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CRATER LAKE, OREGON

Subaqueous geology and a filling model for Crater Lake, Oregon

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Abstract Results of a detailed bathymetric survey of Crater Lake conducted in 2000, combined with previous results of submersible and dredge sampling, form the basis for a geologic map of the lake floor and a model for the filling of Crater Lake with water. The most prominent landforms beneath the surface of Crater Lake are andesite volcanoes that were active as the lake was filling with water, following caldera collapse during the climactic eruption of Mount Mazama ~7700 cal. yr B.P. The Wizard Island volcano is the largest and probably was active longest, ceasing eruptions when the lake was ~80 m lower than present. East of Wizard Island is the central platform volcano and related lava flow fields on the caldera floor. Merriam Cone is a symmetrical andesitic volcano that apparently was constructed subaqueously during the same period as the Wizard Island and central platform volcanoes. The youngest post-caldera volcanic feature is a small rhyodacite dome on the east flank of the Wizard Island edifice that dates from ~4800 cal. yr B.P. The bathymetry also yields information on bedrock outcrops and talus/debris slopes of the caldera walls. Gravity flows transport sediment from wall sources to the deep basins of the lake. Several debris-avalanche deposits, containing blocks up to ~280 m long, are present on the caldera floor and occur below major embayments in the caldera walls. Geothermal phenomena on the lake floor are bacterial mats, pools of solute-rich warm water, and fossil subaqueous hot spring deposits. Lake level is maintained by a balance between precipitation and inflow versus evaporation and leakage. High-resolution bathymetry reveals a series of up to nine drowned beaches in the upper ~30 m of the lake that we propose reflect stillstands subsequent to filling of Crater Lake. A prominent wave-cut platform between 4 m depth and present lake level that commonly is up to 40 m wide suggests that the surface of Crater Lake has been at this elevation for a very long time. Lake level apparently is limited by leakage through a permeable layer in the northeast caldera wall. The deepest drowned beach approximately corresponds to the base of the permeable layer. Among a group of lake filling models, our preferred one is constrained by the drowned beaches, the permeable layer in the caldera wall, and paleoclimatic data. We used a precipitation rate 70% of modern as a limiting case. Satisfactory models require leakage to be proportional to elevation and the best fit model has a linear combination of 45% leakage

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Long-term Limnological Research and Monitoring at Crater Lake, Oregon

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proportional to elevation and 55% of leakage proportional to elevation above the base of the permeable layer. At modern precipitation rates, the lake would have taken 420 yr to fill, or a maximum of 740 yr if precipitation was 70% of the modern value. The filling model provides a chronology for prehistoric passage zones on postcaldera volcanoes that ceased erupting before the lake was filled.

Keywords Crater Lake · Geology · Filling model · Caldera

Introduction

Crater Lake occupies a caldera that is a collapse depression formed during the climactic eruption of Mount Mazama volcano ~7700 cal. yr B.P. This eruption vented ~50 km^3 (dense-rock equivalent) of magma as pumice and ash, and probably lasted no more than a few days. The geology of the lake floor is known from bathymetric surveys, sampling by dredging and coring, and observations by remotely operated vehicle (ROV) and manned submersible (Williams 1961; Nelson et al., 1988, 1994; Collier et al., 1991; Bacon et al., 2002). Dramatic improvement in understanding of lake floor morphology and geology resulted from the 2000 multibeam echo sounding survey (Gardner et al., 2001; Gardner and Dartnell 2001) in which >16 million geographically referenced (to ± 1 m) depth measurements accurate to 0.2% were made virtually to the shoreline. The maximum depth of the lake was found to be 594.0 m relative to the shoreline at 6178 feet (1883.05 m) elevation that appears on U.S. Geological Survey 1:24,000-scale topographic maps. Calculated lake area is 53.4 km^2 and volume is 18.7 km^3. Visualizations made from the 2000 data using geographic information systems allowed detailed interpretation of lake floor morphology in terms of volcanic and sedimentary processes (Bacon et al., 2002). In the present paper, we summarize findings of the interpretive study and highlight aspects we consider pertinent to other papers in this special issue.

Determining the ages of lake floor features is a key element in interpreting the geologic history of Crater Lake. Evidence from the 2000 bathymetric survey provides the basis for a quantitative model for filling the lake with water that serves as a chronometer for fossil shoreline features that track growth of volcanoes on the caldera floor. Estimating the time to fill Crater Lake after the climactic eruption presents some difficulties. The steady-state water balance is known reasonably well (Phillips 1968; Redmond 1990; Nathenson 1992); however, the depth dependence of leakage has been unknown. Phillips (1968) estimated 500–1000 years to fill the lake, assuming that much of the leakage leaves the lake 150 m or more below current lake level. Nelson et al., (1994) provided a minimum estimate of 300 years assuming 50% evaporation but ignoring leakage. Hoffman (1999) calculated a filling time of about 850 years with seepage a varying fraction of the lake volume. He also looked at the impact of reduced precipitation on the filling time from a 1000-year dry period taking place 500 years after the lake started filling and found long times (2000–3000 years) for the lake to fill. The calculation of filling time in this paper is constrained by the appearance of drowned beaches in the upper 30 m of the lake caused by reduced precipitation lasting for 10's to 100's of years. At modern precipitation rates, our calculations show that the lake would have taken 420 yr to fill, or a maximum of 740 yr if precipitation was 70% of the modern value.

Lake floor geology

Crater Lake floor morphology is easily visualized with shaded-relief perspective views. Several appear in Gardner et al., (2001), Gardner and Dartnell (2001), and Bacon et al., (2002), along with shaded relief and acoustic backscatter maps. Figure 1 is a panoramic view of the lake as photographed from the west rim of the caldera (top) with a matching perspective view (bottom) with the geology draped over the bathymetry (Ramsey et al., 2003). A geologic map with bathymetric contours on a shaded-relief base appears in Fig. 2. We describe various aspects of the geology of the lake floor with reference to Figs. 1 and 2.

