National Park Service
US Department of the Interior

Natural Resource Stewardship and Science

Crater Lake National Park

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2013/719

ON THE COVER
In the 1940s, under the guidance of geologist Howel Williams, who wrote the 1942 monograph about the geology of Crater Lake National Park, artist Paul Rockwood painted three renditions of Mount Mazama. The painting shown on the cover illustrates Mount Mazama at the onset of its climactic eruption 7,700 years ago. National Park Service image.

THIS PAGE
Crater Lake. Wizard Island rises above the surface of deep, blue Crater Lake. Llao Rock (middle) and Hillman Peak (left) are high points on the Crater Lake caldera rim. Photograph by Elisa Zercoe.

Crater Lake National Park

Geologic Resources Inventory Report

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National Park Service
Geologic Resources Division
PO Box 25287
Denver, CO 80225

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US Department of the Interior
National Park Service
Natural Resource Stewardship and Science
Fort Collins, Colorado

The National Park Service, Natural Resource Stewardship and Science office in Fort Collins, Colorado, publishes a range of reports that address natural resource topics These reports are of interest and applicability to a broad audience in the National Park Service and others in natural resource management, including scientists, conservation and environmental constituencies, and the public.

The Natural Resource Report Series is used to disseminate high-priority, current natural resource management information with managerial application. The series targets a general, diverse audience, and may contain NPS policy considerations or address sensitive issues of management applicability.

All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and designed and published in a professional manner. This report received informal peer review by subject-matter experts who were not directly involved in the collection, analysis, or reporting of the data.

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Executive Summary

The Geologic Resources Inventory (GRI) is one of 12 inventories funded by the National Park Service Inventory and Monitoring Program. The Geologic Resources Division held a GRI scoping meeting for Crater Lake National Park in Oregon on 3 March 2004 and a follow-up conference call on 18 December 2012 to discuss geologic resources, the status of geologic mapping, and resource management issues and needs. This report synthesizes those discussions and is a companion document to the previously completed GRI digital geologic map data.

This Geologic Resources Inventory (GRI) report was written to assist in resource management and science-informed decision making at Crater Lake National Park in southwestern Oregon. It may also be useful for interpretation. The report highlights the geologic heritage—significant geologic features, landforms, and landscapes characteristic of our nation—of Crater Lake National Park, including iconic Crater Lake. The lake partly fills Crater Lake caldera that formed when Mount Mazama, a 3,700-m- (12,000-ft-) high volcano, climactically erupted and collapsed about 7,700 years ago.

Since that eruption, all volcanic activity within the park area has occurred within the caldera. Five vents extruded lava onto the caldera floor, including the vent for Wizard Island, which is the only "postcaldera" (occurring since the climactic, caldera-forming eruption) volcano to break the surface of Crater Lake. The postcaldera volcanoes, including Wizard Island volcano, were active while Crater Lake was filling with water. Today, Crater Lake is maintained by a balance between precipitation/inflow and surface evaporation/seepage. The lake has no outlet or inlet. An average annual water supply of 224 cm (88 in) and a thick layer of permeable glacial till in the caldera wall, which serves as a "bathtub drain," are significant factors in lake level.

The digital geologic data set that accompanies this report is a compilation of five source maps that cover the Crater Lake area. Bacon (2008) covers the area of Mount Mazama and Crater Lake caldera. Jenks et al. (2008) compiled data that covers an area east and southeast of the park. MacLeod and Sherrod (1992) is a reconnaissance geologic map that covers an area northeast of the park. Sherrod (1991) is a geologic map that provides data that covers the northern part of the park. Smith et al. (1982) is a preliminary geologic map that provided data that covers the southernmost part and an area immediately west of the park. The entire Bacon (2008) map and portions of Jenks et al. (2008), MacLeod and Sherrod (1992), Sherrod (1991), and Smith et al. (1982) are part of the GRI data set. A simplified geologic map (in pocket) illustrates these geologic data, and the Map Unit Properties Table (in pocket) summarizes the report content for the rocks and unconsolidated deposits on the digital geologic map. Refer to the "Geologic Map Data" section for more information.

The accompanying digital data set also includes a map by Bacon et al. (1997), which compiled information about volcano and earthquake hazards for the Crater Lake region. A hazard map graphic (in pocket) illustrates these data.

The report discusses geologic issues facing resource managers at the park, distinctive geologic features and processes within the park, the geologic history leading to the park's present-day landscape, and provides information about the GRI geologic map data produced for the park. This report also contains a glossary and a geologic time scale.

During a 2004 GRI scoping meeting and a 2012 follow-up conference call, participants (see Appendix A) identified geologic issues of particular significance for resource management at Crater Lake National Park. They include the following:

- Slope Movements. Crater Lake caldera is a collapse depression enlarged by slope movements; slumping and sliding of the caldera walls formed the distinctive scalloped outline seen today. The last major landslide event to carry debris to the center of the caldera floor was the Chaski Bay landslide. This landslide, also referred to as a debris-avalanche deposit, moved across the caldera floor soon (an estimated 200 years) after the climactic eruption. A future large landslide or rockfall event into Crater Lake could produce a damaging wave. Present-day slope-related geologic hazards of resource management concern include rockfall along Rim Drive and the Cleetwood Cove Trail, and slope processes on the caldera wall below Crater Lake Lodge.
- Seismic Activity. Earthquake hazards in the greater Crater Lake area are similar to those in other earthquake-prone areas, namely damage to structures, utilities, communication lines, and transportation systems. The West Klamath Lake fault zone, Cascadia subduction zone, and local volcanic earthquakes are sources of seismic activity that have the potential to affect Crater Lake National Park.
- Volcano Hazards. Bacon et al. (1997) studied volcano and earthquake hazards in the Crater Lake region and estimated the likelihood of future volcanic events. The annual probability of an eruption occurring near Crater Lake is about one chance in 10,000. Because

postcaldera volcanoes are concentrated in the western half of the caldera, this is the most likely site of future activity. Potential hazards include pyroclastic surges (hot, rapidly moving clouds of gas and ash) and ballistics (ejected material) from explosive eruptions within the caldera. In addition, lahars (rapidly moving debris flows that originate at volcanoes and consist of rock fragments carried downslope in a matrix of clay or pulverized rock and water) are a possible hazard in valleys extending from the rim. Eruptions from vents below the surface of Crater Lake may be highly explosive in shallow water but much less explosive in deep water. An eruption from a vent in the caldera wall itself also could be explosive because of the abundant groundwater within the mountain. Waves on Crater Lake several meters high could be produced during an explosive eruption within the caldera.

- Hydrothermal Features and Geothermal Development. The Geothermal Steam Act of 1970 as amended in 1988 designated Crater Lake as a significant thermal feature. Physical evidence of hydrothermal activity includes pools of relatively warm and solute-laden water, bacterial mats associated with venting of warm water, and high silica spires (subaqueous thermal-spring deposits) formed by thermal chimneys on the floor of Crater Lake caldera. In January 1984, the Bureau of Land Management granted two leases to the California Energy Company for geothermal exploration in the Winema National Forest, south and east of the park. The company drilled two exploration wells on these leases. Because of Crater Lake's inclusion in the Geothermal Steam Act, consideration of geothermal development in Winema National Forest was terminated. Since then, no other leasing activity has threatened to impact the geothermal system at the park.
- Disturbed Lands Restoration. Crater Lake National Park contains approximately 10 ha (25 ac) of disturbed lands in need of restoration through site preparation, erosion mitigation, and revegetation efforts. In addition, two separate landfills used for 50 years or more, "Summer Dump" and "South Yard," may contain hazardous materials.
- Abandoned Mineral Lands. The Abandoned Mineral Lands (AML) database, maintained by the NPS Geologic Resources Division, documents 15 surface mines at Crater Lake National Park; five of these are in need of hazard mitigation such as signage, closure, or restoration.

Geologic features of particular significance for resource management at Crater Lake National Park include the following:

- Mount Mazama. Mount Mazama consisted of a succession of overlapping shield and stratovolcanoes built upon lava flows older than 400,000 years. Volcanoes that helped to build up the edifice of Mount Mazama each were probably active for a comparatively short period of time—a few thousand years to perhaps 40,000 years. As Mount Mazama grew, the focus of activity migrated in a west–northwest direction. The climactic eruption of Mount Mazama lasted only a few days, but erupted approximately 50 km^3 (12 mi^3) of magma. This eruption took place in two phases: a single-vent phase that produced a towering column of pumice and ash, called a "Plinian eruption," and a ring-vent phase that started as the volcano began to collapse in upon itself, creating circular cracks that opened up around the peak. The ring-vent phase produced pyroclastic flows—rapidly moving, chaotic mixtures of rock fragments, gas, and ash, greater than 800°C (1,470°F)—fed by vents that circumscribed the upper part of Mount Mazama.
- Mazama Ash. During the climactic eruption of Mount Mazama, principally the single-vent phase, ash rose into the air and settled over much of the western United States and southwestern Canada, blanketing an area of about 1.7 million km^2 (656,000 mi^2). The short-lived nature of the climactic eruption and the extent and thickness of the deposit make Mazama ash a valuable stratigraphic marker and an important time horizon across many depositional environments.
- Shield Volcanoes and Cinder Cones. Shield volcanoes and cinder cones partly surround Mount Mazama, and are representative of the magma input to the Mazama system over time. These small, individual volcanoes are a manifestation of regional volcanism.
- Crater Lake Caldera and Fill. The eruption and collapse of Mount Mazama created Crater Lake caldera, which is 1,200 m (3,900 ft) deep and 8–10 km (5–6 mi) in diameter at the rim. Since formation of the caldera 7,700 years ago, volcanic and sedimentary materials have been filling the basin. Initially, the collapsing caldera walls provided ample material. Later, postcaldera volcanic activity and lacustrine sedimentary processes added volcanic rocks and lacustrine sediment, respectively. Sedimentation continues today.
- Crater Lake. With respect to the average surface elevation—1,883 m (6,178 ft) above sea level—the maximum depth of Crater Lake is 594 m (1,949 ft), making it the deepest lake in the United States, second deepest lake in North America, and seventh deepest lake in the world. In addition to depth, Crater Lake's remarkable clarity and blue color are often-cited and treasured features. In light of its exceptional clarity and depth, as well as its nearly pristine condition, Crater Lake is a valuable natural laboratory. Scientific interest began in 1889; systematic study has occurred for more than two decades.
- Glacial Features. Crater Lake National Park has long been noted as a place of "fire and ice," where volcanoes and glaciers met. No glaciers occur on the landscape today, but features such as ice-bounded lava flows with polygonal, columnar jointing, as well as tuyas (table mountains), provide evidence of past glacial activity and lava-ice interactions. In addition, the park contains classic glacial features such as till and moraines, polish and striations, U-shaped valleys and notches, cirques, and horns. As many as six advances

of glacial ice occurred within the park, for example, carving the notches into the heads of Sun and Kerr valleys. A seventh advance is recorded in the caldera walls. Investigators have correlated these advances with global ice ages.

- Caves. Crater Lake National Park contains more than 40 caves. Thirty-one of these are within the rim of Crater Lake caldera, many near the lake surface, making the proximity of clear, blue Crater Lake a distinctive feature. Another five cave sites, with one or more caves, occur outside the rim. Beside the work provided by Allen (1984), the caves at the park have not been inventoried or mapped.

Acknowledgements

The GRI is administered by the Geologic Resources Division of the Natural Resource Stewardship and Science Directorate.

The Geologic Resources Division relies on partnerships with institutions such as US Geological Survey, Colorado State University, the, state geological surveys, local museums, and universities to develop GRI products.

The GRI team would like to thank the participants at the 2004 scoping meeting, who are listed in Appendix A, and Sid Covington (NPS Geologic Resources Division; geologist, now retired), who wrote the scoping summary. In addition, Charlie Bacon (US Geological Survey, research geologist) and Mac Brock (Crater Lake National Park, chief of Resource Management) participated in a post-scoping conference call in December 2012 and provided updated information about park resources and issues. Moreover, Charlie Bacon provided many photographs and other figures and answered numerous questions during the report-writing process. His advice and input are most appreciated. Also, Dave Grimes (Crater Lake National Park, park ranger) searched through park files and provided photos to help illustrate particular geologic features and issues. Julia Brunner (NPS Geologic Resources Division, policy and regulatory specialist) provided information and assisted with writing about geothermal resources and development.

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**Full citations for geologic maps used in the GRI data are in the "Geologic Map Data" section.*

Introduction

This section briefly describes the National Park Service Geologic Resources Inventory Program and the regional geologic setting and history of Crater Lake National Park.

Geologic Resources Inventory Program

The Geologic Resources Inventory (GRI) is one of 12 baseline natural resource inventories funded by the National Park Service (NPS) Inventory and Monitoring Program. The Geologic Resources Division of the NPS Natural Resource Stewardship and Science Directorate administers the GRI.

The objectives of the GRI are to provide geologic map data and pertinent geologic information to support resource management and science-based decision making in more than 270 natural resource parks throughout the National Park System. To realize these objectives, the GRI team undertakes three tasks for each natural resource park: 1) conduct a scoping meeting and provide a scoping summary, 2) provide digital geologic map data in a geographic information system (GIS) format, and 3) provide a GRI report. These products are designed and written for nongeoscientists. Scoping meetings bring together park staff and geologic experts to review available geologic maps, develop a geologic mapping plan, and discuss geologic issues, features, and processes that should be included in the GRI report. Following the scoping meeting, the GRI map team converts the geologic maps identified in the mapping plan to digital geologic map data in accordance with their data model. Refer to the "Geologic Map Data" section for additional map information. After the map is completed, the GRI report team uses these data, as well as the scoping summary and additional research, to prepare the geologic report. This geologic report assists park managers in the use of the map and provides an overview of the park's geology, including geologic resource management issues, geologic features and process, and the geologic history leading to the park's present-day landscape.

The compilation and use of natural resource information by park managers is called for in the 1998 National Parks Omnibus Management Act (section 204), Management Policies 2006, and the Natural Resources Inventory and Monitoring Guideline (NPS-75). Refer to the "Additional References" section for links to these and other resource management documents.

For additional information regarding the GRI, including contact information, please refer to the GRI website (http://www.nature.nps.gov/geology/inventory/). The current status and projected completion dates of GRI products are available on the GRI status website (http://www.nature.nps.gov/geology/GRI_DB/Scoping/Quick_Status.aspx).

Park and Geologic Setting

Crater Lake National Park was established in 1902 and encompasses 74,159 ha (183,224 ac) of pristine forest and alpine terrain (plate 1, in pocket). The park is named for Crater Lake, which partly fills one of the most spectacular calderas in the world—Crater Lake caldera. The caldera is an 8-by-10-km (5-by-6-mi) basin more than 1 km (0.6 mi) deep. It formed by collapse of Mount Mazama, which was once the largest edifice between Mount Shasta and Three Sisters volcanoes in the Cascade Range (fig. 1). Most of Mount Mazama lies within Crater Lake National Park, though its lower flanks are within nearby Rogue River and Winema national forests.

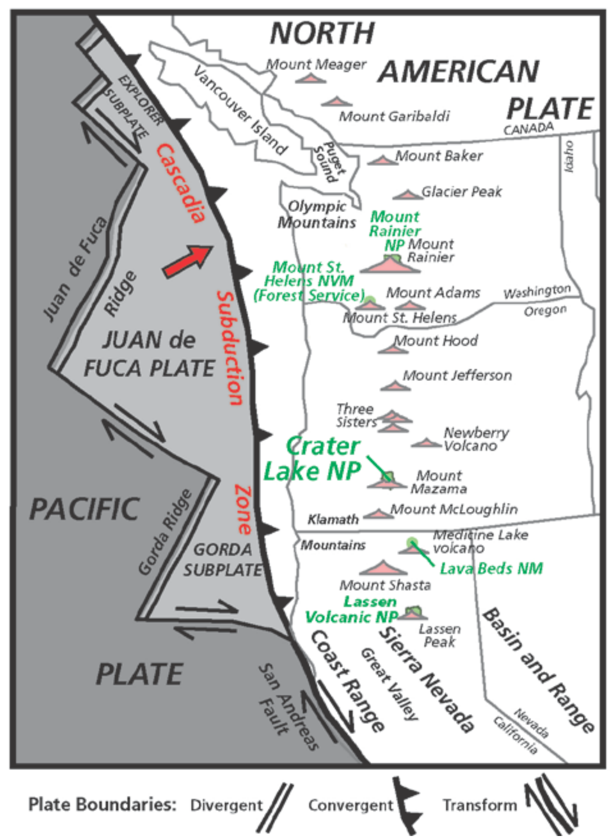


Figure 1. Cascade Range. The Juan de Fuca oceanic plate, and Gorda and Explorer subplates, are diving beneath the North American continental plate at the Cascadia subduction zone. Cascade volcanism, including the climactic eruption of Mount Mazama, and associated seismic activity are results of ongoing subduction. In addition to Crater Lake National Park, Mount Rainier and Lassen Volcanic national parks contain evidence of Cascade volcanism, as does Lava Beds National Monument. The red arrow on the figure indicates the direction of subduction. Black arrows indicate the relative movements/directions of tectonic plates. Graphic from Lillie (2005), modified by Jason Kenworthy (NPS Geologic Resources Division).

Before its caldera-forming explosion, Mount Mazama was one of the major volcanoes of the Cascade arc—a chain of prominent composite cones, also called "stratovolcanoes," and hundreds of smaller regional volcanoes (shield volcanoes and cinder cones) that extend from northern California to southern British Columbia (Bacon 2008). The two highest Cascade-arc volcanoes today are Mount Rainier (see Graham 2005) and Mount Shasta, both of which exceed 4,270 m (14,000 ft) in elevation. Elevations of these mountains have resulted less from uplift than from piling and layering of volcanic materials (Whitney 1989).

Cascade-arc volcanoes, including Mount Mazama, lie above the easterly dipping Cascadia subduction zone, where the Juan de Fuca oceanic plate, and Gorda and Explorer subplates, are sliding beneath the North American continental plate on the western edge of North America (fig. 1). The volcanic arc is active, with eruptions occurring within the past century. Mount St. Helens, which erupted explosively in 1980 and experienced dome building in 2004–2008, and Lassen Peak, which erupted explosively in 1914 and intermittently for three years thereafter, are the two most volatile volcanoes in recent years.

About 7,700 years ago—calendar years, based on a carbon-14 (^{14}C) age of 6,845 ± 50 years before present (BP) (Bacon 1983)—Mount Mazama experienced a climactic (caldera-forming) eruption during which the volcano collapsed in upon itself. Prior to collapse, the volcano had been building up for 400,000 years, since the Middle Pleistocene Epoch (fig. 2). Mount Mazama consisted of several overlapping composite and shield volcanoes, each of which was active for a few thousand years to perhaps 40,000 years (Bacon and Lanphere 2006).

Since the climactic eruption, volcanic activity has been restricted to within the Crater Lake caldera; this activity is referred to as "postcaldera" volcanism. As the lake began to fill with water, lava and pyroclastic material created the central platform (map units Hapc, Hapcb), Merriam Cone (Hamc, Hamcb), and Wizard Island (Hawp, Hawb, Haw) within a few hundred years of caldera collapse (Bacon et al. 2002). A small dome (Hr, Hrb) east of Wizard Island was emplaced most recently. Nelson et al. (1994) assigned a ^{14}C age of 4,240 ± 290 years BP, or approximately 4,800 years ago in calendar years (Stuiver et al.1998).Wizard Island is the only postcaldera volcano to breach the surface of Crater Lake. The last eruptions of Wizard Island took place when Crater Lake was about 80 m (260 ft) lower than today (Bacon et al. 2002).

Before its climactic eruption, Mount Mazama stood roughly 3,700 m (12,000 ft) in elevation. Today the highest point on the caldera rim is Hillman Peak (fig. 3), which is 2,426 m (7,959 ft) above sea level and 604 m (1,980 ft) above the surface of Crater Lake (US Geological Survey 2008). Hillman Peak is a 70,000-year-old stratovolcano and one of the youngest remnants of Mount Mazama (Bacon 2008). Nearby Mount Scott (fig. 4), which is about 420,000 years old, represents the oldest remnant of Mount Mazama. It lies east of Crater Lake caldera. At 2,628 m (8,622 ft) in elevation, Mount Scott is the highest peak in the park.

The 53-km (33-mi) Rim Drive around Crater Lake provides access for viewing the volcanic landscape, leading to more than 30 scenic overlooks. The overlook at Discovery Point is the spot of the first recorded sighting of Crater Lake (fig. 5). In 1853, gold prospector John Wesley Hillman stumbled upon this view of what he called "Deep Blue Lake." The quality of the lake's water enables sunlight to penetrate and create the renowned blue color, as well as provides a mirror-like surface that reflects images of the steep caldera walls. The cliffs rise from 150 to 610 m (500 to 2,000 ft) above the lake's surface.

Generations of visitors have been dazzled by the remarkable color and clarity of Crater Lake. The interaction of people with this place is traceable back to the eruption of Mount Mazama. Archeologists have found sandals and other artifacts buried under layers of ash, dust, and pumice from the climactic eruption. To date, archaeological evidence does not indicate that Mount Mazama was permanently inhabited. Rather, it was used as a place for visionquests and prayer. Accounts of the eruption can be found in stories told by the Klamath Indians today (National Park Service 2010). European contact with Mount Mazama and Crater Lake was fairly recent, starting with Hillman's discovery in 1853.

The geologic setting of Crater Lake National Park is also noted for many glacial features. Ice occupied valleys and the higher parts of Mount Mazama at least six times during the volcano's history (Bacon and Lanphere 2006; Bacon 2008). A seventh glaciation is recorded in the caldera walls. Repeated glacial advances carved the deeper valleys in the park such as Munson, Sun, and Kerr (Bacon and Lanphere 2006).

Facilities and visitor opportunities at the park include two campgrounds (Mazama and Lost Creek), two visitor centers (Steel and Rim), eight picnic areas, 145 km (90 mi) of hiking trails, and a boat tour on Crater Lake. Annual visitation is generally around 400,000; 447,251 people visited the park in 2012 (National Park Service 2013).

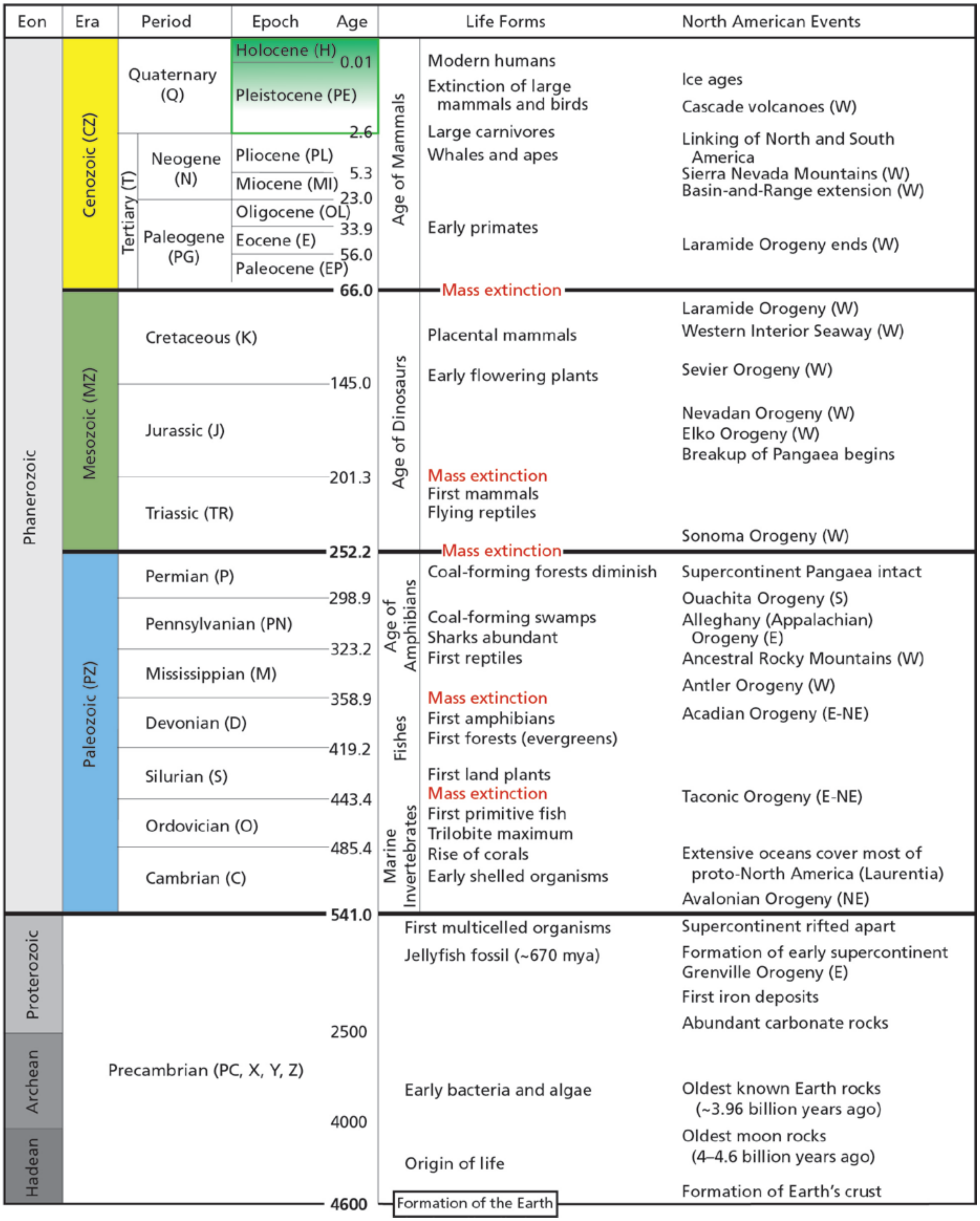


Figure 2. Geologic time scale. The divisions of the geologic time scale are organized stratigraphically, with the oldest at the bottom and youngest at the top. GRI map abbreviations for each geologic time division are in parentheses. The most significant geologic events at Crater Lake National Park took place during the Holocene (H) and Pleistocene (PE) epochs, as indicated by the green shading on the time scale. Rocks immediately outside the boundary of the park are somewhat older; the oldest are from the Oligocene Epoch. Boundary ages are in millions of years. Major life history and tectonic events occurring on the North American continent are included. Compass directions in parentheses indicate the regional location of individual geologic events. Graphic design by Trista Thornberry-Ehrlich (Colorado State University) and Rebecca Port (NPS Geologic Resources Division), using dates published by the International Commission on Stratigraphy (http://www.stratigraphy.org/index.php/ics-chart-timescale; accessed 23 September 2013).

Figure 3. The Watchman and Hillman Peak. The Watchman (left) and Hillman Peak (right) dominate the western wall of Crater Lake caldera. Andesite of Hillman Peak (PEah) forms the summit of its namesake. The Watchman is a glaciated horn sculpted from a thick lava flow—dacite of The Watchman (PEdwf)—whose feeder dike forms sail-like outcrops on the caldera wall. US Geological Survey photograph by Charles R. Bacon.

Figure 4. Mount Scott. Mount Scott (right foreground) stands 2,721 m (8,928 ft) above sea level and is the highest peak in Crater Lake National Park. It is composed entirely of lava and pyroclastic rubble of dacite of Mount Scott (PEds), which is approximately 420,000 years old. The peak has a mantle of pumice (Hcp) that was ejected during the climactic eruption of Mount Mazama. One or more snow avalanches created the long buff-colored scar descending down the flank of the peak (left). In the distance Wizard Island breaks the surface of Crater Lake. The Watchman is directly behind Wizard Island on the caldera rim; Hillman Peak is farther right. Llao Rock is at the right-hand edge of the photograph. US Geological Survey photograph by Charles R. Bacon.

Figure 5. Discovery Point. Rim Drive encircles Crater Lake caldera and provides views of Crater Lake. This overlook is Discovery Point, which offers a fine view of Wizard Island and marks the spot where gold prospector John Hillman first set eyes on Crater Lake in 1853. Note the historic guard wall in this photograph. A proposed project will repair historic features such as guard walls along the road and at some overlooks (see "Slope Movements" section). National Park Service photograph.

Geologic Issues

Geologic issues described in this section may impact park resources or visitor safety and could require attention from resource managers. Contact the Geologic Resources Division for technical and policy assistance.

During the 2004 scoping meeting and 2012 conference call, participants identified the following geologic resource management issues:

- Slope Movements
- Seismic Activity
- Volcano Hazards
- Hydrothermal Features and Geothermal Development
- Disturbed Lands Restoration
- Abandoned Mineral Lands

Resource managers may find *Geological Monitoring* (Young and Norby 2009; http://go.nps.gov/geomonitoring) useful for addressing these geologic resource management issues. The manual provides guidance for monitoring vital signs—measurable parameters of the overall condition of natural resources. Each chapter covers a different geologic resource and includes detailed recommendations for resource managers and suggested methods of monitoring.

Slope Movements

Crater Lake caldera is a collapse depression enlarged by slope movements. The collapse of Mount Mazama's magma chamber created an area of structural subsidence that is approximately 5 km (3 mi) in diameter (Bacon 1983). However, as a result of slope movements, the topographic caldera is nearly twice that size, spanning 10 km (6 mi) east–west by 8 km (5 mi) north–south. Slope movements of the caldera walls formed the distinctive scalloped outline seen today.

The Chaski Bay landslide, or "Chaski slide," was the most recent major landslide event to carry debris to the center of the caldera floor. This landslide, also referred to as a debris-avalanche deposit, has not been dated directly, but likely occurred soon (about 200 years) after the climactic eruption (Charles R. Bacon, US Geological Survey, research geologist, email communication, 25 September 2013). Material from the Chaski slide covers an area of 4.9 km^2 (1.9 mi^2), has a volume of 0.21 km^3 (0.05 mi^3), and is the largest of its kind in the park. The Chaski slide deposit exemplifies landslide deposits (map unit Hls) of Bacon (2008). These deposits consist of large blocks removed from the caldera wall. The largest blocks in the Chaski slide deposit are about 280 m (920 ft) long.

Other landslide deposits occur outside Crater Lake caldera. At a scale of 1:24,000, Bacon (2008) mapped only the largest subaerial earthflows and slumps (Qls) in the vicinity of the park. Some deposits show hummocky topography where debris has moved onto flat terrain; other deposits plaster canyon walls. Notable examples of landslide debris (Qls) occur in the Rogue River valley, west of the park.

Since the creation of Crater Lake caldera, debris chutes have transported sediment—via gravity slides (e.g., rockfall, debris avalanches, and slumps) and sediment-gravity flows (e.g., debris flows, grain flows, and turbidity currents)—to form coalescing sediment aprons at the base of the caldera walls. Finer grained material continues into basins on the floor of the caldera (Nelson et al. 1986, 1994).

Evidence of this gravity-driven scenario is documented by Bacon (2008) and shown as landslide deposits (Hls) and sediment gravity-flow deposits (Hsl) on the geologic map of Crater Lake National Park. Landslide deposits (Hls) include debris-avalanche deposits beneath the surface of Crater Lake. They are composed of unconsolidated, poorly sorted rock debris derived from the caldera walls and transported into the lake by mass-wasting (gravity-driven) processes. Sediment gravity-flow deposits (Hsl) represent modern, ongoing sedimentation as fine-grained debris moves towards the east, northwest, and southwest basins, creating smooth, nearly flat surfaces (Nathenson et al. 2007). Fine-grained sediments may "pond" in local depressions along the way to these basins (see "Crater Lake Caldera and Fill" section). The uppermost sedimentary layers in these basins, and numerous smaller sediment-filled depressions on and between lava flows and landslide deposits, consist of mud and fine-grained sand (Bacon 2008).

In addition, much of the submerged caldera wall is buried under fragmented debris aprons shown as talus (Qt) on the geologic map. Submerged talus (Qt) shed from caldera walls is contiguous with subaerial talus (also delineated by map unit Qt). Conspicuous slopes of talus outside Crater Lake caldera occur at the heads of Kerr and Munson valleys, and on the northern slope of Union Peak (Bacon 2008).

Slope-Related Geologic Hazards

Slope movements can constitute a geologic hazard where these conditions threaten human life, welfare, and property (Neuendorf et al. 2005). Within the park, the following three areas are noted for having slope-related geologic hazards:

Rim Drive

Automobile access into Crater Lake National Park is from the north and south. Oregon Highway 97 leads to the North Entrance Road and North Entrance Station of the park. Oregon Highway 62 leads to the South

Entrance Road and Annie Spring Entrance Station (plate 1). Both the southern and northern roads join Rim Drive, which encircles the Crater Lake caldera. Rim Drive provides scenic views of Crater Lake and is part of the "volcano to volcano" connection (scenic byways) that links Crater Lake and Lassen Volcanic national parks (National Park Service 2005). The road is vital to park operations and local economies (National Park Service 2012b).

Rim Drive was originally completed in 1941 and has periodically needed repairs to address structural deficiencies and normal wear. The road bench supporting the pavement has suffered from incremental erosion due to the soft underlying pumice soil and rock. Portions of the existing pavement have developed ruts, lateral cracking, and severe raveling at pavement edges. In addition, historic guard walls (fig. 5), which are contributing elements to the National Register listing of Rim Drive, are failing in some locations due to erosion and age, and require stabilization to prevent further damage. Also, steep rock cliffs and cut slopes along Rim Drive are eroding, resulting in falling rock onto the road. Rockfall has the potential for damaging the road and endangering travelers (National Park Service 2012b). The National Park Service, in cooperation with the Western Federal Lands Highway Division of the Federal Highway Administration, is taking actions to rehabilitate Rim Drive and mitigate rockfall (Mac Brock, Crater Lake National Park, chief of Resource Management, written communication, 9 April 2013).

Cleetwood Cove Trail

The Cleetwood Cove Trail is a specific area of concern for rockfall hazards (figs. 6 and 7). The trail usually opens mid- to late June. The steep (11% grade) trail is 1.8 km (1.1 mi) long and drops nearly 210 m (700 ft) down to Crater Lake. Park guides list the trail as "strenuous." Cleetwood Cove Trail, however, is the only place in the park where it is legal, and relatively safe, to get down to the lakeshore (National Park Service 2009).

Figure 6. Cleetwood Cove. The scalloped form of Cleetwood Cove is typical of collapse calderas that enlarge via slope movements during and immediately following a caldera-forming eruption. Holocene rhyodacite of the Cleetwood flow (map unit Hrh) forms the cliff at the caldera rim above the cove. Palisade Point juts into the lake at the right of the photograph. On the left are the boat landing and gauging station. Mount Bailey (left) and Mount Thielsen (right) are in the distance. US Geological Survey photograph by Charles R. Bacon.

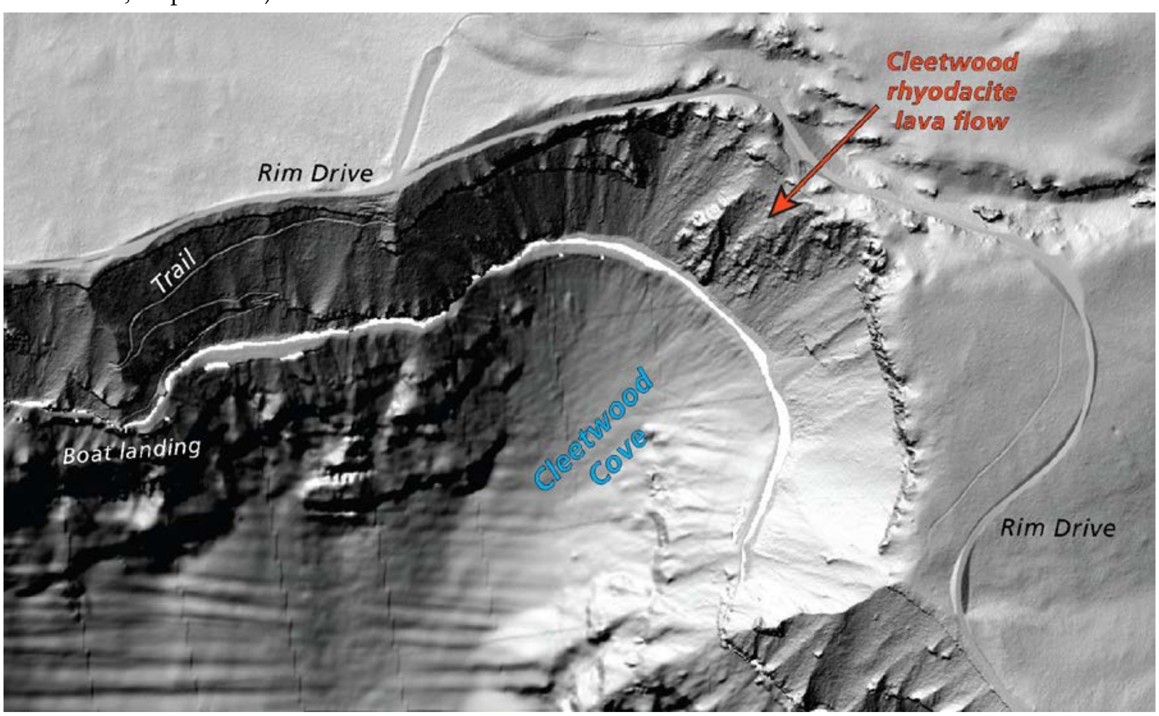


Figure 7. Cleetwood Cove relief. Bathymetric and light detection and ranging (LiDAR) imagery show the amphitheater-shaped Cleetwood Cove on the northeastern edge of Crater Lake. The embayment formed during the climactic eruption of Mount Mazama as the mountain foundered into the opening caldera. The Cleetwood rhyodacite lava flow (Hrhv), which erupted as little as a few months before the climactic eruption, is northeast of the cove (upper, right-hand corner of the image). The Cleetwood Cove Trail and the boat landing are visible on the image. The trail zigzags its way down the caldera wall (middle left). A white band, separating bathymetric from LiDAR survey data, appears on the image. In addition, parallel east–west "grooves" and north–south "stitching" on the lake floor are artifacts of bathymetric data processing. US Geological Survey graphic from Robinson et al. (2012) with annotations by Rebecca Port (NPS Geologic Resources Division).

Capable visitors can hike down the trail and swim or fish in the lake from the shoreline at trail's end. The trail also leads to the boat landing, where visitors can participate in a ranger-led boat tour.

Because the trail was developed on the extremely steep slopes of Crater Lake caldera, it has the potential for rockfall. Holocene rhyodacite of the Cleetwood flow of Williams (1942) (map unit Hrh) forms cliff at the caldera rim above the arcuate cove (Bacon 2008). In 1993, rockfall caused the death of a visitor on the trail (Covington 2004). The trail requires extensive annual monitoring and maintenance to provide safe conditions for park operations and the visiting public (Mac Brock, Crater Lake National Park, chief of Resource Management, conference call, 18 December 2012).

Caldera Wall below Crater Lake Lodge

Crater Lake Lodge is located less than 15 m (50 ft) from the rim of Crater Lake caldera, where the caldera wall descends very steeply for about 270 m (900 ft) down to Crater Lake (fig. 8). In the 1980s, the stability of the caldera wall on the northern side of the lodge was questioned because the lodge, which was constructed in the early 1900s, had experienced fairly severe distress over its lifetime. Cracks had developed in the lodge's foundation and also appeared in structural walls, but the cause—slope movement or poor foundation design—was not clear. The concern was that the weight of the lodge was "loading" the slope, which might be undergoing slow failure or slippage that was, in turn, damaging the historic structure.

Erosion of the slope from water seepage was another concern. Flow from a spring, located about 90 m (300 ft) below the lodge above a lava outcrop, was eroding material around the spring and undermining material above, resulting in a progression of downslope erosion. The presence of large boulders, up to 2 m (6 ft) in diameter, on the slope exacerbated erosion. When erosion reached a point that a boulder was undermined, the rock would tumble down the slope, causing loss of material both above the boulder and along the boulder's path (Denver Service Center 1997).

Figure 8. Crater Lake Lodge. Slope movements are apparent on the caldera wall below Crater Lake Lodge, where the historic lodge is located less than 15 m (50 ft) from the rim. The caldera wall slopes very steeply for about 270 m (900 ft) down to Crater Lake. The lodge was constructed on top of a thick, unconsolidated deposit of dactie of Munson Valley (PEdvb), which consists of material transported by hot debris avalanches derived from the collapse of an unstable lava dome high on Mount Mazama about 35,000 years ago. National Park Service photograph.

In addition, surface drainage over the edge of the slope was a concern. Sources of drainage include natural drainage, runoff from the developed area around the lodge, point drainage from the promenade area, and water from snowmelt on the slope. Moreover, the weight of snow that accumulated on the slope causes downslope movement of soil (Denver Service Center 1997).

Between 1981 and 1993, a series of studies was conducted to determine slope stability and the potential effects of slope movement on Crater Lake Lodge. Based on these investigations, the final slope stability report by the Denver Service Center (1997) concluded that the slope did not contain a failure plane and was stable under static conditions. In the event of an earthquake, calculations did not indicate that the slope would fail, but they also did not clearly find that the slope would remain stable (Denver Service Center 1997). The final report concluded that no action was necessary to mitigate slope failure, but inclinometers used in investigations were left in place. Additional readings could be taken if further cracking of the lodge's foundation, or some other outward indication of movement, occur.

The final slope stability report recommended that slope movement be monitored periodically, including an annual visual inspection by park personnel, and a more thorough inspection by a qualified geologist or geotechnical engineer every three years. A sudden increase in erosion or a significant loss of material might indicate that some type of erosion control system should be installed (Denver Service Center 1997). Wieczorek and Snyder (2009)—the chapter in *Geological Monitoring* about slope movements—described five vital signs for monitoring: (1) types of landslides, (2) landslide causes and triggers, (3) geologic materials in landslides, (4) measurement of landslide movement, and (5) assessing landslide hazards and risks. This information may be useful for resource managers in developing a plan to monitor the caldera wall below Crater Lake Lodge.

Seismically Induced Slope Movements

Should a large mass of rock fall or slide rapidly from the caldera wall into Crater Lake, one or more large waves could be generated. Waves could be many meters high and travel across the lake in as little as two minutes, such as from Chaski Bay to the boat landing at Cleetwood Cove (Bacon et al. 1997). Local volcanic earthquakes, movement on the West Klamath Lake fault zone, or earthquakes on the distant Cascadia subduction zone all could produce shaking adequate to trigger sliding of the fractured and poorly consolidated rock of the caldera walls and talus (Qt) slopes (see "Seismic Activity" section). Earthquake shaking alone, without rapid entry of slide material into Crater Lake, would not be expected to cause dangerous waves (Bacon et al. 1997).

Many examples of large waves caused by landslides are documented in the scientific literature. Those most relevant to the situation at Crater Lake have occurred in deep, glacially scoured bays and fjords where either a large mass of rock has fallen or slid into the water or a submarine slope has failed (Bacon et al. 1997). A spectacular example of a seismically induced rockslide and ensuing wave occurred in Lituya Bay in Glacier Bay National Park, Alaska, on 9 July 1958 (Miller 1960). Lituya Bay—an ice-scoured, nearly landlocked tidal inlet adjacent to the Fairweather Range and Fairweather fault in the Gulf of Alaska—has a maximum depth of 220 m (720 ft). In the 1958 event, a magnitude (M) = 7.9 earthquake on the Fairweather fault triggered a large rockslide with a volume of about 30 million m^3 (1,060 million ft^3) at the head of Lituya Bay. The avalanche of rock generated the so-called "world's biggest tsunami" (Geology.com 2013). The wave—traveling at an estimated 160–210 kph (100–130 mph)—surged down the bay, denuding both shorelines to an elevation of about 60 m (200 ft). On the shore opposite of the slide, the wave run-up reached an elevation of 530 m (1,740 ft). Near the mouth of the bay, 11 km (7 mi) away, two fishing boats sank, resulting in two deaths (Miller 1960).

