The Tahoe-Sierra frontal fault zone, Emerald Bay area, Lake Tahoe, California: History, displacements, and rates

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ABSTRACT

The location and geometry of the boundary between the Sierra Nevada microplate and the transtensional Walker Lane belt of the Basin and Range Province in the Lake Tahoe area have been debated. Two options are that the active structural boundary is (1) a few km west of Lake Tahoe, along the northwest-trending Tahoe-Sierra frontal fault zone (TSFFZ) or (2) within Lake Tahoe, along the largely submerged, north-trending West Tahoe–Dollar Point fault zone (WTDPFZ).

Emerald Bay, a famous scenic locality at the southwest end of Lake Tahoe, is at the juncture between the TSFFZ and the WTDPFZ. There, utilizing high-resolution, multibeam-echosounder maps and derived bathymetric profiles, detailed field studies on land are integrated with bathymetric data and remotely operated vehicle observations to clarify the existence and activity of faults and sedimentology of the bay. Results include the most detailed structural maps of glacial moraines and the bottom of Lake Tahoe ever produced. Glacial moraines on both sides of Emerald Bay clearly have been deformed by normal displacements on faults within the TSFFZ and the WTDPFZ. Tectonic geomorphic features include scarps along moraine crests, locally back-tilted crests, and tectonic reversal of moraine crests, where older, higher moraines locally lie at lower elevations than younger, lower moraines. The alignment of crests of lateral moraines shows that dextral slip has not occurred during or since late Pleistocene glaciations.

On the floor of Emerald Bay, submerged youthful faults that correspond to onshore faults that displace glacial moraines have numerous distinct, well-preserved, postglacial fault scarps, for which the vertical component of slip (vertical separation) is estimated.

This study clearly demonstrates that the TSFFZ is the active structural boundary of the Sierra Nevada microplate and that the TSFFZ has a higher rate of slip than the WTDPFZ. It also provides evidence for complex range-front evolution, with both zones of normal faults active concurrently at various times.

INTRODUCTION

New studies at Emerald Bay, a world-famous, scenic locale in the Lake Tahoe basin, California-Nevada, clarify the relationship between two important fault zones along the eastern edge of the Sierra Nevada microplate. The Lake Tahoe basin (Figs. 1A and 1B), a complex half-graben, is part of the Walker Lane belt, possibly an incipient plate boundary, and a region of dextral transtensional deformation between the internally unfaulted Sierra Nevada and the extensional Basin and Range Province to the east. Numerous studies in the Walker Lane belt have established the following (see, for example, Bormann et al., 2016; Busby, 2013, 2016; Carlson et al., 2013; Dixon et al., 2000; Faulds and Henry, 2008; Hammond et al., 2011; Hammond and Thatcher, 2007; Lifton et al., 2013; Rood et al., 2011a; Schweickert et al., 2004; Surpless et al., 2002; Taylor and Dewey, 2009; Unruh et al., 2003; Wensnousky et al., 2012): The Walker Lane currently takes up about one fifth of the dextral displacement between the Pacific and North American plates. Kinematic complexity characterizes the Walker Lane, with various parts dominated by normal faults, dextral or sinistral strike-slip faults, and/or vertical-axis rotations of crustal blocks. Additionally, in some parts of the Walker Lane, discrepancies have been noted between long-term, geologically determined slip rates and those calculated from instantaneous GPS geodetic studies.

The Lake Tahoe basin, a normal-fault domain, is bounded to the north and south by domains that have conjugate dextral and sinistral faults and earthquake focal mechanisms (Fig. 1B; Schweickert et al., 2004). This study focuses primarily on the Tahoe-Sierra frontal fault zone (TSFFZ), a complex, northwest-trending zone of faults one to five km west of Lake Tahoe (Fig. 1B). Observations are also provided on the southern part of the north-trending West Tahoe–Dollar Point fault zone (WTDPFZ), a largely submerged and relatively simple zone of normal faults within and adjacent to Lake Tahoe.

Statement of the Problem

Normal faults along the western edge of the Lake Tahoe basin provide insights into the evolution of range-front faults along an incipient, transtensional plate boundary. The nature and continuity of faults in the area within and south of Emerald Bay, however, have been debated for more than a decade (Schweickert et al., 2000a, 2000b, 2004; Kent et al., 2005; Schweickert and Lahren, 2006; Dingler et al., 2009; Brothers et al., 2009; Howie et al., 2012; Maloney et al., 2013; Kent et al., 2016; Pierce et al., 2017). Due in part to this ongoing
Figure 1. (A) Tectonic sketch map of the Sierra Nevada microplate and Walker Lane belt, showing location of Lake Tahoe basin (T) (modified from Busby et al., 2016, and Unruh et al., 2003). Limit of Walker Lane belt from Faulds and Henry (2008). Heavy lines represent major faults. ECSZ—eastern California shear zone; MTJ—Mendocino triple junction. (B) Sketch map of the Lake Tahoe region, showing kinematic relations of faults and historic earthquakes (modified from Schweickert et al., 2004, with fault additions from Hunter et al. (2011; PF—Polaris fault); and Gold et al. (2014; MVF—Mohawk Valley fault). Basins are white; mountainous areas are gray. Outline of Figure 2 is shown. Abbreviations for fault zones include: WTDPFZ—West Tahoe–Dollar Point fault zone; NTIVFZ—North Tahoe–Incline Village fault zone. SN:NA—Sierra Nevada motion relative to Colorado Plateau. Modern stress axes from earthquake focal mechanisms: T-axis (= least principal stress) is horizontal, E-W; P-axis (= greatest principal stress) is vertical in normal-fault domains and is horizontal, N-S in areas with conjugate strike-slip faults.
debate, along with the structural importance of the faults and public interest in the Emerald Bay area, the locale deserves a full, accurate characterization.

In the Lake Tahoe basin, which fault zone—the northwest-trending TSFFZ or the north-trending WTDPFZ—represents the active structural boundary of the Sierra Nevada microplate (Fig. 1A). The location and orientation of the active structural boundary are important because kinematic models for transtension (Dewey, 2002; Dewey et al., 1998; Taylor and Dewey, 2009) indicate that they set a kinematic boundary condition (e.g., they determine the direction of maximum instantaneous extension, X) for transtensional deformation in the Walker Lane belt to the east. The active boundary may also pose a significant seismic hazard. Criteria used here to identify the active structural boundary are that it should be marked by faults that have large displacements and are currently active.

Additionally, what is the kinematic history of these normal fault systems along the eastern edge of the microplate? Have they experienced exclusively dip-slip displacement, or have they experienced components of dextral slip? Has activity along these faults migrated progressively from the range front out into the basin, as observed along many range fronts in the Basin and Range Province (e.g., Koehler and Wesnousky, 2011; McCalpin, 2009; Personius et al., 2017; Wesnousky et al., 2005), or has fault activity alternated back and forth between the range front and the basin (e.g., Wallace, 1987)? When both the TSFFZ and the WTDPFZ are considered, are long-term, geological slip rates for the Lake Tahoe basin consistent with instantaneous slip (or strain) rates, or does a discrepancy exist?

Regional Setting

The Tahoe-Sierra frontal fault zone (TSFFZ), whose trend varies from N26° to 45° W (334–315° AZ), extends over 100 km from near Echo Lakes to the Mohawk Valley fault (Figs. 1B and 2; Howle et al., 2012; Schweickert et al., 2000a, 2000b, 2004; Schweickert, 2009; Sylvester et al., 2012). The footwall of the fault zone consists of granitic rocks of the largely unfaulted Sierra Nevada microplate (Howle et al., 2012; Saucedo, 2005; Schweickert et al., 2000b, 2004; Schweickert, 2009; Surpless et al., 2002; Unruh et al., 2004). In places, the granitic rocks are nonconformably overlain by cover sequences of Paleogene and Neogene volcanic rocks, Pleistocene glacial deposits, and, locally, lacustrine deposits (e.g., Saucedo, 2005; Sylvester et al., 2012).

Between ca. 3.5 and 2 Ma, east-side-down displacement on numerous subparallel branch faults of the TSFFZ beheaded various west-flowing Sierra drainages leaving wind gaps along the present crest (Fig. 2B; Schweickert, 2009). Normal displacement along the TSFFZ established the steep, east-facing Sierran escarpment that controlled the development of younger, east-flowing drainages and Pleistocene glacial valleys (Fig. 2A).

The TSFFZ includes several overlapping, northwest-trending, en echelon segments (Howle et al., 2012). From south to north, these include Twin Peaks, Ellis Peak, Rubicon Peak, Mount Tallac, and Echo Peak segments (Figs. 2A and 2B). Each segment, through long-term normal displacements, has developed high-standing bedrock facets (Fig. 2A) that are underlain mainly by granitic bedrock. Two million-year-old and older lacustrine sediments, which were deposited in a lake that predated modern Lake Tahoe are found in the hanging wall of the TSFFZ over much of its length (Fig. 2B; Kortemeier et al., 2018; Lopez et al., 2004; Moore et al., 2006; Schweickert et al., 2005).

The north-trending West Tahoe–Dollar Point fault zone (WTDPFZ), as used in this report, is submerged along a 25-km-long stretch northward from near Emerald Bay to Dollar Point (Fig. 2A), north of which it continues for about another 10 km on land (Howle et al., 2012; Schweickert et al., 2004; Schweickert et al., 2000a, 2000b, 2004; Sylvester et al., 2012).

The combined 1380 m height of footwall facets on both fault zones two to five kilometers north of Emerald Bay gives that area the greatest structural relief of any area within the Lake Tahoe basin.

Geology of the Emerald Bay Area

Emerald Bay, a submerged glacial valley, is well known for its glacial geology and scenery. During parts of its history, it has been a moraine-dammed lake, although at the current level of Lake Tahoe, the two lakes have merged. Prominent lateral moraine complexes that trend N35–45° E (305–045° AZ) form the steep slopes along the sides of Emerald Bay and Cascade Lake (Figs. 3–5) and are ~2.2 km in length. Glacial till within the moraines consists principally of boulders of granodiorite with a sandy matrix. Scenic, State Route 89 (CA 89) traverses high-standing glacial moraines that enclose the bay.

Emerald Bay and Cascade Lake, together with their glacial moraines, span most of the faults of the TSFFZ (Figs. 4 and 5). Emerald Bay lies along a prominent right step in the TSFFZ, where the steep range front steps 1.8 km eastward from Eagle Falls toward Emerald Point (Howle et al., 2012; Figs. 2–5).

