Characterizing the most recent event (MRE) on the North Tahoe/Stateline fault (NTSF), Lake Tahoe (California/Nevada)

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Asian Clams, Small Lake Opportunities, and Debris Flows

Executive Summary: After nearly a year's delay due to boat availability on Lake Tahoe, the joint UNR–Scripps team was poised to conduct their CHIRP survey in early June, 2011. These delays stemmed from invasive species work (Asian Clam) that made renting the UC Davis boat, the R/V LeConte, basically impossible in 2010, and unfortunately 2011 was not looking better. Through additional funding from an Exxon-Mobil student grant, and UNR start-up funds (G. Kent), the team was able to bring Rob Baskin and his boat from the Salt Lake City USGS office to effectively form a UNR-Scripps-USGS team. The upside of working aboard the USGS boat was its slimmed-down size relative to the R/V LeConte, allowing work within smaller lakes in the basin if need be. This delay was fortuitous in many respects: first, several 10 to 12-m-long cores were collected in Fallen Leaf Lake, where the West Tahoe fault was mapped in a previous NEHRP grant, providing opportunities for age-dating (potential) earthquake-triggered slides; second, the basin-wide LiDAR dataset was released in spring, 2011, so targets such as Cascade Lake, would prove critical to verify new strands of the West Tahoe fault that die (or not) into Emerald Bay to the northwest. Also, Washoe Lake with its nearby location could provide another lake of opportunity to study faulting in the Walker Lane (also timed to coincide with the highest lake levels in over a decade).

In total, 7 days of acquisition took place, including 3 days on the North Tahoe/Stateline fault, 1 day spent on the Tahoe City shelf and across the Incline Village fault, 1 day on Fallen Leaf Lake, 1 day on Cascade Lake, and 1 last day on Washoe Lake—the latter proved to be an unfortunate choice due to poor imaging associated with either hard-pan (from a recent dry spell) and/or gas that prevented any sub-lakefloor penetration of acoustic energy. Despite issues on Washoe Lake, imaging in the other 3 lakes was hugely successful, helping to refine the history of rupture/shaking in the Lake Tahoe basin. The North Tahoe/Stateline fault was mapped in its entirety, which helped extend southward the total length of this fault by at least 5 additional kilometers within the lake. Debris flows shed from the Crystal Bay escarpment, likely during episodes of intense shaking, imaged

no fewer than 4 debris flow/turbidites, with the two most recent events (MREs) associated with lake-wide turbidites "D" and "G", or 2610-2250 and 5600-5330 years B.P. , respectively (debris flow chronology from *Smith et al.*, in revision). In particular, the "D" event has no associated earthquake in that time interval, and given its location and thickness distribution, it is likely associated with the most recent event (MRE) on the North Tahoe/Stateline fault (Fig. 1). Debris layer "G" has a basin wide signature, with a maximum thickness of 3-4 m near the Crystal Bay escarpment. Given its basin-wide distribution, however, it may be more difficult to associate this layer with either the West Tahoe fault (where we see a submerged tree in the hanging wall at the south shore during this time period) or the North Tahoe/Stateline fault—or perhaps a multi-segment rupture, including the central Rubicon segment of the West Tahoe fault and a synchronous rupture on the North Tahoe/Stateline fault? More work needs to be done on this front to

