Morphology and processes in Lake Tahoe (California-Nevada)

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ABSTRACT

Lake Tahoe was surveyed using a state-of-the-art, high-resolution, multibeam mapping system to provide an accurate base map for the myriad of ongoing environmental studies in and around the lake. The newly defined basin morphology shows steep basin margins on the northern, eastern, and western sides and a gentle margin on the southern side. Two large, flat plateaus several kilometers wide extend from the shore to about 40 m water depth in the northern and northwestern sections of the basin. A series of ridges in the west and north are presumed traces of faults, some of which border the lake basin and some of which traverse across the northern section of the lake and converge in McKinney Bay. McKinney Bay is a large reentrant in the western margin that was created by a failure of the western margin that occurred about 300 ka. The failure generated a major debris avalanche that carried large blocks, some more than 1000 m long and 80 m high, across the basin. Apparently, the debris avalanche was deflected by the eastern margin of the basin and flowed to the north and south. Small debris flows and slides have continued to occur in this area. Small debris aprons occur along the northern, western, and eastern margins, some apparently the remnants of collapsed terminal moraines formed in the basin from the 160 ka Tahoe Glaciation, which reached the edge of the basin. Eroded plateaus and ridges occur on a glacial outwash plain that covers the gentle southern margin. The plateaus and ridges are inferred to be remnants of another large terminal moraine of the Tahoe Glaciation.

Keywords: backscattering, bathymetry, Lake Tahoe, processes, Sierra Nevada.

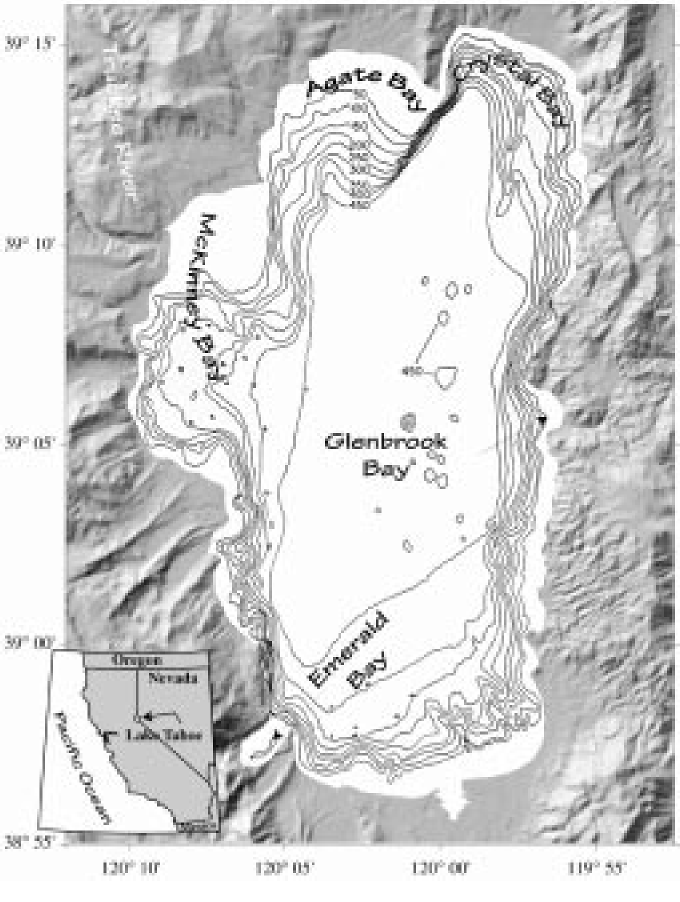

Figure 1. Location map of Lake Tahoe (inset) and names of various bays around Lake Tahoe. The land shaded-relief surface is from the U.S. Geological Survey 30 m digital elevation model (DEM), illuminated from an azimuth of 315° and elevation of 45°. Contoured bathymetry of Lake Tahoe from data from the U.S. Coast and Geodetic Survey (1923), with slight modifications by Hyne (1969). Contour interval is 50 m.

INTRODUCTION

Lake Tahoe, situated in the mountains of the Sierra Nevada astride the California-Nevada border (Fig. 1), is one of the largest lakes in the United States and is ranked the twelfth deepest lake in the world (Herdendorf, 1990). Myths of the lake's great depth, its supposedly strange density, and it's cobalt color caught the attention of the native Washoe Indians, the early trappers, the first white settlers, and the gold-rush-era inhabitants of the area. Only a few depth measurements had been made prior to 1923, either by fishermen or by Charles Burckhalter of the U.S. Naval Observa-

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tory (McGlasham and McGlasham, 1986). The U.S. Coast and Geodetic Survey properly surveyed Lake Tahoe in 1923 (U.S. Coast and Geodetic Survey, 1923) using a state-of-the-art leadline-sounding technique. Navigation for the 1923 survey was by line-of-sight triangulation. Several hundred soundings were recorded in 1923, and, with the exception of 20 poorly navigated echo-sounder lines collected in the late 1960s (Hyne, 1969), the 1923 soundings represent the published bathymetry of Lake Tahoe.

Lake Tahoe was thoroughly resurveyed up to the 5 m contour during 10 days in August 1998, by a team from the U.S. Geological Survey, the University of New Brunswick (Canada), and C&C Technologies, Inc. As with the 1923 survey, we also used a state-of-the-art bathymetric-mapping system. Our system included a high-resolution multibeam echosounder, a vehicle motion sensor with inertial navigator, and a dual differential global positioning system (GPS) navigation system. The survey was conducted because research on Lake Tahoe is increasing, and these investigations have only the 1923 bathymetric map to use as a base. The new survey collected more than 65 million soundings that are geographically referenced using positioning accuracy that is better than ±1 m. Here, we present new maps of the detailed morphology and backscatter of Lake Tahoe and discuss the processes and events that shaped the lake floor and margins.

METHODS

The 1998 survey used a 23 ft (7m), twin-outboard boat specifically designed for a hull-mounted Kongsberg Simrad EM1000 multibeam system (Alleman et al., 1993). The EM1000 system operates at 95 kHz with a 0.2 or 0.7 ms pulse width and generates 60 or 48 electronically steered and stabilized 3.5° × 2.5° receive beams to generate an across-track swath up to 150° wide. Vehicle motion was measured using a TSS POS/MV model 310 sensor that provides roll, pitch, and heave at 100 Hz with accuracies of 0.05° as well as true heading to 0.5°. Positions were provided by the TSS POS/MV inertial-navigation system backed up by a Trimble dual-differential GPS system. The navigation system's accuracy was measured against established U.S. Geological Survey benchmarks along the northern side of Lake Tahoe and was found to provide position accuracies of better than ±1 m. Vertical sound velocity profiles for the lake were determined using a SeaBird CTD (conductivity, temperature, depth) and periodic, expendable bathythermograph measurements. Sound velocity at the transducer was measured by a fixed sound-velocity sensor. The sound-velocity profiles were used to individually raytrace each sounding from each beam to correctly locate the sounding on the lake floor. All of the attitude and sound-velocity data were networked to the Kongsberg Simrad processor for accurate beam forming and preprocessing. The survey was run at about 8 kts during daylight hours only (for safety concerns), and all the data were processed in the field during the survey. Specific details of the systems and processing can be found in Gardner et al. (1998).

The depth accuracy of the EM1000 system when properly compensated is better than 0.5% of water depth. All measured depths were referenced to the lake level as measured by a U.S. Geological Survey lake gauge at the Tahoe City Coast Guard station. However, because the lake level changed only 6 cm during the 10 day survey, no corrections were applied to the data. Measured lake depths were converted to elevations above mean sea level to provide a continuous digital elevation model for the entire Tahoe basin (see Smith et al., 1998).

In addition to bathymetry, the EM1000 system also records the strength of acoustic backscatter from each beam footprint. The backscatter, measured in decibels (dB), is similar in appearance to a sidescan-sonar record. The system and processing software corrects the strengths received at each beam for source-level gain changes, grazing angle, propagation losses, predicted and measured beam patterns, and the insonified area. Each –3 dB change in backscatter represents a 50% decrease in received energy. Backscatter is a function of a combination of surface roughness and volume reverberation within the area of the individual beam footprint (a few meters squared) and an unknown and variable thickness (probably on the order of <25 cm) of sediment. A map of backscatter can be loosely interpreted as some indication of the physical characteristics of the lake floor (Gardner et al., 1991; Hughes Clarke, 1993).

GENERAL GEOLOGY OF THE REGION

Lake Tahoe formed in the westernmost graben of the Basin and Range physiographic province. The Tahoe graben separates the easternmost Sierra Nevada from the Carson Range, the westernmost range of the Basin and Range province. Lindgren (1897) was the first to recognize the graben structure of the Lake Tahoe basin. The timing of the formation of the Lake Tahoe graben is uncertain but is generally considered to have occurred after andesitic volcanism and deformation between 7.4 and 2.6 Ma (Wahrhaftig, 1965). The western boundary faults of the graben are mapped as a series of discontinuous normal faults that pass west of the present lake (LeConte, 1875; Lindgren, 1897; Louderback, 1924; Hudson, 1948, 1951; Pakiser, 1960; Burnett, 1971). The eastern boundary faults have not been mapped but only inferred from the shape of the lake basin (Burnett, 1968). The graben initially was not closed on the northern end. Three different hypotheses have been proposed to account for the formation of Lake Tahoe: (1) a blockage of the northern end of the graben by a buried upfaulted basement block (Birkeland, 1964); (2) a blockage by a buildup of andesitic mudflow breccias from the Martis Peak area (Louderback, 1911); and (3) a combination of warping and faulting (Blackwelder, 1933). Volcanics that overlie the earliest lake deposits have been dated at 1.9 ± 0.1 Ma (Burnett, 1968); consequently, a latest Pliocene–earliest Pleistocene age is suggested for the initial filling of the lake.

