60 k.y. record of extension across the western boundary of the Basin and Range province: Estimate of slip rates from offset shoreline terraces and a catastrophic slide beneath Lake Tahoe

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ABSTRACT

Deformation across three major fault strands within the Lake Tahoe basin has been mapped by using a novel combination of high-resolution seismic chirp, airborne laser- and acoustic-multibeam–derived bathymetry, and deep- and shallow-water sediment cores. Submerged erosional terraces of late Pleistocene age (19.2 ± 1.8 ka) record vertical deformation across fault strands that ranges between 10 and 15 m; offset of 10 m is observed across the southern part of the West Tahoe fault. Avalanche deposits from the catastrophic McKinney Bay slide (ca. 60 ka) are offset across the Stateline fault by at least 21–25 m. The submerged shoreline terraces and debris avalanche provide marker beds with which to constrain the extensional history of the region for the past 60 k.y. This history is then used to assess the future seismic hazard of the region. Data on deformation across these two important marker beds, combined with chronological control from ^{14}C and optically stimulated luminescence measurements, yield an estimate of extension across the Lake Tahoe basin that is 0.4–0.5 mm/yr. On the basis of these measurements, there exists the potential for a large, seiche wave–generating M7 earthquake every ~3 k.y. Late Pleistocene and Holocene vertical deformation rates within the Tahoe basin are characteristic of Basin and Range faulting and place the Tahoe basin within the western limits of the extensional Basin and Range province.

Keywords: Lake Tahoe, normal faulting, seismic imaging, earthquakes, slip rate, seiche.

INTRODUCTION

Lake Tahoe occupies the largest of several fault-controlled basins that define the western edge of the Walker Lane deformation belt (Oldow et al., 2001; Unruh et al., 2003), a distributed zone of transtensional structures that marks the boundary between the central Great Basin and the relatively stable northern Sierra Nevada block. Geodetic measurements indicate that nearly 10 mm/yr of dextral shear occurs along faults within the western margin of the Basin and Range, with smaller amounts of extension, 2–3 mm/yr, across north-trending Sierra Nevada frontal faults (Bennett et al., 2003; Dixon et al., 2000; Hammond and Thatcher, 2004). These measurements, based on global positioning system data, highlight the potential for modest slip rates across faults in the Lake Tahoe region. Paleoseismic investigation of the Genoa fault, the easternmost bounding normal fault of the Tahoe-Carson Range (Fig. 1), has revealed that there were two large-displacement events in the late Holocene, suggesting a recurrence rate of less than a few thousand years (Ramelli et al., 1999). Considering the estimated 3–5.5 m of displacement per event (over a fault segment length of 25–40 km), these two events were comparable in size to some of the largest historical Basin and Range earthquakes. The amount of extension west of the Genoa fault and across the fault-bounded Lake Tahoe basin is the focus of this paper.

The characterization of fault architecture and history within the Tahoe basin has been difficult in large part because of the lake, which covers nearly 40% of the basin. The bounding faults that form the basin are beneath ~300–500 m of water, ruling out any conventional approach to estimating slip history such as paleoseismic trenching. Water depth is also an important factor when considering the consequences of a large earthquake within the Tahoe basin; these include the potential for a tsunami or seiche wave associated with either coseismic deformation or earthquake-triggered landslides. Swath mapping of lake-floor bathymetry beneath Lake Tahoe imaged at least one catastrophic landslide and several fault-related scarps offsetting the lake floor (Gardner et al., 2000), highlighting the potential for seismic and related hazards. On the basis of numerical simulations, coseismic deformation from an M7 normal-fault–generated earthquake has the potential to spawn tsunami or seiche waves with wave heights ranging between 3 and 10 m (Ichinose et al., 2000). Footwall collapse along Lake Tahoe's western shoreline (i.e., McKinney Bay slide) is thought to have generated wave heights of nearly 100 m in the past (Gardner et al., 2000).

