Closing the Gap between On and Offshore Paleoseismic Records in the Lake Tahoe Basin

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Introduction

The challenge of characterizing the active faulting of the Tahoe basin is the water coverage of Lake Tahoe (Hyne et al., 1972; Gardner et al., 2000; Seitz et al., 2003, 2005), with over 80 percent of the faults submerged, and the remainder having limited-exposure in steep tree covered alpine terrain (Figure 1). The basin faults exhibit the greatest activity and cumulative slip within the Lake, and diminishing activity as they extend onshore. Because a significant portion of the Tahoe basin consists of a 500 m deep lake, the earthquake-shaking hazard is greatly compounded by tsunami-generated seiche waves (Ichinose et al., 2000). Although many active faults are submerged, the methodology for assessing paleoseismic behavior offshore lags behind the more established onshore paleoseismic investigative methods in terms of specific detailed paleoseismic data, most valuable for seismic hazard assessments, that can be obtained. On the other hand, the offshore seismic imaging methods provide near full area and greater depth coverage. And with the high-resolution seismic CHIRP we employ, the resolution is approaching trench scale with the ability to image individual layers as thin as 10-20 cm under ideal conditions, and routinely at the 0.5 m scale. Combining this with sediment coring has allowed us to determine slip rates on each of the 3 major Tahoe basin faults (Kent et al., 2005).

The Tahoe basin is a unique natural laboratory to develop an offshore paleoseismic methodology for the following reasons; 1) lake coverage over many active faults, with significant water depth up to 500 m, which is comparable to ocean depths where this methodology may find wider use in the future; 2) glacial sedimentation history provides high resolution, imageable and datable stratigraphy; 3) the faulting activity is normal and displacements are large compared to the resolution of our methods: hence the event signal can be viewed as quasi- 2D, greatly simplifying the deformation analysis; 4) an onshore record is obtainable for validation. The vertical displacements on the shortest identified active fault in the Lake were measured to be approximately 3 meters per event, this represents a significant signal to noise ratio and makes it feasible to image this deformation offshore with seismic methods. So, although the onshore conditions for assessing fault activity are challenging in the Tahoe basin, in combination with the offshore characterization they are indeed quite doable.