Lake Tahoe is underlain primarily by the granodioritic Sierra Nevada batholith and related prebatholithic metamorphic rocks (Burnett, 1968). Andesitic volcanic rocks cover the northern and northwestern sections of the area, and Quaternary glacial deposits blanket the southwestern and southern end of the basin (Burnett, 1968). Late Pleistocene glaciations left a profound influence on the geomorphology of the Sierra Nevada immediately west of the lake but appear to have minimally affected the Carson Range immediately to the east (Burnett, 1968). The thickness of sediment in Lake Tahoe has not been determined. Although Hyne (1969) used a 1 in^3 (16 cm^3) air gun to collect 20 seismic profiles across the lake, the published seismic records only penetrate to about 300 m below the lake floor and show no evidence of basement.

Surprisingly little has been published on the sedimentology of Lake Tahoe. Two studies of the surface sediment (Hyne et al., 1972; Court et al., 1972), provide information from only 60 sample locations. In general, the lake floor is covered with fine-grained sediment (mud and clay) with the northern third having increased silt and sand. The published surface sediment analyses show no trend or pattern that might be indicative of either sediment provinces or depositional processes. Three lithostratigraphic sections from short (5 m) cores correlate closely with one another (Palmer et al., 1979). The bottom 2 m of the sections are composed of interbedded fine-grained silts and muds, turbidites of undescribed composition, and intervals described as varves. The turbidites are overlain by a 0.5-m-thick diatomite that is overlain in turn by about 3 m of silt and mud with thin (decimeter thick) micaceous silt interbeds. One prominent volcanic ash, possibly the Mazama Ash from Crater Lake, Oregon (Hyne, 1969; Bacon, 1983), is described at about 1.5 m subbottom. Conventional radiocarbon dates published from Lake Tahoe sediment suggest an average sedimentation rate of about 15 cm/k.y. for the past 10 k.y. (Hyne et al., 1972).

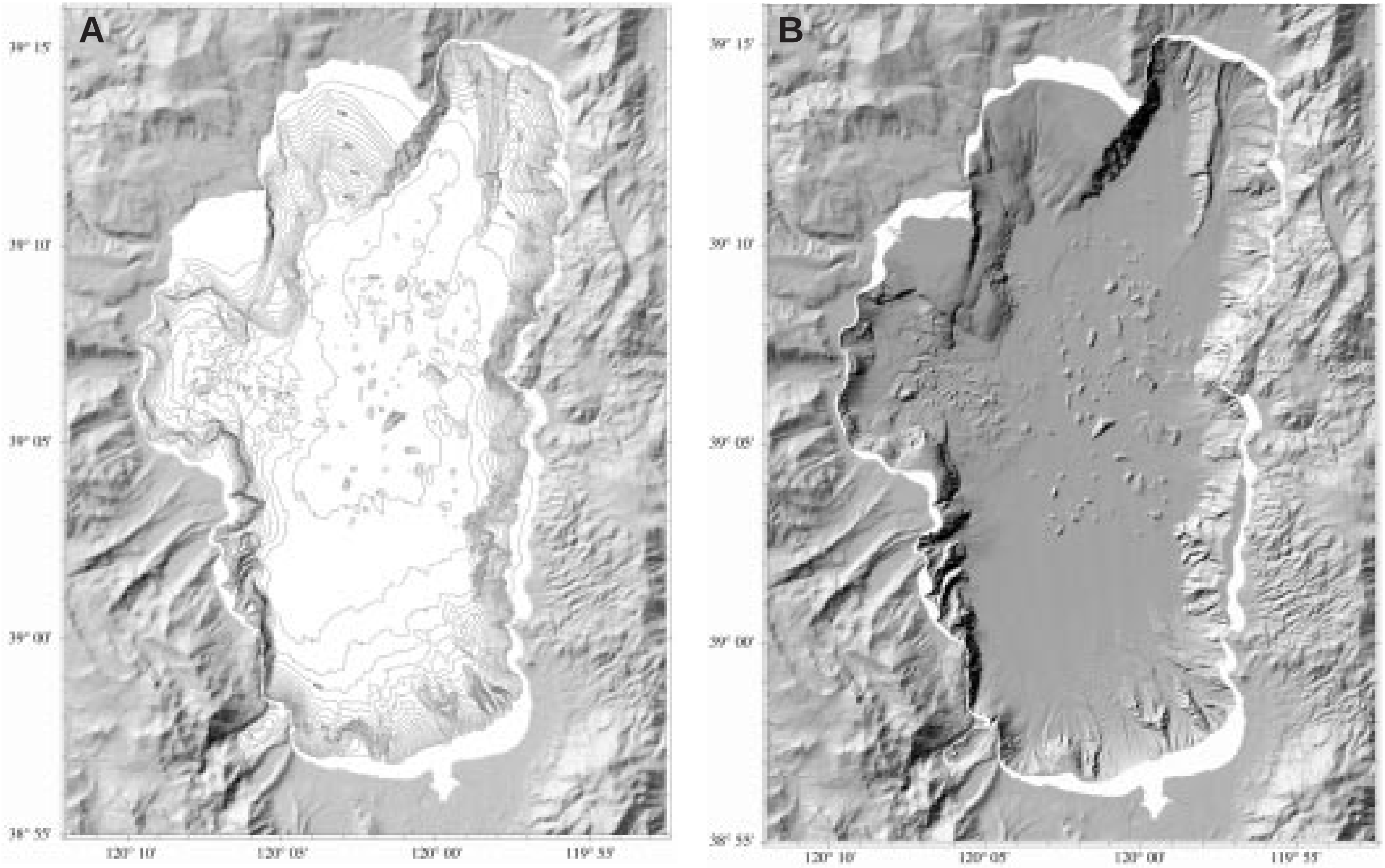

Figure 2. (A) Contoured bathymetry of Lake Tahoe from the 1998 multbeam survey. Isobaths are relative to a 1900 m lake level. Contour interval is 20 m. Bathymetry is referenced to a lake-level elevation of 1900 m. The land shaded-relief surface is from the U.S. Geological Survey (USGS) 30 m digital elevation model (DEM), illuminated from an azimuth of 315° and elevation of 45°. (B) Shaded-relief bathymetry of Lake Tahoe from the 1998 multibeam survey. The land shaded-relief surface is from the USGS 30 m DEM. Both land and lake basin are illuminated from an azimuth of 315° and elevation of 45°. White zone between DEM and bathymetry is area of no data. A color version of this image can be viewed and downloaded on the web at http://walrus.wr.usgs.gov/pacmaps/. A CD-ROM with the images and gridded data (Dartnell and Gardner, 1999) and a paper copy of the colored bathymetry (Gardner et al., 1999) can be obtained from the U.S. Geological Survey, Box 25046, Denver, Colorado 80225-0046.

THE MORPHOLOGY AND BACKSCATTER OF LAKE TAHOE

The 1923 bathymetric survey of the lake by the U.S. Coast and Geodetic Survey was a remarkable mapping achievement. That survey measured to within a few meters the maximum depth of the lake (measured in 1998 to be 499 m), even though fewer than a thousand soundings were collected. A contour map of those data, slightly modified by Hyne (1969), is shown in Figure 1. The general outlines of the lake features were determined in the 1923 survey, and many of the major physiographic features were identified.

The 1998 multibeam survey of Lake Tahoe (Fig. 2, A and B) generated more than 65 million soundings of the depth of the lake floor as well as more than 65 million coregistered values of backscatter (Dartnell and Gardner, 1999). The lake basin is generally characterized by a narrow, relatively flat nearshore zone, a steep slope that plunges >400 m, an abrupt change from slope to basin, and a flat lake floor. The exceptions to this generalization are two broad, flat, shallow plateaus in the northern and northwestern sections of the lake, a gently sloping southern margin, and a large reentrant on the western margin. In a general way, the lake basin is shaped like an early twentieth century bathtub; the northern, eastern, and western margins are steep (30° to >70°) and the southern margin is more gently sloping (5°). The backscatter of the margins of the basin shows intermediate values that range from –29 to –32 dB. The margin values contrast to the very low backscatter values (–45 to –55 dB) of the flat basin floor and the high backscatter values of two plateaus (–25 to –28 dB; see following discussion).

Six steep-sided linear trends in the bathymetry suggest faulting (Figs. 4 and 5). Two of these inferred faults form the western and eastern boundaries of the lake basin (called herein the Eastern Boundary fault and the Western Boundary fault); three others trend north-northeast and traverse the floor of the lake basin (called herein the Kings Beach, State Line, and Incline faults); and the sixth inferred fault strikes roughly east-west across the northern part of McKinney Bay (called herein the McKinney fault). The southward extension of the State Line fault can be clearly seen as a 15 m offset of the lake floor (Fig. 2A) and subbottom reflectors on a seismic profile (Fig. 5). Sections of the State Line and Incline faults have scarps >60° and sections of the Western and Eastern Boundary faults have scarps of more than 45° and 27°, respectively.

