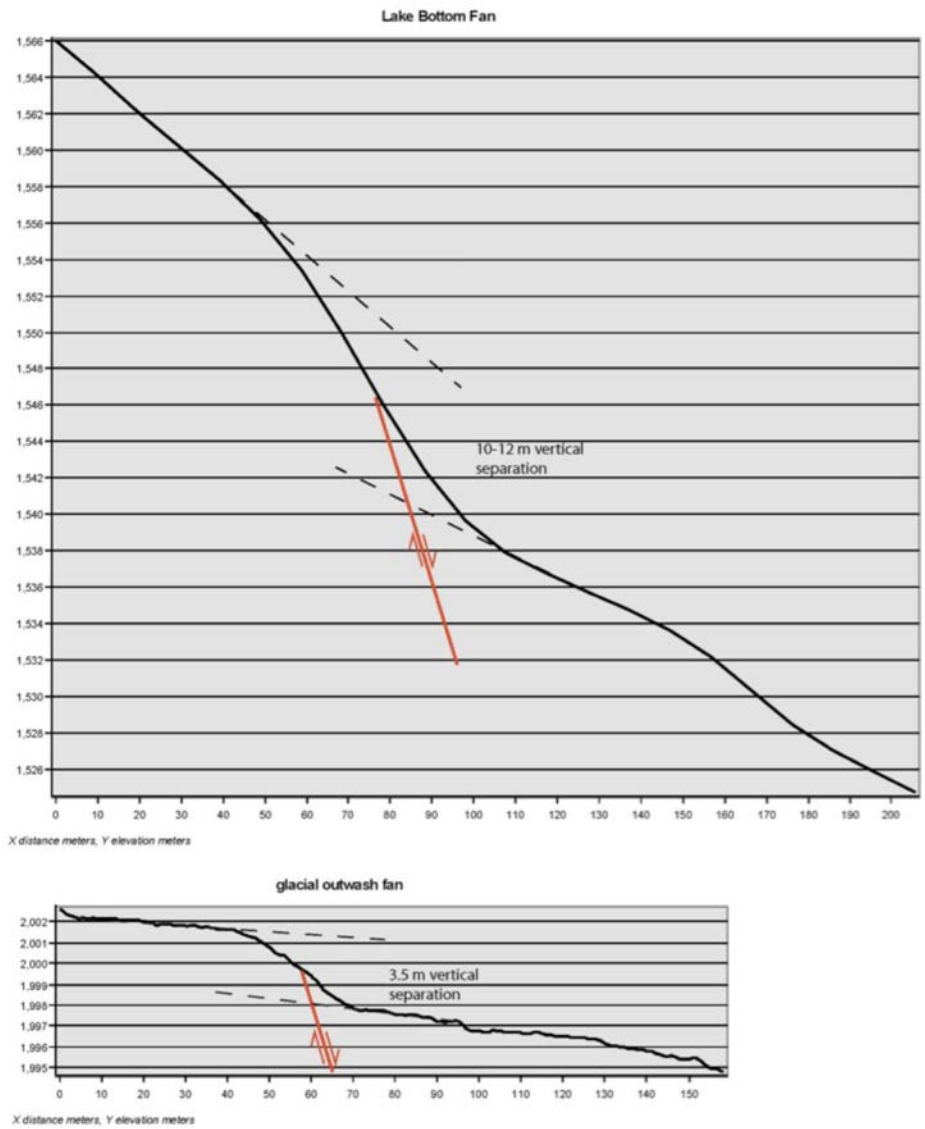


Figure 10 Faulted Glacial-Age Fan at the Lake Bottom. The scarp height across the fan is 10-12 m, east side down. A-A' indicates the profile section shown in figure 11.

In October 2013 Seitz trenched the West Tahoe Fault (Fig. 8 and location Fig.2 and 9) south of Fallen Leaf Lake as shown on Fig. 2 (USGS-NEHRP funded investigation on USFS land and facilitated by their permission). The results from this study relate to the hazard of the West Tahoe Fault in the lake in the following manner. The fault scarp at the trench site is 3.5 m meters high at the bottom of the lake at a

depth of 400 m (Fig. 10) the postulated same-age fan has a vertical scarp of 10-12 meters. Given the size of the earthquakes and the number of earthquakes observed in the paleoseismic records, if the same number of events resulted in the underwater scarp then the events must average about 5-6 m vertical displacement per event. This has serious implications for the generation of lake tsunamis and permanent shoreline subsidence.



