



**VOLCANO AND EARTHQUAKE HAZARDS
IN THE
CRATER LAKE REGION, OREGON**

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COVER: *View of Crater Lake from the south rim of the caldera. The caldera formed 7,700 years ago by collapse of the volcano known as Mount Mazama during the largest explosive volcanic eruption in the past 400,000 years in the Cascades. The lava flows and volcanic deposits exposed in the caldera walls record the growth of Mount Mazama, which attained an elevation of roughly 12,000 feet before the caldera collapsed. The prominent cliff on the north rim of the caldera is Lloa Rock, a lava flow that was erupted just 200 years before the caldera-forming eruption. The cinder cone and lava flows of Wizard Island were erupted within a few hundred years of formation of Crater Lake caldera. Photo by David E. Wieprecht.*

U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

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by

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Summary*

Crater Lake lies in a basin, or *caldera*, formed by collapse of the Cascade volcano known as Mount Mazama during a violent, *climactic eruption* about 7,700 years ago. This event dramatically changed the character of the volcano so that many potential types of future events have no precedent there. This potentially active volcanic center is contained within Crater Lake National Park, visited by 500,000 people per year, and is adjacent to the main transportation corridor east of the Cascade Range. Because a lake is now present within the most likely site of future volcanic activity, many of the hazards at Crater Lake are different from those at most other Cascade volcanoes. Also significant are many faults near Crater Lake that clearly have been active in the recent past. These faults, and historic seismicity, indicate that damaging earthquakes can occur there in the future. This report describes the various types of volcano and earthquake hazards in the Crater Lake area, estimates of the likelihood of future events, recommendations for mitigation, and a map of hazard zones. The main conclusions are summarized below.

VOLCANIC ERUPTIONS WITHIN CRATER LAKE CALDERA—The only volcanic eruptions in the Crater Lake area since the climactic eruption and formation of the caldera have taken place within the caldera itself. The most recent of these was about 5,000 years ago. Future eruptions may occur within the lake where interaction of *magma* (molten rock) and water may produce explosions that can eject *ballistics* (large rock fragments) and volcanic *ash* (rock and volcanic glass fragments smaller than 2 millimeters in diameter) outside of the caldera. Some of the ejected material would rise into the atmosphere along with expanding gas and result in blanketing of the area downwind by falling *tephra* (fragments of rock, frothy bits of magma, and finer-grained ash). Such explosions also can generate *pyroclastic surges*, ground-hugging flows of gas, steam, volcanic rock fragments, and ash moving at speeds that may exceed 100 meters per second (200 miles per hour) and which have the potential to devastate not only the area within the caldera (plate 1, Proximal Hazard Zone A) but also the valleys and upper slopes of Mount Mazama (plate 1, Proximal Hazard Zone B). Eruptions from *vents* in

* Technical terms which appear in bold italics in this report are defined in the glossary. A more comprehensive glossary, descriptions of types of volcanic activity in the Cascades, and more information on volcanoes can be found at the USGS Cascades Volcano Observatory World Wide Web site. URL: <http://vulcan.wr.usgs.gov> The book by Decker and Decker (1989) gives an illustrated, non-technical overview of volcanoes. The book by Francis (1993) is more technical and includes many case histories.

shallow water may be highly explosive while those in the deep lake would be expected to be much less violent. An eruption from a vent in the caldera wall itself also might be explosive because of the abundant groundwater within the mountain. Waves on Crater Lake several meters high could be associated with explosive eruptions within the caldera. Because postcaldera volcanoes are concentrated there, the west half of the caldera is considered the most likely site of future activity. The 30-year probability of renewed volcanic activity within or very near to the caldera is greater than one chance in 330, or 3×10^{-3} . The area within the proximal hazard zones is entirely within Crater Lake National Park where access can be controlled and the potential for loss of life can be minimized by closure of appropriate areas at the onset of seismicity or other phenomena deemed precursory to volcanic activity. The possibility of explosive eruptions that may produce ballistic rock fragments or pyroclastic surges mandates that access to the caldera and the proximal hazard zones be controlled.

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 Cascade volcanoes (for example, Mount Rainier) have produced lahars in the past and are likely to continue to do so. Crater Lake differs from them in that no ice-clad summit or fragile mountaintop remains as a source of water and debris at high elevation. However, should an eruption occur within Crater Lake near the shoreline with sufficient violence 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 resulted in rapid melting of a thick snowpack similarly might produce lahars. Such lahars would be localized in low-lying areas and would tend to be confined to narrow canyons (plate 1, Lahar Hazard Zone). Because of this, and the lack of development within much of the lahar hazard zone, the degree to which communities outside the park need to prepare for inundation by lahars is limited to recognition that such a hazard exists in the drainages around Mount Mazama.