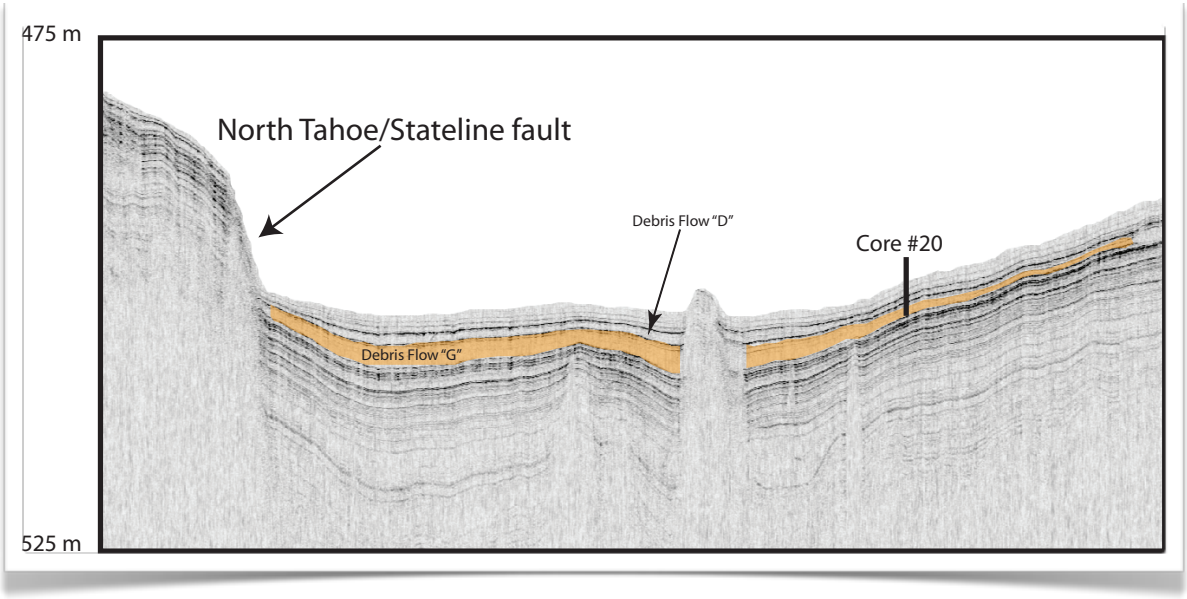

Figure 1 Seismic CHIRP profile D03L07 highlighting the two most recent debris flows "D" (uncolored) and "G" (colored orange). The North Tahoe/Stateline fault scarp is also seen (left). Given the size and distribution of debris flow "D", we suspect that it is associated with the MRE on the NTSF line between 2,610 and 2,250 B.P.

untangle these various scenarios, through mapping of layer thickness and age constraints.

Seismic work in Fallen Leaf Lake and Cascade Lake was used to both confirm results from the recent airborne LiDAR dataset, and to help establish a robust chronologic history of slides in these lakes, along with Emerald Bay in Lake Tahoe, to understand better the past ruptures along the southern Fallen Leaf segment of the West Tahoe fault—aided by new 10 to 12-m-long cores in Fallen Leaf Lake. Based on new work, it would appear that the southern segment has seen 3 events, the MRE at or near 4,600 B.P. as reported by *Brothers et al.* (2009), a penultimate event just prior to 8,000 B.P. (this event also has large debris flows in the southern half of Lake Tahoe), and the triultimate event near 12,000 B.P. The debris layer "G" (5600-5330 B.P.) is not seen in Fallen Leaf Lake, so it is thought to be a central West Tahoe (i.e., Rubicon segment) fault-triggered event (*Smith et al.*, in revision), although new data nearby the North Tahoe/Stateline fault might argue that intense ground motion may have been localized on this fault zone.

Work on the North Tahoe/Stateline fault is ongoing, while work on Fallen Leaf Lake and Cascade Lake is reaching its completion...

Previous work in the Lake Tahoe Basin (LTB), Nevada-California, identified the West Tahoe-Dollar Point Fault (WTDPF) as the most hazardous fault in the region (*Kent et al.*, 2005; *Brothers, et al.* 2009; *Dingler, et al.,* 2009). Onshore and offshore geophysical mapping delineated three segments of the WTDPF extending along the western margin of the LTB. The rupture patterns between the three WTDPF segments remain poorly understood. Fallen Leaf Lake (FLL), Cascade Lake, and Emerald Bay are three sub-basins of the LTB, located south of Lake Tahoe, that provide an opportunity to image primary earthquake deformation along the WTDPF and associated landslide deposits. Results from recent high-resolution seismic CHIRP surveys in FLL reveal major slide deposits that may be linked to seismic activity in the Lake Tahoe region (Fig. 2). Radiocarbon dates obtained from new piston cores acquired in FLL provide age constraints on the

