The potential hazard from tsunami and seiche waves generated by future large earthquakes within the Lake Tahoe basin, California-Nevada

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April 7, 2000 University of Nevada, Reno Press Release

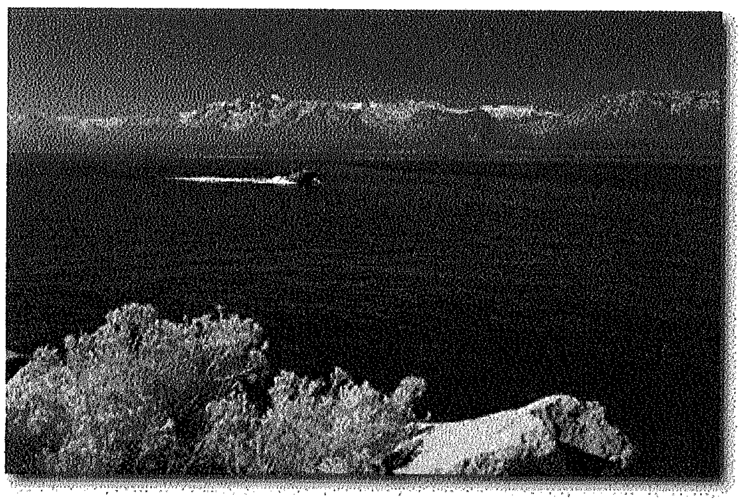
San Fransisco Gate, Monday, April 10, 2000, Tsunami threat to Tahoe analyzed by seismologist

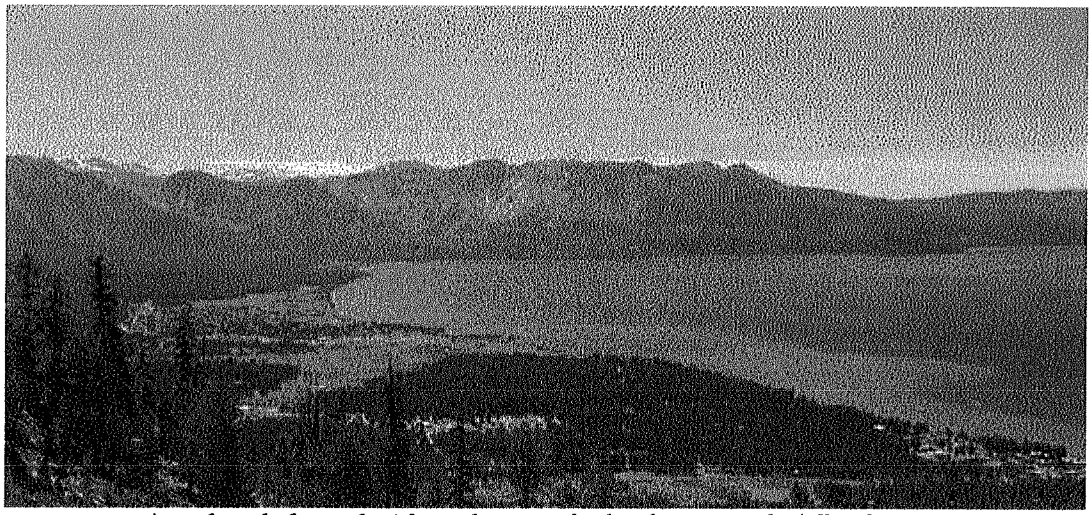
Abstract. Large prehistoric earthquakes have occurred beneath Lake Tahoe. Considering the lake's size and active tectonic history, our objective is to determine if magnitude 7 earthquakes can generate a tsunami or seiche which pose a hazard to shoreline communities.

We use an analysis similar to that used in studying the propagation of tsunamis in oceans. In an enclosed basin, we will refer to the tsunami as the initial wave directly produced by the earthquake and the seiche as the harmonic resonance within the lake.

