Pleistocene volcanism and shifting shorelines at Lake Tahoe, California

Winifred Kortemeier1, Andrew Calvert2, James G. Moore2, and Richard Schweickert3

1Western Nevada College, 2201 West College Parkway, Carson City, Nevada 89703, USA
2U.S. Geological Survey, 345 Middlefield Road, Menlo Park, California 94025, USA
3Department of Geological Sciences and Engineering, University of Nevada, Reno, 1664 N. Virginia Street, Reno, Nevada 89557, USA

ABSTRACT

In the northwestern Lake Tahoe Basin, Pleistocene basaltic and trachyandesitic lavas form a small volcanic field comprising ~1 km² of lava that erupted from seven vents. Most of these lavas erupted subaerially and produced lava flows. However, where they flowed into an early Lake Tahoe (Proto-Tahoe), they produced deltas consisting of hydrovolcanic breccias as well as pillow lavas draped downslope, pillow breccias, hyaloclastites, and mixtures of lava and wet sediments. Consequently, various former shorelines of Proto-Tahoe are marked by subaerial lava flows overlying subaqueous lava deltas. Isolated explosive interactions produced lapilli tuff cones that built upward from vents on the lake floor or grew as littoral cones where subaerial deltas. Isolated explosive interactions produced lapilli tuff cones that built upward from vents on the lake floor or grew as littoral cones where subaerial lava flows crossed the shoreline. Six new 40Ar/39Ar ages define three Pleistocene episodes when lava erupted subaerially and flowed into Proto-Tahoe. Three cycles of canyon damming by lava and down-cutting occurred at the outlet of Proto-Tahoe in the Truckee River Canyon. The canyon was dammed at 2.3 Ma by basaltic lavas at Rampart, which raised lake level from ~1897 m above sea level to 2048 m. The canyon was again dammed at 2.1 Ma by basaltic lavas at the outlet of Proto-Tahoe near Rampart, which raised lake levels from ~1914 m to 2073 m. And finally, the canyon was again dammed at 0.94 Ma by trachyandesitic lavas at Thunder Cliffs, which raised lake level to 2085 m. Hence, ancient shorelines that are nearly 200 m above the present lake level are documented at 0.94, 2.1, and 2.3 Ma. The present outlet of Lake Tahoe through the Truckee River canyon has been operative for at least 2.3 million years. Even though the three lava dams are now eroded away, the repeated construction (and removal by erosion) of lava dams has diminished the erosion and deepening of the Truckee River Canyon that otherwise would have occurred. Hence, the soft-sediment sill of Lake Tahoe has been protected, which has helped to maintain the great depth of the lake (500 m). The timing of this repetitive volcanic activity raises implications for future volcanic eruptions and their hazards. The lake could be dammed by lava again causing extensive shoreline flooding as its level rose, or rapid dam failure could cause extensive downstream flooding along the Truckee River on its path to Reno.

1. INTRODUCTION

Basaltic and trachyandesitic lavas form a small Pleistocene volcanic field of ~1 km² in the northwestern Lake Tahoe Basin (Fig. 1). Lavas and pyroclastic material erupted from approximately seven vents on both sides of the Truckee River, the lake outlet. In this study, a succession of basalt and trachyandesitic lavas was mapped, sampled, analyzed, and radiometrically dated to characterize the nature of the volcanism. The major part of the volcanic sequences erupted from subaerial vents and covered a considerable area of dry land. Some of the lava flowed into the Truckee River Canyon and dammed the river, resulting in a rise in lake level. Continued flow of lava across this raised shoreline then interacted with lake water. In addition, explosive ejecta from subaqueous vents built cones that emerged above the lake surface.

The interaction of basaltic lava with lake water in the Lake Tahoe Basin at elevations above the current shoreline indicates that the lake level has been higher in the past. Using 40Ar/39Ar age dating to constrain the timing of these ancient shorelines, we have produced a more complete understanding of the early history of the lake.

2. GEOLOGIC SETTING

Lake Tahoe, 34 km x 19 km in size, straddles the California-Nevada boundary, lies between the Carson Range to the east and the Sierra Nevada to the west (Fig. 1), and is considered to occupy the most westerly basin of the Basin and Range Province at this latitude. The lake lies within an asymmetric half-graben underlain by granitic rocks of the Jurassic-Cretaceous Sierra Nevada batholith. This tectonically active area is on the western boundary of the Basin and Range Province of ongoing crustal extension (Schweickert et al., 2000a, 2000b; Dickinson, 2001, 2004, 2006). Additionally, the westernmost part of the Basin and Range Province, including the Lake Tahoe Basin, is considered to be part of the Walker Lane belt (Busby, 2013, and references therein).

Paleozoic to Jurassic metavolcanic and metasedimentary rocks form roof pendants within the Sierra Nevada batholith (Fig. 1) and are the oldest rocks in
the region. Mid- to Late Cretaceous granite and granodiorite underlie most of the Sierra Nevada and Carson Ranges (John et al., 1994). Oligocene to Lower Miocene silicic ash flows erupted from volcanic centers east and northeast of Reno, Nevada, and filled paleovalleys carved in Sierran bedrock (Bateman and Wahrhaftig, 1966; Schweickert et al., 2004; Garside et al., 2005).

Subduction-related andesitic volcanoes located west of present-day Lake Tahoe (Schweickert et al., 2004; Harwood et al., 2014) produced a thick sequence of debris flows, lavas, and tuffs from ca. 10–3.6 Ma (Harwood and Fisher, in Saucedo, 2005) that buried the older topography (Dalrymple, 1964; Bateman and Wahrhaftig, 1966; Schweickert, 1981a, 1981b, 2009). These andesitic rocks are exposed in the west and northwest parts of the basin (Figs. 1 and 2). At about the time of cessation of andesitic volcanism, ca. 3.6 Ma, normal faulting began to shape the Lake Tahoe Basin, which filled with water. Fine-grained lacustrine sediments were deposited on eroded andesitic rocks in this shallow lake (Lopez et al., 2004), here called Proto-Tahoe.

Beginning at 2.3 Ma, and continuing to 0.94 Ma (Kortemeier et al., 2009b), small volcanoes in the northwestern and western parts of the basin erupted and produced basaltic and trachyandesitic lavas, cinder cones, breccias, pillows, and tuffs that locally overlie and invade the contemporaneous lake sediments (Fig. 3). This change from arc to rift volcanism may have commenced as early as 3–4 Ma in the region (Farmer et al., 2013; Cousens et al., 2011).

The Lake Tahoe region was extensively glaciated during the Tahoe and Tioga glaciations (Birkeland, 1964; McCaughhey, 2003), estimated to have peaked at 69.2 ± 4.8 ka and 20.8 ± 1.4 ka, respectively (Howie et al., 2012). Glaciers flowed down valleys tributary to the Truckee River such as Squaw, Bear, and Pole Creeks, dammed the Truckee River downstream of the modern Lake Tahoe outlet, and raised the level of the lake as much as 170 m above modern lake level (Birkeland, 1964).

The McKinney Bay megaslide, which occurred between 12–21 ka, was probably triggered by earthquake activity on the Tahoe Sierra Nevada Frontal fault zone (Schweickert et al., 1999a; Schweickert et al., 1999b; Gardner et al., 2000; Ichinose et al., 2000; Moore et al., 2006). The 12 km³ landslide created the large McKinney Bay reentrant on the west side of the lake and carried kilometer-sized blocks east across the lake basin.

3. PREVIOUS WORK

Lindgren (1897) outlined the history of glaciation and volcanism in the Truckee-Tahoe area. Pleistocene glacial moraines were mapped, and the type locality of the Tahoe glacial stage was defined near the south end of the lake (Blackwelder, 1931). A Pleistocene age for the basaltic volcanism in the area was established, as was evidence for lava and glacial dams within the Truckee River Canyon (Birkeland, 1962, 1963, 1964, 1968).

In the northwest part of the Lake Tahoe Basin, Cenozoic volcanic rocks and several basaltic cinder cones were mapped by Matthews (1971). A study of the Pliocene through Quaternary mafic and intermediate lavas of the area around Truckee indicates that most of the normal faulting in the region occurred between ~3 million and 0.7 million years ago (Latham, 1985). The northwestern part of the Lake Tahoe Basin, including the Pliocene–Pleistocene basaltic rocks, has been mapped as part of a larger mapping project by students in summer field camps from the University of California at Santa Barbara (Sylvester et al., 2012).

Three master north-trending, east-side-down normal fault zones have shaped the Lake Tahoe Basin: the Tahoe-Sierra Frontal fault zone, which lies...
Figure 2. Simplified geologic map of northwestern part of the Lake Tahoe Basin. Units shown on map are: MPa (brown)—Miocene–Pliocene andesite flows and breccias; QPs (gray)—Pliocene–Pleistocene lacustrine sediments, locally diatomite rich; Qb, (apple green)—older (2.3 Ma) basaltic lavas; Qb, (light green)—younger (2.1 Ma) basaltic lavas. For Qb units, pillow breccias are marked with red dots. Qb, (bluish stipple)—basaltic tuff; age undetermined. Qb, (yellow green)—0.94 Ma trachyandesite lavas. Auto-brecciated portions marked with red triangles. Qg (light orange)—glacial deposits; mostly pre-Tahoe age. Qta—glacial deposits; Tahoe age. Qu (pale yellow)—undifferentiated cover deposits, including till, colluvium, alluvium, and landslide. Ql (light gray)—McKinney Bay landslide deposits. Contacts are thin black lines. Faults are shown with black lines, and shorelines (with age) are shown with thick red lines. U/D indicates upthrown and downthrown sides of faults. Location of samples with new "Ar/Ar" ages shown by circled X.
in the mountains on the west side of the basin; the mostly submerged West Tahoe–Dollar Point fault zone, which lies to the east of the Tahoe City shelf; and the North Tahoe–Incline Village fault zone, which is partly submerged and passes through Crystal Bay, Incline Village, and areas northeast (Schweickert et al., 2000a, 2000b, 1999a, 2004). The timing and rates of normal faulting have been investigated (Brothers et al., 2009; Dingler et al., 2009; Schweickert, 2009), and a recent study of the Tahoe–Sierra Frontal fault zone where it offset glacial moraines utilized field observations combined with light detection and ranging (LiDAR) imagery to delineate and quantify the rate of movement on this fault zone (Howle et al., 2012).

Multibeam bathymetric mapping imaged a giant landslide (~12 km³) within the lake, which originated at and formed McKinney Bay on the west shore and carried huge blocks east across the lake (Gardner et al., 2000). Dredged samples from these blocks indicate that they are the poorly lithified lake sediment that was uplifted on the west side of the lake by the West Tahoe–Dollar Point fault zone. Such sediment underlies the Tahoe City shelf (Moore et al., 2006). Interaction of the landslide with preexisting Tioga moraines defines an older age limit of 21 ka for the landslide (Schweickert et al., 2000b; Schweickert and Lahren, 2002), and the maximum age of cored and dated sediments atop the landslide debris constrains the landslide age to more than 12 ka (Smith et al., 2013; Moore et al., 2014).