A **A'**

Figure 11 Fault Scarp Profiles. These are cross-fault profiles that show same-age landforms are displaced considerably more at the bottom of the lake. The top profile from the lake bottom (location figure 10) indicates 10-12 m vertical displacement. The bottom profile located at the southern end of the fault (location figure 9, 2) indicates 3.5 m vertical displacement. Both are east side down. The dashed lines indicate surface projections. X axis distance in meters, Y axis elevation in meters. Both profiles are vertically exaggerated, top 4:1, bottom 5:1.

Megaslide

Landslides are common along the steep walled margins of Lake Tahoe, however the 8-kilometer wide McKinney Bay megaslide (Fig. 12, 13) along the west shore has completely reshaped the lake, forming a huge bay and depositing a sediment layer with large rock blocks across the lake bottom extending 20 kilometers to the east shore of the lake. The slide clearly occurred during a time the lake was present. When initially surveyed these rock blocks, which rise hundreds of feet above the lake floor, were thought to be volcanoes. The age of this megaslide is still being discussed, with published ages ranging from 5,000 thousand to 300,000 years. The most accepted age is about 60,000 years and is based on radiocarbon dated sediment cores and high-resolution seismic profiles (Kent et al., 2005, Smith et al., 2013). The megaslide scarp and sediment deposit provide a valuable marker for determining fault activity.

Tsunamis

The McKinney Bay Slide with its massive size and long run out across the entire lake without a doubt generated a giant tsunami wave modeled as a 100 m high wave (Ward, UCSC). However, no direct geologic evidence for this giant wave has been discovered. This is not the typical wave that is generated by the more frequent earthquakes that occur in Lake Tahoe, but rather a very rare occurrence. However, understanding the megaslide and its effects helps to understand other more frequent tsunami waves at Tahoe. Despite the fact that these tsunami waves are generated by different mechanisms, and have different scales, they both should have similar geologic effects and possibly provide similar evidence of their occurrence. And although the megaslide tsunami wave is a rare occurrence, it is an event of such consequence that it warrants further investigation, as the adjacent lake shelves appear to be similar to the one that failed during the megaslide, and one would want to know if they too might be vulnerable to collapse. On the other hand we know that an earthquake on any of the Lake Tahoe faults would generate a more moderate wave scaled to the amount of vertical displacement of the fault, and any landslides triggered by the shaking. Previously moderate fault displacements have been modeled resulting in wave heights of 4-10 m (Ichinose et al., 2000). We consider these wave heights to be low estimates because the vertical displacements used as inputs for the model were significantly lower than our current fault displacement estimates. These can be several times larger, and triggered landslides were not considered.

Research Dives

Originally the project was planned as a single field deployment to test and use both the SIR (Fig. 3) and the percussion coring device. Due to the tight Antarctic research schedule and the SIR not being completed in 2012, field testing and deployment were divided into two separate sessions, the first August 2012, and the second in July 2013.

During the August 2012 field testing, a conventional DOER Marine built ROV (Fig. 4, 5, 6) from Scripps Institute of Oceanography was used. The deep percussion coring device failed with the core barrel separating from the hammer section at a depth of ~ 160 m. No samples were retrieved. A second shallow surface coring device was successful in retrieving short 5-12 cm cores.