Seismic Activity

Earthquake hazards in the greater Crater Lake area are similar to those in other earthquake-prone areas, namely damage to structures, utilities, communication lines, and transportation systems (Bacon et al. 1997). *Volcano and Earthquake Hazards in the Crater Lake Region, Oregon* by Bacon et al. (1997) discussed three sources of earthquakes that could affect Crater Lake National Park—the West Klamath Lake fault zone, Cascadia subduction zone, and local volcanic earthquakes.

West Klamath Lake Fault Zone

Crater Lake National Park lies within the Klamath graben—the westernmost basin of the Basin and Range physiographic province, a region where Earth's crust is being gradually pulled apart. The faults that accommodate this extension could produce damaging earthquakes in the park.

The northern end of the Klamath graben is marked by Mount Mazama and Crater Lake caldera, where the West Klamath Lake fault zone—a N10°W–oriented major Basin and Range structure—impinges upon the north–south-oriented Cascade volcanic arc (Bacon et al. 1999). The West Klamath Lake fault zone bounds the Klamath graben on its western side.

Normal faults, typically 10–15 km (6–9 mi) long, form the fault zone (fig. 9). Its total length is about 70 km (40 mi). The northern part of the zone runs past Crater Lake as the Annie Spring fault to the south of the lake and the Red Cone Spring fault to the north of the lake (see hazards map graphic, in pocket). Crater Lake and the populated area of the park are located on the hanging walls of the Annie Spring and Red Cone Spring faults. The Annie Spring fault is within 1 km (0.6 mi) of the western caldera rim and Rim Village. Facilities at the park are located directly above the rupture plane of the Annie Spring fault. However, a local earthquake of sufficient magnitude to seriously damage structures and disrupt transportation systems in the Crater Lake area probably does not occur more frequently than once every few thousand years (Bacon et al. 1997).

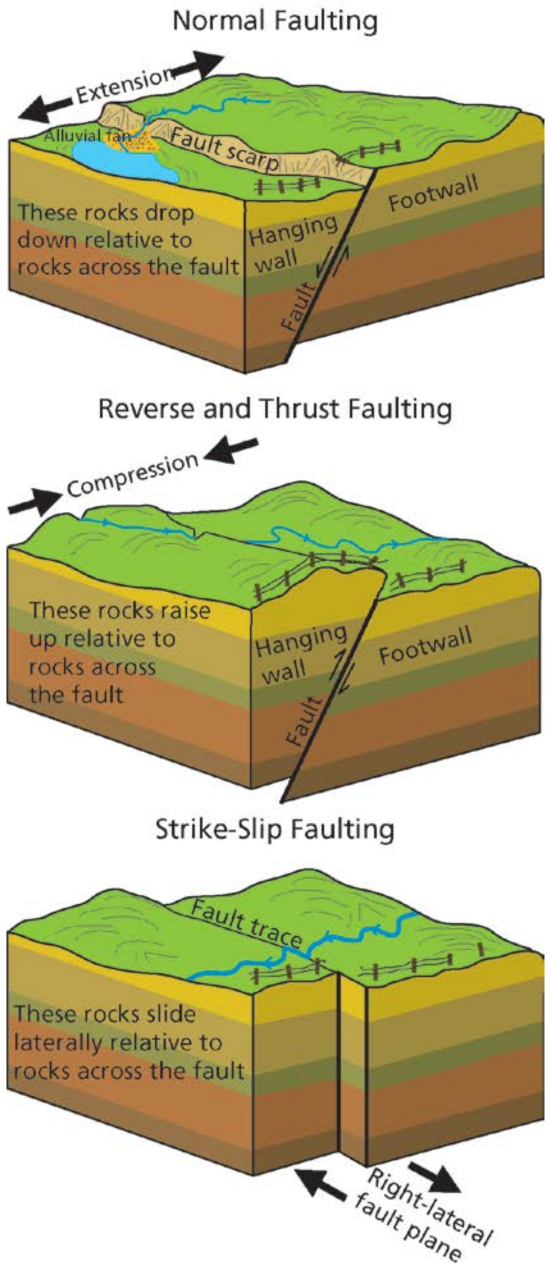


Figure 9. Types of faults. Basin and Range extension manifests itself as normal faults that compose the West Klamath Lake fault zone. The Annie Spring and Red Cone Spring faults are normal faults within Crater Lake National Park. In a normal fault, crustal extension (pulling apart) moves the hanging wall down relative to the footwall. In a reverse fault, crustal compression moves the hanging wall up relative to the footwall. A thrust fault is similar to a reverse fault but has a dip angle of less than 45°. Thrust faulting occurs at the Cascadia subduction zone (fig. 1). In a strike-slip fault, the relative direction of movement of the opposing plate is lateral. The San Andreas Fault is a strike-slip fault (fig. 1). Graphic by Trista Thornberry-Ehrlich (Colorado State University).

The West Klamath Lake fault zone terminates south of the park near the epicentral area of the Klamath Falls earthquakes, where on 20 September 1993, two earthquakes of M = 6.0 occurred about 20 km (12 mi) northwest of Klamath Falls, Oregon, which is approximately 60 km (40 mi) south of Crater Lake. The two earthquakes were separated by a few hours and resulted in widespread damage and two deaths (Sherrod 1993). These quakes were followed by hundreds of aftershocks during succeeding weeks (Bacon et al. 1999). The Klamath Falls earthquake event of 1993 serves as a relevant local example of moderate earthquake damage for Crater Lake National Park.

Cascadia Subduction Zone

Another source of seismic activity affecting the park is the Cascadia subduction zone, where the Juan de Fuca oceanic plate, along with the Gorda and Explorer subplates, are sliding beneath the North American continental plate on the western edge of North America (fig. 1). Subduction generates earthquakes, including the M = 6.7 earthquake that occurred near the California–Oregon state line on 23 November 1873, which was felt from San Francisco to Portland (Ellsworth 1990). The maximum magnitude of an earthquake on the Cascadia subduction zone is at least M = 8 and possibly M = 9 (Satake and Tanioka 1996). Although distant, such a quake could result in several minutes of continued shaking at the park (Bacon et al. 1997). Earthquakes generated in the Cascadia subduction zone may be less violent than earthquakes produced on the West Klamath Lake fault zone for the park, but they are likely to have greater frequency and be of longer duration (Bacon et al. 1997).

Local Volcanic Earthquakes

A third source of seismic activity at the park is a local earthquake resulting from volcanic activity, including the movement of magma, formation of cracks through which magma can move, and gas explosions within a magma conduit (Blong 1984). Local volcanic earthquakes may also be the result of readjustment of a volcano edifice following eruption or movement of magma (Blong 1984).

Local volcanic earthquakes would produce ground motion at the park, but the probable maximum magnitude of such an event is M = 5, which is significant but far smaller than expected for tectonic earthquakes (Bacon et al. 1997). Infrastructure at distances greater than a few tens of kilometers from a volcanic earthquake is not likely to be damaged by such events (Hoblitt et al. 1987).

Seismic Statistics

Studies of tectonic features and processes such as faulting near Crater Lake National Park have yielded some statistics of interest for resource management and interpretation:

- Largest Historic Earthquake. The largest documented earthquake near Crater Lake occurred in 1920 before the Richter scale came into widespread use. The event was an intensity V on the Modified Mercalli scale (I–XII). Vibrations would have been felt by nearly everyone, some dishes and windows would have broken, unstable objects would have overturned, and pendulum clocks would have stopped. This earthquake had an estimated M = 4+ on the Richter scale (Bacon et al. 1999).

- Maximum Possible Earthquake. Earthquakes as large as M = 7.3 are possible on the West Klamath Lake fault zone (Bacon et al. 1999). This estimate is based on the empirical relationship between earthquake magnitude and surface rupture length for normal faults (Wells and Coppersmith 1994), which on the West Klamath Lake fault zone is 70 km (40 mi). According to Bacon et al. (1999), this finding is similar to the conclusion of Hawkins et al. (1989), who reported a maximum earthquake for the West Klamath Lake fault zone of M = 7.25, and is consistent with the findings of Weldon et al. (1996), who studied earthquake potential in central Oregon. The maximum magnitude of a great earthquake on the Cascadia subduction zone is at least M = 8 and possibly M = 9; the maximum possible local volcanic earthquake is M = 5.
- Recurrence Interval. Recurrence intervals are unknown for earthquakes on the West Klamath Lake fault zone (Bacon et al. 1999). However, if all of the displacement on these faults took place in events with about 1–2 m (3–7 ft) of vertical offset (Weldon et al. 1996), major earthquakes (M = 7) would be expected to recur at an average rate of one event in 3,000 to 7,000 years. This result assumes a periodic recurrence model and characteristically sized events having average displacements of 1.5 m (5 ft) (Bacon et al. 1999).
- Displacement and Slip Rate. Bacon et al. (1999) measured seven offsets on the Annie Spring fault, ranging between 15 and 160 m (50 and 525 ft), and one offset on the Red Cone Spring fault. Although the 11 m (36 ft) offset on the Red Cone Spring fault is a minimum value, the age is well constrained at 35,000 years ago, giving a minimum vertical slip rate of 0.31 mm (0.012 in) per year. This rate is consistent with the 0.30 mm (0.011 in) per year minimum slip rate for the northern end of the Annie Spring fault derived from the 15 m (50 ft) measured offset in the dacite of The Watchman (55,000 ± 3,000 years ago; Bacon 2008).

Seismic Monitoring

The National Park Service has an agreement with the Cascades Volcano Observatory (CVO) to conduct seismic monitoring at the park. The principal function of seismic stations in the Crater Lake area is to record local earthquakes that might indicate volcanic "unrest," but these stations also would record tectonic earthquakes (Charles R. Bacon, US Geological Survey, research geologist, written communication, 15 March 2013).

Seismic stations still require repeated upkeep, but coverage has improved since the geologic scoping meeting in 2004 (Covington 2004). From 1979 to 1982, the US Geological Survey operated a single seismic station in the park; it was removed in 1982, resulting in no seismometers operating anywhere within 40 km (25 mi) of the park between 1982 and 2008 (Walkup 2012). In 2008, CVO staff installed four temporary seismic stations that were active for several months within the park. Also in 2008, CVO staff installed two long-term seismic monitoring stations at Cleetwood Cove and Wizard Island. In 2009, both stations were modified to have a continuous Global Positioning System (GPS) receiver. In 2009, CVO scientists installed a third long-term seismic station with GPS at Mount Scott (Walkup 2012).

Braile (2009)—the chapter in *Geological Monitoring* about earthquakes and seismic activity—described the following methods and vital signs for understanding earthquakes and monitoring seismic activity: (1) monitoring earthquakes, (2) analysis and statistics of earthquake activity, (3) analysis of historical and prehistoric earthquake activity, (4) earthquake risk estimation, (5) geodetic monitoring and ground deformation, and (6) geomorphic and geologic indications of active tectonics.

Volcano Hazards

The climactic eruption and collapse of Mount Mazama and resultant formation of Crater Lake caldera changed the character of the volcano system so dramatically that many potential types of future eruptions expected at other Cascade-arc volcanoes have no precedent at Crater Lake National Park (Bacon et al. 1997). Caldera formation caused a drastic reorganization of the magmatic plumbing system. Moreover, the magma reservoir, which fed the climactic eruption, was depleted. Also, a lake is now present within the caldera, making it unique among Cascade-arc volcanoes.

Low-Probability, High-Consequence Events

Bacon et al. (1997) identified three volcano-related events of high consequence, but low probability, at Crater Lake National Park. These are (1) a large pyroclastic eruption, such as the one that formed Crater Lake caldera; (2) sudden gas release from Crater Lake, such as the lethal release of cold CO_2 from Lake Nyos, Cameroon, in 1986; and (3) catastrophic draining of Crater Lake.

A pyroclastic, caldera-forming eruption is not considered likely for many thousands of years because the magma reservoir that fed the climactic eruption of Mount Mazama has not had sufficient time to regenerate a large volume of gas-rich silicic ("explosive") magma. According to Bacon and Lanphere (2006), a period of about 20,000 years was required to form the silicic component of the climactic magma chamber, and only 7,700 years have passed since the climactic eruption.

Sudden gas release from Crater Lake is possible, but natural mixing of deep water with near-surface water prevents volcanic CO_2 that escapes from the lake floor from building up. As long as the natural mixing process continues, sudden gas release is not considered a significant hazard within Crater Lake.

Catastrophic draining of Crater Lake is extremely unlikely, but is an event that would have disastrous consequences for downstream lowlands in the affected tributary drainages. No known mechanism, short of another large-volume eruption, could eject most of the water in the lake or cause the caldera wall to fail.

Eruption Probability and Hazard Zones

The most recent eruptions at the park occurred on the lake floor in the western part of the caldera. Future eruptions are more likely to occur in this area than farther east (Bacon et al. 1997). This hypothesis emphasizes the trend of Mount Mazama's eruptive focus migrating to the west over time. Crater Lake Lodge, Rim Village, and structures in the park headquarters area are at highest risk from an eruption in this quadrant of the lake. An eruption elsewhere in the caldera might not affect this area, except with tephra fall if wind conditions were appropriate (Bacon et al. 1997).

Volcano and Earthquake Hazards in the Crater Lake Region, Oregon by Bacon et al. (1997) estimated the likelihood of future volcanic events based on the total number of eruptive episodes, exclusive of Mount Mazama, in the past 100,000 years. These investigators estimated an average recurrence interval of about 10,000 years. Thus the annual probability of an eruption occurring near Crater Lake is about one chance in 10,000, or 10^{-4}. The 30-year probability is about one chance in 330, or 3×10^{-3}. According to Bacon et al. (1997), these estimates are, at best, very approximate because volcanic eruptions are triggered by the interplay of complex processes, with no guarantee that events occurring in the future will adhere to the simplistic model used to estimate probabilities.

Types of Volcano Hazards

Bacon et al. (1997) described the various types of volcano hazards in Crater Lake National Park and vicinity and provided a map of hazard zones. A digital version of this map is part of the GRI GIS data set and a graphic representation is provided (see hazards map graphic, in pocket).

Bacon et al. (1997) defined the hazard zones on the basis of locations of volcanic vents active during the past 1 million years. Proximal hazard zone PA is the area bounded by the Crater Lake caldera rim and is subject to pyroclastic surges and ballistics (ejected material) from explosive eruptions anywhere within the caldera. Pyroclastic surges are mixtures of air, volcanic gas, steam, and magma or rock fragments that move along the ground surface at high velocities. Unlike lava flows, which are generally confined to valleys, pyroclastic surges are capable of flowing over topographic barriers. Surges may transport debris away from vents at velocities up to hundreds of meters per second (many hundreds of miles per hour). With temperatures that range from the boiling point of water to the temperature of magma, pyroclastic surges can destroy or incinerate most structures and living things in their path.

Proximal hazard zone PB is the area outside zone PA that may be affected by pyroclastic surges and ballistics from explosive eruptions from vents within the lake and close to the shoreline.

Regional hazard zone RH is a zone of relatively high probability of a volcanic eruption. It contains vents less than 100,000 years old.

Regional hazard zone RL is a zone of relatively low probability of a volcanic eruption; it contains vents between 1 million and 100,000 years old.

Lahars

The lahar hazard zone of Bacon et al. (1997) delineated areas potentially inundated by lahars. Lahars are rapidly moving debris flows that originate at volcanoes and consist of rock fragments carried downslope in a matrix of clay or pulverized rock and water. Lahars can travel great distances from their sources. Most large Cascade stratovolcanoes, for example Mount Rainier, have produced lahars in the past and are likely to continue to do so (Bacon et al. 1997). Mount Mazama, however, differs from these volcanoes because it no longer has an ice-clad summit covered in unconsolidated volcaniclastic material, which would serve as a source of high-elevation water and debris. Nevertheless, if an eruption occurs near the shoreline of Crater Lake with sufficient force to eject lake water from the caldera, abundant loose debris left by the climactic eruption on the upper slopes of Mount Mazama and in the valleys might be mobilized to form lahars. Alternatively, an eruption outside of the caldera that results in rapid melting of thick snowpack might produce lahars. Such lahars would be localized in low-lying areas and would tend to be confined to narrow canyons. The lahar hazard zone shown on the digital hazards map of Crater Lake National Park delineates these areas (see hazards map graphic, in pocket).

Volcanic Eruptions within Crater Lake Caldera

The presence of Crater Lake creates potential hazards from future eruptions that did not exist prior to the formation of the caldera (Bacon et al. 1997). These hazards would be a result of the violent mixing of lake water with erupting magma. Interaction of magma and lake water at shallow levels—a few tens of meters (<100 ft)—could generate explosions that throw large rocks and ash out beyond the rim. Waves several meters high on Crater Lake could be associated with explosive eruptions within the caldera. The largest explosions could produce pyroclastic surges, which could move out a few kilometers from vents along the margin of the lake. Eruptions in deeper water are less likely to be explosive or affect areas around the rim. Finally, an eruption from a vent in the caldera wall also might be explosive because of abundant groundwater contained within the bedrock.

Eruptions outside Crater Lake Caldera

Many small volcanoes are situated around and between large Cascade-arc volcanoes. These small volcanoes are a manifestation of regional volcanism and include cinder cones, fissure vents, lava domes, and shield volcanoes, each of which formed in a brief period of time (see "Shield Volcanoes and Cinder Cones" section). Hazards from regional volcanoes include building of cinder cones, production of lava flows, and emission of tephra. Lava flows advance slowly enough that they will pose a threat only to property and structures. Tephra falls may be significant near a vent and for a few kilometers downwind. Hazards also include pyroclastic surges and flows (Bacon et al. 1997).

Volcano Hazard Mitigation

Bacon et al. (1997) made recommendations for mitigation of volcano hazards in the Crater Lake region. They suggested using information about volcano hazards when making decisions about land use and the siting of critical facilities, housing, and rights-of-way for transportation and utilities. Based on hazard zones provided in Bacon et al. (1997), park planners can avoid development in areas deemed as having an unacceptably high risk, plan in such a way as to reduce the level of risk, or include engineering measures to mitigate risk.

Bacon et al. (1997) also highlighted the importance of having an emergency response plan in place, which will be most effective if citizens and public officials have an understanding of volcano hazards. Evacuation planning deserves special consideration at the park because of limited road access to the heavily used area on the southern rim. Although the number of people in this location at any given time is not great, evacuation could be challenging as a result of disruption of the road system. Currently, the only public evacuation plan from the park is for wildland fire emergencies. This plan does not take into account the unique circumstances expected during a volcanic event (Mac Brock, Crater Lake National Park, chief of Resource Management, written communication, 9 April 2013). The NPS Geologic Resources Division and cooperators from the USGS Cascades Volcano Observatory (CVO) could assist park staff in developing an emergency response plan specifically for volcano hazards.

Volcano Monitoring

After the 1980 eruption of Mount St. Helens, Congress provided increased funding that enabled the US Geological Survey to establish the Cascades Volcano Observatory (Dzurisin et al. 1997). Scientists at the observatory quickly recognized that to fully monitor all potentially active Cascade volcanoes was not economically feasible. To address this and similar problems elsewhere, the US Geological Survey developed a suite of portable volcano-monitoring instruments (Dzurisin et al. 1997). In addition, CVO scientists use remote sensing as an early detection tool. Observatory staff members monitor volcanic deformation through electronic distance measuring (EDM). This method measures distances between known points, and is used to calculate changes such as swelling or deflation in a volcano edifice. EDM surveys were conducted at the park in 1982, 1983, 1984, and 1988 (Walkup 2012).

Walkup (2012) initiated an inventory of volcanic features throughout the National Park System, including Crater Lake National Park. This volcanic inventory complements the broader Geologic Resources Inventory and may be of interest to resource managers. Walkup (2012) identified the following potential hazards in the event of renewed volcanism at the park: ash/tephra fall, earthquakes, release of CO_2 gas, lava eruptions, lahars/debris flows, pyroclastic flows, and volcanic projectiles (e.g., lava bombs). In addition, park staff may find Smith et al. (2009)—the chapter in *Geological Monitoring* about volcanoes—useful for understanding and monitoring volcanic activity at the park. The authors described seven vital signs for monitoring volcanoes: (1) earthquake activity, (2) ground deformation, (3) volcanic gas emission at ground level, (4) emission of gas plume and ash clouds, (5) hydrologic activity, and (6) slope instability.

Hydrothermal Features and Geothermal Development

Based on guidance from Neuendorf et al. (2005), this report uses the term "geothermal" to describe Earth as a heat source (e.g., geothermal gradient) or Earth's heat when it is harnessed for use (e.g., geothermal exploration, development, reservoir, and resources). By contrast, the term "hydrothermal" pertains to hot water and its actions and products (e.g., hydrothermal water, alteration, deposit, feature, and eruption). Additionally, a hydrothermal system is a groundwater system that has a source (or area) of recharge, a source (or area) of discharge, and a heat source. This usage conforms to that provided in Heasler et al. (2009) in *Geothermal Monitoring* (Young and Norby 2009); however, the terms "geothermal" and "hydrothermal" may be used differently in other publications.

Hydrothermal Features in Crater Lake

In the late-1980s and early-1990s, exploration of the floor of Crater Lake using one-person submersible and remotely operated vehicles revealed unequivocal evidence of modern hydrothermal circulation (Dymond and Collier 1989; Collier et al. 1991; Wheat et al. 1998). Physical evidence included relatively warm and solute-laden water forming pools, for example below Cleetwood Cove (see "pools" on fig. 22); bacterial mats associated with venting of warm water, for instance near the northwestern margin of the Chaski Bay landslide deposit (see "mats" on fig. 22); iron-rich precipitates and crusts on the lake bottom in marked contrast to normal buff-colored sediments; and 10–12 m (33–40 ft) high silica spires (subaqueous thermal-spring deposits from thermal chimneys) below Skell Head (see "spires" on fig. 22).

Prior to exploration of the lake floor, the recency of a caldera-forming eruption had suggested to investigators that Crater Lake caldera would have features that reflected loss of residual heat from the magmatic and hydrothermal system beneath Mount Mazama (Bacon and Nathenson 1996). Using oceanographic measurement techniques, Williams and Von Herzen (1983) found high convective heat flows in the southern and northeastern parts of the lake floor. In addition, investigations measured salinity gradients much higher than would be expected if direct precipitation were the only source input (Larson et al. 2003b).

Coupled with the overall hydrologic balance, dissolved materials associated with thermally and chemically enriched fluids in Crater Lake control the chemical composition of the lake, including pH, alkalinity, and conductivity. Because the hydrothermal input dominates the flux of most dissolved chemicals into Crater Lake, the hydrothermal processes are highly significant. Furthermore, the geothermal inputs have a direct effect on the density structure of the deep lake and, therefore, can profoundly affect the rate of heat transport and the redistribution of dissolved salts and nutrients within the body of the lake (Collier et al. 1991, 1993).

Geothermal Exploration

The Geothermal Steam Act of 1970 as amended in 1988 (30 U.S.C. §§1001-1028) designated Crater Lake as a significant thermal feature (30 U.S.C. §1001(f)(2)). The act listed 16 units of the National Park System as containing significant thermal features, and prohibited geothermal leasing in these units (16 U.S.C. §1014(c)).

The Geothermal Steam Act is the first step in protecting geothermal features within the National Park System from an immediate threat (Barr 2001). Impacts of geothermal development on park resources involves not only the National Park Service, but also the US Geological Survey, which does research in parks; the Bureau of Land Management, the leasing agency; and the US Forest Service, the principal surface management agency adjacent to many parks. The Department of Energy, which deals with energy issues, may also become involved (Barr 2001).

The development of geothermal resources can have significant adverse effects on hydrothermal features such as geysers; hot springs; fumaroles; mud pots; sinter terraces; and thermal ground, which is habitat for rare and unusual plant species. Development could also impact the hydrothermal input of fluids, such as those that dominate the Crater Lake system. Moreover, hydrothermal features are commonly culturally significant and important tourist attractions.

Reduction or loss of thermal features is generally caused by declining reservoir pressure, which affects the amount of geothermal fluid reaching the surface. If pressure keeps falling, the features may die and geothermal flow may reverse with cold groundwater flowing down into the reservoir (Barr 2001).

In January 1984, the Bureau of Land Management granted two leases for geothermal exploration in the Winema National Forest, east and south of Crater Lake National Park. Notably, drill cores from these exploration wells were later used by USGS scientists to study the geothermal setting in the Crater Lake area (see Bacon and Nathenson 1996); the US Geological Survey retains selected specimens of these cores (Charles R. Bacon, US Geological Survey, research geologist, conference call, 18 December 2012). In March 1984, the developer—California Energy Company—proposed and was granted a lease to drill 24 temperature gradient holes. However, environmental groups worked to appeal this decision, and as a result, a moratorium was placed on geothermal leasing adjacent to the park (Barr 2001).

Because of Crater Lake's eventual inclusion in the Geothermal Steam Act, as amended in 1988, consideration of geothermal development in Winema National Forest was terminated (Barr 2001). Other than this incident, no other leasing activities have threatened to impact the hydrothermal system at Crater Lake National Park (Ketrenos, personal communication on 19 September 2001, as noted in Barr 2001). Moreover, no current leasing activities impact the thermal features at the park (Mac Brock, Crater Lake National Park, chief of Resource Management, conference call, 18 December 2012).

Monitoring Hydrothermal Features

The Geothermal Steam Act, as amended in 1988, also required the National Park Service to maintain a monitoring program of significant thermal features within units of the National Park System, including a research program in cooperation with the US Geological Survey to collect and assess data on the geothermal resources in parks containing significant thermal features. The act directed the National Park Service to begin data collection near areas of current, proposed, and potential geothermal development (30 U.S.C. § 1026(b)). These data would help the Secretary of the Interior to make decisions about geothermal leasing. *Management Policies 2006* § 4.8.2.3 reiterated that the National Park Service must monitor its significant thermal features.

In 1987, in response to the Geothermal Steam Act, the National Park Service funded a three-year program to evaluate possible hydrothermal sources to Crater Lake. The research, which was part of the ongoing limnological study of Crater Lake, was designed to (1) define thermal and chemical variability in the deep lake, (2) examine data for evidence of a hydrothermal source, (3) design and carry out a program that would find possible venting sites and sample any associated fluids, and (4) evaluate alternative mechanisms to explain the observed thermal and chemical variability (Collier et al. 1991).

At present, no direct monitoring of geothermal features is occurring at the park. Heasler et al. (2009)—the chapter in *Geological Monitoring* about geothermal systems and hydrothermal features—described the following methods and vital signs: (1) thermal feature location, (2) thermal feature extent, (3) temperature and heat flow, (4) thermal water discharge, and (5) fluid chemistry. This information may be useful for park managers in developing a monitoring program at the park.

Disturbed Lands Restoration

Disturbed lands restoration is the process of returning areas impacted by human activities or development such as abandoned roads, dams, canals, railroads, grazed areas, campgrounds, and mines to natural conditions (National Park Service 2003). Crater Lake National Park contains approximately 10 ha (25 ac) of disturbed lands in need of restoration through site preparation, erosion mitigation, and revegetation efforts (National Park Service 2012b). Disturbed sites at the park include past efforts to rehabilitate picnic areas, social trails, campgrounds, and facilities; actively used sites with heavy foot or vehicle traffic such as backcountry campsites, parking areas, overlooks, trailheads, and maintenance yards; and disturbed sites including old quarries (see "Abandoned Mineral Lands" section), construction sites, and dumps (National Park Service 2012b). Of note are two old landfills used for 50 years or more, referred to as "Summer Dump" and "South Yard." A buried railroad tanker car filled with road oil and a discarded fuel tank lined with asbestos in South Yard suggest that this and Summer Dump may harbor hazardous materials (Mac Brock, Crater Lake National Park, chief of Resource Management, written communication, 9 April 2013).

Park managers plan to complete a comprehensive restoration plan in the near future (National Park Service 2012b). Past restoration efforts often have failed to document project objectives and methods or conduct post-restoration monitoring, thus hindering efforts to assess efficacy of restoration techniques. A comprehensive restoration plan will outline park goals, priorities, and methods for restoration of disturbed sites at the park, and serve as a vehicle for obtaining necessary funds to complete restoration work (National Park Service 2012b).

Abandoned Mineral Lands

Abandoned mineral lands (AML) are a type of disturbance that may require restoration. AML sites may contain abandoned underground and surface mines; placer and dredge sites; and abandoned oil, gas, and geothermal wells. Commodities mined at such sites range from soft rocks such as coal and sand/gravel to hard-rock minerals such as gold, lead, and copper. Sites can contain waste rock (unprocessed rock), tailings (processed rock), abandoned roads, fuel storage tanks, drainage diversions, buildings such as mills and assay shops, deteriorating structures such as head frames and tramways, and abandoned heavy equipment (National Park Service 2011).

The AML database, maintained by the NPS Geologic Resources Division (GRD), documents 15 surface mines at Crater Lake National Park. The database notes hazards (e.g., rockfall), accessibility (e.g., road access or gated closures), contamination or occurrence of dumping, occurrence of wildlife, condition of vegetation, and whether natural restoration is in progress. The database also notes whether a site may be of interest for interpretation; that is, if a connection to park history can be demonstrated.

GRD staff inventoried AML sites at Crater Lake National Park in 2011 and 2012. Of the 15 total surface mines, five are in need of hazard mitigation such as signage, closure, or restoration:

- Ball Diamond quarry is thought to have been a source of building stone used in park development, and may be of interest for interpretation.
- Roundtop quarry might be considered for interpretation because the sand, gravel, and building stone mined here were used in park development. Slope stabilization is the primary concern at Roundtop quarry, especially at the top of the worked face. Posting signs warning of unstable conditions and possibly announcing an administrative closure of the area would be a relatively inexpensive form of mitigation.
- Anderson Bluffs is currently used by the National Park Service as a source of sand and gravel, and includes an excavation area along the base of the natural cliffs at the northern edge, and piles of stored or dumped gravel, soil, and stone. Loose rock along the excavated cliff wall presents a rockfall hazard. Once use of the area is discontinued, GRD staff members recommend stabilizing loose rock on the bluff, and grading and reseeding dump areas and roads. However, with discontinued use, this area will likely reclaim naturally.
- CRLA 8, locally known as the Pole Bridge Creek quarry, includes a building-materials quarry, now with little or no use, and a staging/storage area currently used to stockpile a variety of waste materials from road and construction projects and brush clearing. Signs placed around the perimeter warning of unstable conditions and possibly announcing an administrative closure may be the most practical and cost-effective mitigation option for this site. The site should be monitored for evidence of exacerbated erosion.
- CRLA 10 (item 99A4 in the Crater Lake National Park disturbed site database) consists of two abandoned excavations and associated benches on Grayback Ridge. The site has multiple erosional surfaces, but these appear generally stable or stabilizing. Signs placed around the perimeter warning of unstable conditions and possibly announcing an administrative closure may be the most practical and cost-effective mitigation option for this site. Earthmoving equipment cannot presently access the site without creating additional resource impacts.

The Geologic Resources Division, which is administering the AML inventory, may be consulted for assistance and guidance regarding AML sites within the park.

Geologic Features and Processes

Geologic resources underlie park ecosystems and geologic processes shape the landscape of every park. This section describes the most prominent and distinctive geologic features and processes in Crater Lake National Park.

Because of good preservation and access, the Crater Lake caldera and the deposits formed by the climactic eruption of Mount Mazama provide excellent opportunities for study of volcanic and magmatic processes (Bacon 2008). Also, researchers have extensively studied lacustrine features such as the lake basin, lake sediments, and the water of Crater Lake. Additionally, Crater Lake National Park is noted for its glacial features such as glaciated outcrops on the slopes of Mount Mazama, U-shaped notches in the caldera rim at the heads of deep glaciated valleys, and lateral moraines in the lower reaches of larger valleys. Finally, caves are a distinctive geologic feature in the park, though they are lesser known and studied than other features.

The following geologic features and processes are discussed in this section:

- Volcanic Rocks
- Mount Mazama
- Mazama Ash
- Shield Volcanoes and Cinder Cones
- Crater Lake Caldera and Fill
- Crater Lake
- Glacial Features
- Caves

Volcanic Rocks

Geologists use silica (silicon dioxide, SiO_2) content as a means for classifying volcanic rocks (table 1). The term "mafic" refers to rocks with lesser amounts of silica, such as basalt and basaltic andesite. The term "silicic" refers to rocks with higher amounts of silica, for instance, dacite, rhyodacite, and rhyolite. Andesite has more silica than basalt and basaltic andesite (mafic rocks), but it is not necessarily considered "silicic." Although there is no firm agreement among petrologists, the amount of silica in a silicic rock is usually said to constitute at least 65% or two-thirds of the rock (Neuendorf et al. 2005).

Examples of well-known volcanoes help to illustrate the influence of silica on volcanic activity: Hawaiian volcanoes produce basalt (low silica) that erupts effusively as lava flows (see Thornberry-Ehrlich 2009, 2011). The lava flows of Medicine Lake volcano in Lava Beds National Monument in California provide a Cascade example of this type of eruption (see KellerLynn 2013c). Stepping up in explosiveness, Lassen Peak in Lassen Volcanic National Park in California erupted dacite (see KellerLynn 2013b), as did Mount St. Helens in Washington. During the 1980 eruption of Mount St. Helens, the upper 400 m (1,300 ft) of the summit was catastrophically removed, leaving a horseshoe-shaped crater now partially filled by a lava dome. A variety of lava types, from basalt to rhyodacite, make up the Mount Mazama edifice. However, rhyodacite dominated the climactic eruption. Finally, deposits of rhyolite represent

Table 1. Volcanic rocks classification and relative characteristics.

Rock Name:	**Rhyolite**	**Rhyodacite**	**Dacite**	**Andesite**	**Basaltic Andesite**	**Basalt**
Silica (SiO_2) content	≥72%	68%–72%	63%–68%	57%–63%	52%–57%	≤52%
Amount of SiO_2	More	⟵	⟶			Less
Viscosity of magma	Thick	⟵	⟶			Fluid
General style of eruption	Explosive	⟵	⟶			Effusive

Source: Bacon (2008).

the most explosive volcanoes on Earth. After a rhyolite eruption, volcano edifices often do not look like volcanoes because the eruptions are so explosive that the volcano ends up collapsing in on itself. Along with the Yellowstone caldera in Yellowstone National Park, the Bursum and Gila Cliff Dwellings calderas, which surround Gila Cliff Dwellings National Monument in New Mexico (see KellerLynn 2013a), are examples of rhyolite explosions that produced calderas in the National Park System. Large calderas such as Yellowstone and Gila Cliff Dwellings represent "supervolcanoes"—a popular term for the largest volcanoes on Earth.

With respect to viscosity (internal friction), low-silica basalts form fluid, lava flows that spread out in broad, thin sheets up to several kilometers wide. In contrast, flows of andesite and dacite tend to be thick and sluggish, traveling only short distances from a vent. Dacite and rhyodacite lavas often squeeze out of a vent to form irregular mounds or lava domes. In this way, the viscosity of magma determines the type of volcano edifice built by an eruption.

Mount Mazama

The edifice of Mount Mazama consists of a succession of overlapping shield and stratovolcanoes, covering 1,040 km^2 (400 mi^2) (Bacon 1983). Associated lava flows generally end within 5 km (3 mi) of the caldera, although a few flows can be traced as far as 11 km (7 mi) from the rim (Bacon and Lanphere 2006). Before its climactic eruption, Mount Mazama stood 3,700 m (12,000 ft) above sea level. It is distinguished from regional shield volcanoes and cinder cones on the basis of form and lava type (see "Shield Volcanoes and Cinder Cones" section). By comparison, regional volcanoes are small, isolated features, composed primarily of basaltic andesite (table 1). Mount Mazama consisted of an andesite through dacite edifice built upon lavas flows older than 400,000 years old. Individual volcanoes that helped to build up the edifice were probably active for a comparatively short period of time—a few thousand years to perhaps 40,000 years. As Mount Mazama grew, the focus of activity migrated in a west to northwest direction.

Buildup of Mount Mazama

The nearly 400,000-year-long buildup of Mount Mazama incorporates many distinctive features within Crater Lake National Park. The remnants of Mount Mazama include the peaks outlining Crater Lake caldera and associated sloping terrain. Most of the vents that produced the lavas of Mount Mazama were within the area circumscribed by the present caldera. Distinctive features of Mount Mazama include Phantom Ship (420,000–400,000 years ago), Sentinel Rock (340,000–300,000 years ago), Llao Rock (170,000–120,000 years ago), Roundtop (159,000 ± 13,000 years ago; Bacon 2008), Pumice Castle (70,000 years ago), The Watchman (55,000 ± 3,000 years ago; Bacon 2008), and Devils Backbone (50,000–40,000 years ago).

Phantom Ship

The oldest lavas assigned to Mount Mazama are the approximately 420,000–400,000-year-old andesite of Phantom Cone (PEapn). The andesite of Phantom Cone accumulated near its source vent in the wall southeast of Phantom Ship. Phantom Ship is an east–west ridge of spires that breaks the surface and towers above Crater Lake. It is composed of the andesite of Phantom Cone, and capped by a distinctive quartz-bearing lava flow (dacite of Phantom Cone, PEdpn). Phantom Ship rises 50 m (170 ft) above the surface of the lake, and is about 150 m (500 ft) long with a maximum width of 60 m (200 ft) near its eastern end (fig. 10). Depending on vantage point, angle of the sun, presence of clouds, and wave activity on Crater Lake, Phantom Ship may go unseen by visitors (National Park Service 2012a). However, visitors are given an opportunity to view this elusive andesite bedrock island at the Phantom Ship Overlook on Rim Drive.

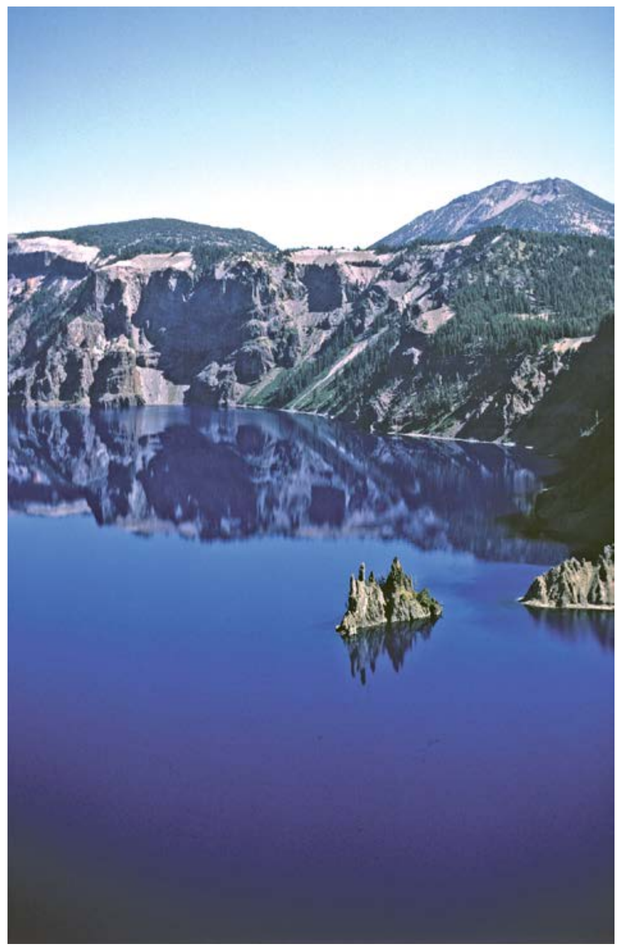


Figure 10. Phantom Ship. The small island of Phantom Ship is composed of lava and breccia of the andesite of Phantom Cone (PEapn). It represents the oldest rock unit of the Mount Mazama edifice. The caldera wall in the distance features Sentinel Rock (see fig. 11). Mount Scott (right) and Cloudcap (left) are on the skyline. US Geological Survey photograph by Charles R. Bacon, available at http://pubs.usgs.gov/sim/2832/data/sim2832_sheet3.pdf (accessed 27 February 2013).

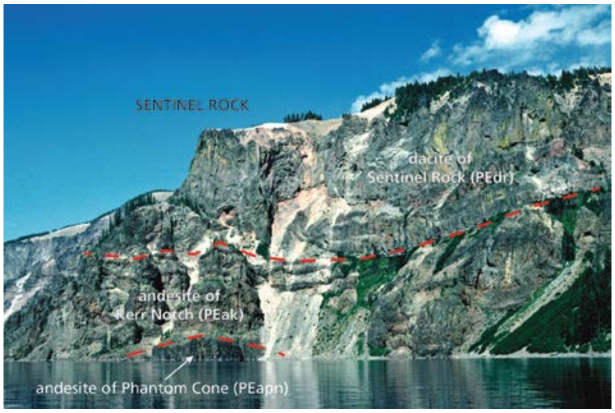


Figure 11. Sentinel Rock. Two thick lava flows of the dacite of Sentinel Rock (PEdr) fill a glacial valley carved in thinner flows of andesite of Kerr Notch (PEak). The outcrop at lake level (left center) is andesite of Phantom Cone (PEapn). US Geological Survey photograph by Charles R. Bacon, annotated by Jason Kenworthy (NPS Geologic Resources Division).

Figure 12. Llao Rock. The great cliff at Llao Rock dominates the northwestern caldera wall. Llao Rock consists of rhyodacite (PErh). Climactic pumice fall (Hcp) rests on the craggy top of the Llao Rock lava flow. Several lava and pyroclastic units exposed in the caldera wall below Llao Rock range in age from andesite of Llao Bay (PEall), which is approximately 170,000–140,000 years old, to andesite of Steel Bay (PEasb), which has K-Ar ages of 42,000 ± 6,000 and 43,000 ± 6,000 years ago (Bacon 2008). US Geological Survey photograph by Charles R. Bacon.

Sentinel Rock

Fed by a dike, the dacite of Sentinel Rock (PEdr) is about 340,000–300,000 years old. It is exposed widely in the caldera wall, fills a glacial valley cut into the andesite of Kerr Notch (PEak) south of Sentinel Rock, and overlies this glaciated unit (PEak) near Skell Head. Sentinel Rock, which is composed of medium-light- to medium-dark-gray dacite (63%–65.5% SiO_2) lava flows, is a distinctive landmark in the southeastern caldera wall between Skell Head and Kerr Notch (fig. 11).

Llao Rock

The great cliff of Llao Rock is composed of rhyodacite lava (PErh; 70.5%–72% SiO_2) that was emplaced about 170,000–120,000 years ago. Llao Rock dominates the northwestern caldera wall and is in striking contrast to the underlying andesite flows—andesite of the west wall (PEaww); andesite of Llao Bay, upper unit (PEalu); and andesite of Llao Bay, lower unit (PEall)—which are between 6 and 30 m (20 and 100 ft) thick (fig. 12). By contrast, the rhyodacite of Llao Rock has a maximum thickness of no less than 370 m (1,200 ft) (Williams 1942). It was erupted into a hummocky glacial valley, approximately U-shaped in cross section, about 0.8 km (0.5 mi) wide and between 150 and 180 m (500 and 600 ft) deep (Williams 1942). The lava filled this valley, as well as accumulated as a broad, dome-like pile above it. Although the flow is exceptionally thick and the eruption apparently had ample material to vent, the lava only spread about 2 km (1 mi) beyond the rim of the caldera. This was partly because of the gentle slope of the glacial valley, but mainly because of the highly viscous nature of the flow (Williams 1942).

Pumice Castle

Pumice Castle Overlook on the Rim Drive provides a view of one of the park's most colorful features—a layer of orange pumice that has been eroded into the shape of a medieval castle (fig. 13). The pumice was deposited about 70,000 years ago during one of Mount Mazama's most voluminous silicic eruptions. The source vent is beneath Cloudcap and immediately north of Pumice Castle. Other vents that erupted the dacite possibly vented to the northwest, within what is now the caldera. The dacite of Pumice Castle (PEdc, PEdcp; 66%–67% SiO_2) is present in the caldera wall from north of Devils Backbone east to Cloudcap Bay (plate 1).