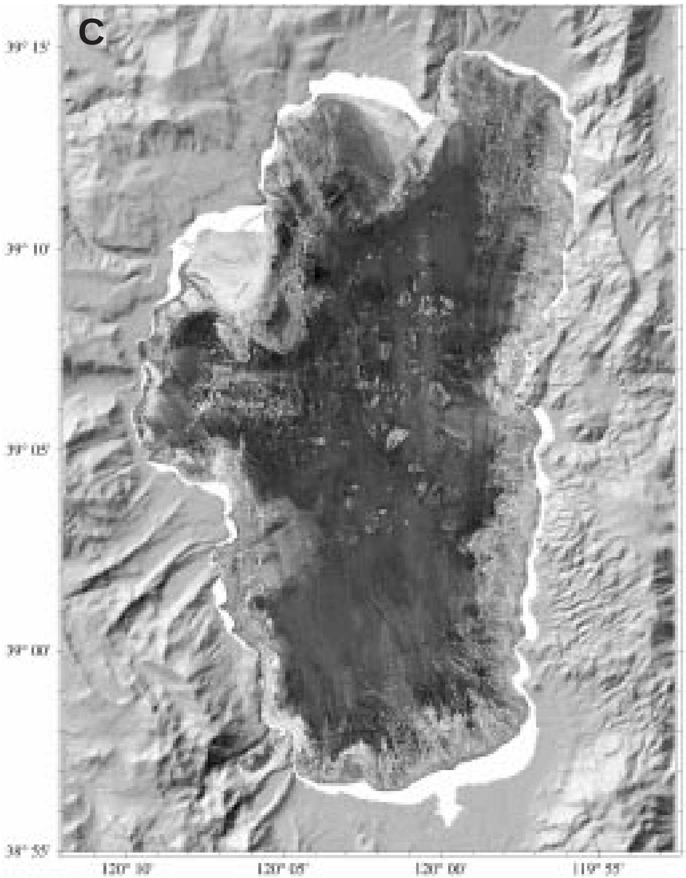

Figure 2. (C) Calibrated backscatter map of the Lake Tahoe basin. The backscatter varies from –25 dB (light) to –55 dB (dark). The land shaded-relief surface is from the U.S. Geological Survey 30 m digital elevation model (DEM), illuminated from an azimuth of 315° and elevation of 45°.

McKinney Bay, the large reentrant on the western margin, and the adjacent basin to the east, have the most dramatic bathymetry of the lake. A 12-km-long, arcuate, 180-m-high headwall scarp with slopes >20° occurs along the western margins of the bay. The floor of the reentrant is hummocky and littered with blocks and rubble that have high backscatter (–30 dB) values (Figs. 2C and 7). A well-developed drainage pattern has developed on the hummocky surface. There is a pronounced ~5-m-high arcuate toe about 9 km east of the headwall scarp that appears to be the termination of a complex debris apron. Beyond the toe, large (up to 1000 m long by as much as 400 m wide) isolated blocks, some rising more than 80 m above the lake floor, are scattered throughout an otherwise flat, middle half of the lake basin floor. The isolated blocks have a very high backscatter (–27 to –31 dB). Goldman and Court (1968) surveyed one of these blocks and attributed it to a volcanic intrusion. However, Henyey and Palmer (1974) analyzed 500 km of magnetic profiles across the lake and found no evidence of volcanic rocks near the lake floor.

The southern end of the lake basin has a different morphology from the rest of the basin. The southern margin gently slopes toward the north with a gradient of only 5° compared with the steep slopes along the other margins. Sediment has built out about 3.5 km farther into the lake on the southeastern side compared with the southwestern side of the lake. The upper margin of the southern end has several large, heavily eroded plateaus and ridges that extend northward (Figs. 2A and 7). The style of erosion of the plateaus and ridges appears as both slumping and gullying all along their margins. Long, shallow, discrete, low-backscatter gullies have formed at the bases of the plateaus and ridges, some more than 5 km in length, that trend toward the middle of the lake floor. The gullies typically are about 150 m wide and a few meters deep. The gully margins and interfluves are covered with fields of asymmetric high-backscatter bedforms (Fig. 7) with heights of 5 m and spacings of about 50 m. The stoss (or gentle) side of each bedform has a higher backscatter (–27 dB) than the lee side (–50 dB).

The two shallow, relatively flat plateaus occur along the northern and northwestern margins of the lake (Fig. 2). The plateau on the northern margin of Agate Bay is at less than 40 m water depth and is roughly triangular in shape with a western side 1.2 km wide increasing to 2.7 km wide over a distance of 4 km. The surface slopes 0.3° toward the south and is tilted 0.1° toward the east. The plateau in the northern end of McKinney Bay also is in less than 40 m of water and is roughly square shaped, with dimensions of 4.6 km east-west by 4.8 km north-south. The surface of the plateau is tilted toward the south at 0.1° and has a surface relief of about 2 m.

Debris aprons (a term used herein as the aqueous equivalent of an alluvial fan) occur in only a few localities at the base of the lake margin. The debris aprons typically have backscatter that is intermediate (–30 to –40 dB) between the low backscatter of the flat lake basin and the higher backscatter of the steep margins. Two relatively small debris aprons occur at the base of the eastern margin. The larger of these two aprons (2.8 km wide at the base and 120 m high at the apex) occurs directly below Glenbrook Bay and can be followed on land to the mouth of a broad valley. The smaller debris apron (1.4 km wide and 120 m high) occurs about 2.5 km south of the Glenbrook Bay apron and also can be followed up the margin to a valley. At the base of the western margin just south of McKinney Bay, two separate debris aprons have coalesced into a 3.4-km-wide subaqueous equivalent of a bajada (Figs. 2 and 8). Both debris aprons can be followed up the canyon to broad glacial valleys on land. A prominent ~2-m-deep gully has developed across the northern of the two aprons and traverses more than 2.5 km onto the basin floor. The bajada is covered with relatively large-scale bedforms (~5 m heights by ~100 m wavelengths) that extend to the basin floor (Fig. 8).

A relatively large debris apron occurs in the northern end of the lake on the northwestern corner of Crystal Bay (Figs. 3 and 10). This apron is about 1.2 km wide, 2.3 km long, and descends more than 200 m to the lake floor. The toe of the debris apron is 13 m higher than the basin floor. Sediment has been fed to the apron by a series of channels that incise the adjacent steep margins, and the upper reach of the sediment wedge is covered with 4-m-high, 160 m wavelength bedforms. Two large isolated blocks (100 × 200 m) lie at the boundary of the upper reaches with the lower debris apron. The blocks stand 30 and 46 m above the basin floor.

A complex debris apron occurs in Crystal Bay. The debris apron has developed at the base of a perched chute that traverses from the northeastern corner of the lake at the shoreline down to the basin floor (Fig. 10). The chute has formed on the eastern side of the linear ridge called here the Incline fault (Fig. 4). The floor of the chute is about 200 m below the crest of the ridge and is about 1.6 km wide. A channel floor is incised about 15 m into the floor of the chute and has formed a gently sinuous course for more than 9 km. Large asymmetrical bedforms in the upper reaches of the channel are ~4 m high and up to 180 m in wavelength, whereas the lower reaches of the channel have symmetrical bedforms that are ~3 m high with wavelengths of about 200 m (Fig. 10A). The lower channel changes course to the west at the lake-basin floor and has formed a 300-m-wide debris lobe with a <1-m-deep channel and levee system perched ~20 m above the basin floor.

Emerald Bay (Fig. 1) is essentially a shallow (maximum 50-m-deep) lake connected to Lake Tahoe by a 70-m-wide, 3-m-deep channel. The

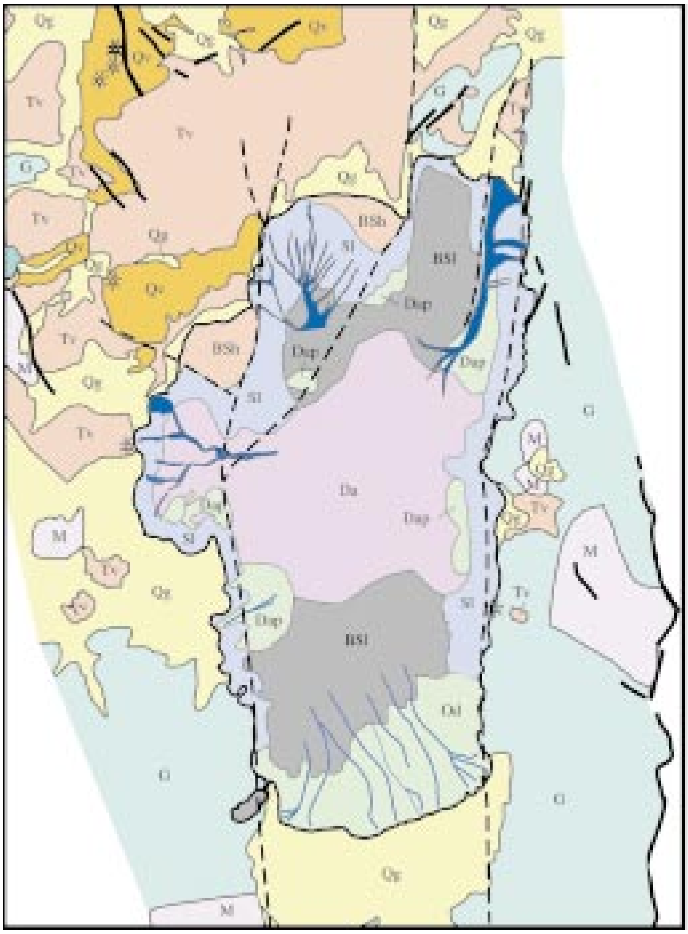

Figure 3. Compilation of the geology of the Tahoe area from Burnett (1968) and a terrain map constructed from the bathymetry and backscatter. Land geology key: heavy solid black line—known fault; heavy dashed line—inferred fault; star pattern—volcanic cone; G—Mesozoic granites; M—Paleozoic and Mesozoic metamorphic rocks; Qg—Quaternary glacial sediments; Qv—Quaternary volcanics; Tv—Tertiary volcanics. Terrain key: dendritic pattern—drainage; BSh—high backscatter plateau; BSl—low backscatter lake floor; Dap—debris apron; Od—glacial outwash delta and moraine; SI—steep lake basin margin. See Figure 4 for fault labels.