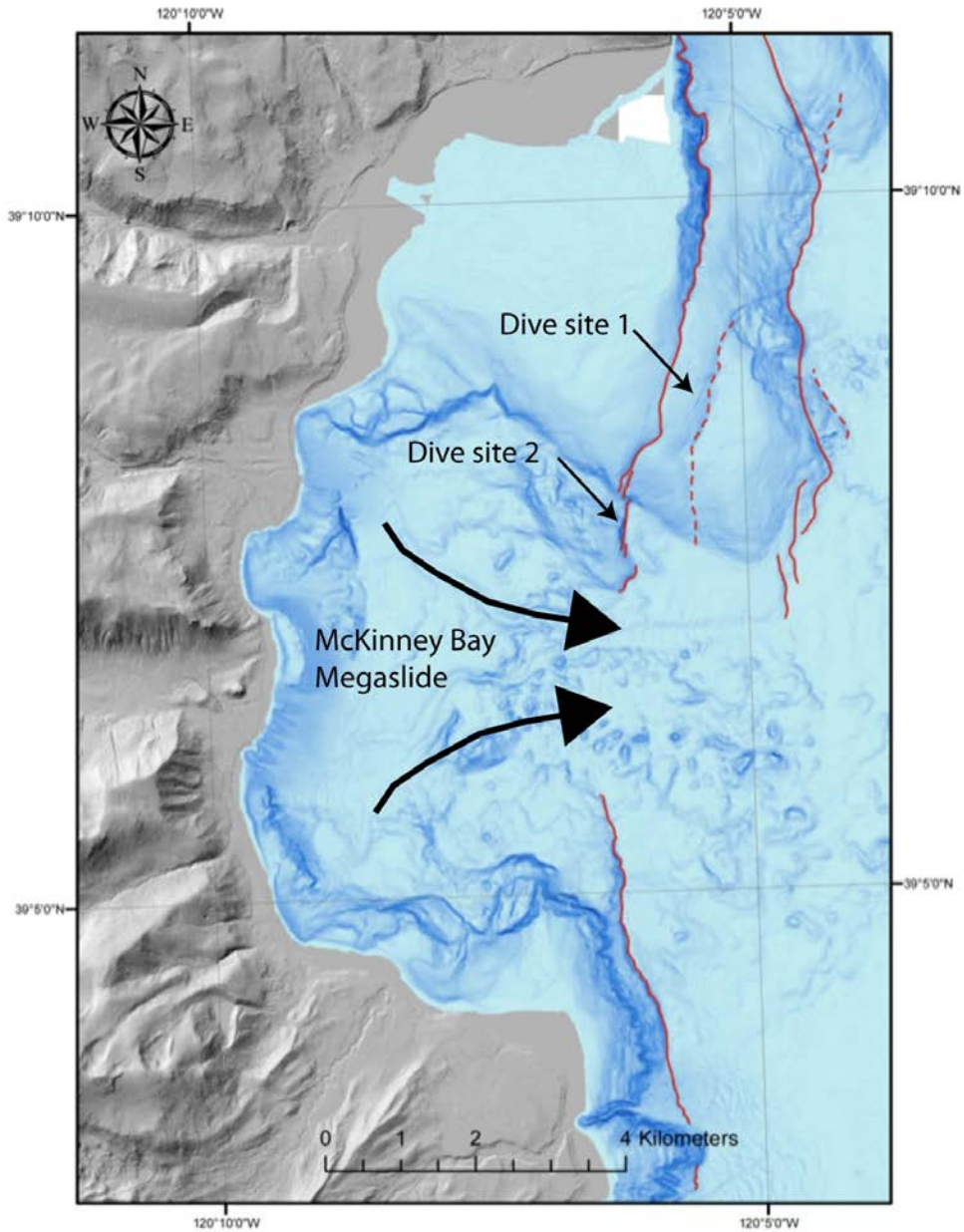


Figure 12. West Tahoe Fault and McKinney Bay Megaslide Slopeshade and Lidar Hillshade Map. Dive site locations are shown. The faults shown are the West Tahoe Fault.

The field deployment in July 2013 was focused on testing the SIR. This was partially successful. The SIR exhibited great promise on its inaugural dive. The basic functionality i.e. how it maneuvers and unfolds worked. Unfortunately a few key issues prevented us from doing the deep fault dives. The hydraulic thrusters and the navigation at depth were compromised.