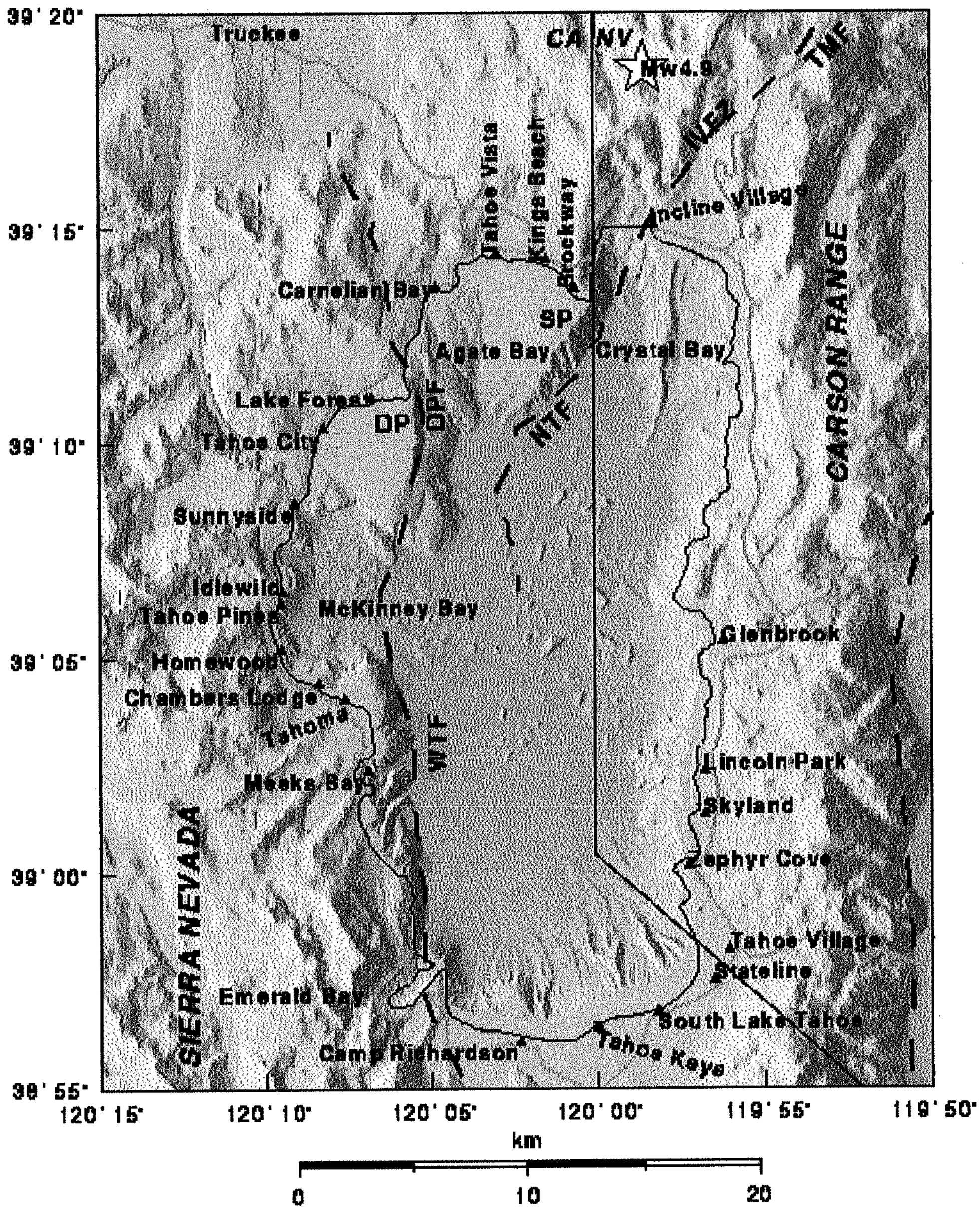
Three hypothetical earthquake scenarios are simulated. Faulting beneath the lake generates a tsunami followed by a seiche that can continue for hours with waves as large as 3 to 10 meters in height at the shore. Areas near the fault rupture will also subside and inundate as a result of fault displacement and elastic rebound.

We also compare synthetic tide gauge records generated by simulated earthquakes to tide gauge records from lake wind swells. We find that the fundamental mode modeled in the simulations is consistent with the fundamental mode generated by the winds.





View of South Shore Lake Tahoe and Camp Richardson from Heavanly Valley Ski Resort.


39' 20"
39' 15"
39' 10"
39' 05"
39' 00"
38' 55"
120' 15"
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km
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Truckee
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Incline Village
Tahoe Vista
Kings Beach
Brockway
Carnelian Bay
SP
Agate Bay
Crystal Bay
CARSON RANGE
Lake Forest
DP
DPF
NTF
Tahoe City
Sunnyside
Idlewild
Tahoe Pines
McKinney Bay
Homewood
Glenbrook
Chambers Lodge
Tahoma
WTF
Meeks Bay
Lincoln Park
Skyland
Zephyr Cove
SIERRA NEVADA
Tahoe Village
Stateline
Emerald Bay
South Lake Tahoe
Camp Richardson
Tahoe Keys

Location Map. Lake Tahoe is located along the border between California and Nevada about 40 km southwest of Reno, Nevada. This alpine lake is 19 km wide, 35 km long, and has 115 km of shoreline. It is currently the tenth deepest lake in the world with a maximum depth of 500 m and has 490 km2 of surface area. Lake Tahoe is situated within a tectonically active region called the Basin and Range Extensional Province and straddles the two most seismically active coterminous states.

Lake Tahoe lies in an intermontane basin formed by an asymmetric half-graben between the uplifted Sierra Nevada to the west and the uplifted/tilted and warped Carson Range to the east. The half-graben is bounded by normal faults on the northern and western sides. The traces of these faults are mostly submerged on the lake bottom or hidden by alluvium, lacustrine and glacial deposits. The northern portion of Lake Tahoe near Stateline Point (SP) appears to be the most tectonically active. The northeast trending North Tahoe fault (NTF) has a 10 to 14 m high scarp displacing lake-bottom deposits revealed by seismic reflection profiles and marine sonar. The northeast trending Incline Village fault (IVFZ) zone is the land extension of this submerged fault and also trends northeast towards the Truckee Meadows fault (TMF). All three of these faults may be part of a system of normal faults which rupture together and will be referred to as the North Tahoe-Incline Village fault zone. Another prominent normal slip fault zone is the north-south trending West Tahoe- Dollar Point fault zone. The West Tahoe fault (WTF) is submerged from Emerald bay to McKinney Bay. The Dollar Point fault (DPF) is the northern continuation of the West Tahoe fault northward from McKinney Bay. It is a reasonable assumption that both of these faults also rupture together.