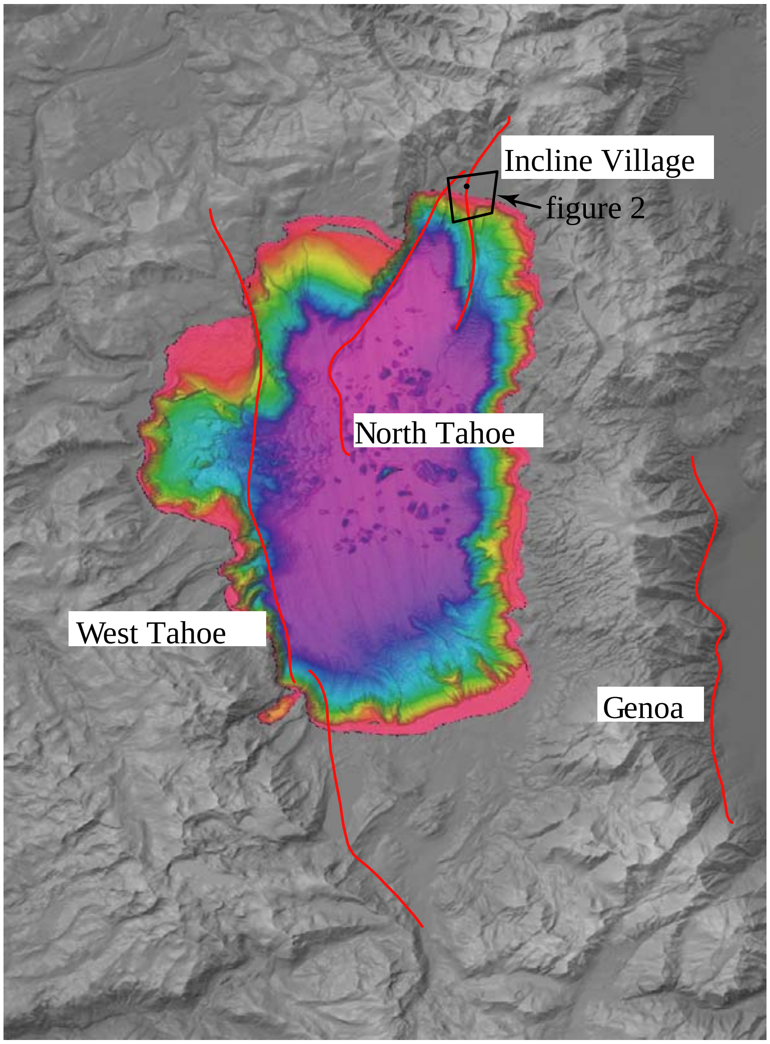

Figure 1 Map of the major Lake Tahoe basin faults.

INVESTIGATION UNDERTAKEN

Paleoseismic Investigation of the Incline Village fault 2004

Of the three major faults that we have identified as active, the easternmost Incline Village fault extends most clearly onshore as evidenced by clear on and offshore scarps (Figure 2). In 2002, we were able to confirm the existence of the Incline Village fault with two seismic CHIRP profiles that showed clear stratigraphic offsets coincident with the onshore fault scarp-looking features. This was important because the in-use “preliminary active fault map” of Schweikert and others (2000) indicated several active faults in the Incline Village area, of which we could only confidently confirm the Incline Village fault. Within a few kilometers of the lake, the fault traverses urban development.

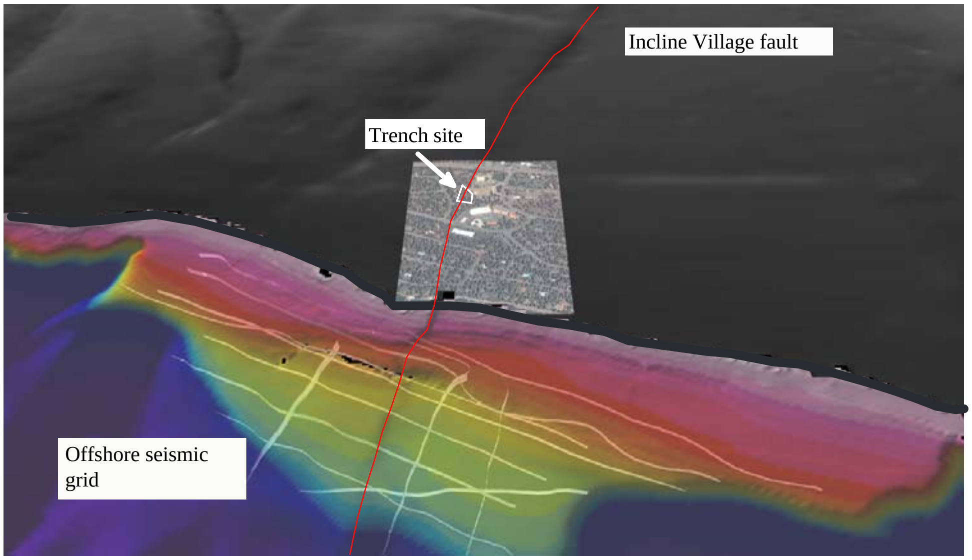

Figure 2 Oblique view of the on and offshore portion of the Incline Village fault investigated in 2004. The offshore bathymetry is shown as a color gradient from deep cool blue colors to shallow warm red colors. The fault is expressed as a clear scarp up to tens of meters high onshore and only a few meters high offshore. The scarp height differences are largely attributed to the faulting of different age surfaces, older onshore. The inset Ikonos satellite image includes the trench site. A more detailed air photo is offered in figure 4. The white lines offshore make up our "acoustic trenching" network, they are projections of the high-resolution CHIRP seismic profiles that we collected in 2004.