TECTONIC MARKERS

Two markers that form tectonic baselines have been identified that are critical for unraveling the late Pleistocene–Holocene fault history of the Tahoe basin: (1) a submerged shoreline terrace and (2) the expansive McKinney Bay slide complex. By coregistering lidar-based bathymetry and seismic chirp images (see Appendix DR1[1]), a suite of sub-

[1]GSA Data Repository item 2005068, Table DR1 and Figures DR1 and DR2, dating results, core photographs, chirp profiles; Appendix DR1, data and methods; and Appendix DR2, optically stimulated luminescence dating, is available online at www.geosociety.org/pubs/ft2005.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

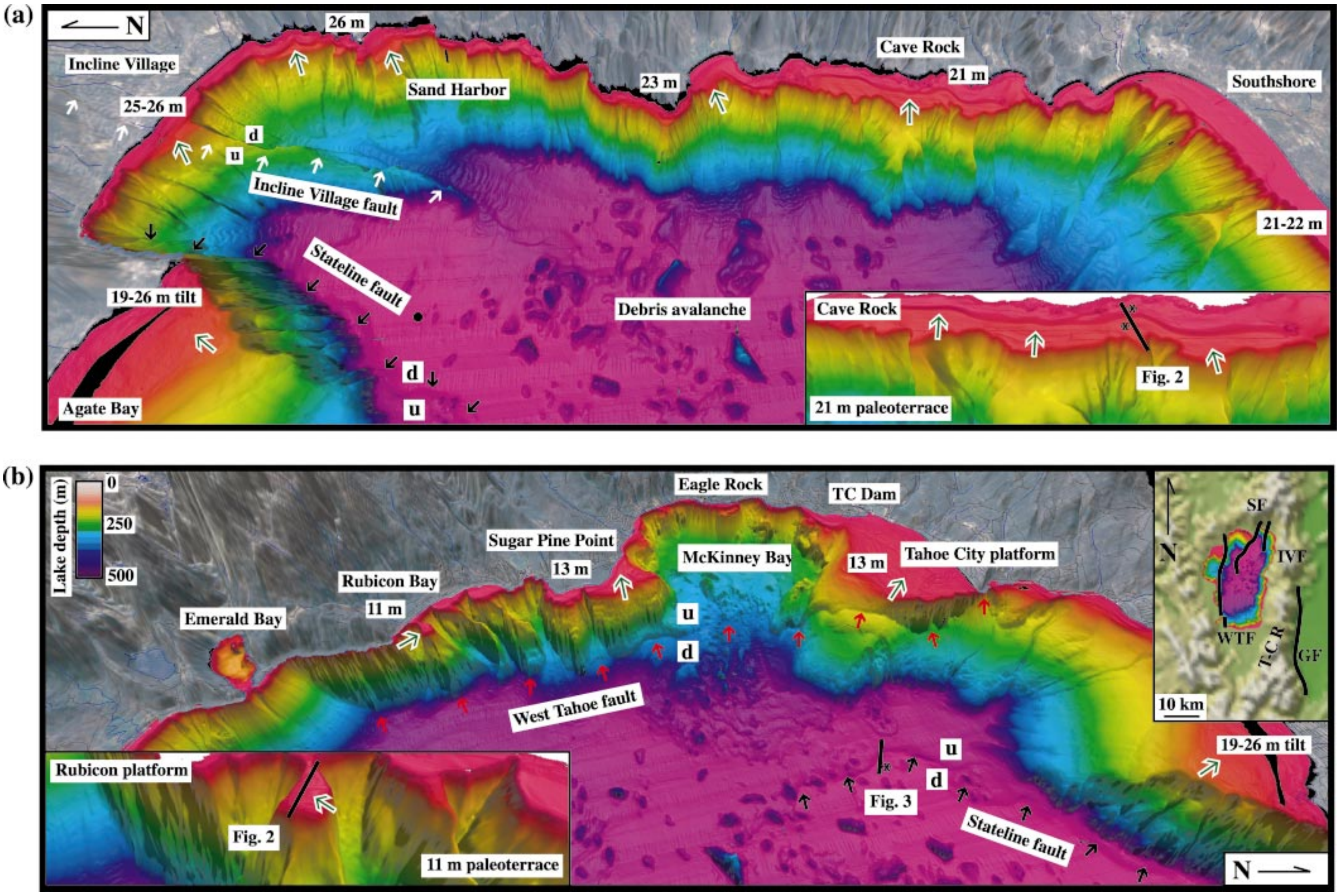

Figure 1. Three-dimensional renderings of eastern (A) and western (B) shoreline beneath Lake Tahoe, highlighting wave-cut terraces and fault structure within basin. Sediment-corrected depths of terraces (silhouetted green arrows) are displayed at various locations around lake. Simplified fault traces (see simple arrows) for major basin faults are shown (white—Incline Village; black—Stateline; red—West Tahoe); throw of normal faults is indicated by u (up) and d (down). Also shown are locations of chirp profiles (black lines in insets) across submerged terraces (Fig. 2), Stateline fault (Fig. 3), sediment cores (asterisks), and wave-cut caves at Eagle Rock (1967 m) and Cave Rock (1937 m). Box inserts in A and B show enlargement of Cave Rock and Rubicon platform, respectively. Inset of regional geography is marked by active traces (black) of West Tahoe (WTF), Stateline (SF), Incline Village (IVF), and Genoa (GF) faults; Tahoe-Carson Range (T-C R) is also shown. Lake Tahoe is ~35 km in length and 20 km in width; its maximum depth (black dot) is 499 m.

merged terraces marking a lower lake stand has been revealed (Figs. 1 and 2). This surface is now deformed, as evidenced by clear vertical offsets and tilting across the West Tahoe and Stateline faults, with only minimal offset observed across the Incline Village fault. In addition, multibeam sonar (Gardner et al., 2000) and seismic chirp images across the McKinney Bay slide, an acoustically transparent sedimentary sequence deposited in the deepest regions of the lake, enable an estimate of vertical deformation across the Stateline fault (Fig. 3). Taken together, these observations of fault-induced deformation, combined with dated sediment cores, record a rate of extensional deformation across the Tahoe basin that is similar in magnitude to the rates documented in other regions of the Basin and Range province (e.g., Friedrich et al., 2003).