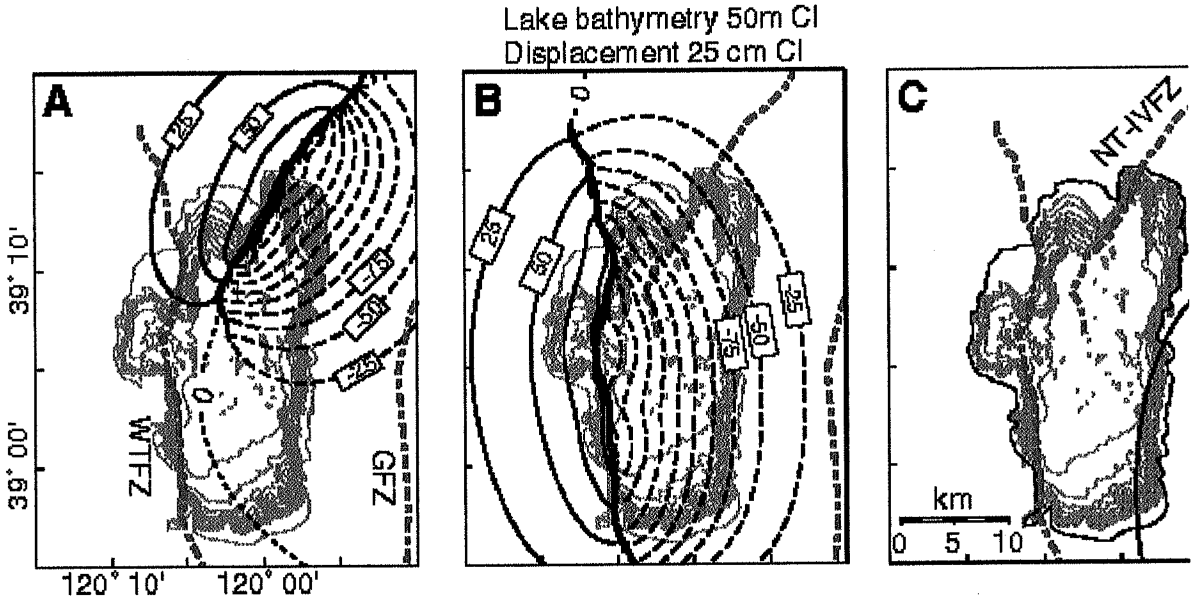
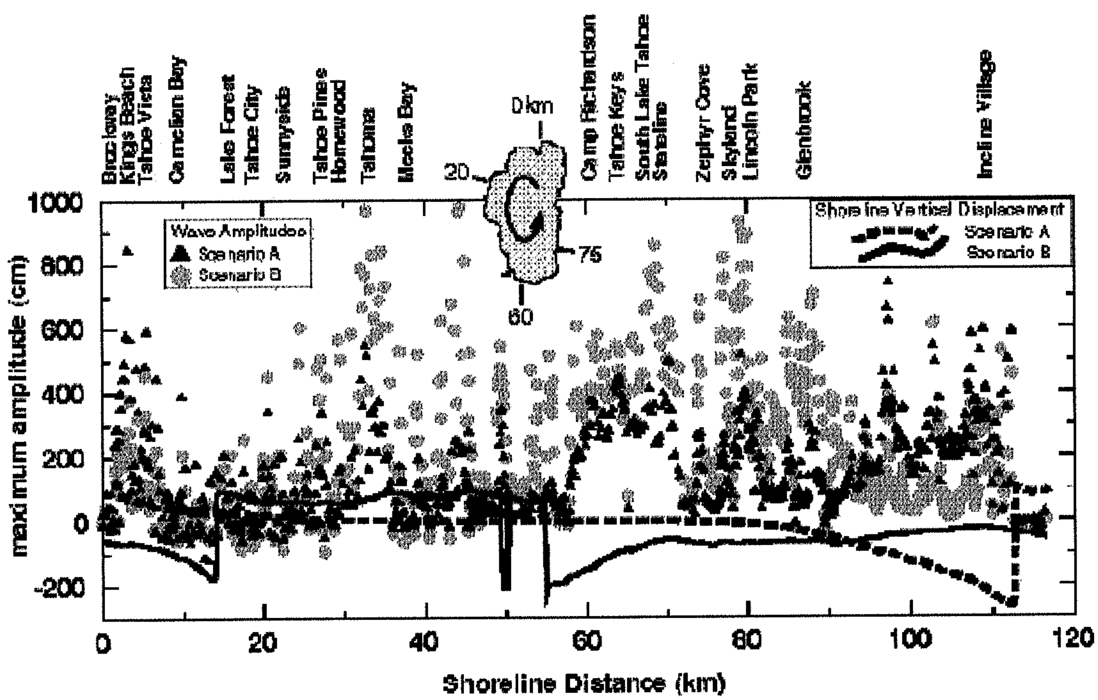


Figure 2. Contours of vertical component ground and lake bottom displacements for scenarios "A", " and "C". The dashed contours represent subsidence and solid uplift. The contour interval is 25 cm a only the first few contours are labeled. The thick dash-dotted lines are the three fault traces used in scenarios: North Tahoe-Incline Village fault zone (NT-IVFZ), West Tahoe-Dollar Point fault zone (WT and Genoa fault zone (GFZ). All of the scenarios are Mw 7+ normal faulting earthquakes with a max slip of 4 meters tapered to zero at the ends of the fault with a trapazoid function.