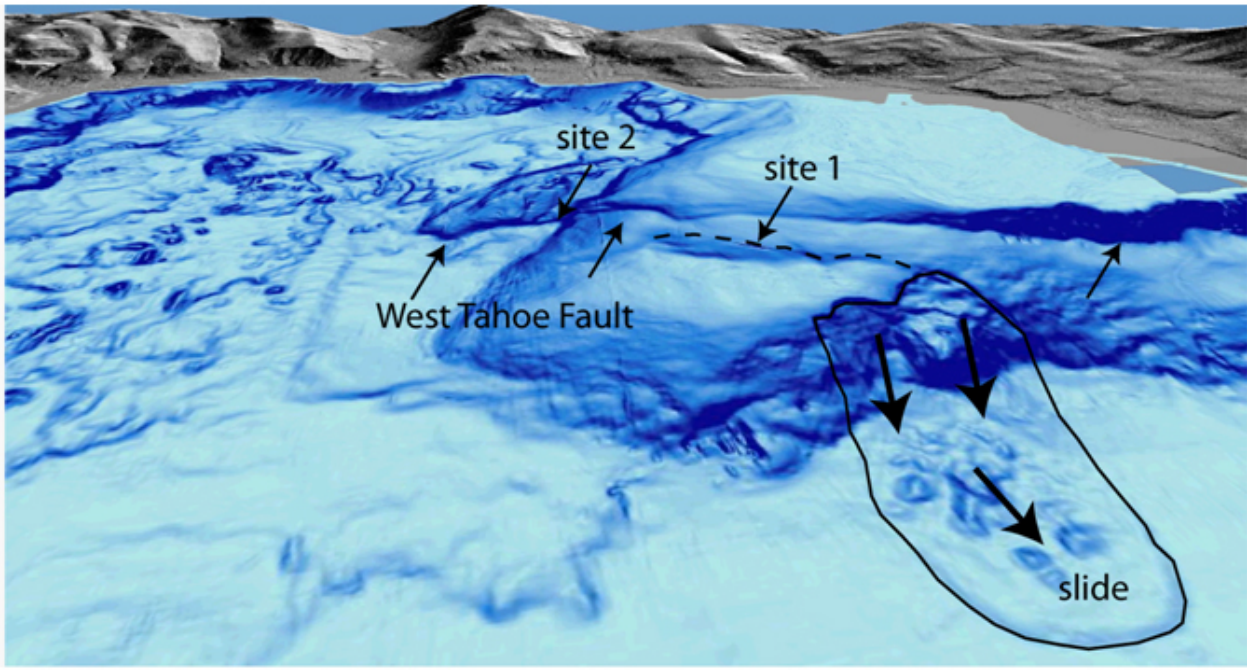


Figure 13. Oblique West Tahoe Fault and Landslide Slopeshade Illustration. The slide is a long run out debris slide. The described dive sites are indicated. Site 1 water depth about 160 m, site 2 about 400 m . Site 1 was targeted as a possible continuation of a landslide scarp. Site 2 was targeted to observe the West Tahoe Fault.

North of the McKinney Bay Slide a smaller composite debris slide exists (Fig. 13). Smith et al. (2013) associated this slide with an earthquake on the West Tahoe Fault. We targeted a linear scarp-like feature at a depth of about 160 m that extends south from the prominent head scarp of this slope collapse. The certainty of correctly identifying smaller scale scarps is largely controlled by the resolution of the available mapping data or imagery. In this case the multibeam bathymetry has a resolution of 10 m, hence we were clearly at a limit of detecting smaller scarps.

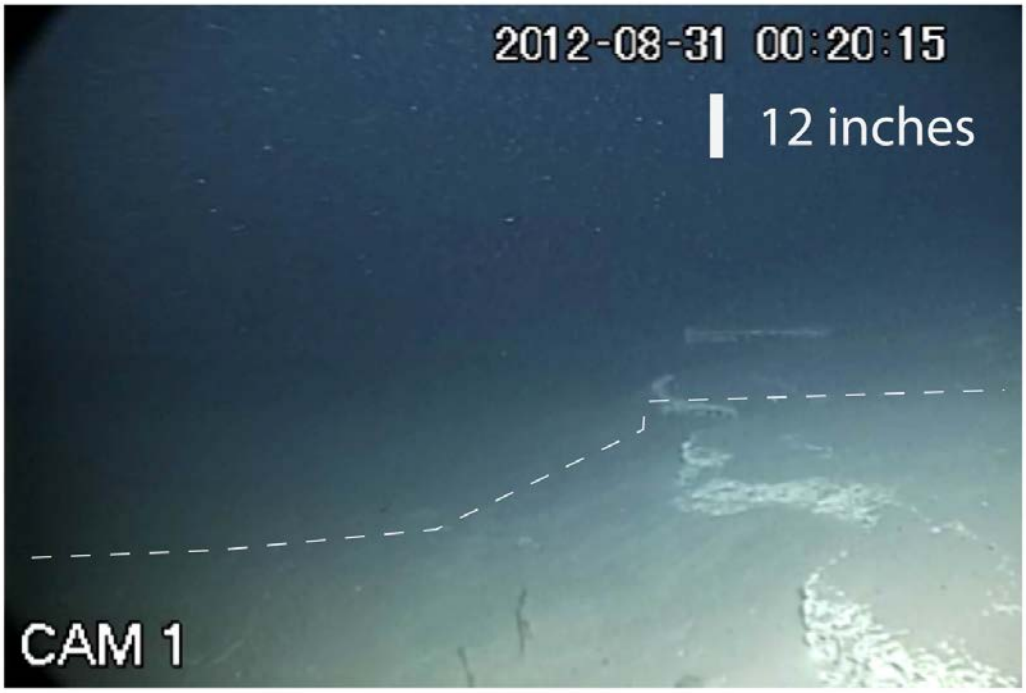


Figure 14. Incipient Landslide West-Facing Head Scarp ROV Image. Site 1. The approximate scale 30 cm (12 inches) applies to the west-facing scarp in the foreground. The dashed line indicates the surface slope profile.

