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: Comment and Reply

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Richard A. Schweickert
Mary M. Lahren
University of Nevada–Reno, Department of Geological Sciences,
MS 172, Reno, Nevada 89557-0138, USA

Kent et al.'s (2005) article, which claims a 60 k.y. record of extension and slip rates across the western boundary of the Basin and Range province, fails to deliver on its promises because of conceptual errors, flawed procedures, omissions, and other problems.

The basic premise of the paper, that shoreline terraces 15 km apart on opposite sides of an extensional basin like Tahoe (CR and RB, Fig. 1) record normal fault slip and slip rates across the basin, is false. It is well known that displacement gradients occur both along and perpendicular to normal faults, with negligible vertical separation 15–20 km into the hanging wall (e.g., Barrientos et al., 1987; Kusznir et al., 1991). Using vertical separation to calculate horizontal components and extension ignores important issues such as oblique slip, transtension, and tilt in half-grabens like Tahoe (Lahren et al., 1999; Schweickert et al., 1999, 2000b). Also, the terrace features themselves are misinterpreted.

Kent et al. also fail to address the Tahoe-Sierra frontal fault zone, with its abundant evidence of Quaternary activity, even though this zone forms the true boundary between the Sierra Nevada and the Basin and Range province (Fig. 1; Schweickert et al., 2000a, 2000b, 2004; Howle, 2000). Furthermore, many faults with youthful scarps within the northern part of Lake Tahoe are ignored, and only one fault is assumed to slip in the south half of the lake, implying that faults in the north half of the lake end at their youngest rupture tiplines (Fig. 1).

In addition, Kent et al. used flawed procedures. Large errors may arise from assuming that ^{14}C ages on charcoal fragments closely date times of lake sedimentation, because charcoal may be sequestered on land for thousands of years before redeposition in the deep lake. The authors also use uncalibrated ^{14}C ages, whereas calibrated calendar ages may be several thousand years older than the ^{14}C ages (Stuiver et al., 1998). Other errors arise in comparing heights of terraces using spot elevations, rather than the elevation of the shoreline angle. The authors ignore variations in sedimentation rates, hiatuses, megaturbidites, etc., and extrapolate sedimentation rates at sites CR and NT (Fig. 1) to intervals far beneath and/or far from dated horizons to estimate ages of terraces and the megalandslide. These errors are compounded, making ages too old and slip rates too low.

Kent et al. have also mislocated important data points. The piston core and seismic profile at NT, which are shown as coincident (Kent et al. Figures 1, 3, and DR1d), are ~1.3 km apart (we were part of the team that selected the site, recorded the coordinates, and collected and analyzed the core), negating the use of the core to interpret the profile. Also, Kent et al.'s Table DR1 reports elevations and location of vibracore data at site CR as above lake level near the China Sea (35°N, 120°E). Elsewhere, reported heights of caves are significantly in error, some above ground level.

Other problems include correlation of terraces at CR and RB, the claim that a terrace surface is overlain by deltaic sediments at site CR, and interpretations of two vibracores at the same site. SHOALS lidar data reveal that two submerged erosional terraces occur around Lake Tahoe, and that the authors miscorrelated the shallower one at RB with the deeper one at CR, yielding an erroneous vertical separation. In addition, although a terrace surface cannot occur shoreward of its incised terrace riser, Kent et al. claim the existence of one at site CR, proven by a 6.5 m vibracore (Kent et al., Figs. 2B, DR1a, DR1b). However, the supposed terrace surface in the east half of their profile is a lake-bottom multiple, and is not visible where reported in the vibracore, which penetrates west-tilted, pre-terrace lake sediments. In a 0.5 m vibracore, the terrace surface is mislocated and misdated because the authors ignore a visible unconformity and a hiatus defined by their ^{14}C data (Kent et al., Figs. 2B, DR1a).

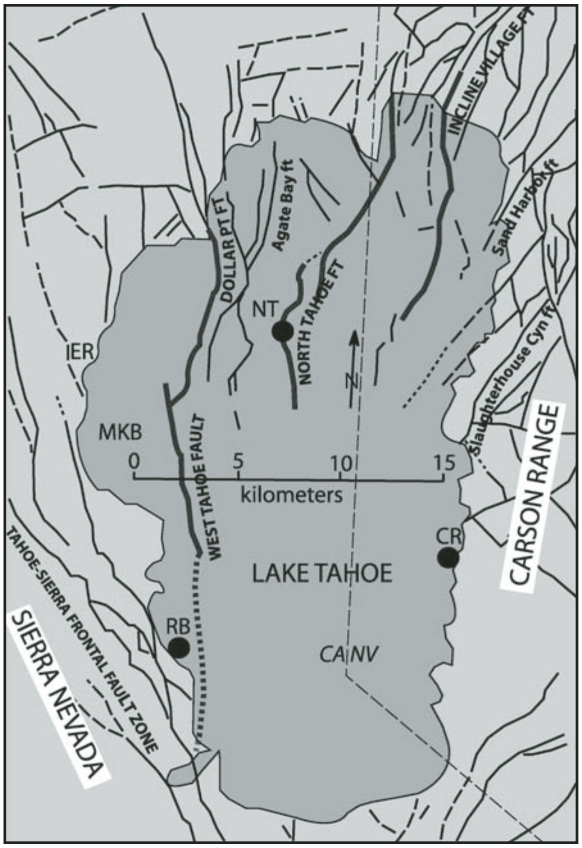

Figure 1. Simplified map of faults of the Lake Tahoe basin (Schweickert et al., 2000a, 2000b). Gray lines are faults discussed by Kent et al. (2005). CR—Cave Rock site, NT—North Tahoe fault site, RB—Rubicon Bay site.