About 10 km northeast of Tahoe City, a deep earthquake swarm occurred on the north shore of Lake Tahoe in 2004. The earthquake hypocenters, 29–33 km deep, defined a distinct upward migration early in the swarm history. Aspects of the swarm as well as upward ground displacement (determined by GPS measurements) are consistent with injection of magma into the lower crust (Smith et al., 2004).

### 4. GEOCHRONOLOGY

Only one previous radiometric age is available from basaltic units within the mapped area of Figure 2. A whole-rock sample from a pillow basalt in the Tahoe City quarry (Fig. 2) yielded a K-Ar age of 2.0 Ma (Dalrymple, 1964). In addition, two basalt samples from near Carnelian Bay, 8 km northeast of Tahoe City, were dated by K-Ar methods at 2.6 and 2.3 Ma (Doell et al., 1966; ages recalculated to reflect modern decay constants and standards; see below).

New 40Ar/39Ar radiometric ages were determined in the U.S. Geological Survey geochronology laboratory in Menlo Park, California. The ages were obtained from incremental heating experiments on groundmass from microcrystalline interiors of lavas (Table 1). Six samples were dated using 40Ar/39Ar

### Table 1. Ar-Ar Ages for Samples from the Northwestern Part of the Lake Tahoe Basin

| Sample | Area (see Fig. 2) | Location Easting (10S) | Northing | Elevation (m) | Unit | Whole-rock SiO₂ | Interpreted eruption age (Ma) |
|--------|------------------|------------------------|----------|--------------|------|----------------|-----------------------------|
| 07719-3 | Rampart | 744176 | 4339070 | 1987 | MPa | 54.5 | 4.160 ± 0.306* |
| 6107-5 | Rocky Ridge | 747742 | 4340624 | 1978 | Qb₁ | 52.3 | 2.303 ± 0.050* |
| ER-9 | Eagle Rock | 745350 | 4332692 | 1974 | Qb₂ | 51.2 | 2.082 ± 0.054* |
| 0789-4 | Granlibakken | 744986 | 4337635 | 2065 | Qb₂ | 51.7 | 2.080 ± 0.007* |
| 71207-1 | Quarry Cliffs | 744882 | 4339412 | 2107 | Qb₁ | 51.7, Sample 71207-4 | 2.092 ± 0.006* |
| 081017-1 | Thunder Cliffs cinder cone | 743134 | 4342006 | 2309 | Qff | 56.4 | 0.940 ± 0.003* |

Note: See Supplemental item for spectrum data [text footnote 1]. Ages recalculated to Taylor Creek sanidine at 28.345 Ma (Fleck and Calvert, 2016).

*40Ar/39Ar weighted-mean plateau age

**40Ar/39Ar recoil model age
incremental heating techniques following methods described in Calvert and Lanphere (2006) and Muffler et al. (2011). Three samples yielded plateau ages, and three samples yielded discordant age spectra here attributed to $^{39}$Ar recoil. Recoil model ages are reported for the discordant results following Fleck et al. (2014). All results have been recalculated to current standards relative to a first-principles GA1550 biotite age of 98.79 ± 0.96 Ma (McDougall and Wellman, 2011). This yields a standard age of 28.345 Ma for Taylor Creek sanidine (Fleck and Calvert, 2016). Age results are listed in Table 1, and the relevant age spectrum and/or isochron diagrams are shown in Supplemental Item 1 (see footnote 1).

5. PLEISTOCENE VOLCANIC ROCKS

Pleistocene volcanic rocks crop out north and west of Lake Tahoe from Eagle Rock, north of Blackwood Creek, to Dollar Point, east of Skylandia Beach (Fig. 2). In most of the area, these units form three subaerial lava flow sequences, each of which flowed into lake water. In addition, four isolated vents of hyaloclastic breccia erupted subaqueously or in water-soaked ground. This entire volcanic complex is located between the Dollar Point fault to the east and the Tahoe Frontal fault zone to the west, but internally, there are a number of minor east-side-down normal faults that displace the rocks and the former shorelines north of Tahoe City (Fig. 2).

Geochemically, most of these rocks can be classified as high-K calc-alkaline (Fig. 3) and include basalt, basaltic andesite, trachybasalt, basaltic trachyandesite, and trachyandesite (Kortemeier, 2012). A few of the basalts fall in the tholeiitic field of MacDonald and Katsura (1964). The Pleistocene volcanic rocks are divided into four sequences (Fig. 3) based on age, location, and geochemistry (Kortemeier et al., 2009a, 2009b), as described below.

Isotopic and trace-element analyses of samples of these rocks point to a higher content of high field strength elements (HFSEs) and phosphorus than magsmas generated simply by slab melting. These compositions suggest that the magsmas were produced by subduction-related melting that was later affected by conductive heating (Farmer et al., 2013). Putirka and Platt (2012) suggest that this type of volcanism is a passive response to extension and that degradation of the submantle root may continue up to 10 Ma after the cessation of subduction.

5.1. Unit Qb₁—Older Basaltic Rocks: 2.3 Ma

Older basaltic rocks, unit Qb₁, crop out over an area of at least 9 km² northeast, north, and west of Tahoe City (Fig. 2). The age of the basalt is 2.30 Ma, based on a new groundmass $^{40}$Ar/$^{39}$Ar date on a sample taken at Rocky Ridge (Table 1). Unit Qb₁ includes subaerial basalt lavas, hydrovolcanic pillow basalt, pillow breccias, and lapilli tuffs. Basalt of unit Qb₁ extends as far west as Ram-part in the Truckee River Canyon.

5.2. Unit Qb₂—Younger Basaltic Rocks: 2.1 Ma

Unit Qb₂ comprises basaltic rocks that crop out west of 120°08′W longitude, a line that corresponds roughly with the west shore of Lake Tahoe. These rocks
form cliffs and slopes along both sides of the Truckee River Canyon. They also extend 6 km south of the canyon to Eagle Rock (Fig. 2).

Three samples of basaltic rocks of unit Qb2 have been dated by the $^{40}$Ar/$^{39}$Ar method: a basaltic trachyandesite lava from Quarry Cliffs yields an age of 2.09 Ma; a basaltic trachyandesite lava from Granlibakken Creek yields an age of 2.08 Ma; and a small, perched basalt flow at Eagle Rock yields an age of 2.08 Ma (Fig. 2 and Table 1). These dates are all within analytical error of one another, and represent eruptions from different vents that erupted in a short time interval.

Unit Qb2 includes subaerial basaltic lavas as well as pillow basalt, pillow breccias, and tuff breccias. These lavas flowed over unit Qb, northwest of Tahoe City, and the basalt now forms the walls of parts of the uppermost Truckee River Canyon (Fig. 2). South of the Truckee River, basalt of unit Qb2 unconformably overlies Neogene andesitic lavas. These basalts flowed into Lake Tahoe and invaded lacustrine sediments.

The greatest thicknesses of basalt of unit Qb2 are found in two places—in the south wall of the Truckee River Canyon, where more than 207 m of basaltic lavas overly Neogene andesite, and on the northeast side of Stanford Rock Ridge, where over 244 m of lava and tuff breccia are exposed (Fig. 2). Tahoe and pre-Tahoe glacial deposits conceal unit Qb, at Page Meadows and obscure the western extent of the basalt.

Basaltic rocks of unit Qb2, are indistinguishable from those of unit Qb, in outcrop, hand specimen, and thin section but can be differentiated using field relationships, geochemistry, and $^{40}$Ar/$^{39}$Ar ages. Basalts of unit Qb are separated geochemically and spatially into three subunits: (1) basalt exposed at Eagle Rock, which is geochemically similar to basalt of unit Qb; (2) basaltic trachyandesite and trachybasalt exposed in Ward and Blackwood canyons, with LREE values intermediate between those of basalt of unit Qb, and subunit 3 of unit Qb2; and (3) basaltic trachyandesite exposed in the canyons of the Truckee River and Granlibakken Creek and on the intervening ridge, which have the highest LREE values of all units (Kortemeier, 2012, her figure 2).

Vents at Eagle Rock, Stanford Rock Ridge, and Granlibakken Ridge (Fig. 2) were the sources of basaltic rocks of unit Qb2. There is a possibility, however, that unrecognized or buried vents in the Page Meadows and/or Thunder Cliffs areas, now concealed by younger deposits, may also have erupted basaltic lavas of unit Qb2.

5.3. Unit Qtf—Trachyandesite: 0.94 Ma

Trachyandesitic lavas of unit Qtf cover an area of ~12 km², cap the highlands northwest of Tahoe City, and overlie the basalts of units Qb and Qb2 (Fig. 2). The vent for lavas of unit Qtf is the Thunder Cliffs cinder cone, at an elevation of 2337 m (Fig. 2). The stratigraphically highest trachyandesite lava, which underlies the Thunder Cliffs cinder cone, yields an $^{40}$Ar/$^{39}$Ar age of 0.940 Ma (Table 1) and is the youngest dated volcanic unit in the Lake Tahoe Basin.

Outcrops of this unit, both subaerial lavas and subaqueous hydroclastic breccias, are only found north of the Truckee River. Lavas of unit Qtf flowed over a fairly smooth erosion surface developed on basalt of unit Qb, north of Tahoe City and basalt of unit Qb, west of Tahoe City and over an irregular erosion surface carved into Neogene andesitic lavas in the Thunder Cliffs area of the Truckee River Canyon. In Jack Pine Canyon, north of Tahoe City (Fig. 2), trachyandesites formed hydroclastic breccias where lava crossed the shoreline and interacted with the water and lacustrine sediments of Proto-Tahoe.

Unit Qtf is 143 m thick at Thunder Cliffs and 207 m thick north of Quarry Cliffs. This unit records a maximum relief of over 381 m from its vent at the Thunder Cliffs cinder cone at 2337 m elevation to the base of trachyandesite lavas in Jack Pine Canyon, at 1951 m elevation (Fig. 2).

Rocks of unit Qtf are high-K calc-alkaline series trachyandesite and have SiO₂ between 56.2 and 59.9 wt%; high Al₂O₃, K₂O, Na₂O, Sr, La, and other LREEs; and low MgO, Cr, Ni, and Y (Kortemeier, 2012).

Outcrops and hand specimens of unit Qtf are very similar in appearance to those of units Qb and Qb2, and are generally indistinguishable in the field. Glassy samples are dark gray to black, and more crystalline samples are light gray in color with a silvery surface sheen. In thin section, the aphanitic and slightly porphyritic samples of Qtf exhibit a trachytic texture with a felty groundmass of plagioclase with minor interstitial clinopyroxene. Some thin sections of samples of unit Qtf reveal relict, oxidized amphibole as a minor phenocryst.