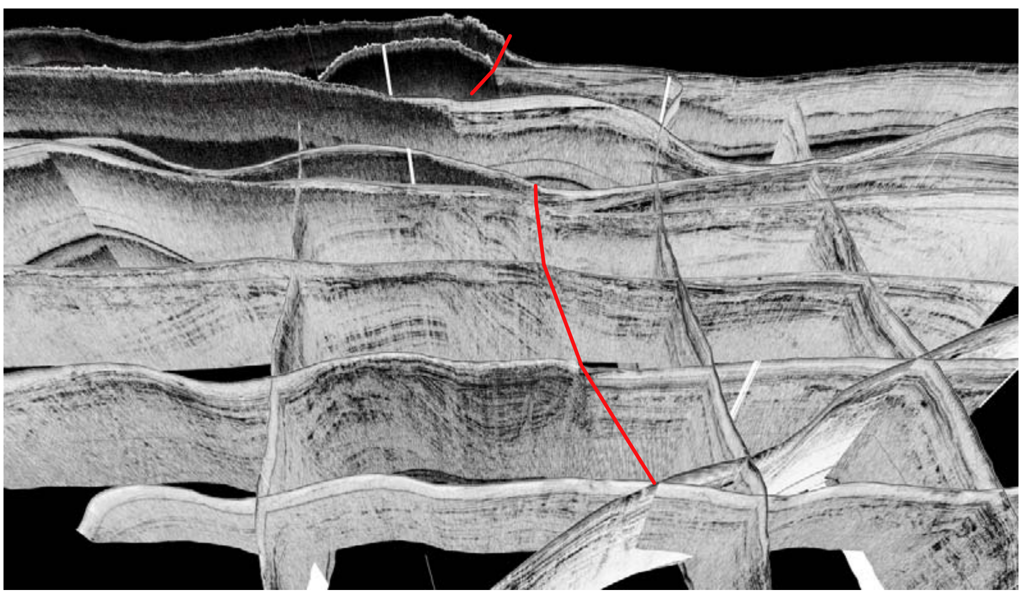

Figure 3 Oblique view of the CHIRP seismic profiles spanning the Incline Village fault, looking north. We are still in the process of analyzing the deformation in terms of paleoearthquake deformation. Preliminary, large magnitude event features similar to those found onshore are recognizable. For example, in the second straight horizontal grid profile from the bottom a colluvial wedge can be seen. The profiles extend about 10 meters in depth.

Offshore Investigation: Acoustic Trenching

We collected a 3D grid of high-resolution seismic CHIRP profiles (Figure 2,3) within 0.5 km of our onshore paleoseismic investigation at the Incline Village Elementary School. This grid coverage allowed imaging the fault zone in unprecedented detail near the trench site, and also provided confirming evidence of multiple, large magnitude events; several profiles recorded colluvial wedge stratigraphy. The quality of these profiles has led us to use the term “acoustic trenching”, because the resolution is approaching that of actual trench exposures. Of equal importance, the offshore grid was able to continuously follow the offshore fault trace to the current shoreline and the onshore trace that was trenched.

Onshore Investigation: Trenching

After investigating the Lake Tahoe basin faults since 1999, we have now started collecting paleoseismic records onshore. For the onshore investigation, we selected a site where the scarp appears to be pristine with no fluvial modification (Figure 4,5). Here the scarp is laterally continuous over a 50 m stretch with a uniform character in terms of scarp height and slope. The scarp profile suggested multiple events, with a lower angle bevel near the top of the scarp. We extended a 7.5 m deep trench across this 5-meter-high scarp.