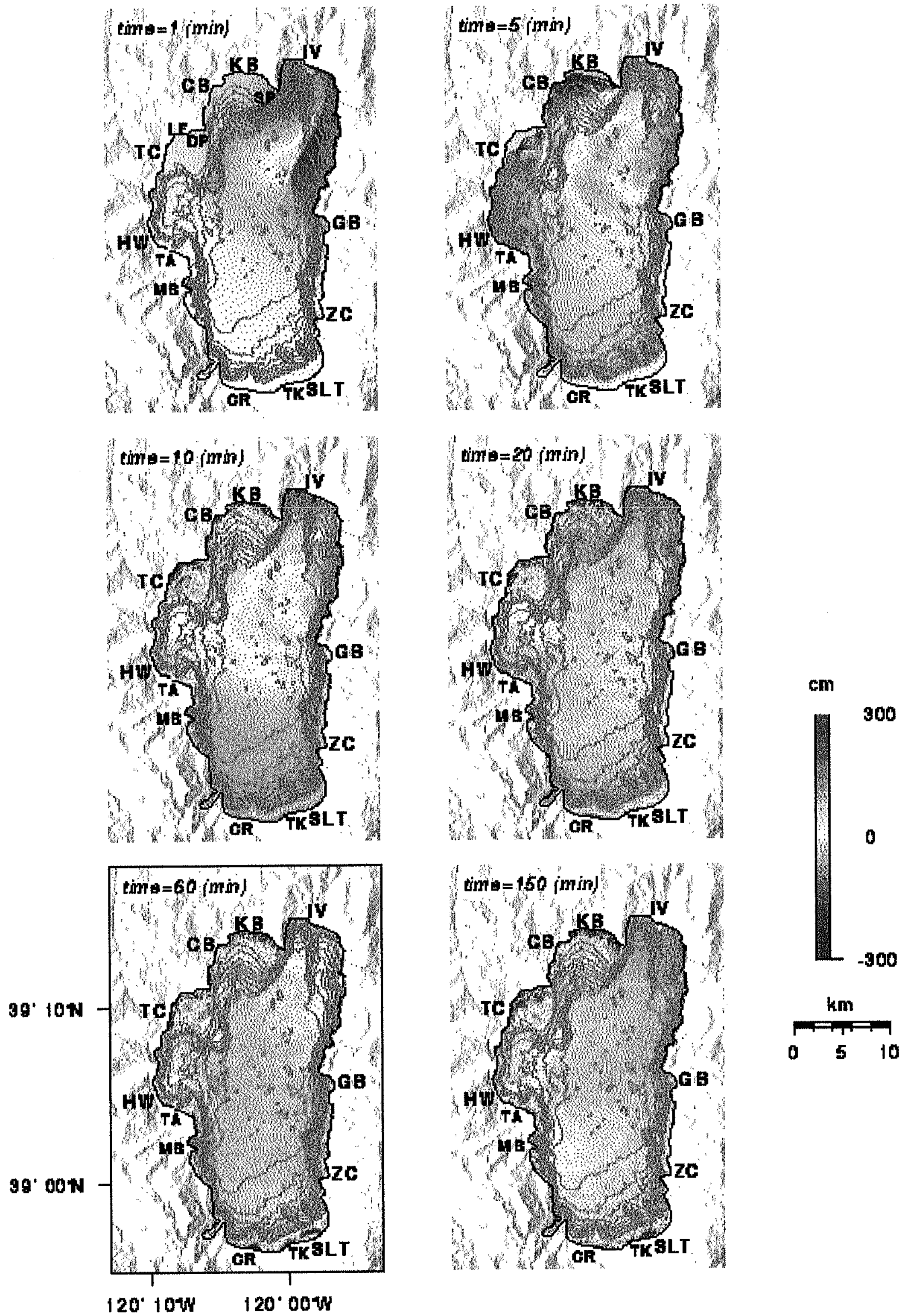
Fault Models. The contours of computed vertical component ground and lake bottom displacements for scenarios "A", "B", and "C". The solid contours represent subsidence and dashed contours represent uplift. The lake bathymetry contours are superimposed as gray lines with a contour interval (CI) of 50 m. The thick dashed-dotted lines are major fault zones used in the scenarios: North Tahoe-Incline Village fault zone (NT-IVFZ), West Tahoe fault (WTF) and Genoa fault zone (GFZ).

We create three hypothetical earthquake scenarios (Fig. 2): North Tahoe-Incline Village fault-"scenario A" (Mw 7.0), West Tahoe fault-"scenario B" (Mw 7.2), and Genoa fault-"scenario C" (Mw 7.2). Previous paleseismic investigations of the Genoa fault have revealed two earthquakes with 3-5.5 meter of normal dip slip (60°dip) in the last 2000-2200 years. These paleoearthquakes are equivalent to the largest M7-7.5 Basin and Range earthquakes. The earthquake source parameters are modeled with similar dip angles and maximum and average slip. From dislocation theory, static displacements in an 3D elastic halfspace are produced by slip on a buried rectangular surface. We compute the vertical component of displacement from these scenarios to use as the initial condition for the seiche wave propagation.



Numerical Modeling Results. *Predicted maximum wave amplitudes and shoreline deformation along the lake shore. The triangles (scenario A) and circles (scenario B) are maximum wave amplitudes at the shoreline from the north shore counter-clockwise around the lake. The dashed line (scenario A) and solid line (scenario B) are the computed vertical component ground displacement.*

Tsunami and Seiche wave propagation of linear long waves were simulated as an initial value problem. The initial lake level values were specified by assuming that the lake surface instantaneously conformed to the lake bottom displacement while horizontal velocities were set to zero. The linear equations of motion are solved by the finite-difference method using a staggard grid scheme.