5.4. Unit Qbu—Skylandia Beach Basaltic Rocks of Unknown Age

Unit Qbu, includes lapilli tuff and pillow basalt exposed in the wave-carved cliffs at Skylandia Beach (Fig. 2). The tuff, which extends at least 0.5 km inland from the beach and over 1 km offshore on the Tahoe City shelf, covers an area of at least 1 km². Whole-rock and trace-element geochemistry of a juvenile bomb as well as electron microprobe analyses of edges of glassy bombs from Skylandia Beach show that the tuffs are chemically distinct from all the other lavas and tuffs in the study area (Kortemeier, 2012).

Absolute dating of volcanic rocks at Skylandia Beach has proven difficult. Both juvenile bombs within the tuff and the vesicular pillow lava in the vent area are too glassy for $^{40}$Ar/$^{39}$Ar dating. Field relationships with other nearby basaltic units are obscured by Quaternary deposits (Fig. 2). Cousens et al. (2011) reported an $^{40}$Ar/$^{39}$Ar age of 2.20 Ma (recalculated to 2.21 Ma for comparison with other dates in this paper) for the tuff at Skylandia Beach. We believe this age is questionable because outcrop and weathering characteristics suggest that the tuff of unit Qbu may be very young. The tuff exposed along the cliffs at Skylandia Beach has proven difficult. Both juvenile bombs within the tuff and the vesicular pillow lava in the vent area are too glassy for $^{40}$Ar/$^{39}$Ar dating. Field relationships with other nearby basaltic units are obscured by Quaternary deposits (Fig. 2). Cousens et al. (2011) reported an $^{40}$Ar/$^{39}$Ar age of 2.20 Ma (recalculated to 2.21 Ma for comparison with other dates in this paper) for the tuff at Skylandia Beach. We believe this age is questionable because outcrop and weathering characteristics suggest that the tuff of unit Qbu may be very young. The tuff exposed along the cliffs at Skylandia Beach has been consolidated and eroded quickly. The cliffs have visibly receded over the course of this study, and it seems unlikely that the tuff at Skylandia Beach has withstood two million years of such erosion. It is possible that the dated sample was obtained from an accidental basaltic fragment from unit Qb, entrained in the tuff.
6. SEDIMENTS OF PROTO-TAHOE

Prior to and during the episodes of Pleistocene basaltic volcanism, fine-grained lacustrine sediments were deposited in a shallow lake called Proto-Tahoe (Lopez et al., 2004). Surface exposures and drill cores of lake beds indicate that this lake extended both north and south of the present lake. Part of the lacustrine sedimentary sequence has been sampled in a 58-m-deep drill hole near the dam at the Truckee River outlet of the lake. Age of the drill core, which includes neither the top nor the bottom of the sediment section, is constrained by dated ash layers and paleomagnetic measurements. It spans the interval from ca. 2.06 to 0.76 Ma (Verosub et al., 2004) and includes older diatom-rich sediments and younger clay-rich, diatom-poor sediments (Muehlberg, 2007). Both older and younger sediments contain some layers of sandy turbidites.

Diatomaceous strata at Skylandia Beach (Fig. 2) are white, thinly bedded, and nearly horizontal. These contain the Late Pliocene–Early Pleistocene diatom species, Tertiarius (Fig. 5A), which is characteristic of a shallow, freshwater, slightly alkaline lake (Starratt, 2005). The topographically highest outcrop of lacustrine sediments, at 2000 m, in Jack Pine Canyon (Fig. 2), is also diatom rich (Fig. 5B).

Lacustrine sediments are well exposed subaequously on the Tahoe City shelf (Moore et al., 2006; Dingler et al., 2009), a submerged platform 4 km by 4 km in size in the northwest part of Lake Tahoe. They are also exposed at elevations as high as 2000 m in small, isolated outcrops from Dollar Point to Ward Creek, north and west of the modern lake (Fig. 2). These outcrops of lake beds are small because they are poorly indurated and easily eroded.

The Tahoe City shelf is bounded to the east by the Dollar Point fault, a large east-side-down normal fault (Gardner et al., 2000; Schweickert et al., 2000b; Schweickert et al., 2004; Dingler et al., 2009; Fig. 2). The subaqueous, east-facing fault scar exposes lake beds overlying andesite breccias and debris-flow deposits. The upper 152 m of the scarp was studied in underwater surveys in 2005–2008, using a remotely operated underwater vehicle (ROV). Images from the vehicle show that the sediments increase in thickness from ~15 m along northern parts of the scarps to over 100 m along southern parts (Fig. 6). This suggests that the northern shoreline of Proto-Tahoe may have been near the present shoreline at Dollar Point and that Proto-Tahoe gradually deepened to the south from there. ROV video images show that most of the Tahoe City shelf is underlain by thinly bedded, horizontal to gently south-dipping lake sediments. Less than 1 km offshore from Commons Beach as well as Skylandia Beach, basaltic lapilli tuff (units Qb_t and Qb_t') overlie the lake sediments (Fig. 2).

The lake beds must partly predate the 2.3 Ma basalt where exposed on the Tahoe City shelf yet span the times of volcanism near the Tahoe City dam. Therefore, they indicate that Proto-Tahoe extended west to the Tahoe City quarry. Hence, Proto-Tahoe had been dammed somehow, perhaps by a fault at Rampart, prior to the 2.3 Ma damming event.

Deep-water dredging of giant landslide blocks in the middle of Lake Tahoe revealed that the sampled blocks consist of poorly lithified lacustrine sediment closely resembling the type that underlies the Tahoe City shelf (Moore et al., 2006). Prior to landsliding, the shelf extended south of Eagle Rock, but landsliding removed most of the southern part producing McKinney Bay, an expression of the giant amphitheater at the head of the east-moving McKinney Bay megaslide (Fig. 2; Moore et al., 2006).

7. LAVA-WATER INTERACTIONS

Three episodes of Pleistocene volcanism dammed the outlet of Proto-Tahoe. These dams caused the level of the lake to rise. Later, however, erosion of the dams lowered the lake level. At various times, lava flows crossed both the low and high stands of the lake shore, and various volcanic deposits formed by the interactions of lava with water and wet sediment. These interactions were generally only mildly explosive when subaerial lava crossed a shoreline and entered the lake. However, in places where a restricted flow entered the water at one point over a protracted period, repeated explosions produced enough ejecta to construct a littoral cone. In addition, volcanic vents of limited output that originated below lake level or on water-soaked ground were explosive and developed tuff cones.

7.1. Shorelines

7.1.1. 2.3 Ma Shoreline

Where 2.3 Ma basaltic lava of unit Qb, crossed the shoreline of Proto-Tahoe, subaqueous largely fragmental deposits formed volcaniclastic deltas. These deposits include pillow basalt and pillow breccia contained in a palagonitized hyaloclastite matrix. In some places, the lava produced large, elongate pillows draped downslope, but most of the pillows were reduced to joint-block fragments as they tumbled downslope. The hyaloclastite matrix formed when flowing lava quenched and shattered when it contacted water. The subaqueous, largely fragmental material is overlain directly by subaerial columnar basalt (Fig. 7). This transition records the lake level and the position of the northern shoreline of Proto-Tahoe at 2.3 Ma (Fig. 2).

This shoreline may be traced 3 km from the North Lake Tahoe High School, 2.6 km northeast of Rocky Ridge, at 2003 m elevation, south to Jack Pine Canyon, 0.7 km southwest of Rocky Ridge, at 1952 m elevation. Over this length, the average elevation is ~1972 m (Figs. 2 and 8). The originally horizontal lake-level horizon is tilted down to the west. Such deviations from the horizontal have resulted from displacement in the hanging wall of one or more north–south–striking normal faults in the Tahoe City area (Fig. 2).

At Rocky Ridge, one km northeast of Tahoe City (Figs. 2 and 8), lava of unit Qb flowed across an erosion surface carved into 4.2 Ma andesite lavas before entering Proto-Tahoe. The erosion surface has ~80 m of relief. The Rocky Ridge locality preserves over 76 m of subaqueous volcanic deposits.
Figure 5. Scanning electron microscope (SEM) photomicrographs of diatoms from lacustrine sediments (A) *Tertiary* (possibly *Pliocene*) from diatomaceous sediments at Skylandia Beach (each fossil 100 μm across; after Starratt, 2005). (B) Both images *Pliocene*? from lacustrine sediments, Jack Pine Canyon (courtesy of John McCormack, Microbeam Laboratory, University of Nevada, Reno).
Where subaerial lava flows crossed the Proto-Tahoe shoreline and invaded wet, diatomaceous sediments, peperites formed. The peperites are characterized by pillowied lava that has penetrated and partly mixed with preexisting sediments (Fig. 9). The lowest outcrops of the lava delta are south of Rocky Ridge, east of andesite outcrops, and 1 m above the modern shoreline (Fig. 2). Pillow basalt is displayed on the east and west flanks of Rocky Ridge from 1914 to 1939 m elevation. These pillowied flows may be large, feeder lobes. A similarly large, invasive pillowied flow is exposed at "The Villas" condominium complex 1 km northeast of Rocky Ridge (Fig. 2). This lens-shaped flow is 7 m high by 42 m long. Lacustrine sediments are exposed beneath and on both sides of the flow.

At both the condominium complex and Rocky Ridge, the thick pillowied flows are overlain by palagonitized pillow breccia. At Rocky Ridge, the pillow breccia is well exposed in road cuts along the access road leading to the top of the ridge (Fig. 8). There, as at Tamarack Lodge, lobate pillows from 2 to 5 m in exposed length, are draped downslope (Fig. 10A).

Columnar basalt directly overlies pillow breccias (Fig. 7) at Rocky Ridge and Tamarack Lodge at ~1972 m, marking the transition from subaqueous delta deposits to subaerial lava flows. At Rocky Ridge columns at the base of the subaerial flow are ~0.2 m wide and merge upward into columns as much as 2 m across (Fig. 7A). Near Tamarack Lodge, columns are ~7 m tall and range from 0.3 m wide at the base to 2.6 m across at the top. The gradation from small, narrow columns at the base to larger, thicker columns higher up in the flow is consistent with quicker cooling of the lower part of the subaerial flow, where it flowed across water-saturated pillow breccia, and slower cooling of the hotter, middle part of the subaerial flow (DeGraff and Aydin, 1987).

The 2.3 Ma shoreline centered at Rocky Ridge formed at a distinct steepening of the terrain (Fig. 8). This change in slope is caused by the low slope required for the flow of molten lava on dry land, as compared to the higher angle of repose for its fragmental equivalent below water level.