The Mount Tallac segment (as used here) of the TSFFZ, which includes at least five subparallel branches or splays within granitic bedrock, extends ~20 km N30°W (330° AZ) along the prominent, 1-km-high range front from near the south end of Fallen Leaf Lake northwestward past the southwest end of Emerald Bay (Howle et al., 2012; Figs. 2, 4, and 5; Fig. S1 in the Supplemental Material*). Eagle Falls and Cascade Falls (Figs. 3 and 4) both lie along this prominent escarpment. It is noteworthy that both deep, U-shaped, glacial valleys of Eagle and Cascade creeks upstream from the falls do not align with the downstream parts of the valleys. The upstream valleys (Figs. 3 and S1 [text footnote 1]), which have been carved into granitic bedrock, appear to have been displaced in a dextral sense relative to the valleys below the falls. This geomorphic relationship suggests that faults within the Mount Tallac segment experienced some dextral displacement during Pleistocene time. Work in progress suggests that a similar relationship exists along many of the glacial valleys north of Emerald Bay (Fig. 2B).

The Stony Ridge fault (SRF) lies between the Mount Tallac fault and the Rubicon Peak fault (Howle et al., 2012; Figs. 4 and 5). Northwest of Emerald Bay, the SRF lies entirely within granitic bedrock, although it displaces glacial

*Supplemental Material. Notes on geologic setting, mapping criteria for glacial moraines, tectonic geomorphology, new mapping of moraines of Emerald Bay and Cascade Lake, high-resolution bathymetry images, ROV observations. Figures show topography and bathymetry, comparisons of submersed scars with subaerial scars, and photos of submersed scars. Please visit https://doi.org/10.1130/GEOS02202.S1 or access the full-text article on www.gsapubs.org to view the Supplemental Material.
Figure 2. Generalized tectonic maps of the western part of the Lake Tahoe basin (modified from Howle et al., 2012) showing N35–45°W (135–145° AZ)-trending Tahoe-Sierra frontal fault zone (TSFFZ) and N-S-trending West Tahoe-Dollar Point fault zone (WTDPFZ). Abbreviations: BW—Blackwood Canyon; CL—Cascade Lake; DP—Dollar Point; EB—Emerald Bay; EL—Echo Lakes; ELP—Ellis Peak; EP—Echo Peak; EPT—Emerald Point; FLL—Fallen Leaf Lake; GC—General Creek; MKB—McKinney Bay; MC—Meeks Creek; McK—McKinney Creek; MT—Mount Tallac; NTFZ—north Tahoe fault zone; RP—Rubicon Peak; RPT—Rubicon Point; SPP—Sugar Pine Point; SR—Stony Ridge; SV—Squaw Valley; TC—Tahoe City; TR—Truckee River outlet; TW—Twin Peaks; WC—Ward Creek. EB and CL denote the Emerald Bay-Cascade Lake area, the subject of this report. Heavy dashed blue lines show limits of 12,000–21,000-year-old McKinney Bay landslide. Pale-yellow shading—Emerald-Fallen Leaf tectonic depression, described in document in Supplemental Material [text footnote 1]. (A) Axes of major glacial valleys are marked by heavy red lines; bedrock facets forming escarpments along major faults are depicted by various colors; black numerals give maximum heights of the facets. Small, red X’s denote localities where glacial moraines have been dated by Howle et al. (2012) and Pierce et al. (2017). (B) Same base map as (A), depicting reconstructed geometry of former west-flowing Sierran drainages truncated by east-side-down normal displacement along the Tahoe-Sierra frontal fault zone (TSFFZ) (Schweickert, 2009). Thick, orange dashed lines—former and present South Fork American River; thick, gold dashed lines—former and present tributaries of Rubicon River. Red hexagons—sites of truncation of west-flowing valleys. Red dashes—sites along the TSFFZ showing apparent right-oblique separation of glacial valleys, discussed in text.
Figure 3. Oblique, shaded, bare-earth view of the Emerald Bay–Cascade Lake area showing some features referred to in text (compare with fig. 4 of Howle et al., 2012): water is removed from Emerald Bay, and shorelines are depicted by thin, black lines. Vertical exaggeration (VE) = 1.5; distance across the bottom of the image is ~4.3 km (3 mi). Abbreviations: CA—California; CC—Cascade Creek; EB—Emerald Bay; EBCC—Emerald Bay–Cascade Creek. Note apparent right-separation of both glacial valleys of Cascade Creek and Eagle Creek along the range front, where branches of the Mount Tallac fault (Figs. 2A and 4) traverse the image, relative to Cascade Lake and Emerald Bay. This separation is ~485–600 m (1600–1980 ft). Also note irregular, glaciated topography above and left (south) of both Cascade and Eagle falls, where Tahoe and Tioga glaciers spread from upper parts of glacial canyons into offset lower parts. See text and Figure 2B for discussion.
Figure 4. Generalized geologic map of Emerald Bay–Cascade Lake area (modified from Howle et al., 2012, with additions from this study); water is removed from Emerald Bay and thin, black lines depict the shoreline. Faults and fault zones shown with white lines include: MTF—Mount Tallac fault (several branches); SRF—Stony Ridge fault; RPF—Rubicon Peak fault; WTF—West Tahoe fault. Other abbreviations: EB—Emerald Bay; EP—Emerald Point; EPT—Eagle Point. Small, white x’s mark localities on Stony Ridge where scarps along the SRF cut glacial moraines.
Figure 5. Oblique, shaded, bare-earth view of Stony Ridge and Emerald Bay (EB) showing topographic expression of major fault segments (compare with fig. 9 of Howle et al., 2012). Abbreviations: MTF—Mount Tallacl fault (several branches); SRF—Stony Ridge fault (two branches); RPF—Rubicon Peak fault (two branches); WTF—West Tahoe fault (two branches). Vertical exaggeration (VE)—1.4; horizontal distance across the bottom of the figure is 3.2 km (1.9 mi). Water is removed from Emerald Bay, and shoreline is depicted by thin, black lines.
moraines near small cirques high on the east flank of Stony Ridge (Figs. 2A and 4). Howle et al. (2012) reported that branches of the fault southeast of Stony Ridge displace lateral moraines on the north side of Emerald Bay and then enter Emerald Bay. Beneath the bay and described in detail here are what appear to be fault scarps that cut through and around Fannette Island and that also form a steep, submerged bedrock escarpment on the northeast side of the island. About 200 m southeast of Fannette Island, these faults are buried beneath modern sediment and apparently form a broad flexure. Southeastward from there, several scarps representing branches of the SRF cross and displace the medial moraine complex south of Emerald Bay.

In the Rubicon Peak segment of the TSFFZ, Howle et al. (2012) reported that two main branches of the Rubicon Peak fault (RPF) cross and displace moraines on the north side of Emerald Bay, and they interpreted a large landslide on the bottom of the bay to have been cut by youthful scarps (Figs. 4 and 5). Where the RPF continues southeastward across the medial moraine complex on the southeast side of Emerald Bay, moraine crests define a monoclinic flexure (Fig. 4). About 200 m southeast from the Emerald Bay moraine complex, the probable RPF passes beneath postglacial fluvial deposits northeast of Cascade Lake. One kilometer farther southeast, prominent scarps along the RPF cut moraines on the south side of Cascade Lake (Figs. 4 and S3 [footnote 1]).

Landslides are present along much of the range front defined by the TSFFZ, particularly along the Mount Tallac and Rubicon Peak segments (Howle et al., 2012; their figures DRF2, DRF5, and DRF16).

**DETAILED STUDIES ALONG THE TSFFZ AT EMERALD BAY**

The following sections present new maps, profiles, and descriptions of: (1) glacial moraines, (2) modern sedimentology, and (3) submerged scarps on the floor of Emerald Bay. Significantly, the moraine crests at Emerald Bay provide plentiful evidence for dip-slip normal displacements, while the submerged scarps allow vertical separation and extension rates to be estimated for many of the normal faults.

Reliable age control on glacial moraines in the region that encompasses Emerald Bay includes results of Howle et al. (2012) at Meeks Creek, 8 km northwest, and Pierce et al. (2017) on right-lateral moraines at Cascade Lake, 2 km south (Fig. 2A). Additionally, Rood et al. (2011b) determined ages on postglacial deposits on the eastern flank of the Carson Range, 25 km east of Emerald Bay. As discussed in the document in the Supplemental Material (footnote 1), we adopt ages of 23.5 ± 3 ka to 20.5 ± 0.6 ka for Tioga-age moraines (Howle et al., 2012).

**Structure of the Glacial Moraines**

Lateral moraines are referred to as left and right lateral, respectively, when viewed downstream or down canyon (Howle et al., 2012). The left-lateral moraines of Emerald Bay (north side) are draped upon granitic bedrock, whereas the right-lateral moraines (south side) are free standing and separate Emerald Bay and Cascade Lake. Moraines of different ages have been differentiated during field mapping using criteria described by McCaughhey (2003) and Howle et al. (2012) (see document in Supplemental Material [footnote 1]). In this study, Tahoe-age moraines (Qta) and two sets of Tioga-age (Qti) moraine crests have been distinguished, an older Qti-1 crest and a younger, inset Qti-2 moraine crest. The Tioga-age crests have similar weathering characteristics and subequal heights (Howle et al., 2012; see document in Supplemental Material [footnote 1]).

Structural maps and topographic profiles of the moraines (Figs. 6–9) have been prepared using established criteria for tectonic geomorphology of faulted moraines (Howle et al., 2012; Schweickert et al., 2004; see document in Supplemental Material [footnote 1]). Careful field examination has allowed recognition of very small scarplets (~1–2 m in height) that are not evident in the light detection and ranging (LiDAR) imagery. The terminology used for scarps, scarp height (SH), and vertical separation (VS) is explained in Figure S4 (footnote 1).

Scarp heights for subaerial scarps cutting moraines have been estimated in the field using a tape and compass and using topographic profiles, as discussed in later sections. All estimates are reported to the nearest half meter and to the nearest foot.

**Faults and Scarps Cutting the Left-Lateral Moraines (Figs. 6 and 7)**

East-facing fault scarps and backtilted moraine crests are prominent where the left-lateral moraines have been cut and displaced by the Mount Tallac, Stony Ridge, and Rubicon Peak faults (Howle et al., 2012; Fig. 6A).

Near the southwest end of the Qta moraine, large gulches along the eastern branch of the Mount Tallac fault have removed the crest; the remnant of the crest east of the large gulles is ~27 m (89 ft) lower than the part southeast of the gulles, reflecting post-Tahoe normal displacement along an eastern branch of the Mount Tallac fault.