The Watchman

Dacite of The Watchman formed The Watchman flow of Williams (1942; PEdwv), its feeder dike (PEdwf), and pumiceous pyroclastic-flow deposits in the western caldera wall (PEdwp). The high point of the 2-km- (1-mi-) long Watchman flow forms a glaciated horn on the flank of Mount Mazama, which is a prominent feature of the western rim of Crater Lake caldera (fig. 3). The feeder dike (PEdwf) to the flow is obvious on the caldera wall. The flow is also locally preserved on a ridge top about 4 km (3 mi) west of Rim Village. This dacite erupted from Mount Mazama 55,000 ± 3,000 years ago (Bacon 2008).

Devils Backbone

A vent or vents fed by the Devils Backbone dike system emitted voluminous outpourings of andesite of Devils Backbone (PEad) and created an extensive lava flow on the northwestern flank of Mount Mazama between 50,000 and 40,000 years ago (fig. 14). The lava flowed 11 km (7 mi) west of the vent and terminated in the drainage of Copeland Creek at an elevation of about 1,430 m (4,690 ft). As seen in the caldera wall, the Devils Backbone dike cuts numerous older lava flows, including the lower andesite below Llao Rock (PEall; 150,000 ± 9,000 years ago), andesite of Merriam Point (PEam; 131,000 ± 18,000 years ago), andesite of the west wall (PEaww; 70,000 ± 4,000 years ago), and andesite south of The Watchman (PEatw; 62,000 ± 7,000 years ago). Bacon (2008) provided potassium (K)–argon (Ar) ages for these units; the K-Ar age of unit PEatw is the weighted mean of three samples.

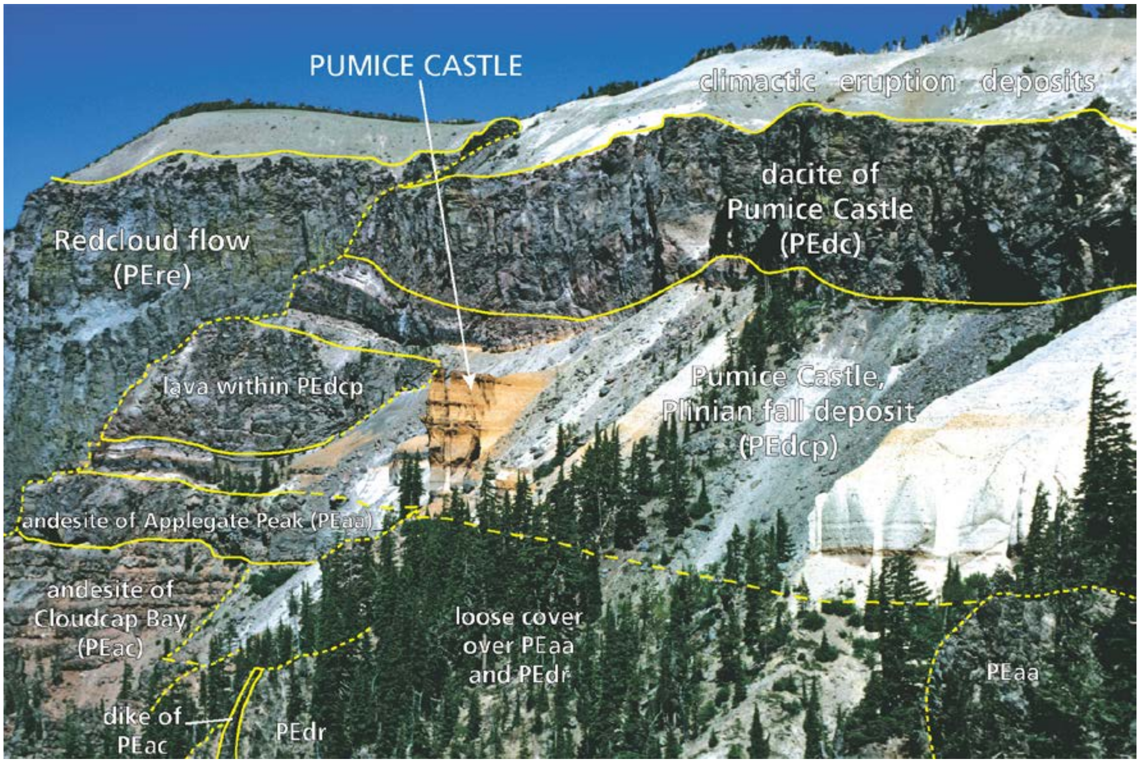


Figure 13. Pumice Castle. From the overlook on Rim Drive, looking northeast, Pumice Castle—the orange outcrop in the center of the photograph—is visible. The feature is composed of a 71,000-year-old Plinian fall deposit of the dacite of Pumice Castle (PEdcp). The cliff above also consists of dacite of Pumice Castle (PEdc), which is overlain by deposits of the Mount Mazama climactic eruption—pumice fall (Hcp); proximal ignimbrite (Hcb); and a wind-reworked, pumice-rich deposit (restricted to caldera rim; included in unit Hcu). Skyline cliff (left) is composed of the Redcloud flow of Williams (1942) (PEre). Dashed lines indicate approximate contacts. Dotted lines indicate an edge or ridge. US Geological Survey photograph and annotations by Charles R. Bacon.

Figure 14. Devils Backbone. This view of the northwestern wall of Crater Lake caldera shows two segments of the Devils Backbone dike. Lava flows correlated with the Devils Backbone dike (PEad) extend as far as 11 km (7 mi) west of the caldera rim. US Geological Survey photograph by Charles R. Bacon.

Climactic Eruption

The climactic eruption of Mount Mazama lasted only a few days, but erupted an estimated 50 km^3 (12 mi^3) of rhyodacitic and andesitic magma (Bacon 2008). This is the largest known eruption from a Cascade Range volcano (Cascades Volcano Observatory 2008). The surrounding terrain was devastated for tens of kilometers. Pyroclastic flows traveled as much as 70 km (40 mi) from the source, flowing down the slopes of the volcano and filling valleys with up to 100 m (300 ft) of pumice. Additionally, the eruption produced ash that spread across the Pacific Northwest and southwestern Canada (see "Mazama Ash" section).

Bacon (2008) mapped five units representing the climactic eruption—Hcp, Hcw, Hcf, Hcb, and Hcu. Sherrod (1991), MacLeod and Sherrod (1992), and Smith (1982) mapped others (see Map Unit Properties Table, in pocket). At least 90% of the material was rhyodacitic pumice and ash. Compositional uniformity of about 70.5% SiO_2 is a striking feature of this pumice (Druitt and Bacon 1988). The remainder of the erupted material was crystal-rich andesitic scoria and mafic crystal mush (partially crystallized magma) with 61%–47% SiO_2.

The climactic eruption of Mount Mazama took place in two phases. First, a single vent on the northeastern side of the volcano produced a towering column of pumice and ash, called a "Plinian eruption," that reached some

50 km (30 mi) high (Bacon 1983). Winds transported ash mainly to the northeast, resulting in pumice-fall deposits (Hcp). Vent widening and an increasing eruption rate eventually caused the Plinian column to collapse to a lower height, producing pyroclastic flows in valleys on the northern and eastern flanks of Mount Mazama; these flows deposited the Wineglass Welded Tuff of Williams (1942) (map unit Hcw). The second phase of eruption—the ring-vent phase—started as the volcano began to collapse in upon itself, creating circular cracks that opened up around the peak. The ring-vent phase produced pyroclastic flows fed by rising columns from vents that circumscribed Mount Mazama. Swiftly moving pyroclastic flows deposited ignimbrite (Hcf), lithic breccia (Hcb), and fine-grained lithic- and crystal-rich ignimbrite (Hcu). The Pinnacles—a popular visitor attraction in the southeastern corner of the park—are composed of ignimbrite (Hcf) from the climactic eruption.

The Pinnacles

The pyroclastic-flow deposits from the ring-vent phase of the climactic eruption of Mount Mazama (Hcf) are well exposed in canyons surrounding Crater Lake caldera today. Of particular interest are the Pinnacles along Wheeler Creek in the southeastern part of the park (figs. 15 and 16). Over the course of a few hours, pyroclastic flows descended from Mount Mazama and deposited this 100-m- (330-ft-) thick unit of pumice, scoria, ash, mineral crystals, and rock fragments (Druitt and Bacon 1986). These deposits partially fill valleys and depressions on the flanks of Mount Mazama and are present well beyond the map area, extending as much as 70 km (40 mi) from the caldera (Williams 1942; Bacon 1983; Druitt and Bacon 1986). Sherrod (1991) mapped these ash-flow deposits as unit Haf, which also covers the Pumice Desert (see "Pumice Desert" section).

The bands of color in the Pinnacles are a distinctive feature and the result of compositional zonation—from silica-rich rhyodacite down into more iron- and magnesium-rich andesite in the magma chamber (Williams 1942). The spires show an inverted view of pre-eruption layering in the magma chamber. Eruption from the zoned magma chamber resulted in the first-erupted and deposited material being light colored and later-erupted magma being dark (fig. 15).

As the pyroclastic deposit cooled, gases escaped upward through open fractures that narrowed into tubes, resulting in growth of new gas-deposited minerals in pore spaces. These minerals cemented together to form tuff, which was more resistant to erosion than the surrounding deposit. As a result of weathering by wind and water, the Pinnacles began to stand out as spires over the past 7,700 years (fig. 16).

A good place to view the Pinnacles is from the Pinnacles Overlook. Reaching this overlook requires an 11-km (7-mi) detour from Rim Drive (plate 1). The colorful, 30-m- (100-ft-) tall spires seen at this vantage point protrude spectacularly from the canyon wall.

Figure 15. The Pinnacles along Wheeler Creek. The pyroclastic flows of the climactic eruption of Mount Mazama are well exposed along Wheeler Creek, where the deposit consists of spectacular spires. The Pinnacles are relatively erosion resistant tuff cemented by precipitation of silica and other minerals. The bottom third of the exposure consists primarily of pumice blocks of rhyodacite. The middle third is a mixture of rhyodacite and andesite. The top third is dominantly andesite (and some crystal-rich, more mafic rock compositions). The fine-ash matrix that is responsible for the gross color of the deposit darkens upward, partly owing to composition and partly to greater heat retention of the later-emplaced material as the eruption waned. The retention of heat resulted in crystallization of tiny iron oxide mineral grains that imparted a gray color. The red band at the top of the bluff in the background is a layer of fine ash in which iron oxidized as it came in contact with the atmosphere as the deposit cooled. US Geological Survey photograph by Willie Scott, available at http://vulcan.wr.usgs.gov/Volcanoes/CraterLake/images.html (accessed 27 December 2012).

Pumice Desert

The Pumice Desert is a flat, open area in the northern part of the park (fig. 17). It contrasts conspicuously with the surrounding forest of lodgepole pine (*Pinus contorta*) (Horn 2002). The desert developed on the pyroclastic-flow deposits of the climactic eruption of Mount Mazama (Haf), which is more than 60 m (200 ft) thick in some places. Isolated lodgepole pine trees have started to colonize the desert, but as a result of the scarcity of organic matter, few plants have taken hold to enrich the soil for additional plant growth (Horn 2002).

Figure 16. The Pinnacles at Godfrey Glen. In 1901, J. S. Dutton of the US Geological Survey took this photograph of the Pinnacles, which consist of pumice from the pyroclastic flows of the ring-vent phase of the climactic eruption of Mount Mazama. Secondary crystallization of tuff created erosion-resistant features such as pinnacles and curtains in many canyons. US Geological Survey photograph.

Sherrod (1991) mapped the Pumice Desert as consisting of ash-flow deposits (Haf). This is the youngest volcanic unit in the area mapped by Sherrod (1991), and consists mainly of unsorted, pale grayish-white ash containing 10%–30% pumiceous lapilli and bombs. Lapilli ranges is size from 2 to 64 mm (0.08 to 2.5 in); bombs are larger, generally greater than 64 mm (2.5 in) in diameter, and are commonly hollow or vesicular (formed by abundant gas bubbles) inside. Bacon (2008) mapped the southernmost edge of the desert as deposits of the Mount Mazama climactic eruption, ring-vent-phase ignimbrite (map unit Hcf).

Figure 17. Pumice Desert. The Pumice Desert is a broad, mostly barren flat in the northern part of Crater Lake National Park. Its thick layer of pumice and ash, more than 60 m (200 ft) in some places, was deposited during the climactic eruption of Mount Mazama. The desolate landscape contrasts sharply with the surrounding pine forest. US Geological Survey photograph by Charles R. Bacon.

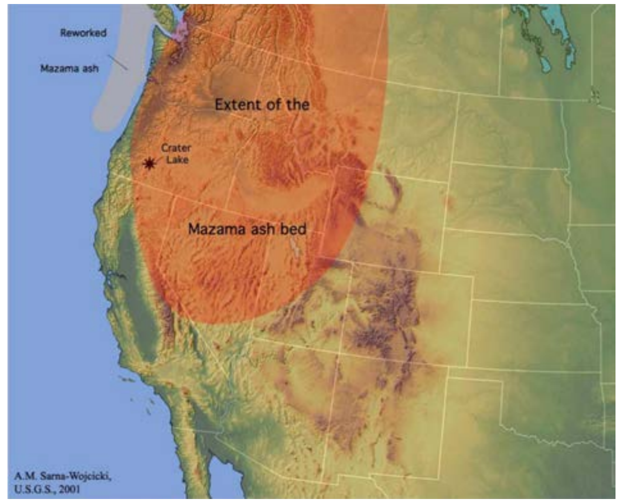


Figure 18. Mazama ash. The Plinian eruption during the climactic single-vent phase of Mount Mazama produced ash that wind transported across the landscape. In addition, rivers moved the ash offshore west of Oregon and Washington. Mazama ash covers an estimated area of 1.7 million km² (656,000 mi²). US Geological Survey graphic by Andrei M. Sarna-Wojcicki.

Mazama Ash

The Plinian eruption of Mount Mazama ejected ash—known as Mount Mazama or Mazama ash, tephra, pumice, or air-fall deposit (Williams 1942; Crandell et al. 1962; Powers and Wilcox 1964; Wilcox 1965; Randle et al. 1971; Mullineaux 1974; Mullineaux and Wilcox 1980; Bacon 1983). "Tephra" is a collective term for all pyroclastic material, regardless of size, shape, or origin, ejected during an explosive volcanic eruption. The term "Mazama ash" is applied to fine-grained deposits some distance from the park. Although deposits of Mazama ash typically are composed of material from the Plinian phase of the eruption, deposits also may contain fine particles from the ring-vent-phase.

Mazama ash forms the most widespread late Quaternary tephra layer in the United States and southwestern Canada, blanketing an area of about 1.7 million km^2 (656,000 mi^2) (Sarna-Wojcicki et al. 1983). It was deposited over most of Oregon and Washington, all of Idaho, northeastern California, northern Nevada, northwestern Utah, western Wyoming and Montana, southern British Columbia and Alberta, and southwestern Saskatchewan (fig. 18). Mazama ash also was transported westward 600–700 km (370–440 mi) along deep-sea channels by turbidity currents (swiftly flowing bottom currents laden with suspended sediment) onto the Pacific Ocean floor (Nelson et al. 1988). Dust-size particles were carried many hundreds of kilometers from the source, as noted by a study of Mazama ash in the Greenland Ice Sheet Project 2 (GISP2) ice cores (Zdanowicz et al. 1999).

Deposits of Mazama ash are about 40 cm (16 in) thick at points 200 km (125 mi) northeast of the volcano, and 4–5 cm (1.6–2 in) thick at 1,000 km (620 mi) (Hoblitt et al. 1987). Specifically, Mazama ash is >50 cm (20 in) thick at Newberry Volcano, 110 km (68 mi) northeast of Crater Lake, and >1 cm (0.5 in) thick in southwestern

Saskatchewan, 1,200 km (745 mi) from the source (Bacon 1983).

Volcanic ash layers are highly useful for making geological and archeological correlations and age determinations. Layers can be dated by isotopic or other methods and correlated over long distances by petrographic and chemical methods (Sarna-Wojcicki et al. 1983). Once an ash layer has been accurately dated, it becomes an important time horizon at all localities where it occurs and helps to connect diverse depositional environments (Sarna-Wojcicki et al. 1983). Ample thickness and a homogeneous mineralogy are characteristics that make Mazama ash a valuable stratigraphic marker, essentially representing an instant in geologic time.

The usefulness of Mazama ash in scientific studies is widespread. Layers of Mazama ash occur among strata of archeological sites in Oregon, Washington, Idaho, and British Columbia (Cressman et al. 1940; Butler 1962; Fryxell 1962; Sanger 1967). Occurrences of Mazama ash in stratigraphic contexts have been reported in studies of climate (Zdanowicz et al. 1999), glacial stratigraphy (Crandell and Miller 1964; Easterbrook 1969), marine sediments (Nayudu 1964; Royse 1967; Nelson et al. 1968), lacustrine sediments (Stockner and Benson 1967), and soil development (Parsons and Herriman 1970). Today, the extent of Mazama ash as an "eolian mantle" is represented by the distribution of Andisols (soils formed in volcanic ash), which comprise approximately 621,000 ha (1.5 million ac) of surveyed areas of Washington, Idaho, Oregon, and western Montana (McDaniel and Hipple 2010). Andisols represent thick ash mantles, greater than 36 cm (14 in); tend to be found in areas of higher precipitation; and are closely associated with forests. Distribution of these soils across the region is of considerable interest because thicker ash mantles have been tied to greater forest productivity (Kimsey et at. 2008).

Shield Volcanoes and Cinder Cones

Bacon (2008) mapped the shield volcanoes and cinder cones in the vicinity of Crater Lake caldera as part of "regional volcanism." These cones and shields are monogenetic volcanoes (developing at one place and time) similar to other cones and shields throughout the High Cascades (Wood and Kienle 1990). These vents produced primarily basaltic andesite, with lesser amounts of andesite and tholeiitic basalt (Bacon 1990). These outputs are representative of the Mazama magma system over time and typical of High Cascade volcanism in Oregon (Bacon and Lanphere 1990).

Cinder cones and shield volcanoes partly surround Mount Mazama (fig. 19). Bacon (2008) identified 40 of these monogenetic vents in the vicinity of the Crater Lake caldera, including Crater Peak (98,000 years old; PEacrp), Red Cone (36,000 years old; PEbr; fig. 20), Williams Crater (35,000 years old; PEbwp), and vents around Castle Point (undated; PEbc). These cones are

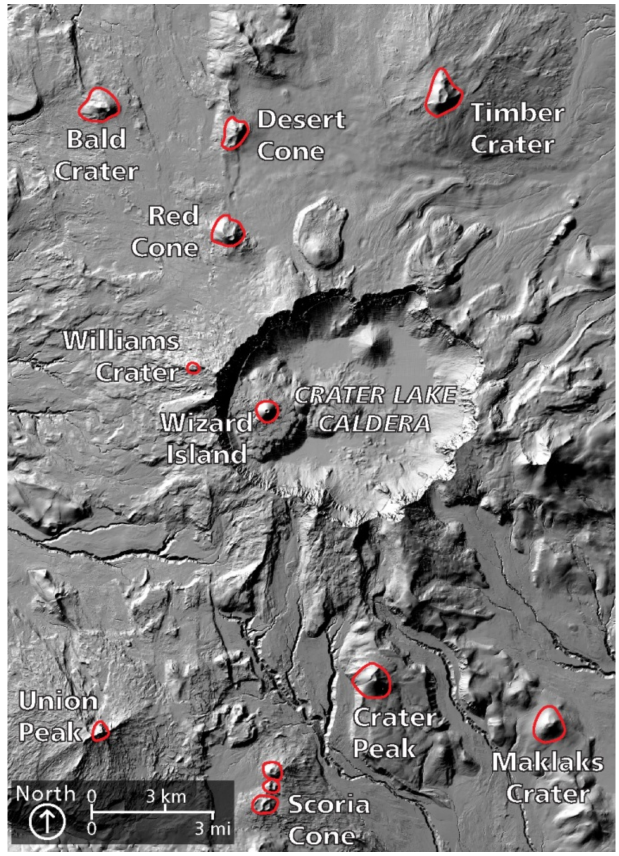


Figure 19. Cinder cones at Crater Lake National Park. Bacon (2008) identified more than 40 vents of regional volcanoes in the Mount Mazama area, including many cinder cones and a few small shield volcanoes within the boundaries of the park. Selected cinder cones are labeled on this figure and detailed on table 2. National Park Service graphic by Rebecca Port (NPS Geologic Resources Division).

Figure 20. Red Cone. Red Cone is an exemplary example of a cinder cone at Crater Lake National Park. Red Cone (map unit PEbr) erupted 35,000 ± 4,000 years ago (table 2), and is part of regional volcanism northwest as mapped by Bacon (2008). US Geological Survey photograph by Charles R. Bacon.

composed of basaltic andesite, except Bald Crater, which is composed of basalt (tables 1 and 2). Monogenetic vents in the area often form north–south alignments of similar ages and compositions. For example, Red Cone has an associated fissure system that runs about 1.5 km (0.9 mi) north (PEbr, PEbrw).

As delineated by Bacon (2008), the cinder cones and shield volcanoes situated to the northwest of Crater Lake

Table 2. Selected cinder cones at Crater Lake National Park, locations on figure 19.

Cinder Cone	Approximate Age (years ago)	Age Type	Map Unit Symbol	Rock Type	Volcanism
Wizard Island	7,200	Estimated age	Hawp	Andesite	Postcaldera
Williams Crater	35,000	Estimated age	PEbw, PEbwp	Basaltic andesite	Regional, northwest
Red Cone	35,000 ± 4,000	$^{40}Ar/^{39}Ar$	PEbr, PEbrp	Basaltic andesite	Regional, northwest
Scoria Cone	53,000 ± 4,000	$^{40}Ar/^{39}Ar$	PEbsc, PEbscp	Basaltic andesite	Regional, southwest
Crater Peak	100,000–130,000	Estimated age range	PEacr, PEacrp	Andesite	Regional, east
Timber Crater	137,000 ± 10,000	$^{40}Ar/^{39}Ar$	QTmv	Andesite	Regional, east
Union Peak	164,000 ± 11,000	K-Ar	PEbu, PEbui, PEbup	Basaltic andesite	Regional, southwest
Bald Crater	192,000 ± 20,000	K-Ar	QTmv	Basalt	Regional, northwest
Desert Cone	213,000 ± 26,000	K-Ar	QTmv	Basaltic andesite	Regional, northwest
Maklaks Crater	220,000 ± 67,000	K-Ar	PEbmc, PEbmcp	Andesite	Regional, east

Sources: Bacon et al. (2002), Bacon and Lanphere (2006), and Bacon (2008).

caldera, and roughly northwest of Crater Creek, are part of "regional volcanism northwest." The cones and shields southwest of Crater Lake caldera, and roughly Annie Creek, are part of "regional volcanism southwest." Those east of the longitude of Munson Valley (and park headquarters) are part of "regional volcanism east." These classifications are useful for locating cones and shields on the Crater Lake landscape and have no genetic significance (Charles R. Bacon, US Geological Survey, research geologist, written communication, 21 March 2013).

Crater Lake Caldera and Fill

The eruption and collapse of Mount Mazama created Crater Lake caldera (fig. 21). The diameter of the caldera at the rim is 10 km (6 mi) east–west by 8 km (5 mi) north–south. Its depth is 1,200 m (3,900 ft). It has a volume of 38 km^3 (9 mi^3) (Bacon 1983). The walls of the caldera slope an average of 45° and rise 150–160 m (490–525 ft) above the surface of Crater Lake. Beneath the lake's surface, the caldera's walls slope about 30° to a basin floor covered in sediment (Nelson et al. 1994).

Since formation of Crater Lake caldera 7,700 years ago, volcanic and sedimentary materials have been filling the basin (fig. 22). Initially, hundreds of meters of debris accumulated as the caldera subsided and its walls failed inward. The initial fill likely consisted of pumice and ash of the climactic eruption and landslide debris from the caldera walls. Failure of the walls resulted in the distinctive scalloped outline around the lake, where many named bedrock promontories separate embayments (Bacon et al. 2002). In addition, phreatic explosions, or "hot fill," and groundwater–rich slope movements, dominated by sheetwash and mudflows, helped to fill the basin.

Figure 21. Crater Lake and Crater Lake caldera. Crater Lake is a closed basin, having no permanent outlet or inlet streams. The level of Crater Lake, presently at 1,883 m (6,178 ft) above sea level, is maintained by direct precipitation and inflow from the caldera walls, and losses by evaporation from the 53-km^2 (20-mi^2) lake surface and leakage through a permeable layer of glacial till in the caldera wall. US Geological Survey photograph.

The next stage of basin filling began as thick wedges of material composed of multiple debris flows, including the last major caldera-wall landslide, the Chaski Bay landslide (see "Slope Movements" section), slumped into the basin. This landslide (debris-avalanche) deposit is interpreted as "early postcaldera" in age, possibly 7,000 years old or older (Charles R. Bacon, US Geological Survey, research associate, email communication, 25 September 2013). This "vintage" of debris flow may have formed in response to seismic activity associated with postcaldera volcanism (Nelson et al. 1988). Deposits within Crater Lake caldera include landslide deposits (Hls), talus (Qt), and sediment gravity-flow deposits (Hsl).

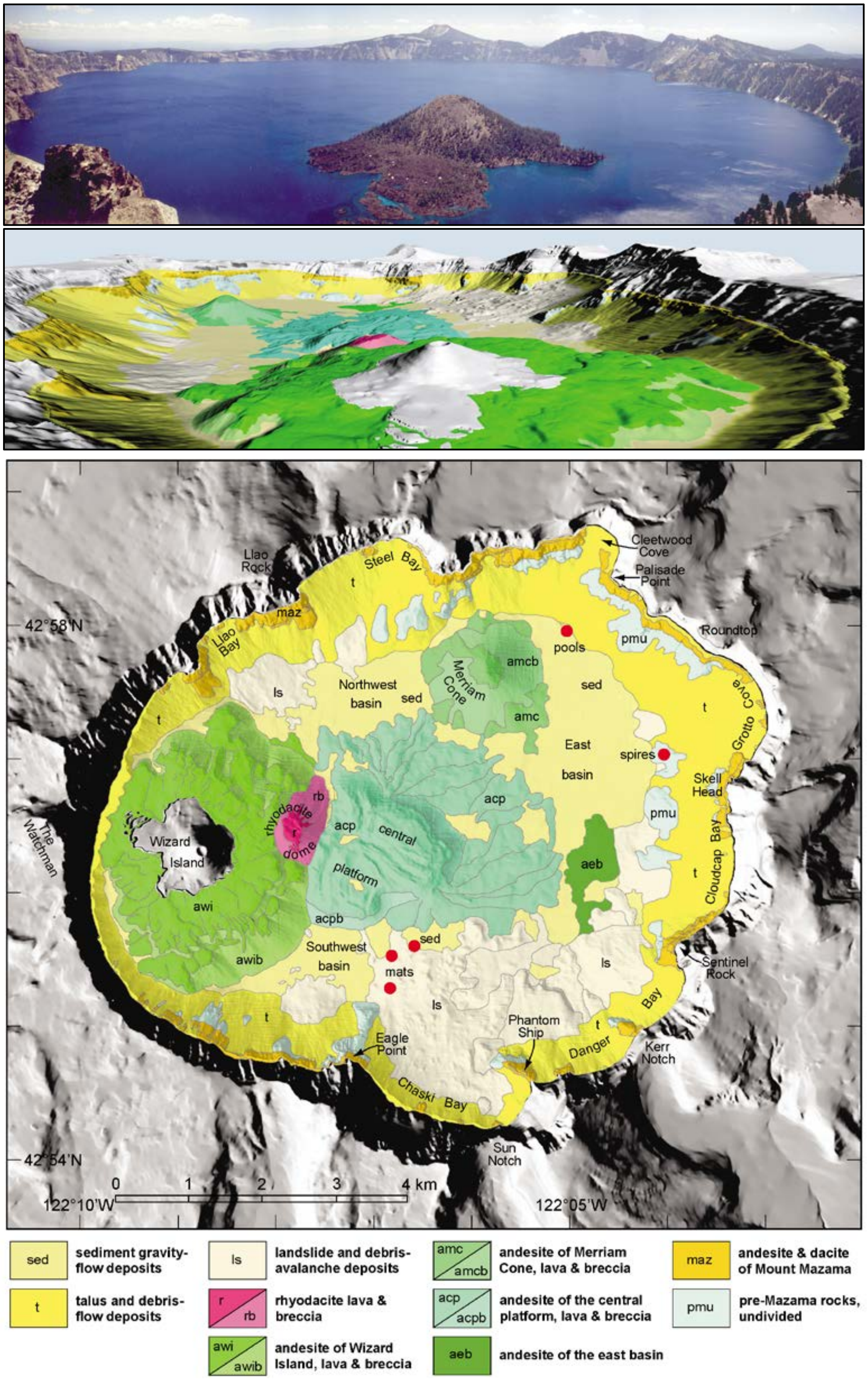


Figure 22. Geologic features on the floor of Crater Lake. A bathymetric survey in 2000 revealed the details of the Crater Lake caldera floor, including sedimentary deposits, lava flows, and thermal features. Note the locations of thermal features on the lower map (red dots) and labels "mats," "spires," and "pools," which are evidence of hydrothermal activity. Figures extracted from Ramsey et al. (2003) with thermal feature locations from Bacon et al. (2002). The photograph was taken from the visitor overlook on The Watchman, looking east (US Geological Survey photograph by Peter Dartnell). Middle image is a digital perspective view of generalized geologic map of the lake floor draped over shaded relief image 2-m bathymetry (Digital processing by Eleanore Ramsey). Scale varies with distance. US Geological Survey graphic created with ArcInfo and USGS perspective view calculation program.

Renewed volcanic activity since the climactic eruption, all of which has occurred within the caldera, also helped to fill Crater Lake caldera. Four vents—represented by the andesites of east basin (Hae), central platform (Hape, Hapcb), Merriam Cone (Hamc, Hamcb), and Wizard Island (Haw, Hawb, Hawp)—erupted lava onto the caldera floor. The most-recent postcaldera eruption occurred on the northeastern flank of Wizard Island about 4,800 years ago. It vented rhyodacite lava and breccia (Hr and Hrb), forming a subaqueous dome.

While postcaldera andesitic vents were erupting, Crater Lake was filling to nearly its present level (see "Crater Lake" section). As a result, except for Wizard Island, postcaldera volcanic features are below the surface of deep, blue Crater Lake. Three basins are hidden from view but are known from bathymetric surveys (see "Bathymetric Data" section). The Wizard Island, central platform, and Merriman volcanic cones separate these basins. East basin is the deepest of the three and contains approximately 75 m (250 ft) of sedimentary fill (Nelson et al. 1986); the southwest and northwest basins have less than 50 m (160 ft) of fill (Nelson et al. 1986). The east, northwest, and southwest basins are the ultimate repositories of sedimentary material transported and deposited within Crater Lake caldera today (Bacon et al. 2002).

The initial pyroclastic fill and overlying debris-flow materials represent the majority of post-caldera sedimentation (Nelson et al. 1994), that is, as much as 90% of the total thickness of caldera fill (Charles R. Bacon, US Geological Survey, research geologist, written communication, 21 March 2013). These layers were deposited rapidly in the first few years after caldera collapse and before Crater Lake began to fill with water. By contrast, the uppermost 20–40 m (70–130 ft) of material was slowly deposited within Crater Lake (Nelson et al. 1994). These lacustrine sediments probably represent less than 10% of the total thickness of caldera fill but the majority of post-collapse history (Nelson et al. 1994; Charles R. Bacon, US Geological Survey, research geologist, written communication, 21 March 2013).

Bathymetric Data

The first indications of what the bottom of Crater Lake looks like came in 1886 during a joint survey of the US Geological Survey and US Army led by William G. Steel, under the direction Clarence E. Dutton (Dutton 1889). This survey collected 186 soundings using a Millers lead-line sounding machine.

In 1959, work by the US Coast and Geodetic Survey provided a better indication of the lake bottom. This survey used an acoustic echo sounder and radar navigation to collect 4,000 soundings. These data were contoured by Williams (1961) and Byrne (1962) and resulted in a fairly detailed map of the large-scale features below the surface of Crater Lake. This map served as the best bathymetric information available for almost 40 years (Mac Brock, Crater Lake National Park, chief of Resource Management, written communication, 10 April 2013).

In summer 2000, the USGS Pacific Seafloor Mapping Project in cooperation with the National Park Service and the Center for Coastal and Ocean Mapping at the University of New Hampshire used a state-of-the-art multibeam sonar system to collect high-resolution bathymetry and calibrated, co-registered, acoustic backscatter to support both biological and geological research. This survey collected more than 16 million soundings. The resulting data portray the bottom of Crater Lake at a spatial resolution of 2 m (7 ft) (Gardner et al. 2000; Gardner and Dartnell 2001). The 2000 bathymetric data were described and interpreted by Bacon et al. (2002).

Combined with light detection and ranging (LiDAR) data collected in 2010, Robinson et al. (2012) used bathymetric data to produce a continuous view of Crater Lake National Park—from the highest peak (Mount Scott) to the deepest part of Crater Lake. The LiDAR survey resulted in a digital elevation map of the ground surface beneath forest canopy. The average resolution is 1.6 laser returns per square meter yielding vertical and horizontal accuracies of ± 5.0 cm (2.0 in). The high precision of LiDAR and the technology's ability to "see" through the forest canopy revealed previously unrecognized landscape features, even when walked over, because their full extent is normally hidden by vegetation (Robinson et al. 2012).

Crater Lake

Crater Lake fills steep-sided Crater Lake caldera to an average elevation of 1,883 m (6,178 ft) above sea level. The lake level is about 300 m (980 ft) below the rim, 604 m (1,980 ft) below the highest point at Hillman Peak, and 165 m (540 ft) below the lowest points on the rim at Kerr Notch, Wineglass, and northwest of Roundtop (Bacon et al. 1997). Crater Lake has a surface area of 53 km^2 (20 mi^2). The diameter of the lake ranges between 8 km (5 mi) and 10 km (6 mi).

Crater Lake is a closed basin, having no permanent outlet or inlet streams. Lake elevation can vary as much as 5 m (16 ft) over periods of 5–10 years, relative to the amount of snow and rain that falls onto the lake's surface (Larson et al. 2003b). Snow meltwater is the primary source of intermittent flow into the lake. Springs also provide some groundwater discharge (Nelson et al. 1994). The level of Crater Lake is maintained by a balance between precipitation and inflow versus evaporation and leakage (see "Lake Level" section).

Depth

Crater Lake is the deepest lake in the United States, second deepest lake in North America, and seventh deepest lake in the world. Lake Baikal in southern Russia is the world's deepest lake at 1,637 m (5,314 ft) deep. In North America, only Great Slave Lake in the Northwest Territories of Canada, 614 m (2,010 ft) deep, is deeper than Crater Lake. With respect to the average surface elevation—1,883 m (6,178 ft) above sea level—the maximum depth of Crater Lake is 594 m (1,949 ft) (Bacon et al. 2002).

Clarity

In addition to depth, Crater Lake's remarkable clarity is an often cited and treasured feature (Larson et al. 2007a). Many scientific studies have focused directly or indirectly on water clarity—from time-series observations of a Secchi disk, a 20-cm- (8-in-) diameter, black and white "dinner plate" lowered into the water, to basic scientific research on inherent optical properties of the lake's water, particles, and dissolved substances (Larson et al. 2007a). Research findings at Crater Lake along with data collected through the park's monitoring program (see "Long-Term Monitoring" section) show just how amazing Crater Lake's clarity is (Girdner 2003). The waters of Crater Lake have reset the standards for optical properties of pure water, and may have the highest clarity of any lake in the world (Girdner 2003).

Clarity readings using a Secchi disk vary seasonally and annually, but typically are highest in June and lowest in August (Larson et al. 2007b). The maximum individual clarity reading was 41.5 m (136 ft) in June 1997. The lowest reading was 18.1 m (59 ft) in July 1995. From 1896 (using a white dinner plate, rather than a Secchi disk) to 2003, the average August reading was 30 m (98 ft) (Larson et al. 2007b). Notably, the lowest reading occurred after a torrential summer storm (rain and hail) that caused extensive mudflows into the lake (Larson et al. 2007b).

Other factors that affect clarity are high densities of phytoplankton (McIntire et al. 2007) and abiotic particles originating from the atmosphere, intracaldera springs and streamlets, and suspended nearshore lake sediments (Larson et al. 2007b). Near the bottom of the lake, factors include deposition of particles from the water column and flux of particles from the edges of the lake that move down along steep slopes (Dymond et al. 1996).

Color

Another dramatic feature of Crater Lake is its blue color, which is related to clarity. When sunlight penetrates into the lake, the red through green portions of the light spectrum are preferentially absorbed by water and suspended particles. The blue light, which penetrates more deeply, is eventually scattered by water molecules and returns to the lake surface (and our eyes). The blueness of water is greatest when densities of abiotic (sediment) and biotic (phytoplankton) particles are low (Larson et al. 2003a).

Thermal Characteristics and Mixing

Owing to its great volume and heat (thermal inertia), Crater Lake is rarely covered by snow and ice as are other lakes in the Cascade Range (Larson et al. 2007b). Crater Lake has frozen over completely only three times since 1949 (Redmond 2007). In winter, the lake is isothermal (maintaining a constant temperature) except for a slight increase in temperature in the deep lake from hyperadiabatic (related to its great depth, with compression of water causing a rise in temperature) processes and inflow of hydrothermal fluids (see "Hydrothermal Features in Crater Lake" section).

During winter and spring, wind energy and convection mix the water column to a depth of about 200–250 m (660–820 ft). Circulation of the deep lake periodically occurs in winter and spring when cold, near-surface waters sink to the lake bottom, a process that results in the upwelling of nutrients, especially nitrate, into the upper strata of the lake. Crater Lake becomes thermally stratified in late summer and early fall. When stratified, the maximum thickness of the epilimnion (uppermost layer) of Crater Lake is about 20 m (65 ft) and the metalimnion (layer with rapid decrease in temperature with depth, below the epilimnion) extends to a depth of about 100 m (330 ft). Thus, most of the lake volume is a cold hypolimnion (layer below the metalimnion). The year-round near-bottom temperature of Crater Lake is about 3.5°C (38.3°F).

Lake Level

The level of Crater Lake—presently at 1,883 m (6,178 ft) above sea level—is maintained by direct precipitation and inflow from the caldera walls, and losses by surface evaporation and leakage (Phillips 1968; Redmond 1990; Nathenson 1992). The water supply to Crater Lake is about 224 cm (88 in) per year; evaporation is about 85 cm (33 in) per year, and leakage is about 139 cm (55 in) per year (Nathenson et al. 1992). In a model for filling Crater Lake, Nathenson et al. (2007) noted the significance of the lake's depth, which affects hydrologic head and the amount of leakage from the basin, as well as surface area, which affects the amount of evaporation. Additionally, rock permeability (the capacity for transmitting fluids) is related to the filling of Crater Lake. Bacon and Lanphere (1990) noted that the caldera floor and walls likely have low permeability owing to hydrothermal sealing of fractures and breccias. Thus the level of Crater Lake may be controlled by deposits of relatively permeable glacial debris (till) in the northeastern caldera wall, below Roundtop (see figs. 33 and 35). These deposits occur between an elevation of 1,844 and 1,859 m (6,050 and 6,099 ft) and are sandwiched between lava flows composed of andesite of Cloudcap Bay (PEac) that extend down to a depth of about 39 m (128 ft) below the present lake surface (Bacon et al. 2002) and the overlying andesite of Roundtop (PEar). These lava flows are evident on bathymetric data gathered in 2000 (Gardner and Dartnell 2001).

High-resolution bathymetry also shows a series of drowned beaches in the upper 30 m (100 ft) of Crater Lake that probably resulted from reduced precipitation (periods drier than today) and may reflect still stands after Crater Lake filled. The deepest drowned beach approximately corresponds to the base of the permeable layer in the northeastern caldera wall (Bacon et al. 2002; Nathenson et al. 2007). Moreover, bathymetry revealed a prominent wave-cut platform, up to 40 m (130 ft) wide, between the present lake level and 4 m (13 ft) depth. The platform is much larger than any of the drowned beaches. Its width suggests that the lake spent most of its history at an elevation around 1,879 m (6,165 ft) above sea level. This is between 1 m (3 ft) and a few meters below the level of the last 40 years, which have been wetter than most of the time since Crater Lake filled.

Nathenson et al. (2007) calculated filling histories for three values of precipitation—modern, 70% of modern, and 95.6% of modern. At the modern value of precipitation, the lake would have taken about 420 years to fill. At 70% of modern precipitation, which Bacon et al. (2002) used for their proposed filling history, the filling time increases to about 740 years. Using the results of the 2000 bathymetric survey, Nathenson et al. (2007) were able to add geologic constraints such as drowned beaches and the wave-cut platform to improve hydrologic modeling. The 95.6% value equilibrates lake level at the wave-cut platform, where lake level likely spent much of its history. At this percentage, filling would have taken about 460 years.

Water Quality

During the 1980s, concern arose that the optical properties and water quality of Crater Lake had declined. However, these concerns were based on comparison to sparse historical information. A 10-year study ending in 1993 concluded that the lake had not declined in water quality, including clarity (Larson et al. 1993). In short, no long-term trend of decline is apparent, and variations within a single year often encompass much of the variation seen in the full dataset (Larson et al. 2007a).

Petroleum hydrocarbon contamination is a water-quality issue for Crater Lake. Visitors to the park have the opportunity to explore the lake and its surroundings from many vantage points, including Rim Drive and on the lake itself (fig. 23). From mid- to late-June through mid-September, a concessioner offers seven daily commercial boat tours of Crater Lake accompanied by NPS interpreters, and one trip to Wizard Island for passenger transport (National Park Service 2005). Contamination of the lake by hydrocarbons and combustion products from the operation of vehicles within the park, around the caldera and on the lake, is a concern (Larson et al. 2007a).

Oros et al. (2007) conducted the first detailed investigation of the quantity and quality of both natural and anthropogenic hydrocarbons in Crater Lake. Petroleum-derived hydrocarbons occur at very low concentrations in slicks on the lake surface and in some lake sediments, particularly near the Cleetwood Cove area that has the highest concentration of boat use and fuel transfers. Combustion products, including polycyclic aromatic hydrocarbons (PAH), which can cause cancer and abnormal development, are found at very low to undetectable concentrations in bulk lake sediments. Oros et al. (2007) concluded that no adverse effects are expected to occur in benthic biota exposed to these sediments. Nevertheless, boating activities are leaving a detectable level of petroleum in surface waters and lake sediments albeit at very low concentrations (Oros et al. 2007). Although these concentrations are orders of magnitude below threshold effect levels for sensitive aquatic organisms and are similar to those reported in some of the most remote environments on Earth, these compounds are present and show evidence of both direct input and atmospheric transport to the lake surface (Larson et al. 2007a). Thus this finding highlights the significance long-term monitoring at the park.

Figure 23. Boat on Crater Lake. Riding in a boat on Crater Lake provides a unique perspective on the inside of the caldera. Each summer, hundreds of visitors participate in ranger-led boat tours on Crater Lake. Participants must first hike down the steep Cleetwood Cove Trail to access the boat launch. National Park Service photograph.

Long-Term Monitoring

In light of its exceptional clarity and depth, as well as its nearly pristine condition, Crater Lake is a valuable natural laboratory for studying lakes. The only notable human impacts to the lake are the introduction of fish, which occurred in 1888, and the introduction of crayfish as a food source for these fish. Before then, the lake was presumably fishless (Larson 2007). Of the 600 fish transported for stocking, only 37 survived the trip from a ranch 66 km (41 mi) away.

In the early 1940s, the National Park Service discontinued periodic stocking of rainbow, cutthroat, and brown trout; and coho salmon. Currently the lake’s fish population consists of rainbow trout and kokanee salmon. Kokanee salmon were never stocked, and the means of introduction are unknown (Larson 2007).