At Rocky Ridge and Tamarack Lodge, the subaerial portion of the lava flows formed an emergent lobe extending out into Proto-Tahoe. In the subaqueous, hyaloclastic breccia at Rocky Ridge, eight elongate pillows have long axes trending from 70° to 120°; these axes hence are more easterly than the downslope direction indicated by a direction perpendicular to the shoreline (120°). At Tamarack Lodge, ten elongate pillows have long axis azimuths from 90° to 174°, which here trend downslope about perpendicular to the preserved coastline. Local irregularities in the developing coastline can account for these deviations.

West and northwest of Tahoe City, basalt and hyaloclastic breccias of unit Qb, define a lake level 2.5 km long between 2033 m and 2048 m elevation. This is 30–60 m higher than the lake-level horizon at Rocky Ridge. We attribute this deviation to east-side-down displacement on the normal faults near Tahoe City (Fig. 2).

Before Qb, basalt dammed the Truckee River and raised lake level, it flowed into the lake across a shoreline similar in elevation to the modern one. Here the Commons Beach littoral tuff cone was built on the shores of Proto-Tahoe. This littoral cone extends down to current lake level (1889 m) along the shoreline cliffs at Tahoe City. Remnants of the cone are also on the submerged Tahoe City shelf extending ~500 m eastward from Commons Beach and in a road cut at the Tahoe City quarry (Fig. 2). Geochemically the Commons Beach littoral tuff closely matches that of the Tahoe City quarry. This largely subaerial littoral cone (Moore and Ault, 1965) developed when 2.3 Ma lavas initially flowed into lake waters that were slightly lower than at present. Lake level rose throughout this eruption, or series of eruptions, as shown by the 146-m-thick pile of peperites and pillow breccias overlying subaerial tuffs at the Tahoe City quarry. During the period of these eruptions, lake level, therefore, rose at least 152 m, which here trend downslope about perpendicular to the preserved coastline. Local irregularities in the developing coastline can account for these deviations.

Circa 2.3 Ma, lavas of unit Qb, apparently dammed the Truckee River at Rampart below the outlet of the lake. At Rampart, 4.3 Ma andesite crops out up to 1981 m elevation in cliffs on the south side of the canyon and up to 2073 m elevation in walls on the north side of the canyon. This wall of andesite lavas (unit MPa) may be the footwall of a concealed normal fault (east-side down) that defined the loci of Pleistocene vents at Thunder Cliffs, Granlibakken Ridge, Stanford Rock Ridge, and Eagle Rock (Kortemeier, 2012; Sylvester et al., 2012) (Fig. 2).

Rampart is the site of the westernmost occurrence of subaqueous pillow breccia and subaerial columnar basalt of unit Qb, within the Truckee River Canyon (Fig. 2). Damming of the river at Rampart and the ensuing filling of the lake
Figure 7. Base of subaerial, columnar-jointed lava of older basalt lavas of unit Qb, at Rocky Ridge. (A) Contact between pillow breccia below, and columnar basalt above, marks the transition from subaqueous lava delta deposits to subaerial lavas, and defines the lake level at 2.3 Ma. Large column at center is 1 m in diameter. (B) Columnar basalt with small columns (0.2 m diameter) that are reddish at the base where in contact with underlying pillow breccia. Medium columns are 0.6 m in diameter in middle of photo, and large columns are up to 1.8 m in diameter at top. Yellow notebook (bottom center) is 12 cm x 19 cm. (C) Base of subaerial columnar basalt showing narrowing of columns toward the flow base where cooling by lake water is extreme. Hammer is 33 cm long.
during this eruptive cycle resulted in the formation of lava delta deposits from 1902 to 2048 m elevation. Hence Rampart was the outlet of Proto-Tahoe within the Truckee River Canyon as early as 2.3 Ma.

At the Tahoe City quarry, the lava delta section is remarkably complete and is exposed in road cuts, in the quarry itself, and on the steep slopes of the Truckee River Canyon. The base of the lava delta section, a 3-5-m-thick lapilli tuff equivalent to the tuff of Commons Beach, includes rip-up clasts of diatomaceous sediment (Fig. 11B). Pillow breccia, composed of 2-3-m-long elongate pillows in a hyaloclastite matrix, overlies the tuff (Fig. 11C). These units crop out at 1902 m elevation in the road cut at the entrance to the Tahoe City quarry. The transition from tuff to pillow breccia suggests lava production increased, or available water decreased, as the eruptions progressed (Kortemeier and Schweickert, 2007a).

Approximately 20 m upslope from the pillow breccia, quarrying has exposed lacustrine sediments invaded by pods and large (1-5-m-thick), tabular sills of basaltic peperite. The peperites exhibit corrugated or crenulated (Lavine and Aalto, 2002), glassy, palagonitized edges. These peperites are similar to sill-like peperites at Mount Baker, Washington (Tucker and Scott, 2009).

Pillow breccias overlie the peperites and form the steep slopes from ~1914 m to 2048 m elevation, where they are overlain by subaerial columnar basalt. The transition from pillow breccia to columnar basalt marks the top of the lava delta at this locality and the lake level of Proto-Tahoe during eruption of these lavas (unit Qb1) at 2.3 Ma. The peperite and pillow breccia together comprise a 146 m thickness of lava delta deposits formed as subaerially erupted lava entered the lake. This also indicates that

Figure 8. High-resolution, bare-earth, airborne light detection and ranging (LiDAR) image, looking obliquely northwest into Rocky Ridge. Image units correspond to those of Figure 2: MPa—Miocene–Pliocene andesite lavas and breccias; QPs—Pliocene–Pleistocene lacustrine sediments, locally diatomite-rich; Qb1—older basalt lavas (2.3 Ma); Qtf—0.94 Ma trachyandesite lavas; Qu—undifferentiated, unconsolidated deposits, including till, colluvium, alluvium, and landslide deposits. Lake levels are shown by red lines. Lake level at 2.3 Ma (1975 m) marks transition from subaqueous pillow lavas and pillow breccias below to subaerial lavas of unit Qb1 above. Lake level at 0.94 Ma is at 2085 m elevation and marks transition from subaqueous hydroclastic breccias below to subaerial lavas of unit Qtf above. Distance from Jack Pine Canyon to Rocky Ridge is 800 m.
Proto-Tahoe was at least 146 m deep at the Tahoe City quarry locality ~2.3 million years ago.

### 7.1.2 2.1 Ma Shoreline

Three dated samples from different volcanic constructs produce remarkably similar results, which have been rounded to 2.1 Ma. The perched lava pond at Eagle Rock yields an age of 2.082 ± 0.054 Ma; the lava of Granlibakken yields an age of 2.080 ± 0.007 Ma; and the lava of Quarry Cliffs yields an age of 2.092 ± 0.006 Ma. Because of their similar ages, these volcanic units have all been included in the Qb₂ unit despite the fact that several different vents were involved, some of which erupted lavas of somewhat different composition.

The transition between subaerial and subaqueous basalt of unit Qb₂ (2.1 Ma) marks the elevations of the Proto-Tahoe shoreline at ca. 2.1 Ma. The hydrovolcanic fragmental nature of units exposed at Eagle Rock indicates that the vent erupted in shallow water or water-soaked ground. The small, ponded basalt flow (dated at 2.08 Ma) near the summit of Eagle Rock indicates that lake level was below its summit of 1975 m and was probably below the 1914 m elevation of the lowest exposed tuff beds. Hence, the 2.3 Ma basalt dam at Rampart had been eroded down to ~1914 m by ca. 2.1 Ma. This provides an estimate of at least a rate of erosional downcutting of 0.06 mm/yr.

Two kilometers north of Eagle Rock, lava flows interacted explosively with water and produced the tuff cone on Stanford Rock Ridge (Fig. 2).

Soon after the eruption of basalt at Eagle Rock, the Truckee River was again dammed in the vicinity of Rampart by a series of Qb₂ lava flows that crop out on both sides of the river (Fig. 2). Below the shoreline, subaqueous lava breccias and pillow lava were deposited and then were overlain by subaerial basalt with characteristic columnar joints.

The highest elevation of subaqueous basaltic rocks of this age (ca. 2.1 Ma; unit Qb₂) indicates that the level of Proto-Tahoe rose ~189 m to as high as 2073 m in elevation. The new shoreline (which has an average elevation of 2054 m) can be traced almost 3 km from Tahoe Park Heights (2036 m) in the south to Granlibakken Creek (2073 m). North of the Truckee River Canyon, the shoreline extends ~2 km west of the Tahoe City quarry (2036 m) (Fig. 2). This shoreline, like the 2.3 Ma shoreline, has no doubt been displaced and tilted by normal faults, accounting for the range in elevations. North of the Truckee River Canyon, and west of Tahoe City, both the 2.3 and 2.1 Ma shorelines are horizontal.

Basalt of unit Qb₂ flowed over an irregular erosion surface carved into 3 Ma andesite and overlying diatomaceous lake sediments south of the Truckee River Canyon. West of Tahoe City, and north of the canyon in the Quarry Cliffs–Twin Crags area (Fig. 2), they flowed over a nearly planar erosion surface established on the 2.3 Ma basalt. Where the lava of unit Qb₂ flowed across the northwestern and western shorelines and into water or sediment, peperitic deposits formed from the non-explosive intermingling of invading lava and wet sediment, similar to that described in Németh and White (2009).

At Tahoe Park Heights, on the north side of the Ward Creek drainage (Fig. 2), ~61 m of pillow breccia of unit Qb₂ crops out between 1975 m and 2036 m. The pillow breccia is highly palagonitized and is overlain by a subaerial lava exhibiting weakly developed columnar joints at its base.

The base of the lava delta in this area is exposed at 1951 m in the bed of Ward Creek (Fig. 2), where peperitic pillows and pods have invaded lacustrine sediments. One km east-northeast of the Ward Creek exposure, similar pods of basalt form a north-south linear array (Kortemeier, 2012; Sylvester et al., 2012). These beehive-shaped knobs, which average 2 m high by 3 m across, appear to have been emplaced along a north-south fissure vent.

At Granlibakken and Quarry Cliffs–Twin Crags, the contacts between the lava delta and the base of the columnar basalt record a lake level at 2073 m elevation. Basalt of unit Qb₂, therefore, formed subaqueous deposits from 1951 m to 2073 m and records a minimum depth for Proto-Tahoe of 122 m in this area.