FLL slide deposits, which can be correlated to slide deposits in Emerald Bay and Lake Tahoe. Additionally, CHIRP data beneath Cascade Lake image the WTDPF for the first time in this sub-basin, which is located near the transition zone between the FLL and Rubicon Point Sections of the WTDPF (Fig. 3). These data provide an opportunity to observe fault geometry and offsets in this transition zone.

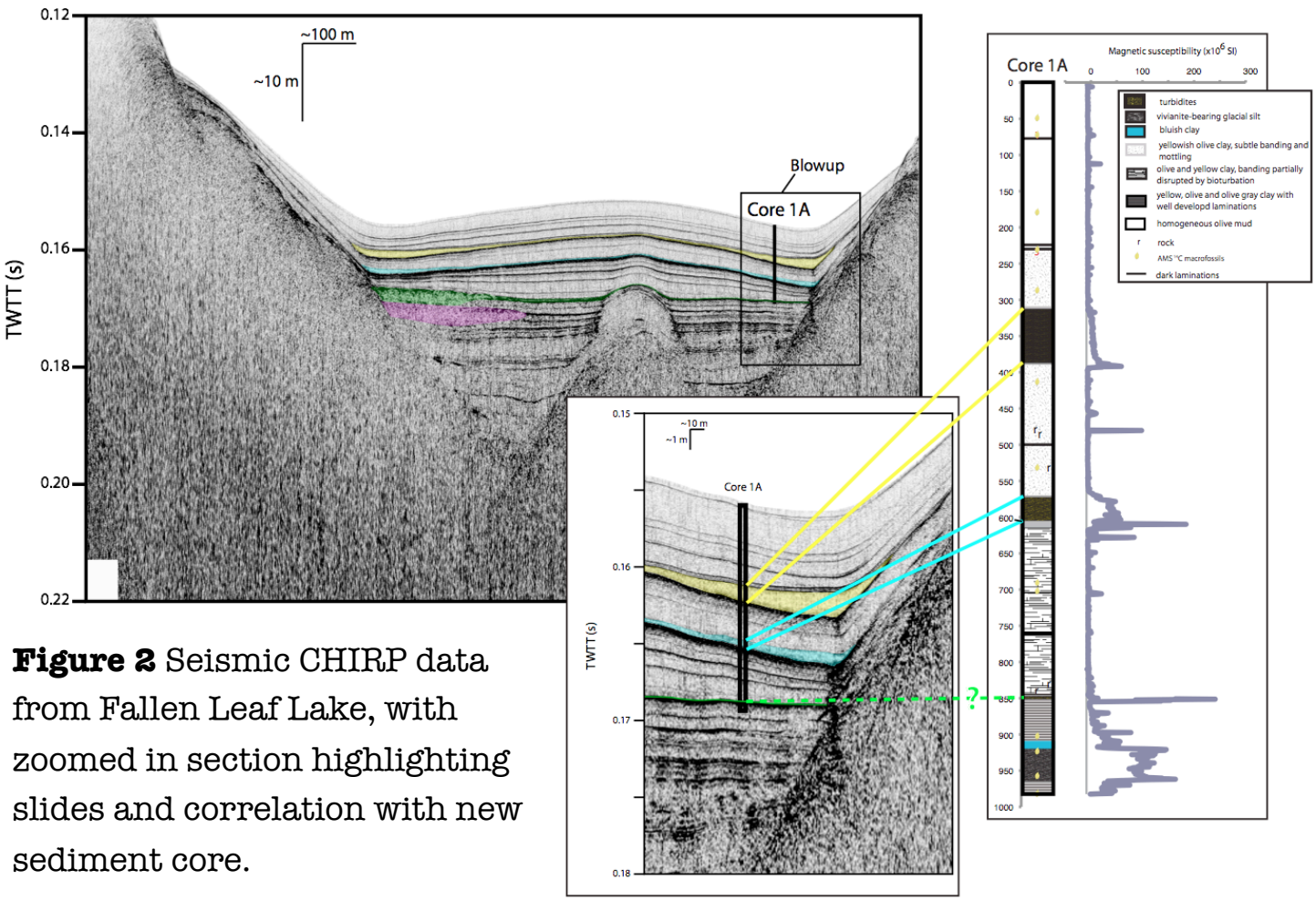

Figure 2 Seismic CHIRP data from Fallen Leaf Lake, with zoomed in section highlighting slides and correlation with new sediment core.

The CHIRP data beneath FLL image slide deposits that appear to correlate with contemporaneous slide deposits in Emerald Bay and Lake Tahoe. Three major slide deposits are identified beneath FLL: the most recent event (MRE) slide (4850-4570 cal yrs BP), the Tsoyowata ash (TA) slide (7900-7620 cal yrs BP), and