The clearest evidence for a prolonged lowstand of lake level is truncated strata around the shallowest parts of the lake. Chirp profiles collected along the eastern shoreline reveal modern prograding deltaic deposits overlying erosional terraces, which are characterized by oblique clinoforms (Fig. 2). Conversely, erosion and truncation along the western shores of Lake Tahoe are more prevalent as a consequence of east-side-down fault geometry. Several trends are observed within both shallow-water chirp (Fig. 2) and airborne lidar bathymetry data sets that assist in the determination of slip rates for the West Tahoe and Stateline faults: (1) a systematic vertical displacement of 10–15 m exists between shoreline terraces on the east and west sides of the lake, and (2) to the north toward Incline Village, the eastern shoreline erosional terrace deepens by 5 m.

Independent evidence for late Pleistocene–Holocene slip on faults within the Tahoe basin comes from the Stateline fault (Hyne et al., 1972), where chirp profiles show the McKinney Bay slide complex has been displaced by at least 21 m (Fig. 3). The overlying stratigraphic record shows preferential thickening of sediments on the downfaulted eastern block, indicating a long-term period of ongoing slip. Moreover, thickening and divergence of the uppermost few meters of hanging-wall sediments toward the Stateline fault zone is indicative of Holocene fault-related slip. When on-fault measurements are combined with an age estimate for the McKinney Bay slide and the observed pattern of terrace deformation, slip rates across the three most active faults in the Tahoe basin can be estimated.

CHRONOLOGICAL CONTROL

Coarse-grained sediments overlying the paleoterrace along the eastern shoreline near Cave Rock were sampled in 2002. Three Vibracores measuring 0.5, 6.5, and 8.0 m were collected through the deltaic complex overlying the erosional surface. Accelerator mass spectroscopy (AMS) ^{14}C–dated and optically stimulated luminescence (OSL)–dated samples provide an age estimate between 17.3 and 19.2 ka for the abrasion surface (Appendix DR2, Table DR1, Fig. DR1; see footnote 1). These dates are also consistent with an inundation mechanism that would allow lake level