US Geological Survey, Oregon State University, and National Park Service scientists have systematically studied Crater Lake for more than two decades. Between 1985 and 1988, collaboration between park managers and researchers finalized a study plan and standard sampling procedures, and developed a set of working hypotheses and objectives; Larson (1996) summarized this effort. The primary goals were to develop a reliable database for use in the future; improve understanding of physical, chemical, and biological characteristics and processes; and establish a long-term monitoring program to examine the limnological characteristics of the lake through time. The establishment of a long-term monitoring program in 1994 and the promotion of lake research and education in the current general management plan (National Park Service 2005) work towards continued fulfillment of these goals.

As part of the National Park System, Crater Lake has a high degree of protection from human activities. The baseline of information gathered from long-term monitoring serves as a reference for studying Crater Lake, as well as identifying impacts from climate disruption and human activities, such as agriculture and urban growth, on other lakes (Larson et al. 2003b). Research and monitoring of Crater Lake remains a priority (Mac Brock, Crater Lake National Park, chief of Resource Management, conference call, 18 December 2012).

Glacial Features

In the 1940s, under the direction of geologist Howel Williams—author of the classic 1942 monograph about Crater Lake National Park—artist Paul Rockwood painted three renditions of Mount Mazama (fig. 24). These paintings help to visualize glaciers on a landscape that presently lacks glacial ice. One of the paintings depicts Mount Mazama covered in glacial ice at its height during the Pleistocene Epoch (fig. 24, top). Another shows ice-clad Mount Mazama at the onset of its climactic eruption 7,700 years ago (fig. 24, middle; and cover photo). The third shows a pumice-mantled, devastated landscape and a freshly collapsed Crater Lake caldera (fig. 24, bottom).

The Rockwood paintings are excellent representations of the late history of Mount Mazama, and show the benefit of linking geology and art for public education and park interpretation. However, in an interesting outcome of this linkage, two of the paintings show past geologic interpretations that have since been revised. Williams (1942) hypothesized that various deposits at the caldera rim had glacial origins, and apparently directed Rockwell to paint glacial ice at these locations. These deposits are now known to be lithic breccia (Hcb), not glacial till. Thus, the painting of Mount Mazama at the onset of its climactic eruption (fig. 24, middle) shows glaciers descending down the southern valleys to an elevation of about 1,900 m (6,330 ft) (Bacon 2008). However, paleoclimatic reconstructions since Williams' time indicate that during the climactic eruption, the Crater Lake region was relatively warm and dry. Thereby, any ice would have been restricted to the highest part of Mount Mazama during this time (fig. 24, middle). Moreover, in the painting that shows Mount Mazama after its climactic eruption (fig. 24, bottom), glaciers are shown in Munson Valley, and Sun and Kerr notches (Bacon 2008). However, paleoclimatic reconstructions indicate that at elevations of the caldera rim, the southern slope of Mount Mazama, in particular, would have been ice free. Nevertheless, Williams' interpretation that glaciers covered Mount Mazama during the Pleistocene Epoch (fig. 24, upper) is indeed indicated by glacial erosion and ice-lava interactions of many of the lava flows within the park.

In an interesting connection to the National Park Service, Williams built his account of glaciation of Mount Mazama upon work by Atwood (1935), who literally crawled on hands and knees across precipitous slopes of Crater Lake caldera in search of glacial material. Wallace W. Atwood Jr. was a National Park Service employee, and started his quest for glacial evidence in 1931. Williams included many modified versions of Atwood's drawings in his 1942 monograph.

Figure 24. Scenes of Mount Mazama. In the 1940s, Paul Rockwood painted three renditions of Mount Mazama—at its height during the Pleistocene Epoch (top), at the onset of the climactic eruption (middle), and after formation of Crater Lake caldera (bottom). All three paintings show glaciers on the landscape. No glaciers exist in Crater Lake National Park today. At the time of the climactic eruption, glacial ice was not as extensive as shown in the lower two paintings. National Park Service images, available at http://www.nps.gov/crla/photosmultimedia/Rockwood-Paintings.htm (accessed 7 February 2013).

Classic Glacial Forms

The geologic setting of Crater Lake National Park is noted for glacial features (figs. 25 and 26). Between the Phantom Ship Overlook and park headquarters on the Rim Drive, visitors can see Vidae Falls tumbling over a

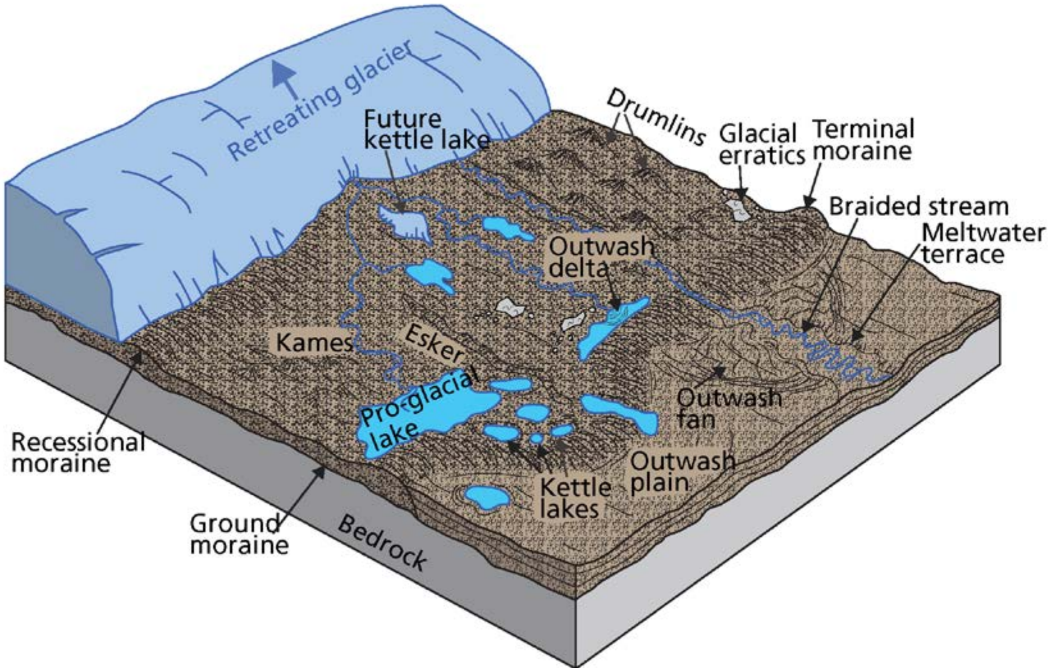


Figure 25. Glacial deposits. This schematic graphic illustrates deposits and features associated with glacial processes. Typically, glacial landscapes only preserve a fraction of the possible deposits. Within Crater Lake National Park, till (generic term for material deposited by glacial ice) and moraines (composed of till) are widespread. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

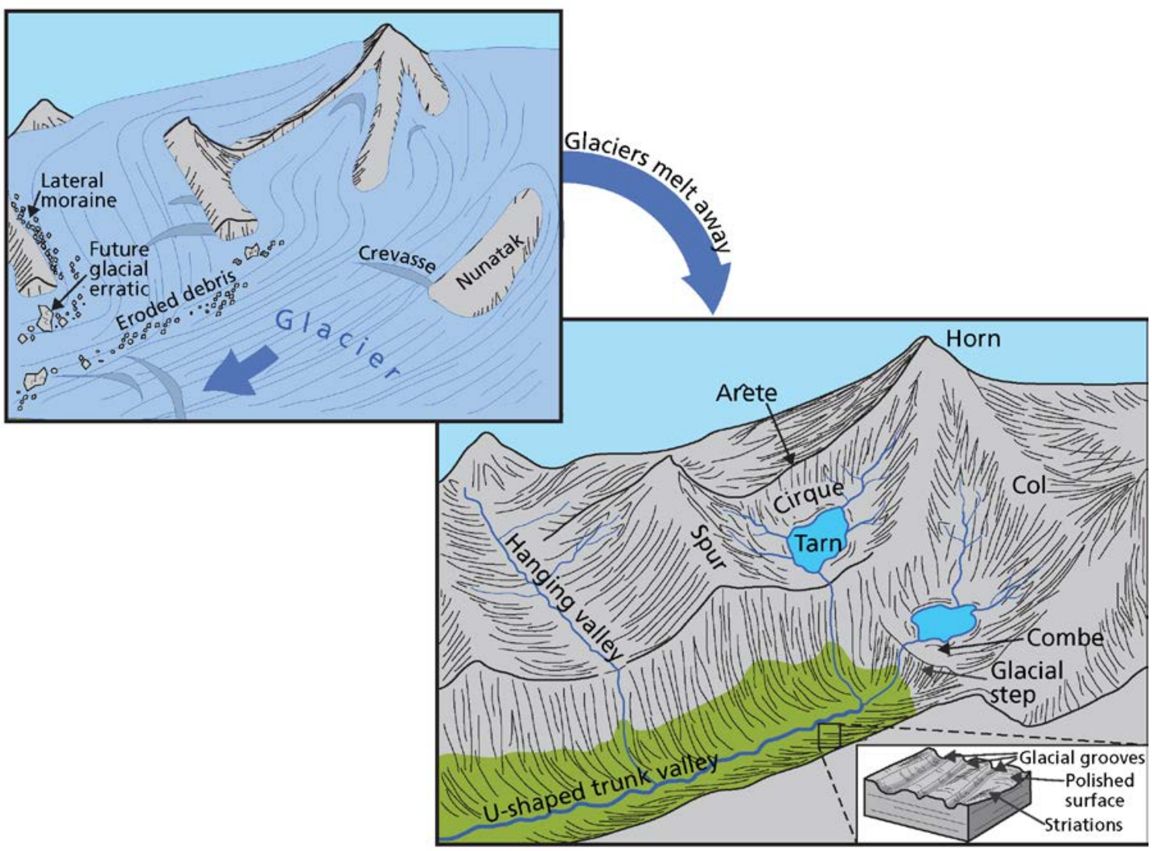


Figure 26. Glacial landforms. This schematic graphic illustrates "classic" landforms common to areas that were glaciated. Not every landscape contains examples of every feature. Many of these can be found within Crater Lake National Park such as polish and striations (fig. 31), U-shaped valleys (e.g., Sun and Kerr; fig. 28), cirques (fig. 29), and horns (figs. 3 and 30).

Figure 27. Vidae Falls. Between Phantom Ship Overlook and park headquarters on the Rim Drive, Vidae Falls cascades over a glacially carved cliff and drops 30 m (100 ft) over a series of ledges. The water spills over an outcrop of andesite of Kerr Notch (PEak). National Park Service photograph.

glacially carved cliff and dropping 30 m (100 ft) over a series of ledges (fig. 27). The glaciated bedrock is the andesite of Kerr Notch (PEak).

The slopes of Mount Mazama show classic glacial features, including U-shaped valleys that were carved by repeated advances of glacial ice. Munson, Sun, Kerr, Sand, and Annie Creek valleys have this notable glacial form. Each resembles the letter "U" in cross profile, with steep walls and a broad floor. Similarly, U-shaped notches in the caldera rim and heads of valleys, for instance Kerr and Sun, are evidence of past glacial activity (fig. 28).

Figure 28. U-shaped notches. Glaciers flowed down Kerr (left) and Sun (right) valleys, scouring U-shaped notches at the heads of these valleys. National Park Service photograph.

Another classic glacial form is the cirque—a bowl-shaped, amphitheater-like hollow eroded into the side of a mountain. Mount Scott hosts a cirque on its northwestern side (fig. 29), and Union Peak was once surrounded by glaciers that carved cirques on all sides. The best preserved cirque on Union Peak is at the head of the major glacial valley that runs more-or-less northwest from the horn-shaped summit (Charles R. Bacon, US Geological Survey, research geologist, written communication, 29 January 2013).

Figure 29. Mount Scott. The highest peak in Crater Lake National Park, Mount Scott, consists entirely of dacite (PEds) that erupted from low lava fountains about 420,000 years ago. The peak's hydrothermally altered interior is exposed in a cirque on the right. The smooth dark cliff in the foreground is the northern flank of the 27,000-year-old Redcloud rhyodacite flow (PEre), where lava chilled against glacial ice and was subsequently sculpted by glacial action. US Geological Survey photograph by Charles R. Bacon, available at http://pubs.usgs.gov/sim/2832/photos/4-Mount_Scott.html (accessed 27 February 2013), annotation by Jason Kenworthy (NPS Geologic Resources Division).

Glacial horns, such as the Matterhorn in the Swiss Alps, can be conspicuous features on a landscape and a telltale sign of glacial activity. Within the park, Union Peak has a distinctive horn shape and, indeed, glacial ice descended down the sides of this volcano (fig. 30). However, Williams (1942) pointed out that Union Peak's horn is largely a result of volcanic processes. The horn is the remains of massive intrusive rock that made up the core of a former cinder cone that was perched atop the Union Peak shield volcano. Glacial erosion removed cinders and cleaned off the intrusive core, leaving a horn-shaped volcanic "plug" or "neck." By contrast, The Watchman (fig. 3) is an unequivocal glacial horn, sculpted from a thick dacite lava flow (PEdwf).

Figure 30. Union Peak. Horn-shaped Union Peak in the southwestern corner of Crater Lake National Park formed via a combination of volcanic and glacial processes. It is the remains of a cinder cone that erupted atop a shield volcano. Although glacial erosion stripped cinders from the sides of the cone, the horn shape is largely an outcome of the resiliency of a massive core of intrusive rock. US Geological Survey photograph by J. S. Diller, 1901.

At the park, glacial features are commonly obscured by the ring-vent phase pyroclastic flows of Mount Mazama.

Also, the relatively soft lava surfaces at the park do not take to glacial polishing like harder rock types, such as granite in the glaciated valleys of Yosemite National Park in California (see Graham 2012). However, notable surfaces with glacial polish and striations (scratches) occur at Arant Point and Cleetwood Cove, in particular the "jumping off" rock near the boat landing (Charles R. Bacon, US Geological Survey, research geologist, written communication, 29 January 2013). These features formed as rocks and sediment frozen to the base and sides of a glacier acted like sandpaper and scratched and polished bedrock surfaces over which they passed (fig. 31). Atwood (1935) highlighted the striations and polish at Skell Head.

Figure 31. Glacial striations. Glacial striations are exposed in outcrops along the West Rim Drive. This particular glacially scratched outcrop is 0.8 km (0.5 mi) south of North Junction, roughly above the Devils Backbone. National Park Service photograph.

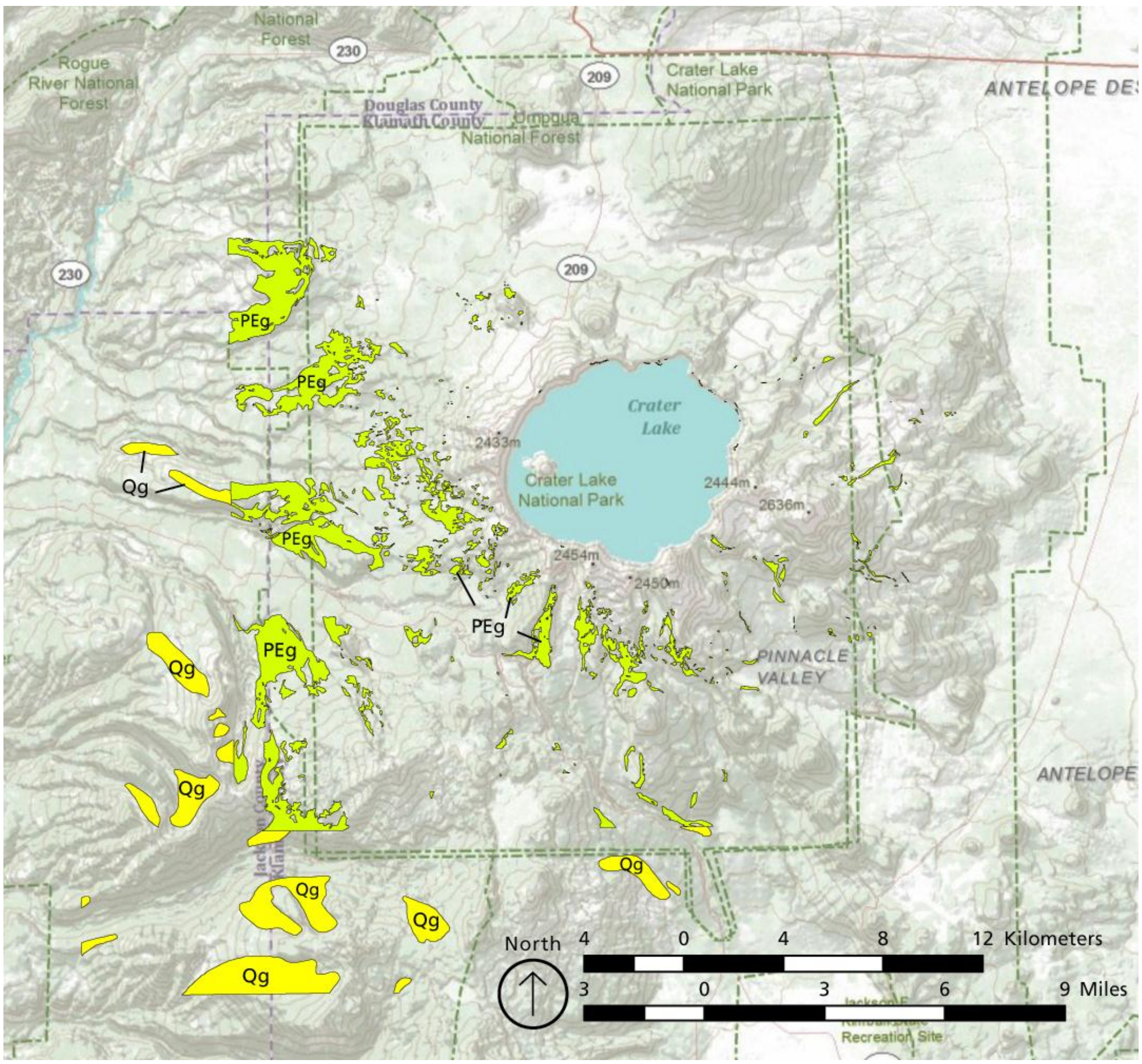


Figure 32. Extent of glaciation. At present no glaciers occur within Crater Lake National Park. Glacial deposits mapped by Bacon (2008) and Smith et al. (1982)—map unit symbols PEg and Qg, respectively—show the general distribution and extent of past glacial activity on the landscape. However, deposits of the caldera-forming (climactic) eruption probably buried glacial deposits. Graphic by Rebecca Port (NPS Geologic Resources Division) using GRI GIS data and ESRI ArcMap terrain base map layer.

Till and Moraines

Bacon (2008) collectively mapped all glacial deposits (map unit PEg) at the park, and did not differentiate this material by age. Smith et al. (1982) mapped glacial deposits as unit Qg. The overall distribution of units PEg and Qg indicates the extent of glaciers on the Mount Mazama landscape (fig. 32).

Much unit PEg of Bacon (2008) is till and minor associated outwash (sand and gravel deposited by glacial meltwater streams). "Till" is the general term for the poorly sorted mixture of fine- to coarse-grained rock debris deposited directly from glacial ice. This material forms a discontinuous mantle on the slopes of Mount Mazama and at lower elevations. Till may also be interlayered with volcanic flows and deposits and incorporated into the caldera wall, for example, at the Wineglass in the northeastern caldera wall (fig. 33). Below the Palisades (and the lake's surface), an especially thick deposit of till likely provides a permeable pathway for leakage from Crater Lake (see "Lake Level" section).

Till at the park is characterized by an assemblage of dense, abraded or rounded volcanic rocks, and the presence of ultrafine material in an unsorted matrix (Bacon 2008). A notable deposit of glacial till of the Munson Valley occurs between the turnout and the park road about 0.2 km (0.1 mi) north of Duwee Falls. This deposit would be good for park interpretation because it is easily accessible, and its ultrafine sediment, rounded cobbles, and variety of rock types are unmistakably glacial (Charles R. Bacon, US Geological Survey, research geologist, telephone communication, 1 February 2013).

Figure 33. The Palisades and Wineglass. The central topographic high in this aerial view of the northeastern wall of Crater Lake caldera is Roundtop, which is composed of andesite of Roundtop (PEar). The tall cliffs below Roundtop are the Palisades, which also consist of the andesite of Roundtop. The andesite flow rests on a deposit of thick glacial till and associated (possibly fluvial) sediments, which is largely obscured by talus. To the right of the Palisades is the scree chute known as the Wineglass. The bowl of the glass is scree that originated as Holocene pumice-fall deposits—preclimactic rhyodacite (Hrhp), Plinian and other Holocene pumice-fall deposits (Hcp), and the overlying Wineglass Welded Tuff and proximal ignimbrite (Hcw and Hcb, respectively). The stem of the glass crosses subglacial and subaerial andesite of Applegate Peak (PEaa) overlying glacial till obscured by talus. The cliff at the caldera rim to the right of the Wineglass consists of an ice-bounded lava flow—the andesite of Grotto Cove (PEagc). Walker Rim is visible in the distance beyond the Wineglass. US Geological Survey photograph by Charles R. Bacon.

Generally, moraines are the most obvious landforms composed of till. They can be undulating mounds or sharp ridges, depending on how long a glacier remained stable in a particular position or how much erosion and weathering have taken place since deposition. LiDAR images (see Robinson et al. 2012) help to reveal moraine features on the landscape of the park, for example, in the Annie Creek drainage midway in the "panhandle" at the southern boundary (Charles R. Bacon, US Geological Survey, research geologist, telephone communication, 1 February 2013). Lateral moraines, which form along the sides of a glacier, are preserved in the Annie, Cavern, Scott, Pothole, and Bear Creek drainages. Arc-shaped recessional moraines, built during the retreat of a glacier, are rare at the park, but one occurs in the drainage 3 km (2 mi) west of Discovery Point. Remnants of the Annie Creek glacier's terminal moraine are present near the park's southern boundary. These moraines presumably date from the last glacial maximum, roughly 20,000 years ago (Charles R. Bacon, US Geological Survey, research geologist, written communication, 29 January 2013).

Figure 34. Columnar joints. Spectacular columnar joints (note geologist for scale at lower right) formed in the andesite of Applegate Peak vitrophyre (PEaa), approximately 270,000–210,000 years ago. As a result of lava flowing against or beneath glacial ice, columns formed perpendicular to a cooling surface as meltwater penetrated solidifying lava along growing fractures (joints). The cliff in the distance is another ice-bounded lava flow, the southeastern margin of andesite of Roundtop (PEar), which has a K-Ar age of 159,000 ± 13,000 years ago (Bacon 2008). The exposure shown here is below the Wineglass. US Geological Survey photograph by Charles R. Bacon.

Lava-Ice Interactions

Diagnostic features of glacial activity in a volcanic environment range in scale from lava outcrops that have thick, glassy margins with polygonal jointing (e.g., map unit PEaa; fig. 34) and fractures that formed while lava was in contact with ice; to the gross morphology of ice-bounded lava flows (e.g., PEre and PEar) and volcanic table mountains called "tuyas" (e.g., PEab and PEat).

The term "tuya" originated with Mathews (1947) for these features near the Tuya River in northern British Columbia, which are flat-topped, steep-sided volcanoes that erupted under glacial ice. A volcanic eruption beneath glacial ice melts out a cavity that enlarges to a lake within the glacier. Meanwhile, a pile of volcanic breccia forms within the lake because erupting magma, charged with gas bubbles, breaks into centimeter-sized fragments on contact with water or, if gas manages to largely escape, may form lava pillows that break apart. The end result is a pile of volcanic breccia. If the eruption goes on long enough, the volcanic vent within the breccia pile may breach the surface of the lake, allowing lava to flow over the flat-topped breccia pile to make a resistant cap. Finally, when the ice melts away, a table mountain (tuya) is left that has a rather flat top composed of subaerial lava, and sloping sides composed of subaqueous breccia. Tuyas occur south of Bear Bluff and at Arant Point in the park.

The tall cliff in the northeastern caldera wall, known as the Palisades, is made up of an ice-bounded lava flow of andesite of Roundtop (PEar). The medium-light-gray andesite was emplaced 159,000 ± 13,000 years ago (Bacon 2008) and consists of 62% SiO_2. The andesite flowed between two tongues of glacial ice (or melted a channel into a glacier). It formed a 2.5-km- (2-mi-) long, more than 130-m- (430-ft-) thick lava flow that rests on about 115 m (380 ft) of till and associated (possibly fluvial) sediment on the northeastern flank of Mount Mazama (fig. 35). An especially thick accumulation of sediment below Roundtop and the Wineglass appears to be a relatively permeable horizon in the caldera wall that may regulate lake level (see "Lake Level" section).

Figure 35. The Palisades. The Palisades below Roundtop on the northeastern side of Crater Lake caldera consist of andesitic lava that flowed between two tongues of glacial ice, or melted a channel into a glacier, about 160,000 years ago. The flow lies on a thick deposit of glacial till and other (probably fluvial) sediments. Talus from the cliffs lies atop these sediments. National Park Service photograph.

Another lava–ice interaction is represented by Sentinel Rock on the eastern rim of the caldera. At this location, a dacite lava flow (PEdr) extended into a glacial valley that had been carved into the eastern flank of Mount Mazama (PEak) about 305,000 years ago (Bacon and Lanphere 2006). The lava flows built up and now form the cliffs at Sentinel Rock (fig. 11).

Caves

Most caves of the world formed in limestone as a result of the dissolution of calcium carbonate ($CaCO_3$) (Moore and Sullivan 1997). No limestone occurs within Crater Lake National Park, but caves, called "lava tubes," can also form in lava. Examples of this type of cave occur in the National Park System. Particularly well-preserved lava tubes occur in the basaltic lava flows of Craters of the Moon National Monument and Preserve in Idaho, El Malpais National Monument in New Mexico (see KellerLynn 2012), Hawaii Volcanoes National Park in Hawaii (see Thornberry-Ehrlich 2009), and Lava Beds National Monument in California (see KellerLynn 2013c). Although the majority of andesitic and rhyodacitic lavas at the park are much too viscous to form lava tubes (Allen 1984), a few very small lava tubes exist east of Castle Point in the postglacial, preclimactic eruption basalt of Castle Point (PEbc) (Skeels 2010).

Allen (1984) identified more than 40 caves within the park, including 31 caves within the rim of Crater Lake caldera, and another five sites with one or more caves outside the rim. Those within the rim are "along the water's edge" and may be seen from the surface of Crater Lake (Allen 1984, p. 5). Notably, however, lake level fluctuates and has changed since 1935 when John Eliot Allen explored and first described the caves at the park. Thus caves within the rim may be above or below present-day lake level. Allen (1984) described these caves as forming primarily in strongly jointed andesitic lava flows. Major vertical joints in the andesite governed where plates (or platy flow structures) broke out and caves formed.

Comparing the locations of caves identified by Allen (1984) outside the caldera rim and the digital geologic map of Crater Lake National Park, caves seem to have formed in the Holocene preclimactic rhyodacite (Hrh) of the Llao Rock and Cleetwood flows, rhyodacite (PEre) flow at Redcloud Cliff, ring-vent-phase ignimbrite (Hcf), and a mudflow deposit underlying andesite of Garfield Peak (PEag) (see Map Unit Properties Table, in pocket).

Allen (1984) suggested five means of cave formation at the park: (1) wave erosion within the rim (25 caves), (2) erosion of less-resistant mudflow or glacial-till deposits between more resistant lava flows (11 caves), (3) forming beneath a jumble of large blocks (2 caves), (4) incision by a meandering stream (1 cave), and (5) a steam vent that opened by fracturing of an extremely viscous rhyodacite flow while still hot (1 cave).

Besides the work provided by Allen (1984), the caves at the park have not been inventoried or mapped (Covington 2004; Mac Brock, Crater Lake National Park, chief of Resource Management, conference call, 18 December 2012). A cave resource summary for Crater Lake National Park is currently (October 2013) underway by Geologic Resources Division staff (Dale Pate, Cave and Karst Program Manager, NPS Geologic Resources Division, personal communication, 21 October 2013). Protocols for monitoring the cave environments in two other National Park System units in the Klamath Network—Lava Beds and Oregon Caves national monuments—were under review as of winter 2012; revision and approval were scheduled for summer 2013. Daniel Sarr, network coordinator, is the contact for these monitoring programs (National Park Service 2007).

Toomey (2009)—the chapter in *Geological Monitoring* about caves and associated landscapes—described methods for inventorying and monitoring cave–related vital signs. This information may be useful to park managers in the development of a cave management plan. The Geologic Resources Division could help park managers develop such a plan.

Geologic History

This section describes the rocks and unconsolidated deposits that appear on the digital geologic map of Crater Lake National Park, the environment in which those units were deposited, and the timing of geologic events that formed the present landscape.

The geologic history of Crater Lake National Park is an explosive one. Bacon (2008) mapped 111 eruptive units underlying, building up, and ejected out of Mount Mazama, not to mention the Mazama ash that blew out of the volcano and was transported by wind far across the landscape. From least to most explosive, the eruptive units include five basalt, 32 basaltic andesite, 46 andesite, 19 dacite, and 9 rhyodacite. Since the climactic eruption, five additional postcaldera units—four andesite and one rhyodacite—vented onto the floor of Crater Lake caldera. While the mountain was active, glaciers moved down its slopes and across the landscape.

Pre-Mazama Volcanism

Bacon and Lanphere (2006) referred to the rocks and volcanoes that predate Mount Mazama as "pre-Mazama volcanics" or "pre-Mazama volcanoes." Bacon (2008) referred to them as "pre-Mazama silicic rocks." Silicic rocks such as dacite and rhyodacite, which make up the pre-Mazama volcanoes. These rocks include the dacites of Dry Butte (PEdd), Sand Creek (PEdsc), and west of the Pinnacles (PEdw), which erupted 1.3 million, 1.1 million, and 612,000 years ago, respectively; the 724,000-year-old rhyodacite dome west of Cavern Creek (PErcc); and the rhyodacites of Scott Creek (PErsc), Crater Peak (PErcs), and Pothole Butte (PErpb), which erupted between 460,000 and 410,000 years ago.

These 400,000-year-old and older lava flows are known from various sources, including exposures in deep canyons on the southern flank of Mount Mazama, samples retrieved from submerged caldera walls (PEsu), and cores from two geothermal exploration wells (Bacon 2008).

Regional Volcanism

Mount Mazama and now Crater Lake caldera are situated among regional volcanoes that are characterized by dominantly basaltic andesitic lava flows (tables 1 and 2). Cones and shields that partly surround Mount Mazama are manifestations of regional volcanism spreading northwest, southwest, and east of Crater Lake caldera. Lava flows of regional volcanoes interfinger with some distal Mazama lavas and overlie others (Bacon 2008).

Regional volcanism probably has been active for at least the last 700,000 years, with episodic activity since 200,000 years ago (Bacon 2008). Between 100,000 and 40,000 years ago, regional volcanism experienced a less-active stage but became voluminous while Mount Mazama's magma chamber was growing about 40,000–7,700 years ago. Bacon (2008) identified more than 40 vents for regional lavas in the Crater Lake area. Notable among these are Crater Peak (PEacrp; 130,000–100,000 years old), Red Cone (PEbrp; 35,000 ± 4,000 years ago), Williams Crater (PEbwp; approximately 35,000 years old), and three vents that sit astride Castle Point (Qbc), which are less than about 16,000–14,000 years old and comprise the youngest regional volcano near Crater Lake caldera (table 2).

Buildup of Mount Mazama

Mount Mazama began to erupt and build about 420,000 years ago, starting with the andesite of Phantom Cone (PEapn). The buildup of Mount Mazama encompasses 47 named units, including lava, breccia, and pyroclastic material of primarily andesite and low-silica dacite, fed mostly by low fountains of lava. The 35,000-year-old mingled lava of Williams Crater (PEmw) represents the youngest unit produced during this constructional phase.

Rhyodacite Domes and Flows

In addition to these 47 units, some rhyodacite lava domes and flows erupted between about 30,000 and 7,700 years ago. These eruptions preceded the caldera-forming eruption, and represent early leaks from the top of the climactic magma chamber as it grew (Druitt and Bacon 1988). Bacon (2008) divided these rhyodacite deposits into four map units: (1) evolved Pleistocene preclimactic rhyodacite (PEre), which includes the Grouse Hill and Redcloud flows of Williams (1942); (2) a small dome consisting of rhyodacite of Bear Bluff (PErbb); (3) rhyodacite of Sharp Peak (PErs); and (4) Holocene preclimactic rhyodacite (Hrh), which includes the Cleetwood and Llao Rock flows (fig. 36).

Figure 36. Llao Rock in profile. Llao Rock is a landmark on the rim of Crater Lake caldera. It is composed of rhyodacite (Hrh) that vented from Mount Mazama before the climactic eruption. US Geological Survey photograph by J. S. Diller, 1901.

Glaciations

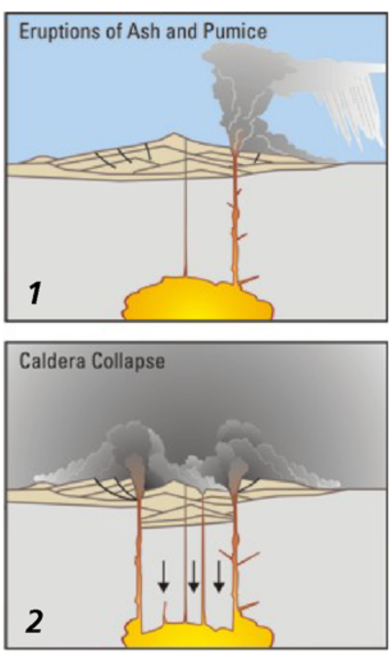
As many as six advances of glacial ice within the last 300,000 years carved the valleys of Mount Mazama, including those below Sun and Kerr notches (Bacon 2008). A seventh advance is recorded in the caldera walls. Bacon and Lanphere (2006) correlated these advances with marine isotope stages (MIS)—a chronological listing of alternating cold and warm periods on Earth going back 2.6 million years. Marine isotope stage (MIS) 2 is sometimes referred to as the "last glacial maximum" and records the most recent ice advance (ice age) of the Pleistocene Epoch. The last glacial maximum occurred between 24,000 and 10,000 years ago, though the disappearance of ice and timing of the last glacial maximum varied in mountainous valleys in the western United States. Many glacial features at the park date from MIS 2, including the tuya formed by the andesite south of Bear Bluff (PEab). Glacial activity also occurred in the park during MIS 4 (71,000–57,000 years ago), 5b (97,000–86,000 years ago), 5d (122,000–106,000 years ago), 6 (186,000–127,000 years ago), 8 (301,000–244,000 years ago), and 10 (364,000–334,000 years ago) (Bassinot et al. 1994).

Climactic Eruption of Mount Mazama

Crater Lake caldera formed 7,700 years ago as a result of a climactic eruption of approximately 50 km^3 (12 mi^3) of magma from Mount Mazama (fig. 37). The eruption can be divided into two phases—a single-vent phase and a ring-vent phase. The single-vent phase produced a Plinian pumice-fall deposit (Hcp) and pyroclastic flows of the Wineglass Welded Tuff of Williams (1942) (Hcw; fig. 38). During the single-vent phase, approximately half of the magma erupted as air-fall pumice and ash that covered the Pacific Northwest and southwestern Canada as "Mazama ash." Lack of support from the roof of the magma chamber caused the caldera to collapse, which ended the single-vent phase. During collapse and resultant ring-vent phase, multiple vents around the subsiding caldera floor generated a compositionally zoned pyroclastic flow deposit, including ignimbrite (Hcf) and lithic breccia (Hcb). Violent pyroclastic flows deposited pumiceous ignimbrite in stream valleys, and coarse lithic breccia near the caldera. Additionally, fine-grained lithic- and crystal-rich ignimbrite (Hcu) overlies lithic breccia (Hcb) on the slopes and interfluves of Mount Mazama or grades laterally into lithic breccia or ignimbrite (Hcf) in valleys. Most of the erupted volume was hydrous rhyodacitic pumice (70.4% SiO_2); minor amounts of basaltic to andesitic scoria compose the upper part of the ring-vent-phase ignimbrite (Druitt and Bacon 1986, 1989).

Postcaldera Volcanism and Basin Filling

The basin that now contains Crater Lake is the collapsed caldera of Mount Mazama. In a matter of only a few hundred years, the 1,200-m- (3,900-ft-) deep caldera was partially filled. Initially, hundreds of meters of debris accumulated as the caldera subsided and its walls failed inward. Afterward, renewed volcanic activity vented lava onto the floor of Crater Lake caldera and deposited the andesites of east basin (Hae), central platform (Hapc,



1. The climatic eruption of Mount Mazama started from a vent on the northeastern side of the volcano. A towering column of ash extruded from the vent, and pyroclastic flows spread to the northeast.

2. As the volcano erupted more magma, cracks opened up around the summit, which began to collapse. Fountains of pumice and ash surrounded the collapsing summit, and pyroclastic flows raced down all sides of the volcano.

3. The new caldera was 8 km (5 mi) in diameter and 1.6 km (1 mi) deep. Groundwater interacted with hot rock, causing explosions of steam and ash.

4. In the first few hundred years after the climactic eruption, renewed volcanism within the caldera built Wizard Island, Merriam Cone, the central platform, and a dome on the northeastern flank of Wizard Island. Water filled the new caldera to form the deepest lake in the United States. Wizard Island is the only postcaldera volcano to break the surface of the lake.

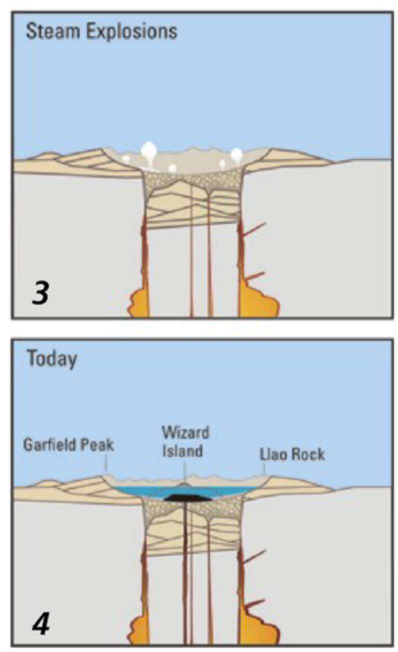


Figure 37. Climactic eruption of Mount Mazama to the present. US Geological Survey images from Williams and Bacon (1988).

Hapcb), Merriam Cone (Hamc, Hamcb), and Wizard Island (Haw, Hawb, Hawp). Bacon (2008) provisionally identified the andesite of the east basin on the basis of bathymetry and acoustic backscatter, as investigators do not have a sample of this submerged lava flow (Charles R. Bacon, US Geological Survey, written communication, 21 March 2013). This andesite makes up a probable lava flow extending 1.7 km (1 mi) south of east basin in Crater Lake.

Postcaldera andesite volcanoes divide the lake floor into three basins: northwest, southwest, and the largest and deepest east basin. Venting of these andesite volcanoes was completed within 500 years of the climactic eruption, that is, by 7,200 years ago (Bacon et al. 2002). East basin likely erupted first, followed by Wizard Island and the central platform; Wizard Island continued venting after the central platform. The timing and duration of the Merriam Cone eruption is uncertain, but probably occurred more than 300 years after the caldera collapsed (Bacon et al. 2002). The youngest postcaldera eruption produced a subaqueous dome on the northeastern flank of Wizard Island about 4,800 years ago. This eruption deposited rhyodacite lava and breccia (Hr, Hrb).

Since 4,800 years ago, the geologic history of the caldera floor is marked by a distinct absence of volcanic activity. Slope movement on the caldera walls continues but on a much reduced scale and rate than during failure of the caldera walls as Mount Mazama foundered. Lake-bottom sediments now cover the chaotic subaerial debris wedges and volcanic deposits laid down as the lake was forming. This sedimentary blanket consists of a variety of sediment sizes ranging from gravel at the edge to very fine sand toward the lake center. Additionally, organic-rich muds have accumulated on the submerged volcanic features. At present, the lake sedimentation rate is high, but remains considerably lower than that during the subaerial slope movements that occurred before the lake formed (Nelson 1995).

Within the next several thousand years, another eruption of the magnitude of the caldera-forming event is unlikely (Bacon et al. 1997). This interpretation is based on evidence that no volcanic rocks or layers of ash younger than the rhyodacite dome on the side of Wizard Island (Hr, Hrb) are known from Crater Lake. Also, seismic profile studies of lake sediment show no evidence of subsurface magma movement, and no earthquake of the kind associated with volcanism has occurred. However, future activity in a place where it has been occurring for at least 400,000 years is expected. Should there be an eruption within the caldera, it would likely happen underwater, increasing the possibility of enhanced explosive power due to the interaction of magma with water (Bacon et al. 1997).

Figure 38. Wineglass welded tuff at Skell Head. Wineglass welded tuff (Hcw) came from a collapsed column that issued from an enlarged, single vent that had produced the Plinian phase of the climactic eruption. The distribution of the tuff indicates that the vent was north of the summit of Mount Mazama, in the northeastern quadrant of the area of caldera collapse. The pinkish-orange to light-brown, partly welded to densely welded tuff is as much as 10 m (30 ft) thick in paleovalleys at the caldera rim. US Geological Survey photograph by Charles R. Bacon.

Geologic Map Data

This section summarizes the geologic map data available for Crater Lake National Park. The simplified geologic map (in pocket) displays the geologic map data draped over a shaded relief image of the park and surrounding area. The hazards map graphic (in pocket) illustrates volcano and earthquake hazards in the Crater Lake region. The Map Unit Properties Table (in pocket) summarizes this report's content for each geologic map unit. Complete GIS data are included on the accompanying CD and are also available at the GRI publications website: http://www.nature.nps.gov/geology/inventory/gre_publications.cfm.

Geologic Maps

Geologic maps facilitate an understanding of an area's geologic framework and the evolution of its present landscape. Using designated colors and symbols, these maps show the location, extent, and age of rocks and unconsolidated deposits. The two primary types of geologic maps are surficial and bedrock. Surficial geologic maps encompass deposits that are frequently unconsolidated and formed during the past 2.6 million years (the Quaternary Period; fig. 2). Surficial map units are differentiated by geologic process or depositional environment. Bedrock geologic maps encompass older, generally more consolidated sedimentary, metamorphic, and/or igneous rocks. Bedrock map units are differentiated based on age and/or rock type. Both bedrock and surficial geologic map data are provided for Crater Lake National Park.

Geologic maps also may show geomorphic features, structural interpretations, anthropogenic features such as mines and quarries, and locations of past geologic hazards that may be prone to future activity.

Source Maps and Data

The Geologic Resources Inventory (GRI) team converts digital data and/or paper maps into a GIS format that conforms to the GRI GIS data model. The GRI digital geologic map product also includes essential elements of the source maps such as a correlation chart of map units, unit descriptions, map legend, map notes, references, and figures. The GRI team used the following source maps in preparation of the digital geologic data set for Crater Lake National Park. These source maps provided information for the "Geologic Issues," "Geologic Features and Processes," and "Geologic History" sections of this report.

Bacon, C. R. 2008. Geologic map of Mount Mazama and Crater Lake caldera, Oregon (scale 1:24,000). Scientific investigations map SIM-2832. US Geological Survey, Washington, DC, USA. http://pubs.er.usgs.gov/publication/sim2832 (accessed 25 January 2013).

Bacon, C. R., L. G. Mastin, K. M. Scott, and M. Nathenson. 1997. Volcano and earthquake hazards in the Crater Lake region, Oregon (scale 1:100,000). Open-file report OF-97-487. US Geological Survey, Washington, DC, USA. http://vulcan.wr.usgs.gov/Volcanoes/CraterLake/Hazards/OFR97-487/framework.html (accessed 11 February 2013).