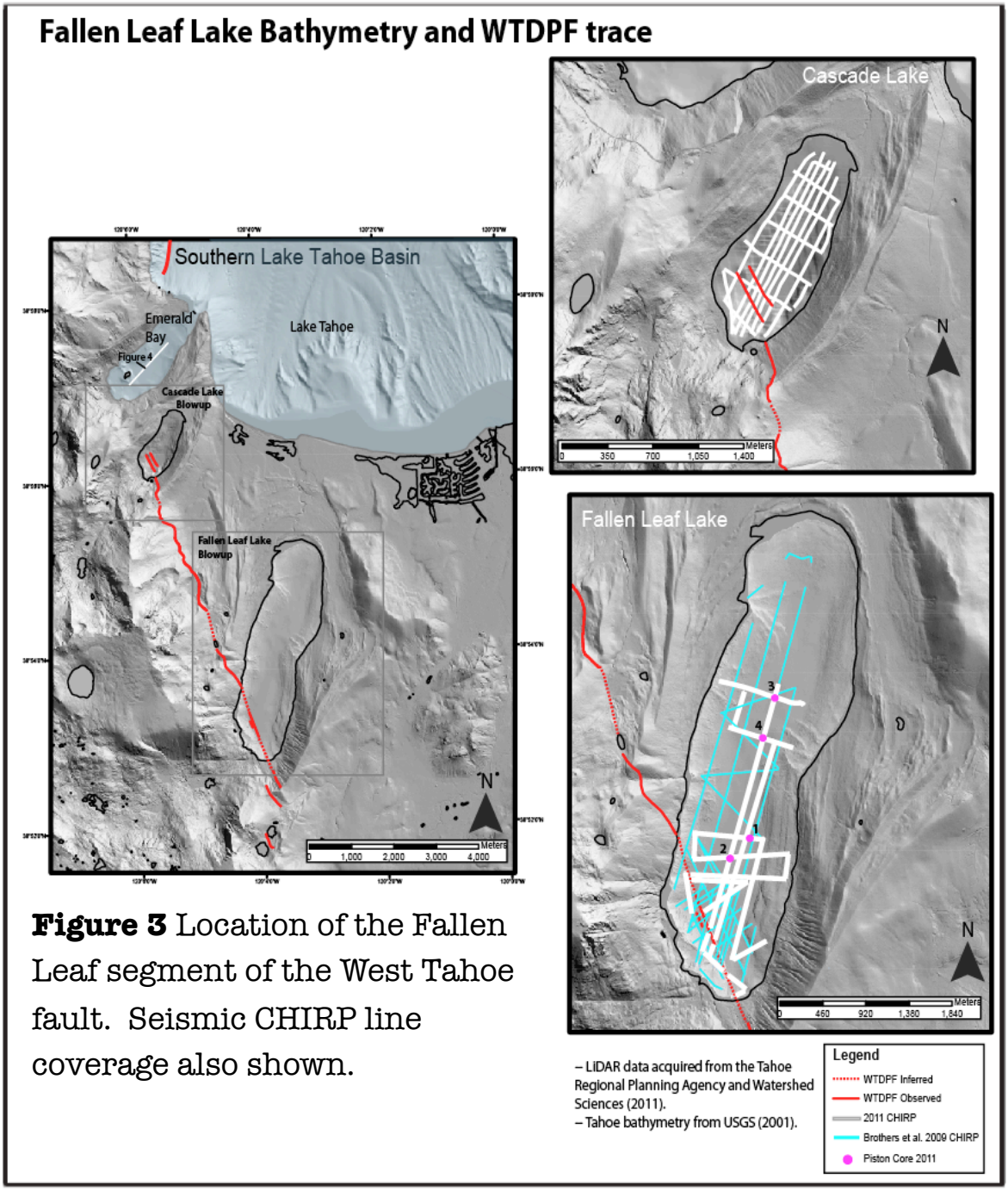

Figure 3 Location of the Fallen Leaf segment of the West Tahoe fault. Seismic CHIRP line coverage also shown.

the ~12 ka slide (~11,900-13,800 cal yrs BP). The MRE slide fills the accommodation created by the MRE on the FLL section of the WTDPF, which was dated at 4100-4500 cal yrs. BP (*Brothers, et al.* 2009). Furthermore, a synchronous slide is observed beneath Lake Tahoe (4510-4070 cal yrs BP) (*Smith et al.,* in revision). The TA slide sits just above the Tsoyowata ash deposit and is correlated with slide deposits in Emerald Bay (~8,300-8,000 cal yrs BP) and Lake Tahoe (7890-7190 cal yrs BP; *Smith et al.*, in revision). The equivalent age of these slides

suggests the penultimate earthquake on the WTDPF may have triggered them. The oldest slide observed in FLL is also correlated with slides in Emerald Bay (~12,200-12,600 cal yrs BP) and Lake Tahoe (12,490-11,200 cal yrs BP). These synchronous slides suggest seismic triggering and may further extend the paleoseismic record for the WTDPF. If correct, we postulate a recurrence interval on the WTDPF of ~3-4 k.y. These results suggest the FLL segment of the WTDPF is near the end its seismic recurrence cycle. Furthermore, the size and extent of these deposits may provide insight to the rupture patterns on the three segments of the WTDPF.

In Cascade Lake we observe two fault-strands trending N45°W across southern Cascade Lake for ~450 m (Fig. 3). The strands produce scarps of ~5 m and ~2.7