Fig. 1 Panoramic photograph (by Peter Dartnell) and matching perspective view (after Ramsey et al., 2003). Geologic map has been draped over bathymetry. See Fig. 2 for key to geologic units

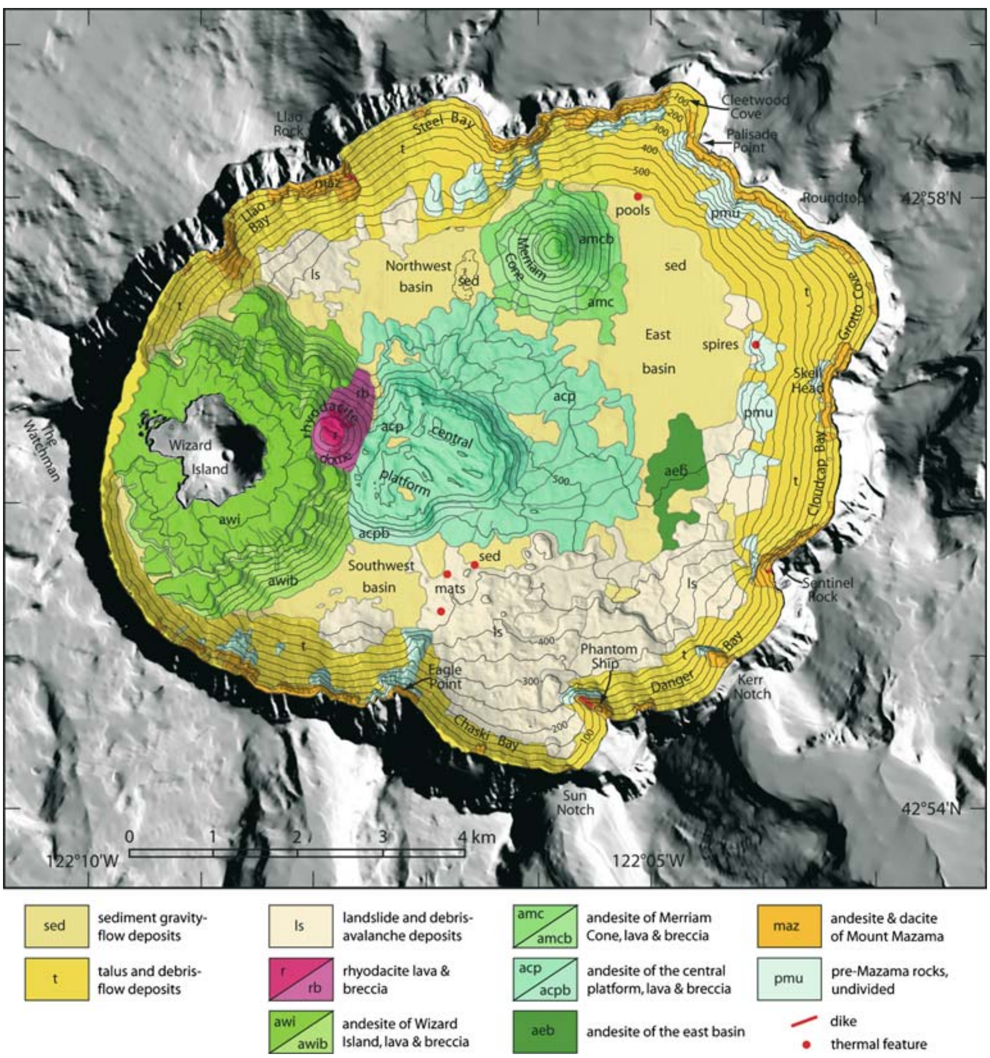


Fig. 2 Geologic map on shaded-relief bathymetric base (after Bacon et al., 2002, Fig. 7). Bathymetric contour interval 50 m relative to lake surface elevation of 6178 feet (1883.05 m)

Volcanic features

The volcanoes on the floor of Crater Lake post-date collapse of the caldera ~7700 cal. yr B.P. Virtually all postcaldera volcanic rocks are andesite of similar or related composition (Nelson et al., 1994). The sole exception is a rhyodacite dome, the youngest eruptive unit, that amounts to ~2% of the total postcaldera erupted volume of 4.1 km^3. Detailed descriptions of each of the postcaldera volcanoes are summarized here, and a table of their volumes and footprint areas is given in Bacon et al., (2002).

The Wizard Island volcano rises 750 m above the lake floor and has a volume of at least 2.6 km^3. The subaerial part of Wizard Island represents only 2.4% of the volume of the total edifice. Blocky subaerial lava flows emanating from the base of the cone form a platform extending up to 1.5 km. The lake has risen ~80 m since Wizard Island eruptions ceased, drowning much of this lava. On the west side of the island, lava abuts the caldera wall and the flow surface is buckled into convex-west arcuate ridges (foreground of Fig. 1). Elsewhere the lava drops abruptly and immediately transforms to 29°–36° sloping talus composed of chilled andesite fragments that formed at the shoreline at the time of lava effusion. The transition from subaerial lava to subaqueous breccia (talus) was called a *passage zone* by Jones and Nelson (1970). The overall structure of a gently-sloping lava field that rides over earlier-formed subaqueous breccia is known as a lava delta, after numerous historic examples and studies of ancient volcanic rocks exposed in cross section (e.g., Fuller 1931). Locally, lava streams that were particularly vigorous cascaded down the breccia slope as coherent subaqueous flows with slopes as steep as 45°.

The subaqueous flanks of the Wizard Island volcano are interrupted by benches that mark earlier lava deltas formed during the growth of this edifice. The elevations of passage zones are at consistent elevations (1805, 1700, 1600, 1540–1560 m; Bacon et al., 2002, Fig. 4) and indicate that the Wizard Island volcano was growing as the lake filled. The lake filling model presented below provides a chronology for these features. Preservation of successive passage zones as benches that would otherwise have been overridden by younger lava implies changes in source-vent location or decrease in eruption rates in comparison to lake-level rise. The breccia slopes are ready sources of sediment for supply to the deep basins by gravity flows.

The andesitic central platform volcano extends east from the Wizard Island edifice. The central platform, as its name implies, has a comparatively flat upper surface. Its flanks slope 30°–37° from the top lava surface at a ~1600-m elevation passage zone and others are present at ~1510 and ~1540–1560 m. The flanks appear to be breccia that is draped in its upper reaches by more coherent lava. The central platform differs from the Wizard Island volcano in the relief on its upper surface and in the presence of extensive lava fields in the deep water around much of its base. The sinuous flows that extend up to 2 km beyond the volcano's base on the north and east can be traced up slope into prominent lava channels or collapsed tubes on top of the central platform, showing that these flows are subaqueous. The central platform itself has a volume of 0.76 km^3, and the deep flow fields are 0.30 km^3 above the lake floor. The main east–southeast-trending channel on top of the central platform heads in an apparent crater at its west end. Two shorter but similar lava channels lead to a flow field at the north base of the central platform. Another possible lava channel leads to the south.