Animated Gif of Finite Difference Simulation for Scenario A

Animated Gif of Finite Difference Simulation for Scenario B

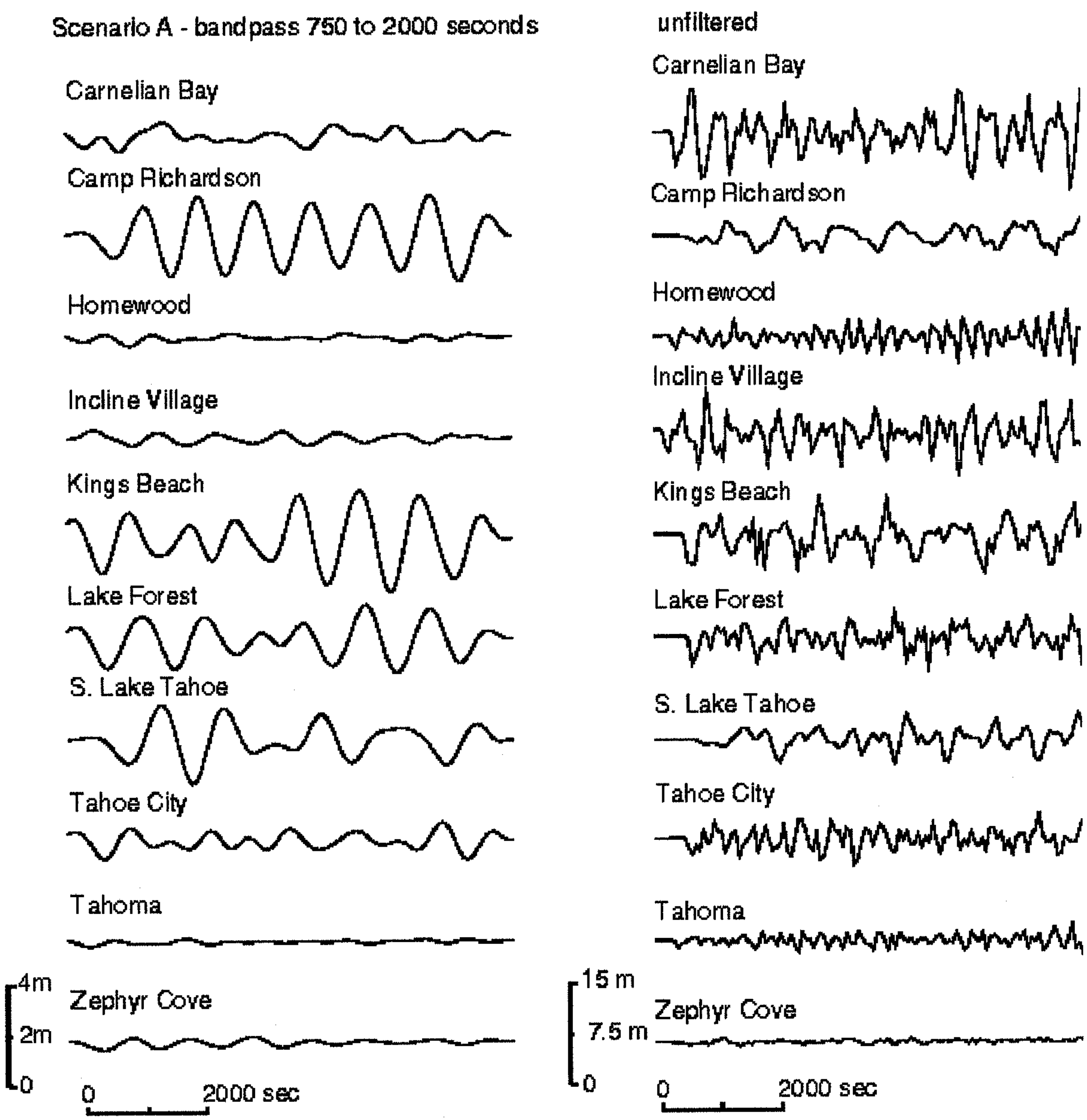


Figure 4a. Filtered and unfiltered time histories of synthetic tide gauge records computed using earthquake scenario A.