Reasonable alternative interpretations to Kent et al.'s conclusions are: 1) the terraces do not record the full amount of normal fault slip across the lake; 2) the Cave Rock terrace is a Holocene lowstand surface, with a large hiatus along it; 3) the age estimate on the megalandslide is too old; 4) reported slip rates on the West Tahoe and North Tahoe faults are too low; and 5) no reliable slip rate estimates are possible from the data presented.

Kent et al. provide neither credible estimates on individual faults in the Tahoe basin nor a 60 k.y. record of extension across the western boundary of the Basin and Range province.

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REPLY

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G.M. Kent
J.M. Babcock
N.W. Driscoll
A.J. Harding
J.A. Dingler
Scripps Institution of Oceanography, University of California–San Diego, La Jolla, California 92093, USA
G.G. Seitz
Department of Geological Sciences, San Diego State University, San Diego, California 92182, USA
R. Karlin
Department of Geological Sciences, University of Nevada–Reno, Reno, Nevada 89557, USA

We welcome the opportunity to address the issues raised by Schweickert and Lahren in their Comment, which claims, among other charges, that we are guilty of flawed procedures and conceptual errors. It should be emphasized from the outset that we have employed a conservative approach in estimating slip rates—one that requires clear evidence for Holocene movement across features such as paleoshoreline terraces or slides that have been either directly sampled and dated, or based on an estimated date using a straightforward extrapolation of sedimentation rate. We recognize that it is possible to concoct scenarios to either increase or decrease slip rates across faults based on the geological evidence at hand. However, we have taken an Occam's Razor approach, making as few assumptions as possible in determining slip rate to ensure that our methodology produces a robust minimum slip rate. Below, we address the most significant issues raised by Schweickert and Lahren.

Tahoe-Sierra Frontal Fault Zone

Schweickert and Lahren are critical of our work, in part, because we did not address the presence of the Tahoe-Sierra frontal fault zone (Schweickert et al., 2004). In 2002, we collected a dense grid of over 25 km of seismic chirp sonar data to image any post-Tioga movement across the mapped Tahoe-Sierra frontal fault where it crosses Emerald Bay (Howle, 2000). The seismic data reveal no offset of post-Tioga sediments or offset bedrock scarps within the basin (Fig. 1), despite the fact that the slip rate estimate provided by Howle (2000) should produce 10–20 m of post-Tioga vertical slip across the Tahoe-Sierra frontal fault. The magnitude of slip rate estimated by Howle precludes the possibility that strain has accumulated during the Holocene, but has not ruptured or produced faulted sediments or bedrock, because the 10–20 m of vertical offset represents at least several earthquake cycles. The simplest explanation, requiring the fewest assumptions, is that the Tahoe-Sierra frontal fault has not been active in the Holocene (or potentially at any time in the past). Although the Tahoe-Sierra frontal fault zone was published on a preliminary fault map through the Nevada Bureau of Mines and Geology (Schweickert et al., 2000), a subsequent California Geological Survey map (Saucedo et al., 2005) based on community input and consensus eliminated the Tahoe-Sierra frontal fault from the updated geologic map of the region.

Basin Asymmetry

Issues of fault rotation may indeed affect the estimate of slip in cases where off-fault deformation is used to infer total vertical slip. Schweickert and Lahren's complaint is that basin asymmetry associated with tilt (e.g., listric geometry) would underestimate total displacement across the fault—which is true. The proper question, however, is how to best estimate basin asymmetry (if it does occur) at Lake Tahoe so that slip rate estimates derived from displaced shoreline terraces can be updated (and increased if necessary). There are three features within the bathymetric and seismic data that suggest basin asymmetry: 1) an offset delta near Sugar Pine Point; 2) asymmetry of lake floor bathymetry in the Rubicon–Cave Rock corridor; and 3) tilt of the catastrophic slide within this same corridor. Each of these features point to perhaps a doubling of slip rate across the West Tahoe fault if: 1) the isolated, faulted fan delta records only post-Tioga slip, due to negligible sediment input during the Holocene; 2) sediment deposition during glaciation in-filled fault-induced accommodation, and thus reset and flattened lake floor topography post-Tioga; and/or 3) the distal portions of the catastrophic slide within this corridor were laid down flat. Each of these ideas is testable, but require additional seismic imaging, coring, and dating to test the degree of asymmetry within this basin. The cautious approach, however, is to stick with minimum slip rates, only shifting them upwards when, and if, any of these assumptions are found to be true. Schweickert and Lahren's Comment also asserts that our west-east correlation of the paleoshoreline terraces is flawed and that we have misidentified the outer half of the eastern terrace surface as a lake-bottom multiple. Such an accusation is without merit. Down-to-the-east normal faulting offers the simplest explanation for the east-west asymmetry observed in the SHOALS lidar data.