The presence of passage zones at similar elevations indicates that the Wizard Island and central platform volcanoes were active at the same time. The central platform volcano was constructed of lava deltas until late in its life, when formation of discrete lava channels or tubes, or perhaps increased eruption rate, allowed lava to flow into the lake without fragmenting. These lava streams descended over the breccia slopes to form fan-shaped lava flow fields on the lake floor. Its partially drowned subaerial lava flows clearly indicate when the Wizard Island volcano ceased to erupt. Timing of the end of central platform activity is less certain. It is possible that the central platform volcano was fed by overflow or lateral dike transport from the Wizard Island vent or conduit.

Merriam Cone is an andesitic volcano named by Williams (1961) after J. C. Merriam. Rising

430 m above the east basin (151 m depth below lake level), Merriam Cone has a volume of 0.34 km^3. Most of the surface of this symmetrical cone slopes 30°–32°, decreasing to ~20° near its base, and probably is composed of breccia. Radial ridges, some with lobate downhill terminations, and buttresses near the cone's base suggest lava flows. The uppermost fourth of the craterless cone appears to be lava. Surface features visible in ROV video and the character of dredge samples suggest that Merriam Cone was constructed by subaqueous eruptions, the last of which occurred in shallow water. Dredge samples are compositionally similar to the most chemically differentiated Wizard Island lava. The compositional similarity and the apparently shallow-water final eruptions suggest that Merriam Cone was active during the later stages of growth of the Wizard Island volcano.

Approximate morphologies of the central platform and Merriam Cone were known from a 1959 echo sounding survey (Byrne 1965). In the 2000 survey, a fourth probable andesitic lava field (aeb, Fig. 2) was discovered protruding into the south end of the east basin. Although there are no samples of material from this feature, its outline, slopes, and backscatter suggest sediment-covered lava flows from a vent between Kerr Notch and Sentinel Rock, now buried by debris-avalanche deposits. The unit has a minimum volume of 0.032 km^3 and may be the oldest exposed post-caldera volcanic rock.

On the east flank of Wizard Island is a rhyodacite lava dome that reaches 1854 m elevation (29 m depth) and has a volume of 0.074 km^3. Capped by relatively smooth lava, the dome has sides that slope 32°–34° and are composed of talus or breccia. Much, if not all, of the dome apparently was emplaced subaqueously. Correlative ash found in a core recovered from the surface of the central platform is bracketed by radiocarbon dates that yield a calendrical age for the dome of 4830 +460/–410 yr B.P. (Nelson et al., 1994; Bacon et al., 2002).

Caldera walls

The submerged caldera walls continue the same types of bedrock outcrops and debris slopes found above water (Fig. 1). When the ~5 × 6 km central block subsided during the climactic eruption, the unsupported walls failed by sliding, resulting in the scalloped outlines of the lake shore and caldera rim where embayments are separated by bedrock promontories. Subaerial bedrock outcrops are composed of sets of lava flows and pyroclastic deposits from vents that were active during comparatively short periods in the eruptive history of Mount Mazama. Contacts between these units commonly are expressed by benches on the caldera walls. Similar features are evident in the 2000 bathymetry, some of which have been observed and sampled by manned submersible. Many of these benches are identified as parts of the Mount Mazama edifice but the deeper ones do not have obvious counterparts and are shown as undivided pre-Mazama volcanic and intrusive rocks on the geologic map (Fig. 2). The steep triangular-faceted spur below Eagle Point (Figs. 1 and 2) may be a remnant of the footwall of a ring fault along which the central block of the caldera subsided. Observations with the submersible indicate that steep faces are bare rock, but ledges and gentle slopes are dusted with sediment.

Much of the submerged caldera wall is buried under fragmental debris aprons shown as talus on the geologic map (Fig. 2). The higher-elevation sublacustrine debris commonly is continuous with subaerial talus and has slopes of 29°–35° that systematically decrease to lower values with increasing depth in the lake. Talus cones appear to grade downslope into debris-flow or landslide material that is buried at its distal end by sediment of the deep basins. A few coarse rockfalls have been identified at the bases of steep cliffs that lack talus sources above, as off Phantom Ship.

A glaciated lava flow has been recognized in the caldera wall near Roundtop, (Bacon et al., 2002) and its extension below lake level, as interpreted from bathymetry and back-scatter imagery, is shown on the geologic map (Fig. 2) as part of the andesite and dacite of Mount Mazama continuing west towards Palisade Point. The glaciated upper surface of the lava flow appears at elevations ranging from 1838 m to 1859 m, 24–45 m below lake level. Unconsolidated, fragmental glacial deposits rest on this lava flow below the andesite of Roundtop (Bacon et al., 2002; Fig. 14), and the fragmental deposits are likely to provide a permeable pathway for leakage from Crater Lake.

Landslides

Hummocky topography and scattered large blocks on the lake floor are the expression of landslide and debris-avalanche deposits below many of the embayments in the caldera wall. The latter resemble the much larger submarine landslide deposits from volcanoes in the oceans (e.g., Moore et al., 1989). Debris-avalanche deposits are best developed below embayments in the south and southeast caldera walls in hydrothermally-altered rocks of the older part of Mount Mazama. The largest, the Chaski Bay debris-avalanche deposit, contains blocks up to ~280 m long that have traveled as much as 2–3 km from its source on the south rim to apparently run up on lava flows at the south flank of the central platform. Secondary slides have formed by mobilization of the lower reaches of the larger debris-avalanche deposits, leaving source-scar headwalls (e.g., north of Phantom Ship). The debris avalanches and secondary slides may have been triggered by earthquake shaking. Debris-avalanche deposits probably are abundant in the caldera fill below the lake floor, interlayered with pyroclastic material that accumulated during the climactic, caldera-forming eruption of Mount Mazama.

Apparent landslide deposits that lack coarse blocks on their surfaces occur west of Eagle Point and below Llao Bay, Steel Bay, and Grotto Cove. Each is essentially continuous with the talus/debris apron above it. These slide deposits appear to have formed by superposition of flow lobes and they have been mapped separately from the more uniform talus/debris surface above them. They slope from a maximum of 25° to a 3°–7° distal runout surface.

Sediment ponds and basins

The east, northwest, and southwest basins contain relatively fine-grained sediment transported from caldera wall sources by sediment gravity flows (Nelson et al., 1986). These basins, and numerous smaller sediment-filled depressions on and between lava flows and landslide deposits, have smooth, nearly flat surfaces. On the basis of seismic-reflection profiling, Nelson et al., (1986) suggested a maximum sediment thickness of 75 m in the east basin and <50 m in the southwest and northwest basins. Sediment flows toward the basins along channels between postcaldera volcanoes and the caldera wall, ponding in local depressions along its path to the basins. Sediment ponds also occur on lava flows, on debris-avalanche deposits, below secondary slide headwall scarps, and where debris avalanches terminate against central platform lavas. The northwest basin and many of the smaller sediment ponds are dammed by low ridges (sills), and sediment apparently moves through this system to ultimate sinks in the east and southwest basins.