The Stony Ridge fault (SRF) has two distinct branches that have produced scarps of similar height in the Qti-1 moraine (Figs. 6A and 6B). A few tens of meters northeast of the Stony Ridge fault, the Qta moraine has been buried beneath the Qti-1 moraine (this is called tectonic reversal, which indicates significant fault displacement occurred between the deposition of Qta and Qti-1 moraines; see document in Supplemental Material [footnote 1]).

Along both branches of the Rubicon Peak fault (RPF), prominent, northeast-south down scarps are within the Qta and Qti-1 moraines (the Qti-2 moraine crest where crossed by the RPF has been removed by landsliding [Figs. 6A and 6C]). Field estimates for heights of two scarps in the Qti-1 moraine are 8 and 6 m (~26 and 20 ft), respectively (the topographic profile in Fig. 6C gives estimates of 9 and 6 m (30 and 20 ft) for heights of the two scarps), in general agreement with the Howle et al. (2012) estimate of VS for the scarps cutting Qti-1.

The submerged West Tahoe fault (WTF; the southern part of the WTDPFZ) continues southward onshore near the northeast end of the left-lateral moraine complex (Fig. 7). There, a bedrock escarpment ~90 m (297 ft) high separates
Figure 6. Detailed structure of left-lateral glacial moraines, faults, and scarps along northwest side of Emerald Bay. (A) Structural map. Figure 7 is outlined at upper right. In this and subsequent figures, spot elevations are provided for comparison of heights of Tahoe-age and Tioga-age moraines. (B) and (C) Topographic profiles along crest of left-lateral Qti-1 moraines, extracted from light detection and ranging (LiDAR) data using QT Mapper; vertical and horizontal scales in feet. VE—vertical exaggeration. Thick, blue lines emphasize parts of crest with normal down-canyon slopes, and thick, red lines highlight parts of moraine crests that have been back-tilted up canyon. Faults are assumed to dip 60°, and dips have been corrected for vertical exaggeration. Scarp height (SH) is shown with thin, vertical, red lines. (B) Profile A–A’ along crest of left-lateral Qti-1 moraine where crest has been displaced by normal slip on branches of Stony Ridge fault (SRF). (C) Profile B–B’ along crest of left-lateral Qti-1 moraine where crest has been displaced by normal slip on branches of Rubicon Peak fault (RPF). HWM—high-water mark. (Continued on following page.)
Qta, Qti-1, and Qti-2 crests to the southwest from much lower Qti-1 and Qti-2 moraine crests near Emerald Point; Qta is not exposed in the hanging wall east of the escarpment, due to tectonic reversal. In contrast, the Qti-1 moraine crest projects across this escarpment with little apparent displacement. Two possible explanations are: (1) that at least 90 m of post-Qta and pre-Qti-1 normal displacement occurred along the fault at the base of the escarpment, or (2) the Qta glacier flowed down a preexisting bedrock escarpment, and further fault displacement occurred prior to deposition of the Qti-1 moraine. We tentatively favor the second hypothesis. A few tens of meters northeast of the bedrock escarpment (Fig. 7), an eastern branch of the WTF has noteworthy, fresh scarps, as mapped by Howle et al. (2012).

**Faults and Scarps Cutting the Right-Lateral Moraines (Figs. 8 and 9)**

The high-standing, 1-km-long, remnant of the Qta moraine near the range front has a strongly backtilted segment in the hanging wall of the eastern branch of the Mount Tallac fault (Fig. 8A). The Qta remnant has several small, 2–3-m-high scarps along its crest, and at its northeast end, the moraine terminates in a 15-m-(50-ft)-high triangular facet along the eastern branch of the Stony Ridge fault (SRF).

Near CA 89 and Inspiration Point (Figs. 8A and 8B), a 10-m-(33-ft)-high scarp along an unnamed fault separates granodiorite capped by Qti-2 in the footwall from backtilted Qti-2 moraine in the hanging wall. This scarp may mark a separate branch of the MTF.

Along the western branch of the SRF, the Qti-2 crest has been removed where a deep gully cuts into the moraine (Figs. 8A and 8B). The Qti-2 crests on opposite sides of the gully have a difference in elevation of ~10.5 m (35 ft). The Qti-2 crest has not been displaced or disrupted adjacent to the large triangular facet at the end of the Qta moraine (Figs. 8A and 8B). This observation strongly suggests that major displacement on the eastern branch of the SRF, which resulted in tectonic reversal of Qta, was post-Qta and pre-Qti-2. The Qti-2 moraine is the only moraine exposed for a distance of ~240 m northeast of the SRF, where it is surmounted by a very narrow stretch of CA 89.
Figure 7. Structural sketch of area near Emerald Point (oblique, shaded, bare-earth image using light detection and ranging [LiDAR] data), showing branches of West Tahoe fault (WTF). North is to right; vertical exaggeration (VE) ~1.5:1. Distance along the bottom of the figure is ~1 km (0.6 mi). The smooth, subdued topography between the bedrock escarpment and Emerald Point is interpreted to reflect beveling of glacial moraines by tsunamis generated by the McKinney Bay landslide (Schweickert et al., 2000b, 2004; Moore et al., 2014), between 12,000 and 21,000 years ago. HWM—high-water mark; RPF—Rubicon Peak fault.
Figure 8. Detailed structure of right-lateral moraines. (A) Structural map. Outline of Figure 9 is at upper right. Thin, red lines delineate bathymetric profiles (profiles 1, 7, 15, 16, and 17) shown in later figures. Map of moraines enclosing Cascade Lake is in Figure S3B and S3C (text footnote 1). Topographic profiles along crests of right-lateral Qti-2 and Qti-1 moraines, extracted from light detection and ranging (LiDAR) data using QT Mapper; vertical and horizontal scales in feet. Abbreviations and line ornament as in Figures 6B and 6C. (B) Profile C–C′ along crest of right-lateral Qti-2 moraine where crest has been displaced by normal slip on unnamed faults at Inspiration Point and western branch of the Stony Ridge fault (SRF). (C) Profile D–D′ along crest of right-lateral Qti-2 and Qti-1 moraines where crest has been deformed by normal displacement on branches of the Rubicon Peak fault (RPF; here, a blind fault), West Tahoe fault (WTF), and an unnamed fault near Eagle Point (EP). MTF—Mount Tallac fault; SH—scarp height; grd—granodiorite. (Continued on following page.)
Near the switchbacks along CA 89 (Figs. 8A and 8C), the slope of the Qti-2 crest steepens markedly down canyon. This steeper section of the moraine crest was interpreted by Howle et al. (2012) as a fault-propagation fold, formed during the post-Qti-2 interval, along concealed (or blind) branches of the RPF. A few tens of meters northeast of the fold, the Qti-1 and Qta crests are at a slightly lower elevation than the Qti-2 crest, and then both Qti-1 and Qta moraines rise gradually northeast to elevations greater than that of Qti-2. The latter observation indicates growth of the fold (or fault displacement) occurred during the interval between deposition of the Qti-1 and Qti-2 moraines, as well as in post-Qti-2 times.

A fault or faults cut through the Qta moraine 0.6 km (0.4 mi) northeast of the switchbacks on CA 89 (Figs. 8A and 8C). More than one interpretation of the faults is possible. One option is that a branch of the West Tahoe fault (WTF) may continue southeastward from Emerald Point across the bay (where a submerged scarp is present; see below) toward the large Qta moraine remnant northeast of CA 89 (Howle et al., 2012; Figs. 8 and 9). Alternatively, the fault cutting the Qta moraine may be a continuation of a submerged fault marked by the southeast ridge within Emerald Bay (discussed later, Figs. 8 and 9).

Faults near Eagle Point (Fig. 9), which lie in the hanging wall of the WTF, are not discussed further; more work is necessary in that area (see document in Supplemental Material [footnote 1]). Each fault in the glacial moraines shows evidence of significant post-Tahoe displacement and postglacial displacement (Table 1). As discussed later, faults and scarps cutting the moraines align closely with scarps on the floor of the bay.

**Bathymetry and Sedimentology of Emerald Bay**

**Procedures**

High-resolution bathymetry of Emerald Bay has been mapped in two campaigns, the first in 2009, using techniques described by Howle et al. (2012), and the second, in 2011, 2012, and 2013, during which bathymetric mapping used an autonomous vessel, “SWATH,” built by C. Kitts and students, Santa Clara University, Mechanical Engineering Group (see document in Supplemental Material for details [footnote 1]).

Continuous video images of the bottom of Emerald Bay were scanned along ~34 traverses across scarps along the bottom of Emerald Bay over 11 days in May and September 2011, 2012, 2013, and 2014, utilizing the remotely operated vehicle (ROV) Triton (Mechanical Engineering Department, University of Santa Clara) (Table 2, Fig. 10).
Figure 9. Structural map of right-lateral moraines near Eagle Point, showing Qta, Qti-1, and Qti-2 moraine crests and probable faults lying northeast of West Tahoe fault (WTF). HWM—high-water mark.
TABLE 1. STRUCTURAL OBSERVATIONS ON FAULTS CUTTING LATERAL MORAINE COMPLEXES AT EMERALD BAY

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<td>Major backtilt of Qta towards the fault</td>
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<td>Stony Ridge fault*</td>
<td>-16 m elevation difference in Qta and tectonic reversal across fault;</td>
<td>Truncation of Qta and tectonic reversal of crests; 12 m elevation</td>
<td></td>
<td>Significant post-Tahoe and post-Tioga fault displacement</td>
</tr>
<tr>
<td>Rubicon Peak fault*</td>
<td>Vertical separation (VS) 30 m in Qta moraine (Howle et al., 2012);</td>
<td>Large fault-propagation fold in Qti-2 crest with about 30 m of relief</td>
<td></td>
<td>Significant post-Qta and post-Qti-2 displacement</td>
</tr>
<tr>
<td>West Tahoe fault*</td>
<td>Qta—tectonic reversal across major bedrock escarpment; Qti-1 and Qti-2 have several 2-m-high scarps on eastern splay; Qti-1 and Qti-2 spacing increases across bedrock escarpment</td>
<td>Qta—prominent scarps; Qti moraines have minor scarps</td>
<td></td>
<td>Significant post-Qta and post-tsunami displacement§ in left-lateral moraines; displacement decreasing southward</td>
</tr>
<tr>
<td>Faults near Eagle Point**</td>
<td></td>
<td>Qta—significant scarps cut Qta, Qti-1, and Qti-2</td>
<td></td>
<td>Significant post-Qta and post-Qti-2 displacement</td>
</tr>
</tbody>
</table>

*Tahoe (Qta) moraines (ca. 70 ka) always show larger and more numerous scarps than Tioga (Qti-1 and Qti-2) moraines (ca. 23 and 21 ka); together with several cases of tectonic reversal, this indicates that considerable displacement occurred along all faults during interglacial times.