Figure 15. Incipient Landslide East-Facing Head Scarp ROV Image. Site1. The approximate scale 30 cm (12 inches) applies to the scarp in the foreground.

Figure 16. Incipient Landslide East-Facing Head Scarp ROV Image. Site 1. The approximate scale 30 cm (12 inches) applies to the scarp in the near field.

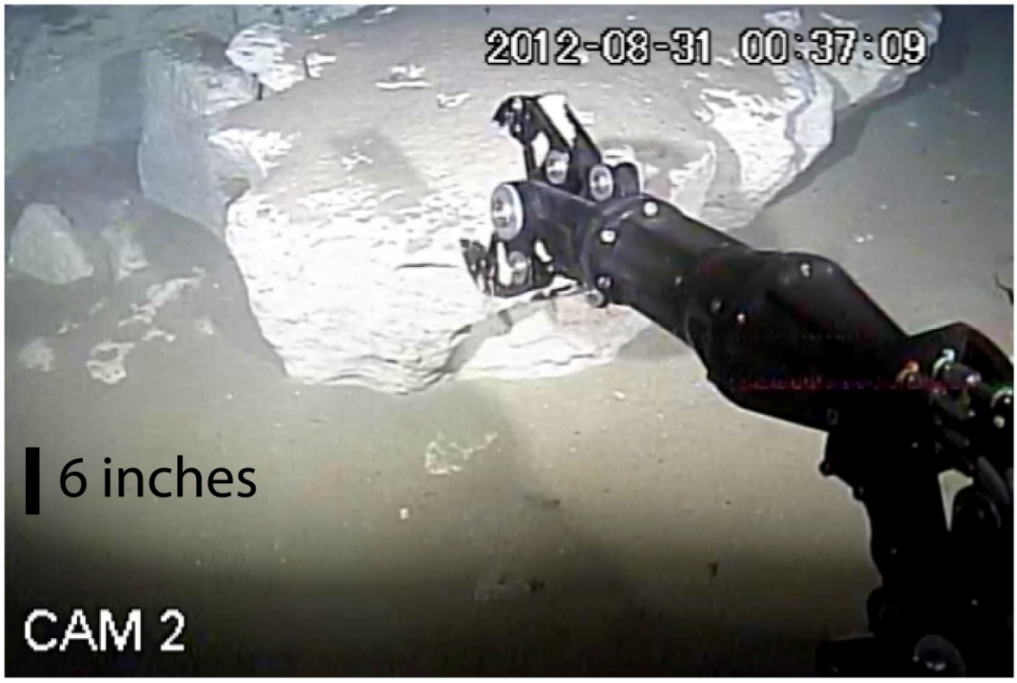


Figure 17. Incipient Landslide East Facing Head Scarp ROV Image. Probing with grab arm. Site 1. The approximate scale 15 cm (6 inches) applies to the scarp in the near field.

Figure 18. Incipient West-Facing Landslide Head Scarp ROV Image. Horizontally layered glacial sediments. Site 1. The scarp face shows Tafoni, i.e. honeycomb-like weathering. This is most common in desert environments, and the significance of its existence here is still unclear. The approximate scale 30 cm (12 inches) applies to the scarp in the near field.

The observed scarps at site 1 (Fig. 13-18) appear to be incipient landslide scarps associated with the slide to the north as shown on figure 13. The scarp consists of a larger east-facing scarp about 0.6m high and a much smaller sub-parallel west-facing scarp spaced about 20-30 meters east of the main scarp. We probed the scarp face with the grab arm and the stiff horizontally layered sediments appear to be the glacial deposits dated at about 12.5 ka in sediment cores (Smith et al., 2013).