Geothermal phenomena

The recency of the caldera-forming eruption suggests that the lake floor should have features that reflect loss of residual heat from the magmatic and hydrothermal system beneath Mount Mazama (Bacon and Nathenson, 1996). Williams and Von Herzen (1983) found high convective heat flows in the south and northeast parts of the lake floor using oceanographic measurement techniques. Submersible and ROV investigations of these areas revealed unequivocal evidence of modern hydrothermal circulation (Dymond and Collier, 1989; Collier et al., 1991; Wheat et al., 1998). Bacterial mats associated with venting of warm water are present locally in the southern area near the northwest margin of the Chaski Bay debris-avalanche deposit (Fig. 2, ‘‘mats’’). Relatively warm and solute-laden water forms pools below Cleetwood Cove (Fig. 2, ‘‘pools’’). Silica spires ~10–12 m high below Skell Head are fossil subaqueous thermal-spring deposits (Fig. 2, ‘‘spires’’). None of these features are large enough to have been resolved in the 2000 bathymetric survey. No doubt, there are many more thermal features undiscovered on the lake floor.

Filling of Crater Lake

The detailed bathymetry produced by the 2000 multibeam survey provides evidence of fossil shorelines that record periods of low lake level from reduced precipitation subsequent to the lake filling. The bathymetry also shows a layer of glacial deposits below Roundtop that provides a likely location for a permeable pathway for leakage from Crater Lake. These observations form anchor points in a new model for the filling of Crater Lake.

Drowned beaches

The high resolution of the multibeam bathymetry makes it possible to determine that there are drowned beaches at Crater Lake reflecting periods where the lake was significantly lower in elevation (Fig. 3). Beaches reflect stillstands from periods of reduced precipitation, and their existence constrains models for the distribution of leakage out of Crater Lake.

In order to quantify the elevations of the drowned beaches, we constructed profiles of elevation versus distance in areas that contain these features (Fig. 4). The origin of the profiles is near to but not at shoreline as the surveying boat had to stay some distance from exposed rock. We identified possible locations on the profiles where there might be a beach (vertical lines) based on

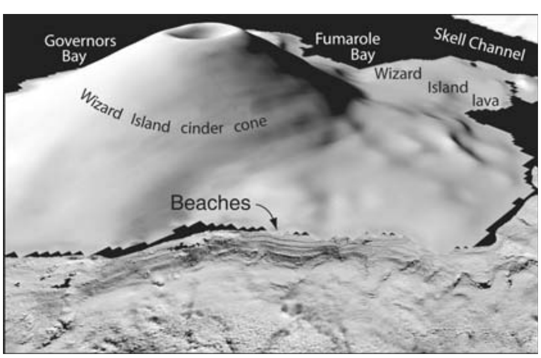


Fig. 3 Perspective view of drowned beaches on the northeast flank of Wizard Island (after Bacon et al., 2002, Fig. 12). Slumps have modified some beaches, particularly on the right half of the image. Bathymetry not shown in background (black). Subaerial terrain from USGS 10-m DEM. No vertical exaggeration

the pattern of depth versus distance and changes in the slope. Possible drowned beaches from a number of profiles were compared (Fig. 5), and those confirmed by their appearance in multiple profiles are marked with a B (Fig. 4). The Wizard Island profile (Fig. 4 top) and has a large number of possible drowned beaches. The wide, nearly level portion of the profile between 1852 and 1855 m also appears on profiles 103 and 23 of Wizard Island, but it is not found on other profiles and is probably related to local rather than lake-wide effects. Only a few of the possible beaches on the Roundtop profile (Fig. 4) are confirmed by other profiles. The contact noted on the Roundtop profile is the top of the Mount Mazama lava flow that is covered by glacial debris that we propose as an area of shallow leakage.

The summary of beaches found on multiple profiles (Fig. 5) shows nine drowned beaches ranging in elevation from 1848.5 to 1877.5 m. The relatively high elevation of the deepest beach provides a fairly strong constraint on models for where leakage occurs in the lake in response to climate change (see below). The contact found near Roundtop ranges from 1838 to 1859 m (Fig. 5) and is a likely region for some of the leakage.

In addition to the drowned beaches shown in the bathymetry, there is a wave cut platform that is a much larger feature. The photograph shown in Fig. 6 was taken between August 15 and 31, 1931 (Stephan R. Mark, NPS, written communication, 2002). In September 1931, the lake elevation was 1878.6 m (Phillips, 1968), about 4.5 m lower than the reference elevation as a result of the 1920s to 1930s drought (see water level plot in Redmond, 1990). The wave cut platform commonly is up to 40 m wide (Fig. 4, Bacon et al., 2002), much wider than any of the drowned beaches seen in the bathymetry. This difference in width implies that the lake has actually spent most of its history at an elevation of around 1879 m (1 to a few meters below the level of the last 40 years), and the recent few decades have been wetter than most of the time since Crater Lake filled. The bathymetric profile near Roundtop (Fig. 4) shows low slope in the first 7 m of the profile between elevations of 1878.8 and 1876.7 m. This is a bit lower in elevation than the