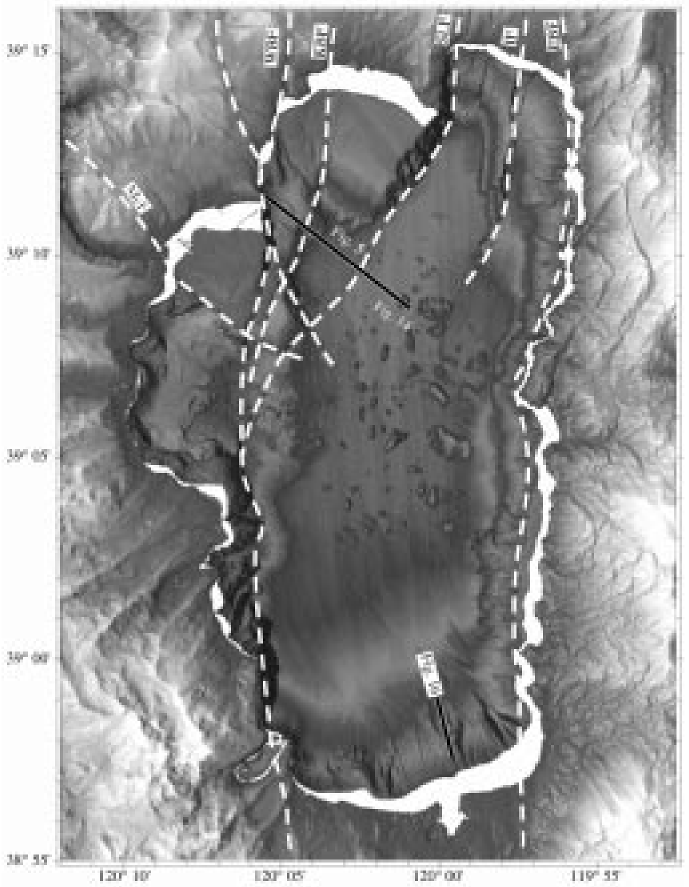

Figure 4. Map of inferred faults (heavy dashed lines) in the Lake Tahoe area. Fault key: EBF—Eastern Boundary fault; IF—Incline fault; KBF—Kings Beach fault; McF—McKinney fault; SLF—State Line fault; WBF—Western Boundary fault. The land shaded-relief surface is from the U.S. Geological Survey 30 m digital elevation model (DEM). Shaded-relief land and lake basin are illuminated from an azimuth of 315° and elevation of 45°. Location lines for Figures 5 and 16 are shown as heavy solid lines.

morphology of the bay is fairly simple. An island in the northwestern section of the bay rises from the eastern edge of a 10-m-high, 500-m-long shelf, and a 10-m-high ridge crosses the eastern end of the bay just west of the shallow connection. About 2 km north of Emerald Bay, a large (550-m-wide × 160-m-deep), U-shaped hanging valley lies 180 m beneath the lake surface (Fig. 11). This is the only hanging valley identified around the perimeter of the lake.

DISCUSSION

Lake Tahoe occupies the westernmost Basin and Range graben that has been blocked off at both ends. The most significant morphological change that occurred once the lake formed was the creation of McKinney Bay. The geomorphology of the McKinney Bay reentrant and the adjacent basin floor represents a major failure of the western margin of the lake. The failure does not easily fit into the classification of landslide types proposed by Varnes (1978). However, the presence of a well-developed amphitheater in the upper end and the presence of large blocks scattered tens of kilometers away on the basin suggest that the failure can be classified as a debris avalanche, following the descriptions of such failures by Crandell et al. (1984), Moore et al. (1989), and Glicken (1998). The term is not an exact fit because debris avalanches typically are narrow relative to a long run-out dimension and have a hummocky terrain at their *distal* end, rather than their proximal end. The resulting deposit should be very similar to a megabreccia as described by Longwell (1951). Not surprisingly, piston cores from Lake Tahoe (Hyne, 1969; Palmer et al., 1979) recovered thin interbedded turbidites, a facies commonly recovered in large lakes (e.g., Sturm and Matter, 1978; Kelts and Hsü, 1980; Anadón et al., 1989; Giovanoli, 1990).

Hyne (1969) suggested a failure origin for what he called large “mounds” found on the middle of the lake basin floor, and he speculated that the failure was related to glacial-age slumping of ice-cemented lake-margin sediment. Hyne et al. (1973) suggested that the mounds were the result of mass wasting of the western margin caused by a proposed collapse of ice dams near the outlet of Lake Tahoe that catastrophically lowered the lake level (Birkeland, 1964).

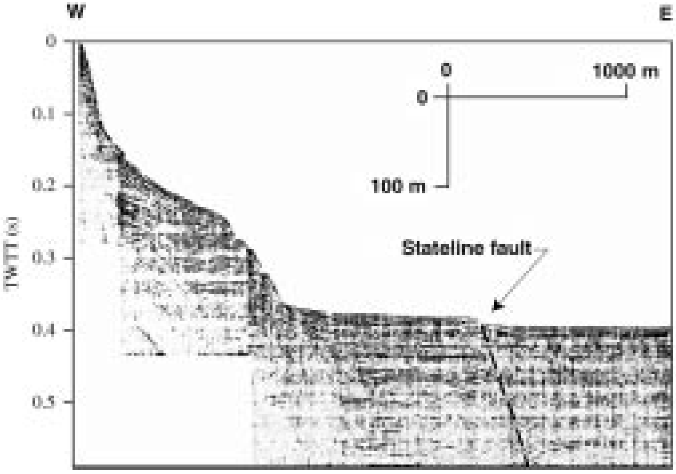

Figure 5. Scan of seismic record across northwestern part of Lake Tahoe (from Hyne et al., 1972). See Figure 4 for location of line. State line fault is shown by both a surface offset and offset subbottom reflectors. Two-way traveltime (TWTT) is converted to depth using 1500 m/s sediment velocity.

Figure 6. Oblique view of the bathymetry of McKinney Bay. The opening of the bay toward the lake basin is about 6.5 km across. Note the toe of large debris apron (white arrows) and the large blocks strung out along suspected flow paths. Wheel diagram in upper left shows vertical exaggeration and view azimuth.

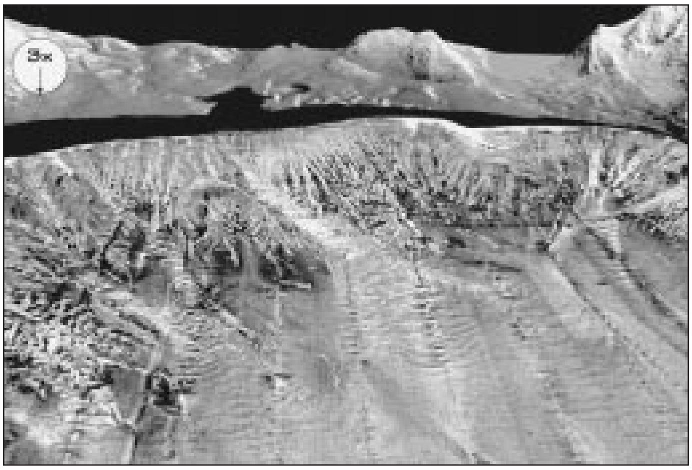

Figure 7. Oblique view of backscatter draped over bathymetry of southern end of Lake Tahoe. A straight line across the shoreline would be about 23 km long. Note extensive fields of bedforms and gullies leading out across the basin away from the margin. Wheel diagram in upper left shows vertical exaggeration and view azimuth.

Figure 8. Shaded-relief bathymetry of the southwestern margin and proximal basin floor just south of McKinney Bay. Prominent headlands (middle of image) rise ~350 m above two coalesced debris aprons (bajada). Large bedforms have formed on the surface of the bajada (see text). The horizontal scale across the middle of the figure is ~10 km. Smaller debris aprons are seen to the south. Wheel diagram in upper left shows vertical exaggeration and view azimuth.

To better understand the nature of the failure, measurements of block length, width, height (all above the sediment surface), and distance from an arbitrary point immediately east of the headwall scarp were made on each of the 113 blocks from the floor of McKinney Bay out to the toe of a debris apron and on each of the 110 blocks from beyond the toe to the eastern margin. A distinct break in trend of block length, width, and height with distance (Fig. 12) corresponds to the location of the toe of the debris apron. The dimensions of the blocks in the basin have more scatter than those west of the toe. Furthermore, of those blocks in the eastern part of the basin, there is a wider distribution of block sizes than occurs in the western part. The best-documented debris avalanche is the 1980 debris avalanche from Mount St. Helens volcano (Glicken, 1998). Glicken's data show that the widest scatter of displaced-block dimensions at Mount St. Helens occurs less than halfway along the path of the debris avalanche. The most reasonable explanation for the distribution of block dimensions of the Tahoe debris avalanche is that the major failure traversed across the lake floor, reflected against the eastern margin, and was then deflected to the north, south, and back toward the west, effectively flowing back onto itself (Fig. 13). The changes in trends of block dimensions with distance at the toe suggest that additional smaller failures continued to occur in the reentrant after the major failure.