### 7.1.3 0.94 Ma Shoreline

At 0.94 Ma, trachyandesite (unit Qtf) erupted from the cinder cone above Thunder Cliffs, 2337 m in elevation 5 km northwest of Tahoe City. This vent is located at the top of the 427-m-high cliffs on the north side of the Truckee

---

**Figure 9.** Peperite along the modern shoreline of Lake Tahoe south of Rocky Ridge. Isolated, spherical pillow formed as lava invaded lacustrine sediments. Note radial joints and cauliflower-like glassy edges of the pillow. Hammer is 33 cm long.
River Canyon, opposite the confluence of Bear Creek. The morphology of the cinder cone has been largely obliterated by preparatory site grading and trenching for a sewage disposal project (Matthews and Franks, 1971; Cave, 1987; Cave and Dickinson, 1987). Apparently, initial massive lava flows erupted from this vent dammed the Truckee River at Bear Creek and raised the level of Proto-Tahoe again. Below the lake level, subaqueous, hydroclastic breccias (Fig. 12) were deposited.

The trachyandesite lavas flowed across unit Qb, and down into and filled at least one canyon carved into the 2.1 Ma basalt and sediments. Trachyandesite lavas do not occur south and west of the Truckee River, suggesting that trachyandesite lava flowed into and filled the canyon and that the lava dam has since been eroded away by downcutting along the river. The lava dam inferred at 0.94 Ma would have been ~3.5 km downstream of, and 37 m higher, than the lava dam at Rampart at 2.1 Ma (Fig. 2). An average rate of downcutting of...
Figure 11. Basaltic tuff at Commons Beach, Tahoe City: (A) north-dipping tuff along littoral cone tuff outcrop along Commons Beach boardwalk; (B) rip-up clasts of diatomaceous lake sediment in hyaloclastic tuff in road cut at Tahoe City quarry; (C) pillow breccia overlying diatomaceous lake sediment, in road cut at Tahoe City quarry. Hammer is 33 cm long.
0.2 mm/yr, from 0.94 Ma to the present, would account for the current lake level of 1897 m.

The trachyandesitic lavas generally form massive, cohesive deposits above 2085 m elevation. Approximately 1 km north of Tahoe City, however, trachyandesite crops out as low as 1932 m elevation. In that area below 2085 m, the cohesive lava flows give way to pervasively fractured flow breccia composed of angular, cobble-sized fragments that fit together like pieces of a jigsaw puzzle with little or no matrix (Fig. 12). The breccia fragments are largely composed of black devitrified glass, but the palagonitized surfaces and edges of the breccia fragments display characteristic yellow and orange colors (Fig. 12). The fragments have textures that can be described as hobnail, alligator skin, hackly, corrugated, or crenulated (Lavine and Aalto, 2002, their figure 18b). The transition from the massive lava flows to the hydroclastic palagonitized breccia (Fig. 2) is exposed over a distance of ~1 km and marks a fossil shoreline crossed by the lava flows.

North and west of Jack Pine Canyon, trachyandesite lava appears to have flowed down into and to have filled a paleocanyon carved into 2.1 Ma basalt (unit Qb1), lacustrine sediments, and older andesite. The lowest subaerial lava flow appears to have traveled down canyon, crossed the Proto-Tahoe shoreline, and invaded wet diatomaceous lacustrine sediments to form peperite, a small outcrop of which (unit QPs) is downslope from the gravel pit in Jack Pine Canyon (Fig. 2). The downslope transition at 2085 m elevation from cohesive subaerial lava flows to in situ hydroclastic breccias marks the lake level of Proto-Tahoe ~0.94 million years ago, when the trachyandesite erupted (Fig. 2).

7.2. Explosive Lava-Water Interactions

Lava-water interactions where the water/lava ratios are 0.1–0.3 tend to be most explosive and to produce fragmented volcanic products, which commonly form tuff rings (Sheridan and Wohletz, 1983; Wohletz and Sheridan, 1983). In the study area, fragmental debris forms tuff cones with tuff beds having initial dips >25°. Five tuff cones produced by explosive activity are discussed below.

7.2.1. Commons Beach and Tahoe City Quarry Tuff Cone

As noted earlier, outcrops of a basaltic tuff cone are found at Commons Beach in Tahoe City and near the Tahoe City quarry, 800 m southwest of Commons Beach (Fig. 11). The tuffs are a part of the 2.3 Ma unit Qb5. Observations by ROV show that submerged outcrops of this tuff cone also extend offshore ~500 m from Commons Beach (unit Qb5 on Fig. 2).

The lapilli tuff of Commons Beach has sparse and small juvenile bombs and few surge features such as cross bedding, chute-and-pool scour features, winnowing of fines, and reverse grading. Tuff beds at the Tahoe City quarry...
include rip-up clasts of diatomaceous lake sediments (Fig. 11B) within the basal layers. These layers grade upward into a hyaloclastite pillow breccia.

The tuff of Commons Beach closely matches geochemically with hyaloclastite pillow breccia and a subaerial lava flows up-section in unit Qb, at the Tahoe City quarry and is geochemically distinct from the tuff of Skylandia Beach, as determined from microprobe analyses of glass from ash and edges of juvenile bombs, and the whole-rock geochemistry of crystalline centers of juvenile bombs and lava flows.

The Commons Beach tuff cone is interpreted as a rootless littoral cone formed by explosive activity where subaerial lava flows of the older basalt sequence (Qb) crossed the Proto-Tahoe shoreline and invaded diatomaceous lake beds. As noted earlier, the tuff of Commons Beach, the overlying extensive hyaloclastic deposits, and the columnar basalt flows are all part of the older sequence of basaltic lavas (unit Qb, on Fig. 2). The littoral cone formed when the shoreline was low (near the current lake level) prior to the damming of the lake and elevation of the shoreline to the Rocky Ridge–Tamarack Lodge areas.

7.2.2. Burton Creek

The tuff cone at Burton Creek, 3 km north of Tahoe City, is a roughly circular feature, 0.5 km in current diameter (Fig. 2). It is exposed at elevations ranging from 2018 m to 2064 m, ~132 m to 178 m above lake level. The tuff cone has been bisected by Burton Creek, and good exposures of lapilli tuff are found on the edges of the tuff cone, especially west of the creek where the tuff forms barren, steep slopes (Fig. 4). The tuff is lithologically similar to the tuffs at Commons Beach and Skylandia Beach. The lapilli tuff is palagonitized and contains armored lapilli and juvenile basaltic bombs and accessory andesite blocks up to 20 cm across. Tuff beds are from 0.15 to 1 m thick and form planar and wavy bed forms that dip 20°–38° outward (Fig. 4). Toward the center of the tuff cone in Burton Creek, chaotic and steeply dipping beds delineate the edge of the vent.

A 1.5-m-thick basaltic dike striking N70E with vertical flow foliation cuts through the tuff and is exposed for ~30 m, beyond which it is obscured in an area of cinders. A second basaltic dike, 3–6 m thick, striking N20W and with subvertical flow foliation, crosscuts the tuff, cinders, and the N70E dike. The presence of basaltic dikes and cinders near the vent area suggests that the Burton Creek tuff cone formed at a primary vent and is therefore not a littoral cone.

Rock in the tuff cone of Burton Creek is geochemically similar to both the basaltic dikes that cut it and to the surrounding basaltic lavas of unit Qb (Kortemeier, 2012). The tuff cone may therefore mark a vent for at least some of the basaltic lavas of unit Qb.

The tuff cone is 40 m higher than the 2.3 Ma shoreline near Tamarack Lodge, thus suggesting that lake level rose between the time of eruption of the basalt at Tamarack Lodge and the tuff cone at Burton Creek.

7.2.3. Eagle Rock Tuff Cone

Eagle Rock is a 250-m-diameter promontory that rises over 60 m from 1914 m to 1975 m in elevation above the floor of the canyon of Blackwood Creek on the west shore of Lake Tahoe (Figs. 2 and 13). The basaltic lava and tuff breccia of Eagle Rock are geochemically distinct from other nearby basalts (Kortemeier, 2012). As noted earlier, the 2.08 Ma tuff cone formed at an explosive volcanic vent that began subaquously or on water-soaked ground and erupted through stream and/or beach gravels.

The tuff cone has suffered extensive erosion. It was overridden by Tahoe- and Tioga-age glaciers in Blackwood Creek Canyon. Glacial scouring of the top surface of Eagle Rock is demonstrated by its roche moutonnée shape, by the firmly cemented planar surface of the tuff, and by the presence of numerous granitoid glacial erratics resting upon the tuff breccia (Schweickert and Lahren, 2002). Eagle Rock was later subjected to giant splash waves generated by movement of the adjacent, McKinney Bay megaslide. These processes scoured away most of the tuff cone (Schweickert et al., 2000a; Schweickert and Lahren, 2002) and left only subvertical tuff beds and an intra-vent tuff breccia.

Eagle Rock consists primarily of palagonitized basaltic tuff breccia containing abundant juvenile clasts up to 50 cm in diameter and accidental clasts of rounded andesitic pebbles and cobbles up to 30 cm in diameter (Kortemeier and Schweickert, 2007b). Abundant lapilli coated with a layer of fine ash indicate explosive transport through a wet eruption cloud and subaerial deposition. On the west, north, and east sides of Eagle Rock are arcuate, inward-dipping layers of the tuff breccia (Figs. 13A and 13B) that were apparently deposited within the vent. In the central vent area, on a steep cliff face forming the southern side of Eagle Rock, a basaltic mega-breccia with juvenile clasts up to 3 m in size fills a diatreme-like structure. One juvenile clast encloses a 1-m-diameter andesitic cobble (Fig. 13C). This central vent area exposes multiple vertical basaltic dikes up to 2 m wide and irregularly shaped intrusive bodies. One vertical dike thickens upward and is brecciated toward its top. A small (less than 12 m²) ponded basalt flow is exposed at the top of the cliff (Fig. 13D).

A sample from the ponded flow in the vent area yielded a 40Ar/39Ar date of 2.08 ± 0.054 Ma (Table 1). The exposed base of the tuff and/or breccia beds at Eagle Rock is slightly above current lake level indicating that the level of Proto-Tahoe was close to the current lake level ~2.08 million years ago.

7.2.4. Stanford Rock Ridge Tuff Cone

The Stanford Rock Ridge tuff cone is 1.5 km northwest of Eagle Rock on the steep escarpment on the northeast end of Stanford Rock Ridge (Fig. 2). There, well-bededded lapilli tuff and tuff breccia of unit Qb, crop out from 2042 to 2121 m, ~143–222 m above current lake level. At 2161 m elevation, a 1.3 km² flat area is blanketed with cinders, cindery spatter, and cindery agglutinate, marking the probable location of the vent for the tuff cone (Fig. 2). The tuff breccia is overlain by a 46-m-thick, basaltic trachyandesite lava flow (Kortemeier, 2012). The
Figure 13. Basaltic tuff and vent complex at Eagle Rock: (A) looking south at the 250-m-diameter Eagle Rock promontory. Tuff breccia fills vent area on south side of hill, at center of photo. (B) Close-up of tuff-breccia beds dipping south into vent. Dog is 0.7 m tall. (C) Vent breccia in diatreme structure, south side of Eagle Rock. Note large, pink, rounded andesite boulders in dark-gray, fractured, basalt and in tan-colored tuffaceous matrix. Field of view: ~5 m wide. (D) Vertical basaltic dike (2.5-m-wide) in vent area, looking east. Note well-developed columnar joints perpendicular to wall and thickening and brecciation of basalt toward top of dike. In upper left of photo is small remnant (4 m x 3 m) of ponded lava flow, from which sample ER-9 was collected for 40Ar/39Ar geochronology.
base of the flow directly overlying the tuff breccia has crude columnar joints, which suggest that the lava flowed over wet tuff beds and cooled quickly. The tuff cone and lava flows on Stanford Rock Ridge are geochemically distinct from lava and tuff of Eagle Rock but are similar to basalt of unit Qb, exposed in and north of the canyon of Ward Creek. Because of this similarity and the fact that the vent is close to, and on line with, the Eagle Rock vent, the Stanford Rock Ridge basalt is here tentatively assigned to the Qb2 eruptive episode (Fig. 2) (Kortemeier et al., 2009a).