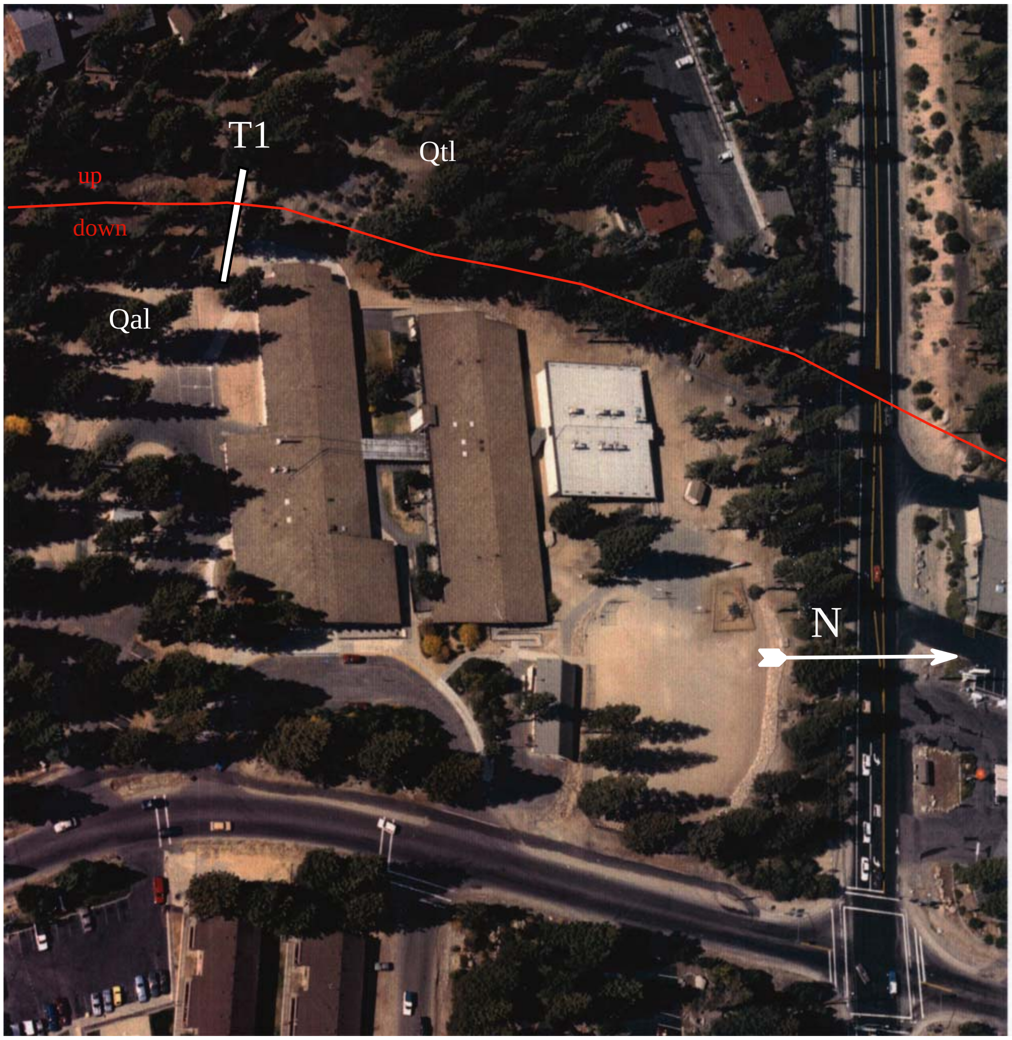

Figure 4 Air photo of the Incline Village Elementary School Site.


Figure 5 Fault scarp at the trench site. The trench was dug in the clearing to the right of the playground slide. The shown portion of the scarp is very uniform showing no obvious signs of fluvial erosion.

RESULTS

Fault zone Stratigraphy and Event Evidence

The excavation across the scarp exposed Tahoe-age or older near shore lacustrine sediments consisting of consolidated layered sands and gravels on the uplifted footwall faulted against Holocene/Pleistocene-age colluvial/fluvial sediments consisting of layered gravels and sands in the hanging wall (Figure 6). Here we focus on the colluvial deposits, which contain and comprise the event evidence. The colluvial deposits consist of three distinct packages, each resulting from a large displacement event. The most recent event deposits infill two fissures, a smaller fissure at about 3.5 meters height from the base of the scarp, and a larger fissure at the base of the scarp. The most recent event (MRE), colluvial wedge deposits consist of coarse gravels fining to the east, with individual clasts up to 1 m in the larger fissure. The penultimate colluvial wedge deposits consist of two distinct gravel units, a basal unit which is clast supported and contains almost no fines (Photo 3), overlain by a gravel unit which is matrix supported with a silty sand. The important characteristic of these colluvial deposits that help distinguish them from alluvial sediments is that they are confined to the fault zone, having been deposited onto the scarp face, significantly above the scarp base. For example, large clasts clearly infill the larger MRE fissure, and the geometry of the fissure walls do not appear modified by fluvial action. The event evidence is not limited to the existence of colluvial wedge deposits that we interpret to have a scarp-derived origin, additionally the ground rupture location has stepped to the east in the MRE thus faulting the penultimate wedge deposits.