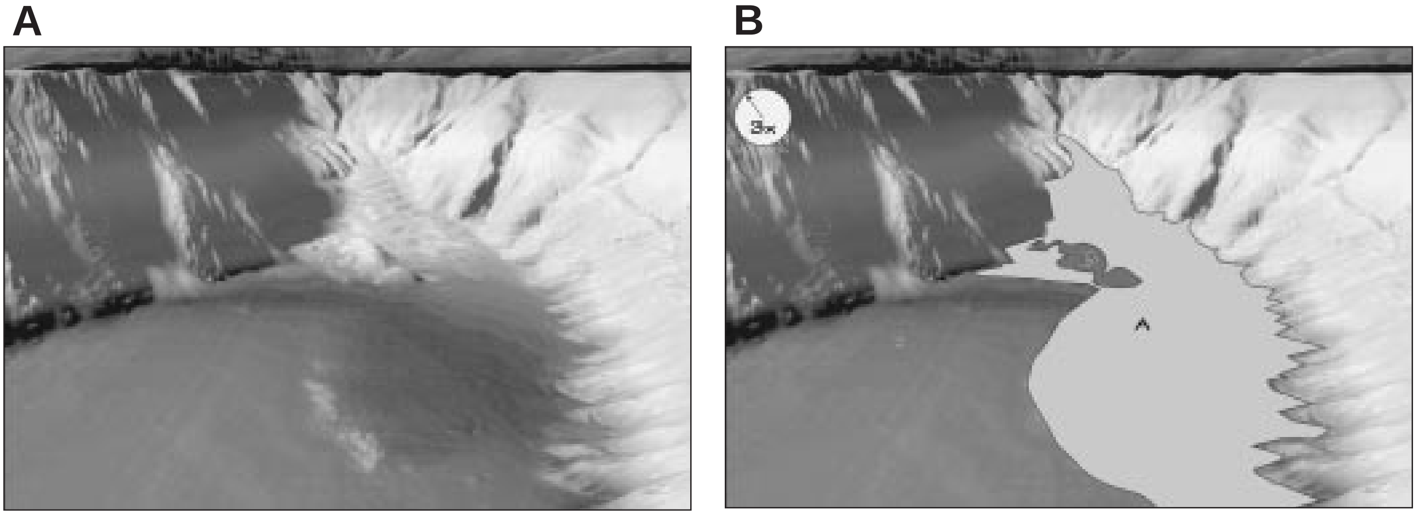

Figure 9. (A) Oblique view of shaded-relief bathymetry looking into Crystal Bay. Steep margin on left of image is the Kings Beach fault; some sections with slopes >70°. (B) Interpretation shown by overlays. Relatively small debris apron (light pattern, A) is covered with large bedforms; debris apron is ~4.5 km long. Two large blocks (dark gray area, B) lie at the toe of debris apron. Basin-floor sediments (gray area, C) have a subtly lower backscatter than the sediments of the debris apron. Wheel diagram in upper left shows vertical exaggeration and view azimuth.

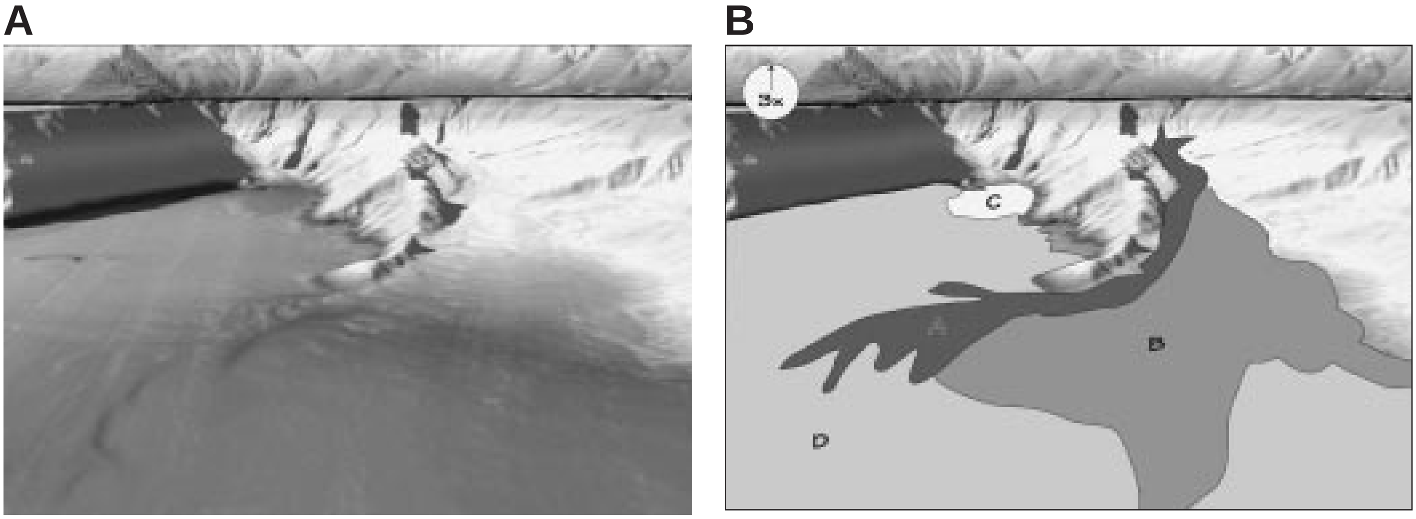

Figure 10. (A) Oblique view of shaded-relief bathymetry looking into Crystal Bay. The sinuous ridge in middle of view is the fault ridge of the Incline fault. (B) Interpretation shown by overlays. Relatively large debris apron (dark gray area, B) developed in a perched chute between the eastern margin and the ridge of the Incline fault. The debris apron is covered with large bedforms. Within the debris apron, a channel (very dark gray area) has incised into the upper debris apron, and a depositional lobe has developed at its distal end (area of A) on top of the basin-floor sediments (light gray area, D). A small debris apron (white area, C) is seen in the background. Wheel diagram in upper left shows vertical exaggeration and view azimuth.

The most convincing evidence that explains the clast nature of the blocks is found in a figure of Hyne et al. (1973; their Fig. 6). Subparallel, acoustically stratified reflectors occur beneath one of the large blocks (section C in Fig. 14). These reflectors are gently tilted and diverge to the west and appear to be undisturbed by the emplacement of the large block. A disturbed reflector overlies the stratified-reflector packet (section B in Fig. 14). A 50-m-thick zone (using 1500 m/s for sediment velocity) of disturbed reflectors (section A′ in Fig. 14) overlies the basal disturbed zone. The base of the block is not well defined in the seismic profile but this block appears to be about 100 m tall. About 80 m of sediment extend from the disturbed layer to the top of the adjacent sediment column, and only the upper half of that section is well stratified. This observation suggests the lower half of the upper section (A in Fig. 14) is matrix material of the debris avalanche, and the upper half of section A (~ 40 m) represents post-failure sedimentation. The average sedimentation rate of 15 cm/k.y. is based on ^{14}C dates (Hyne et al., 1972). Although this rate is not necessarily representative for the entire sediment sequence, it nevertheless suggests an age in the range of ca. 300 ka for the occurrence of the debris avalanche.

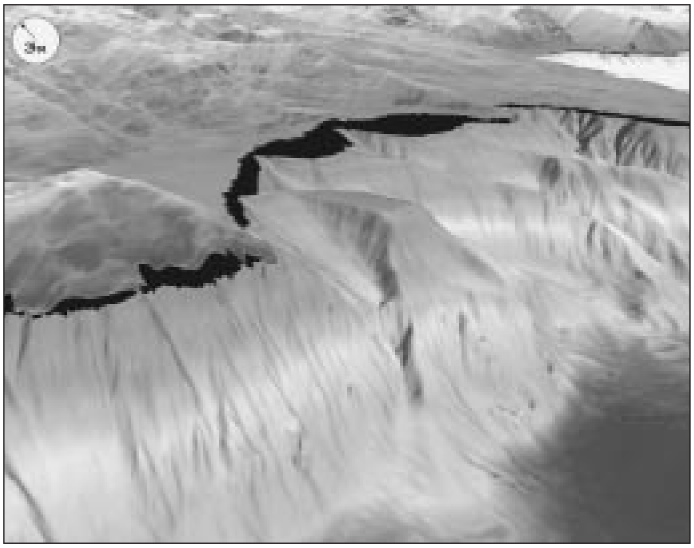

Figure 11. Oblique view of shaded-relief bathymetry looking at southwestern margin of Lake Tahoe. Note large, U-shaped hanging valley in middle of image. Valley is 700 m across with 140 m of relief at the shelf break. The floor of the valley is presently beneath 180 m of water.