7.2.5. Skylandia Beach Tuff Cone

A section of basaltic lapilli tuff and pillow lava of uncertain age is exposed along ~1 km of wave-carved cliffs and shoreline at Skylandia Beach (unit Qb,t, Fig. 2) (Kortemeier et al., 2005). Juvenile basaltic clasts predominate in both tuff and tuff breccia, and rounded, accidental, andesitic clasts are less abundant. The tuff breccia, which contains clasts up to 0.3 m in length, dips on average 25°–30° south. Accretionary (armored) lapilli in the palagonitized tuff were formed within a wet, ash-filled eruption plume and were most likely deposited subaerially by a surge (evidence below).

The tuff crops out at least 0.5 km inland from the beach and over 1 km offshore on the Tahoe City shelf. As noted earlier, several ROV dives in 2005–2008 examined the submerged tuff beds. Free divers collected samples of tuff and the underlying diatomaceous lake sediments in ~8 m of water. One ROV dive west of the Dollar Point fault and southeast of Skylandia Beach (Fig. 2) indicated that the tuff there is 25–30 m thick. In 10-m-high cliffs at Skylandia Beach, well-bedded tuff generally dips 15° to 35° south (Fig. 14A). The steep dip of the tuff beds, a measure of the cohesiveness of the material, indicates fairly wet emplacement conditions (Wohletz and Sheridan, 1983).

The tuffs consist of 1–40-cm-thick beds of ash and vesicular lapilli with three distinctive bed forms. An ash-rich and lapilli-poor type forms thin (~20 cm) beds and is dark gray to black (Fig. 14B). A second bedding type is lapilli rich and ash poor and forms up to 1-m-thick beds that are tan to yellow and poorly indurated. A third bedding type consists of equal amounts of ash and lapilli, is of medium thickness (up to 50 cm), and is well indurated. The variations in thickness and coarseness of these beds were apparently caused by variations in energy of individual pulsating explosive events. At least 25 explosive pulses are recorded by the exposed outcrops, but apparently no prolonged pauses in activity occurred because no major unconformities or layers of very fine grained tuff are present.

In all three bedding types, armored lapilli coated with a layer of fine-grained ash are abundant (Fig. 14C), reflecting their eruption into clouds of water-vapor charged with fine ash (White, 2001) and deposition on land or, possibly, in shallow water (Moore and Peck, 1962). Since much of the tuff cone is currently submerged under as much as 10 m of water, lake levels must have been lower when the tuff was deposited to allow subaerial deposition and preservation of armored lapilli.

Accidental andesitic and basaltic clasts up to 12 cm in diameter and juvenile bombs up to 75 cm in length are relatively abundant in the tuff. Some juvenile bombs exhibit cauliflower and plastic shapes, others have breast-crust margins, and many have radial joints (Fig. 15). All of these features indicate the juvenile bombs were hot when deposited. Most, but not all, bombs formed sag structures in the tuff (Fig. 15), suggesting that the tuff beds were wet and ductile when they were impacted by the bombs (White, 2001).

The tuffs exhibit several other features typical of deposition by surges, including sand-wave bed forms such as cross bedding, chute-and-pool features, winnowing of fines, and reverse grading (Moore et al., 1966; Waters and Fisher, 1971; Schmincke et al., 1973; Wohletz and Sheridan, 1979).

At Skylandia Beach proper, a complex, 24-m-wide zone of contorted and vertical tuff beds has been intruded by a 14-m-wide body of fractured, highly vesicular pillow lava. The pillow lava also invaded Pliocene–Pleistocene lake sediments along the contact with the tuff and formed fluidal peperitic margins that interfinger with the sediment. Similar features are described by Tucker and Scott (2009, see their figure 6a, p. 317).

The lacustrine sediments are disturbed in a 12-m-wide zone along the contact with tuff and pillow lava. This complex zone may perhaps be the southern edge of the vent for the tuff cone, and the pillow lava intruded and chilled along the contact between wet tuff beds within the vent and the lacustrine sediments. It is likely that the vent extends to the north of Skylandia Beach but is not exposed at the surface. The southerly dip of the tuff beds at Skylandia Beach, as well as the southerly direction of transport ascertained from chute-and-pool features and from the winnowing of fines from lee sides of clasts, indicate that the tuff erupted from a vent 100–200 m north of the beach (Fig. 2).

Abundant armored lapilli and lithic fragments in the tuff, together with the high vesicularity of the pillow lava in the vent area, suggest Skylandia Beach, like similar vents on Hawaii (Walker, 1992), exposes a primary vent rather than a littoral cone. However, the absence of any water-laid tuff, the presence of sizable bomb sags, and the presence of armored lapilli indicate that fragments flew through the air and were generally deposited on land, even though water and lacustrine sediments were nearby.

8. SHIFTING OF SHORELINES

The outlet of Lake Tahoe and Proto-Tahoe has been located within the area of the Truckee River Canyon throughout the past 2.3 million years. At least three cycles of volcanism have dammed the outlet by lava flows, which caused lake levels to rise. Subsequent erosional down-cutting through the lava dams has led to repeated lowering of the lake and lowering of shorelines (Fig. 16). At 2.3 Ma, lava dams raised the lake outlet from about its current elevation to produce a new lake level up to 149 m higher and the shoreline to migrate 0.2–1.2 km inland. By 2.1 Ma, the previous basalt dam had been eroded, lowering the lake and returning the shoreline again to near its modern
Figure 14. Basaltic tuff at Skylandia Beach. (A) Ash and lapilli tuff beds exposed along ~50 m of the shoreline at Skylandia Beach. Beds generally dip 25°–35° south. (B) Lapilli tuff forms three distinctive bedding types: (1) ash-rich and lapilli-poor, thinly bedded (<20 cm) and dark-gray to black; (2) lapilli-rich and ash-poor, thicker beds (up to 1 m), tan to yellow, and poorly indurated; (3) equally ash- and lapilli-rich, medium thickly bedded (up to 50 cm) and well indurated by palagonitized ash. (C) Majority of lapilli are coated with an accretionary thin layer of fine-grained, light-gray ash, as shown in enlargement of 1-cm-long lapillus.
elevation. Circa 2.1 Ma, new lava flows again dammed the lake outlet raising the lake level up 174 m and moving the shoreline 0.6–1.8 km inland. Before 0.94 Ma, the lava dam had again been removed and lake level had dropped an unknown amount. New lava flows erupted ca. 0.94 Ma, again dammed the lake outlet and raised the lake level ~186 m to a position ~2 km inland from its present location (Fig. 2). If erosion through the 0.94 Ma trachyandesite dam took the entire 940,000 years, that would indicate a down-cutting rate of 2 mm/yr.

Remarkably, the outlet canyon of the Truckee River repeatedly established and reestablished itself in the area near Rampart during each of these damming cycles. This location may mark the western extent of the Proto-Tahoe basin throughout the past 2.3 million years. The thick sequence of andesite lavas and breccias exposed at and west of Rampart (Fig. 2) may, as discussed earlier, be exposed on the footwall of a concealed north-south normal fault with east-side-down displacement (Kortemeier, 2012; Sylvester et al., 2012). This footwall ridge may have prevented lavas of units Qb1 and Qb2 from flowing farther west. The third damming event, at ca. 0.94 Ma, apparently occurred several kilometers downstream from Rampart. Subsequent episodes of down-cutting within the canyon involved the erosion of Pleistocene lava—both subaerial and fragmental subaqueous deposits—to expose the underlying more resistant Pliocene andesite.

Hydrovolcanic breccias that were produced as Pleistocene lavas entered Proto-Tahoe record water depths in the Tahoe City area that ranged from shallow—only a few meters—as at the Commons Beach littoral cone, to deep where 152 m of 0.94 Ma hydroclastic breccias are present in Jack Pine Canyon. During each eruptive cycle, the lavas invaded diatomaceous sediments and formed peperites, thereby establishing the contemporaneity of lava and sediments (Skilling et al., 2002). The diatoms in these lacustrine sediments (Fig. 5) indicate that Proto-Tahoe was at times a shallow, slightly alkaline lake, unlike present-day Lake Tahoe.

The present greatest depth of Lake Tahoe is 497 m. However, since the earliest phase of Proto-Tahoe, considerable thicknesses of lacustrine sediments have accumulated and numerous landslides have occurred. This shallowing effect has been offset by displacement along multiple normal faults, primarily east side down (Fig. 2) (Schweickert et al., 2000a; Brothers et al., 2009; Dingler et al., 2009). The increase in depth of the lake from normal fault displacements occurred even as the Truckee River cut down through the trachyandesite dam into the underlying andesite at Thunder Cliffs, and the lake surface dropped from its 2085 m elevation at 0.94 Ma to the 1897 m elevation at present. These relations show that normal fault displacements within the lake have exceeded rates of down-cutting of the outlet during the past million years.

Surprisingly, the present sill of Lake Tahoe where it is drained by the Truckee River is not resistant volcanic rock but instead is poorly indurated lacustrine deposits or tuff, both easily erodible materials. A small dam, built atop this material, controls the lake level over a few meters for irrigation purposes downstream. The powerful erosive action of the Truckee River is graphically shown in Figure 16 as it cut rapidly through at least three massive lava dams in the past 2.3 m.y. If these dams had not formed during volcanic events, it is likely that the history of Lake Tahoe would be very different. The Truckee River Canyon would by now be much deeper, the sill impounding the lake would be deeply incised, and the lake—if it still existed—would be considerably shallower.

The repeated volcanic activity in the northwest Tahoe region raises the question of future volcanic hazard. The three documented Pleistocene volcanic outbreaks from multiple vents (Figs. 2 and 16) indicate future volcanic activity is possible, and the undated Skylandia vent adds a fourth, apparently younger, event. The 2003 deep seismic swarm northeast of Tahoe City points to deep magma injection (Smith et al., 2004). Future damming of the lake outlet by lava would cause the lake level to rise, causing inundation of many
habitats in the Lake Tahoe Basin. If the impounding dam were to fail rapidly, serious flooding would occur downstream along the Truckee River to Reno and beyond.