Reconstructions allow the measurement of vertical displacements of approximately 2.75 m per event. These displacements are greater than one observes from empirical data from similar faults 20 km in length (Wells and Coppersmith, 1994), which may indicate that this fault ruptures together with the two other identified active faults in the basin, the West Tahoe and North Tahoe faults (Figure 1). This is a testable hypothesis that we are pursuing by obtaining paleoseismic records on the adjacent faults. Incidentally, the age of the MRE is essentially indistinguishable from the MRE on the Genoa fault (Ramelli et al., 1999).

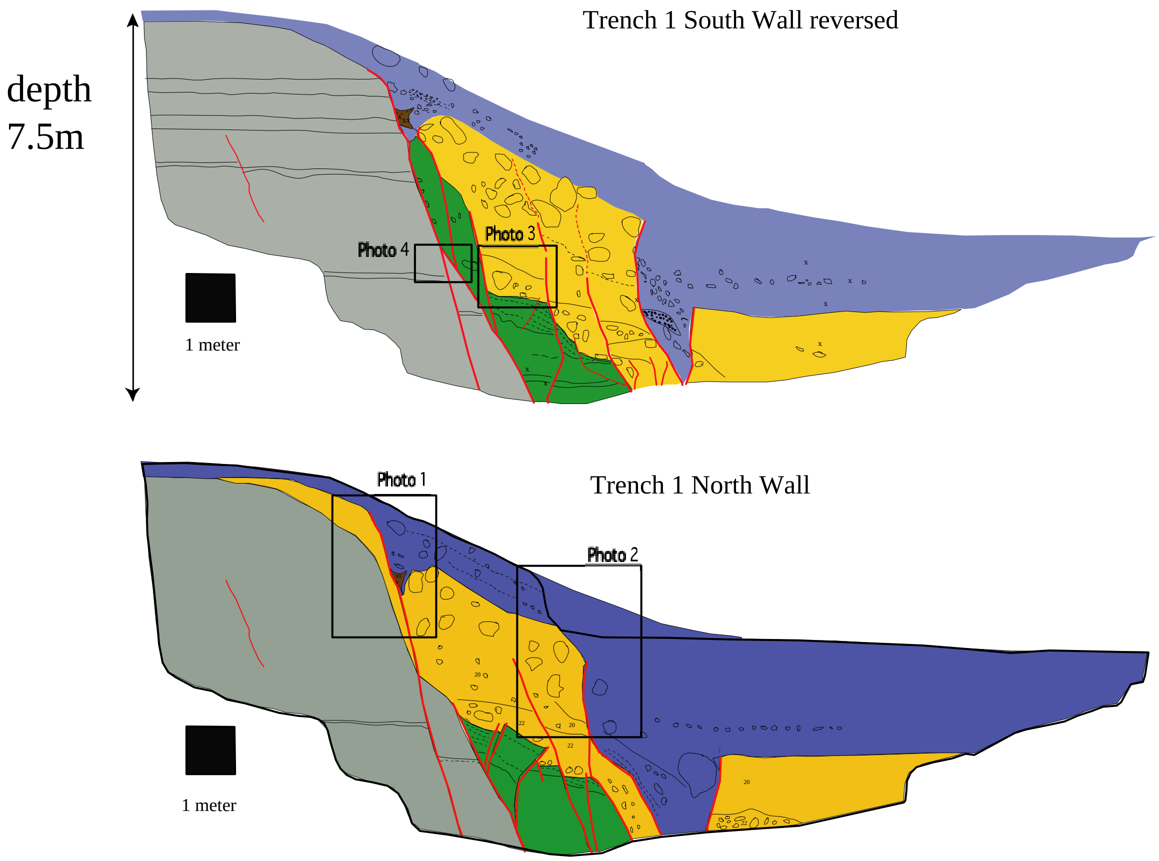

Figure 6 Incline Village fault trench logs. The summer 2004 excavation at the Incline Village elementary school across the 5+ meter high fault scarp exposed Pleistocene-age shallow lacustrine sands in the footwall juxtaposed to scarp derived Holocene-age colluvial deposits on the hanging wall block. Blue: most recent event deposits, Yellow: penultimate event deposits, Green: triultimate deposits, X: C-14 sample. Photo locations indicated shown in figures 7 and 8.

Photo 1 Photo 2