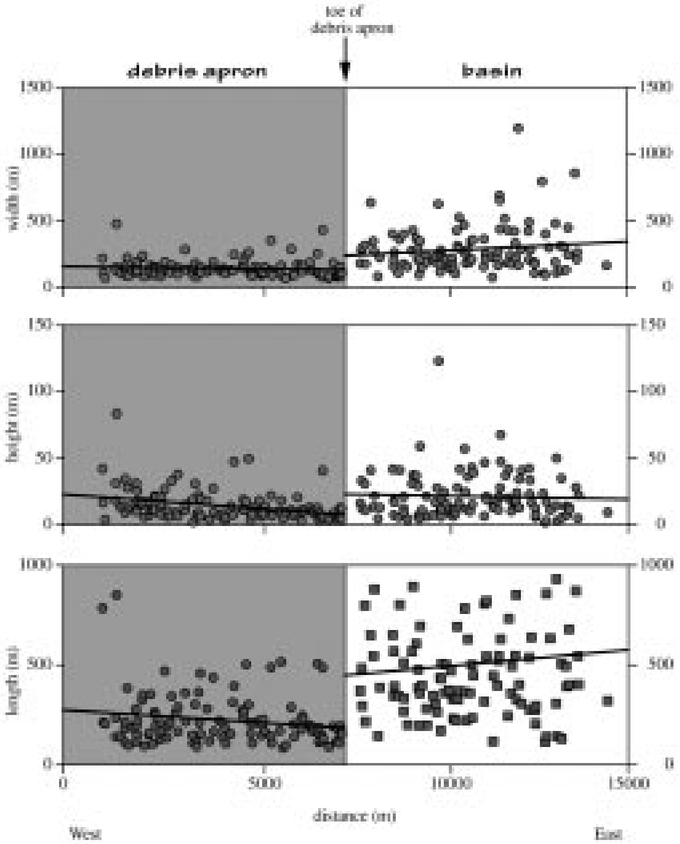

Figure 12. Plots of length, width, and height measurements on all blocks from the McKinney Bay debris avalanche. Solid line is linear regression. Note the break in trends that separates blocks of the debris apron from those of the basin proper.

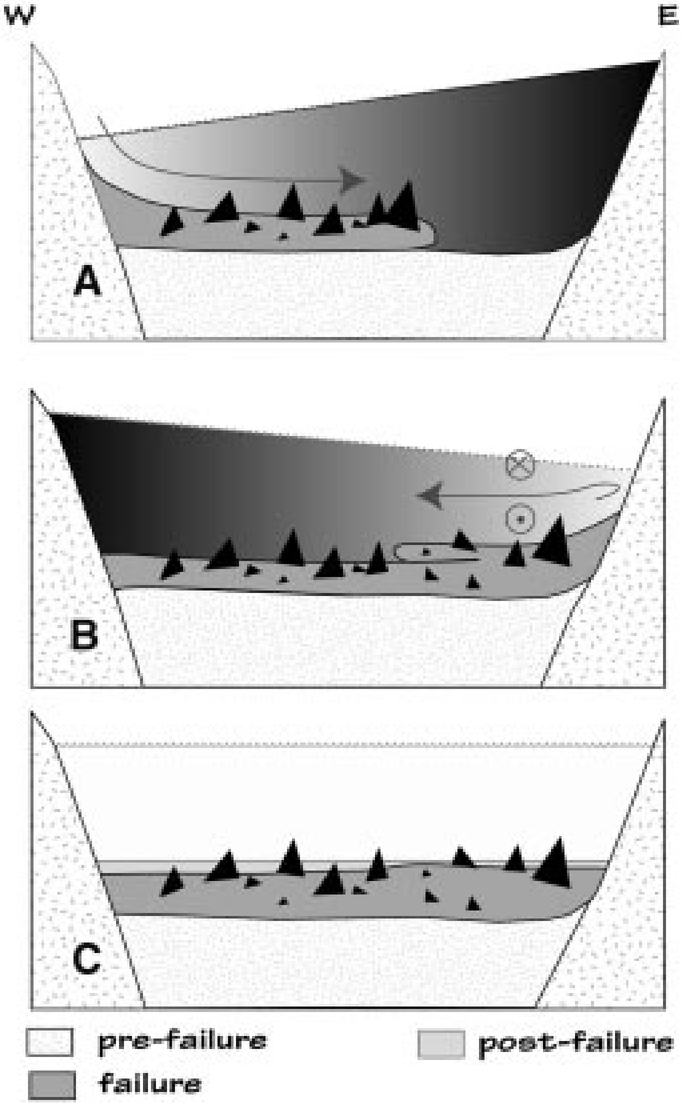

Figure 13. Diagrams showing conceptual evolution of McKinney Bay debris avalanche. (A) Panel shows initial stage when large blocks are carried out into basin. (B) Panel shows flow reflected against eastern margin and back toward west, north, and south. (C) Panel shows debris avalanche deposit being buried by post-failure sedimentation.

Sediment-transport processes following the debris avalanche created a series of sinuous channels that funneled sediment across the hummocky reaches of the upper debris-avalanche field toward the center of the basin (Fig. 6). The channels are as great as 100 m wide, 1 to 2 m deep, and some traverse more than 3.8 km across the area.

The bathymetry shows that the State Line, McKinney, and Western Boundary faults all pass through a zone at the northeastern side of McKinney Bay (Fig. 4), suggesting an earthquake mechanism for the trigger of the failure. The fresh appearance of a small debris flow along the Kings Beach fault (Fig. 15) suggests relatively recent seismic activity. This small debris flow was deposited on top of the large debris avalanche.

One of the effects of the Tahoe debris avalanche might well have been a considerable lake seiche. If the seiches were violent enough, they may have generated large runup waves onto the land (Geist, 1998). The runup waves might have produced the equivalent of tsunami deposits at various

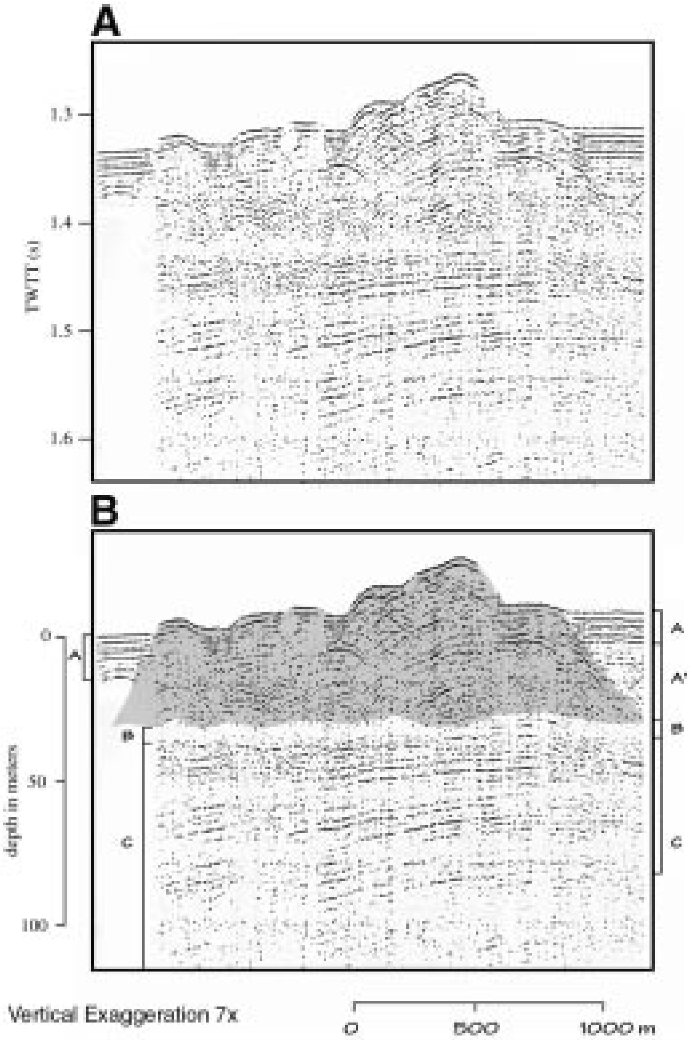

Figure 14. (A) Seismic profile across large allochthonous block in center of Lake Tahoe (from Hyne et al., 1973). See Figure 4 for location of line. Two-way traveltime (TWTT) is converted to depth using 1500 m/s sediment velocity. (B) Overlay showing interpretation of seismic record; section labeled A is acoustically stratified surficial material, sections A′ and B are matrix of the debris avalanche, and section C is acoustically stratified material, undisturbed by the debris avalanche, beneath the block.

locations around the lake. The well-studied Kitimat slide in British Columbia (see Prior et al., 1982, and references therein) is thought to have produced a solitary water wave similar to a tsunami. The wave was estimated by observers to be as high as 8 m and was modeled by Murty (1979) to be 6.3 m high. Murty (1979) developed an equation to predict the height of a solitary wave given various geomorphic parameters. Although the Kitimat slide is much smaller in scale than the Tahoe debris avalanche, application of the equation would predict that the Tahoe debris avalanche might have produced a solitary wave 101 m high.

Birkeland (1964) described scattered glacial till and erratics that have been mapped at elevations at least 30 m higher than the present lake level and explained their presence as a result of higher lake levels produced by glacial tongues that blocked the outlet to the lake. According to his hypothesis, once the lake level reached a critical height, the ice tongues became buoyant, causing a catastrophic collapse of ice dams (jökulhlaup). An alternate hypothesis is that the scattered till and erratics might be the result of lake seiches created by the Tahoe debris avalanche that produced the equivalent of a tsunami deposit above lake level. Birkeland (1964) described the deposits as boulders overlain by soil with abnormally high (24%) clay content. This description is similar to those of interpreted tsunami deposits (i.e., Moore and Moore, 1984; Bryant et al., 1992). It seems probable that the effects of the Tahoe debris avalanche might have left deposits stranded well above the lake level.