The West Tahoe Fault crosses the McKinney Bay slide near its base, and at its margins is expressed as 50+ meter high scarps (Fig. 19). In the central portion of the slide the fault scarp is obscured by ongoing landsliding. Dive site 2 (Fig. 2, 12, 13) targeted the prominent fault scarp within the McKinney Bay slide embayment at its northern margin. This target was chosen to observe the fault and potentially the slide plane of the megaslide. With the ROV we dove to the top of the fault scarp and encountered a gently sloping silt covered lake floor. The transect proceeded east over the steep rocky scarp face as illustrated in figure 19. The upper portion of the scarp cliff consists of Miocene-age volcanics (Mva). These rocks are Lahar flows and breccias, the reddish matrix with dark andesitic clasts can be identified. At an

absolute elevation of about 1562 m the volcanic rocks overlie layered metasedimentary rocks with a sharp contact.

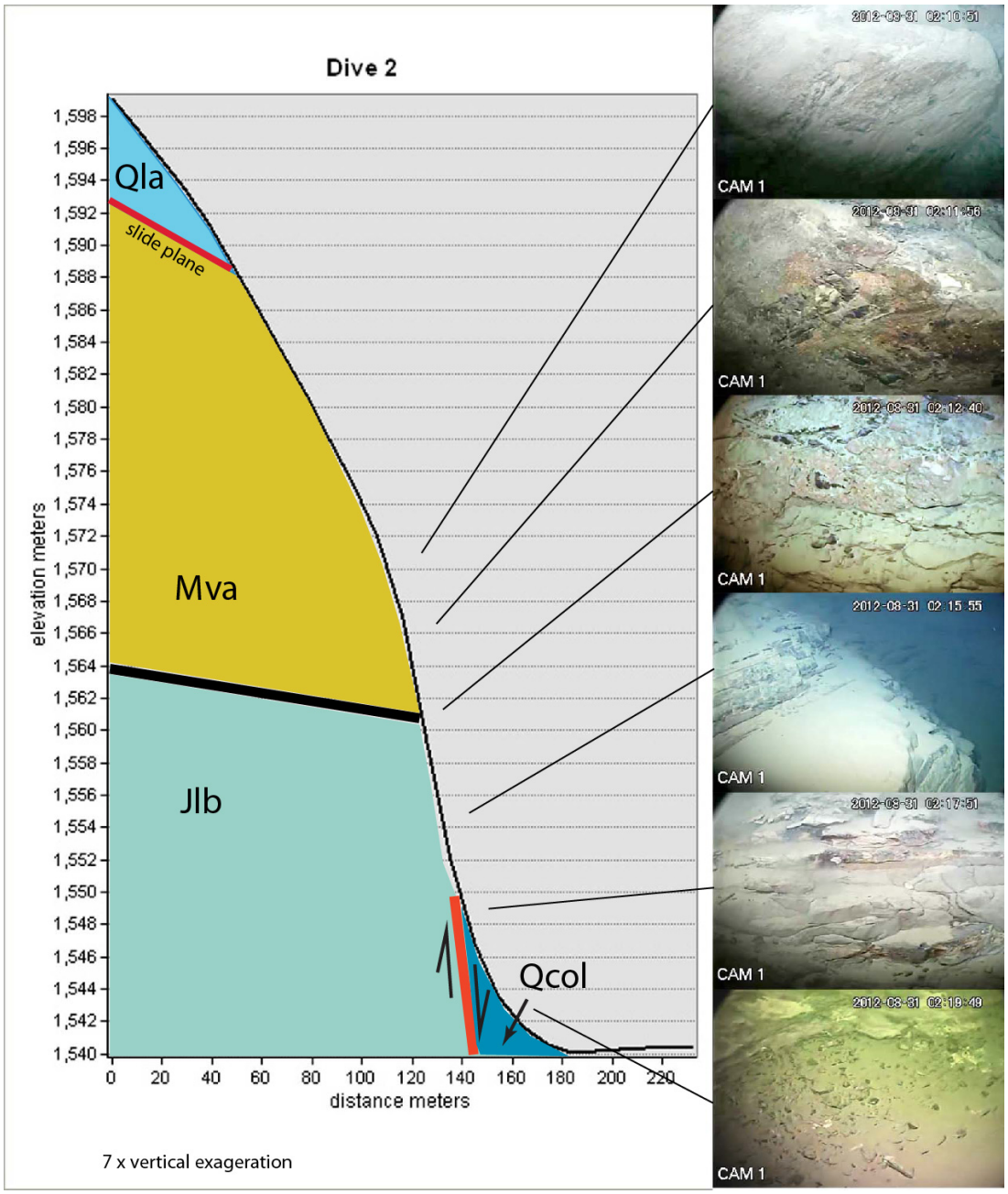


Figure 19. **West Tahoe Fault Dive 2 Stratigraphic Profile.** The lake surface elevation is 1899 m; the water depth at the 1540 m level is 359 m. Left side schematic shows the geologic cross section with the east-facing normal fault scarp shape indicated by the X-Y axis plot. Right side images were taken from an ROV camera as we investigated the scarp face. The geologic contact between the lower Jlb the Jurrassic-age Blackwood Creek Formation and the

overlying Mva Miocene-age volcanic Lahar flows was previously unknown. This contact promises to help unravel the tectonic history of Lake Tahoe as it provides a markers for long-term strain. The McKinney Bay megaslide slide plane and the West Tahoe Fault are indicated schematically. Qla-post slide lake sediments. Qcol- scarp derived colluvium and talus, and lake sediments. Rock identifications were greatly facilitated by Harwood (per. com.) and correlations with mapped on land formations (Saucedo et al. 2005).

The layered rocks are part of the Jurassic-age Blackwood Creek Formation and extend to the base of the cliff. Generally one would expect the active fault trace to be near the base of the cliff. Given what we know about the West Tahoe Fault in terms of slip rate and recurrence behavior, we expect the fault ruptures the surface with vertical displacements in the 2 to 7 m range. We were not able to clearly identify a free face from the most recent event. At the base of the cliff a wedge-shaped debris apron with abundant clasts exists as seen on the bottom image. This dive showed that it is feasible to map geologic units with an ROV. Additionally, also it allowed a evaluation of the lake floor for coring feasibility. The gently sloping area at the top of the scarp may be well suited to future coring when targeting the age of the megaslide. The post slide sedimentary deposition rate in this location should be much lower than in the central portion of the lake because the above cliff location is sheltered from turbidite currents.

Summary