Figure 7 Trench photos located on the log figure 6. The string grid is 0.5 m x 1 m. Photo 1 shows the most recent event fissure fill from which 4 charcoal samples were dated (orange labels are sample locations). Dark brown topsoil has infilled the base of the fissure, and was observed on both trench walls. Photo 2 shows the MRE colluvial wedge deposits infilling a large fissure formed by faulted penultimate colluvial wedge deposits.

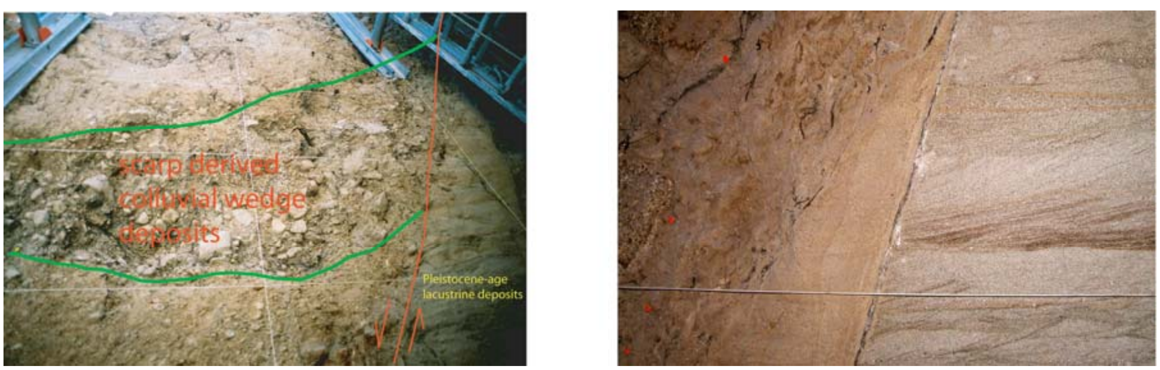

Photo 3 Photo 4

Figure 8 Trench photos located on the log figure 6. Photo 3 shows the penultimate event colluvial wedge basal unit faulted against Pleistocene-age lacustrine during the MRE. Photo 4 shows the spectacularly distinct fault, with the Pleistocene-age lacustrine deposits juxtaposed triultimate colluvial wedge deposits.

The dating of these three events is still in progress, however an initial batch of 12 AMS C-14 dates of detrital charcoal from the scarp derived colluvial wedges provides the following event chronology: 1) The most recent event (MRE) occurred about 500 years ago constrained by four individual detrital charcoal samples from a clear fissure fill deposit (Photo1; C-14 years B.P.: 575±35, 620±35, 705±35, 835±35). 2) The penultimate event occurred between 0.5 ka and 36.7 ka based on age bracketing samples from the

MRE and the penultimate colluvial wedge deposits. The third event colluvial wedge deposits are more consolidated and appear to be significantly older; we will seek age control with OSL dating (Seitz et al., 2005).