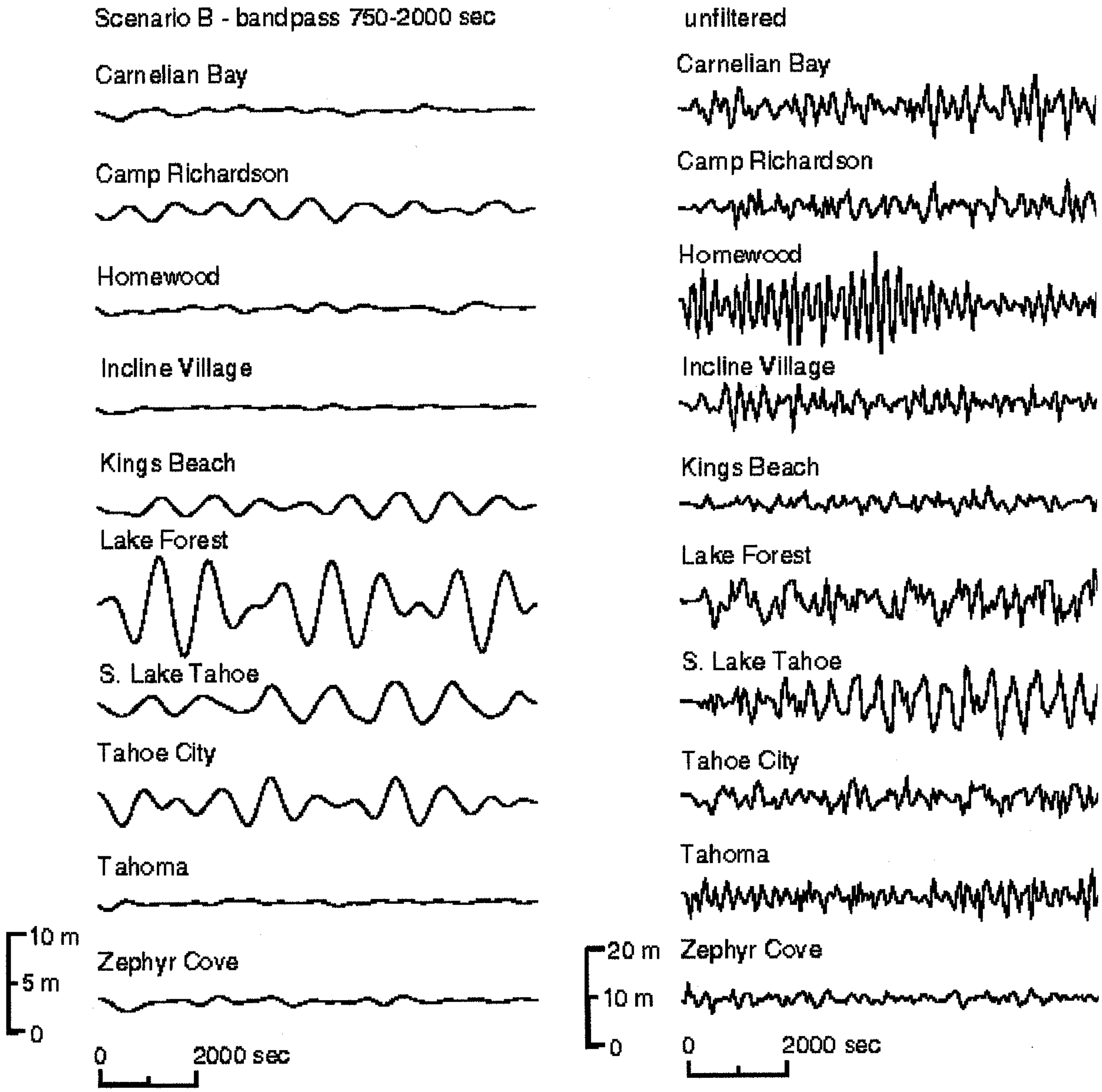


Figure 4b. Filtered and unfiltered time histories of synthetic tide gauge records computed using earthquake scenario B.

Scenarios A and B were simulated for 2.5 hours elapsed from the time of the earthquake. In Scenario A, shoreline areas on the hanging wall near the fault rupture will be inundated due to permanent ground subsidence as a result of coseismic elastic rebound. Other shoreline areas would be temporarily inundated by tsunami and seiche waves. The largest amplitudes in the synthetic tide gauge records associate with the seiche rather than the tsunami. Wave amplitudes can exceed heights of 3 meters within shallow bays and shores between Incline Village and Carnelian Bay, and at South Lake with amplitudes as large as 6 meters at some locations. Scenario B produces a similar pattern of maximum wave amplitudes as Scenario A except that the wave amplitudes in some areas are as high as 10 meters. This may suggest that the maximum wave amplitude pattern is controlled more by the offshore bathymetry than by the location or size of the earthquake. Scenarios C produces waves with average amplitudes of 0.5 meters. Since the static coseismic displacements decrease as the inverse cube of the distance, magnitude 7 earthquakes along faults outside of the lake will not displace enough of the lake bottom to create a large seiche.