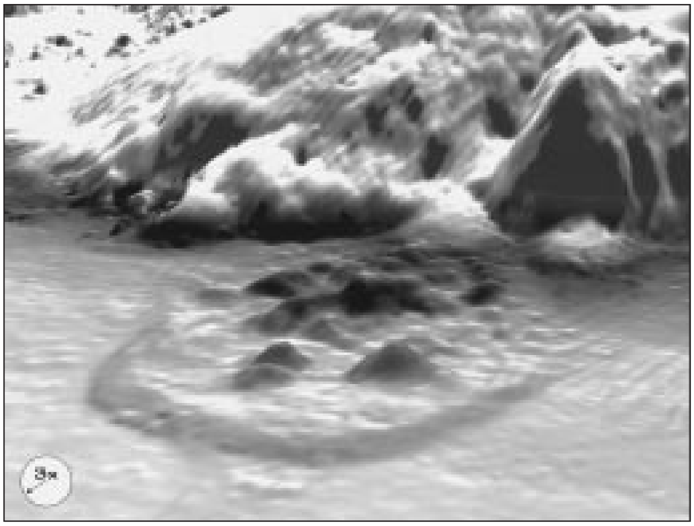

Figure 15. Oblique view of shaded-relief bathymetry of small debris flow near the junction of the Kings Beach fault and the Western Boundary fault. The debris flow is 1550 m long and 1200 m wide at its midpoint. More than a dozen large (up to 15 m tall), isolated blocks have been carried out onto the basin floor. The toe of the debris flow rises about 6 m above the basin floor.

The glaciers of the penultimate Tahoe Glaciation (~160 ka) reached the southern shore of Lake Tahoe, but the glaciers of the last glacial maximum, the Tioga Glaciation (~20 ka) did not extend that far (M. Clark, 1998, personal commun.). The two large bathymetric plateaus on the southern margin of the lake (Figs. 2B and 7), presently at 200 to 400 m below lake level, appear to be large masses of material pushed into position by the Tahoe age glaciers. A seismic profile published by Hyne (1969) and Hyne et al. (1972) crosses one of the blocks. The record (Fig. 16A) clearly shows an acoustically stratified section that probably represents periglacial outwash that is overlain by a hummocky, acoustically unstratified mass that rises ~60 m above the periglacial outwash section. The size of the unstratified mass, the presence of the plateaus only along the southern margin, and the lack of internal acoustic stratification within the highs suggest that the plateaus are the remnants of a terminal moraine. The unit I sequence in Figure 16B is acoustically parallel stratified and is overlain by an acoustically unstratified unit II, similar to the sequence highlighted in Figure 16B. The seismic record also shows an older sequence beneath the plateau that might represent an even older glacial-interglacial cycle.

The heavy dissection along the margins of the southern plateaus suggests that erosional processes were active over a considerable period of time. Erosional gullies and channels on the margin do not align with any above-lake topography, suggesting they formed solely by lake processes. The eroded sediment has developed narrow, sublinear channels that trend north-northwest toward the center of the basin (Fig. 7). Most of the channels are bounded by fields of large (5-m-high, 25 m wavelength) bedforms

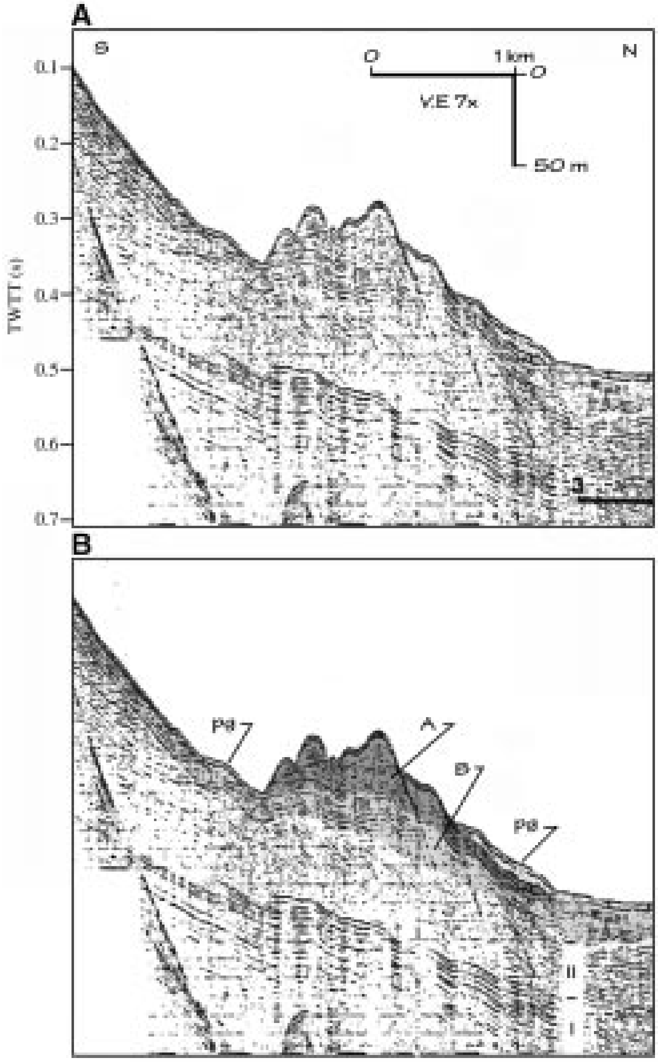

Figure 16. (A) Scan of seismic record across the southern margin of Lake Tahoe (from Hyne, et al., 1972). See Figure 4 for location of line. Two-way traveltime (TWTT) is converted to depth using 1500 m/s sediment velocity. (B) Overlay showing interpretation: Unit A (dark gray) is terminal moraine from Tahoe Glaciation; unit B (medium gray) is outwash delta of Tahoe Glaciation; Unit I is older outwash delta overlain by unit II, its associated terminal moraine; Unit pg is post-glacial deposits.

that were produced by vigorous flow events, probably similar to the slump and turbidity current described by Kelts and Hsü (1980). However, without samples for grain-size analyses, it is impossible to predict the flow regime required to generate the bedforms. The most reasonable scenario to explain the geomorphology of the southern end of the lake is that the plateau highs and ridges represent what remains of the terminal moraine of the Tahoe-age glaciers. The lake must have been much lower than at present sometime during the past 160 000 yr so that these poorly consolidated morainal deposits could be continuously reworked by vigorous lake processes.

Each of the debris aprons can be followed up the margin and onto land where they can be traced into a valley. The valleys with corresponding debris aprons on the western side of the lake lie in broad glacial valleys bordered by lateral moraines; however, no terminal moraines are evident in the land topography. This fact suggests that the debris aprons in the lake at the base of the margin in these areas might represent the missing terminal moraines. Although the two debris aprons on the eastern side of the lake can be followed onto land to present creeks, there do not appear to be any large glacial valleys in their paths.

The U-shaped hanging valley on the southwestern side of the lake (Fig. 11) suggests that the lake level was much lower sometime during the past 2 m.y. than at present so that a glacier could advance to this position. All of the mountain valleys and moraines of the Tahoe Glaciation (160 ka) and Tioga Glaciation (20 ka) suggest that the lake levels at these times were close to the present level and certainly not 180 m lower (M. Clark, 1998, personal commun.). Consequently, the U-shaped valley must have been carved during an earlier, presumably more severe glaciation, when the lake level was much lower.

The very low backscatter of the basin floor suggests that the surficial sediment is composed of a mixture of glacial flour and clays and not silty clay as indicated from analyses from piston cores (Court et al., 1972). Piston cores from Lake Tahoe typically did not sample the upper few tens of centimeters of sediment (Hyne, 1969), but the 1.5 cm wavelength of the multibeam system interacts with approximately the top 10 cm of sediment. Consequently, the interpretations of surficial facies from the piston cores is probably misleading. The signal-to-noise ratio is at the limit of detection for the EM1000 system. There are no indications of deltas building out into the lake, and the only inflowing streams are small and ephemeral; consequently, it is not surprising that the lake-floor sediments are fine grained. The high backscatter of the northern, eastern, and western margins probably represents rock outcrops. The very high backscatter of the two large plateaus probably represents a surface roughness of the Quaternary volcaniclastics that are found immediately onshore adjacent to these two areas (Fig. 3).

CONCLUSIONS

The 1998 mapping of Lake Tahoe was undertaken to fulfill a commitment to provide the Lake Tahoe research community with a highly accurate base map of the lake basin. The diversity and scale of geological features found in the lake were not anticipated, although earlier studies hinted at them. The major geomorphic features of Lake Tahoe are summarized in a terrain map that is superposed on the geologic map of the area (Fig. 3). The detailed bathymetry suggests that a series of faults defines the eastern and western boundaries of the graben, as well as cut across the northern and western portions of the lake floor. The faults converge at a zone within McKinney Bay. The large reentrant of McKinney Bay is the site of a large failure that occurred about 300 ka and produced a debris avalanche that traversed eastward across the lake and reflected against the eastern margin. The failure may well have generated a severe lake seiche that produced the equivalent of tsunami deposits previously described as elevated lakeshore sediments.

Debris aprons are found at the base of the lake margins on the western, southern, and eastern sides of the lake. The presence of these debris aprons suggests the terminal moraines of the Tahoe Glaciation, generated on the western and southern sides of the lake, were formed in the present-day lake basin and are now found on the floor of the lake.

It seems strange that more is not known about the sedimentation history of Lake Tahoe. From what little can be found in the literature, it would seem that a detailed record of the past several hundred thousand years of sedimentation, including a detailed climate history for this region, is there for the collecting.