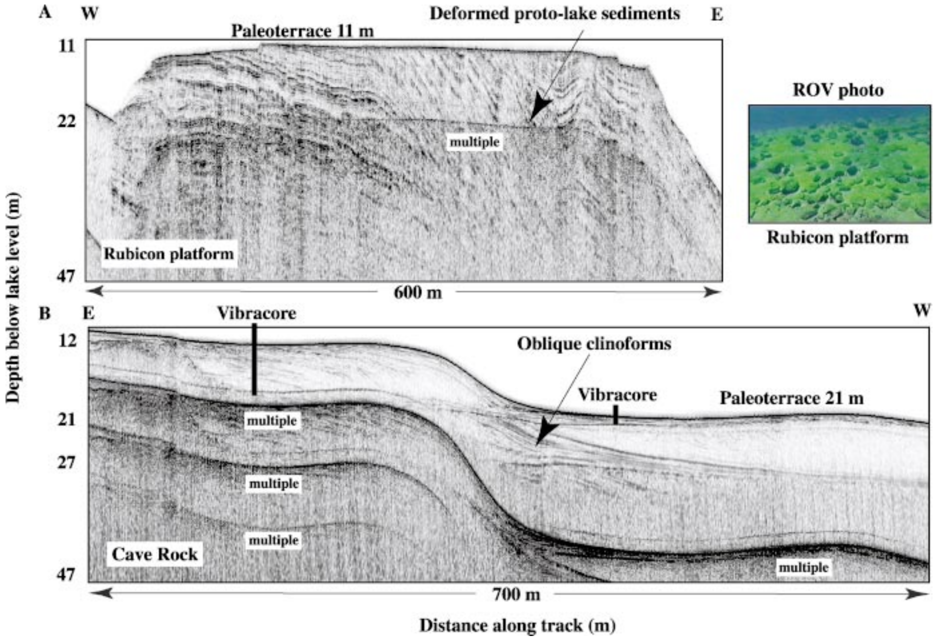

Figure 2. Submerged erosional surfaces imaged by using seismic chirp at Rubicon (A) and Cave Rock (B); depths to surfaces were measured at 11 m (A) and 21 m (B) below present lake level. Sediment-corrected terrace depths vary along eastern shoreline from 21 to 26 m between Cave Rock and Incline Village, corresponding to at least 5 m of additional east-side-down movement in northern part of lake across Stateline and Incline Village faults. Remotely operated vehicle (ROV) submersible image of erosional terrace at Rubicon reveals a beveled platform overlain with rounded cobbles.

to rise and thus flood the paleosurface. Tioga glacial damming that infilled the outflow channel would provide such a mechanism (Fig. DR2; see footnote 1). Estimates for Tioga glaciation vary from 13.6 to 24.5 ka (Phillips et al., 1996) throughout the Sierra, with a glacial maximum near 20 ka.

The timing of failure for the McKinney Bay slide complex is difficult to estimate directly. The depth of the lake floor is nearly 500 m, and the slide is buried by ~15–25 m of sediment. The top of the slide is vertically offset across the Stateline fault by a minimum of 21 m, and some profiles record as much as 25 m. During the summers of 2000 and 2002, nearly 12 piston cores ranging in length from 3 to 5 m were collected. A piston core located in the hanging wall of the Stateline fault has provided the best estimate of sedimentation rates during the Holocene and allows an estimate of slide age to be made through extrapolation of early to middle Holocene rates. We dated 11 carbon samples within a 3-m-long core, suggesting an early to middle Holocene sedimentation rate of ~0.4 mm/yr or an extrapolated slide age of ca. 60 ka. Pre-Holocene rates may have been greater during the melting of Tioga glaciers, suggesting that the timing of failure could be younger.

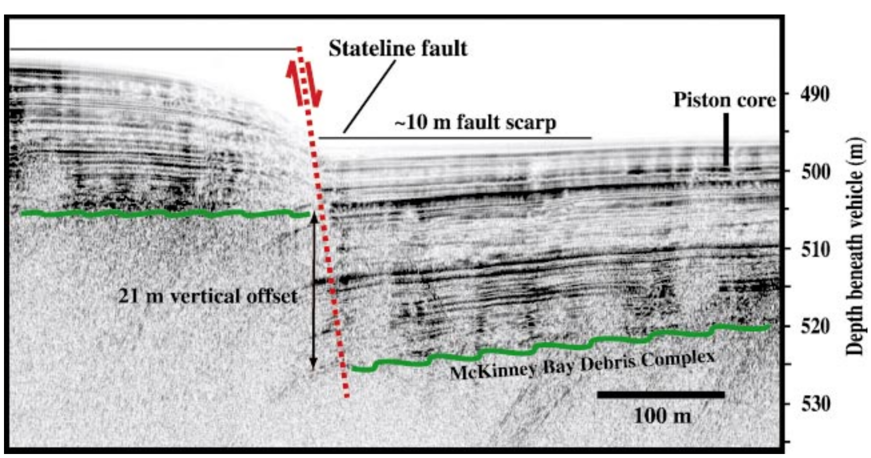

Figure 3. Chirp profile across Stateline fault. McKinney Bay debris avalanche (below green wavy line) is acoustically transparent. Top of this thick unit provides excellent marker bed on which to measure 21 m of vertical deformation. Other chirp profiles crossing Stateline fault show between 21 and 25 m of offset. No antithetic deformation was imaged in hanging wall of Stateline fault; top-of-slide topography is several meters in amplitude.