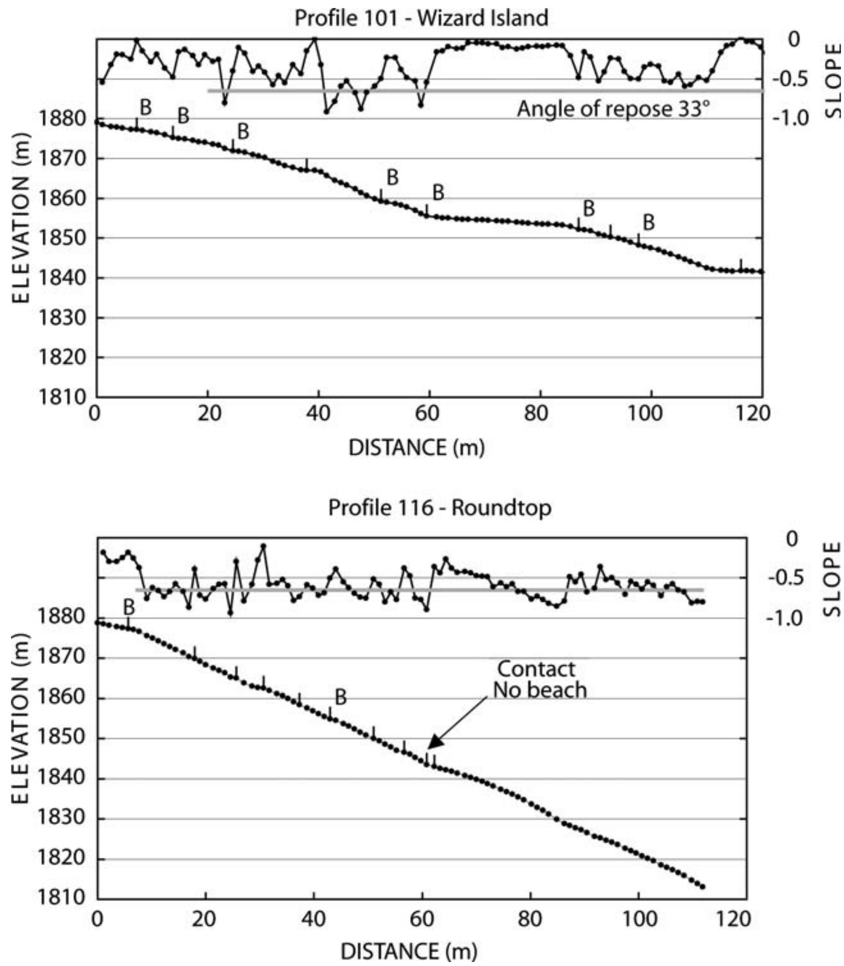


Fig. 4 Bathymetric profiles off Wizard Island and near Roundtop. Vertical lines indicate possible drowned beaches. Vertical lines marked with B's indicate features confirmed by other profiles. Slope for profiles shown along with that for angle of repose of 33°

1878.6-m elevation obtained from the 1931 photo for the shallow, wave-cut platform, but there could be some uncertainty in ties to the reference elevation used to report past elevations. Elevation of the platform on other profiles generally ranges between 1876 and 1878 m.

Filling model

Crater Lake receives water from direct precipitation and inflow from the caldera walls and loses water by surface evaporation and leakage (Phillips 1968; Redmond 1990; Nathenson 1992). No streams flow out of Crater Lake. From the water balance for the years 1961–1988 (Nathenson 1992), the precipitation at the Park Headquarters rain gauge for the lake to remain at a constant level is 169.2 cm/y. The water supply to the lake from direct precipitation and inflow from the caldera walls is 224.2 cm/y over the 53.2 km^2 area of the lake. Based on an analysis of daily data, Nathenson (1992) estimated that the direct precipitation averaged over the area of the lake is about 10% higher than that at Park Headquarters. The 17% remaining of the total water supply to the lake comes from inflow from the caldera walls. Nathenson (1992, pp. 10) chose a value for evaporation of 85 cm/y and calculated the leakage of 139 cm/y by difference from the total water supply.

In order to explain the occurrence of the drowned beaches and their relatively narrow depth range, leakage through the caldera walls must vary with depth and cannot occur just at the lake bottom or at the modern lake level. A reasonable and simple model is that leakage is

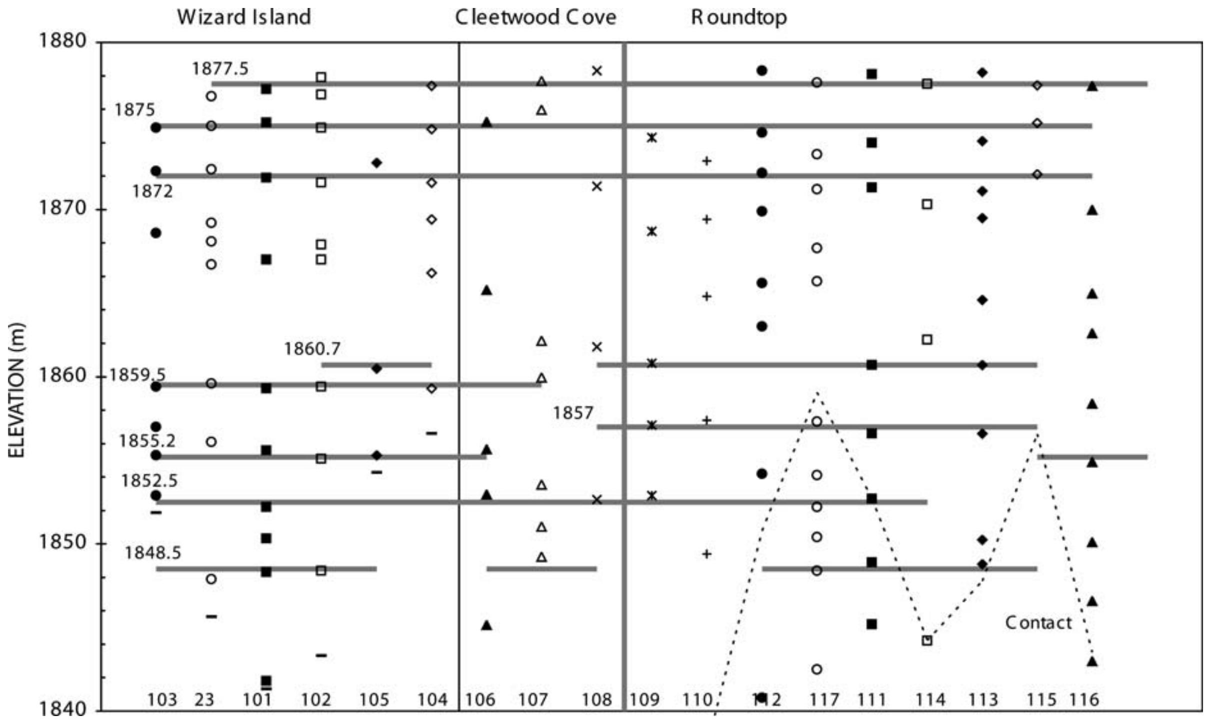


Fig. 5 Possible drowned beaches from various profiles (profile numbers at bottom of figure) on Wizard Island, Cleetwood Cove, and area near Roundtop. Chosen drowned beaches based on appearance in multiple profiles. Contact is top of lava flow covered by fragmental debris that could be an area of leakage

proportional to elevation above the bottom of the lake. Recognition that there is a thick layer of relatively permeable debris resting on glaciated lava in the northeast caldera wall above an elevation of ~1844 m suggests a variant of this model where leakage is proportional to elevation above 1844 m.