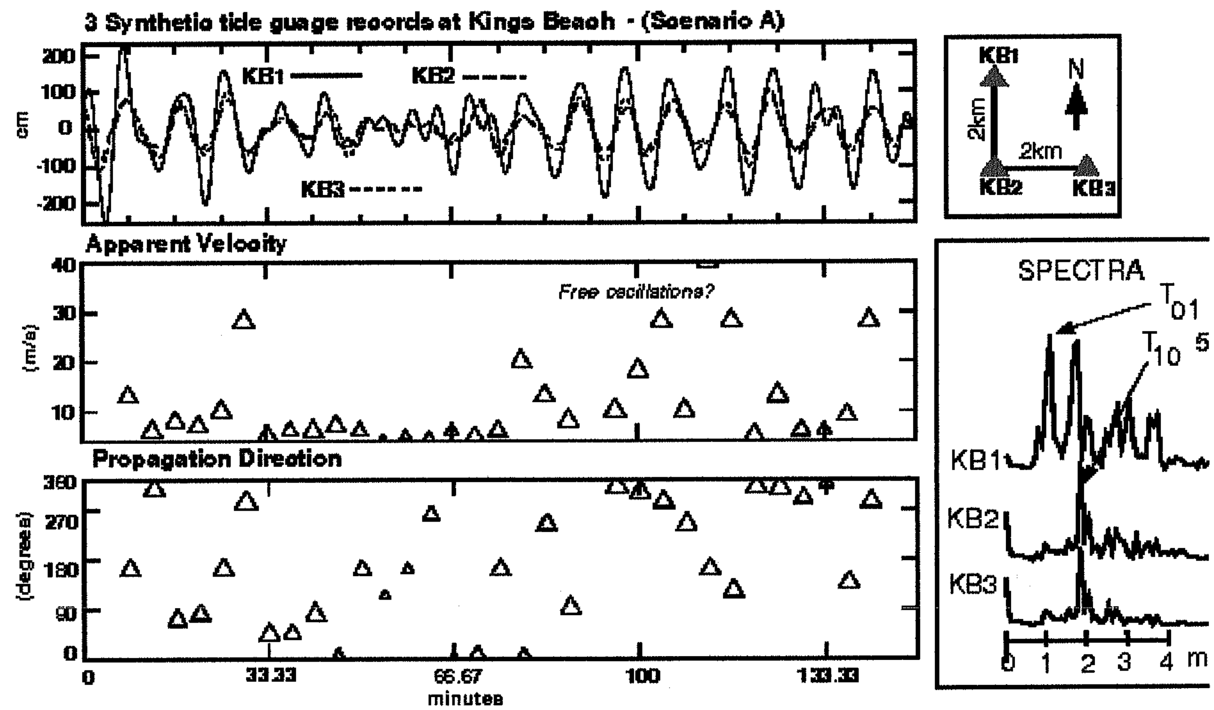


Figure 5. Moving window slowness analysis on synthetic tsunami tide gauge records computed from scenario The top panel shows 3 computed tsunami waveforms for sites KB1, KB2 and KB3 offshore of Kings Beach. Th sites are arranged in an "L" shaped array [see adjacent diagram]. Trace KB1 is closer to the shore in shallowe water, therefore it has amplitudes larger than KB2 and KB3. The horizontal apparent phase velocities are com for 32 sliding windows each 1000 seconds in length [middle panel]. The triangle size represents the maximum cross correlation across the array which range from 77% (small triangles) to 99% (largest triangles). The maxi coherency across the array associates with higher (> 10 m/s) apparent phase velocities which may indicate lake free oscillations. These become most apparent in the simulation at KB2 and KB3 after 70 minutes and ha 540 second period of oscillation. KB1 has two spectral peaks at 560 and 985 seconds period.

Moving Window Slowness Analysis. To examine the characteristics of the simulated tsuami and seiche wave propagation in Lake Tahoe, we estimate the apparent horizontal velocity and propagation direction of waves versus arrival time using the moving window slowness analysis. This analysis was made on "Scenario A" simulated time histories extracted from 3 grid cell sites near the shore in Agate Bay (Kings Beach). The sites are arranged in an "L" shaped array to sample both horizontal components. The grid cell site seperations are equivalent to a distance offsets of 2 km. The simulated time histories are first bandpass filtered from 1000 to 200 sec period. Each window is 1000 sec in length with 500 sec of overlap resulting in 32 coherency (triangles), apparent horizontal velocity (Vapp) and propagation direction (phi) estimates. The waveforms are shifted by -dt over a range of east-west px and north-south py slowness given by dt = px * dx + py * dy, where dx is the east-west and dy is the north-south distances between the a site and some arbitrary reference point. We use px and py increments of 25 sec/km and a minimum velocity of 4 m/s. The maximum of the average cross-correlation between all station pairs pro- vides an estimate of the px and py for the arrivals in the windowed waveform. The apparent horizontal velocity is given by Vapp = 1/sqrt(px2 + py2) and the back azimuth is given by phi = arctan(px / py) where phi in the opposite direction of wave propagation.

The correlation is apparently highest (up to 99%) across the array for velocities from 10 to 40 m/s and the correlation is poorest (down to 77%) across the array when the velocities are lower from 3 to 10 m/s. The propagation directions across the array are scattered but longer period waves appear to arrive onshore and then reflect offshore more coherently. Seiche waves in deep water travel at the long wave group velocity cg given by

$$cg = sqrt(g\ d)$$

where g is the acceleration of gravity and d is the water depth. The wave group velocity should range from 3 m/s within 1m depth to 70 m/s in the deepest portions of the lake which is consistent with range of wave group velocities from the simulation.

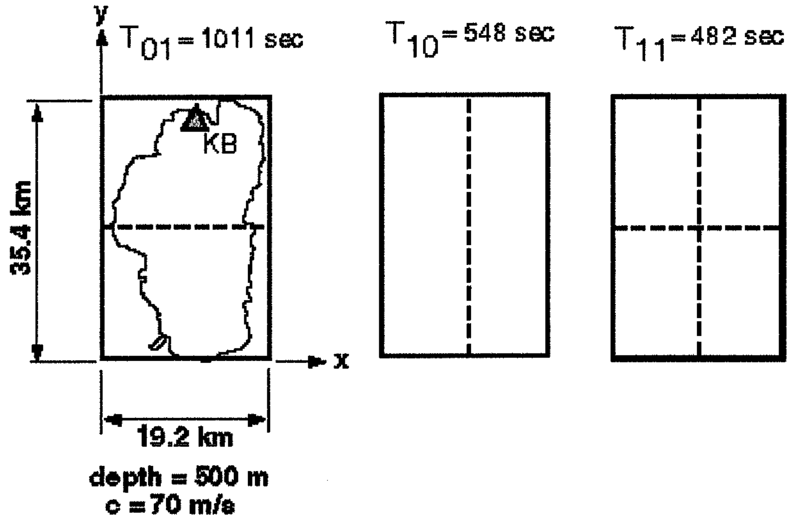


Figure 6. Fundamental and first higher modes for a rectangular lake basin with dimensions similar to Lake Tahoe. The dashed lines are the nodes. We can make first order estimates of the expected period of oscillation for each mode using the period equation determined from the 3D wave equation with free boundar conditions on all sides. The fundamental mode in the y-direction is the longest at 1011 sec and has a node x-direction along the center of the lal The fundamental mode in the x-direction is 548 sec and has a node the y- direction. The first higher moc for both x and y-directions has node: which separate the lake into 4 quadr The triangle marks the location of th KB array.