ESTIMATION OF VERTICAL DEFORMATION RATE

The combination of tectonic markers and chronological control provided by ^{14}C and OSL measurements enable an estimate of vertical deformation rate across the primary faults in the Tahoe Basin, over time intervals spanning the late Pleistocene and Holocene. Additionally, the en echelon geometry of normal faults in the Tahoe basin (Schweickert et al., 1999) can be used to separate the contributions of vertical displacement for individual faults. Comparison of terrace elevations at Rubicon and Cave Rock (Fig. 4) give a vertical displacement estimate due solely to the West Tahoe fault. Any vertical offset contribution from either the Stateline or Incline Village fault is not recorded in southern Lake Tahoe because these faults die out ~10–15 km to the north. The Rubicon and Cave Rock terraces have been vertically offset by 10 m in slightly less than 20 k.y.: these data give rise to a vertical displacement rate of ~0.5 mm/yr. There is additional evidence regarding longer time windows of vertical displacement across the West Tahoe fault; wave-cut caves located above current lake level found at Eagle Rock and Cave Rock (Fig. 4) are vertically offset by 29.7 m. These caves were likely cut during younger Tahoe glaciation, while the lake was significantly higher because of damming during the most extensive period of glaciation in the Lake Tahoe region (Birkeland, 1964). If confirmed, these measurements suggest an average ongoing vertical deformation rate of ~0.5 mm/yr across the West Tahoe fault over the past 60 k.y.

Rate estimation of vertical displacement across the Stateline fault to the north is more complicated because of the overlapping nature of the West Tahoe and Stateline faults. Here, the observed offset of the McKinney Bay slide complex, in addition to northward deepening of submerged shoreline terraces along the eastern shore, helps to separate the individual contributions from each fault. Inspection of terraces along the eastern shore reveals an additional 5 m of displacement toward Incline Village during the past 20 k.y. If the observed 5 m northward tilt was due solely to additional east-side-down displacement across the Stateline fault, this amount of tilt would extrapolate to 15 m of displacement in 60 k.y., the estimated age of the slide complex. This value is close to the measured 21–25 m of offset across the Stateline fault. The deepening of shoreline terraces attributable to displacement across the Incline Village fault is minimal, amounting to no more than 2 m, during the past 20 k.y. Thus, for a 60 ka slide age, the rate of vertical offset for the Stateline fault ranges between 0.35 and 0.4 mm/yr. Over this