The water balance for Crater Lake for the change in lake elevation z referenced to the bottom of the lake is (Phillips 1968; Redmond 1990; Nathenson 1992):

$$Q_\mathrm{i} + Q_\mathrm{p} - Q_\mathrm{o} - q_\mathrm{e} A = A\frac{\mathrm{d}z}{\mathrm{d}t}$$

where $Q_\mathrm{i} + Q_\mathrm{p}$ is the water supply from inflow plus precipitation and is assumed constant, Q_o is the leakage from various models discussed below, q_e is the evaporation per unit area and is assumed constant, and A is the area as function of elevation $A(z)$ from the bathymetry in Fig. 2. The area of the lake is a curvilinear function of elevation that is well approximated by a series of straight lines over 50 m intervals (Fig. 7). The water balance equation is solved by arranging it as an integral over z,

$$t = \int_0^Z [A/(Q_\mathrm{i} + Q_\mathrm{p} - Q_\mathrm{o} - q_\mathrm{e}A)]\mathrm{d}z$$

doing the integration using the trapezoidal rule, and solving for time as z increases from zero to the equilibrium level z_o. We neglect the extra volume currently taken up by lava flows and volcanoes on the floor and only fill the current volume of the lake. Because the eruptions took place during the filling, the missing volume was filled in by lava contemporaneously with filling by water.

The model with the longest filling time is where the total leakage Q_L (139 cm/y times the reference area of the lake) is out of the bottom of the lake

$$Q_\mathrm{o} = Q_\mathrm{L} \quad 0 \le z \le z_\mathrm{o},$$

Fig. 6 Photograph of Phantom Ship taken between August 15 and 31, 1931 by George Grant (Stephan R. Mark, NPS, written communication, 2002) showing wave cut platform just above shoreline. Photograph also appears in Atwood (1935, p. 147)

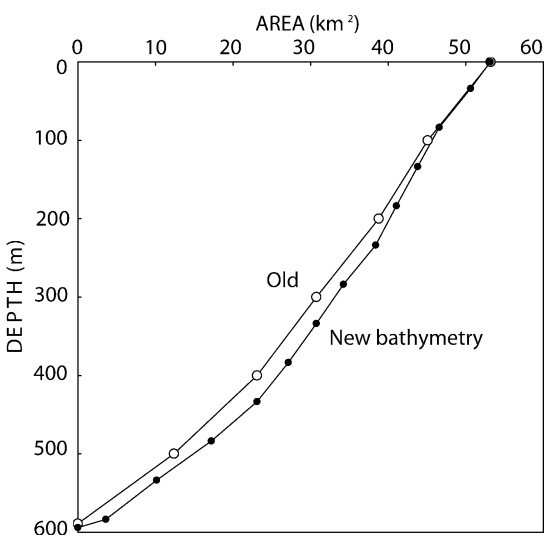


Fig. 7 Area versus depth for Crater Lake from new bathymetry from Gardner and Dartnell (2001) and old bathymetry from Byrne (1965). Note that lake area and volume given in Byrne (1965, Table 1) are not correct for his map

and the model with the shortest filling time is where there is no leakage until the lake reaches its equilibrium level z_o

$$Q_o = \begin{cases} 0 & 0 \leq z < z_o \\ Q_L & z = z_o. \end{cases}$$

Given the increase in lake area with elevation from the bottom and the increasing head driving leakage as the lake fills, a reasonable model is that the leakage is proportional to elevation

$$Q_o = Q_L\, z/z_o \quad 0 \leq z \leq z_o.$$

For the model of leakage starting at the elevation of the glaciated lava z_s above the lake floor, the leakage function is

$$Q_o = \begin{cases} 0 & 0 \leq z < z_s \\ Q_L\, (z - z_s)/(z_o - z_s) & z_s \leq z \leq z_o. \end{cases}$$

It turns out that in order to match the constraint from drowned beaches (see below), a combination of the last two models is needed

$$Q_o = \begin{cases} (1-\alpha)\, Q_L \dfrac{z}{z_o} & 0 \leq z \leq z_s \\ (1-\alpha)\, Q_L \dfrac{z}{z_o} + \alpha\, Q_L \dfrac{(z - z_s)}{z_o - z_s} & z_s \leq z \leq z_o \end{cases}$$

where α is the fraction leaking out in the fragmental deposits above the glaciated lava.

The time to fill the lake assuming modern values for precipitation, inflow, and leakage (Nathenson 1992) has a large range of values for the various models (Fig. 8). The calculations are only shown to within 1 m of the equilibrium level, because the function asymptotically approaches the equilibrium level requiring an infinite time to fill. However, water levels change by about half a meter each year, and the asymptote is not practically significant. In order to choose the proper model, we use the constraint provided by the drowned beaches that resulted from periods of reduced precipitation after the lake was filled. Crater Lake was filled near the end of a dry period in the Pacific northwest that started in the early Holocene (Barnosky et al., 1987). Evidence

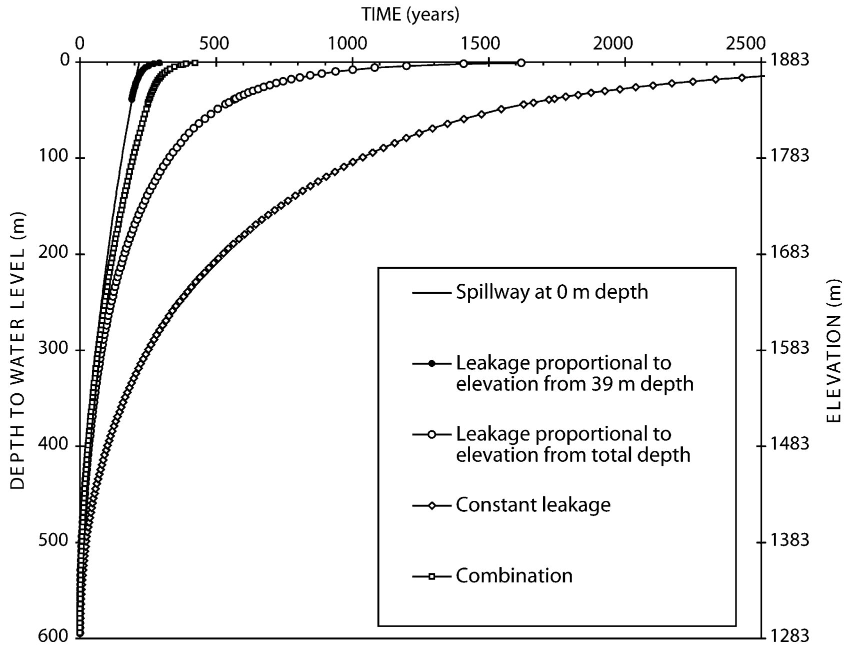


Fig. 8 Filling history for various models. Calculations stopped at 1 m below equilibrium level

for a dry period at the time of the climactic eruption is found at lower elevation in Lower Klamath Lake and Tule Lake south of Crater Lake (Nelson et al., 1994). However, studies of pollen in Crater Lake itself indicate that the period when the lake was filling was not dry at the elevation of Crater Lake, and the dry period occurred later there, between 6,000 and 5,000 C-14 years BP (Nelson et al., 1994).