Onshore and offshore studies have revealed that the geological process resulting in the most significant hazard in Lake Tahoe is faulting, which is ongoing with three active faults that cross the basin and lake floor. These faults are among the most significant seismic sources in the region and appear to have their most active portions in the lake. In addition to ground shaking and surface ruptures from earthquakes, the exceptional depth of Lake Tahoe creates the additional hazard of tsunamis. The hazard for even moderate earthquakes is greatly increased around Lake Tahoe because any associated surface ruptures or triggered landslides may generate a tsunami wave that can impact the entire shoreline with inundation and permanent subsidence. Although it's generally accepted that an ancient 8-kilometer wide landslide must have caused a giant tsunami wave, the dimensions of the tsunami are uncertain and have only been modeled. While the tsunamis expected to be generated by faulting are expected to be much smaller, they are potentially destructive in their own right, and they are much more frequent.

Our ROV test dives have clearly shown that visual observations are valuable because they reveal details in faulting and landsliding. These types of observations are needed to fill an important gap in our current overall seismic hazard assessment, namely how much did the lake bottom shift in the last earthquake. These data are needed as input for constructing realistic tsunami source scenarios and tsunami wave modeling which allows the estimation of wave heights. Although it is difficult to obtain observations at these water depths, we have learned that the geomorphic record of past earthquakes may be better preserved in the lake because earthquake and landsliding scarps degrade more slowly than on land. In effect the deep water cover protects the scarps. Given this finding, we believe these deep water investigations are very promising in providing valuable paleoseismic observations to complement on land investigation efforts.

Our experience at Lake Tahoe has motivated us to seek higher resolution multibeam surveys of the active faults in the lake at resolutions comparable to on land lidar surveys. This is possible by operating the multibeam sensor closer to the lake floor, which can be done from the SIR. By combining visual scarp observations with surveys from onboard sensors such as high-resolution seismic profilers CHIRP

(compressed high intensity radar pulse) and the multibeam bathymetry we expect to assess geologic hazards with much greater confidence and accuracy.

Lake Tahoe is an ideal area to refine these methods as field deployments are much simpler and less costly than in true ocean settings and it is clear that Lake Tahoe has considerable seismic hazard and risk; however the methodologies that we develop here will clearly be used elsewhere. California has many hazardous offshore faults, essentially along its entire shoreline, which remain largely uncharacterized due to the lack of such methodology.

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