9. CONCLUSIONS

Pleistocene basaltic to trachyandesitic lava flowed into, or erupted within, the ancient Lake Tahoe (Proto-Tahoe) Basin and invaded wet lacustrine sediments in the northwestern part of the lake basin. Lava flows dammed the Truckee River outlet of the lake, thereby causing the lake to rise to nearly 200 m. The lava-water interaction produced a succession of hyaloclastic products, including hydroclastic tufts and tuff breccias, pillow lavas and breccias, peperites, and in situ hydroclastic breccias.

Six new \(^{40}\text{Ar}/^{39}\text{Ar}\) ages date volcanism in the area from Pliocene andesite at 4.2 Ma (unit MPa), through Pleistocene predominantly basalt and trachybasalt at 2.3 Ma (unit Qbu), basaltic trachyandesite at 2.1 Ma (unit Qtf), and trachyandesite at 0.94 Ma (unit Qtf). These new age determinations, together with field relations, define a detailed history of Quaternary volcanic activity and associated fluctuations in lake level within the basin.

In addition to the basaltic and andesitic rocks listed above, a tuff cone of undetermined age (unit Qb,) is probably the youngest volcanic product. The four units of Pleistocene volcanic rocks can be distinguished by field relationships, age determinations, and geochemical analyses. Seven vents were active, including four tuff cones and three cinder cones. An additional tuff cone at Commons Beach in Tahoe City is a littoral cone formed when a lava flow of unit Qb entered Proto-Tahoe.

Within the Pleistocene volcanic rocks, transitions from subaerial lava flows to subaqueous lava deltas mark three elevated ancient shorelines of Proto-Tahoe. The distribution of hydrovolcanic products established episodes of damming within the Truckee River Canyon; these episodes raised the level of Proto-Tahoe. The first episode was at 2.3 Ma, when basaltic lavas flowed from the north and dammed the outlet of Proto-Tahoe at Rampart in the Truckee River Canyon, and raised lake level from ~1897 m to 2048 m. The second episode was at 2.1 Ma, when basaltic lavas from the west and/or northwest flowed east- and southward, dammed the lake outlet at Rampart, and raised lake level from ~1914 m to 2073 m. A third episode was at 0.94 Ma, when trachyandesitic lavas dammed the outlet west of Thunder Cliffs in the Truckee River Canyon, and raised lake level to 2085 m. Displacement of the basin along normal faults has exceeded the rate of down-cutting of the river over the past 940,000 years.

The damming of Proto-Tahoe that raised its water level three times in the past 2.3 m.y. has had a profound effect on the history of the lake. Without these damming episodes, the outlet of the lake that is underlain primarily by soft lake beds would have been lowered by erosion, the Truckee River Canyon would have deepened, and the lake would have been shallower. The timing of these Pleistocene volcanic events raises the possibility of recurrent volcanism and its hazards in the future. A future lava dam at the lake outlet would raise the lake level and flood most of the infrastructure in the Lake Tahoe Basin. Rapid failure of a new lava dam could cause extensive flooding down the Truckee River to Reno and beyond.

ACKNOWLEDGMENTS

Diatom images were obtained with the scanning electron microscope in the Geology Department, University of Nevada, Reno, aided by John McCormack. Major-, trace-, and rare-earth element data were obtained from ALS Chemex, Sparks, Nevada, with the help of Tommy Thompson at University of Nevada, Reno. Microprobe analyses of volcanic glass were made at the laboratories of the U.S. Geological Survey (USGS), Menlo Park, aided by Robert Oscarson. Four campaigns (2005, 2006, 2008, and 2011) utilizing the underwater, remotely operated vehicle, Triton, recovered images from the Tahoe City shelf and other shallow areas of the north lake under the direction of Chris Kitts and students from the Department of Engineering, Santa Clara University, California. Barry Moring provided valuable assistance with the illustrations. Volcanic rock samples were prepared and dated at the \(^{40}\text{Ar}/^{39}\text{Ar}\) Laboratory, USGS, Menlo Park. Critical reviews by Cathy Busby, Michael Clyne, Juliet Ryan-Davis, and Arthur Sylvester have significantly improved the manuscript and are greatly appreciated. The help and support of these institutions and individuals are gratefully acknowledged. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

REFERENCES CITED

Bateman, P.C., and Wahshafiq, C., 1966, Geology of the Sierra Nevada, in Bailey, E.A., et al., eds., California Division of Mines and Geology Bulletin 190, p. 107–172.

Birkeland, P.W., 1962, Pleistocene history of the Truckee area, north of Lake Tahoe, California [Ph.D. thesis]: Stanford, California, Stanford University, 126 p.

Birkeland, P.W., 1963, Pleistocene volcanism and deformation of the Truckee area, north of Lake Tahoe, California: Geological Society of America Bulletin, v. 74, p. 1453–1463, https://doi.org/10.1130/0016-7606(1963)74[1453:PVADOT]2.0.CO;2.

Birkeland, P.W., 1964, Pleistocene glacieration of the northern Sierra Nevada, north of Lake Tahoe, California: The Journal of Geology, v. 72, p. 810–825, https://doi.org/10.1086/627033.

Birkeland, P.W., 1968, Correlation of Quaternary stratigraphy of the Sierra Nevada with that of the Lake Lahontan area, in Morrison, R.B., and Wright, H.E., eds., Quaternary Soils: Boulder, Colorado, International Union for Quaternary Research (INQUA) VII Congress, 631 p.

Blackwell, P.E., 1931, Pleistocene glaciation in the Sierra Nevada and Basin Ranges: Geological Society of America Bulletin, v. 42, p. 865–922, https://doi.org/10.1130/0016-4472.42-865.

Brothers, D.S., Kent, G.M., Driscoll, N.W., Smith, S.B., Karlin, R., Dingler, J.A., Harding, A.J., Seitz, G.G., and Babcock, J.M., 2009, New constraints on deformation, slip rate, and timing of the most recent earthquake on the West Tahoe-Dollar Point Fault, Lake Tahoe Basin, California: Bulletin of the Seismological Society of America, v. 99, p. 489–519, https://doi.org/10.1785/0120080135.

Busby, C., 2013, Birth of a plate boundary at ca. 12 Ma in the Ancient Cascades arc, Walker Lane belt of California and Nevada: Geosphere, v. 9, p. 1147–1160, https://doi.org/10.1130/GES00828.1.

Calvert, A.T., and Lanphere, M.A., 2006, Argon geochronology of Kilauea’s early submarine history: Journal of Volcanology and Geothermal Research, v. 151, p. 1–18, https://doi.org/10.1016/j.jvolgeores.2005.07.023.

Cave, D.L., 1981, Geochemical Reactions between primary-treated sewage and volcanic phase assemblages near Tahoe City, California [M.S. thesis]: Reno, University of Nevada at Reno, 171 p.

Cave, D.L., and Dickinson, W.R., 1987, Chemical reactions between applied sewage and latite phase assemblages: Geological Society of America Abstracts with Programs, v. 19, p. 615.

Cousens, B.L., Henry, C.D., Harvey, B.J., Browning, T., Pfytyuk, J., and Allan, J.F., 2011, Secular variations in magmatism during a continental arc to post-arc transition: Plio-Pleistocene volcanism in the Lake Tahoe/Truckee area, Northern Sierra Nevada, California: Lithos, v. 123, p. 225–242, https://doi.org/10.1016/j.lithos.2010.09.009.

Dalrymple, G.B., 1964, Cenozoic chronology of the Sierra Nevada, California: University of California Publications in Geological Sciences, v. 42, p. 41.
DeGraff, J.M., and Aydin, A., 1983, Surface morphology of columnar joints and its significance to mechanics and direction of joint growth: Geological Society of America Bulletin, v. 99, p. 605-617, https://doi.org/10.1130/0016-7606(1983)99<605:SMOCAJ>2.0.CO;2.

Dickinson, W.R., 2001, Tectonic setting of the Great Basin through geologic time; implications for tectonic setting of the western Basin and Range Province, near Truckee, California [Ph.D. thesis]: Davis, California, University of California at Davis, 340 p.

Latham, T.S., Jr., 1985, Stratigraphy, structure, and geochemistry of Pli-Pleistocene volcanic rocks of the western Basin and Range Province, near Truckee, California [Ph.D. thesis]: Davis, California, University of California at Davis, 340 p.

Kortemeier, W.T., Moore, J.G., Schweickert, R.A., and Calvert, A.T., 2009b, Ar-Ar ages of Lake Tahoe basaltic sequences confirm several eruptions at 2.3 to 2.0 Ma and establish 0.94 Ma activity: Eos (Transactions, American Geophysical Union), v. 90, no. 52, Abstract V41B-2177.

Latham, T.S., Jr., 1985, Stratigraphy, structure, and geochemistry of Pli-Pleistocene volcanic rocks of the western Basin and Range Province, near Truckee, California [Ph.D. thesis]: Davis, California, University of California at Davis, 340 p.

Neves, J.A., and Aalto, K.R., 2002, Morphology of a crater-filling lava lake margin, The Peninsula tuff cone, Tule lake National Wildlife Refuge, California: Implications for formation of peperite textures: Journal of Volcanology and Geothermal Research, v. 114, p. 147-163, https://doi.org/10.1016/S0377-0273(01)00285-2.

Le Bas, M.J., Le Maitre, R.W., Streckeisen, A., and Zanetti, B., 1986, A chemical classification of volcanic rocks based on the total alkali-silica diagram: Journal of Petrology, v. 27, no. 3, p. 745-750, https://doi.org/10.1093/petrology/27.3.745.

Lindgren, W., 1897, Description of the Truckee quadrangle, California: U.S. Geological Survey Geologic Atlas Folio 39, scale: 1:125,000.

Lithgow-Bertelloni, C., and Richards, J.M., 2010, Initiation of extensional magmatism along a propagating rift zone: Nature, v. 468, p. 99-102, https://doi.org/10.1038/nature09638.

Moore, J.G., Schweickert, R.A., Lahren, M.M., Howle, J., Kitts, C., Ota, J.M., Richards, J.M., and Anonynous, 2004, Submarine geology within the western part of Lake Tahoe, California: Geological Society of America Abstracts with Programs, v. 36, no. 5, p. 137.

Moore, J.G., and Ault, W.U., 1966, Historic littoral cones in Hawaii: Pacific Science, v. XIX, p. 3-11.

Moore, J.G., and Peck, D.L., 1962, Accumulation rates of peperite in volcanic rocks of the western continental United States: The Journal of Geology, v. 70, p. 182-193, https://doi.org/10.1086/248807.