**Only exposed on right-lateral moraines.

Results

Multibeam-echosounder bathymetry for Emerald Bay (Figs. 10 and S5A and SSB [footnote 1]) reveals a shallow bottom near the mouth of the bay; the bottom slopes gently (slightly over 3°) southwest toward the deep (>65 m [>200 ft]), relatively flat, central part of the bay. The southwestern end of Emerald Bay between the SRF and the mouth of Eagle Creek is a shallow shelf (~3–30 m [10–100 ft] deep) upon which a shallow, sandy delta is developing nearshore, and muddy sediment is accumulating south of Fannette Island. Nearby all Eagle Creek sediment that bypasses the delta is routed through the channel south of Fannette Island, because the channel to the north is partially blocked by bedrock promontories and by submerged recessional moraines (Fig. 11; see below). Both glacial till and talus exist in places, especially near steep escarpments.

In the central basin, near the presumed trace of the RPF (Figs. 10 and S5 [footnote 1]), measured water depths range from ~60–65 m (198–215 ft). The basin floor in that area is flat and featureless and is blanketed by water-rich, muddy sediment, derived from currents passing south of Fannette Island. In the northeastern part of the basin, sand derived from the subaerially exposed lateral moraines blankets the bottom.

The deep, central basin is interrupted along its northern margin by a large, post-Qti-2 landslide (Figs. 4 and 8; Howle et al., 2012). This landslide and several other smaller landslides in Emerald Bay developed along mapped faults and resulted from failure of steep sidewalls of lateral moraines.

Published seismic-reflection profiles (Dingler et al., 2009; Maloney et al., 2013) depict depocenters in places including subbasins east of the SRF and subbasins east of the RPF. In profile section, each depocenter is wedge shaped, with strata thickening to the southwest. These depocenters are interpreted here to be fault-bounded half grabens in the hanging walls of major normal faults. In the subbasin between the SRF and RPF, Maloney et al. (2013; their figure 10; shown schematically in Fig. 13) reported that the sediments may reach thicknesses greater than 25 m (82 ft) (see document in Supplemental Material for discussion). East of the RPF, one subbasin may have a sediment thickness greater than ~10 m (33 ft), and a more easterly subbasin along the WTF may have a thickness greater than ~5 m (17 ft) (see also Dingler et al., 2009). New interpretations of relations among these depocenters and mapped faults are discussed below.

Maps and Bathymetric Profiles on Submerged Scarps within Emerald Bay

Submerged scarps within Emerald Bay were first reported by Howle et al. (2012). Because several authors cited earlier have maintained that submerged faults are not evident within Emerald Bay, however, and to verify the existence and nature of scarps and active faults as reported by Howle et al. (2012), all of these features have been examined and mapped using ROV dives, and bathymetric profiles have been constructed from the multibeam-echosounder data using QT mapper. Profiles were constructed perpendicular to scarps at their highest points.

ROV observations reveal that the submerged scarps are generally better preserved than subaerial scarps, probably due to a lack of slope wash and mass wasting of scarps in the lacustrine environment. Debris slopes, colluvial wedges, and wash slopes (Fig. S4B [footnote 1]), which are common
to subaerial scarps (McCalpin and Nishenko, 1996; McCalpin, 2009; Wallace, 1977), are not developed on most of the submerged scarps and very poorly developed on others. Talus has accumulated locally near the bases of some high bedrock scarps (Fig. 11), probably a result of freeze-thaw frost wedging along episodically exposed upper parts of the scarps.

### TABLE 2. DIVES WITH REMOTELY OPERATED VEHICLE TO INVESTIGATE FAULTS IN EMERALD BAY

<table>
<thead>
<tr>
<th>Objective</th>
<th>Date</th>
<th>Dive number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mount Tallac fault (3 dives)</td>
<td>7 September 2011</td>
<td>2011-H</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2011-I</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2011-J</td>
</tr>
<tr>
<td>Stony Ridge fault (18 dives)</td>
<td>27 May 2011</td>
<td>2011-1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2011-2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2011-3</td>
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<tr>
<td></td>
<td>6 September 2011</td>
<td>2011-B</td>
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<td></td>
<td>18 May 2012</td>
<td>2012-E-2</td>
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<td></td>
<td>13 September 2012</td>
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<td></td>
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<td>2013-3-2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2013-3-3</td>
</tr>
<tr>
<td>Southeast ridge (2 dives)</td>
<td>11 September 2011</td>
<td>2011-K</td>
</tr>
<tr>
<td></td>
<td>13 September 2012</td>
<td>2012-4A</td>
</tr>
<tr>
<td>West Tahoe fault (2 dives)</td>
<td>14 May 2014</td>
<td>2014-1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2014-2</td>
</tr>
</tbody>
</table>

### ROV Dives and Scarp Profiles along a Submerged Branch of the Mount Tallac Fault (MTF)

Two ROV dives and a bathymetric profile revealed a probable scarp at the eastern edge of the Eagle Creek delta (Figs. 8, 11, and 12A). Along dive 2011-H, the flat, sandy bottom of the shelf, at 22–25 m (73–82 ft) depth, rises gradually westward to 15 m (50 ft) depth. Between 15–10 m (50–33 ft) depth, a possible scarp is in loose sand. Profile 1 (Figs. 8, 11, and 12A) was constructed across the submerged scarp ~75 m (248 ft) south of dive 2011-H, where the scarp height reaches a maximum. The scarp face has a maximum slope angle of 27°, a remarkably steep face in loose sand, much steeper than typical delta fronts (which rarely exceed 5°–6°; Patruno et al., 2015), suggesting the scarp is a youthful feature. A rough estimate of maximum scarp height from the profile, which includes the (unknown) height of the delta front is ~17 m (~56 ft; discussed later). This youthful, submerged scarp at the edge of the Eagle Creek delta aligns with the eastern branch of the MTF to north and south (Figs. 6 and 8). Dive observations and profile 1 suggest that significant postglacial, even Holocene, normal displacement has occurred on the eastern branch of the MTF.

### ROV Dives and Scarp Profiles along Submerged Parts of the Stony Ridge Fault (SRF)

The granodiorite bedrock high marked by Fannette Island resembles a classic roche moutonnée (Easterbrook, 1999), with a relatively gentle up-canyon slope and a very steep, down-canyon slope. Howle et al. (2012) indicated that the steep slope facing down canyon also has a tectonic origin, however, because they interpreted two prominent sets of scarps around Fannette Island as fault scarps along the SRF. Maloney et al. (2013; like Howle et al., 2012) depicted a short fault segment along the east side of Fannette Island on their maps but referred to it as part of the “West Tahoe–Dollar Point fault” (a designation with which we disagree, as discussed below). The scarps were examined in this study to determine whether they are related to faults.

#### Eastern (main) scarps.

The eastern scarps, the more prominent of the scarps, were imaged in four ROV dives (Fig. 11), including, from north to south, 2011 dive E, 2012 dive 2A, 2013 dive 5, and 2011 dive A (Fig. 11; Table 2). Bathymetric profiles 4–6 were constructed across this scarp (Figs. 12D–12F).

The eastern scarp (Fig. 11) is ~200 m (660 ft) in length and extends well beyond the limits of granodiorite bedrock; it dies out ~100 m (330 ft) north and 50 m (165 ft) southeast of the island. The central part of the scarp is dominated by a steep, east-facing, wall of granodiorite (see photos in Figs. S6A and S6B) that extends from ~64 m (210 ft) depth up to lake level and continues nearly 30 m (66 ft) above lake level. Glacial polish on the granodiorite surface was observed at 24 m (80 ft) depth in one dive, indicating that Tioga glaciers covered parts of the scarp. The nearly horizontal surface in the hanging wall of the eastern scarp is underlain by mud at depths of ~53–64 m (175–213 ft; Fig. 11). This deposit extends directly to the base of the nearly vertical wall of granodiorite, with...
Figure 10. Shaded relief map of Emerald Bay utilizing light detection and ranging (LiDAR) and echosounder data, with water removed, showing areas covered by 2011–2014 remotely operated vehicle (ROV) dive tracks and outlines of geologic maps in Figures 11 and 14. Areas mapped with ROV are in yellow. Green, dotted lines marked M and D are approximate locations of seismic-reflection profiles (Dingler et al., 2009; Maloney et al., 2013). Core site EB2 (Dingler et al., 2009) is approximately located by white X.
Figure 11. Geologic map (plotted on multibeam-echosounder image) of floor of Emerald Bay near Fannette Island. Bathymetric profile 1 (60 m [200 ft] south of the south edge of this map) is shown in Figure 8A. Abbreviations: MTF—Mount Tallac fault; ROV—remotely operated vehicle; SRF—Stony Ridge fault; HWM—high-water mark.
Profile 1 across MTF eastern branch, showing scarp at edge of Eagle Creek delta (see Figs. 8, 11)

![Figure 12. Bathymetric profiles across eastern branch of Mount TPLac fault (MTF) and branches of Stony Ridge fault (SRF). Profiles extracted from multibeam-echosounder data (see Figs. 8A and 11 for locations). V (vertical) and H (horizontal) scales are in feet; VE—vertical exaggeration; grd—granodiorite. For profiles 2–6, fault is projected to toe of scarp, as discussed in Figures S4C and S4D [text footnote 1]. Vertical red lines delineate scarp height (SH) and vertical separation (VS). In profiles 1, 2, and 5, surface slopes are approximately parallel, and, therefore, the VS estimate is independent of position of fault. Conversely, because surface slopes are non-parallel in profiles 3, 4, and 6, VS estimate depends upon correct location of fault. (A) Profile 1 across Mount TPLac fault (MTF) eastern branch. Part of profile marked by thin, black dashed line is a data gap where surface has been extrapolated. See text for discussion. (B) Profile 2 across western branch of SRF north of Fannette Island. (C) Profile 3 across western branch of SRF on south side of Fannette Island. (Continued on following two pages.)](https://pubs.geoscienceworld.org/gsa/geosphere/article-pdf/15/3/783/4708655/783.pdf)
Figure 12 (continued). (D) Profile 4 across eastern branch of SRF near northeast tip of Fannette Island. (E) Profile 5 across eastern branch of SRF near east end of Fannette Island. (F) Profile 6 across eastern branch of SRF near southeastern side of Fannette Island. (Continued on following page.)
Figure 12 (continued). (G) Profile 7 across eastern branch of SRF southeast of Fannette Island.