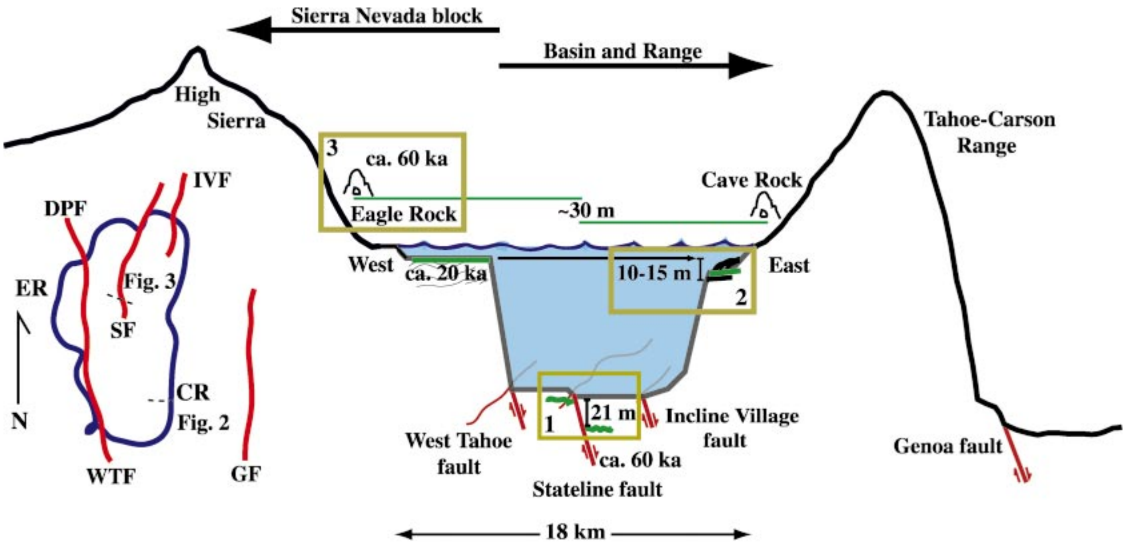

Figure 4. Schematic cross section across Tahoe Basin highlights geometrical relationships among various markers used in this study. (1) Offset McKinney Bay slide deposits reveal 21–25 m of vertical separation across Stateline fault; slide was emplaced ca. 60 ka. (2) Offset shoreline terraces are vertically displaced ~10 m across West Tahoe fault, with greater offsets to north owing to cumulative east-side-down slip on all three normal faults. Optically stimulated luminescence–dated and ^{14}C-dated cores yield age date for this surface at or near Last Glacial Maximum (ca. 20 ka). (3) Located above present lake level, shoreline caves are vertically displaced 30 m; preliminary studies suggest younger Tahoe age for this higher excursion of lake level. See map-view inset of active fault traces. Locations of Cave Rock and Eagle Rock are also provided. Abbreviations: West Tahoe (WTF), Stateline (SF), Incline Village (IVF), Dollar Point (DPF), and Genoa (GF) faults; Cave Rock (CR); Eagle Rock (ER).

period, the offshore Incline Village fault records ~0.1 mm/yr vertical offset based on the height of the fault scarp preserved on a paleoterrace.

SLIP-RATE ESTIMATION

Slip rates can be readily estimated from vertical-offset rates, under the assumption of simple fault geometries. For a 60° dipping normal fault, the vertical deformation rates across the West Tahoe and Stateline faults are transformed into slip rates of 0.57 and 0.40–0.46 mm/yr, respectively. The combined extension across both faults, based on the integrated deformation of the submerged terraces, is ~0.4–0.5 mm/yr, or ~20% of total extension observed across the Sierra Nevada frontal faults (e.g., Hammond and Thatcher, 2004). Errors in these estimates can arise from several factors, including the depth of terraces and or slides, the age models of marker beds, fault dip, and the extrapolation of sedimentation rates back in time. Errors in measuring terrace depth are <10%, or no more than a change of ±0.05 mm/yr in slip rate. The OSL dating errors of submerged terraces are also ~10%, or when added to depth estimates for the West Tahoe fault, are no more than ±0.1 mm/yr. Slip-rate error estimation for the Stateline fault is more difficult because of the extrapolation of sedimentation rate. Although AMS ^{14}C measurements are very accurate, sedimentation rates during Pleistocene time were likely greater owing to melting glaciers, resulting in extrapolation errors. Consequently, the 0.4–0.46 mm/yr slip-rate estimate for the Stateline fault may be viewed as a minimum end-member value.

DISCUSSION

The existence of significant fault scarps on the lake floor (10–15 m in height) suggests that extension is accommodated by a small number of larger-magnitude earthquakes, because ground rupture is typically associated with events that are M6 or greater in size (Wells and Coppersmith, 1994). If we use the 4 m maximum slip model of Ichinose et al. (2000) as a characteristic Basin and Range event, then the time needed to accumulate the equivalent amount of strain (or ~2.75 m of average slip) on the West Tahoe and Stateline faults is ~4.8 k.y. and 6.8 k.y., respectively. Thus, the potential of an event capable of generating a 10-m-high tsunami event, when averaged over time, is roughly every 3 k.y. yr. Although the characteristic size (and hence recurrence interval) has not been directly estimated for faults within the Tahoe basin, the long-term averaged slip rates are similar to those measured for the Genoa fault (Ramelli et al., 1999) to the east, where deformation is concentrated in a few larger normal events that measure between 3 and 5.5 m.

ACKNOWLEDGMENTS

The Lake Tahoe research was funded through grants from the National Science Foundation (EAR-0003839), Lawrence Livermore National Laboratory (02-GS-008), and National Earthquake Hazard Reduction Program (U.S. Geological Survey; 02HQGR0072). We thank Donald Wells and an anonymous reviewer for their thoughtful comments.

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Manuscript received 24 September 2004
Revised manuscript received 13 January 2005
Manuscript accepted 17 January 2005

Printed in USA