In order to make quantitative estimates of the reduced precipitation to Crater Lake, we compare it to the history of Mono Lake (Stine, 1990, 1994). Droughts in California in 1928 to 1934 and 1987 to 1992 also appear in the lake-level record for Crater Lake (Redmond, 1990; Nathenson, unpublished). The behavior is not identical, but the overall character of these periods being much drier than normal is similar. Based on this comparison, we assume that the history of Mono Lake can provide data on amounts of precipitation reduction and durations that can be applied to Crater Lake. Stine (1990) reports periods of drought at Mono Lake over the last thousand years based on dated lake deposits. The drought about 1000 years BP was especially strong with inflow (precipitation) only 68% of the modern period, and one of similar magnitude occurred about 1800 years BP. Four droughts in the last thousand years had inflows ranging from 74 to 84% of the modern period. Stine (1994) estimates that the drought of 1000 years BP lasted for 220 years and the one about 600 years BP lasted for about 140 years with inflow 79% of the modern period. In order to calibrate the leakage models, we choose a minimum value for precipitation of Crater Lake as 70% of modern, and assume that this lowered precipitation produced the drowned beach at 1852.5 m (the deepest beach is somewhat suspect). This minimum value of precipitation of 70% of modern is also used to calculate one of the filling histories, assuming that it occurred over the entire time to fill the lake during an extended dry period.

The steady state values for lake level as a function of the fraction of water supply have been calculated from the water balance equation by iteration, and values are shown in Fig. 9. For the model with leakage proportional to total depth, such a large decrease in precipitation as 70–80% of modern would require drowned beaches below depths of 120 m, and we see no evidence for such deep beaches. For the model with leakage proportional to elevation above the layer of permeable debris, the deeper beaches require reductions in precipitation larger than 70%, and that seems unlikely given the climate data.

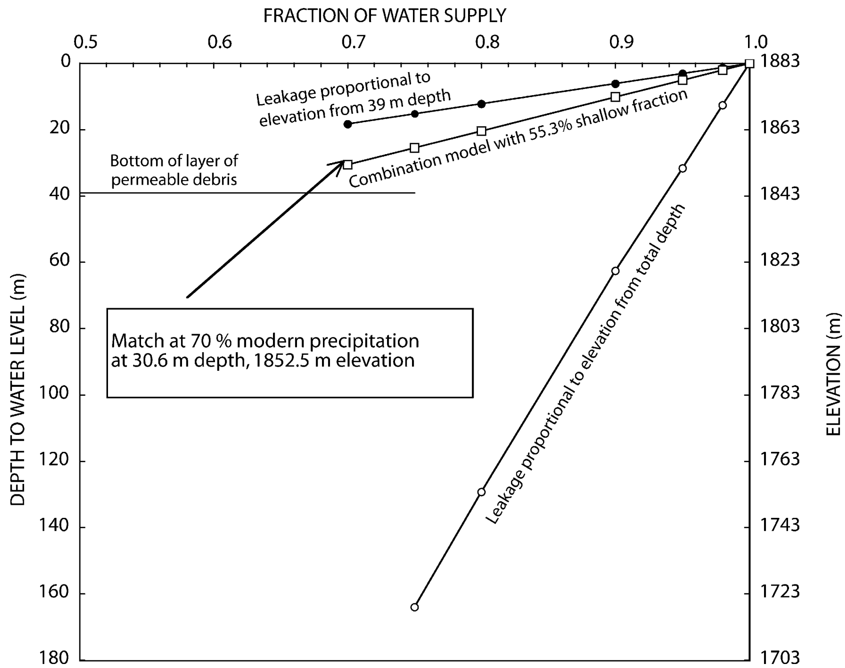


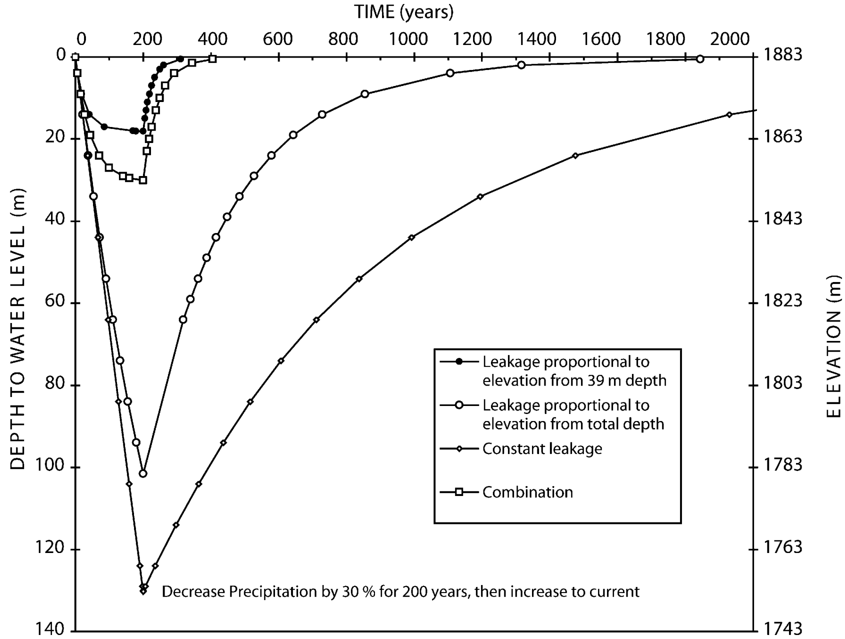
Fig. 9 Equilibrium values for depth to water level versus fraction of modern water supply for various models. Shallow fraction of 55.3% for combination model chosen to match equilibrium level of 30.6 m depth at 70% of modern precipitation

A simple linear combination of these two models with 55.3% of the leakage proportional to elevation above the layer of permeable debris and the remainder occurring proportional to total depth matches the constraint provided by the beach at 1852.5 m. Varying the minimum value for precipitation away from the 70% value would change the relative contributions of the two models, and the value for the relative percentages of leakage is reported to higher precision than justified because of the need to make calculations consistent. The particulars of the model are not unique, but the general idea that there is high-elevation leakage that depends on depth seems necessary to produce drowned beaches at various elevations as the fraction of water supply takes various values.