Figure 13. Line drawing of seismic-reflection profile in figure 10 of Maloney et al. (2013), as reinterpreted here; see Figures 10 and 11 for approximate location. Vertical exaggeration (VE) reportedly ~20:1. TWTT—two-way travel time in seconds; sound velocity assumed to be 1450 m/s for both water and sediments (see document in Supplemental Material [text footnote 1] for discussion). "Data omitted" refers to parts of profile in which Maloney et al. (2013) omitted data from their figure 10; the entire profile is shown in figure 15 of Dingler et al. (2009). Various reflectors are shown with yellow, orange, green, blue, and white lines. Yellow reflector, interpreted as Tsoyowata ash (7930–7790 cal. yr B.P.; Bacon, 1983; Sarna-Wojcicki et al., 1991), terminates abruptly at the Stony Ridge fault, suggesting some displacement postdates this horizon. Geometry of reflectors near the RPF may suggest west-side-down displacement along a west-dipping fault, but this is an artifact of great vertical exaggeration. Bathymetry images (Figs. S5A, S5B [see text footnote 1]) do not support such a fault. The orange reflector may mark a 5.0–5.4 ka horizon (Maloney et al., 2013). The black line separates sediment with multiple reflectors above from material lacking reflective layering below. See text for discussion.
no evidence of a colluvial wedge; however, in some places, loose granitic boulders dislodged from the cliff above rest upon mud.

Near the eastern tip of Fannette Island (Fig. 11), the main scarp splits into two, with a high-standing bedrock scarp striking S40°W (220° AZ; past points 2011-A-8 and A-10) and a less prominent bedrock scarp continuing due south; the south-trending scarp face consists of granodiorite and, then, a few tens of meters farther south, of bouldery till.

In some places, lower parts of the main bedrock scarp are mantled with postglacial, bouldery talus (Fig. S6C [footnote 1])—some with angular boulders up to 1.5 m (5 ft) in diameter. Over-steepened slopes have developed in the talus at the base of the scarp, suggesting that the most recent fault displacement postdates accumulation of the talus.

At sites 2011 A-5, A-8, and A-10 at the bases of both scarps, slabs of dark, reddish, iron-oxide–cemented breccia lie within mud (Fig. S6D [footnote 1]). These rocks lack foliation and are interpreted to be spilled-off slabs of crush breccia formed by frictional slip along the fault (see Sibson, 1977). In dive 2012-2A along the main escarpment (Fig. 11), a similar breccia was observed as a steeply dipping veneer on the steep granodioritic face at a depth of ~45 m (~150 ft).

At its northern tip (site 2011-E-3), the main scarp is developed entirely in talus shed from the north edge of the island, some with angular boulders up to 1.8 m (6 ft) across. Again, an over-steepened slope in talus indicates that the talus has been displaced by the most recent rupture along the fault. In profile 4 (Fig. 12D) a few meters south of this site, the scarp face in talus has a slope angle near 60°, and the scarp has a vertical separation of ~5.5 m (18 ft). One hundred meters (330 ft) south of profile 4, the same scarp has vertical separations of 4.5–5 m (15–16 ft) (profiles 5 and 6; Figs. 12E and 12F).

About 100 m (330 ft) southeast of Fannette Island, beneath the south channel, a probable monoclinal (fault-propagation) fold developed in unconsolidated sediments along the SRF (Howle et al., 2012). Water depths range from ~70 m (231 ft) in the hanging wall to ~30 m (100 ft) in the footwall, with a scarp-like slope ~30–40 m (100–132 ft) in height. Several ROV dives traversed this slope in mid-channel southeast of Fannette Island, where the hanging wall at ~61–64 m (200–210 ft) depth consists of flat-lying muddy sediment. The entire slope (profile 7, near the southern edge of Fig. 11; Figs. 12G and S5 [footnote 1]) is smooth and draped with muddy sediment indistinguishable from that of the hanging wall. The mud is covered with algal masses, is water-rich, lacks strength, and is easily disturbed by propellers on the ROV. Abrupt steps or slope breaks were not observed in the slope. Either the muddy deposits have been draped across a preexisting fault, or the muds have been warped during displacement, as proposed by Howle et al. (2012).

The eastern scarps are indeed fault scarps developed along the eastern branch of the SRF. This is borne out by the facts that the scarps extend north and south well beyond the limits of the bedrock, align with mapped branches of the SRF in the moraines, and sediment in the hanging wall adjacent to the scarp consists of muddy sediment rather than glacial till. In a few places, postglacial, bouldery talus from Fannette Island stands in sharp relief against muddy deposits of the hanging wall (Fig. S6C [footnote 1]), arguing for youthful (postglacial, e.g., post–14 ka) displacement along the scarps. The escarpment formed largely by displacement along the SRF; however, as indicated by the presence of crush breccia along its lower parts. Higher parts of the escarpment comprise a sheen wall of granodiorite, parts of which are glacially polished. The presence of youthful scarps both north and south of the gently sloping escarpment in the mid-channel (Figs. 8A and 11) supports the conclusion that the slope is indeed an expression of a fault-propagation fold.

A published seismic-reflection profile (Maloney et al., 2013; Fig. 13), in addition to depicting a depocenter in the hanging wall of the SRF also appears to show that the inferred Tsuyowata ash horizon has been displaced. If so, post-ca. 7.7 ka (and pre–5.0 ka) displacement has occurred on this branch of the SRF.

**Western scarps projecting through Fannette Island.** Prominent scarps both north and south of Fannette Island (Fig. 11), ~120 m (400 ft), west of the main scarps, are described briefly below.

**South side of island.** A submerged granodioritic promontory projects south-eastward from the western part of Fannette Island (Fig. 11). Its eastern margin is a prominent fault-related scarp ~11.5 m (>39 ft) in height (profile 3, Fig. 12C). The hanging wall of this scarp is a gently sloping, nearly flat surface at 30 m (100 ft) depth, underlain by sand. The lower part of the scarp face exposes bouldery talus resting in places upon till. Locally, the talus forms an over-steepened slope and appears to have been displaced during a youthful slip event.

**North side of island.** A steep, east-facing escarpment (Fig. 11) lies beneath the north channel on the north side of Fannette Island. This scarp, which is underlain by granodiorite, has a height of 15.5 m (51 ft) and a VS of 11 m (36 ft) (profile 2, Fig. 12B). The lower part of the scarp face is a steep, bouldery talus slope (with a slope angle up to 35°). As on the scarp to the south, the steep, sloping surface of the talus in places suggests that the deposit has been cut or deformed by displacement on the fault.

On Fannette Island, exposed granodiorite is intensely fractured but lacks any obvious topographic expression of a west-dipping normal fault. This observation suggests that any pre-glacial bedrock scarp on the upstream side of the roche moutonnée surface may have been eroded smooth by Tahoe and Tioga glaciers, and that post-Tioga displacements are not detectable in the fractured granodiorite.

As with the eastern (main) set of scarps, the submerged scarps projecting through the western part of Fannette Island clearly represent fault scarps both because they cut talus deposits and because they align with prominent scarps developed in moraines along the western branch of the SRF (see Figs. 6A, 8A, and 11).

**ROV Dives and Profiles on Submerged Scarps along the Rubicon Peak Fault (RPF)**

The large, post-Qti-2 landslide near the north shore of Emerald Bay (mentioned earlier; Fig. 14) has two sets of submerged, north-trending, east-facing, scarp-like features developed in glacial till that was displaced from the left-lateral Qti-2 moraine. These scarps have been examined with the ROV to...
Figure 14. Geologic map (plotted on multibeam-echosounder image) of fault scarps along branches of Rubicon Peak fault (RPF), developed in large landslide in north part of Emerald Bay. HWM—high-water mark. Figures S7A–S7D are in the Supplemental Material (see text footnote 1).
determine whether they are fault-related topographic features (Howle et al., 2012) or are related to landslide lobes.

The western set of east-facing scarps (Fig. 14) begins ~20 m (66 ft) south-east of the pier at the boaters’ campground continues, southward within the central part of the landslide, and includes three southwest-trending splays near its southern end. About 125 m (412 ft) east of the western scarps, the eastern scarps, which are near the eastern exposed limits of the landslide, include three discontinuous, arcuate, east-facing segments. Both sets of scarps continue to the southern exposed limit of the landslide but cannot be traced into deeper water, suggesting that the scarps predate the late Holocene muds of the central basin.

**ROV dives and profiles on the western set of scarps.** The scarps are abrupt, east-facing walls of bouldery till, typically 3 m (10 ft) or more in height (see photos in Figs. S7A and S7B [footnote 1]). The hanging wall east of the scarps is a smooth, flat, sandy surface, with a gentle slope to the east and south, developed upon the landslide. Westward, beyond the top of the scarp, the bottom (footwall), which is the surface of the landslide, is again level, smooth, and mantled by sand.

Bathymetric profiles indicate that all of the scarps have typical fault geometry, with flat, smooth surfaces on the hanging walls and footwalls and abrupt, steep scarp faces. Scarp profiles 8 and 9 (Figs. 14, 15A, and 15B) reveal scarp faces with maximum slopes of 18° to 39° and vertical separations (VS) of 3.5 m (11 ft) and 2.5 m (8 ft). The scarps near the southern edge of the exposed landslide are less prominent (Figs. 15C and 15D).

**ROV dives and profiles on the eastern set of scarps.** The scarp faces are held up by abrupt, steep walls of granodioritic boulders varying from ~0.5–2.5 m (1.6–8 ft) in diameter (Figs. S7C and S7D [footnote 1]) in glacial till displaced onto the floor of the bay by the large landslide in Figure 14. In places, loose boulders have tumbled down from the scarp face and rest upon sand at the base of the scarp. A possible bevel at the top of one scarp (Fig. S7D) suggests that more than a single slip event may have produced the scarp. A flat, smooth, sandy bottom east of the arcuate scarps (e.g., in the hanging wall) slopes gradually to the east and south. The footwall west of the scarp is a flat, smooth surface underlain by sand. In bathymetric profiles (Figs. 15E–15G), these scarps, like the western scarps, all have geometry typical of fault scarps, with flat surfaces on hanging walls and footwalls and with abrupt, steep scarp faces (maximum slope angles of scarp faces range from ~21° to 32°). The arcuate scarp segments have vertical separations of 2 m (7 ft), 4 m (13 ft), and 6.5 m (21 ft), increasing in magnitude from north to south.