Conclusions

Prior to this study there were no direct paleoseismic observations in the Lake Tahoe basin. Although recently determined slip rates (Kent et al., 2005) suggested a significant earthquake hazard, it was not known in what magnitude earthquakes, the strain is released. This study provides clear evidence for multiple large magnitude 7-range earthquakes, and the non-existence of any smaller ground rupturing events. The event chronology is consistent with the previously estimated slip rate. Additionally this study benefited from the offshore seismic data to confirm the existence of an active fault. The future collection of independent on and offshore paleoseismic records throughout the basin, will lead to an understanding of the past earthquake behavior and hence improve seismic hazard assessments for the region. Also a refined event chronology will allow a comparison to deepwater core data and provide a test of the"earthquake induced turbidite model"(Karlin et al., 2005).

NON-TECHNICAL SUMMARY

The Incline Village fault recognized as one of 3 faults to generate earthquakes in the Lake Tahoe basin was investigated offshore by seismic imaging and onshore by a 7.5 meter deep fault excavation. This trench provided the first direct evidence of large magnitude M7 range prehistoric earthquakes in the Lake Tahoe basin, each showing vertical displacements of 2.75 meters. This is the best forecast of the earthquake magnitude to be expected and to prepare for. Preliminary radiocarbon dates suggest that the most recent earthquake occurred 500 years ago, and the previous earthquake may have occurred up to 36,000 years ago.

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DATA AVAILABILITY

Information and data associated with the investigation is available in the publication listed above and in preparation. For additional more detailed data please contact the principal investigators. Visual compilations are available online at: http://siovizcenter.ucsd.edu/

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Future Work

Additional dating involving AMS C-14 and OSL methods are planned in order to better define the recurrence interval. Characterization of the paleoseismic behavior of other basin faults will allow a more confident seismic hazard assessment.

Review and Outreach

Recognizing the subjective nature of paleoseismic trench observations, we made a concerted effort to have extensive field reviews by any interested parties and recognized experts. We felt this was especially important because the basin faults have not been previously formally characterized as seismogenically active. These reviews consisted of several individual site visits by local paleoseismic experts from UNR, and NBMG, during all stages of the investigation. We were excited about the interest generated by our major public trench viewing that was attended by approximately 50 people on July 20th, 2005. Other groups such as DWR and CGS were accommodated with individual viewings. We also led several smaller field trips for local groups such as an emergency response team (fire and sheriff department members), for a group of teachers. Towards the conclusion of the fieldwork we had a more formal review by the USGS seismic hazards team that included: David Schwartz, Tom Fumal and Heidi Stenner. The media also showed interest with reports in the Reno Gazette, San Francisco Chronicle, Tahoe Tribune and North Lake Tahoe Bonanza.
In April 2005 Seitz and Kent led an SSA "Lake Tahoe Active Tectonics" fieldtrip associated with the annual meeting held in Incline Village.

Partial list of fault trench visitors and reviewers:

Ken Adams, DRI
Michael Applegarth, Staffer Assembly Member Tim Leslie
Bob Anderson, CA Seismic Safety Commission
Robert Barry, CA Dept Water Resources
John Bell, UNR/NBMG
Glenn Biasi , UNR
Richard Booth, Lahontan RWQCB
Garry Bowen, Marketexture/Sierra Nevada College
Bill Bryan, Seismic Hazards, California Geologic Survey
John Caskey, San Fransisco State University
Ted Bruce, CA DWR
Gayle Dana, DRI
Craig dePolo, UNR/NBMG
Warren and Candy Dodd, Sunroad Enterprises
Tom Fumal, USGS
Frank Glick, DWR
Charles Goldman, TRG
Judy Harkins, Legislative Aid, Superviosr David Solaro
Chris Henry, UNR
Alan Heyvaert, TRG
Jim Howle, USGS
Steve Killingsworth,DWR
Mary Lahren
John Lorman, Procopio, Cory, Hargreaves & Savitch
Tammy Lunquist, Lahontan RWQCB
Craig Morgan, Avalex
Brandy O'Neil Converse Consultants
Susan Olig, URS
Mark Pagenkopp, DWR
Alan Ramelli, UNR/NBMG
George Saucedo, California Geologic Survey
David Schwartz, USGS
Rich Schweikert, UNR

Andy Seitz, HP
Ken Smith, UNR
Kaname Suzuki, Shizouka Prefecture, Japan
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