Moore, J.G., Kazuaki, N., and Alizar, A., 1966, The 1965 Eruption of Taal Volcano: Science, v. 151, p. 965-969, https://doi.org/10.1126/science.151.3713.965.

Moore, J.G., Phillips, R.L., Grigg, R.W., Peterson, D.W., and Swanson, D.A., 1973, Flow of lava into the sea, 1969-1971, Kilauea Volcano, Hawaii: Geological Society of America Bulletin, v. 84, p. 537-546, https://doi.org/10.1130/0016-7606(1973)84<537:FOLITS>2.0.CO;2.

Moore, J.G., Schweickert, R.A., Robinson, J.E., Lahren, M.M, and Kitts, C.A., 2006, Tsunami-generated boulder ridges in Lake Tahoe, California: Geology, v. 34, p. 965-968, https://doi.org/10.1130/G22643A.1.

Moore, J.G., Schweickert, R.A., and Kitts, C.A., 2014, Tsunami generated sediment wave channels at Lake Tahoe, California-U.S.A.: Geology, v. 40, no. 4, p. 673-676, https://doi.org/10.1130/GES01025.1.

Muehlberg, J.M., 2007, Geology of the Tahoe City sub-basin, Lake Tahoe, California-Nevada [MS thesis]: Reno, University of Nevada-Reno, 95 p.

Muffler, L.J.P., and Champion, D.E., 1981, Geochemical evolution of carbonate sediments in the western Great Basin: U.S. Geological Survey Open-File Report 81-244A, 80 p.

Moore, J.G., and Ault, W.U., 1966, Historic littoral cones in Hawaii: Pacific Science, v. XIX, p. 3-11.

Moore, J.G., and Peck, D.L., 1962, Transectionary alignment of volcanic rocks in the western continental United States: The Journal of Geology, v. 70, p. 182-193, https://doi.org/10.1086/248807.

Moore, J.G., Kazuaki, N., and Alizar, A., 1966, The 1965 Eruption of Taal Volcano: Science, v. 151, p. 965-969, https://doi.org/10.1126/science.151.3713.965.

Moore, J.G., Phillips, R.L., Grigg, R.W., Peterson, D.W., and Swanson, D.A., 1973, Flow of lava into the sea, 1969-1971, Kilauea Volcano, Hawaii: Geological Society of America Bulletin, v. 84, p. 537-546, https://doi.org/10.1130/0016-7606(1973)84<537:FOLITS>2.0.CO;2.

Moore, J.G., Schweickert, R.A., Robinson, J.E., Lahren, M.M, and Kitts, C.A., 2006, Tsunami-generated boulder ridges in Lake Tahoe, California: Geology, v. 34, p. 965-968, https://doi.org/10.1130/G22643A.1.

Moore, J.G., Schweickert, R.A., and Kitts, C.A., 2014, Tsunami generated sediment wave channels at Lake Tahoe, California-U.S.A.: Geology, v. 40, no. 4, p. 673-676, https://doi.org/10.1130/GES01025.1.

Muehlberg, J.M., 2007, Geology of the Tahoe City sub-basin, Lake Tahoe, California-Nevada [MS thesis]: Reno, University of Nevada-Reno, 95 p.

Muffler, L.J.P., and Champion, D.E., 1981, Geochemical evolution of carbonate sediments in the western Great Basin: U.S. Geological Survey Open-File Report 81-244A, 80 p.

Moore, J.G., and Ault, W.U., 1966, Historic littoral cones in Hawaii: Pacific Science, v. XIX, p. 3-11.

Moore, J.G., and Peck, D.L., 1962, Transectionary alignment of volcanic rocks in the western continental United States: The Journal of Geology, v. 70, p. 182-193, https://doi.org/10.1086/248807.

Moore, J.G., Kazuaki, N., and Alizar, A., 1966, The 1965 Eruption of Taal Volcano: Science, v. 151, p. 965-969, https://doi.org/10.1126/science.151.3713.965.

Moore, J.G., Phillips, R.L., Grigg, R.W., Peterson, D.W., and Swanson, D.A., 1973, Flow of lava into the sea, 1969-1971, Kilauea Volcano, Hawaii: Geological Society of America Bulletin, v. 84, p. 537-546, https://doi.org/10.1130/0016-7606(1973)84<537:FOLITS>2.0.CO;2.

Moore, J.G., Schweickert, R.A., Robinson, J.E., Lahren, M.M, and Kitts, C.A., 2006, Tsunami-generated boulder ridges in Lake Tahoe, California: Geology, v. 34, p. 965-968, https://doi.org/10.1130/G22643A.1.

Moore, J.G., Schweickert, R.A., and Kitts, C.A., 2014, Tsunami generated sediment wave channels at Lake Tahoe, California-U.S.A.: Geology, v. 40, no. 4, p. 673-676, https://doi.org/10.1130/GES01025.1.

Muehlberg, J.M., 2007, Geology of the Tahoe City sub-basin, Lake Tahoe, California-Nevada [MS thesis]: Reno, University of Nevada-Reno, 95 p.
Schweickert, R.A., 1981b, Tectonic evolution of the Sierra Nevada Range, in Ernst, W.G., ed., The Geotectonic Development of California (Rubey Volume 1): Englewood Cliffs, New Jersey. Prentice-Hall, p. 87–131.

Schweickert, R.A., 2009, Beheaded west-flowing drainages in the Lake Tahoe region, northern Sierra Nevada: Implications for timing and rates of normal faulting, landscape evolution and mechanism of Sierran uplift: International Geology Review, v. 51, p. 984–1033, https://doi.org/10.1080/00206810903122481.

Schweickert, R.A., and Lahren, M.M., 2002, Glacial geology of Blackwood Canyon, Lake Tahoe, California: Implications for landslides and tsunami: Geological Society of America Abstracts with Programs, v. 34, no. 6, p. 130–131.

Schweickert, R.A., Lahren, M.M., Smith, K., and Karlin, R., 1999a, Preliminary fault map of the Lake Tahoe Basin, California and Nevada: Seismological Research Letters, v. 70, no. 3, p. 306–312, https://doi.org/10.1785/gssrl.70.3.306.

Schweickert, R.A., Lahren, M.M., Smith, K., and Karlin, R.E., 1999b, Holocene megalandslides in Lake Tahoe triggered by earthquakes along active faults: Geological Society of America Abstracts with Programs, v. 31, no. 6, p. 93.

Schweickert, R.A., Lahren, M.M., Karlin, R., Howle, J., and Smith, K., 2000a, Lake Tahoe active faults, landslides, and tsunamis, in Lageson, D.R., Peters, S.G., and Lahren, M.M., eds., Great Basin and Sierra Nevada: Geological Society of America Field Guide 2, p. 1–21.

Schweickert, R.A., Lahren, M.M., Karlin, R.E., Smith, K.D., and Howle, J.F., 2000b, Lake Tahoe Basin (Ltb): Asymmetric half-graben with active faults, megalandslides, and tsunamis: Geological Society of America Abstracts with Programs, v. 32, no. 6, p. 67.

Schweickert, R.A., Lahren, M.M., Smith, K.D., Howle, J.F., and Ichinose, G.A., 2003, Transtensional deformation in the Lake Tahoe region, California and Nevada, USA: Tectonophysics, v. 392, p. 303–323, https://doi.org/10.1016/j.tecto.2004.04.019.

Schweickert, R.A., Lahren, M.M., Howle, J.F., and Kortemeier, W., 2011, Geology of the Lake Tahoe region, Nevada and California: Northern California Geological Society, 39 p.

Sheridan, M.F., and Wohletz, K.H., 1983, Hydrovolcanism: Basic considerations and review: Journal of Volcanology and Geothermal Research, v. 17, p. 1–29.

Skilling, I.P., White, J.D.L., and McPhie, J., 2002, Peperite: A review of magma-sediment mingling: Journal of Volcanology and Geothermal Research, v. 114, p. 1–17, https://doi.org/10.1016/S0377-0273(01)00278-5.

Smith, K.D., von Seggern, D., Blevitt, G., Preston, L., Anderson, J.G., and Wernicke, B.P., 2004, Evidence for deep magma injection beneath Lake Tahoe, Nevada-California: Science, v. 305, p. 1277–1280, https://doi.org/10.1126/science.1103104.

Smith, S.B., Karlin, R.E., Kent, G.M., Seitz, G.G., and Driscoll, N.W., 2013, Holocene subaqueous paleoseismology of Lake Tahoe: Geological Society of America Bulletin, v. 125, no. 5/6, p. 691–708, https://doi.org/10.1130/B30629.1.

Starratt, S.W., 2005, Latest Pliocene and Quaternary diatom floras of the Lake Tahoe Basin, California and Nevada, USA: Eos (Transactions, American Geophysical Union), v. 86, no. 851, p. D-0245.

Sylvestre, A.G., Wise, W.S., Hastings, J.T., and Moyer, L.A., 2012, Geologic Map of the Tahoe–Donner Pass Region, Northern Sierra Nevada, California: California Geological Survey, Map Sheet 60, scale 1:48,000.

Tucker, D.S., and Scott, K.M., 2009, Structures and facies associated with the flow of suberial basaltic lava into a deep freshwater lake: The Sulphur Creek lava flow, north Cascades, Washington: Journal of Volcanology and Geothermal Research, v. 185, no. 4, p. 311–322, https://doi.org/10.1016/j.jvolgeores.2008.11.028.

Verosub, K., Davis, J.O., Sarna-Wojcicki, A.M., and Anonymous, 2004, Pleistocene lacustrine sediments in the Lake Tahoe basin, California: Geological Society of America, Abstracts with Programs, v. 36, no. 5, p. 499, paper 214–18.

Walker, G.P.L., 1992, Puu Mahana near South Point in Hawaii is a primary Surtseyan ash ring, not a sandhills-type littoral cone: Pacific Science, v. 46, no. 1, p. 1–10.

Waters, A.C., and Fisher, R.V., 1971, Base Surges and Their Deposits: Capelinhos and Taal Volcanoes: Journal of Geophysical Research, v. 76, p. 5596–5614, https://doi.org/10.1029/JB076i023p05596.

White, J.D.L., 2001, Eruption and reshaping of Palvant Butte Volcano in Pleistocene Lake Bonneville: Special Publication of the International Association of Sedimentologists, v. 30, p. 61–80.

Wohletz, K.H., and Sheridan, M.F., 1979, A model of pyroclastic surge, in Chapin, C.E., and Elston, W.E., eds., Ash-Flow Tufts: Geological Society of America Special Paper 180, p. 177–194.

Wohletz, K.H., and Sheridan, M.F., 1983, Hydrovolcanic explosions: II, Evolution of basaltic tuff rings and tuff cones: American Journal of Science, v. 283, no. 5, p. 385–413, https://doi.org/10.2475/ajs.283.5.385.