**Interpretation of the scarps in the large landslide.** The ROV data and bathymetric profiles support the conclusion that these submerged scarps are fault scarps. The surface of the landslide, which is mantled by sand, is relatively flat and smooth, with no evidence for lobes within the landslide. The submerged scarps also correlate favorably with mapped scarps and faults along the RPF within moraines to the north, and to a feature in a profile of Maloney et al. (2013; Fig. 13) interpreted here as a buried branch of the RPF. Because the scarps developed in the large landslide derived from the left-lateral Qti-2 moraine (Howle et al., 2012), the scarps postdate at least part of the deglaciation (e.g., they are post–21 ka and possibly post–14 ka). Furthermore, the facts that scarp faces are steep, no colluvium mantles their lower parts, and postglacial sand mantles both hanging walls and footwalls but not the scarp faces themselves also attest to youthful, postglacial displacement.

**ROV Dives and Profiles across the Southeast Ridge**

A bathymetric feature in the east-central part of Emerald Bay and here referred to as the “southeast ridge” (see Figs. 6A, 8A, and 10) was interpreted as a north-facing fault scarp by Howle et al. (2012). The ridge is linear, ~0.2 km (660 ft) in length, and trends west-northwest, perpendicular to Qti recessional moraines along the right-lateral moraine complex (Fig. 8A). ROV observations support the interpretation of Howle et al. (2012), because bouldery Qti till is exposed along the scarp face. Several unusual features of this scarp include its short, exposed length, its linearity, and the fact that it strikes at a high angle to the RPF. It also shows a gently south-tilted footwall slope. LiDAR images suggest that a continuation of this fault to the southeast may disrupt and offset crests of Qti-2 recessional moraines (Fig. 8A; discussed earlier); conceivably, the south-east ridge could be a link between the RPF and the southern part of the WTF.

**Profiles and ROV Dives along Scarp Possibly Related to the West Tahoe Fault (WTF)**

The bedrock escarpment along the West Tahoe fault (WTF) near Emerald Point lacks bathymetric expression within Emerald Bay. However, Howle et al. (2012) mapped a short, ~140–(480-ft)-long, submerged, northwest-striking scarp (shown in Figs. 8A and 9) on the flat bottom of the bay ~0.8 km (0.5 mi) northeast of the submerged landslide discussed above, as part of the WTF. Our observations support that conclusion. In plan view, the scarp is slightly arcuate, with at least two subtle steps. ROV dives (2014 dives 1 and 2) revealed that this scarp has a northeast face (scarp face) exposing fresh Qti till, with prominent granodiorite boulders, and a gently sloping southwestern flank. Smooth, postglacial sand mantles both the footwall and hanging wall. Profile 17 (Figs. 8A and 15J) shows a vertical separation of only ~1 m (3 ft) and a scarp-face slope angle of 20°. A few tens of meters north of the profile, the scarp height is 2 m (7 ft). Development of this scarp postdated Qti-2 (post–21 ka), but it is unknown if it postdated complete deglaciation at 14 ka. Along strike ~200 m (660 ft) south-east of the scarp, a kink along the crest of an onshore Qti recessional moraine (see Fig. 9) may represent deformation related to displacement on the WTF.

**Summary of ROV Dives and Detailed Maps**

ROV dives, together with echosounder bathymetry, confirm the fault mapping and conclusions of Howle et al. (2012) and in particular the continuation of active branches of the MTF, SRF, RPF, and WTF beneath the floor of Emerald
Figure 15. Bathymetric profiles extracted from multibeam-echosounder data across scarps along Rubicon Peak fault (RPF), southeast ridge, and West Tahoe fault (WTF; see Figs. 8A and 14 for locations of profiles). In all profiles, fault surface is projected toward toe of scarp (see Figs. S4C and S4D [text footnote 1]). V (vertical) and H (horizontal) scales all in feet. For profiles 8, 9, 11, 13, and 14, hanging-wall and footwall slopes are non-parallel; estimates of vertical separation (VS) depend on correct position of fault. (A) Profile 8 across western branch of RPF near central part of scarp. (B) Profile 9 across western branch of RPF. (C) Profile 10 across western branch of RPF near south end of scarp. SH—scarp height. VE—vertical exaggeration. (Continued on following three pages.)
Figure 15 (continued). (D) Profile 11 across small scarps west of RPF western branch (see Fig. 14). (E) Profile 12 across eastern branch of RPF, along northern scarp. (F) Profile 13 across eastern branch of RPF, along central scarp. (Continued on following two pages.)
Figure 15 (continued). (G) Profile 14 across eastern branch of RPF, along southern scarp. (H) Profile 15 across western end of southeast ridge. (I) Profile 16 across central part of southeast ridge. (Continued on following page.)
Bay (Fig. 16). Youthful scarps exist along all the faults, and crush breccia is preserved along the SRF.

**Comparison of Results with Seismic-Reflection Profiles in Emerald Bay**

As noted previously, some authors have stated that active faults do not exist within Emerald Bay (Dingler et al., 2009; Kent et al., 2006), based upon unfaulted, horizontal layering in seismic-reflection profiles. Although precise locations and scales for the profiles were not provided, enlargements of the seismic profiles have been compared with new bathymetric images and the locations of scarps described above.

The seismic-reflection profile sketched in Figure 13 (from Maloney et al., 2013), as noted earlier, appears to image the eastern branch of the SRF and possibly contains evidence for post-Tsoyowata displacement. This profile also appears to intersect a branch of the RPF and depicts a wedge-shaped deposit in the hanging wall of the fault. Other seismic profiles of Dingler et al. (2009) and Kent et al. (2006) image the large postglacial landslide cut by the RPF discussed above (Fig. 14) as an amorphous mass with no internal reflections. The lack of a well-layered succession in the landslide makes recognition of faults problematic, because in seismic-reflection profiles, the existence of steeply dipping faults is usually inferred from offsets of planar layering (Alcalde et al., 2017; McCalpin, 2009; Yeats et al., 1996). Subtle bathymetric steps in the top surface of the landslide are evident in the seismic profiles, however, and these most likely are the scarps shown in Figure 14. Prominent, unfaulted, horizontal layering in other parts of the seismic profiles consists dominantly of sediment younger than ca. 8 ka (Maloney et al., 2013). From this comparison, the seismic-reflection profiles appear to be compatible with the existence of the scarps and faults described by Howle et al. (2012) and this study.

**Estimates of Slip Rates**

Heights of scarps and vertical separations have been estimated in many places in this study. Most scarps in the glacial moraines have been excluded from VS analysis, however, because, in most cases, the hanging wall has been backtilted toward the fault scarp. In such cases, VS cannot be determined precisely (Howle et al., 2012; McCalpin, 2009).

There are many uncertainties in determinations of VS, including correct placement and dip of faults (see discussions in Rood et al., 2011a; Wesnousky et al., 2005; also see Fig. S4 [footnote 1]). In this study, normal faults are assumed to dip an average of ~60°, following many other published works (e.g., Gilbert, 1890, 1928; Howle et al., 2012; Personius et al., 2017; Rood et al., 2011a; Wesnousky et al., 2005); this value is consistent with bedrock scarp faces in Emerald Bay that dip 50°–75°. Howle et al. (2012) used 3D modeling and three-point solutions to obtain a mean of 62 ± 12° for seven measurements of fault dip along the RPF.

The exact point of intersection of a fault surface with a scarp also may affect the VS estimate, especially in cases where hanging-wall and footwall surfaces are not parallel. Many other studies in unconsolidated deposits have assumed that fault surfaces project to midpoints or steepest parts of scarps (Howle et al. 2012; Wesnousky et al., 2005; also see Fig. S4 [footnote 1]).
Figure 16. Oblique view looking northwest across Emerald Bay (water removed) showing major faults of the Tahoe-Sierra frontal fault zone (TSFFZ) and West Tahoe fault (WTF) traversing Emerald Bay and locations discussed here and in Howle et al. (2012). Vertical exaggeration (VE) = 1.4. Distance along the bottom of figure is 2.4 km (1.4 mi). Shoreline of Emerald Bay depicted with thin, black lines. Scarps along Mount Tallac fault (MTF) where it cuts the Emerald Bay right-lateral moraines are a few hundred meters off the figure at far left. VSR—vertical separation rate; RPF—Rubicon Peak fault; SRF—Story Ridge fault; WTDPFZ—West Tahoe–Dollar Point fault zone.
Tahoe fault”). At that site, we mapped three scarps ranging from 1–7 m (3–23 ft) in height. Therefore, fault surfaces are projected in most cases to intersect the profiles near the bases or toes of the scarps (Figs. S4C and S4D [footnote 1]).

Below and in Table 3, for estimation of vertical separation rates (VSR), an age of 21 ka is assumed for Qti-2 moraines, and 14 ka is assumed for the age of final deglaciation.

Approximate vertical separation rates are provided below, using estimated vertical separations and broad age estimates, together with previously published rates. The estimates from this study, which are conservative minimum values, are approximate, owing to uncertainties in age constraints and factors mentioned above. Rates therefore are reported to one significant figure only (e.g., 0.36 mm/yr is reported as 0.4 mm/yr, etc.). Nevertheless, these data provide a basis for comparison with other published data for slip rates within the Lake Tahoe basin and the Walker Lane belt.

Mount Tallac Fault (MTF)

Several strands of the MTF lie within bedrock west of Emerald Bay, but youthful markers have not been identified along these branches, and therefore it is unknown if youthful displacements have occurred. However, latest Quaternary to Holocene displacement likely occurred along the eastern branch of the MTF where it bounds the Holocene delta of Eagle Creek (Figs. 4, 8A, and 11). There, the prominent scarp (Fig. 12A, profile 1) is assumed to be post–14 ka (e.g., postglacial retreat).

Because the height or relief of the unfaulted or unmodified delta and the foreset slope are unknown, VS on this scarp is tentatively approximated as follows (see profile 1, Fig. 12A). The slope break is reconstructed by extending the footwall surface and the scarp face until they intersect. Two 6° sloping lines (defining an upper limit to delta foreset slopes [Patruno et al., 2015]) are constructed from the slope break and base of the scarp. An approximate VS of ~13 m (44 ft) is obtained as the vertical height between the 6° sloping lines. A rough VSR estimate of ~0.9 mm/yr is then obtained. This is three times the VSR of 0.3 ± 0.1 mm/yr (post–23.5 ka) at a youthful scarp along the MTF, ~5 km southeast of Emerald Bay, between Cascade Lake and Fallen Leaf Lake (Fig. 18; Howle et al., 2012). At Emerald Bay, owing to the uncertainties in estimating VS, half of the estimated VSR, 0.45 mm/yr (rounded to 0.5 mm/yr), is taken as a conservative estimate of minimum VSR for the eastern branch of the MTF.