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REFERENCES CITED

Anadón, P., Cabrra, L., Juliá, R., Roca, E., and Rosell, L., 1989, Lacustrine oil-shale basins in Tertiary grabens from northeastern Spain (western European rift system): Palaeogeography, Palaeoclimatology, Palaeoecology, v. 70, p. 7–28.

Alleman, P.J., Chance, T.S., and Kleiner, A.A., 1993, New-generation mapper for shallow water hydography: Sea Technology, v. 34, p. 17–22.

Bacon, C.R., 1983, Eruptive history of Mount Mazama and Crater Lake caldera, Cascade Range, U.S.A.: Journal of Volcanology and Geothermal Research, v. 18, p. 57–115.

Birkeland, P.W., 1964, Pleistocene glaciation of the northern Sierra Nevada, north of Lake Tahoe, California: Journal of Geology, v. 72, p. 810–825.

Blackwelder, E., 1933, Eastern slope of the Sierra Nevada, in middle California and western Nevada, *in* International Geological Congress, 16th, Guidebook 16, p. 81–95.

Bryant, E.A., Young. R.W., and Price, D.M., 1992, Evidence of tsunami sedimentation on the southeastern coast of Australia: Journal of Geology, v. 100, p. 753–765.

Burnett, J.L., 1968, Geology of the Lake Tahoe basin, *in* Evans, J.R., and Matthews, R.A., eds., Geologic studies in the Lake Tahoe area, California and Nevada: Geological Society of Sacramento, Annual Field Trip Guidebook, p. 1–13.

Court, J.E., Goldman, C.R., and Hyne, N.J., 1972, Surface sediments in Lake Tahoe, California-Nevada: Journal of Sedimentary Petrology, v. 42, p. 359–377.

Crandell, D.R., Miller, C.D., Glicken, H.X., Christiansen, R.L., and Newhall, C.G., 1984, Catastrophic debris avalanche from ancestral Mount Shasta volcano, California: Geology, v. 12, p. 143–146.

Dartnell, P., and Gardner, J.V., 1999, Sea-floor images and data from multibeam surveys in San Francisco Bay, southern California, Hawaii, the Gulf of Mexico, and Lake Tahoe, California-Nevada: U.S. Geological Survey Digital Data Series DDS-55 (CD-ROM).

Gardner, J.V., Field, M.E., Lee, H., Edwards, B.E., Masson, D.G., Kenyon, N., and Kidd, R.B., 1991, Ground truthing 6.5-kHz sidescan sonographs: What are we really imaging?: Journal of Geophysical Research, v. 96, p. 5955–5974.

Gardner, J.V., Mayer, L.A., and Hughes Clarke, J.E., 1998, Cruise Report, RV *Inland Surveyor* Cruise IS-98: The bathymetry of Lake Tahoe, California-Nevada: U.S. Geological Survey Open-File Report 98-509, 28 p. (available at http://blt.wr.usgs.gov).

Gardner, J.V., Dartnell, P., Mayer, L.A., and Hughes Clarke, J.E., 1999, Bathymetry and selected perspective views of Lake Tahoe, California and Nevada: U.S. Geological Survey Water Resources Investigation Report 99-4043, 2 sheets.

Geist, E.L., 1998, Local tsunamis and earthquake source parameters: Advances in Geophysics, v. 39, p. 117–209.

Giovanoli, F., 1990, Horizontal transport and sedimentation by interflows and turbidity currents in Lake Geneva, *in* Tilzer, M.M., and Serruya, C., eds., Large lakes: Ecological structure and function: New York, Springer-Verlag, p. 175–195.

Glicken, H., 1998, Rockslide-debris avalanche of May 18, 1980, Mount St. Helens volcano, Washington: Bulletin of the Geological Survey of Japan, v. 49, p. 55–106.

Goldman, C.R., and Court, J.E., 1968, Limnological studies of Lake Tahoe, *in* Evans, J.R., and Matthews, R.A., eds., Geologic studies in the Lake Tahoe area, California and Nevada: Geological Society of Sacramento, Annual Field Trip Guidebook, p. 60–66.

Henyey, T.L., and Palmer, D.F., 1974, Magnetic studies on Lake Tahoe, California-Nevada: Geological Society of America Bulletin, v. 85, p. 1907–1912.

Herdendorf, C.E., 1990, Distribution of the world's large lakes, *in* Tilzer, M.M., and Serruya, C., eds., Large lakes: Ecological structure and function: New York, Springer-Verlag, p. 3–38.

Hudson, F.S., 1948, Donner Pass zone of deformation, Sierra Nevada, California: Geological Society of America Bulletin, v. 59, p. 796–800.

Hudson, F.S., 1951, Mount Lincoln–Castle Peak area, Sierra Nevada, California: Geological Society of America Bulletin, v. 59, p. 795–800.

Hughes Clarke, J.E., 1993, The potential for seabed classification using backscatter from shallow water multibeam sonars, *in* Pace, N., and Langhorne, D.N., eds., Acoustic classification and mapping of the seafloor: Proceedings of the Institute of Acoustics, v. 15, p. 381–388.

Hyne, N.J., 1969, Sedimentology and Pleistocene history of Lake Tahoe, California-Nevada [Ph.D. dissertation]: Los Angeles, University of Southern California, 121 p.

Hyne, N.J., Chelminski, P., Court, J.E., Gorsline, D.S., and Goldman, C.R., 1972, Quaternary history of Lake Tahoe, California-Nevada: Geological Society of America Bulletin, v. 83, p. 1435–1448.

Hyne, N.J., Chelminski, P., Court, J.E., Gorsline, D.S., and Goldman, C.R., 1972, Quaternary history of Lake Tahoe, California-Nevada: Geological Society of America Bulletin, v. 83, p. 1435–1448.

Hyne, N.J., Goldman, C.R., and Court, J.E., 1973, Mounds in Lake Tahoe, California-Nevada: A model for landslide topography in the subaqueous environment: Journal of Geology, v. 81, p. 176–188.

Kelts, K., and Hsü, K.J., 1980, Resedimented facies of 1875 Horgen slumps in Lake Zurich and a process model of longitudinal transport of turbidity currents: Eclogae Geologicae Helvetiae, v. 73, p. 271–281.

Le Conte, J., 1875, On some ancient glaciers of the Sierra: American Journal of Science, 3rd Series, v. 10, p. 126–139.

Lindgren, E., 1897, Geologic atlas of the United States, Truckee Folio. U.S. Geological Survey Folio 39, 10 p., scale 1:125 000.

Lauderback, G.D., 1911, Lake Tahoe, California-Nevada: Journal of Geography, v. 9, p. 277–279.

Longwell, C.R., 1951, Megabreccia developed downslope from large faults: American Journal of Science, v. 249, p. 343–355.

Louderback, G.D., 1924, Period of scarp production in the Great Basin: University of California Publications in Geological Sciences, v. 15, p. 1–44.

McGlasham, M.N., and McGlasham, B.H., eds., 1986, From the desk of Truckee's C.F. McGlasham: Spokane, Washington, The Arthur H. Clark Company, 242 p.

Moore, J.G., and Moore, G.W., 1984, Deposit from a giant wave on the island of Lanai, Hawaii: Science, v. 226, p. 1312–1315.

Moore, J.G., Clague, D.A., Holcomb, R.T., Lipman, P.W., Normark, W.R., and Torresan, M.E., 1989, Prodigious submarine landslides on the Hawaiian Ridge: Journal of Geophysical Research, v. 94, p. 17 465–17 484.

Murty, T.S., 1979, Submarine slide-generated water waves in Kitimat Inlet, British Columbia: Journal of Geophysical Research, v. 84, p. 7777–7779.

Pakiser, L.C., 1960, Volcanism in eastern California—A proposed eruption mechanism: U.S. Geological Survey Professional Paper 400-B, p. B411–B414.

Palmer, D.F., Henyey, T.L., and Dodson, R.E., 1979, Paleomagnetic and sedimentological studies at Lake Tahoe, California-Nevada: Earth and Planetary Science Letters, v. 46, p. 125–137.

Prior, D.B., Bornhold, B.D., Coleman, J.M., and Bryant, W.R., 1982, Morphology of a submarine slide, Kitimat Arm, British Columbia: Geology, v. 10, p. 588–592.

Smith, J.L., Stone, J.C., Rowe, T.G., and Gardner, J.V., 1998, Selected hydrographic features of Lake Tahoe basin and surrounding area, California and Nevada: U.S. Geological Survey Open-File Report 98-649 (map).

Sturm, M., and Matter, A., 1978, Turbidites and varves in Lake Brienz (Switzerland): Deposition of clastic detritus by density currents, *in* Matter, A., and Tucker, M.E., eds., Modern and ancient lake sediments: International Association of Sedimentologists Special Publication 2, p. 145–168.

U.S. Coast and Geodetic Survey, 1923, Lake Tahoe, Chart 5001, reissued as National Oceanic and Atmospheric Administration, Lake Tahoe, Chart 18665, (1992), scale 1:40 000.

Varnes, D.J., 1978, Slope movement types and processes, *in* Schuster, R.L., and Krizek, R.J., eds. Landslides, analysis and control: Washington, D.C., National Research Council, Transportation Research Board Special Report 176, p. 11–33.

Wahrhaftig, C. 1965, Tahoe City to Hope Valley, *in* Wahrhaftig, C., Morrison, R.B., and Birkeland, P.W., eds., Northern Great Basin and California: International Association for Quaternary Research, VII Congress, Guidebook for Field Conference, p. 59–71.

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