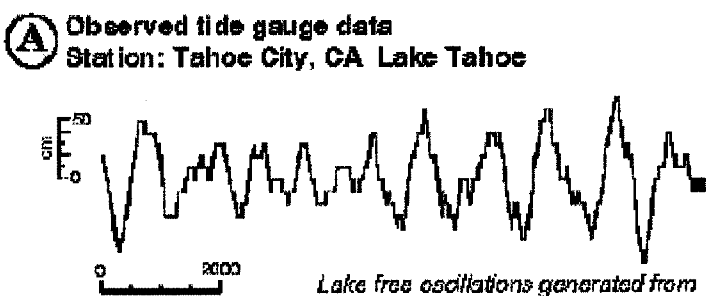
Examining Lake Basin Free Oscillations (Seiche)

Excitation of lake free oscillations can be caused by low damping or absorption in an enclosed basin trapping trap wave energy for many hours and perhaps days after an earthquake. The moving window slowness analysis above indicates the arrival of coherent waves 75 minutes after the earthquake with higher horizontal apparent velocities. This suggest the model is producing free osillations. The bandpass synthetic tide gauge records also indicate that the period of these waves may be on the order of 1000 seconds with a higher mode around 500 seconds but varies from site to site. We can compare this model result with wind swell observations.

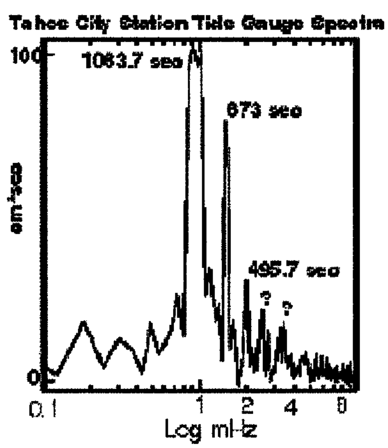
We can first associate the expected fundamental mode and higher modes to wave modal patterns. For standing waves in a rectangular basin, the the 2-dimensional wave equation is solved with zero slope boundary conditions on all sides to give the allowed eigenperiods, T nm,

$$T_{nm} = 2/c_g * [(n / L_x)^2 + (m / L_y)^2]^{-1/2}$$

where cg is the long wave group velocity, Lx is the lake width, Ly is the length, n and m=1,2,3,...,oo are the integer number of modes allowed in the x and y directions. We calculated T01, T10, and T11 using a lake length of 35.4 km, a width of 19.2 km, and a wave group velocity of 70 m/s assuming a constant water depth of 500 meters. The fundamental mode T01 is 1011 seconds and has a node in the x-direction along the center of the lake, the other fundamental mode T10 is 548 seconds and has a node along the y direction of the lake. The first higher mode is expected to be 482 seconds and has two nodes which seperates the lake in 4 quadrants.



Lake free oscillations generated from wind swells recorded by a tide gauge station on a pier at Tahoe City, CA. (1 sps).



Wind Swell Observations. *We have now identified that the simulation predicts a fundamental mode with a period of around 1000 seconds. It is possible to compare this prediction with wind swell observations. Long lasting winds can pile water up on one side of the lake. When the winds calm, the water will equilibriate and excite a seiche comparable in frequencies to those generated by earthquakes. The frequencies depend mainly on the structure of the offshore bathymetry but their excitation will depend on the direction and strength of the wind.*

Wind swells were recorded at a pier in Lake Forest over the evening hours of May 15, 1999. A 2.5 hour tide gauge record, at 1 sample per second, was fast Fourier transformed. The spectral show three modes of decreasing strength at 1065, 673 and 496 seconds. The observed fundamental mode is consistent with the expected fundamental mode for a rectangular lake at 1011 seconds and the simulations produce fundamental modes which range from site to site around 1000 seconds. The other fundamental and higher modes are more questionable but one could correlate the other fundamental mode to the 673 second period mode in the wind swell data and the 496 second period mode to the first higher mode.

Conclusions. The results of this study demonstrate the existence of a potential hazard posed by future large Mw 7 earthquakes within Lake Tahoe. This hazard affects California and Nevada lakeside communities and lifelines. We construct 3 realistic but conservative hypothetical earthquake scenarios. Simulation of scenarios "A" and "B", occurring along faults within the lake basin, both resulted in generating seiche waves along the shorelines exceeding 3m and as large as 10m in amplitude with similar maximum amplitude patterns. Simulation of earthquake scenarios "C", occurring along a fault outside of the lake basin, only produced maximum wave amplitudes of 0.5m. Shoreline areas near the fault rupture are also immediately inundated due to the permanent ground subsidence from the coseismic elastic rebound effect. A lake seiche can cause large waves to arrive an hour after the tsunami waves and the earthquake, and can perhaps suprise returning evacuees.

In the future, we plan to simulate wave run-up heights using non-linear equations of motion, bottom friction and topography to determine the land inundation patterns. This will allow us to make a map of maximum wave run-up offering a minimum level of high ground one can seek after an earthquake and help address mitigation needs.

See proposal to the USGS National Earthquake Hazard Reduction Program Fiscal Year 2000. (Postscript file)

Budget Summary