A VSR estimate of 1.4 ± 0.7 mm/yr was reported for the MTF where it forms a very high scarp on the right-lateral Tioga moraine of Cascade Lake (Pierce et al., 2017; Fig. S3 [footnote 1]; those authors considered this scarp to be the “West Tahoe fault”). At that site, we mapped three scarps ranging from 1–7 m (3–23 ft) high in the Qti-2 moraine (Fig. S2; Howle et al., 2012). As discussed in the document in the Supplemental Material, it seems likely that the very high bedrock scarp discussed by Pierce et al. (2017) represents both pre-and post-Tioga displacement.

Eight km (4.8 mi) southeast of Emerald Bay, Howle et al. (2012) concluded that the submerged faults at the head of Fallen Leaf Lake are splays of the MTF. On one of these faults, an estimated “vertical deformation” rate of 0.4–0.7 mm/yr was reported by Brothers et al. (2009; Fig. 18).

Stony Ridge Fault (SRF)

No previous estimate of VSR has been made for the SRF. Some scarps along the submerged eastern branch of the SRF are younger than the 14 ka deglaciation. The vertical separation of 5.5 m (18 ft) at the north end (Figs. 11 and 12D, profile 4) and a limiting age of 14 ka produce a minimum VSR of 0.4 mm/yr along the fault (Table 3). Actual rates may be somewhat higher, because Holocene displacement may have occurred (see discussion above). The morphological similarity of scarps along the submerged western branch of the SRF to those on the eastern branch suggests that both branches have similar VSRs. If so, then the combined, minimum, VSRs from both branches would be ~0.8 mm/yr.

Rubicon Peak Fault (RPF)

For a conservative estimate of VSRs, the submerged scarps are assumed to be younger than 21 ka, the age for Qti-2. On the western branch of the RPF (Figs. 14 and 15A–15C), scarps have VS up to ~3.5 m (11 ft), yielding a 0.16 (0.2) mm/yr (post–21 ka) VSR. On the eastern branch (see Figs. 14 and 15E–15G), submerged scarps have VS of up to 6.5 m (21 ft), yielding a minimum VSR of 0.3 mm/yr (post–21 ka). The estimated VSRs on the submerged scarps combine to give an aggregate minimum VSR of ~0.5 mm/yr (post–21 ka). This result is consistent with the estimate of Howle et al. (2012) where the RPF displaced the left-lateral Qti-1 moraine of Emerald Bay.

Southeast Ridge

Scarp heights along the southeast ridge, a scarp cutting post–Qti-2 till, range from 3.5–5.5 m (11–18 ft; see Figs. 15H and 15I). VS cannot be estimated directly, however, because the footwall has been tilted to the south. A very rough estimate of VS of ~3 m (10 ft) and a maximum limiting age of 21 ka for Qti-2, yield a minimum VSR of 0.1 mm/yr (with large uncertainties).

West Tahoe Fault (WTF)

Estimates of VSR have not previously been reported for the southern part of the WTF. The Qti-2 moraine northwest of Emerald Point (Fig. 7) has at least three scarps with approximate heights ranging from ~2–3.5 m (7–11 ft). The hanging wall is backtilted, however, and no estimate of VSR is made there. The...
### TABLE 3. SUMMARY OF VERTICAL SEPARATION AND EXTENSION RATES

A. SUMMARY OF ESTIMATES OF VERTICAL SEPARATION RATES ON SUBAERIAL AND SUBMERGED SCARPS ALONG FAULTS AT EMERALD BAY

<table>
<thead>
<tr>
<th>Fault</th>
<th>Branch, profile, figure(s)</th>
<th>Scarp height (SH)</th>
<th>Vertical separation (VS)</th>
<th>Limiting age (ka)</th>
<th>Vertical separation rate (VSR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mount Tallac fault (MTF)</td>
<td>Eastern branch at delta</td>
<td>~13 m (44 ft)</td>
<td>14</td>
<td>*0.9 mm/yr</td>
<td>0.5 mm/yr</td>
</tr>
<tr>
<td></td>
<td>(profile 1, Figs. 8, 11, 12A)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unnamed fault</td>
<td>Near Inspiration Point (Fig. 8)</td>
<td>10 m (33 ft)</td>
<td>--</td>
<td>21</td>
<td>*N.A.</td>
</tr>
<tr>
<td>Stony Ridge fault (SRF)</td>
<td>Western branch</td>
<td>15.5 m (51 ft)</td>
<td>11 m (36 ft)</td>
<td>*N.A.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>north of Fannette Island</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(profile 2, Figs. 11 and 12B)</td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>Western branch</td>
<td>11.5 m (39 ft)</td>
<td>*N.A.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>south of Fannette Island</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td></td>
<td>(profile 3, Figs. 11 and 12C)</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Eastern branch</td>
<td>5.5 m (18 ft)</td>
<td>14</td>
<td>0.4 mm/yr</td>
<td></td>
</tr>
<tr>
<td></td>
<td>NE end of Fannette Island</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>(profile 4, Figs. 11 and 12D)</td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>Eastern branch</td>
<td>5 m (16.5 ft)</td>
<td>14</td>
<td>0.2 mm/yr</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SE of Fannette Island</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>(profile 5, Figs. 11 and 12E)</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Eastern branch</td>
<td>4.5 m (15 ft)</td>
<td>14</td>
<td>0.2 mm/yr</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SE of Fannette Island</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(profile 6, Figs. 11 and 12F)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rubicon Peak fault (RPF)</td>
<td>Western branch</td>
<td>3.5 m (11 ft)</td>
<td>21</td>
<td>0.2 mm/yr</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(profile 8, Figs. 14 and 15A)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Western branch</td>
<td>2.5 m (8 ft)</td>
<td>21</td>
<td>0.1 mm/yr</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(profile 9, Figs. 14 and 15B)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Western branch</td>
<td>1 m (3 ft)</td>
<td>21</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(profile 10, Figs. 14 and 15C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Western branch</td>
<td>1.5 m (5 ft)</td>
<td>21</td>
<td>&lt;0.1 mm/yr</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(profile 11, Figs. 14 and 15D)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(profile 16, Figs. 14 and 15D)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Eastern branch</td>
<td>2 m (7 ft)</td>
<td>21</td>
<td>&lt;0.1 mm/yr</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(profile 12, Figs. 14 and 15E)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Eastern branch</td>
<td>4 m (13 ft)</td>
<td>21</td>
<td>0.2 mm/yr</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(profile 13, Figs. 14 and 15F)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Eastern branch</td>
<td>6.5 m (21 ft)</td>
<td>21</td>
<td>0.3 mm/yr</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(profile 14, Figs. 14 and 15G)</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

(continued)
### TABLE 3. SUMMARY OF VERTICAL SEPARATION AND EXTENSION RATES (continued)

#### A. SUMMARY OF ESTIMATES OF VERTICAL SEPARATION RATES ON SUBAERIAL AND SUBMERGED SCARPS ALONG FAULTS AT EMERALD BAY

<table>
<thead>
<tr>
<th>Fault</th>
<th>Branch, profile, figure(s)</th>
<th>Scarp height (SH)</th>
<th>Vertical separation (VS)</th>
<th>Limiting age (ka)</th>
<th>Vertical separation rate (VSR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southeast ridge</td>
<td>West end (profile 15, Figs. 8 and 15H)</td>
<td>3.5 m (11 ft)</td>
<td>21</td>
<td></td>
<td>0.1 mm/yr*</td>
</tr>
<tr>
<td></td>
<td>Central part (profile 16, Figs. 14 and 15-I)</td>
<td>5.5 m (18 ft)</td>
<td>~3 m (10 ft)</td>
<td>21</td>
<td></td>
</tr>
<tr>
<td>West Tahoe fault (WTF)†</td>
<td>(profile 17, Figs. 8 and 15-J)</td>
<td>1 m (3 ft)</td>
<td>21</td>
<td>&lt;0.1 mm/yr</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Central part (direct measurement, Figs. 9 and 10)</td>
<td>1.5 m (5 ft)</td>
<td>21</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### B. SUMMARY OF ESTIMATES OF EXTENSION RATES††

<table>
<thead>
<tr>
<th>Transect</th>
<th>Total VSR estimate (mm/yr)</th>
<th>Tan dip</th>
<th>Total extension rate (EXR) estimate (mm/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tahoe-Sierra frontal fault zone (TSFFZ)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Northern transect 050° AZ (General and Meeks Creeks; Howle et al., 2012; this report); Figure 18</td>
<td>1.5</td>
<td>1.732</td>
<td>1</td>
</tr>
<tr>
<td>West Tahoe fault (WTF)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Northern transect 090° AZ (this report); Figure 18</td>
<td>0.4</td>
<td>1.732</td>
<td>0.2</td>
</tr>
<tr>
<td>TSFFZ</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Southern transect 050° AZ (Emerald Bay; this report); Figure 18</td>
<td>2.1</td>
<td>1.732</td>
<td>1.2</td>
</tr>
<tr>
<td>West Tahoe fault (WTF)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Southern transect (Emerald Bay; this report); Figure 18</td>
<td>0.2</td>
<td>1.732</td>
<td>&lt;0.1</td>
</tr>
</tbody>
</table>

*Not considered reliable.
†At Emerald Point, we estimate a VSR of 0.2 mm/yr from two small scarps on land. See text.
**Extension rate perpendicular to faults (~050° azimuth, Fig. 18, inset) estimated as follows (after Koehler and Wesnousky, 2011; Personius et al., 2017): the highest VSR estimates for MTF (0.5 mm/yr), SRF (0.8 mm/yr), southeast ridge (0.1 mm/yr), RPF (0.5 mm/yr), and WTF (0.2 mm/yr) are summed, and the total (2.1 mm/yr) is divided by tan dip (estimated as 60°) (as below); for southern transect, total VSR/1.732 = 1.2 mm/yr minimum extension rate for TSFFZ. Using total VSR may slightly underestimate extension rate because VS slightly underestimates VD (vertical displacement) in some cases (Fig. S4 in the Supplemental Material [see text footnote 1]).
For northern transect, minimum extension rate on TSFFZ = 1.0 mm/yr. For WTF in northern transect, E-W extension rate is estimated as follows: Maximum VSR estimate (0.4 mm/yr) is divided by tan dip (estimated as 60°); extension rate for WTF = 0.4/1.732 = 0.2 mm/yr.
All extension results are sensitive to fault dip; for example, for average dips of 50° to 70°, extension rate of 1.2 mm/yr above could vary from 1.8 mm/yr to 0.8 mm/yr.
youngest Qti-2 recessional moraine (Fig. 7) has been cut by two scarps, ~2 m and 1.5 m (7 ft and 5 ft) in height (because the crests are approximately horizontal, SH there approximates VS). Using a limiting age of 21 ka and a combined VS of 3.5 m, a minimum VSR of 0.2 mm/yr is obtained for the WTF at Emerald Point. The post–21 ka submerged scarp along the WTF, with a VS of ~1 m (3 ft) from profile 17 (Fig. 15J), yields an approximate minimum VSR of <0.1 mm/yr.