Jenks, M. D., T. J. Wiley, M. L. Ferns, P. E. Staub, L. Ma, I. P. Madin, C. A. Niewendorp, R. J. Watzig, E. M. Taylor, and S. A. Mertzman. 2008. Oregon geologic data compilation (OGDC) v4 (scale 1:100,000). Oregon Department of Geology and Mineral Industries, Portland, Oregon, USA. http://www.oregongeology.com/sub/ogdc/ (accessed 25 January 2013).

MacLeod, N. S., and D. R. Sherrod. 1992. Reconnaissance geologic map of the west half of the Crescent 1 by 2 degree quadrangle, central Oregon (scale 1:250,000). Miscellaneous investigations series map I-2215. US Geological Survey, Washington, DC, USA. http://pubs.er.usgs.gov/publication/i2215 (accessed 25 January 2013).

Sherrod, D. F. 1991. Geologic map of a part of the Cascade Range between latitudes 43°–44°, central Oregon (scale 1:125,000). Miscellaneous investigations series map I-1891. US Geological Survey, Washington, DC, USA. http://pubs.er.usgs.gov/publication/i1891 (accessed 25 January 2013).

Smith, J. G., N. J. Page, M. G. Johnson, B. C. Moring, and F. Gray. 1982. Preliminary geologic map of the Medford 1 by 2 degree quadrangle, Oregon and California (scale 1:250,000). Open-file report OF-82-955. US Geological Survey, Washington, DC, USA. http://pubs.er.usgs.gov/publication/ofr82955 (accessed 25 January 2013).

The entire Bacon (2008) map and portions of Jenks et al. (2008), MacLeod and Sherrod (1992), Sherrod (1991), and Smith et al. (1982) were compiled for the GRI digital geologic map of Crater Lake National Park (fig. 39). The Bacon et al. (1997) map delineates areas of volcano and earthquake hazards (see "Simplified Geologic Map and Hazard Map Graphics" section).

The GRI team converted the following source data for Crater Lake National Park:

Ramsey, D. W., D. R. Dutton, and C. R. Bacon. 2008. Database for geologic map of Mount Mazama and Crater Lake Caldera, Oregon (scale 24,000). Scientific investigations map 2832, version 1.0. US Geological Survey, Denver, Colorado, USA. http://pubs.usgs.gov/sim/2832/ (accessed 15 November 2013).

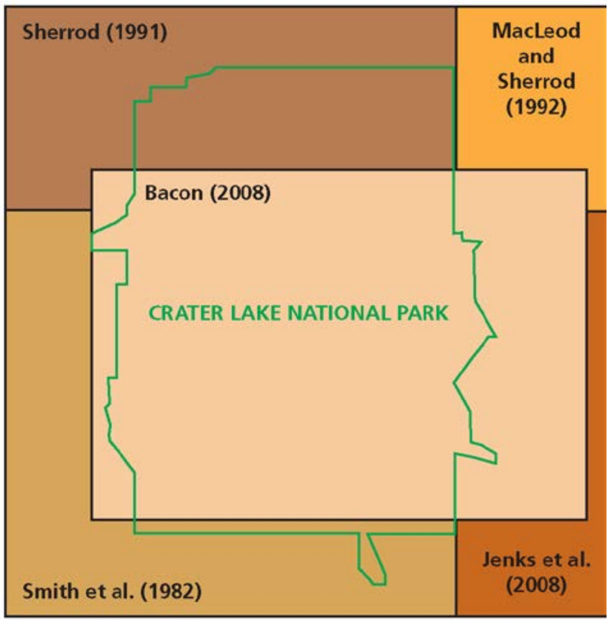


Figure 39. Geologic source maps. Five source maps cover Crater Lake National Park and the surrounding area. Bacon (2008) covers the extent of Mount Mazama. The green outline delineates the boundary of the park. National Park Service graphic.

Geologic GIS Data

The GRI team implements a GIS data model that standardizes map deliverables. The data model is included on the enclosed CD and is also available online (http://science.nature.nps.gov/im/inventory/geology/GeologyGISDataModel.cfm). This data model dictates GIS data structure, including layer architecture, feature attribution, and relationships within ESRI ArcGIS software. The GRI team digitized the data for Crater Lake National Park using data model version 2.1.

GRI digital geologic data are included on the attached CD and are available through the NPS Integrated Resource Management Applications (IRMA) portal (https://irma.nps.gov/App/Reference/Search?SearchType=Q). Enter "GRI" as the search text and select Crater Lake National Park from the unit list.

The following components and geology data layers are part of the data set:

- Data in ESRI geodatabase and shapefile GIS formats
- Layer files with feature symbology (see tables 3 and 4)
- Federal Geographic Data Committee (FGDC)–compliant metadata
- A help file (PDF) document that contains all of the ancillary map information and graphics, including geologic unit correlation tables, and map unit descriptions, legends, and other information captured from source maps
- An ESRI map document file (.mxd) that displays the digital geologic data

Table 3. Geology data layers in the Crater Lake National Park GIS data

Data Layer	Data Layer Code	On Overview Graphic?
Geologic attitude and observation points	crlaatd	No
Mine point features	crlamin	No
Geologic sample localities	crlagsl	No
Isopach lines	crlacn1	No
Glacial feature lines	crlagfl	No
Hazard feature lines	crlahzl	No
Volcanic point features	crlavpf	No
Volcanic line features	crlavlf	No
Geologic line features	crlaglf	No
Map symbology	crlasym	No
Faults	crlaflt	No
Linear dikes	crladke	Yes
Geologic contacts	crlaglga	No
Crater lake	crlaglg	No
Geologic units	crlaglg	Yes, simplified

Table 4. Volcano and earthquake hazards data layers in the Crater Lake National Park GIS data

Data Layer	Data Layer Code	On Overview Graphic?
Volcanic vents	clhzvpf	Yes
Map symbology	clhzsym	Yes
Hazard faults	clhzflt	Yes
Lahar hazard area feature boundaries	clhzlaha	Yes
Lahar hazard area feature	clhzlah	Yes
Ash (pumice) contacts	clhzasha	Yes
Ash (pumice) units	clhzash	Yes
Volcanic eruption hazard area boundaries	clhzhzaa	Yes
Volcanic eruption hazard areas	clhzhza	Yes

Simplified Geologic Map and Hazard Map Graphics

The simplified geologic map (in pocket) displays GRI digital geologic data draped over a shaded relief image of the park and surrounding area. For graphic clarity and legibility, not all GIS feature classes are visible, as indicated in table 3. Cartographic elements and basic geographic information have been added. Digital elevation data and geographic information, which are part of the map graphic, are not included with the GRI digital geologic GIS data for the park, but are available online from a variety of sources.

The simplified geologic map of Crater Lake National Park compiled hundreds of map units from the source maps into 36 categories. The volcanic rocks were grouped by volcano (i.e., Mount Mazama, southwest, northwest, east, or Cascades volcanism) and then by rock type (e.g., basalt, basaltic andesite, and rhyodacite). Mount Mazama deposits were further differentiated by preclimactic, climactic, or postclimactic. Non-volcanic rocks and deposits were grouped into major categories: alluvial deposits, glacial deposits, lake deposits, diatomite and volcaniclastic sediments, slope movements, submerged caldera walls, and undivided sediments.

The GRI digital geologic map data set for Crater Lake National Park also includes a map that highlights volcano and earthquake hazards in the Crater Lake region (Bacon et al. 1997); the map delineates hazard zones and shows faults and volcanic vents around Crater Lake. A graphic of this map is included in the pocket of this report. All the data layer feature classes of the Bacon et al. (1997) map are part of the hazard map graphic (table 4).

Map Unit Properties Table

The geologic units listed in the Map Unit Properties Table (in pocket) correspond to the accompanying digital geologic data. Following the structure of the report, this table summarizes the geologic issues, features and processes, and geologic history associated with each map unit. The table also lists the geologic time period, map unit symbols (GIS data and simplified geologic map), and a geologic description of the unit.

Use Constraints

Graphic and written information provided in this section is not a substitute for site-specific investigations. Ground-disturbing activities should neither be permitted nor denied based upon the information provided here. Minor inaccuracies may exist regarding the location of geologic features relative to other geologic or geographic features on the map graphics. Horizontal accuracy varies based on US National Map Accuracy Standards and the scales of the source maps, as shown in table 5.

Table 5. GIS data horizontal accuracy

Map Scale	To Within
1:24,000	12 m (40 ft)
1:100,000	51 m (167 ft)
1:125,000	63 (208 ft)
1:250,000	127 m (417 ft)

Glossary

This glossary contains brief definitions of selected geologic terms relevant to this report. Definitions are based on those in the American Geosciences Institute Glossary of Geology *(5th edition; 2005). Additional terms are defined at: http://geomaps.wr.usgs.gov/parks/misc/glossarya.html.*

agglomerate. A term originally used by Lyell in 1831 for a chaotic assemblage of coarse angular pyroclastic materials. The term has been variously defined since then, and should be defined in context to avoid confusion.

agglutinate. A welded pyroclastic deposit. The term is commonly used for deposits of bombs fused while hot and viscous. Agglutinate typically occurs in spatter cones.

air-fall deposit. Shower-like fall of pyroclastic fragments from an "eruption cloud." Usage not recommended because term suggests falling air.

alluvial fan. A fan-shaped deposit of sediment that accumulates where a hydraulically confined stream flows to a hydraulically unconfined area. Commonly out of a mountainous area into an area such as a valley or plain.

alluvium. Stream-deposited sediment.

andesite. Volcanic rock (or lava) characteristically medium dark in color and containing 57%–63% silica and moderate amounts of iron and magnesium.

arc. See "volcanic arc" and "magmatic arc."

ash (volcanic). Fine material ejected from a volcano (also see "tuff").

ash cloud. Another term for "eruption cloud;" that is, a cloud of volcanic gases, with ash and other pyroclastic fragments (tephra), that forms by volcanic explosion.

ash flow. A density current, generally a hot mixture of volcanic gases and tephra that travels across the ground surface; produced by the explosive disintegration of viscous lava in a volcanic crater, or from a fissure or group of fissures. The solid materials contained in a typical ash flow are generally unsorted and ordinarily include volcanic dust, pumice, scoria, and blocks in addition to ash.

basalt. Volcanic rock (or lava) that characteristically is dark in color (gray to black), contains <53% silica, and is rich in iron and magnesium. Basaltic lavas are more fluid than andesites or dacites, which contain more silica.

basaltic andesite. Volcanic rock, commonly dark gray to black, with about 53%–57 silica.

basin (sedimentary). Any depression, from continental to local scales, into which sediments are deposited.

bed. The smallest sedimentary strata unit, commonly ranging in thickness from one centimeter to a meter or two and distinguishable from beds above and below.

bedding. Depositional layering or stratification of sediments.

bedrock. A general term for the rock that underlies soil or other unconsolidated, surficial material.

block. A pyroclast ejected in a solid state, having a diameter greater than 64 mm (2.5 in).

bomb. A pyroclast ejected while still viscous and shaped while in flight. Commonly greater than 64 mm (2.5 in) in diameter and often hollow or vesicular inside.

breccia (volcanic). A coarse-grained, generally unsorted volcanic rock consisting of partially welded angular fragments of ejected material such as tuff or ash.

caldera. A large bowl- or cone-shaped depression at the summit of a volcano. Formed by explosion or collapse.

carapace. The outer "shell" or covering of a lava flow.

cinder. A glassy pyroclastic fragment that falls to the ground in an essentially solid condition.

cinder cone. A conical volcanic feature formed by the accumulation of cinders and other pyroclasts, normally of basaltic or andesitic composition.

cirque. A deep, steep-walled, half-bowl-like recess or hollow located high on the side of a mountain and commonly at the head of a glacial valley. Produced by the erosive activity of a mountain glacier.

clast. An individual grain or rock fragment in a sedimentary rock, produced by the physical disintegration of a larger rock mass. Also, the term is often used in lieu of "pyroclast" for igneous (pyroclastic or debris flow) deposits.

clastic. Describes rock or sediment made of fragments of pre-existing rocks (clasts). Also see "epiclastic."

colluvium. A general term for any loose, heterogeneous, and incoherent mass of soil material and/or rock fragments deposited through the action of surface runoff (rainwash, sheetwash) or slow continuous downslope creep. Usually collects at the base of a slope or hillside, but includes loose material covering hillsides.

columnar joints. Parallel, prismatic columns, polygonal in cross section, in basaltic flows and sometimes in other extrusive and intrusive rocks; they form as a result of contraction during cooling.

continental crust. Crustal rocks rich in silica and alumina that underlie the continents; ranging in thickness from 35 km (22 mi) to 60 km (37 mi) under mountain ranges. "Continental" is also used in reference to a plate. See "plate tectonics."

cross section. A graphical interpretation of geology, structure, and/or stratigraphy in the third (vertical) dimension based on mapped and measured geological extents and attitudes depicted in a vertically oriented plane.

crust. Earth's outermost compositional shell, 10 to 40 km (6 to 25 mi) thick, consisting predominantly of relatively low-density silicate minerals. Also see "oceanic crust" and "continental crust."

cumulate. An igneous rock formed by the accumulation of crystals that settle out from a magma by the action of gravity.

dacite. Volcanic rock (or lava) that characteristically is light in color and contains 63%–68% silica and moderate amounts of sodium and potassium. Dacite lavas are viscous and tend to form thick blocky lava flows or steep-sided piles of lava called lava domes. Dacitic magmas tend to erupt explosively, thus also ejecting abundant ash and pumice.

debris flow. A moving mass of rock fragments, soil, and mud, in which more than half of particles are larger than sand.

deformation. A general term for the processes of rock faulting, folding, and shearing as a result of various Earth forces, such as compression (pushing together) and extension (pulling apart).

dike. A narrow igneous intrusion that cuts across bedding planes or other geologic structures.

diktytaxitic. Volcanic igneous texture characterized by numerous jagged, irregular vesicles bounded by crystals, some of which protrude into the cavities.

displacement. A general term for the relative movement of the two sides of a fault, measured in any chosen direction; also, the specific amount of such movement.

dome (volcanic). A steep sided rounded accumulation of lava extruded from a volcano to form a dome-shaped or bulbous mass of congealed lava above and around the vent.

dredge. A floating machine for sucking or scooping up or excavating earth material form the bottom of a body of water, raising it to the surface, and discharging it to the bank through a floating pipeline or conveyor, into a scow for removal, or, in the case of certain mining dredges, into the same body of water after removal of the ore mineral.

drift (glacial). A general term applied to all rock material (clay, silt, sand, gravel, and boulders) transported by a glacier and deposited directly by or from the ice, or by running water emanating from a glacier.

edifice. The constructional mass of a volcano.

enclave. A compositionally or texturally distinct part of an igneous rock, commonly elongate or ellipsoidal in shape and typically smaller than 1 m (3 ft) across, which may result from mingling of enclave-forming, relatively mafic magma with relatively felsic host magma.

eolian. Describes materials formed, eroded, or deposited by or related to the action of the wind. Also spelled "Aeolian."

epiclastic. Describes a rock that formed at the Earth's surface by consolidation of fragments of preexisting rocks; a sedimentary rock whose fragments are derived by weathering or erosion.

extrusive. Describes molten (igneous) material that has erupted onto Earth's surface.

fault. A break in rock characterized by displacement of one side relative to the other.

felsic. Describes an igneous rock having abundant light-colored minerals such as quartz, feldspars, or muscovite. Compare to "mafic."

felsite. A general term for any light-colored, fine-grained extrusive rock composed chiefly of quartz and feldspar.

fissure. In geology, a fissure is a fracture or crack in rock along which there is a distinct separation; fissures are often filled with mineral-bearing materials. On volcanoes, a fissure is an elongate fracture or crack at the surface from which lava erupts.

fluvial. Of or pertaining to a river or rivers.

footwall. The mass of rock beneath a fault surface (see "hanging wall").

fracture. Irregular breakage of a mineral. Any break in a rock (e.g., crack, joint, fault).

fumarole. A vent from which steam and volcanic gases issue.

geology. The study of Earth including its origin, history, physical processes, components, and morphology.

geyser. A type of hot spring that intermittently erupts jets of hot water and steam, the result of groundwater coming into contact with rock or steam hot enough to create steam under conditions preventing free circulation; a type of intermittent spring.

graben. A down-dropped structural block bounded by steeply dipping, normal faults.

granite. An intrusive igneous (plutonic) rock composed primarily of quartz and feldspar. Mica and amphibole minerals are also common. Intrusive equivalent of rhyolite.

hanging wall. The mass of rock above a fault surface (see "footwall").

horn. A high pyramidal peak with steep sides formed by the intersection walls of three or more cirques.

hornblende. The most common mineral of the amphibole group. Hornblende is commonly black and occurs in distinct crystals or in columnar, fibrous, or granular forms.

hot spring. A thermal spring whose temperature is above that of the human body.

hummocky. Said of topographic land of ice forms that are abounding in small hills and depressions meters to tens of meters across (hummocks). The shape of hummocks is variable and irregular.

ignimbrite. A pyroclastic flow deposit.

induration. The hardening of rock or rock material by heat, pressure, or the introduction of cementing material, especially the process by which relatively consolidated rock is made harder or more compact.

interfluve. The area between rivers, especially the relatively undissected upland or ridge between two adjacent valleys containing streams flowing in the same general direction.

joint. A break in rock without relative movement of rocks on either side of the fracture surface.

lacustrine. Pertaining to, produced by, or inhabiting a lake or lakes.

lahar. A mixture of water and volcanic debris that moves rapidly downstream. Consistency can range from that of muddy dishwater to that of wet cement, depending on the ratio of water to debris. Also called a volcanic mudflow or debris flow. A key characteristic of a lahar is that it has a substantial component (generally >50 %) of fine-grained material, clay- and sand-sized that acts as a matrix to give the deposit the strength it needs to carry the bigger clasts.

landslide. Any process or landform resulting from rapid, gravity-driven mass movement.

lapilli. Pyroclastic materials that may be essential, accessory, or accidental in origin, of a size range that has been variously defined within the limits of 2 and 64 mm (0.08 and 2.5 in). The fragments may be either solidified or still viscous when they land (though some classifications restrict the term to the former); thus there is no characteristic shape. An individual fragment is called a lapillus.

last glacial maximum. Time period when continental ice sheets and glaciers reached their maximum extent during the most recent ice age (about 20,000 years ago).

lava. Molten or solidified magma that has been extruded onto Earth's surface though a volcano or fissure.

lithic. A sedimentary rock or pyroclastic deposit that contains abundant fragments of previously formed rocks.

mafic. Describes dark-colored rock, magma, or minerals rich in magnesium and iron. Compare to "felsic."

magma. Molten rock beneath Earth's surface capable of intrusion and extrusion.

magma reservoir. A chamber in the shallow part of the lithosphere from which volcanic materials are derived; the magma has ascended from a deeper source.

magmatic arc. Zone of plutons or volcanic rocks formed at a convergent boundary. The arc is generally 100–200 km (60–120 mi) or more behind the surface expression of the convergent boundary, that is the oceanic trench.

mantle. The zone of Earth's interior between the crust and core.

mass wasting. A general term for the downslope movement of soil and rock material under the direct influence of gravity.

maximum credible earthquake. The largest hypothetical earthquake that may be reasonably expected to occur along a given fault.

mineral. A naturally occurring, inorganic crystalline solid with a definite chemical composition or compositional range.

monogenetic. Resulting from one process or formation or derived from one source, or originating or developing at one place and time, for example, a volcano built up by a single eruption.

moraine. A mound, ridge, or other distinct accumulation of unsorted, unstratified glacial drift, predominantly till, deposited by glacial ice movement.

mud pot. A type of hot spring contains boiling mud, usually sulfurous and often multicolored, as in a "paint pot." Mud pots are commonly associated with geysers and other hot springs in volcanic areas.

mush. Partially crystallized magma.

neck (volcanic). An eroded, vertical, pipe-like intrusion that represents the vent of a volcano.

normal fault. A fault in which the hanging wall appears to have moved downward relative to the footwall. The angle of dip is usually 45°–90°.

nuée ardente. A swiftly flowing, turbulent, sometimes incandescent gaseous cloud erupted from a volcano; its lower portion contains ash and other pyroclastic materials. Synonymous with "pyroclastic flow."

obsidian. A black or dark-colored volcanic glass, usually of rhyolite composition with conchoidal fracture. Can be used as a raw material for arrowheads, jewelry, and art objects.

oceanic crust. Earth's crust, formed at spreading ridges, that underlies ocean basins; 6 to 7 km (3 to 4 mi) thick and generally of basaltic composition. "Oceanic" is also used in reference to a plate. See "plate tectonics."

olivine. An olive-green mineral rich in iron, magnesium, and manganese that is commonly found in low-silica (basaltic) igneous rocks.

outcrop. Any part of a rock mass or formation that is exposed or "crops out" at Earth's surface.

outwash. Glacial sediment transported and deposited by meltwater streams.

palagonite. An altered basaltic glass, brown to yellow or orange and found in pillow lavas as interstitial material or in amygdules.

permeability. A measure of the relative ease with which fluids move through the pore spaces of rocks or sediments.

phenocryst. A coarse (large) crystal in a porphyritic igneous rock.

phreatic eruption. An eruption that primarily involves steam explosions. Usually groundwater flashed (became suddenly converted) into steam by the heat of subsurface magma.

phreatomagmatic. Another term for "hydrovolcanic;" that is, encompassing all volcanic activity that results from the interaction between lava, magmatic heat, or gases and meteoric or connate water at or near the surface of the Earth.

pillow lava. A general term for those lavas displaying pillow structure (bun-shaped mass) and considered to have formed in a subaqueous environment; such lava is usually basaltic or andesitic.

placer. A surficial mineral deposit formed by mechanical concentration of mineral particles from weathered debris. The common types are beach placers and alluvial placers.

plagioclase. An important rock-forming group of feldspar minerals.

Plinian eruption. An explosive eruption in which a steady, turbulent stream of fragmented magma and magmatic gas is released at a high velocity from a vent. Large volumes of tephra and tall eruption columns are characteristic.

plate tectonics. The concept that the lithosphere is broken up into a series of rigid plates that move over Earth's surface above a less viscous asthenosphere.

porphyritic. Describes an igneous rock of any composition that contains conspicuous phenocrysts in fine-grained groundmass.

plug (volcanic). A vertical, pipe-like body of magma that represents the conduit to the former volcanic vent. Also, a crater filling with lava, the surrounding material of which has been removed by erosion.

plume. A persistent, pipe-like body of hot material moving upward from Earth's mantle into the crust.

pumice. Solidified "frothy" lava; highly vesicular and very low density.

pumiceous. Volcanic vesicular texture involving tiny gas holes such as in pumice. Finer than scoriaceous.

pyroclast. An individual particle ejected during a volcanic eruption.

pyroclastic. Describes clastic rock material formed by volcanic explosion or aerial expulsion from a volcanic vent; also pertaining to rock texture of explosive origin. In the plural, the term is used as a noun.

pyroclastic flow. A density current of pyroclastic material, usually very hot and composed of a mixture of gases and particles. The term is a synonym for "ash flow" using in a more general sense in that an ash flow is composed of ash-sized pyroclasts.

pyroclastic surge. Low-density, dilute, turbulent pyroclastic flow.

pyroxene. A common rock-forming mineral. It is characterized by short, stout crystals.

quartz. Crystalline silica, an important rock-forming mineral: SiO_2.

radiocarbon age. Also, carbon-14 (^{14}C) age. An isotopic age expressed in years and calculated from the quantitative determination of the amount of carbon-14 remaining in an organic material.

rhyodacite. Volcanic rock (or lava) that is intermediate in composition between rhyolite and dacite. It contains 68%–72% silica.

rhyolite. Volcanic rock (or lava) that characteristically is light in color, contains >72% of silica, and is rich in potassium and sodium. Rhyolitic lavas are viscous and tend to form thick blocky lava flows or steep-sided piles of lava called lava domes. Rhyolite magmas tend to erupt explosively, commonly also producing abundant ash and pumice.

rock. An aggregate of one or more minerals (e.g., granite, shale, marble), a body of undifferentiated mineral matter (e.g., obsidian), or a body of solid organic material (e.g., coal).

rockfall. The most rapid mass-wasting process, in which rocks are dislodged and move downslope rapidly.

sand. A clastic particle smaller than a granule and larger than a silt grain, having a diameter in the range of 1/16 mm (0.0025 in) to 2 mm (0.08 in).

sandstone. Clastic sedimentary rock of predominantly sand-sized grains.

scoria. A bomb-size pyroclast that is irregular in form and generally very vesicular.

scoriaceous. Volcanic igneous vesicular texture involving relatively large gas holes such as in vesicular basalt. Coarser than pumiceous.

scoria cone. A conical volcanic feature formed by the accumulation of cinders and other pyroclasts, normally of basaltic or andesitic composition.

sediment. An eroded and deposited, unconsolidated accumulation of rock and mineral fragments.

sedimentary rock. A consolidated and lithified rock consisting of clastic and/or chemical sediment(s). One of the three main classes of rocks—igneous, metamorphic, and sedimentary.

seriate. A variety of igneous porphyritic texture in which the sizes of the grains range gradually down to the size of ground mass grains.

sheetwash (sheet erosion). The removal of thin layers of surface material more or less evenly from an extensive area of gently sloping land by broad continuous sheets of running water rather than by streams flowing in well-defined channels.

shield volcano. A volcano in the shape of a flattened dome, broad and low, built by flows of very fluid basaltic lava. The Hawaiian Mauna Loa volcano is one example.

silica. Silicon dioxide, SiO_2. It occurs as crystalline quartz, crytocrystalline chalcedony, and amorphous opal; dominantly in sand, diatomite, and chert; and combined in silicates as an essential constituent of many minerals.

silicic. Describes a silica-rich igneous rock or magma.

sill. An igneous intrusion that is of the same orientation as the surrounding rock.

sinter. Also known as siliceous sinter. The lightweight, porous, opaline variety of silica that is white or nearly white and deposited as an incrustation by precipitation from the waters of geysers and hot springs.

slope. The inclined surface of any geomorphic feature or measurement thereof. Synonymous with "gradient."

slump. A generally large, coherent mass movement with a concave-up failure surface and subsequent backward rotation relative to the slope.

soil. Surface accumulation of weathered rock and organic matter capable of supporting plant growth and often overlying the parent material from which it formed.

spring. A site where water issues from the surface due to the intersection of the water table with the ground surface.

stratovolcano. A volcano that is constructed of alternating layers of lava and pyroclastic deposits, along with abundant dikes and sills.

stream. Any body of water moving under gravity flow in a clearly confined channel.

striations (glacial). One of a series of long, delicate, finely cut, commonly straight and parallel furrows or lines inscribed on a bedrock surface by the rasping and rubbing of rock fragments embedded at the base of a moving glacier, and usually oriented in the direction of ice movement; also formed on the rock fragments transported by the ice.

subduction zone. A convergent plate boundary where oceanic lithosphere descends beneath a continental or oceanic plate and is carried down into the mantle.

subsidence. The gradual sinking or depression of part of Earth's surface.

talus. Rock fragments, usually coarse and angular, lying at the base of a cliff or steep slope from which they have been derived.

tectonic. Describes a feature or process related to large-scale movement and deformation of Earth's crust.

tectonics. The geologic study of the broad structural architecture and deformational processes of the lithosphere and asthenosphere.

tephra. A collective term used for all pyroclastic material, regardless of size, shape, or origin, ejected during an explosive volcanic eruption.

tholeiite. A basalt characterized by the presence of orthopyroxene and/or pigeonite in addition to clinopyroxene and calcic plagioclase.

theleiitic basalt. The preferred name of the common subalkaline basalt. Not restricted to a particular tectonic environment. Also, any of the basaltic members of a tholeiitic magma series.

thermal. Of or relating to heat. At volcanoes, thermal features are observed to determine whether temperatures are changing (e.g. fumaroles, vents, and lava surfaces). These changes help scientists to understand volcanic processes.

thermal spring. A spring whose water temperature is appreciably higher than the local mean annual atmosphere temperature. A thermal spring may be a "hot spring" of a "warm spring."

till. Unstratified drift, deposited directly by a glacier without reworking by meltwater, and consisting of a mixture of clay, silt, sand, gravel, and boulders ranging widely in size and shape.

topography. The general morphology of Earth's surface, including relief and locations of natural and anthropogenic features.

tuff. Generally fine-grained, igneous rock formed of consolidated volcanic ash.

tuya. A synonym of table mountain (volcanic); that is, a flat-topped and steep-sided intraglacial volcano composed typically of pillow lava overlain by hyaloclastite which, in turn, is overlain by subaerial sheet lava. Examples of tuyas occur in northern British Columbia and Iceland.

vent. Any opening at the Earth's surface through which magma erupts or volcanic gases are emitted.

vesicle. A void in an igneous rock formed by a gas bubble trapped when the lava solidified.

vesicular. Describes a volcanic rock with abundant holes that formed from the expansion of gases while the lava was molten.

vitric. Describes pyroclastic material that is characteristically glassy.

vitrophyre. Any porphyritic igneous rock having a glassy groundmass.

volcanic. Describes anything related to volcanoes. Can refer to igneous rock crystallized at or near Earth's surface (e.g., lava).

volcanic arc. A commonly curved, linear zone of volcanoes above a subduction zone. On the scale of hundreds of kilometers.

volcaniclastic. Describes clastic volcanic materials formed by any process of fragmentation, dispersed by any kind of transporting agent, deposited in any environment.

warm spring. A thermal spring whose temperature is appreciably above the local mean annual atmospheric temperature, but below that of the human body.

weathering. The physical, chemical, and biological processes by which rock is broken down.

Wisconsinan. Pertaining to the classical fourth glacial stage of the Pleistocene Epoch in North America, following the Sangamonian interglacial stage and preceding the Holocene Epoch.

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Additional References

This section lists additional references, resources, and websites that may be of use to resource managers. Web addresses are current as of November 2013. Refer to Appendix B for laws, regulations, and policies that apply to NPS geologic resources.

Geology of National Park Service Areas

National Park Service Geologic Resources Division (Lakewood, Colorado): http://nature.nps.gov/geology/

NPS Geologic Resources Inventory: http://www.nature.nps.gov/geology/inventory/

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NPS Geoscientist-in-the-Parks (GIP) internship and guest scientist program: http://www.nature.nps.gov/geology/gip/index.cfm

NPS Views Program (geology-themed modules are available for Geologic Time, Paleontology, Glaciers, Caves and Karst, Coastal Geology, Volcanoes, and a wide variety of geologic parks): http://www.nature.nps.gov/views/.

NPS Resource Management Guidance and Documents

1998 National Parks Omnibus Management Act: http://www.gpo.gov/fdsys/pkg/PLAW-105publ391/pdf/PLAW-105publ391.pdf

NPS 2006 Management Policies (Chapter 4; Natural Resource Management): http://www.nps.gov/policy/mp/policies.html#_Toc157232681

NPS-75: Natural Resource Inventory and Monitoring Guideline: http://www.nature.nps.gov/nps75/nps75.pdf

NPS Natural Resource Management Reference Manual #77: http://www.nature.nps.gov/Rm77/

Geologic Monitoring Manual: Young, R., and L. Norby, editors. 2009. Geological monitoring. Geological Society of America, Boulder, Colorado, USA. http://nature.nps.gov/geology/monitoring/index.cfm

NPS Technical Information Center (TIC) (Denver, Colorado; repository for technical documents): http://www.nps.gov/dsc/technicalinfocenter.htm

Geological Surveys and Societies

Oregon Department of Geology and Mineral Industries: http://www.oregongeology.org/sub/default.htm

US Geological Survey: http://www.usgs.gov/

Geological Society of America: http://www.geosociety.org/

American Geosciences Institute: http://www.agiweb.org/

Association of American State Geologists: http://www.stategeologists.org/

US Geological Survey Reference Tools

US Geological Survey Cascades Volcano Observatory (CVO): http://volcanoes.usgs.gov/observatories/cvo/

US Geological Survey Volcano Hazards Program: http://volcanoes.usgs.gov/

US Geological Survey National Geologic Map Database (NGMDB): http://ngmdb.usgs.gov/

US Geological Survey Geologic Names Lexicon (GEOLEX; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex/geolex_home.html

US Geological Survey Geographic Names Information System (GNIS; official listing of place names and geographic features): http://gnis.usgs.gov/

US Geological Survey GeoPDFs (download searchable PDFs of any topographic map in the United States): http://store.usgs.gov (click on "Map Locator & Downloader")

US Geological Survey Publications Warehouse (USGS publications, many available online): http://pubs.er.usgs.gov

US Geological Survey Tapestry of Time and Terrain (descriptions of physiographic provinces): http://tapestry.usgs.gov/Default.html

Appendix A: Scoping Participants

The following people attended the GRI scoping meeting for Crater Lake National Park, held on 3 March 2004, or the follow-up report writing conference call, held on 18 December 2012. Discussions during these meetings supplied a foundation for this GRI report. The scoping summary document is available on the GRI publications website: http://www.nature.nps.gov/geology/inventory/gre_publications.cfm.

2004 Scoping Meeting Participants

Name	Affiliation	Position
Charlie Bacon	USGS Volcano Hazards Team	Research Geologist
Pete Biggam	NPS Natural Resources Information Division	Soil Scientist
Mac Brock	Crater Lake National Park	Chief of Resource Management
Mark Buktenica	Crater Lake National Park	Aquatic Ecologist
Tim Connors	NPS Geologic Resources Division	Geologist
Sid Covington	NPS Geologic Resources Division	Geologist
Chris Currens	USGS Biological Resources Division	Aquatic Biologist
Marsha Davis	NPS Columbia Cascades Support Office	Geologist
Ron Kerbo	NPS Geologic Resources Division	Cave Specialist
Anne Poole	NPS Geologic Resources Division	Geologist
Daniel Sarr	NPS Klamath Network	Network Coordinator
Bob Truitt	NPS Klamath Network	Data Manager
Hanna Waterstat	NPS Klamath Network	Data Miner
Tom Wiley	Oregon Department of Geology	Geologist

2012 Conference Call Participants

Name	Affiliation	Position
Charlie Bacon	USGS Volcano Science Center	Research Geologist
Mac Brock	Crater Lake National Park	Chief of Resource Management
Katie KellerLynn	Colorado State University	Geologist, Research Associate
Jason Kenworthy	NPS Geologic Resources Division	Geologist, GRI Reports Coordinator

Appendix B: Geologic Resource Laws, Regulations, and Policies

The Geologic Resources Division developed this table to summarize laws, regulations, and policies that specifically apply to National Park Service minerals and geologic resources. The table does not include laws of general application (e.g., Endangered Species Act, Clean Water Act, Wilderness Act, National Environmental Policy Act, or National Historic Preservation Act). The table does include the NPS Organic Act when it serves as the main authority for protection of a particular resource or when other, more specific laws are not available. Information is current as of September 2013. Contact GRD for detailed guidance.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Caves and Karst Systems	**Federal Cave Resources Protection Act of 1988, 16 USC. §§ 4301–4309** requires Interior/Agriculture to identify "significant caves" on Federal lands, regulate/restrict use of those caves as appropriate, and include significant caves in land management planning efforts. Imposes civil and criminal penalties for harming a cave or cave resources. Authorizes Secretaries to withhold information about specific location of a significant cave from a FOIA requester. **National Parks Omnibus Management Act of 1998, 16 USC. § 5937** protects the confidentiality of the nature and specific location of cave and karst resources. **Lechuguilla Cave Protection Act of 1993, Public Law 103-169** created a cave protection zone (CPZ) around Lechuguilla Cave in Carlsbad Caverns National Park. Within the CPZ, access and the removal of cave resources may be limited or prohibited; existing leases may be cancelled with appropriate compensation; and lands are withdrawn from mineral entry.	**36 C.F.R. § 2.1** prohibits possessing/ destroying/disturbing . . . cave resources . . . in park units. **43 C.F.R Part 37** state that all NPS caves are "significant" and set forth procedures for determining/releasing confidential information about specific cave locations to a FOIA requester.	**Section 4.8.1.2** requires NPS to maintain karst integrity, minimize impacts. **Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.2** requires NPS to protect caves, allow new development in or on caves if it will not impact cave environment, and to remove existing developments if they impair caves. **Section 6.3.11.2** explains how to manage caves in/adjacent to wilderness.
Paleontology	**National Parks Omnibus Management Act of 1998, 16 USC. § 5937** protects the confidentiality of the nature and specific location of paleontological resources and objects. **Paleontological Resources Preservation Act of 2009**, **16 USC. § 470aaa *et seq.*** provides for the management and protection of paleontological resources on federal lands.	**36 C.F.R. § 2.1(a)(1)(iii)** prohibits destroying, injuring, defacing, removing, digging or disturbing paleontological specimens or parts thereof. Prohibition in **36 C.F.R. § 13.35** applies even in Alaska parks where the surface collection of other geologic resources is permitted. Regulations in association with 2009 PRPA are being finalized (February 2013).	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.1** emphasizes I & M, encourages scientific research, directs parks to maintain confidentiality of paleontological information, and allows parks to buy fossils only in accordance with certain criteria.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Rocks and Minerals	**NPS Organic Act**, **16 USC. § 1 *et seq.*** directs the NPS to conserve all resources in parks (which includes rock and mineral resources) unless otherwise authorized by law. **Exception: 16 USC. § 445c (c) – Pipestone National Monument enabling statute** authorizes Native American collection of catlinite (red pipestone).	**36 C.F.R. § 2.1** prohibits possessing, destroying, disturbing mineral resources…in park units. **Exception: 36 C.F.R. § 7.91** allows limited gold panning in Whiskeytown. **Exception: 36 C.F.R. § 13.35** allows some surface collection of rocks and minerals in some Alaska parks (not Klondike Gold Rush, Sitka, Denali, Glacier Bay, and Katmai) by non-disturbing methods (e.g., no pickaxes), which can be stopped by superintendent if collection causes significant adverse effects on park resources and visitor enjoyment.	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity.
Geothermal	**Geothermal Steam Act of 1970, 30 USC. § 1001 *et seq.*** as amended in 1988, states -No geothermal leasing is allowed in parks. -"Significant" thermal features exist in 16 park units (the features listed by the NPS at 52 Fed. Reg. 28793-28800 (August 3, 1987), plus the thermal features in Crater Lake, Big Bend, and Lake Mead). -NPS is required to monitor those features. -Based on scientific evidence, Secretary of Interior must protect significant NPS thermal features from leasing effects. **Geothermal Steam Act Amendments of 1988, Public Law 100- 443** prohibits geothermal leasing in the Island Park known geothermal resource area near Yellowstone and outside 16 designated NPS units if subsequent geothermal development would significantly adversely affect identified thermal features.	None Applicable.	**Section 4.8.2.3** requires NPS to -Preserve/maintain integrity of all thermal resources in parks. -Work closely with outside agencies. -Monitor significant thermal features.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Mining Claims	**Mining in the Parks Act of 1976, 16 USC. § 1901 *et seq.*** authorizes NPS to regulate all activities resulting from exercise of mineral rights, on patented and unpatented mining claims in all areas of the System, in order to preserve and manage those areas. **General Mining Law of 1872, 30 USC. § 21 *et seq.*** allows US citizens to locate mining claims on Federal lands. Imposes administrative & economic validity requirements for "unpatented" claims (the right to extract Federally-owned locatable minerals). Imposes additional requirements for the processing of "patenting" claims (claimant owns surface and subsurface). Use of patented mining claims may be limited in Wild and Scenic Rivers and OLYM, GLBA, CORO, ORPI, DEVA. **Surface Uses Resources Act of 1955, 30 USC § 612** restricts surface use of unpatented mining claims to mineral activities.	**36 C.F.R. § 5.14** prohibits prospecting, mining, and the location of mining claims under the general mining laws in park areas except as authorized by law. **36 C.F.R. Part 6** regulates solid waste disposal sites in park units. **36 C.F.R. Part 9, Subpart A** requires the owners/operators of mining claims to demonstrate bona fide title to mining claim; submit a plan of operations to NPS describing where, when, and how; prepare/submit a reclamation plan; and submit a bond to cover reclamation and potential liability. **43 C.F.R. Part 36** governs access to mining claims located in, or adjacent to, National Park System units in Alaska.	**Section 6.4.9** requires NPS to seek to remove or extinguish valid mining claims in wilderness through authorized processes, including purchasing valid rights. Where rights are left outstanding, NPS policy is to manage mineral-related activities in NPS wilderness in accordance with the regulations at 36 C.F.R. Parts 6 and 9A. **Section 8.7.1** prohibits location of new mining claims in parks; requires validity examination prior to operations on unpatented claims; and confines operations to claim boundaries.
Nonfederal Oil and Gas	**NPS Organic Act, 16 USC. § 1 *et seq.*** authorizes the NPS to promulgate regulations to protect park resources and values (from, for example, the exercise of mining and mineral rights). Individual Park Enabling Statutes: 16 USC. § 230a (Jean Lafitte NHP & Pres.) 16 USC. §450kk (Fort Union NM), 16 USC. § 459d-3 (Padre Island NS), 16 USC. § 459h-3 (Gulf Islands NS), 16 USC. § 460ee (Big South Fork NRRA), 16 USC. § 460cc-2(i) (Gateway NRA), 16 USC. § 460m (Ozark NSR), 16 USC.§698c (Big Thicket N Pres.), 16 USC. §698f (Big Cypress N Pres.)	**36 C.F.R. Part 6** regulates solid waste disposal sites in park units. **36 C.F.R. Part 9, Subpart B** requires the owners/operators of nonfederally owned oil and gas rights to: - Demonstrate bona fide title to mineral rights; - Submit a plan of operations to NPS describing where, when, how they intend to conduct operations; - Prepare/submit a reclamation plan; and - Submit a bond to cover reclamation and potential liability. **43 CFR Part 36** governs access to nonfederal oil and gas rights located in, or adjacent to, National Park System units in Alaska.	**Section 8.7.3** requires operators must comply with 9B regulations.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Federal Mineral Leasing (Oil & Gas, Salable Minerals, and Non-locatable Minerals)	**The Mineral Leasing Act, 30 USC. § 181 *et seq.***, and the **Mineral Leasing Act for Acquired Lands, 30 USC. § 351 *et seq.*** do not authorize the BLM to lease federally owned minerals in NPS units. **Exceptions**: Glen Canyon NRA (16 USC. § 460dd et seq.), Lake Mead NRA (16 USC. § 460n et seq.), and Whiskeytown-Shasta-Trinity NRA (16 USC. § 460q et seq.) authorizes the BLM to issue federal mineral leases in these units provided that the BLM obtains NPS consent. Such consent must be predicated on an NPS finding of no significant adverse effect on park resources and/or administration. **Exceptions**: Native American Lands Within NPS Boundaries Under the Indian Allottee Leasing Act of 1909, (25 USC. § 396), and the Indian Leasing Act of 1938 (25 USC. §§ 396a, 398 and 399) and Indian Mineral Development Act of 1982 (25 USC.S. §§ 2101-2108), all minerals are subject to lease and apply to Native American trust lands within NPS units. **Federal Coal Leasing Amendments Act of 1975, 30 USC. § 201** does not authorize the BLM to issue leases for coal mining on any area of the national park system.	**36 C.F.R. § 5.14** states prospecting, mining, and…leasing under the mineral leasing laws [is] prohibited in park areas except as authorized by law. **BLM regulations at 43 C.F.R. Parts 3100, 3400, and 3500** govern Federal mineral leasing. **Regulations re: Native American Lands within NPS Units:** 25 C.F.R. pt. 211 governs leasing of tribal lands for mineral development. 25 C.F.R. pt. 212 governs leasing of allotted lands for mineral development. 25 C.F.R. pt. 216 governs surface exploration, mining, and reclamation of lands during mineral development. 25 C.F.R. pt. 224 governs tribal energy resource agreements. 25 C.F.R. pt. 225 governs mineral agreements for the development of Indian-owned minerals entered into pursuant to the Indian Mineral Development Act of 1982, Pub. L. No. 97-382, 96 Stat. 1938 (codified at 25 USC.S. §§ 2101-2108). 30 C.F.R. §§ 1202.100-1202.101 governs royalties on oil produced from Indian leases. 30 C.F.R. §§ 1202.550-1202.558 governs royalties on gas production from Indian leases. 30 C.F.R. §§ 1206.50-1206.62 & §§ 1206.170-1206.176 governs product valuation for mineral resources produced from Indian oil and gas leases. 30 C.F.R. § 1206.450 governs the valuation coal from Indian Tribal and Allotted leases. 43 C.F.R. pt. 3160 governs onshore oil and gas operations, which are overseen by the Bureau of Land Management	**Section 8.7.2** states that all NPS units are closed to new federal mineral leasing except Glen Canyon, Lake Mead and Whiskeytown-Shasta-Trinity NRAs.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Nonfederal minerals other than oil and gas	**NPS Organic Act, 16 USC. §§ 1 and 3** **Surface Mining Control and Reclamation Act of 1977, 30 USC § 1201 *et. seq.*** prohibits surface coal mining operations on any lands within the boundaries of a NPS unit, subject to valid existing rights.	**NPS regulations at 36 C.F.R. Parts 1, 5, and 6** require the owners/operators of other types of mineral rights to obtain a special use permit from the NPS as a § 5.3 business operation, and § 5.7 – Construction of buildings or other facilities, and to comply with the solid waste regulations at Part 6. **SMCRA Regulations at 30 C.F.R. Chapter VII** govern surface mining operations on Federal lands and Indian lands by requiring permits, bonding, insurance, reclamation , and employee protection. Part 7 of the regulations states that National Park System lands are unsuitable for surface mining.	**Section 8.7.3** states that operators exercising rights in a park unit must comply with 36 CFR Parts 1 and 5.
Park Use of Sand and Gravel	**Materials Act of 1947, 30 USC. § 601** does not authorize the NPS to dispose of mineral materials outside of park units. **Exception:** 16 USC. §90c 1(b) the non-wilderness portion of Lake Chelan National Recreation Area, where sand, rock and gravel may be made available for sale to the residents of Stehekin for local use as long as such sale and disposal does not have significant adverse effects on the administration of the National Recreation Area.	None applicable.	**Section 9.1.3.3** clarifies that only the NPS or its agent can extract park-owned common variety minerals (e.g., sand and gravel), and: - Only for park administrative uses. - After compliance with NEPA & other federal, state, and local laws, and a finding of non-impairment. - After finding the use is park's most reasonable alternative based on environment and economics. - Parks should use existing pits and create new pits only in accordance with park-wide borrow management plan. - Spoil areas must comply with Part 6 standards - NPS must evaluate use of external quarries. Any deviations from this policy require written waiver from the Secretary, Assistant Secretary, or Director.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Upland and Fluvial Processes	**Rivers and Harbors Appropriation Act of 1899, 33 USC. § 403** prohibits the construction of any obstruction, on the waters of the united states, not authorized by congress or approved by the USACE. **Clean Water Act 33USC. § 1342** requires a permit from the USACE prior to any discharge of dredged or fill material into navigable waters (waters of the US (including streams)). **Executive Order 11988** requires federal agencies to avoid adverse impacts to floodplains. (see also D.O. 77-2) **Executive Order 11990** requires plans for potentially affected wetlands (including riparian wetlands). (see also D.O. 77-1)	None Applicable.	**Section 4.1** requires NPS to manage natural resources to preserve fundamental physical and biological processes, as well as individual species, features, and plant and animal communities; maintain all components and processes of naturally evolving park ecosystems. **Section 4.1.5** directs the NPS to re-establish natural functions and processes in human-disturbed components of natural systems in parks unless directed otherwise by Congress. **Section 4.4.2.4** directs the NPS to allow natural recovery of landscapes disturbed by natural phenomena, unless manipulation of the landscape is necessary to protect park development or human safety. **Section 4.6.4** directs the NPS to (1) manage for the preservation of floodplain values; [and] (2) minimize potentially hazardous conditions associated with flooding **Section 4.6.6** directs the NPS to manage watersheds as complete hydrologic systems and minimize human- caused disturbance to the natural upland processes that deliver water, sediment, and woody debris to streams **Section 4.8.1** directs the NPS to allow natural geologic processes to proceed unimpeded. Geologic processes…include…erosion and sedimentation…processes. **Section 4.8.2** directs the NPS to protect geologic features from the unacceptable impacts of human activity while allowing natural processes to continue.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Soils	**Soil and Water Resources Conservation Act, 16 USC. §§ 2011 – 2009** provides for the collection and analysis of soil and related resource data and the appraisal of the status, condition, and trends for these resources. **Farmland Protection Policy Act, 7 USC. § 4201 *et. seq.*** requires NPS to identify and take into account the adverse effects of Federal programs on the preservation of farmland; consider alternative actions, and assure that such Federal programs are compatible with State, unit of local government, and private programs and policies to protect farmland. NPS actions are subject to the FPPA if they may irreversibly convert farmland (directly or indirectly) to nonagricultural use and are completed by a Federal agency or with assistance from a Federal agency. Applicable projects require coordination with the Department of Agriculture's Natural Resources Conservation Service (NRCS).	**7 C.F.R. Parts 610 and 611**are the US Department of Agriculture regulations for the Natural Resources Conservation Service. Part 610 governs the NRCS technical assistance program, soil erosion predictions, and the conservation of private grazing land. Part 611 governs soil surveys and cartographic operations. The NRCS works with the NPS through cooperative arrangements.	**Section 4.8.2.4** requires NPS to: - Prevent unnatural erosion, removal, and contamination. - Conduct soil surveys. - Minimize unavoidable excavation. - Develop/follow written prescriptions (instructions).