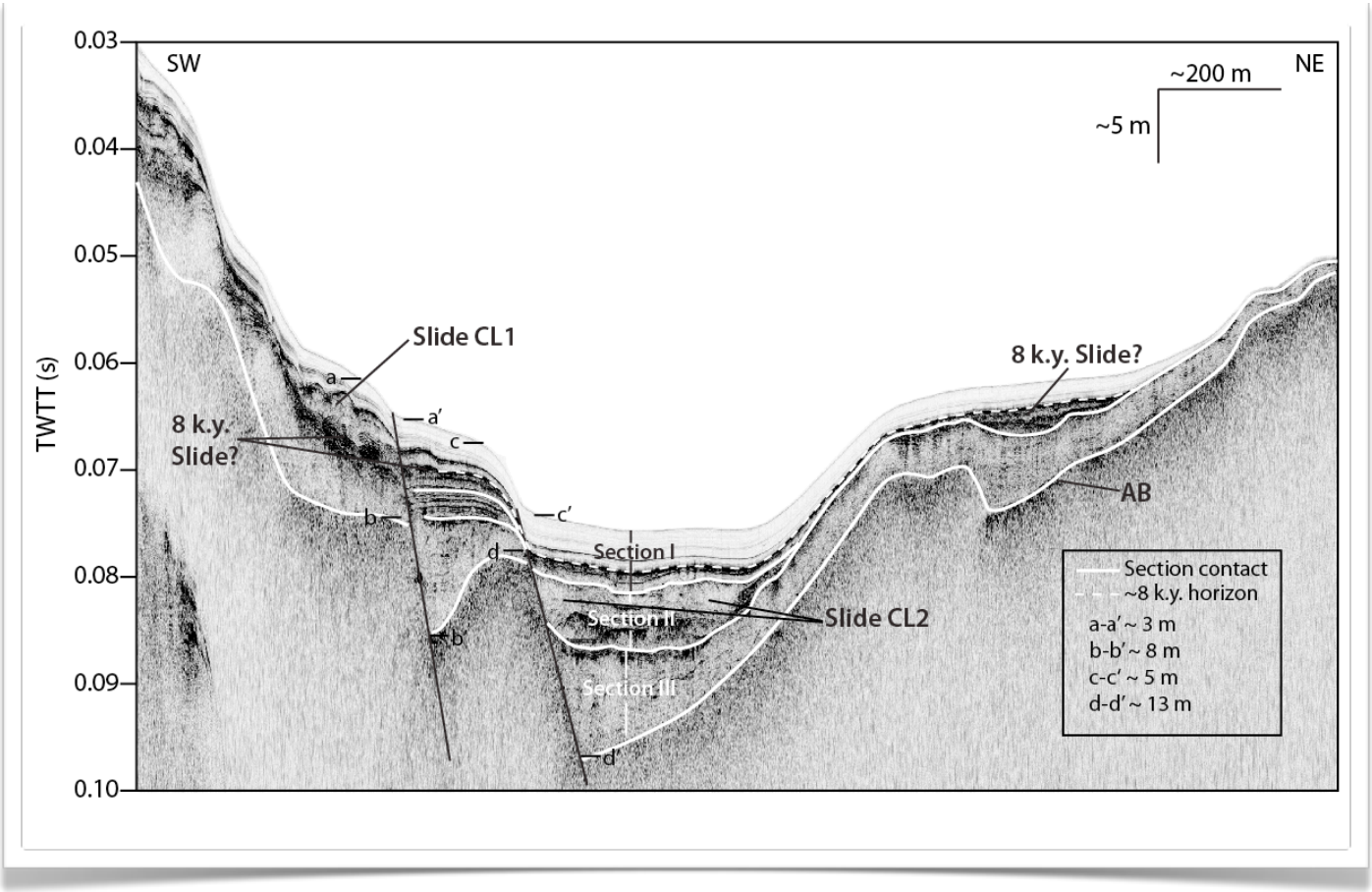

Figure 4 Seismic CHIRP profile from Cascade Lake highlighting two strands of the West Tahoe fault, with associated stratigraphy and debris slides.

m, respectively, on the lake floor, but offset increases down-section to ~14 m and ~8 m at the acoustic basement (Fig. 4). Previous mapping of the WTDPF did not extend the fault trace into Cascade Lake. These data combined with onshore LiDAR data trace the WTDPF continuously between FLL and Cascade Lake. Additionally, in the CHIRP line closest to the northwestern lakeshore we observe multiple fault strands with more distributed deformation than the two distinct strands observed in the southeastern lines. Studying the style and timing of earthquake deformation in Cascade Lake, combined with data from Emerald Bay, Fallen Leaf Lake, and Lake Tahoe will help us to understand how strain is partitioned between adjacent segments and the potential rupture magnitude of the WTDPF.

Publications:

Presently, Jillian Maloney (Scripps) and Gretchen Schmauder (UNR) are working on two separate manuscripts that cover results from these exciting new CHIRP data, with a focus on paleoseismology based on debris flows in Fallen Leaf Lake, Cascade Lake and Emerald Bay, and a new comprehensive fault map for the Tahoe basin based on both in-lake data and airborne lidar. The latter paper will also cover new results on the MRE for the North Tahoe–Stateline fault.

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