For the WTF, ~12 km (7 mi) north of Emerald Bay near Sugar Pine Point, a “vertical deformation rate” of 0.43–0.81 mm/yr has been reported (location shown in Fig. 18; Brothers et al., 2009; Dingler et al., 2009). If the fault surface is projected toward the midpoint of the scarp (Fig. 17), an improved estimate of VS is ~8 m (26 ft). This fan surface, its associated canyon, and incised channels formed by backflow during and after a major tsunami (Moore et al., 2014), which gives limiting ages of 21–12 ka. These data (~8 m VS in 21 ka) yield an improved estimate of minimum VSR of ~0.38 (rounded to 0.4) mm/yr for the WTF at this site.

**Rates for TSFFZ versus WTF and GPS Geodesy**

At Emerald Bay, each major fault in the TSFFZ has a VSR greater than the WTF. Taken together, the various segments of the TSFFZ have an estimated combined vertical separation rate up to three times greater than that for the WTF. Available data also suggest that VSRs for both the RPF and the WTF decrease southward; this is consistent with the fact that these two fault zones die out as mappable scarps a few kilometers southeast of Emerald Bay.

Minimum extension rates along two transects of the TSFFZ, one near Meeks Bay and the other at Emerald Bay, calculated from VSR data (Table 3) are comparable, ~1.1–1.2 mm/yr, in a direction N50–55°E (050–055° AZ; Fig. 18, inset). How do these estimates based upon geologic data compare to modern GPS results?

Modern strain rates across the Lake Tahoe basin based on GPS geodesy are ~0.8–1.1 mm/yr in a direction S45°E (145° AZ) (Hammond et al., 2011; Wesnousky et al., 2012). Notably, the extension directions for the two geological transects are at right angles to strain directions calculated from geodesy. Wesnousky et al. (2012) noted that the GPS data provide evidence for ongoing dextral displacement between the Sierra Nevada microplate and ranges to the east of the Lake Tahoe basin, despite the fact that there is little direct evidence for strike-slip displacements in the region. They also observed that directions and magnitudes of fault slip from geologic data do not agree with GPS results, a conclusion supported by results here.
Figure 18. Tectonic map of west half of Lake Tahoe basin with estimates of vertical separation rates (VSRs) and extension rates and directions (white boxes) for two transects across the Tahoe-Sierra frontal fault zone (TSFFZ) and West Tahoe-Dollar Point fault zone (WTDPFZ); northern transect at General and Meeks Creeks utilizes results of Howle et al. (2012), and southern transect at Emerald Bay uses data reported here (methods used for these estimates are summarized in Table 3B [footnote]). Abbreviations: EBLL—Emerald Bay left-lateral moraine; EXR—extension rate; GMCM—General and Meeks Creek medial moraines; MCRL—Meeks Creek right-lateral moraines; RPF— Rubicon Peak fault; SER—southeast ridge in Emerald Bay; SRF—Stony Ridge fault; VSR—estimated vertical separation rate; WTF—West Tahoe fault; other abbreviations as in Figure 2. Inset: Comparison between extension rates for TSFFZ and WTF from Howle et al. (2012) and this study (N and S transects, red arrows) and GPS strain rate estimated for Lake Tahoe basin (blue arrow; Wesnousky et al., 2012).

Summary of extension rates & directions

- WTF 0.4 mm/yr VSR-D,B2009 (revised)*
- GMCM 1.5 mm/yr VSR-H2012
- MCRL 0.8-0.9 mm/yr VSR-H2012
- EBLL RPF 0.5 mm/yr VSR-H2012
- EBLL WTF 0.2 mm/yr VSR-this study
- EB WTF <0.1 mm/yr VSR-this study
- EB RPF 0.5 mm/yr VSR-this study
- EB SRF 0.8 mm/yr VSR-this study
- EB SER 0.1 mm/yr VSR-this study
- EB MTF ~0.5 mm/yr VSR-this study
- Tallac Creek MTF 0.3 mm/yr VSR-H2012

- Sites along TSFFZ
- Sites along WTDPFZ (WTF)

Sources of data:
This study
B2009—Brothers et al., 2009
D2009—Dingler et al., 2009
H2012—Howle et al., 2012
W2012—Wesnousky et al., 2012
DISCUSSION

New observations demonstrate that the TSFFZ continues through the Emerald Bay area, is active, and owing to its large displacement, the fault zone represents the active structural boundary of the Sierra Nevada microplate in the region around the Lake Tahoe basin. These new results contradict statements and conclusions of several previous studies (e.g., Brothers et al., 2009; Dingler et al., 2009; Kent et al., 2006, 2016; Maloney et al., 2013; Schmauder, 2013; and Smith et al., 2013) that discounted the existence or importance of the TSFFZ.

As noted by many previous studies, the TSFFZ includes geologic features typical of major range-bounding normal fault systems throughout the Basin and Range Province. Such features include large topographic relief along the eastern front of the Sierra Nevada, high-standing bedrock facets, topographic control of east-flowing glacial valleys, and glacial moraines at the mouths of bedrock glacial valleys. The authors of the papers cited above were unaware of or disregarded the work of Howle et al. (2012), who made a compelling case for activity along the TSFFZ.

The TSFFZ, which has set the kinematic boundary conditions for transtension in the Lake Tahoe region, has had a long and complex history, as described briefly in an introductory section. Kinematic changes may have occurred at various times along this fault zone and may have led to some of the structural complexity. As interpreted above, during the Pleistocene, after large normal displacements had formed a high, northeast-facing escarpment, minor dextral displacement appears to have occurred along some of the faults. Normal slip then continued during and after the Tahoe glaciation and continues to the present.

The WTDPFZ is clearly younger than the TSFFZ, because 2–2.3 Ma basaltic volcanic rocks and lacustrine sediments are in both hanging-wall and footwall positions on the WTDPFZ (Kortemeier et al., 2018; Schweickert, 2009; Schweickert et al., 2004). Yet both fault systems appear to have been active during late Pleistocene and Holocene times (Howle et al., 2012; this study).

The evolution of these two normal fault systems has important implications for the migration of activity and evolution of range-front fault systems in the Basin and Range Province, supporting the conclusions of Wallace (1984, 1987). Although it is commonly assumed that range-front normal fault systems have a clear progression of activity from the range front toward the adjacent basin along with deactivation of the range-front system, Wallace’s (1984, 1987) work and this study reveal that some range fronts have a much more complex pattern of evolution, with activity both migrating from range front into the basin but also with concurrent activity occurring within both systems.

Within the Basin and Range Province and, in particular, the Walker Lake belt, discrepancies commonly exist between geodetically determined strain rates and slip rates determined from geologic measurements along component range-bounding faults (e.g., Bormann et al., 2016; Gold et al., 2014; Herbert et al., 2013; Lifton et al., 2013; Personius et al., 2017; Wesnousky et al., 2005, 2012). This study, like many previous reports, emphasizes the fact that geodetic strain rates do not necessarily reflect long-term slip rates on discrete faults.

SUMMARY AND CONCLUSIONS

Extensive field mapping, analysis of LiDAR data and multibeam-echosounder bathymetric data, and numerous ROV dives in Emerald Bay have been combined to determine the character, relative age, and offsets along scarps of the three faults (and their branches) of the Tahoe-Sierra frontal fault zone (TSFFZ) and the WTF (southern continuation of the West Tahoe–Dollar Point fault zone [WTDPFZ]). These are the most detailed structural maps to date of glacial moraines and parts of the lake bottom in the entire Lake Tahoe region.

The new data confirm previous reports (e.g., Howle et al., 2012) that several important, northwest-striking, normal faults (Mount Tallac [MTF], Stony Ridge [SRF], and Rubicon Peak [RPF] faults, etc.) do pass beneath Emerald Bay and displace both lake-bottom sediments and glacial moraines. Additionally, the SRF is confirmed as an active fault lying in the footwall of the Rubicon Peak segment of the TSFFZ. The TSFFZ now has the most dense array of VSR data of any part of the microplate boundary. The continuity of the faults mapped by Howle et al. (2012) precludes any direct connections between the WTF and the Mount Tallac fault (MTF). Significantly, both glacial moraines and bottom sediments of Emerald Bay provide excellent records of late Quaternary to Holocene fault displacements.
Submerged scarps, in particular, are exceptionally well preserved. Faults of the TSFZF have a combined VSR of about 2.1 mm/yr. The TSFZF, a complex zone with several en echelon segments, each with numerous subparallel branches, forms the eastern edge of the rigid Sierra Nevada microplate. Geologic relations and patterns of range-front normal faulting indicate that the TSFZF is the older, more long-lived normal fault system. The WTDPFZ is a relatively simple zone with a single main trace.

The fact that both fault zones have been active during late Quaternary to Holocene times has important implications for the migration of activity of range-front fault systems, emphasizing the importance of conclusions of Wallace (1987), who described examples from the Basin and Range Province (BRP) both where fault activity migrated basinward from range fronts and where fault activity has jumped back and forth from range front to the basin and back through time.

Howe et al. (2012) noted that the TSFZF is important both for youthful normal fault displacements and for potential seismogenic earthquake ruptures in the Lake Tahoe basin. The activity of faults within the TSFZF is important for another reason. During normal fault earthquakes, ground motion in hanging walls may be significantly greater than in footwalls (e.g., Anderson et al., 2000; Brune and Anooshehpoor, 1999). Because the head scar of the 10–12.5 km³ McKinney Bay WTDPFZ is a relatively simple zone with a single main trace.

Acknowledgments

Many people contributed to this project. In particular, we gratefully acknowledge James Howe for his assistance in providing detailed LiDAR and sonar images and in preparing numerous scarp profiles for us. We also are grateful to Brant Allen, Tahoe Research Group; Jamie McCaughey, former M.S. student at University of Nevada, Reno (UNR); undergraduate and graduate mechanical engineering students at Santa Clara University; undergraduate students and graduate teaching assistants in UNR-geology field camps in 2003, 2004, 2007, 2008, and 2009; and Brent von Twissten for acquisition of the detailed echosounder map of the floor of Emerald Bay. Financial support for ROV work from Santa Clara University is also gratefully acknowledged. Several anonymous reviewers and Geosphere editors provided comments that materially improved this report.

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