The Department of the Interior protects and manages the nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its special responsibilities to American Indians, Alaska Natives, and affiliated Island Communities.

NPS 106/122539, November 2013

National Park Service
US Department of the Interior

Natural Resource Stewardship and Science
1201 Oakridge Drive, Suite 150
Fort Collins, CO 80525

www.nature.nps.gov

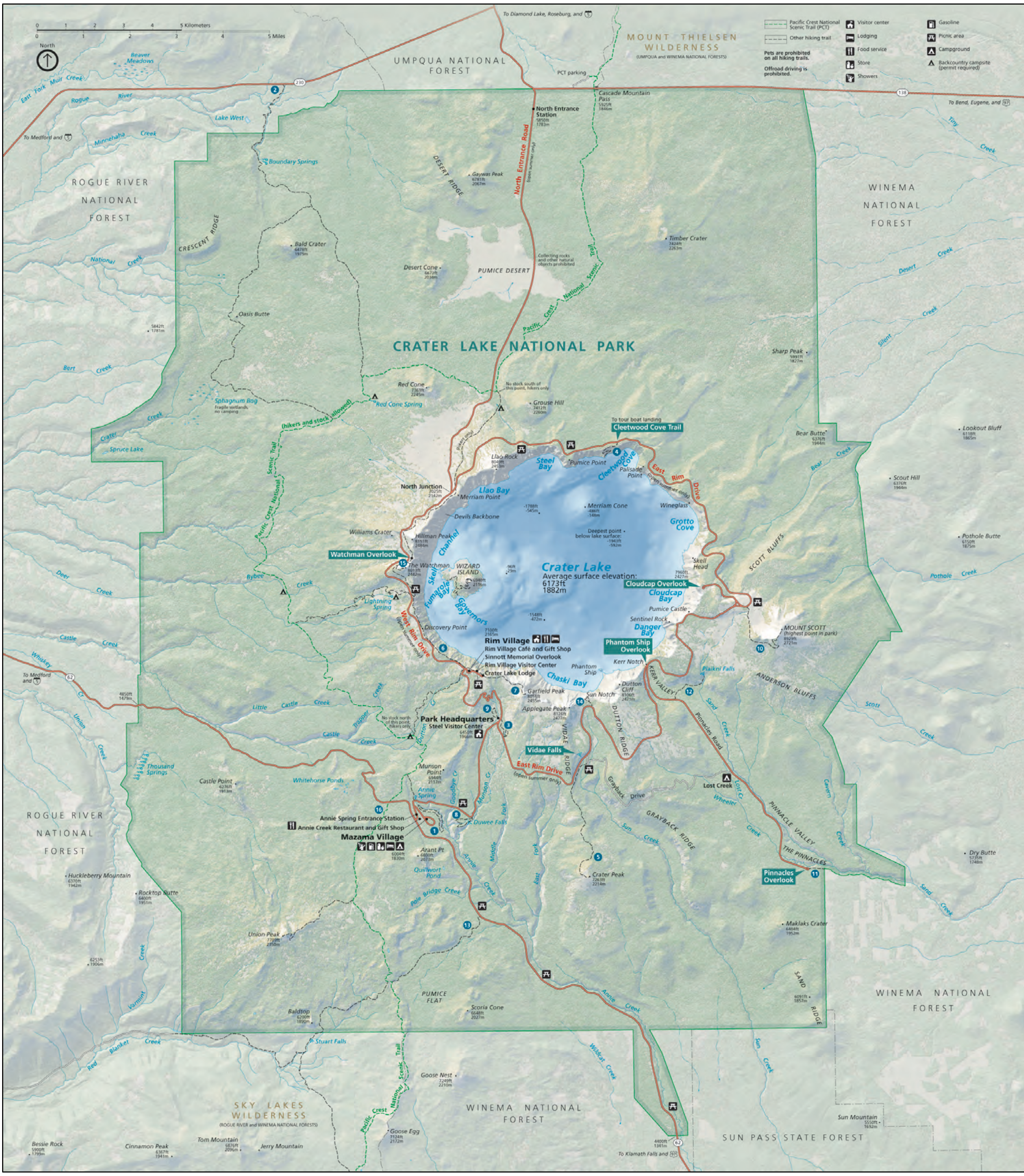
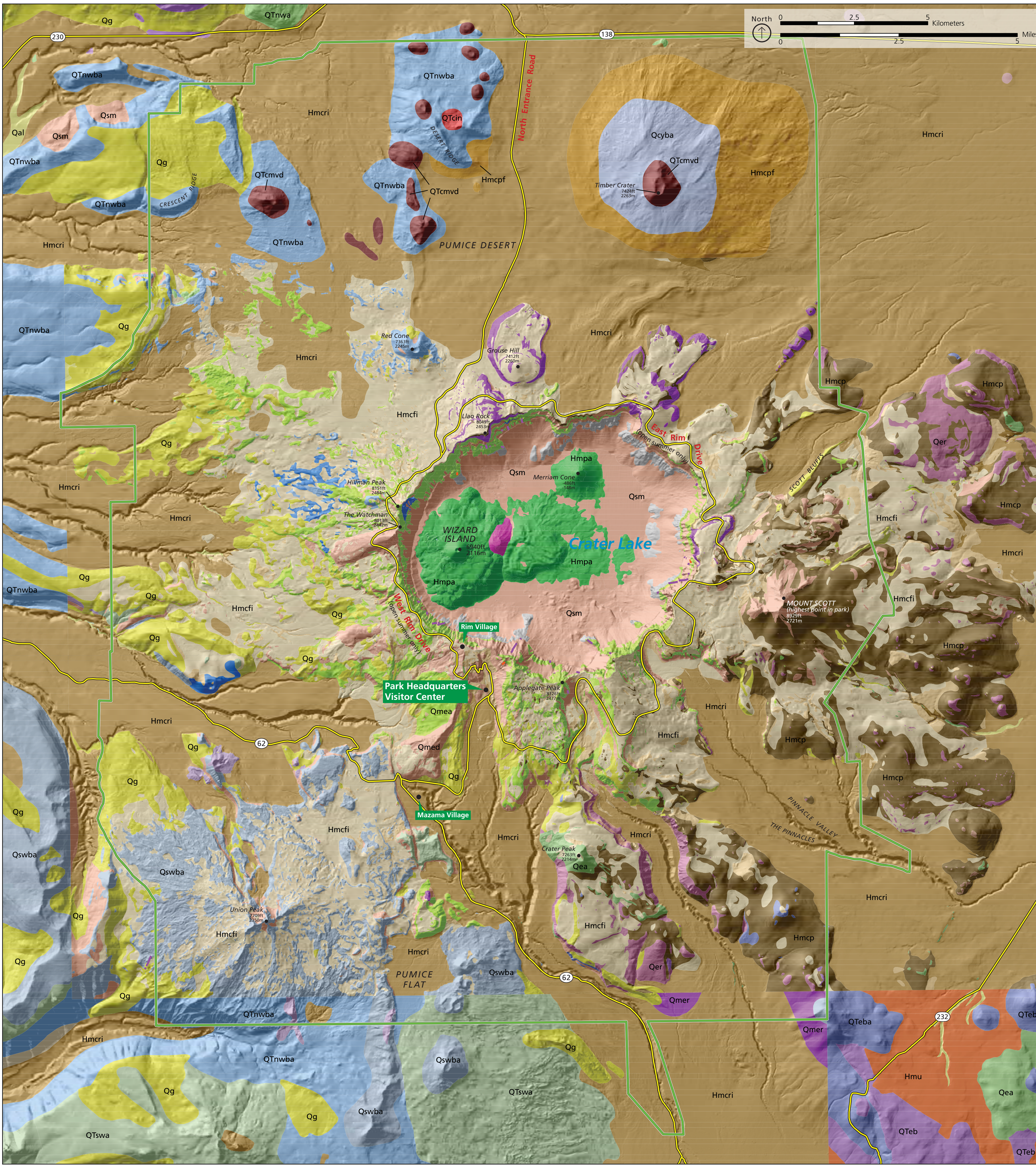


Plate 1. Location map of Crater Lake National Park. The park encompasses 74,151 ha (183,224 ac) of land in southwestern Oregon that ranges in elevation from about 1,160 m (3,800 ft) to 2,720 m (8,920 ft) above sea level. Mount Scott, east of Crater Lake, is the highest point in the park at 2,721 m (8,929 ft) above sea level. The numbers in blue circles on the map correspond to hiking trails: 1—Annie Creek Canyon, 2—Boundary Springs, 3—Castle Crest Wildflower, 4—Cleetwood Cove, 5—Crater Peak, 6—Discovery Point, 7—Garfield Peak, 8—Godfrey Glen, 9—Lady of the Woods, 10—Mount Scott, 11—Pinnacles, 12—Plaikni Falls, 13—Stuart Falls, 14—Sun Notch, 15—The Watchman, and 16—Union Peak. National Park Service graphic, available online: http://www.nps.gov/hfc/cfm/carto-detail.cfm?Alpha=CRLA (accessed 30 September 2013).

Simplified Geologic Map of Crater Lake NP



NPS Boundary

Infrastructure

- Points of Interest
- Roads

Linear Dikes

- Mount Mazama and Regional Volcanism units
- dk - Unidentified dikes, known or certain

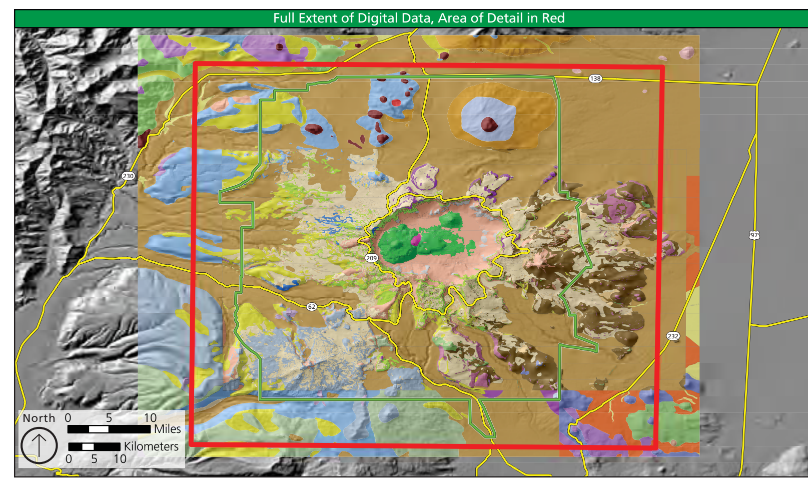
Simplified Geologic Units

Unit	Description
Qal	Alluvial deposits
Qsm	Slope movements
Qg	Glacial deposits
Qs	Undivided sediments
Hl	Lake deposits
scw	Submerged caldera walls
Tdvs	Diatomite and volcaniclastic sediments
Hmpr	Mount Mazama postclimactic dome, rhyodacite, lava and breccia
Hmpa	Mount Mazama postclimactic eruption andesites
Hmu	Mount Mazama deposits, undivided
Hmcfi	Mount Mazama climactic eruption, fine-grained lithic- and crystal-rich ignimbrite
Hmclb	Mount Mazama climactic eruption, lithic breccia
Hmcri	Mount Mazama climactic eruption, ring-vent-phase ignimbrite
Hmcp	Mount Mazama climactic eruption, Plinian and other Holocene pumice-fall deposits
Hmcwt	Mount Mazama climactic eruption, Wineglass Welded Tuff of Williams (1942)
Hmcpf	Mount Mazama climactic eruption, pumice-flow deposits
Qmer	Mount Mazama preclimactic eruption, rhyodacite
Qmed	Mount Mazama preclimactic eruption, dacite
Qmeba	Mount Mazama preclimactic eruption, basaltic andesite
Qmea	Mount Mazama preclimactic eruption, andesite
QTswb	Southwest volcanism (Cascades), basalt
QTswa	Southwest volcanism (Cascades), andesite
Qswba	Southwest volcanism (Cascades), basaltic andesite
Qswa	Southwest volcanism (Cascades), andesite
QTnwba	Northwest volcanism (Cascades), basaltic andesite
QTnwb	Northwest volcanism (Cascades), basalt
QTnwa	Northwest volcanism (Cascades), andesite
Qea	East volcanism (Cascades), andesite
QTeb	East volcanism (Cascades), basalt
QTeba	East volcanism (Cascades), basaltic andesite
Qer	East volcanism (Cascades), rhyodacite
QTed	East volcanism (Cascades), dacite
Qcyba	Cascades volcanism, younger basaltic andesite
Qcv	Cascades volcanism, cinder cone and fissure vent deposits
QTcmvd	Cascades volcanism, mafic vent deposits
QTcin	Cascades volcanism, intrusive rocks and dikes

NOTE: This simplified geologic map compiled hundreds of map units from the source maps into 36 categories. The volcanic rocks were grouped by volcano and then by rock type. Mount Mazama deposits were further differentiated by preclimactic, climactic, or postclimactic.

Non-volcanic rocks and deposits were grouped into major categories: alluvial, slope movements, glacial, and lake deposits; diatomite and volcaniclastic sediments; submerged caldera walls; and undivided sediments.

Full Extent of Digital Data, Area of Detail in Red



This map is an overview of compiled geologic data prepared as part of the NPS Geologic Resources Inventory. It is not a substitute for site-specific investigations.

The source map used in creation of the digital geologic data was:

Bacon, C.R. 2008. Geologic Map of Mount Mazama and Crater Lake Caldera, Oregon (1:24,000 scale). Scientific Investigations Map SIM-2832. U.S. Geological Survey.

Jenks, M.D. and others. 2008. Oregon Geologic Data Compilation v4 (OGDC) (1:100,000 scale).

MacLeod, N.S. and Sherrod, D.R. 1992. Reconnaissance Geologic Map of the West Half of the Crescent 1 by 2 degree Quadrangle, Central Oregon (1:250,000 scale). Miscellaneous Investigations Series Map I-2215U.S. Geological Survey.

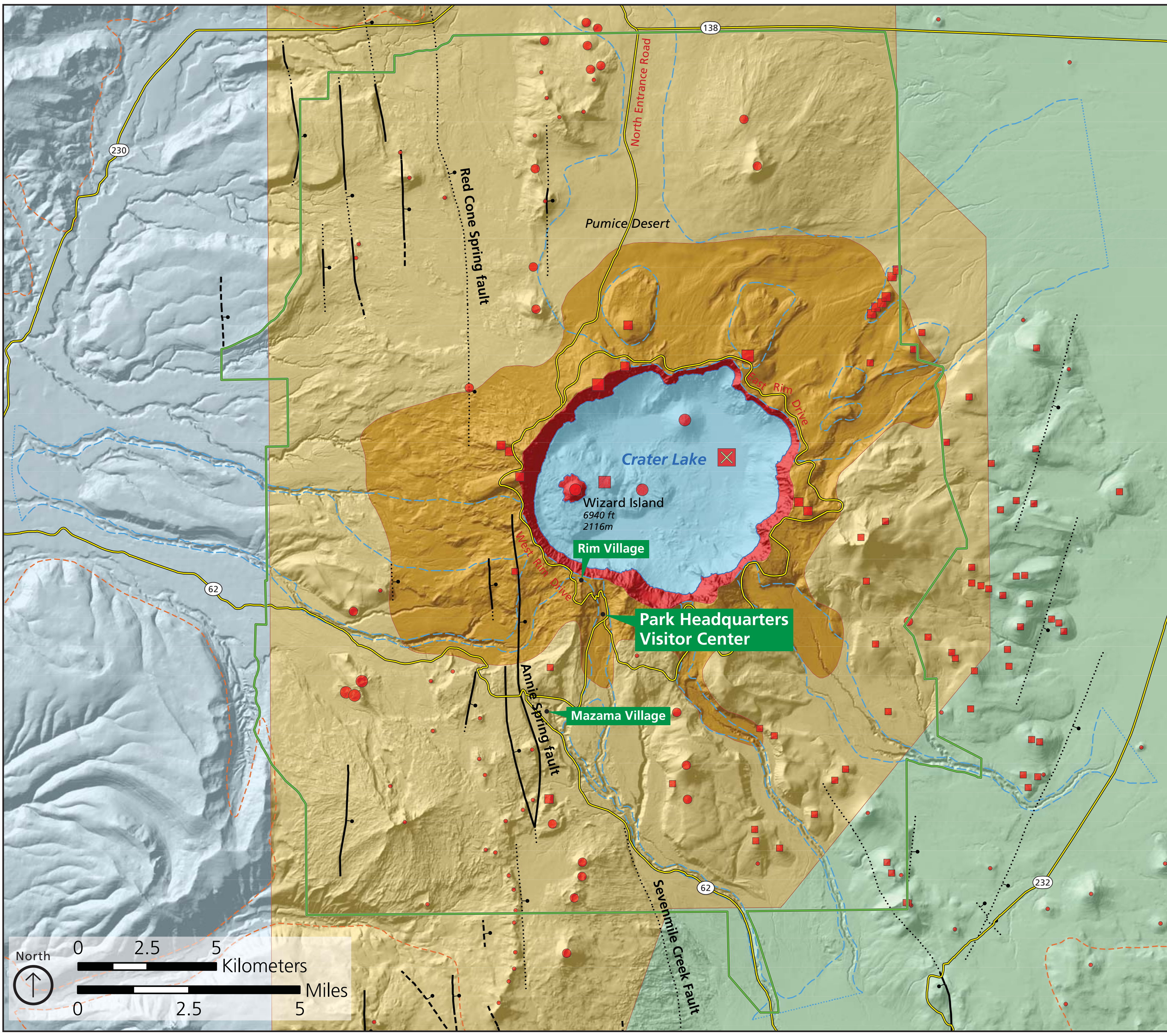
Sherrod, D.F. 1991. Geologic Map of a Part of the Cascade Range between latitudes 43 degrees -44 degrees, Central Oregon (1:125,000 scale). Miscellaneous Investigations Series Map I-1891. U.S. Geological Survey.

Smith, J.G. Page, N.J. Johnson, M.G. Moring, B.C. and Gray, F. 1982. Preliminary Geologic Map of the Medford 1 by 2 degree Quadrangle, Oregon and California (1:250,000 scale). Open-File Report OF-82-955. U.S. Geological Survey.

As per source map scale and U.S. National Map Accuracy Standards, geologic features represented here are within 12 m (40 ft) (1:24,000 scale data), 51 m (166) ft (1:100,000 scale data), 63 m (203) ft (1:125,000 scale data), or 127 m (416) ft (1:250,000 scale data) of their true location.

All digital geologic data and publications prepared as part of the Geologic Resources Inventory are available at the NPS Integrated Resource Management Applications Portal (IRMA): https://irma.nps.gov/App/Reference/Search. Enter “GRI” as the search text and select a park from the unit list.

Volcano and Earthquake Hazards Map of Crater Lake NP



NPS Boundary

Infrastructure

- Points of Interest
- Roads

Volcanic Vents

Approximate location of the initial vent of climactic eruption; ~7,7000 yrs

<10,000 yrs

10,000-100,000 yrs

100,000-1,000,000 yrs

-Squares represent silicic vents, circles represent mafic vents.

Volcanic Eruption Hazard Areas

surface of Crater Lake (water)

proximal hazard zone, PB; area that may be affected by pyroclastic surges and ballistics

proximal hazard zone, PA; area bounded by Crater Lake rim

regional hazard zone, RL; zone of relative low probability of a volcanic eruption

regional hazard zone, RH; zone of relative high probability of a volcanic eruption

zone of insignificant hazard

Lahar Hazard Area Feature

lahar hazards

Ash (Pumice) Units

maximum extent of pumiceous deposits

Lahar Hazard Area Boundaries

approximate

scratch boundary

Ash (Pumice) Contacts

approximate

Volcanic Eruption Hazard Boundaries

known or certain

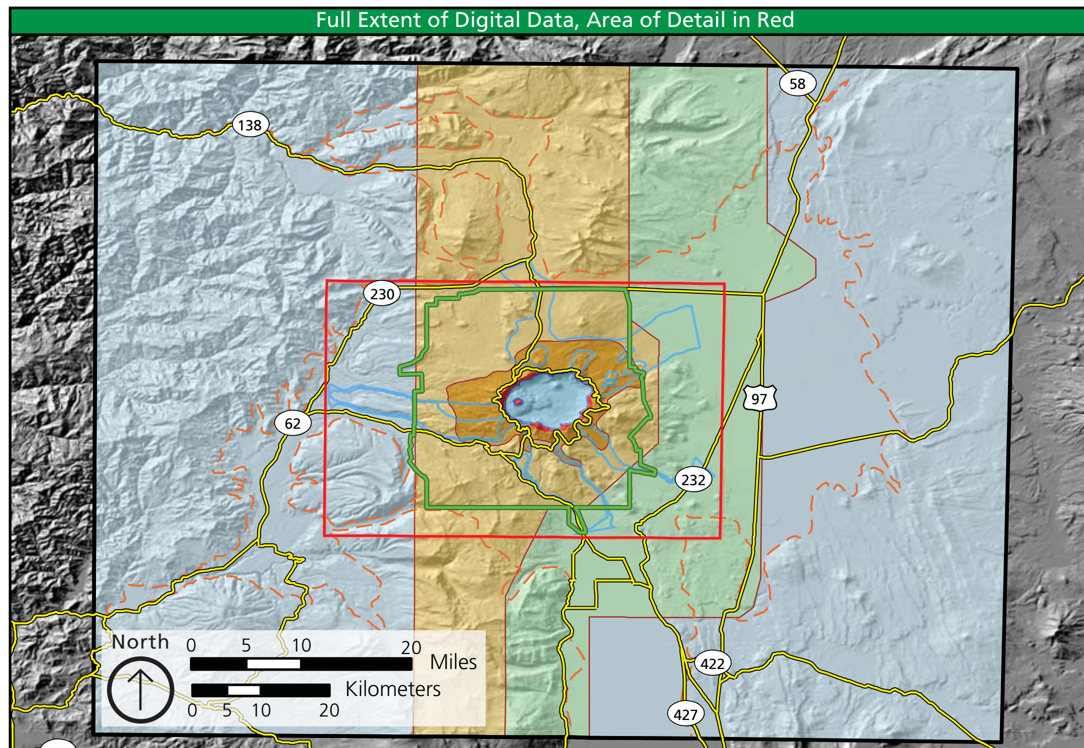
map boundary

water or shoreline

Hazard Faults

dotted where concealed; bar and ball on downthrown side

Full Extent of Digital Data, Area of Detail in Red



This figure is an overview of compiled digital geologic data. It is not a substitute for site-specific investigations.

Minor inaccuracies may exist regarding the location of geologic features relative to other geologic or geographic features on the figure. Based on the source map scale (1:100,000) and U.S. National Map Accuracy Standards, geologic features represented here are within 51 meters / 167 feet (horizontally) of their true location.

This figure was prepared as part of the NPS Geologic Resources Division's Geologic Resources Inventory. The source map used in creation of the digital geologic data product was:

Bacon, C.R. Mastin, L.G. Scott, K.M., and Nathenson, M. 1997. Volcano and Earthquake Hazards in the Crater Lake Region, Oregon (1:100,000 scale). Open-File Report OF-97-487. U.S. Geological Survey.

Digital geologic data and cross sections for Crater Lake National Park, and all other digital geologic data prepared as part of the Geologic Resources Inventory, are available online at the NPS Integrated Resource Management Applications Portal (IRMA): https://irma.nps.gov/App/Reference/Search. Enter "GRI" as the search text and select Crater Lake National Park from the unit list.

Map Unit Properties Table: Crater Lake National Park

Gray-shaded units are not mapped within Crater Lake National Park. Refer to the “Geologic Map Data” section of the report for information regarding how the GIS units were grouped on the Simplified Geologic Map.

Age	GRI GIS Map Unit (Symbol) *GIS data online and on CD*	Simplified Geologic Map Unit (Symbol) *poster in pocket*	Source Map	Geologic Description	Geologic Issues, Features, and Processes	Geologic History
QUATERNARY (Holocene)	Alluvium (Hal)	Alluvial deposits (Qal)	Bacon (2008)	Unconsolidated water-transported mud, sand, gravel, and coarser debris deposited in or adjacent to present-day streams.	Mount Mazama—typically contains a large fraction of material reworked from deposits of climactic eruption of Mount Mazama, 7,700 years ago.	The fluvial history, as represented by **Qal**, is secondary to the volcanic history of the park. **Qal** mapped in two areas: northwest and southeast of Crater Lake caldera.
	Sediment gravity-flow deposits (Hsl)	Slope movements (Qsm)	Bacon (2008)	Clastic sediment in the three primary basins and in depressions on and between lava flows and landslide deposits on the floor of Crater Lake. Maximum thicknesses 75 m (250 ft) in east basin and <50 m (160 ft) in the southwest and northwest basins. Uppermost layers consist of mud and fine-grained sand thought to have been deposited by sheet-flow turbidity currents.	Slope Movements—modern deposits, primarily on the floor of Crater Lake caldera. Crater Lake Caldera and Fill—represent modern, ongoing sedimentation.	Postcaldera Basin Filling.
	Landslide deposits (Hls)		Bacon (2008)	Landslide and debris-avalanche deposits, mainly beneath the surface of Crater Lake. Composed of unconsolidated, poorly sorted, typically heterolithologic debris derived from the caldera walls and transported into the lake by slope movements. Debris-avalanche deposits have hummocky surfaces and contain lithic blocks as large as many tens of meters across in a matrix that may contain a range of particle sizes from clay to boulders. Largest debris-avalanche deposit, below Chaski Bay, has a volume of 0.2 km^3 (0.05 mi^3) and traveled 2–3 km (1–2 mi) from its source.	Slope Movements—primarily mapped beneath the surface of Crater Lake. Includes Chaski Bay landslide deposit. Crater Lake Caldera and Fill—helped to fill caldera/basin of Crater Lake.	Postcaldera Basin Filling.
	Mazama deposits, undivided (Hmz)	Mount Mazama deposits, undivided (Hmu)	Jenks et al. (2008)	Air-fall tuff and rhyodacite tuff.	Mount Mazama and Mazama Ash—associated with Plinian eruption of Mount Mazama.	Climactic Eruption of Mount Mazama.
	Mount Mazama; rhyodacite of the postcaldera dome, lava (Hr) and breccia (Hrb)	Mount Mazama postclimactic dome, rhyodacite, lava and breccia (Hmpr)	Bacon (2008)	Finely porphyritic medium-gray rhyodacite (71.5% SiO_2) lava (**Hr**) and breccia (**Hrb**) of small dome reaching within 27 m (89 ft) of the lake surface east-northeast of Wizard Island.	Volcano Hazards—represents volcanic activity since climactic eruption. Crater Lake Caldera and Fill—postcaldera volcanic rocks helped to fill caldera.	Postcaldera Volcanism. Radiocarbon age: 4,240 ± 290 years before present (BP), or approximately 4,800 calendar years old.
	Mount Mazama; andesite of Wizard Island, lava flows (Haw), breccia (Hawb), and cinder cone (Hawp)	Mount Mazama postclimactic eruption andesites (Hmpa)	Bacon (2008)	Porphyritic, commonly seriate-textured, dark-gray to grayish-black blocky andesite (58.5%–60% SiO_2) lava flows (**Haw**) and breccia (**Hawb**). Lava forming Wizard Island was extruded from vents at base of cinder cone (**Hawp**) and flowed into lake, forming pillowed flows and glassy breccia mantling the slopes below the lake’s surface.	Volcano Hazards—represents volcanic activity since climactic eruption. Shield Volcanoes and Cinder Cone—only postcaldera cinder cone. Crater Lake Caldera and Fill—postcaldera volcanic rocks helped to fill caldera.	Postcaldera Volcanism. Approximately 7,200 years old.
	Mount Mazama; andesite of Merriam Cone, lava (Hamc) and breccia (Hamcb)		Bacon (2008)	Porphyritic medium- to dark-gray blocky andesite (60.5% SiO_2) lava (**Hamc**) and breccia (**Hamcb**) of 430-m- (1,410-ft-) high subaqueous cone south of Pumice Point.	Volcano Hazards—represents volcanic activity since climactic eruption. Crater Lake Caldera and Fill—postcaldera volcanic rocks helped to fill caldera.	Postcaldera Volcanism. Only a few hundred years younger than the caldera.
	Mount Mazama; andesite of central platform, lava (Hapc) and breccia (Hapcb)		Bacon (2008)	Porphyritic andesite (57.5%–62.5% SiO_2) lava (**Hapc**) and breccia (**Hapcb**) of 300-m- (980-ft-) high flat-topped mound beneath west-central part of Crater Lake and lava-flow fields to north and east.	Volcano Hazards—represents volcanic activity since climactic eruption. Crater Lake Caldera and Fill—postcaldera volcanic rocks helped to fill caldera.	Postcaldera Volcanism. The central platform volcano was active during the filling of Crater Lake, concurrently with the early eruptions of the Wizard Island volcano. Models for filling Crater Lake suggest that eruption of the central platform volcano ceased within at most 200 years after collapse of the caldera.
	Mount Mazama; andesite of east basin, breccia (Hae)		Bacon (2008)	Probable lava flows extending 1.7 km (1.1 mi) south of east basin in Crater Lake. Possible vent obscured by landslide deposits (**Hls)** south of mapped extent of unit **Hae**.	Volcano Hazards—represents volcanic activity since climactic eruption. Crater Lake Caldera and Fill—postcaldera volcanic rocks helped to fill caldera. East basin is deepest basin on the caldera floor.	Postcaldera Volcanism. Younger than caldera collapse.

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Age	GRI GIS Map Unit (Symbol) *GIS data online and on CD*	Simplified Geologic Map Unit (Symbol) *poster in pocket*	Source Map	Geologic Description	Geologic Issues, Features, and Processes	Geologic History
QUATERNARY (Holocene)	Lacustrine deposits (Hla)	Lake deposits (Hl)	Sherrod (1991)	Unconsolidated crystal-lithic-pumice sand and gravel adjacent to Diamond Lake (north of Crater Lake National Park).	None reported.	None reported.
	Mount Mazama; deposits of the climactic eruption, fine-grained lithic- and crystal-rich ignimbrite (Hcu)	Mount Mazama climactic eruption, fine-grained lithic- and crystal-rich ignimbrite (Hmcfi)	Bacon (2008)	Primary deposit is gray or reddish-brown, fine-grained crystal-rich nonwelded or, rarely, indurated ignimbrite that either overlies unit **Hcb** on slopes and interfluves or grades laterally into unit **Hcb** or **Hcf** in valleys. Consists of either a few meters of late-deposited ignimbrite veneer or thicker deposits of fine-grained ignimbrite near the heads of valleys. Also includes areas of fine-grained lithic breccia, pumiceous or scoriaceous ignimbrite, and fall deposits that are poorly exposed or too small to map separately.	Mount Mazama and Mazama Ash—deposited during climactic eruption, ring-vent phase. Includes some ash material from climactic eruption.	Climactic Eruption of Mount Mazama.
	Mount Mazama; deposits of the climactic eruption, lithic breccia (Hcb)	Mount Mazama climactic eruption, lithic breccia (Hmcbl)	Bacon (2008)	Typically massive, clast-supported deposit consisting of a variety of types of lithic fragments within a sand-sized matrix of lithic fragments and crystals that is poor in vitric ash. Many blocks are cracked or shattered, yet coherent. Clast lithologies correlate with geographic position around the caldera.	Mount Mazama—deposited during climactic eruption, ring-vent phase. Glacial Features—deposited on glaciated lava.	Climactic Eruption of Mount Mazama.
	Mount Mazama; deposits of the climactic eruption, ring-vent-phase ignimbrite (Hcf)	Mount Mazama climactic eruption, ring-vent-phase ignimbrite (Hmcri)	Bacon (2008)	Consists of poorly sorted rhyodacitic pumice (70.5% SiO_2) and crystal-rich andesitic to mafic-cumulate scoria (61%–47% SiO_2; up to 25% MgO) clasts, vitric ash, crystals, and lithic fragments.	Mount Mazama—deposited during climactic eruption, ring-vent phase. The Pinnacles are composed of **Hcf**. Caves—The Music Shell–Llao’s Hallway of Allen (1984) formed in pumice and ash flow near junction of Castle and Little Castle creeks.	Climactic Eruption of Mount Mazama.
	Ash-flow deposits (Haf)		Sherrod (1991); MacLeod and Sherrod (1992)	Pumiceous rhyodacitic to dacitic ash-flow deposits.	Mount Mazama—deposited during climactic eruption.	Climactic Eruption of Mount Mazama. Derived from climactic eruption of Mount Mazama immediately after pumice-fall deposits (**Hpf**) of Mount Mazama.
	Ash-flow deposits; ash-cloud deposits (Haf(fg))		Sherrod (1991)	Fine-grained ash-cloud deposits that separated from the main parts of ash flow.	Mount Mazama—only slightly younger than the Mount Mazama climactic eruption.	Climactic Eruption of Mount Mazama. Overlies but is only slightly younger than magmatically related pumice-fall deposits (**Hpf**).
QUATERNARY-TERTIARY (Holocene–Pliocene)	Ash-flow deposits concealing mafic vent deposits (Haf/QTmv)		Sherrod (1991)	Ash-flow deposits (**Haf**) concealing mafic vent deposits (**QTmv**).	Mount Mazama—deposited during climactic eruption.	Climactic Eruption of Mount Mazama.
QUATERNARY (Holocene)	Pumice-fall deposits (Hpf)		Sherrod (1991); MacLeod and Sherrod (1992)	Air-fall deposits of pumiceous lapilli and ash.	Mount Mazama and Mazama Ash—ash from climactic eruption blankets most of area mapped by MacLeod and Sherrod (1992).	Climactic Eruption of Mount Mazama. Radiocarbon age: 7,650 ± 55 years BP.
QUATERNARY-TERTIARY (Holocene–Pliocene)	Pumice-flow deposits concealing mafic vent deposits Hpf/QTmv	Mount Mazama climactic eruption, pumice-flow deposits (Hmcpf)	Sherrod (1991)	Pumice-flow deposits (Hpf) concealing mafic vent deposits (QTmv).	Mount Mazama—deposited during climactic eruption.	Climactic Eruption of Mount Mazama.

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QUATERNARY (Holocene)	Pumice and ash of Mount Mazama (Hpm)	Mount Mazama climactic eruption, ring-vent-phase ignimbrite (Hmcri)	Smith et al. (1982)	White, pink, buff, gray, and black rhyodacite, dacite, and andesite, unwelded to partly welded ash-flow tuff, ash-cloud deposits, and unconsolidated ash-fall deposits.	None reported.	Climactic Eruption of Mount Mazama.
QUATERNARY (Holocene)	Mount Mazama; Wineglass Welded Tuff of Williams (1942) (Hcw)	Mount Mazama climactic eruption, Wineglass Welded Tuff of Williams (1942) (Hmcwt)	Bacon (2008)	Pinkish-orange to light-brown, partly welded to densely welded ignimbrite as much as 10 m (30 ft) thick in paleovalleys at the caldera rim and thin to absent on topographic highs. Consists of up to four flow units that form a single cooling unit. Juvenile clasts are mostly (>99%) rhyodacite and rare andesite.	Mount Mazama—deposited during climactic eruption, single-vent phase; formed as a result of collapse of Plinian column.	Climactic Eruption of Mount Mazama.
QUATERNARY (Holocene)	Mount Mazama; Plinian and other Holocene pumice-fall deposits (Hcp)	Mount Mazama climactic eruption, Plinian and other Holocene pumice-fall deposits (Hmcp)	Bacon (2008)	Consists of bedded, well-sorted rhyodacitic pumice lapilli and bombs with a total thickness of as much as 20m (70 ft) at the caldera rim.	Mount Mazama and Mazama Ash—ash from climactic eruption, single-vent phase.	Climactic Eruption of Mount Mazama.
QUATERNARY (Holocene)	Mount Mazama; Holocene preclimactic rhyodacite—felsite (Hrh), vitrophyre (Hrhv), pumiceous carapace (Hrhc), and phyclastic (Hrhp)	Mount Mazama climactic eruption, rhyodacite (Hmer)	Bacon (2008)	Porphyritic rhyodacite of the Llao Rock and Cleetwood flows of Williams (1942) and related pyroclastic deposits and dikes in the northern caldera wall. Lava outcrops of medium-gray pumiceous carapace (**Hrhc**), dark-gray to black obsidian (vitrophyre; **Hrhv**), and medium-light-gray felsite (**Hrh**) mapped separately where possible; pumice-fall deposits (**Hrhp**) are shown where sufficiently thick.	Slope Movements—steep slopes, composed of **Hrhv** and **Qt** along the Cleetwood Cove Trial, are prone to rockfall. Mount Mazama—rhyodacite lava flows and domes helped to build up Mount Mazama. Represents early leaks from the top of the climactic magma chamber. Glacial Features—**Hrh** of Llao Rock lies on glacial till; good exposures along the trail to the boat landing. Caves—North Entrance Cave of Allen (1984) formed in rhyodacite on the backside of Llao Rock; Rugged Crest Caves formed in Cleetwood rhyodacite flows (possibly **Hrhrv** or **Hrh**).	Rhyodacite Domes and Flows. Part of preclimactic domes that erupted 30,000–7.700 years ago.
QUATERNARY (Holocene)	Mazama deposits, undivided (Hmz1)	Mount Mazama deposits, undivided (Hmu)	Jenks et al. (2008)	Air-fall tuff and rhyodacite tuff.	Mazama Ash—associated with Plinian eruption of Mount Mazama.	Climactic Eruption of Mount Mazama.
QUATERNARY (Holocene)	Mazama potholes (Hmzp)	Mount Mazama climactic eruption, ring-vent-phase ignimbrite (Hmcri)	Jenks et al. (2008)	Ash-flow rhyodacite tuff breccia.	None reported.	Climactic Eruption of Mount Mazama.
QUATERNARY (Early Holocene or late Pleistocene)	Regional volcanism, southwest; basalt of Castle Point—lava (Qbc) and pyroclastic (Qbcp)	Southwest volcanism (Cascades), basalt (QTswb)	Bacon (2008)	Medium-gray variably porphyritic basalt, high-alumina olivine tholeiite (HOAT; 48%–50% SiO_2) lava (**Qbc**) and grayish-red cinders (**Qbcp**) at Castle Point, southwest of the caldera.	Glacial Features—not modified by glacial activity; overlies lateral moraines west and north of Castle Point of last glacial maximum.	Regional Volcanism. Youngest regional volcano (<16,000–14,000 years old).
QAUTERNARY (Holocene and Pleistocene)	Alluvium (Qal)	Alluvial deposits (Qal)	Smith et al. (1982); MacLeod and Sherrod (1992); Jenks et al. (2008)	Mixed fluvial sediment. Sand and gravel of active stream beds.	Glacial Features—includes some upper Pleistocene outwash deposits.	None reported.