Dating Issues

We applaud Schweickert and Lahren's concern for the ambiguities of detrital charcoal ^{14}C dating, and agree that large errors could arise if one simply assumed that detrital charcoal samples represented the ages of sediments. Fortunately, we did not exclusively rely on detrital charcoal dates as the Comment's authors assumed, but rather included a suite of short-lived macrofossils such as pine needles and insects. Short-lived macrofossils are not prone to reworking issues, because they are less chemically inert than charcoal. Furthermore, our deep-water cores included the Tsoyowata ash, and the corresponding bounding dates are consistent with the age determination of this ash layer. We found that dated samples from several identified turbidite layers did include outlier ages that were too old, and were excluded from our analysis. The age shift from

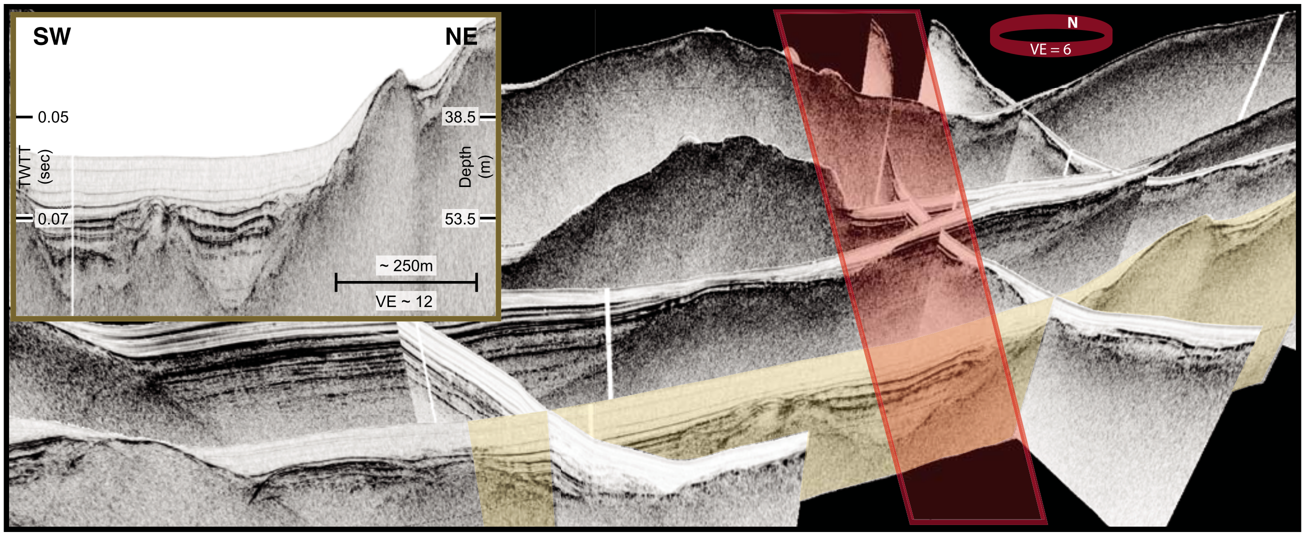

Figure 1. A three-dimensional grid of seismic chirp sonar profiles spanning Emerald Bay, highlighting the absence of post-Tioga faulting associated with the Tahoe-Sierra frontal fault (see red swath). Close-up of a seismic profile (inset) shows an absence of any offset across layered sediments where the Tahoe-Sierra frontal fault is inferred to cross.

dendrocalibration is insignificant compared to the age extrapolation that we used to estimate the age of the McKinney Bay slide. The age estimate of the paleoshoreline terrace used ^{14}C dates only as supporting evidence and relied almost exclusively on the optically stimulated luminescence dating techniques. Presently, there are several piston cores located in the vicinity of the dated core presented in our *Geology* article, including a site location that is coincident with the profile and map shown in Kent et al. (2005; their Figures 1 and 3). The stratigraphy identified within several piston cores located adjacent to the fault scarp, on the hanging wall block, are nearly identical—including depths to the Tsoyowata ash and several turbidite layers. As such, we projected the dates from one core to the next, based on stratigraphic layering and their close proximity—a practice that is not uncommon in seismic stratigraphy.

In summary, we have provided the first quantitative slip rate estimates for the Tahoe basin, using a conservative methodology to ensure robust minimum slip rate estimates. This effort has now led to the first successful onshore paleoseismic investigation, providing a clear measure of earthquake magnitude within the basin (Seitz et al., 2005). The authors of the Comment believe that the normal faults within the Tahoe basin have significantly higher slip rates than presented in our article; however, they have not presented quantitative constraints to back this speculation.

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