Phillips (1968: Fig. 5) calculated the leakage versus elevation for a number of time periods. He drew a curve through calculated points but indicated that a straight line is probably all that is justified by the calculated points of leakage versus elevation. Fitting a straight line to his points by eye, the change in seepage with lake elevation is 0.05 $m^3 s^{-1} m^{-1}$. For the combination model with 55.3% of the leakage occurring as leakage proportional to elevation above the layer of permeable debris and the remainder occurring proportional to total depth, the change in seepage with lake elevation above the layer of permeable debris is 0.035 $m^3 s^{-1} m^{-1}$. Considering the uncertainties in the calculations, this is quite good agreement.

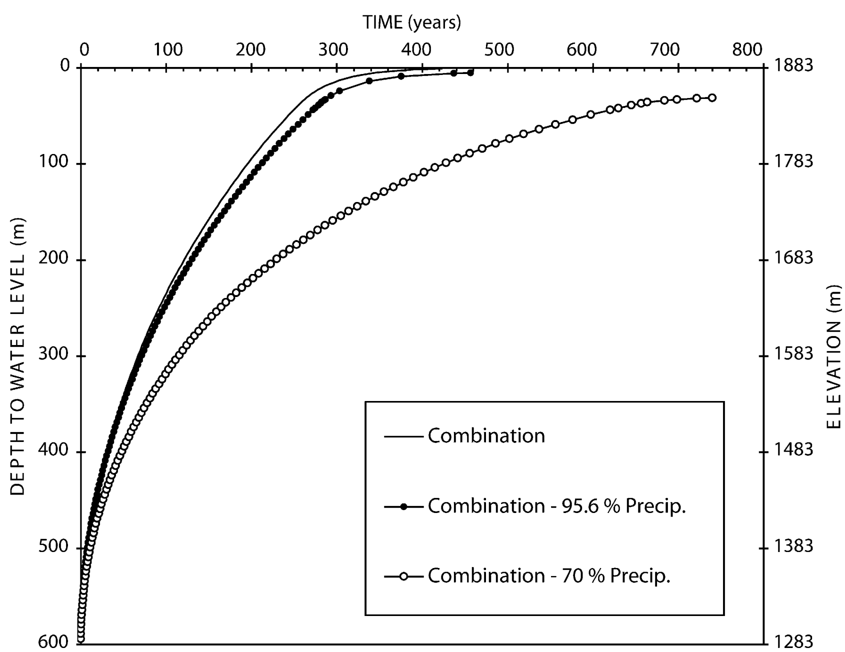
For a reduction in precipitation of 30% for a period of 200 years such as that seen at Mono Lake, the combination model nearly reaches steady state (Fig. 10), and the water level is within 1 m of its lowest elevation for about 60 years. Although this may not have been enough time to produce a beach, if the reduction in precipitation lasted for a longer time such as during the dry period between 5,000 and 6,000 C-14 years BP, there would have been plenty of time to produce a beach. The lake level for the model with leakage proportional to elevation from 39 m depth reaches steady state faster and is within 1 m of its equilibrium level for about 115 years. The models with constant leakage and with leakage proportional to total depth do not reach steady state and cannot produce drowned beaches in the time available. For smaller reductions in precipitation, the times to reach steady state for the model with leakage proportional to elevation from 39 m depth and for the combination model are reduced, and reasonable times are available to produce beaches.

Fig. 10 Model histories for modern precipitation, then precipitation decreased by 30% for 200 years, followed by increase to modern precipitation



For the combination model, filling histories have been calculated for three values of precipitation (Fig. 11). Under the assumption that precipitation was at its modern value, the lake takes about 420 years to fill. Based on the occurrence of the wave cut platform at 1879 m, the lake may have spent most of its history at a level below the assumed equilibrium level of 1883 m, and normal precipitation would have been 95.6% of modern to yield an equilibrium level of 1879 m. Filling time only increases to about 460 years. If by chance the lake actually filled during a dry period not recognized because of poor preservation of the earliest few hundred years in the core record

Fig. 11 Filling history for various fractions of modern precipitation for combination model with 55.3% shallow fraction. Calculations stopped at 1 m below equilibrium level



for Crater Lake (Nelson et al., 1994), a filling history with 70% of modern precipitation increases the filling time to about 740 years. The models with modern precipitation and 70% of modern have been used in Bacon et al., (2002) to bracket the times for passage zones of lava flow features that occurred while the lake was filling.

Chronology for postcaldera geologic events

The lake filling model provides a chronology for postcaldera geologic history. It is reasonable to assume that the lake began to fill virtually immediately following caldera collapse. Granted that evaporation rate probably was enhanced owing to hot caldera fill and exposure of the interior of Mount Mazama, a large amount of groundwater would have flowed into the caldera from the fractured walls. Applying the combination lake filling models to fossil shorelines (passage zones on volcanoes) indicates that andesitic volcanism ceased by 215–490 yr after caldera collapse (the time to fill to the highest elevation drowned lava delta passage zone on the Wizard Island volcano). Eruption rates calculated from postcaldera volcano volumes and filling models of 19–8.2 × 10^6 m^3/y are comparable to long-term lava effusion rates at historically active andesite-dacite volcanoes (Bacon et al., 2002, Table 2). The debris-avalanche deposits on the lake floor were emplaced sometime after much or all of the andesitic volcanism. Downslope movement of debris from the caldera walls to the deep basins is ongoing. Further details of the geologic history of Crater Lake are presented in Bacon et al., (2002).

Conclusions

The geology of the floor of Crater Lake is now reasonably well known from detailed bathymetry, sampling by submersible and dredging, and observations by submersible and ROV. The morphology of postcaldera volcanoes, including lava deltas and subaqueous breccias, reveals that all but the youngest were active during the period of lake filling. Also visible in the 2000 bathymetric survey are bedrock outcrops and talus/debris slopes of the caldera walls, debris-avalanche deposits below embayments in the walls, and sediment-filled deep basins. Thermal features, some active and others fossil, were discovered in earlier manned submersible and ROV exploration.

Models for the filling of Crater Lake with water are constrained by the presence of drowned beaches and a permeable layer in the caldera wall delineated by the 2000 bathymetric survey and suggest the lake took 420–740 years to fill. The level of Crater Lake is maintained by a balance between precipitation and inflow versus evaporation and leakage. Existence of the beaches and a broad wave-cut platform at 0–5 m depth can be explained by variations in precipitation with models for lake filling with 45% of leakage proportional to elevation plus 55% of leakage proportional to elevation above 1844 m, the elevation of the base of the permeable layer in the northeast caldera wall. The models provide a chronology for postcaldera volcanism, much of which ceased by 215–490 yr after the lake began to fill, depending of an assumed precipitation rate of 100% to 70% of the modern rate.

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