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QUATERNARY	Alluvial fan deposits (Qafn)	Alluvial deposits (Qal)	Jenks et al. (2008)	Mixed alluvial sediments.	None reported.	None reported.
QAUTERNARY (Holocene and Pleistocene)	Talus (Qt)	Slope movements (Qsm)	Bacon (2008)	Unconsolidated talus and thick colluvium. Beneath lake surface, includes post–7,700-year-old talus, scree, sand, and probable debris-flow and minor landslide material generally sloping at least 13°.	Slope Movements—occurs both inside and outside the rim of Crater Lake caldera. Steep slopes, composed of Qt and Hrhv, along the Cleetwood Cove Trail are prone to rockfall. Crater Lake Caldera and Fill—provides material to caldera/basin of Crater Lake.	Postcaldera Volcanism and Basin Filling.
QAUTERNARY (Holocene and Pleistocene)	Landslide debris (Qls)	Slope movements (Qsm)	Sherrod (1991)	Earthflow and slumps. Some deposits show hummocky topography where debris has moved onto flat terrain; other deposits plaster canyon walls.	Slope Movements—map shows only largest deposits in vicinity of Crater Lake National Park (e.g., in the Rogue River valley). Crater Lake Caldera and Fill—unit occurs outside the caldera. Compare to Hls that occurs within Crater Lake caldera.	Corresponds to timing of postcaldera deposits.
QAUTERNARY (Holocene? and Pleistocene)	Cinder cone and fissure vent deposits (Qcv)	Cascades volcanism, cinder cone and fissure vent deposits (Qcv)	MacLeod and Sherrod (1992)	Unconsolidated to agglutinated cinders, bombs, and blocks. Deposits mark vents for basaltic andesite (**Qba**), basalt and basaltic andesite of Mount Bachelor (**Qbb**), and the younger and older basaltic andesites of Cascade Range (**Qbc** and **QTbc**).	Shield Volcanoes and Cinder Cones—represents cinder cones and vents older than Mount Mazama climactic eruption. Mazama Ash—some cones buried by ash from climactic eruption.	Regional Volcanism. Older than pumice-fall deposits (**Qpf**) of Mount Mazama.
QAUTERNARY (Holocene? and Pleistocene)	Younger basaltic andesite (Qyba)	Cascades volcanism, younger basaltic andesite (Qcyba)	Sherrod (1991)	Lava flows and breccia of medium-gray and grayish-red, vesicular to massive, slightly porphyritic basaltic andesite. Locally includes basalt and andesite.	Glacial Features and Processes—most of the unit is glaciated.	Regional Volcanism. Less than about 250,000 years old.
QAUTERNARY Holocene and Pleistocene)	Volcanic rocks of the High Cascade Range; andesite (Qa)	Southwest volcanism (Cascades), andesite (QTswa)	Smith et al. (1982)	Rocks of this unit are extremely varied in texture and mineralogy, but majority are porphyritic pyroxene andesite.	Shield Volcanoes and Cinder Cones—forms youthful-looking stratovolcanoes, steep-sided shields, and smaller vent areas.	Regional Volcanism.
QAUTERNARY Holocene and Pleistocene)	Volcanic rocks of the High Cascade Range; dacite and rhyolite (Qd)	Mount Mazama preclimactic eruption, rhyodacite (Qmer)	Smith et al. (1982)	Gray to black stubby flows and domes. Crops out only in Crater Lake National Park.	None reported.	Regional Volcanism.
QAUTERNARY Holocene and Pleistocene)	Volcanic rocks of the High Cascade Range; younger pyroclastic deposits of basaltic and andesitic cinder cones (Qp)	Mount Mazama preclimactic eruption, basaltic andesite (Qswba)	Smith et al. (1982)	Unconsolidated to poorly consolidated well-stratified red, brown, and black, fine- to coarse-grained basaltic to andesitic ejecta of ash, cinder, scoria, agglomerate, and bombs. Includes minor flows and feeder dikes, as well as yellow to buff-colored tuff, deposited in tuff rings.	None reported.	Regional Volcanism.
QAUTERNARY Holocene and Pleistocene)	Volcanic rocks of the High Cascade Range; intermediate intrusive rocks (Qii)	Mount Mazama preclimactic eruption, basaltic andesite (Qswba)	Smith et al. (1982)	Many small intrusive bodies are present in the volcanic rocks of the High Cascade Range. Unit mostly consists of solidified lava in central conduits, plugs, dikes, and sills. Only the larger bodies are shown on the map.	None reported.	Regional Volcanism.

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QAUTERNARY (Holocene and Pleistocene)	Glacial deposits (Qg)	Glacial deposits (Qg)	Jenks et al. (2008)	No description provided.	Glacial Features and Processes—glacial deposits in southern and western parts of Crater Lake National Park.	Coeval with buildup of Mount Mazama.
QUATERNARY	Sedimentary deposits (Qs)	Undivided sediments (Qs)	Jenks et al. (2008)	Mixed fluvial and lacustrine deposits.	None reported.	None reported.
QUATERNARY	Andesite of Egan Springs (Qega)	East volcanism (Cascades), andesite (Qea)	Jenks et al. (2008)	Andesite flows.	Hydrothermal Features and Geothermal Development—exploration east of Crater Lake National Park.	Regional Volcanism.
QUATERNARY	Basalt of Sun Pass (Qsun)	East volcanism (Cascades), basalt (QTeb)	Jenks et al. (2008)	Basalt flows.	Hydrothermal Features and Geothermal Development—exploration east of Crater Lake National Park.	Regional Volcanism.
QUATERNAR (Pleistocene)	Glacial deposits, undivided (PEg)	Glacial deposits (Qg)	Bacon (2008)	Till and minor associated outwash forming a discontinuous mantle on the slopes of Mount Mazama. Characterized by a heterolithologic assemblage of dense, abraded or rounded volcanic clasts and presence of ultrafine material in unsorted matrix.	Crater Lake, Lake Level—till in northeastern caldera wall is permeable layer that allows leakage and maintains lake level. Glacial Features—comprises all glacial deposits mapped by Bacon (2008).	Glaciations are coeval with buildup of Mount Mazama.
QUATERNARY (Late Pleistocene)	Mount Mazama; rhyodacite of Sharp Peak (PErs)	Mount Mazama preclimactic eruption, rhyodacite (Qmer)	Bacon (2008)	Porphyritic medium-gray rhyodacite (70.5% SiO_2) lava composing 12 small domes.	Mount Mazama—rhyodacite lava domes and flows that are part of preclimactic buildup of Mount Mazama. Represents early leaks from the top of the climactic magma chamber. Glacial Features—glaciated during last Pleistocene ice advance.	Rhyodacite Domes and Flows. $^{40}Ar/^{39}Ar$ isochron age: 18,000 ± 4,000 years ago. Glaciations—marine isotope stage (MIS) 2.
QUATERNARY (Late Pleistocene)	Mount Mazama; andesite south of Bear Bluff, pyroclastic (PEabp), lava (PEab), and tuff breccia (PEabt).	Mount Mazama preclimactic eruption, andesite (Qmea)	Bacon (2008)	Porphyritic medium-dark-gray andesite (58%–59.5% SiO_2) capping lava (**PEab**), oxidized cinders and bombs (**PEabp**) of subaerial vent at southeastern top of tuya, and palagonitic tuff (**PEabt**) containing bombs as large as 60 cm (24 in) across and underlying lava of tuya south of Bear Bluff. Note: **PEabt** is listed here with other units associated with the andesite of Bear Bluff but is actually older than unit **PErbb**.	Glacial Features—PEab forms a tuya.	Coeval with Rhyodacite Domes and Flows—**PErbb** ($^{40}Ar/^{39}Ar$ isochron age: 24,000 ± 3,000 years ago). Glaciations—erupted during last glacial maximum (MIS 2).
QUATERNARY (Late Pleistocene)	Mount Mazama; rhyodacite of Bear Bluff (PErbb)	Mount Mazama preclimactic eruption, rhyodacite (Qmer)	Bacon (2008)	Medium-light-gray porphyritic rhyodacite (69.5% SiO_2) lava dome at the northern edge of tuya of unit **PEab** in south-central part of map. Grayish-black vitrophyre present locally along southern margin. Composition similar to, but slightly less differentiated than, rhyodacite of climactic eruption.	Mount Mazama—rhyodacite lava domes and flows that are part of preclimactic buildup of Mount Mazama. Represents early leaks from the top of the climactic magma chamber. Glacial Features—Bear Bluff is glaciated hill at northern end of **PEab** tuya.	Rhyodacite Domes and Flows. $^{40}Ar/^{39}Ar$ isochron age: 24,000 ± 3,000 years ago. Emplaced during last glacial maximum. Glaciations—MIS 2.

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Age	GRI GIS Map Unit (Symbol) *GIS data online and on CD*	Simplified Geologic Map Unit (Symbol) *poster in pocket*	Source Map	Geologic Description	Geologic Issues, Features, and Processes	Geologic History
QUATERNARY (Late Pleistocene)	Mount Mazama; evolved Pleistocene preclimactic rhyodacite, felsite (PEre), pyroclastic (PErep), vitrophyre (PErev), pumiceous carapace (PErec)	Mount Mazama preclimactic eruption, rhyodacite (Qmer)	Bacon (2008)	Porphyritic rhyodacites (70%–72% SiO_2) of Redcloud and Grouse Hill flows of Williams (1942), dome at northern caldera rim above Steel Bay, and related pyroclastic deposits that are the most chemically evolved (differentiated) of the Pleistocene preclimactic rhyodacites. Lava outcrops of medium-gray pumiceous carapace (**PErec**), dark-gray obsidian (vitrophyre; **PErev**), and medium-light-gray felsite (**PEre**) mapped separately where possible. Pumice-fall deposit (**PErep**), locally exposed beneath Redcloud flow in caldera wall and on road to Redcloud Cliff viewpoint.	Mount Mazama—rhyodacite lava domes and flows that are part of preclimactic buildup of Mount Mazama. Represents early leaks from the top of the climactic magma chamber. Glacial Features—**PEre** has ice-contact features on Redcloud and Grouse Hill flows, also ice-bounded lava at Grouse Hill. Caves—Bear Creek Cave of Allen (1984) formed at the northeastern end of the Redcloud rhyodacite; largest known cave in Crater Lake National Park.	Rhyodacite Domes and Flows. About 27,000 years old. Glaciations—MIS 2 or 3.
	Regional volcanism, northwest; basaltic andesite northwest of Williams Crater, lava (PEbwn) and pyroclastic (PEbwnp)	Northwest volcanism (Cascades), basaltic andesite (QTnwba)	Bacon (2008)	Medium-dark-gray porphyritic basaltic andesite (52.5% SiO_2) lava flow (**PEbwn**) and small cinder cone remnant (**PEbwnp**) 2.6 km (1.6 mi) north-northwest of Williams Crater, west-northwest of Crater Lake caldera.	Shield Volcanoes and Cinder Cones—northwest of Crater Lake caldera and roughly Crater Creek.	Regional Volcanism.
	Mount Mazama; mingled lava of Williams Crater (PEmw)	Mount Mazama preclimactic eruption, andesite (Qmea)	Bacon (2008)	Coarsely porphyritic light-gray dacite interlayered (mingled) with dark-gray hybrid andesite (60.5%–67% SiO_2) forming small dome and lava flows. Assigned to Mount Mazama because dacitic magma of unit was derived from that source.	Mount Mazama—part of Williams Crater complex.	Buildup of Mount Mazama. About 35,000 years old.
	Regional volcanism, northwest; basaltic andesite of Williams Crater, lava (PEbw) and pyroclastic (PEbwp)	Northwest volcanism (Cascades), basaltic andesite (QTnwba)	Bacon (2008)	Medium-gray porphyritic basaltic andesite (51.5% SiO_2) lava flow (**PEbw**) and grayish-red cinders (**PEbwp**) of Williams Crater complex west of Crater Lake caldera.	Shield Volcanoes and Cinder Cones—northwest of Crater Lake caldera and roughly Crater Creek.	Regional Volcanism. About 35,000 years old.
	Regional volcanism, northwest, basaltic andesite northwest of Red Cone (PEbrw)		Bacon (2008)	Medium-gray porphyritic basaltic andesite (53.5% SiO_2) lava flows erupted from vent 1.7 km (1.1 mi) north of Red Cone, northwest of Crater Lake caldera. Similar to lavas of unit **PEbr** but contains larger plagioclase phenocrysts.	Shield Volcanoes and Cinder Cones—northwest of Crater Lake caldera and roughly Crater Creek.	Regional Volcanism. About 35,000 years old.
	Regional volcanism, northwest; basaltic andesite of Red Cone, lava (PEbr) and pyroclastic (PEbrp)		Bacon (2008)	Light- to medium-gray porphyritic basaltic andesite (52.5%–54% SiO2) lava flows (**PEbr**), bombs, and cinders (**PEbrp**) erupted from vent marked by Red Cone and from fissure vent system 1.5 km (0.9 mi) north of Red Cone, northwest of the caldera. Lava flowed to west-northwest around source of unit **PEarw** to within approximately1 km (0.6 mi) of Oasis Butte.	Shield Volcanoes and Cinder Cones—northwest of Crater Lake caldera and roughly Crater Creek. Glacial Features and Processes—Red Cone is heavily glaciated (Bacon 1983).	Regional Volcanism. K-Ar age: 36,000 ± 12,000 years ago; $^{40}Ar/^{39}Ar$ plateau age: 35,000 ± 4,000 years ago.
	Regional volcanism, southwest; basaltic andesite north of Little Castle Creek (PEblcp)	Mount Mazama preclimactic eruption, basaltic andesite (Qmeba)	Bacon (2008)	Dark-gray porphyritic basaltic andesite (52.5% SiO_2) bombs and grayish-red cinders of breached cone and adjacent tephra mantle on northern wall of valley of Castle Creek near confluence with Little Castle Creek, southwest of the caldera.	Shield Volcanoes and Cinder Cones—southwest of Crater Lake caldera and roughly Annie Creek.	Regional Volcanism. Preservation of cone and tephra at valley margin suggests that the unit erupted during last interglacial.
	Regional volcanism, northwest; basalt east of Oasis Butte (PEboe)	Northwest volcanism (Cascades), basalt (QTnwb)	Bacon (2008)	Medium-gray porphyritic basalt lava at northern-northwestern boundary of map area; part of extensive field of similar basalt (high-alumina olivine tholeiite, HAOT; 48.5%, rarely to 50% SiO_2) flows from vent marked by low cinder mound 1.5 km (0.9 mi) east-southeast of Bald Crater (north of map area).	Shield Volcanoes and Cinder Cones—northwest of Crater Lake caldera and roughly Crater Creek.	Regional Volcanism. K-Ar and paleomagnetic data suggest similar age to overlying unit **PEbr** ($^{40}Ar/^{39}Ar$ plateau age 35,000 ± 4,000 years ago).

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QUATERNARY (Late Pleistocene)	Mount Mazama; dacite of Munson Valley, prismatically jointed block unit (PEdvb) and monolithologic breccia (PEdv)	Mount Mazama preclimactic eruption, dacite (Qmed)	Bacon (2008)	Unconsolidated fragmental deposits of porphyritic dacite (juvenile clasts contain 63.5%–69.5% SiO_2; most <65%) mainly on the southwestern flank of Mount Mazama. **PEdv** is monolithologic breccia with medium-gray to grayish-black dense to pumiceous dacite clasts, is locally oxidized reddish brown or bleached. **PEdv** is a debirs-avalanche deposit formed by collapse of a lava dome high on the southwestern flank of Mount Mazama. The apparently younger **PEdvb** is characterized by medium-light to medium-dark-gray, dense, intact prismatically jointed blocks 1 m (3 ft) across, rarely to 3 m (10 ft), commonly is heterolithologic containing a variety of lithic blocks. **PEdvb** deposited by pyroclastic flows originating at the same source as and virtually contemporaneous with the monolithologic avalanches.	Mount Mazama—part of volcano edifice.	Buildup of Mount Mazama. Prismatically jointed blocks in **PEdvb** record an unusual paleomagnetic pole position similar to that of **PEbr**, which has K-Ar and $^{40}Ar/^{39}Ar$ ages of 36,000 ± 12,000 years ago and 35,000 ± 4,000 years ago, respectively.
	Mount Mazama; andesite of Lightning Spring (PEals)	Mount Mazama preclimactic eruption, andesite (Qmea)	Bacon (2008)	Porphyritic medium- to dark-gray andesite (61.5%–65.5% SiO_2; most <64% SiO_2) lava flows at the caldera rim from west of Rim Village northwest to the Lightning Spring trailhead, where unit is well exposed in road cuts, and on the southwestern flank of Mount Mazama as far as 4 km (2.5 mi) from the caldera in the drainage of Bybee Creek. Pumiceous vitric pillow-like blocks, to 1.5 m (5 ft) across, form surface overlain by till 1.3 km (0.8 mi) west of Discovery Point parking area as though lava flowed in meltwater channel beneath ice; alternatively, blocks are cauliflower bombs in a volcanic flowage deposit.	Mount Mazama—part of volcano edifice.	Buildup of Mount Mazama. K-Ar age: 47,000 ± 8,000 years ago.
	Mount Mazama; andesite of Steel Bay (PEasb)	Mount Mazama preclimactic eruption, andesite (Qmea)	Bacon (2008)	Porphyritic medium- to dark-gray andesite (59%–61% SiO_2) lava flows high on the caldera wall.	Mount Mazama—part of volcano edifice.	Buildup of Mount Mazama. K-Ar ages: 43,000 ± 6,000 and 42,000 ± 6,000 years ago.
	Mount Mazama; andesite of Pumice Point (PEapu)		Bacon (2008)	Sparsely porphyritic medium-gray andesite (59.5%–61% SiO_2).	Mount Mazama—part of volcano edifice.	Buildup of Mount Mazama. K-Ar age: 47,000 ± 20,000 years ago.
	Regional volcanism, southwest; basaltic andesite of Scoria Cone, lava (PEbsc) and pyroclastic (PEbscp)	Southwest volcanism (Cascades), basaltic andesite (Qswba)	Bacon (2008)	Medium-gray porphyritic basaltic andesite (54.5%–55% SiO_2) lava flows (**PEbsc**) and cinders (**PEbscp**) erupted from Scoria Cone (just south of map area) and associated vents in 1-km- (0.6-ft-) long, north–northeast alignment between Pumice Flat and Annie Creek.	Shield Volcanoes and Cinder Cones—southwest of Crater Lake caldera and roughly Annie Creek.	Regional Volcanism. $^{40}Ar/^{39}Ar$ plateau age of **PEbsc**: 53,000 ± 4,000 years ago.
	Mount Mazama; andesite of Devils Backbone (PEad)	Mount Mazama preclimactic eruption, andesite (Qmea)	Bacon (2008)	Moderately porphyritic dark- to light-gray andesite (57.5%–61% SiO_2; most 60%–61% SiO_2) lava flows, emanating from a vent fed by the Devils Backbone dike on western caldera wall.	Mount Mazama—part of volcano edifice. Glacial Features—glacial activity removed parts of lava flows.	Buildup of Mount Mazama. Probable age 50,000–40,000 years ago. Glaciations—MIS 2.
	Mount Mazama; dacite of The Watchman, felsite (PEdwf), pumiceous carapace and dense vitrophyre (PEdwv), and pyroclastic-flow deposits (PEdwp)	Mount Mazama preclimactic eruption, dacite (Qmed)	Bacon (2008)	Porphyritic dacite (65.5%–68% SiO_2; most 67%) forming The Watchman flow of Williams (1942), its feeder dike, and pumiceous pyroclastic-flow deposits in the western caldera wall and locally preserved on ridge top approximately 4 km (2.5 mi) west of Rim Village. Medium-gray pumiceous carapace (upper surface of The Watchman flow) and grayish-black to black dense vitrophyre (**PEdwv**), medium-light-gray crystalline lava and dike (**PEdwf**), and nonwelded to densely welded vitric pyroclastic-flow deposits (**PEdwp**).	Mount Mazama—part of volcano edifice. Glacial Features—**PEdwp** overlies glaciated lava surface on **PEaww** in western caldera wall between The Watchman and Discovery Point.	Buildup of Mount Mazama. K-Ar age: 50,000 ± 3,000 years ago. Glaciations—MIS 4.
	Mount Mazama; andesite south of The Watchman (PEatw)	Mount Mazama preclimactic eruption, andesite (Qmea)	Bacon (2008)	Coarsely porphyritic medium-light-gray silicic andesite (62.5%–63.5% SiO_2) forming thick lava flows on western caldera rim.	Mount Mazama—part of volcano edifice.	Buildup of Mount Mazama. K-Ar age: 55,000 ± 3,000 years ago.
	Mount Mazama; andesite of Hillman Peak (PEah)		Bacon (2008)	Markedly porphyritic dark- to medium-light-gray andesite (57.5%–59% SiO_2) lava flows forming summit of Hillman Peak and exposed in western caldera walls and on western flank of Mount Mazama. Vent was east of Hillman Peak.	Mount Mazama—part of volcano edifice. Form summits of westernmost andesitic stratovolcano that makes up Mount Mazama.	Buildup of Mount Mazama. K-Ar age: 61,000 ± 8,000 years ago.

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QUATERNARY (Late Pleistocene)	Mount Mazama; dacite below Llao Rock (PEdlp)	Mount Mazama preclimactic eruption, dacite (Qmed)	Bacon (2008)	Porphyritic pinkish- to brownish-gray and medium-dark-gray dacite pumice (66%–67.5% SiO_2) occurring as fall and pyroclastic-flow deposits in northwestern and northern caldera walls from north of Devils Backbone to Palisade Point. Welded fall deposit dipping into caldera wall above Steel Bay indicates proximity to vent to south, in area of present caldera.	Mount Mazama—part of volcano edifice.	Buildup of Mount Mazama. Approximately 70,000 years old.
	Mount Mazama; andesite of Grotto Cove (PEagc)	Mount Mazama preclimactic eruption, andesite (Qmea)	Bacon (2008)	Porphyritic medium-light- to medium-dark-gray andesite (61.5%–63% SiO_2) lava flows in the caldera wall from Pumice Point (northern wall) to Cleetwood Cove. Forms 100-m- (330-ft-) high cliffs at caldera rim at Grotto Cove (northeastern wall). Includes related block-and-ash flow deposit between flows at Grotto Cove.	Mount Mazama—part of volcano edifice. Glacial Features—has ice-contact feature at Grotto Cove. Caves—Castle Creek Caves of Allen (1984) formed in mudflow deposit underlying andesite flow on steep cliff on the eastern side of Munson Valley; can see these caves from park headquarters.	Buildup of Mount Mazama. K-Ar age: 71,000 ± 5,000 years ago. Glaciations—MIS 4.
	Mount Mazama; basaltic andesite of Hillman Peak, lava (PEbh), intrusive (PEbhi), and pyroclastic (PEbhp)	Mount Mazama preclimactic eruption, basaltic andesite (Qmeba)	Bacon (2008)	Medium-gray porphyritic hornblende basaltic andesite and andesite (55.5%–59% SiO_2) lava flows (**PEbh**), intrusions (**PEbhi**), and fall deposits (**PEbhp**) of western caldera wall and flank of Mount Mazama. Distinguished by ubiquitous hornblende needles, which appear black in hand specimens.	Mount Mazama—part of volcano edifice. Part of westernmost andesitic stratovolcano that makes up Mount Mazama.	Buildup of Mount Mazama. K-Ar age: 73,000 ± 6,000 years ago.
	Mount Mazama; dacite of Pumice Castle, lava (PEdc) and pyroclastic (PEdcp)	Mount Mazama preclimactic eruption, dacite (Qmed)	Bacon (2008)	Porphyritic light- to dark-medium-gray dacite lava flows (**PEdc**; 66%–67% SiO_2) in caldera wall from north of Devils Backbone east to Cloudcap Bay, at Cloudcap, and forming Scott Bluffs. Extensive Plinian fall of pinkish-gray to light-brown dacite pumice (**PEdcp**; 66%–68% SiO_2) forms approximately 75-m- (250-ft-) thick deposit of alternating welded and nonwelded layers at Pumice Castle and nonwelded fall, pyroclastic-flow, or reworked deposits exposed locally from north of Devils Backbone to Palisade Point, above Cloudcap Road, and in small exposure in roadcut near intersection of Rim Drive with Dutton Ridge.	Mount Mazama—part of volcano edifice.	Buildup of Mount Mazama. Approximately 71,000 years old.
	Mount Mazama; andesite of the west wall (PEaww)	Mount Mazama preclimactic eruption, andesite (Qmea)	Bacon (2008)	Finely porphyritic seriate-textured medium- to dark-gray andesite (57%–61% SiO_2) lava flows exposed in western caldera wall and on the western flank of Mount Mazama as far as 5–7 km (3–4 mi) west of the caldera rim.	Mount Mazama—part of volcano edifice. Glacial Features—**PEaww** has glaciated lava surface and overlies glaciated lava surface on **PEdsb** at Steel Bay. **PEaww** glaciated surface overlain by **PEdwp**.	Buildup of Mount Mazama. K-Ar age: 70,000 ± 4,000 years ago. Glaciations—MIS 4.
QUATERNARY (Late? Pleistocene)	Regional volcanism, east; andesite of Scott Creek, lava (PEasc) and pyroclastic (PEascp)	East volcanism (Cascades), andesite (Qea)	Bacon (2008)	Porphyritic medium-gray olivine andesite (57.5%–59% SiO_2) lava flow (**PEasc**) and source vent marked by eroded cinder cone (**PEascp**) southeast of caldera. Lava crops out locally south of Scott Creek above about 1,630 m (5,350 ft) and forms incised intracanyon flow below about 1,590 m (5,220 ft) in elevation. **Peascp** occurs in Crater Lake National Park, but no**t PEasc**.	Hydrothermal Features and Geothermal Development—exploration east of Crater Lake National Park. Shield Volcanoes and Cinder Cones—east of the longitude of Munson Valley and park headquarters.	Regional Volcanism. Glaciations—erupted before last glacial maximum (MIS 2), consistent with $^{40}Ar/^{39}Ar$ age of 87,000 ± 15,000 years ago.
QUATERNARY (Late Pleistocene)	Mount Mazama; andesite west of Red Cone (PEarw)	Mount Mazama preclimactic eruption, andesite (Qmea)	Bacon (2008)	Finely porphyritic seriate-textured medium-gray andesite (59% SiO_2) lava flows.	Mount Mazama—part of volcano edifice.	Buildup of Mount Mazama. K-Ar age: 84,000 ± 13,000 years ago.
	Mount Mazama; andesite of the boat landing (PEabl)		Bacon (2008)	Porphyritic medium- to dark-gray andesite (63%–63.5% SiO_2) lava flows and underlying related fragmental deposit between Pumice Point and Cleetwood Cove.	Mount Mazama—part of volcano edifice. Glacial Features—trail to boat landing descends along the base of the lower flow of this unit where it lies on probable till.	Buildup of Mount Mazama. K-Ar age: 102,000 ± 10,000 years ago. Glaciations—MIS 5d.
	Mount Mazama; dacite east of Palisade Point (PEdpe)	Mount Mazama preclimactic eruption, dacite (Qmed)	Bacon (2008)	Porphyritic medium-light-gray dacite (65% SiO_2) lava flow approximately 150 m (490 ft) thick, forming northeastern caldera wall midway between Palisade Point and Roundtop.	Mount Mazama—part of volcano edifice.	Buildup of Mount Mazama. K-Ar age: 111,000 ± 9,000 years ago.
	Mount Mazama; andesite west of Pumice Point (PEapw)	Mount Mazama preclimactic eruption, andesite (Qmea)	Bacon (2008)	Porphyritic dark-gray andesite lava flows (61% SiO_2) midway up the northern caldera wall and feeder dike (59.5% SiO_2) at Steel Bay.	Mount Mazama—part of volcano edifice.	Buildup of Mount Mazama. Possibly about 110,000 years old.

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QUATERNARY (Late Pleistocene)	Mount Mazama; basaltic andesite of Steel Bay, lava (PEbs)	Mount Mazama preclimactic eruption, basaltic andesite (Qmeba)	Bacon (2008)	Medium-dark-gray porphyritic basaltic andesite (53% SiO_2) lava flows.	Mount Mazama—part of volcano edifice.	Buildup of Mount Mazama. Approximately 115,000 years old.
	Regional volcanism, east; andesite of Crater Peak, lava (PEacr) and pyroclastic (PEacrp)	East volcanism (Cascades), andesite (Qea)	Bacon (2008)	Moderately porphyritic medium-gray to medium-dark-gray andesite lava flows (**PEacr**) and Crater Peak cinder cone (**PEacrp**) marking vent south of Crater Lake caldera.	Hydrothermal Features and Geothermal Development—exploration east of Crater Lake National Park. Shield Volcanoes and Cinder Cones—east of the longitude of Munson Valley and park headquarters.	Regional Volcanism. K-Ar ages: 136,000 ± 8,000 and 98,000 ± 8,000 years ago.
	Regional volcanism, east; basaltic andesite south of Crater Peak (PEbcsp)	East volcanism (Cascades), basaltic andesite (QTeba)	Bacon (2008)	Medium-dark-gray sparsely porphyritic basaltic andesite (53.5% SiO_2) bombs and lava of small exposure that probably mark vent approximately 1 km (0.6 mi) south of Crater Peak south of Crater Lake caldera.	Hydrothermal Features and Geothermal Development—exploration east of Crater Lake National Park. Shield Volcanoes and Cinder Cones—east of the longitude of Munson Valley and park headquarters.	Regional Volcanism. K-Ar age: 118,000 ± 48,000 years ago.
QUATERNARY (Late? Pleistocene)	Regional volcanism, east; basaltic andesite north of Crater Peak (PEbcnp)	East volcanism (Cascades), basaltic andesite (QTeba)	Bacon (2008)	Grayish-red oxidized basaltic andesite (53.5% SiO_2) cinders and agglutinate of poorly exposed cinder cone banked against eastern wall of canyon of East Fork of Annie Creek approximately 2 km (1.2 mi) north of Crater Peak, south of Crater Lake caldera.	Hydrothermal Features and Geothermal Development—exploration east of Crater Lake National Park. Shield Volcanoes and Cinder Cones—east of the longitude of Munson Valley and park headquarters.	Regional Volcanism.
QUATERNARY (Late Pleistocene)	Regional volcanism, southwest; basaltic andesite northwest of Pumice Flat, lava (PEbf), intrusive (PEbfi), and pyroclastic (PEbfp)	Southwest volcanism (Cascades), basaltic andesite (Qswba)	Bacon (2008)	Medium-gray finely porphyritic basaltic andesite (55%–55.5% SiO_2) lava flows (**PEbf**), plugs and dikes (**PEbfi**), and grayish-red cinders (**PEbfp**).	Shield Volcanoes and Cinder Cones—southwest of Crater Lake caldera and roughly Annie Creek.	Regional Volcanism. K-Ar age: 116,000 ± 24,000 years ago.
	Mount Mazama; dacite of Steel Bay, lava (PEdsb) and pyroclastic (PEdsbp)	Mount Mazama preclimactic eruption, dacite (Qmed)	Bacon (2008)	Porphyritic medium-light- to medium-gray dacite (64.5%–66.5% SiO_2) lava and dikes (**PEdsb**) in northern caldera wall from Llao Rock to Pumice Point and pyroclastic-flow deposit (**PEdsbp**) below Hillman Peak carrying medium-dark-gray dacite (64.5% SiO_2) prismatically jointed blocks. Two prominent dikes fed a small dome and a lava flow at Steel Bay.	Mount Mazama—part of volcano edifice. Glacial Features—**PEdsb** has glaciated lava surface at Steel Bay.	Buildup of Mount Mazama. K-Ar ages: 116,000 ± 9,000 and 116,000 ± 5,000 years ago. Glaciations—MIS 4, 5b, and 5d.
	Mount Mazama; andesite of Merriam Point (PEam)	Mount Mazama preclimactic eruption, andesite (Qmea)	Bacon (2008)	Porphyritic light-gray to medium-dark-gray andesite (60.5%–61.5% SiO_2) lava flows, domes, and breccia in the northwestern caldera wall from below Hillman Peak to below Llao Rock. Thickest, approximately 200 m (660 ft), near feeder, which displaced and tilted andesite of Llao Bay, lower unit (**PEall)**, southwest of Merriam Point.	Mount Mazama—part of volcano edifice.	Buildup of Mount Mazama. K-Ar age: 131,000 ± 18,000 years ago.
	Mount Mazama; andesite of Llao Bay, upper unit (PEalu)		Bacon (2008)	Variably porphyritic medium- to dark-gray basaltic andesite and andesite (54.5%–61% SiO_2) lava flows in northwestern caldera wall from Merriam Point to east of Pumice Point. Andesite lava flow forms prominent cliff midway up wall at Steel Bay. Subtle basaltic andesite dike mapped as **PEalu** cuts flows of **PEall** below Llao Rock. Together with unit **PEall** forms broad shield making up lower part of northwestern caldera wall.	Glacial Features—**PEalu** has ice-contact features and overlies glaciated lava surface of **PEall** at Pumice Point.	Buildup of Mount Mazama. $^{40}Ar/^{39}Ar$ age: 117,000 ± 3,000 years ago. Glaciations—MIS 5d.
QUATERNARY (Late and/or Middle Pleistocene)	Sedimentary deposits, undivided (PEs)	Undivided sediments (Qs)	Bacon (2008)	Deposits of clastic sediment exposed locally in the caldera walls. Typically inaccessible and poorly exposed, probably consists of laharic or local fluvial sediment.	Volcano Hazards—probably deposited by a lahar.	Buildup of Mount Mazama.
	Mount Mazama; andesite east of Spruce Lake (PEasl)	Mount Mazama preclimactic eruption, andesite (Qmea)	Bacon (2008)	Porphyritic medium-gray silicic andesite poorly exposed in South Fork of Crater Creek approximately 2 km (1.2 mi) east of Spruce Lake.	Mount Mazama—part of volcano edifice.	Buildup of Mount Mazama. Probably older than 80,000–50,000 years old.

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Age	GRI GIS Map Unit (Symbol) *GIS data online and on CD*	Simplified Geologic Map Unit (Symbol) *poster in pocket*	Source Map	Geologic Description	Geologic Issues, Features, and Processes	Geologic History
QUATERNARY (Late and/or Middle Pleistocene)	Mount Mazama; dacite of Palisade Point (PEdpt)	Mount Mazama preclimactic eruption, dacite (Qmed)	Bacon (2008)	Porphyritic medium-gray dacite (66% SiO_2) lava flow on northern shore of Crater Lake at Palisade Point and east of Pumice Point.	Mount Mazama—part of volcano edifice.	Buildup of Mount Mazama. About 120,000 years old.
QUATERNARY (Middle Pleistocene)	Mount Mazama; andesite of Llao Bay, lower unit (PEall)	Mount Mazama preclimactic eruption, andesite (Qmea)	Bacon (2008)	Variably porphyritic medium- to dark-gray andesite (57%–60.5% SiO_2) lava flows forming the lowest unit in the northwestern caldera wall from south of Devils Backbone to east of Pumice Point. Together with unit **PEalu** forms broad shield making up lower part of northwestern caldera wall. Consists of coarsely porphyritic lavas below Llao Rock, and finely porphyritic lavas lower in the section.	Mount Mazama—part of volcano edifice. Glacial Features—glaciated surface at Pumice Point.	Buildup of Mount Mazama. Between about 170,000 and 140,000 years old. Glaciations—MIS 5d and 6.
	Mount Mazama; andesite of Roundtop (PEar)		Bacon (2008)	Porphyritic medium-light-gray andesite (62% SiO_2) forming cliff in northeastern caldera wall at Roundtop and extending 2.5 km (1.6 mi) to northeast of caldera rim. Joint pattern in cliffs suggests vent beneath Roundtop.	Mount Mazama—part of volcano edifice. Glacial Features—rests on 115 m (380 ft) of glacial deposits. **PEar** lava is probably an ice-bounded flow.	Buildup of Mount Mazama. K-Ar age: 159,000 ± 13,000 years ago. Glaciations—MIS 6.
	Regional volcanism, east; andesite south of Lookout Butte, lava (PEalb) and pyroclastic (PEalbp)	East volcanism (Cascades), andesite (Qea)	Bacon (2008)	Sparsely porphyritic medium-dark- to dark-gray andesite (59% SiO_2) lava (**PEalb**) and cinder cone (**PEalbp**) marking vent near northeastern map boundary.	Hydrothermal Features and Geothermal Development—exploration east of Crater Lake National Park. Shield Volcanoes and Cinder Cones—east of the longitude of Munson Valley and park headquarters.	Regional Volcanism. K-Ar age: 155,000 ± 6,000 years ago.
	Regional volcanism, southwest; basaltic andesite of Union Peak, lava (PEbu), intrusive (PEbui), and pyroclastic (PEbup)	Southwest volcanism (Cascades), basaltic andesite (Qswba)	Bacon (2008)	Light- to medium-light-gray porphyritic basaltic andesite (54%–56.5% SiO_2) lava flows (**PEbu**), grayish-red and yellowish-orange (palagonitic) cinders (**PEbup**), and very light gray to medium-light-gray intrusive rock (**PEbui**) composing the Union Peak shield volcano in southwestern part of map area. **PEbup** and **PEbui** are restricted to eroded core preserved as Union Peak itself and in remnants within glacial valley to the north.	Shield Volcanoes and Cinder Cones—southwest of Crater Lake caldera and roughly Annie Creek. Glacial Features—glaciers eroded slopes of Union Peak.	Regional Volcanism. K-Ar age: 164,000 ± 11,000 years ago.
	Mount Mazama; andesite east of Munson Valley (PEamv)	Mount Mazama preclimactic eruption, andesite (Qmea)	Bacon (2008)	Porphyritic medium-gray andesite (57% SiO_2) lava flows capping ridge between Middle and East forks of Annie Creek. Vent must have been approximately 500 m (1,640 ft) north of Rim Drive.	Mount Mazama—part of volcano edifice.	Buildup of Mount Mazama. K-Ar age: 172,000 ± 15,000 years ago.
	Mount Mazama; andesite of the gaging station (PEags)		Bacon (2008)	Porphyritic medium-light-gray andesite (60% SiO_2) lava flow at gauging station west of boat landing, northern shore of Crater Lake.	Mount Mazama—part of volcano edifice. Glacial Features—glaciated surface at gauging station.	Buildup of Mount Mazama. $^{40}Ar/^{39}Ar$ plateau age at gauging station: 189,000 ± 3,000 years ago. Glaciations—MIS 6.
	Regional volcanism, northwest; basaltic andesite of Oasis Butte, intrusive (PEboi), lava (PEbo), and pyroclastic (PEbop)	Northwest volcanism (Cascades), basaltic andesite (QTnwba)	Bacon (2008)	Medium-gray porphyritic basaltic andesite (53%–53.5% SiO_2) plug (**PEboi**) at Oasis Butte and lava (**PEbo**) and cinders (**PEbop**) vented from Oasis Butte and dissected cinder cone 1 km (0.6 mi) to the south near the northwestern corner of map area. Lava outcrops traced as far southwest as 1,460 m (4,800 ft) in elevation on a tributary of Crater Creek.	Shield Volcanoes and Cinder Cones—northwest of Crater Lake caldera and roughly Crater Creek.	Regional Volcanism. K-Ar age: 201,000 ± 13,000 years ago.
	Mount Mazama; dacite north of Castle Creek; lava (PEdcn) and pyroclastic (PEdcnp)	Mount Mazama preclimactic eruption, dacite (Qmed)	Bacon (2008)	Finely porphyritic medium-light- to medium-dark-gray dacite lava (**PEdcn**; 64.5%–66.5% SiO_2) present southwest of the caldera from approximately 1 km (0.6 mi) west of Rim Village to drainages of Copeland and Bybee creeks. Flow forming divide between Bybee and Castle creeks reached at least 10 km (6 mi) west of vent marked by agglutinate (**PEdcnp**). Dikes (65%–66% SiO_2) in caldera wall match compositions and petrography of specific flows, the more northerly dikes corresponding to the relatively crystal-rich, northern flows.	Mount Mazama—part of volcano edifice. Glacial Features—**PEdcn** overlies glaciated lava surface on **PEaa** north of Castle Creek.	Buildup of Mount Mazama. K-Ar age: 216,000 ± 4,000 years ago. Glaciations—MIS 7 and 8.

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QUATERNARY (Middle Pleistocene)	Regional volcanism, east; basalt west of Sun Creek (PEbsw)	East volcanism (Cascades), basalt (QTeb)	Bacon (2008)	Medium-gray coarsely porphyritic basalt (51% SiO_2) lava west of Sun Creek near southern boundary of map area. Apparently extruded from subtle vent at approximately 1,555 m (5,100 ft) in elevation.	Hydrothermal Features and Geothermal Development—exploration east of Crater Lake National Park. Shield Volcanoes and Cinder Cones—east of the longitude of Munson Valley and park headquarters.	Regional Volcanism. Degree of preservation suggests late middle Pleistocene age.
QUATERNARY (Middle Pleistocene)	Regional volcanism, east; basaltic andesite of Maklaks Crater, lava (PEbmc) and pyroclastic (PEbmcp)	East volcanism (Cascades), basaltic andesite (QTeba)	Bacon (2008)	Grayish-red cinders (**PEbmcp**) of Maklaks Crater cone and associated medium-dark-gray finely porphyritic basaltic andesite (53.5% SiO_2) lava (**PEbmc**) southeast of Crater Lake caldera.	Hydrothermal Features and Geothermal Development—exploration east of Crater Lake National Park. Shield Volcanoes and Cinder Cones—east of the longitude of Munson Valley and park headquarters.	Regional Volcanism. K-Ar age: 220,000 ± 67,000 years ago.
QUATERNARY (Middle Pleistocene)	Mount Mazama; andesite of Garfield Peak (PEag)	Mount Mazama preclimactic eruption, andesite (Qmea)	Bacon (2008)	Moderately porphyritic medium-gray andesite (60.5%–61.5% SiO_2) lava flows and breccia at Garfield Peak, on slope to south, and on the western side of Munson Valley. Characterized by small—<3 mm (0.1 in)—hornblende phenocrysts. Dike (**PEag?**) in caldera wall east of Garfield Peak provisionally assigned to this unit.	Mount Mazama—part of volcano edifice. Glacial Features—**PEag** overlies glaciated lava surface on **PEaa** south of Garfield Peak.	Buildup of Mount Mazama. K-Ar age: 224,000 ± 9,000 years ago. Glaciations—MIS 7 and 8.
QUATERNARY (Middle Pleistocene)	Mount Mazama; dacite south of Garfield Peak (PEdg)	Mount Mazama preclimactic eruption, dacite (Qmed)	Bacon (2008)	Porphyritic medium-gray dacite lava (64.5%–65.5% SiO_2) traceable south of the caldera from 1 km (0.6 mi) south of Garfield Peak for nearly 6 km (4 mi) to vicinity of Pole Bridge Creek approximately 2 km (1 mi) southeast of Arant Point; medium-dark-gray to black vitrophyre locally preserved at top of fault scarp north of Arant Point.	Mount Mazama—part of volcano edifice.	Buildup of Mount Mazama. Between about 269,000 and 224,000 years old.
QUATERNARY (Middle Pleistocene)	Mount Mazama; andesite of Applegate Peak, lava (PEaa) and intrusive (PEaai)	Mount Mazama preclimactic eruption, andesite (Qmea)	Bacon (2008)	Light- to dark-gray porphyritic andesite and dacite (57%–66.5% SiO_2) flow-banded lava flows, agglutinated bombs, and near-vent fall deposits. Consists of multiple lava flows believed to have come from Mount Mazama summit vent or possibly satellite vents fed by same magma system. **PEaa** comprises the upper southern slopes of Mount Mazama and high cliffs at Applegate Peak and Dutton Cliff. Small andesite exposure (**PEags**) at lake level on northern side of caldera may be from same source vent as **PEaa**. Correlated with a large intrusive body (**PEaai**) in caldera wall below Applegate Peak.	Mount Mazama—part of volcano edifice. **PEaa** is the most extensive unit of Mount Mazama; it is exposed in the caldera wall from the Wineglass to Discovery Point, as far as 9 km (6 mi) from the eastern rim of the caldera near Scout Hill, and 8 km (5 mi) from the western rim in Bybee Creek. Glacial Features—**PEaa** has widespread ice-contact features, for example at Dutton Cliff and north of Kerr Notch, and glaciated lava surfaces north of Castle Creek and south of Garfield Peak.	Buildup of Mount Mazama. Between about 269,000 and 211,000 years old. Glaciations—MIS 7 and 8.
QUATERNARY (Middle? Pleistocene)	Regional volcanism, northwest; basaltic andesite north of Red Cone (PEbn)	Northwest volcanism (Cascades), basaltic andesite (QTnwba)	Bacon (2008)	Medium-gray coarsely porphyritic basaltic andesite (52.5% SiO_2) lava flows erupted from fissure system now marked by low north–south ridge, north-central map boundary.	Shield Volcanoes and Cinder Cones—northwest of Crater Lake caldera and roughly Crater Creek.	Regional Volcanism. May be related to flows from Desert Cone (north of map area; K-Ar age 213,000 ± 26,000 years ago).
QUATERNARY (Middle Pleistocene)	Mount Mazama; andesite east of Wineglass (PEawe)	Mount Mazama preclimactic eruption, andesite (Qmea)	Bacon (2008)	Strongly porphyritic medium-dark-gray andesite (60%–60.5% SiO_2) lava flows locally exposed low in northeastern caldera wall for approximately 0.5 km (0.3 mi) east of the Wineglass.	Mount Mazama—part of volcano edifice.	Buildup of Mount Mazama. Probably about 240,000–220,000 years ago.
QUATERNARY (Middle Pleistocene)	Mount Mazama; andesite of Cloudcap Bay (PEac)	Mount Mazama preclimactic eruption, andesite (Qmea)	Bacon (2008)	Moderately porphyritic medium-light- to dark-gray andesite (55.5%–60% SiO_2; most >57% SiO_2) sheet-like lava flows midway up the caldera wall between Grotto Cove and Cloudcap Bay and east–northeast-oriented andesite (57.5%–61% SiO_2) dikes south of lava outcrops. Presence of dikes and relative abundance of oxidized reddish-brown scoriaceous material indicate source vent was above Cloudcap Bay.	Mount Mazama—part of volcano edifice. Crater Lake, Lake Level—lava flows that underlie glacial till in northeastern caldera wall; till provides permeable layer for leakage that maintains lake level.	Buildup of Mount Mazama. K-Ar ages: 288,000 ± 13,000 and 231,000 ± 6,000 years ago; older age probably more accurate.
QUATERNARY (Middle Pleistocene)	Mount Mazama; dacite of Munson Ridge (PEdm)	Mount Mazama preclimactic eruption, dacite (Qmed)	Bacon (2008)	Porphyritic medium-light- to medium-dark-gray dacite lava (64.5%–65% SiO_2) forming crest of Munson Ridge from 1 km (0.6 mi) south of Rim Drive to Munson Point. Vitric breccia and columns on upper surface, particularly well developed on south-southeastern flank of Munson Point, indicate that lava flowed beneath glacial ice. Joint and flow-banding patterns, and relatively abundant enclaves, suggest vent beneath Munson Point; other vents or eruptive fissures may be present beneath Munson Ridge.	Mount Mazama—part of volcano edifice. Glacial Features—**PEdm** has ice-contact feature at Munson Ridge.	Buildup of Mount Mazama. K-Ar age: 276,000 ± 11,000 years ago. Glaciations—MIS 8.

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	Mount Mazama; andesite west of Fumarole Bay (PEaf)	Mount Mazama preclimactic eruption, andesite (Qmea)	Bacon (2008)	Finely porphyritic medium-light-gray to medium-gray andesite (61.5%–62% SiO_2) lava flows low in the western caldera wall between Discovery Point and The Watchman.	Mount Mazama—part of volcano edifice.	Buildup of Mount Mazama. K-Ar age: 276,000 ± 8,000 years ago.
QUATERNARY (Middle Pleistocene)	Regional volcanism, northwest; andesite southwest of Oasis Butte (PEao)	Northwest volcanism (Cascades), andesite (QTnwa)	Bacon (2008)	Porphyritic medium-gray andesite lava exposed in block between parallel north–south-oriented normal faults approximately 1–2 km (0.6–1 mi) southwest of Oasis Butte in northwestern corner of map area.	Shield Volcanoes and Cinder Cones—northwest of Crater Lake caldera and roughly Crater Creek.	Regional Volcanism. Younger than 201,000 years old.
	Regional volcanism, southwest; basaltic andesite of Whitehorse Bluff, lava (PEbx), intrusive (PEbxi), and pyroclastic (PEbxp)	Southwest volcanism (Cascades), basaltic andesite (QTswba)	Bacon (2008)	Medium-gray finely porphyritic basaltic andesite (55%–56.5% SiO_2) lava flows (**PEbx**), grayish-red cinders (**PEbxp**), and medium-gray plugs (**PEbxi**).	Shield Volcanoes and Cinder Cones—southwest of Crater Lake caldera and roughly Annie Creek. Glacial Features—named for lava forming tuya at Whitehorse Bluff southwest of the caldera.	Regional Volcanism. K-Ar age: 217,000 ± 16,000 years ago near southern extreme of outcrop area; northern portion may be older.
	Regional volcanism, southwest; andesite of Arant Point, lava (PEat), vitric (PEatg), and intrusive (PEati)	Southwest volcanism (Cascades), andesite (Qswa)	Bacon (2008)	Sparsely porphyritic to virtually aphyric andesite (57%–58% SiO_2) comprising the hill in the south-central part of the map area known as Arant Point and the down-faulted tuya to the east. Arant Point is the heavily glaciated light-gray intrusive core (**PEati**) of a cinder cone that marks the vent for light- to medium-gray lava of **PEat**. Cinders are locally preserved in the area mapped as at on the hill of Arant Point. **PEatg** is blocky to finely columnar jointed grayish-black vitric andesite of the chilled margin of the intrusion and carapace of the tuya where lava contacted glacial ice.	Shield Volcanoes and Cinder Cones—southwest of Crater Lake caldera and roughly Annie Creek. Glacial Features—**PEat** forms tuya at Arant Point.	Regional Volcanism. K-Ar age: 297,000 ± 12,000 years ago. Glaciations—MIS 8.
	Mount Mazama; andesite below Rim Village (PEarv)	Mount Mazama preclimactic eruption, andesite (Qmea)	Bacon (2008)	Porphyritic medium-gray andesite (59%–62% SiO_2) forming lower part of southwestern caldera wall between Rim Village and Discovery Point.	Mount Mazama—part of volcano edifice. Glacial Features—**PEarv** overlies glaciated lava surface of **PEab** on southwestern shore of Crater Lake.	Buildup of Mount Mazama. K-Ar age: 302,000 ± 10,000 years ago. Glaciations—MIS 10.
	Mount Mazama; dacite of Sentinel Rock (PEdr)	Mount Mazama preclimactic eruption, dacite (Qmed)	Bacon (2008)	Porphyritic medium-light- to medium-dark-gray dacite lava flows (63%–65.5% SiO_2) in southeastern caldera wall between Skell Head and Kerr Notch. Related fragmental deposit forms lower half of unit approximately 500 m (1,640 ft) south of Skell Head.	Mount Mazama—part of volcano edifice. Glacial Features—**PEdr** overlies glaciated lava surface of **PEak** at Sentinel Rock and Grotto Cove.	Buildup of Mount Mazama. Between about 340,000 and 300,000 years old. Glaciations—MIS 10.
QUATERNARY (Middle? Pleistocene)	Regional volcanism, southwest; basalt northwest of Whitehorse Bluff, lava (PEbxn) and intrusive (PEbxni)	Southwest volcanism (Cascades), basalt (QTswb)	Bacon (2008)	Medium-dark-gray porphyritic basalt and basaltic andesite (51%–54% SiO_2) lava flows (**PEbxn**) and light-gray diabase plug (**PEbxni**) 0.5 km (0.3 mi) north-northwest of Whitehorse Bluff, southwest of the caldera. Intrusive core and flows on top of small cinder cone remnant are coarsely porphyritic basalt.	Shield Volcanoes and Cinder Cones—southwest of Crater Lake caldera and roughly Annie Creek.	Regional Volcanism. Possibly younger than **PEbwc**.
QUATERNARY (Middle Pleistocene)	Regional volcanism, southwest; basaltic andesite west of Arant Point (PEbaw)	Southwest volcanism (Cascades), basaltic andesite (Qswba)	Bacon (2008)	Medium-dark-gray sparsely porphyritic basaltic andesite (55.5%–56% SiO_2) extending approximately 1 km (0.6 mi) west of Arant Point in south-central part of map area where it forms low hill marking probable source. Also exposed locally south and north of Arant Point and in cut along Oregon Highway 62 in scarp of Annie Springs fault near park entrance station where **PEbaw** flow overlies **PEbcw** lavas.	Shield Volcanoes and Cinder Cones—southwest of Crater Lake caldera and roughly Annie Creek.	Regional Volcanism. Probably about 200,000 years old.
	Mount Mazama; andesite of Kerr Notch (PEak)	Mount Mazama preclimactic eruption, andesite (Qmea)	Bacon (2008)	Variably porphyritic andesite and dacite (59%–66% SiO_2; most 60%–63% SiO_2) lava flows exposed in caldera wall from Skell Head (east) to Chaski Bay (south) and in the valleys of Sun and Sand creeks up to 7 km (4 mi) southeast of the caldera.	Mount Mazama—part of volcano edifice. Glacial Features—glaciated lava surfaces at Sentinel Rock and Grotto Cove.	Buildup of Mount Mazama. Between about 340,000 and 300,000 years old. Glaciations—MIS 10.

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	Mount Mazama; dacite of Chaski Bay (PEdb)	Mount Mazama preclimactic eruption, dacite (Qmed)	Bacon (2008)	Porphyritic andesite and dacite (59.5%–67% SiO_2; predominantly low-silica dacite) lava flows and breccia exposed low in the southern caldera wall from Kerr Notch to Rim Village, in Kerr and Munson valleys, and near the headwaters of the Middle and East forks of Annie Creek.	Mount Mazama—part of volcano edifice. Glacial Features—glaciated lava.	Buildup of Mount Mazama. Between about 380,000 and 350,000 years old. Glaciations—MIS 10.
QUATERNARY (Middle Pleistocene)	Mount Mazama; andesite south of Mount Scott (PEams)	Mount Mazama preclimactic eruption, andesite (Qmea)	Bacon (2008)	Porphyritic medium-gray silicic andesite lava (63% SiO_2) forming small dome and flow remnants on southern flank of Mount Scott.	Mount Mazama—part of volcano edifice.	Buildup of Mount Mazama. Stratigraphy and degree of erosion suggest an age of approximately 400,000–300,000 years old.
	Regional volcanism, east; basalt of Sand Ridge lava (PEbsr) and pyroclastic (PEbsrp)	East volcanism (Cascades), basalt (QTeb)	Bacon (2008)	Brownish-gray porphyritic basalt (52% SiO_2) lava (**PEbsr**) and cinders (**PEbsrp**) of eroded cone at southeastern boundary of map area.	Hydrothermal Features and Geothermal Development—exploration east of Crater Lake National Park. Shield Volcanoes and Cinder Cones—east of the longitude of Munson Valley and park headquarters.	Regional Volcanism.
QUATERNARY (Middle Pleistocene?)	Regional volcanism, east; basaltic andesite northeast of Boundary Butte, lava (PEbt) and pyroclastic (PEbtp)	East volcanism (Cascades), basalt andesite (QTeba)	Bacon (2008)	Medium-dark-gray porphyritic basaltic andesite (54.5%–56.5% SiO_2) lava (**PEbt**) and grayish-red cinders (**PEbtp**) of cone 3 km (2 mi) east-northeast of Boundary Butte and low hill 1 km (0.6 mi) farther north, southeastern corner of map area.	Hydrothermal Features and Geothermal Development—exploration east of Crater Lake National Park. Shield Volcanoes and Cinder Cones—east of the longitude of Munson Valley and park headquarters.	Regional Volcanism. Morphology suggests middle Pleistocene age.
QUATERNARY (Middle? Pleistocene)	Mount Mazama; dacite of Phantom Cone (PEdpn)	Mount Mazama preclimactic eruption, dacite (Qmed)	Bacon (2008)	Porphyritic medium-gray dacite forming lowest exposed lava flow below Rim Drive approximately 1 km (0.6 mi) south of Kerr Notch southeast of the caldera. Correlated with identical intrusive dacite (66% SiO_2) feeding lava at the top of Phantom Cone in the southeastern caldera wall.	Mount Mazama—part of volcano edifice.	Buildup of Mount Mazama. Probably the same age as youngest **PEapn**, which has a K-Ar age of 346,000 ± 20,000 years ago.
	Regional volcanism, northwest; basaltic andesite west of Oasis Butte (PEbow)	Northwest volcanism (Cascades), basaltic andesite (QTnwba)	Bacon (2008)	Medium-gray porphyritic basaltic andesite lava near northwestern corner of map area.	Shield Volcanoes and Cinder Cones—northwest of Crater Lake caldera and roughly Crater Creek.	Regional Volcanism.
	Regional volcanism, southwest; basaltic andesite west of Bear Bluff, intrusive (PEbbi) and pyroclastic (PEbbp)	Southwest volcanism (Cascades), basaltic andesite (Qswba)	Bacon (2008)	Medium-gray porphyritic olivine basaltic andesite (53%–54% SiO_2) necks and minor lava (**PEbbi**) and locally adhering grayish-red cinders (**PEbbp**) forming two low hills west of Bear Bluff in south-central part of map area.	Shield Volcanoes and Cinder Cones—northwest of Crater Lake caldera and roughly Crater Creek.	Regional Volcanism.
	Regional volcanism, southwest; basaltic andesite west of Mazama Campground (PEbcw)		Bacon (2008)	Medium-gray porphyritic basaltic andesite (55.5% SiO_2) lava. Named for exposures south-southeast of the caldera along east-facing scarp of Annie Springs fault south of Oregon Highway 62 and provisionally correlated outcrops north of where highway descends into drainage of Castle Creek.	Shield Volcanoes and Cinder Cones—southwest of Crater Lake caldera and roughly Annie Creek.	Regional Volcanism. Possibly early or middle Pleistocene age.
QUATERNARY (Middle Pleistocene)	Mount Mazama; dacite of Mount Scott, lava (PEds), mudflow breccia (PEdsf), and pyroclastic (PEdsp)	Mount Mazama preclimactic eruption, dacite (Qmed)	Bacon (2008)	Porphyritic medium-gray dacite (63.5%–67% SiO_2; most 65% SiO_2) erupted from Mount Scott and related vents to east. Grades from pyroclastic breccia and agglutinate sheets high on Mount Scott itself to massive lava (**PEds**) distally. Related mudflow breccias (**PEdsf**) are locally preserved high on the northern side of Mount Scott; oxidized indurated cinder and agglutinate (**PEdsp**) marks a flank vent on the northeast.	Mount Mazama—along with **PEapn**, oldest lava assigned to Mount Mazama.	Buildup of Mount Mazama. K-Ar ages: 422,000 ± 10,000; 416,000 ± 7,000; and 355,000 ± 8,000 years ago.

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QUATERNARY (Middle? Pleistocene)	Mount Mazama; dacite of Cavern Creek (PEdcc)		Bacon (2008)	Finely porphyritic medium-gray dacite (64.5% SiO_2) lava exposed south-southeast of Mount Scott where Cavern Creek enters Pinnacle Valley and about 1 km (0.6 mi) to the west.	Mount Mazama—part of volcano edifice.	Buildup of Mount Mazama. Probably younger than **PErcc**, which has a K-Ar age of 724,000 ± 5,000 years ago.
QUATERNARY (Middle Pleistocene)	Mount Mazama; andesite of Phantom Cone; lava (PEapn) and intrusive (PEapni)	Mount Mazama preclimactic eruption, andesite (Qmea)	Bacon (2008)	Moderately porphyritic silicic andesite (60.5%–61.5, rarely 63.5% SiO_2) indurated near-vent fall deposits and lava flows (**PEapn**) and dikes and larger intrusions (**PEapni**) of Phantom Cone form approximately the lower half of the southeastern subaerial caldera wall adjacent to Phantom Ship. Phantom Ship island is composed of altered **PEapn** lava flows.	Mount Mazama—oldest lava of Mount Mazama exposed above lake level in caldera.	Buildup of Mount Mazama. K-Ar ages: 403,000 ± 12,000 years ago at lake level southeast of Phantom Ship; 346,000 ± 20,000 years ago at lake level at Kerr Notch.
	Regional volcanism, southwest; basaltic andesite of Whitehorse Creek; lava (PEbwc), intrusive (PEbwci), and pyroclastic (PEbwcp)	Southwest volcanism (Cascades), basaltic andesite (Qswba)	Bacon (2008)	Medium-gray finely porphyritic basaltic andesite (53.5%–54.5% SiO_2) lava flows (**PEbwc**), palagonitic tuff (**PEbwcp**), and light-gray dike (**PEbwci**) north of Whitehorse Bluff and approximately 0.7 km (0.4 mi) east of Whitehorse Creek, southwest of the caldera. Dike forms 800-m- (2,630-ft-) long, north–south ridge of unnamed hill at elevation 1,854 m (6,082 ft).	Shield Volcanoes and Cinder Cones—southwest of Crater Lake caldera and roughly Annie Creek.	Regional Volcanism. K-Ar age of **PEbwci** sample of 1,379,000 ± 22,000 years ago appears to be inconsistent with field relations.
	Pre-Mazama volcanism; rhyodacite of Pothole Butte; felsite (PErpb) and vitrophyre (PErpbv)	East volcanism (Cascades), rhyodacite (Qer)	Bacon (2008)	Porphyritic light- to medium-gray and light-brownish-gray felsite (**PErpb**) and local dark-gray vitrophyre (**PErpbv**) (71.5%–73% SiO_2) lava domes and thick lava flows east and south of Mount Mazama. **PErpbv** is not mapped within Crater Lake National Park.	Hydrothermal Features and Geothermal Development—exploration east of Crater Lake National Park. Pre-Mazama rhyodacite.	Pre-Mazama Volcanism. K-Ar ages: 468,000 ± 9,000 years ago (west of Sun Creek) and 448,000 ± 8,000 years ago (Pothole Butte).
	Pre-Mazama volcanism; rhyodacite south of Crater Peak (PErcs)		Bacon (2008)	Porphyritic light- to medium-gray and light-brownish-gray felsite and local dark-gray vitrophyre (71%–72% SiO_2) lava flows south of the caldera, west of Sun Creek, and south of Crater Peak. Phenocryst content and chemical composition distinguish **PErcs** from other pre-Mazama rhyodacites.	Hydrothermal Features and Geothermal Development—exploration east of Crater Lake National Park. Pre-Mazama rhyodacite.	Pre-Mazama Volcanism. Estimated at 550,000–450,000 years old.
	Pre-Mazama volcanism; rhyodacite of Scott Creek (PErsc)	East volcanism (Cascades), rhyodacite (Qer)	Bacon (2008)	Porphyritic light- to medium-gray and light-brownish-gray felsite and local medium-dark-gray vitrophyre (68%–71.5% SiO_2) lava domes and lava flows east and south of Mount Mazama.	Hydrothermal Features and Geothermal Development—exploration east of Crater Lake National Park. Pre-Mazama rhyodacite.	Pre-Mazama Volcanism. Estimated at 550,000–450,000 years old.
QUATERNARY (Middle? Pleistocene)	Regional volcanism, east; andesite of Sand Creek quarry (PEaq)	East volcanism, andesite (Qea)	Bacon (2008)	Porphyritic medium-gray olivine andesite (59% SiO_2) lava exposed at top of north–northeast-oriented down-to-the-east normal fault scarp from vicinity of Sand Creek to northern flank of low hill at elevation 1,652 m (5,420 ft), approximately 2.5 km (1.6 mi) south of Sand Creek Pinnacles; forms upper lava flow at Sand Creek quarry; also exposed in cut on Oregon Highway 232 at 1,555 m (5,100 ft) in elevation (southeastern corner of map area).	Hydrothermal Features and Geothermal Development—exploration east of Crater Lake National Park. Shield Volcanoes and Cinder Cones—east of the longitude of Munson Valley and park headquarters.	Regional Volcanism.
QUATERNARY (Middle Pleistocene)	Regional volcanism, southwest; andesite north of Castle Creek, lava (PEacc) and pyroclastic (PEaccp)	Southwest volcanism (Cascades), andesite (Qswa)	Bacon (2008)	Sparsely porphyritic medium-gray to medium-dark-gray andesite (58.5% SiO_2) lava flows (**PEacc**) on the ridge north of Little Castle and Castle Creeks and descending to Castle Creek near the western boundary of Crater Lake National Park; eroded cinder cone (**PEaccp**) forms highest point of the ridge.	Shield Volcanoes and Cinder Cones—southwest of Crater Lake caldera and roughly Annie Creek.	Regional Volcanism. K-Ar age: 587,000 ± 18,000 years ago.
	Regional volcanism, east; andesite northeast of Annie Falls (PEaaf)	East volcanism (Cascades), andesite (Qea)	Bacon (2008)	Dark-gray porphyritic andesite (57.5% SiO_2) flow exposed at base of cliffs 1 km (0.6 mi) north–northeast of Annie Falls, south-central part of map area. Joint pattern suggests source north–northeast of outcrops.	Shield Volcanoes and Cinder Cones—east of the longitude of Munson Valley and park headquarters.	Regional Volcanism. K-Ar age: 517,000 ± 15,000 years ago.

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QUATERNARY (Middle? Pleistocene)	Regional volcanism, east; basaltic andesite east of Cavern Creek (PEbep)	East volcanism (Cascades), basaltic andesite (QTeba)	Bacon (2008)	Grayish-red basaltic andesite (52.5% SiO_2) cinders and bombs locally exposed on eroded cinder cone east of Cavern Creek southeast of Mount Scott.	Shield Volcanoes and Cinder Cones—east of the longitude of Munson Valley and park headquarters.	Regional Volcanism. Appears to be older than **PErsc**, which has a K-Ar age of 415,000 ± 11,000 years ago.
	Regional volcanism, east; andesite south of Sand Creek, lava (PEacs) and pyroclastic (PEacsp)	East volcanism, andesite (Qea)	Bacon (2008)	Sparsely porphyritic medium-gray hornblende andesite (61.5%–62.5% SiO_2) lava (**PEacs**) and cinders (**PEacsp**) poorly exposed on low hill at elevation 1,652 m (5,420 ft) marking vent approximately 2.5 km (1.5 mi) south of Sand Creek Pinnacles, southeastern part of map area.	Shield Volcanoes and Cinder Cones—east of the longitude of Munson Valley and park headquarters.	Regional Volcanism.
QUATERNARY (Middle? Pleistocene)	Regional volcanism, east; basaltic andesite east of Dry Butte (PEbdp)	East volcanism (Cascades), basaltic andesite (QTeba)	Bacon (2008)	Medium-dark-gray porphyritic basaltic andesite (56% SiO_2) bombs and grayish-red cinders locally exposed on small cinder cone approximately 4 km (2.5 km) east of Dry Butte near the southeastern edge of map area.	Shield Volcanoes and Cinder Cones—east of the longitude of Munson Valley and park headquarters.	Regional Volcanism. Morphology suggests middle Pleistocene age.
	Regional volcanism, east; basaltic andesite of Boundary Butte (PEbap)		Bacon (2008)	Medium-dark-gray porphyritic basaltic andesite (53% SiO_2) agglutinate and grayish-red cinders exposed in upper part of Boundary Butte cinder cone in southeastern corner of map area.	Shield Volcanoes and Cinder Cones—east of the longitude of Munson Valley and park headquarters.	Regional Volcanism. Morphology suggests middle Pleistocene age.
QUATERNARY (Middle Pleistocene)	Regional volcanism, east; andesite of Sun Creek (PEas)	East volcanism (Cascades), andesite (Qea)	Bacon (2008)	Porphyritic medium-gray andesite (62.5% SiO_2) lava cropping out at northeastern end of Sun Creek valley at elevation 1,890 m (6,200 ft), south of the caldera.	Shield Volcanoes and Cinder Cones—east of the longitude of Munson Valley and park headquarters.	Regional Volcanism. K-Ar age: 623,000 ± 16,000 years ago.
	Pre-Mazama volcanism; dacite west of the Pinnacles (PEdw)	East volcanism (Cascades), dacite (QTed)	Bacon (2008)	Coarsely porphyritic medium-gray dacite (64%–65% SiO_2) lava domes west of the Pinnacles and at the western base of Maklaks Pass, southeast of the caldera.	Pre-Mazama dacite.	Pre-Mazama Volcanism K-Ar age: 612,000 ± 8,000 years ago below Maklaks Pass.
	Regional volcanism, east; basaltic andesite north of Lookout Butte (PEblp)	East volcanism (Cascades), basaltic andesite (QTeba)	Bacon (2008)	Medium-gray porphyritic basaltic andesite (53% SiO_2) lava and grayish-red cinders (**PEblp**) exposed on small cinder cone approximately 1 km (0.6 mi) north-northwest of Lookout Butte in northeastern corner of map area.	Shield Volcanoes and Cinder Cones—east of the longitude of Munson Valley and park headquarters.	Regional Volcanism. K-Ar age: 605,000 ± 25,000 years ago.
	Regional volcanism, east; andesite west of Sand Creek (PEasw)	East volcanism, andesite (Qea)	Bacon (2008)	Sparsely porphyritic medium-dark-gray silicic andesite or low-silica dacite (62.5% SiO_2) lava cropping out in two places at western edge of valley of Sand Creek at approximately 1,860 m (6,100 ft) and 1,920 m (6,300 ft) in elevation, southeast of the caldera.	Shield Volcanoes and Cinder Cones—east of the longitude of Munson Valley and park headquarters.	Regional Volcanism. K-Ar age: 670,000 ± 12,000 years ago.
	Regional volcanism, east; basaltic andesite east of Annie Falls (PEbaf)	East volcanism (Cascades), basaltic andesite (QTeba)	Bacon (2008)	Medium-gray porphyritic basaltic andesite lava flow(s) (52.5% SiO_2) forming canyon wall east of Annie Falls, south-central part of map area.	Shield Volcanoes and Cinder Cones—east of the longitude of Munson Valley and park headquarters.	Regional Volcanism. K-Ar age: 651,000 ± 28,000 years ago.
	Pre-Mazama volcanism; rhyodacite west of Cavern Creek (PErcc)	East volcanism (Cascades), rhyodacite (Qer)	Bacon (2008)	Light-gray felsite and rare black obsidian of deeply eroded, poorly exposed lava dome of hill at elevation 2,015 m (6,610 ft) (73% SiO_2) and altered porphyritic light-gray felsite of eastern Anderson Bluffs (72.5% SiO_2) south of Mount Scott.	Pre-Mazama rhyodacite.	Pre-Mazama Volcanism. K-Ar age of dome 724,000 ± 5,000 years ago.
QUATERNARY (Middle or Early Pleistocene)	Regional volcanism, southwest; basalt of Castle Creek (PEbcc)	Southwest volcanism (Cascades), basalt (QTswb)	Bacon (2008)	Medium-gray porphyritic basalt (47.5% SiO_2) lava flows exposed in Castle Creek near confluence with Little Castle Creek.	Shield Volcanoes and Cinder Cones—southwest of Crater Lake caldera and roughly Annie Creek.	Regional Volcanism. Provisionally correlated with 1-million-year-old flows west of map area along Rogue River.

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QUATERNARY (Early Pleistocene)	Pre-Mazama volcanism; basaltic andesite of Bert Creek, mudflow (PEbbf)	Northwest volcanism (Cascades), basaltic andesite (QTnwba)	Bacon (2008)	Weathered monolithologic mudflow deposit (**PEbbf**) with clasts as large as 40 cm (16 in) underlying glacial till on high ground in northwestern corner of map. Associated with basaltic andesite lava flows (**PEbbc**).	None reported.	Regional Volcanism. Undated but overlies **PEbck**, which has a K-Ar age of 1,879,000 ± 22,000 years ago.
QUATERNARY (Early? Pleistocene)	Regional volcanism, southwest; basaltic andesite northwest of Little Castle Creek (PEbln)	Southwest volcanism (Cascades),basaltic andesite (Qswba)	Bacon (2008)	Medium-gray porphyritic basaltic andesite (54.5%–55.5% SiO_2) lava on northern wall of valley of Castle Creek west of confluence with Little Castle Creek, southwest of the caldera.	Shield Volcanoes and Cinder Cones—southwest of Crater Lake caldera and roughly Annie Creek.	Regional Volcanism.
QUATERNARY (Early Pleistocene)	Regional volcanism, southwest; basalt north of Castle Creek (PEbcn)	Northwest volcanism (Cascades), basaltic andesite (QTnwba)	Bacon (2008)	Medium-light-gray porphyritic basalt flows north of Castle Creek near western boundary of map (outside the park). Undated but overlain by unit PEacc, which has K-Ar age of 587,000 ± 18,000 years ago.	None reported.	Regional Volcanism.
	Regional volcanism, southwest; basaltic andesite of Castle Point (PEbac)	Southwest volcanism (Cascades),basaltic andesite (Qswba)	Bacon (2008)	Medium-gray sparsely porphyritic basaltic andesite (52.5%–54% SiO_2) of ridge below approximately 1,860 m (6,100 ft) in elevation, southwest of caldera and nearby lower part of canyon wall north of Castle Creek, approximately 1,585 m (5,200 ft) in elevation. Source vent probably was north of Castle Point.	Shield Volcanoes and Cinder Cones—southwest of Crater Lake caldera and roughly Annie Creek. Glacial Features—ridge of Castle Point is glaciated.	Regional Volcanism.
	Pre-Mazama volcanism; dacite of Sand Creek (PEdsc)	East volcanism (Cascades), dacite (QTed)	Bacon (2008)	Porphyritic medium-light- to medium-dark-gray dacite (65.5%–68% SiO_2) domes forming low hills between Sand Creek and Dry Butte near southeastern edge of map area.	Pre-Mazama dacite.	Pre-Mazama Volcanism. K-Ar age: 1,058,000 ± 16,000 years ago.
	Regional volcanism, east; andesite south of Dry Butte (PEadsi)	East volcanism, andesite (Qea)	Bacon (2008)	Medium-gray porphyritic andesite (57% SiO_2) of plug and minor flows exposed on northeastern flank of hill immediately south of Dry Butte, southeastern part of map area.	Shield Volcanoes and Cinder Cones—east of the longitude of Munson Valley and park headquarters.	Regional Volcanism. K-Ar age 1,088,000 ± 13,000 years ago.
	Pre-Mazama volcanism; basaltic andesite of Bert Creek, lava (PEbbc)	Northwest volcanism (Cascades), basaltic andesite (QTnwba)	Bacon (2008)	Dark-gray finely porphyritic basaltic andesite lava flows (**PEbbc**) underlying glacial till on high ground in northwestern corner of map. Distinguished from underlying basalt flows by abundant conspicuous plagioclase. Associated with mudflow deposit (**PEbbf**).	None reported.	Regional Volcanism. Undated but overlies unit **PEbck**, which has K-Ar age of 1,879,000 ± 22,000 years ago.
	Pre-Mazama volcanism; dacite of Dry Butte (PEdd)	East volcanism (Cascades), dacite (QTed)	Bacon (2008)	Porphyritic light-greenish-gray hornblende dacite (63% SiO_2) of poorly exposed domes near southeastern edge of map area that form Dry Butte.	Pre-Mazama dacite.	Pre-Mazama Volcanism. K-Ar age: 1,275,000 ±14,000 years ago.
	Regional volcanism, northwest; basaltic andesite north of Crater Creek (PEbck)	East volcanism (Cascades), dacite (QTed)	Bacon (2008)	Medium-gray sparsely porphyritic basaltic andesite flows underlying the bulk of the high area in the northwestern corner of the map area between the drainages of Crater and National creeks and bounded on the east by fault-line scarp. May contain flows of differing ages and source vents.	None reported.	Regional Volcanism. K-Ar age: 1,879,000 ± 22,000 years ago.

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QUATERNARY (Pleistocene)	Mount Mazama; submerged outcrops of the caldera walls, undivided (PEsu)	Submerged caldera walls (scw)	Bacon (2008)	Bedrock outcrops submerged below the surface of Crater Lake. Have not been correlated with exposed map units.	Slope Movements—some of the deeper outcrop areas may be large slump blocks. Mount Mazama—part of Mount Mazama edifice. Crater Lake Caldera and Fill, Bathymetic Data—revealed during 2000 survey.	Buildup of Mount Mazama and pre-Mazama volcanism.
QUATERNARY (Pleistocene)	Glaciogenic deposits (PEgd)	Glacial deposits (Qg)	Sherrod (1991)	Till and outwash deposited during Pleistocene glacial advances, divided into Drift—stratified and unstratified deposits (mostly till) that form ground, lateral, and terminal moraines. Includes minor alluvium where reworked by streams. Grades upslope into talus and colluvium. Outwash—poorly to moderately sorted, unconsolidated to well-consolidated sand and gravel that form terraces along North Umpqua River, and Salmon and Hills creeks. Locally overlain by late Pleistocene lava flows.	Glacial Features—till and outwash deposits.	Chiefly Wisconsinan (late Pleistocene) but may include older deposits.
QUATERNARY (Pleistocene)	Older basaltic andesite (PEoba)	Northwest volcanism (Cascades), basaltic andesite (QTnwba)	Sherrod (1991)	Lava flows and breccia petrographically similar to younger basaltic andesite (**Qyba**) but associated with moderately eroded vents or not assignable to a particular vent. Divided into older basalt (**PEob**) and older andesite (**PEoa**).	None reported.	Regional Volcanism. Mostly younger than 730,000 years old.
QUATERNARY (Pleistocene)	Older basalt (PEob)	Northwest volcanism (Cascades), basalt (QTnwb)	Sherrod (1991)	Lava flows and breccia similar to older basaltic andesite (**PEoba**) but of basaltic composition.	None reported.	Regional Volcanism. Mostly younger than 730,000 years old.
QUATERNARY (Pleistocene)	Older andesite (PEoa)	Northwest volcanism (Cascades), andesite (QTnwa)	Sherrod (1991)	Lava flows and breccia similar to older basaltic andesite (**PEoba**) but of andesitic composition.	None reported.	Regional Volcanism. Mostly younger than 730,000 years old.
QUATERNARY-TERTIARY (Holocene? to Pliocene)	Mafic vent deposits (QTmv)	Cascades volcanism, mafic vent deposits (QTcmvd)	Sherrod (1991)	Poorly to well-bedded, thin- to very thick-bedded tuff, lapilli tuff, and tuff breccia ranging from basalt to basaltic andesite. Comprises chiefly red to black cinders and agglutinate, yellow to brown palagonitic tuff, lesser lithic breccia, and minor lava flows and intrusions.	None reported.	Regional Volcanism. Pliocene, Pleistocene, and late Holocene (?), as inferred from age of adjacent lava flows (e.g., **QTba**, **Qoba**, and **Qyba**).
QUATERNARY -TERTIARY (Pleistocene or Pliocene)	Regional volcanism, southwest; basaltic andesite, undivided, lava (QTb)	Southwest volcanism (Cascades), basaltic andesite (Qswba)	Bacon (2008)	Light- to dark-gray variably porphyritic basaltic andesite lava flows.	None reported.	Regional Volcanism.
QUATERNARY-TERTIARY (Pleistocene or Pliocene)	Regional volcanism, southwest; basaltic andesite of Union Creek, lava (QTbuc) and intrusive (QTbuci)	Southwest volcanism (Cascades), basaltic andesite (Qswba)	Bacon (2008)	Medium-gray to brownish-gray porphyritic basaltic andesite (52%–55% SiO_2) lava flows (**QTbuc**; locally includes cinders north of Rocktop Butte) and intrusive rock (**QTbuci**) near the headwaters of Union Creek in southwestern corner of map area. Consists mainly of lavas and intrusive core of dissected Rocktop Butte volcano but also includes related (?) intrusion of south-facing slopes northwest of Varmint Creek; dike near hill at elevation 1,771 m (5,811 ft), 1.1 km (0.7 mi) southeast of Varmint Camp; and patch of diktytaxitic basalt at 1, 646 m (5,400 ft) in elevation, 1.0 km (0.6 mi) south of Varmint Camp.	Shield Volcanoes and Cinder Cones—southwest of Crater Lake caldera and roughly Annie Creek.	Regional Volcanism.

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QUATERNARY-TERTIARY Pleistocene and Pliocene)	Basaltic andesite (QTba)	Northwest volcanism (Cascades), basaltic andesite (QTnwba)	Smith et al. (1982); Sherrod (1991)	Slightly to moderately porphyritic lava flows and breccia west of Crater Lake National Park and at Garwood Butte. Includes minor basalt and andesite. Lava at Garwood Butte is chiefly basaltic andesite and has blue-gray microvesicular olivine and olivine-bearing flows forming deeply eroded coalescing shield volcanoes along the crest of the Cascade Range.	None reported.	Regional Volcanism. K-Ar age of 1,870,000 ± 60,000 years ago.
	Mafic intrusive rocks (QTmi)	Southwest volcanism (Cascades), basaltic andesite (Qswba)	Smith et al. (1982)	No description provided.	None reported.	Regional Volcanism.
	Intrusive rocks (QTi)	Cascades volcanism, intrusive rocks and dikes (QTcin)	Sherrod (1991)	Plugs of basalt, basaltic andesite, and andesite, chiefly conduit-filling necks and shallow intrusions of volcanoes. Volcanoes younger than about 250,000 years old are only slightly eroded, and their intrusions are not exposed.	None reported.	Regional Volcanism. Pliocene and Pleistocene in age, as inferred from surrounding lava flows (**QTba** and **Qoba**) that are cut or fed by intrusions.
QUATERNARY-TERTIARY	Basaltic andesite of Boundary Butte (QTbdy)	East volcanism (Cascades), basaltic andesite (QTeba)	Jenks et al. (2008)	Massive basaltic andesite.	Hydrothermal Features and Geothermal Development—exploration east of Crater Lake National Park.	Regional Volcanism.
TERTIARY (Pliocene)	Basalt of Copeland Canyon (Tcop)	East volcanism (Cascades), basalt (QTeb)	Jenks et al. (2008)	No unit description provided.	Hydrothermal Features and Geothermal Development—exploration east of Crater Lake National Park.	Regional Volcanism.
	Dacite (Tdac)	East volcanism (Cascades), dacite (QTed)	Jenks et al. (2008)	Thinly layered dacite.	Hydrothermal Features and Geothermal Development—exploration east of Crater Lake National Park.	Regional Volcanism.
	Basaltic andesite of Wood River Spring (Twod)	East volcanism (Cascades), basaltic andesite (QTeba)	Jenks et al. (2008)	No unit description provided.	Hydrothermal Features and Geothermal Development—exploration east of Crater Lake National Park.	Regional Volcanism.
TERTIARY (Pliocene and Miocene)	Diatomite and volcaniclastic sediments (Td)	Diatomite and volcaniclastic sediments (Tdvs)	Smith et al. (1982)	Flat-lying lake beds and deltaic beds in the upper Rogue River Valley.	None reported.	None reported.
TERTIARY (Pliocene and upper Miocene)	Volcanic rock of the High Cascade Range, basalt (Tb)	Southwest volcanism (Cascades), basalt (QTswb)	Smith et al. (1982)	Fine-grained high-alumina olivine basalt flows and deeply incised coarse-grained diktytaxitic olivine basalt flows. Forms subdued and greatly eroded shields. Areas underlain by this unit are generally covered by thick clay-rich red soils.	None reported.	Regional Volcanism.
	Volcanic rock of the High Cascade Range; basaltic andesite (Tba)	Southwest volcanism (Cascades), basaltic andesite (QTswba)	Smith et al. (1982)	The most common lithology is light-blue-gray fine-grained high-alumina olivine basaltic andesite. Occurs as large deeply eroded coalescing shield volcanoes, interbedded cogenetic near-vent pyroclastic deposits, and extensive valley-filling flows.	None reported.	Regional Volcanism.
	Volcanic rock of the High Cascade Range; andesite (Ta)	Southwest volcanism (Cascades), andesite (QTswa)	Smith et al. (1982)	Mostly pyroxene andesite, but contains rocks with a variety of textures and mineralogies. Occurs as deeply eroded large composite volcanoes, steep-sided shields, smaller vent areas, and extensive valley-filling flows.	None reported.	Regional Volcanism.

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TERTIARY (Pliocene and upper Miocene)	Volcanic rock of the High Cascade Range; intermediate intrusive rocks (Tii)	Southwest volcanism (Cascades), andesite (QTswa)	Smith et al. (1982)	No unit description provided.	None reported.	Regional Volcanism.
TERTIARY (Pliocene and upper Miocene)	Mafic vent deposits (Tmv)	Cascades volcanism, mafic vent deposits (QTcmvd)	Sherrod (1991)	Near-vent tuff, lapilli tuff, and tuff breccia of basalt and basaltic andesite volcanoes.	None reported.	Regional Volcanism. Similar to younger basaltic vents (**QTmv**) but early Pliocene and older in age, as inferred from adjacent or overlying strata.
TERTIARY (Miocene)	Basalt and andesite of Western Cascades; basalt (Twb)	Northwest volcanism (Cascades), basalt (QTnwb)	Sherrod (1991)	Basalt lava flows and breccia of slightly porphyritic basalt and basaltic andesite.	None reported.	Regional Volcanism.
TERTIARY (Miocene)	Basalt and andesite of Western Cascades; andesite (Twa)	Northwest volcanism (Cascades), andesite (QTnwa)	Sherrod (1991)	Andesite lava flows and breccia of slightly porphyritic two-pyroxene andesite and minor amounts of basaltic andesite, hornblende andesite, dacite, and quartz-bearing rhyodacite or rhyolite. Includes some tuff, tuff breccia, and lapilli tuff.	None reported.	Regional Volcanism.
TERTIARY (Miocene)	Basalt and andesite of Western Cascades; tuffaceous volcaniclastic rocks (Twt)	Northwest volcanism (Cascades), basaltic andesite (QTnwba)	Sherrod (1991)	Thin- to very thick-bedded debris- and pyroclastic-flow deposits, tuffaceous sandstone, and breccia. Includes minor interbedded andesite lava flows. Pyroclastic flows are predominantly intermediate and silicic in composition.	None reported.	Regional Volcanism.
TERTIARY (Miocene and Oligocene)	Little Butte volcanics; andesite (Tla)	Northwest volcanism (Cascades), andesite (QTnwa)	Sherrod (1991)	Predominantly tuffaceous volcaniclastic rocks (chiefly andesite to rhyodacite in composition), fewer andesite lava flows, and minor basalt lava flows and silicic domes.	None reported.	Regional Volcanism. Lower part of sequence mostly younger than 24 million years old. Regionally, oldest part of the Little Butte volcanics is about 35 million years old. K-Ar ages near top of section are about 19 million–17 million years old.