ERUPTIONS OUTSIDE OF THE CALDERA— The Oregon Cascades include many small volcanoes around and between the large volcanoes such as Mount Mazama. These small volcanoes include *cinder cones*, fissure vents, lava *domes*, and *shield volcanoes*, each of which formed in a brief period of time. They are the result of *regional volcanism*. Hazards include slow-moving lava flows and viscous domes, and associated tephra falls, surges, and pyroclastic flows. If surges or *pyroclastic flows* occur, such as might be expected for an eruption in a low-lying (wet) location, the area affected by them likely would be only a few square kilometers. Tephra falls may be significant near the vent and for a few kilometers downwind. Lava flows will advance slowly enough that they will pose a threat only to property and structures. Because exact locations of future eruptions cannot be predicted, we have estimated annual and 30-year probabilities of an eruption occurring in a particular area. The two hazard zones for regional volcanism shown on plate 1 (RH and RL) indicate higher probabilities approximately west of the main axis of the Cascades and lower probabilities to the east. The probability of eruption of a new volcanic vent near Crater Lake is sufficiently small (30-year probability = 3×10^{-3} to 3×10^{-4}) that potential hazards from regional volcanism need only be considered significant when even this small degree of risk to a specific facility is unacceptable.

VOLCANO-RELATED EVENTS OF HIGH CONSEQUENCE BUT LOW PROBABILITY— (1) *A large pyroclastic eruption*, such as the one during which the caldera formed or the (smaller) 1991 eruption of Mount Pinatubo, Philippines, is not considered likely for many thousands of years in the future because the magma reservoir which fed the climactic eruption of Mount Mazama has not had sufficient time to regenerate a large volume of gas-rich magma. (2) *Sudden gas release from Crater Lake* would seem to be a possibility by comparison with the lethal release of cold carbon dioxide gas from Lake Nyos, Cameroon, in 1986. However, natural mixing of deep water with near-surface water in Crater Lake prevents volcanic carbon dioxide from accumulating near the lake bottom. As long as the natural mixing process continues, sudden gas release is not considered to be a significant hazard at Crater Lake. (3) *Catastrophic draining of Crater Lake*

is an extremely unlikely event but one which would have disastrous consequences for downstream lowlands in the affected tributary drainages. There appears to be no mechanism, short of another caldera-forming eruption, that could either eject most of the water in the lake or cause the caldera wall to fail.

EARTHQUAKES—The West Klamath Lake fault zone (WKLFZ), composed of several individual faults with lengths of up to 15 km and an aggregate length of 50 to 70 km, has been mapped through Crater Lake National Park west of the caldera (plate 1). One of its constituent faults, the Annie Spring fault, passes less than 1 km west of Rim Village. All of the faults of the WKLFZ trend approximately north–south and have mainly dip-slip displacement such that the east side is dropped down relative to the west side. By determining the ages of lava flows that have been offset by the faults, the long-term rate of vertical displacement is known to be about 0.3 millimeters per year. The lengths of the faults and the measured displacements suggest that the WKLFZ is capable of **tectonic earthquakes** as large as magnitude (M) $7^{1/4}$. The recurrence interval of large earthquakes is unknown but probably is between 3,000 and 10,000 years. Although few earthquakes have been recorded in the Crater Lake area, the known events are consistent with the WKLFZ being active. Moreover, the September 1993, Klamath Falls earthquakes (the two largest events were $M \approx 6.0$) occurred farther south along the same general zone. Many other potentially active faults are present east of the Cascades, notably along the east side of Klamath valley (East Klamath Lake fault zone). Local volcanic earthquakes would produce ground motion at Crater Lake but the likely maximum magnitude of such events is about 5, significant but far smaller than for tectonic earthquakes. An additional source of earthquakes is the Cascadia subduction zone, the fault zone that forms the boundary between the tectonic plates that contain the North American continent and the Pacific Ocean floor. Although distant, the potential for this zone to generate $M = 8 - 9$ earthquakes means that shaking of up to several minutes duration could occur at Crater Lake.

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. Rockfalls and landslides are significant hazards below steep canyon or caldera walls. 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. Volcanic, local tectonic, or distant Cascadia subduction zone earthquakes all could produce shaking adequate to trigger sliding of the fractured and poorly consolidated rock of the caldera walls and talus slopes. Earthquake shaking alone, without rapid entry of slide material into Crater Lake, would not be expected to cause dangerous waves.

INTRODUCTION

Crater Lake National Park is visited by about 500,000 people each year, with heaviest use during the summer months. Crater Lake partially fills a type of volcanic depression called a **caldera** that formed by collapse of a 12,000 foot volcano known as Mount Mazama during an enormous pyroclastic eruption approximately 7,700 years ago. Although this Cascade volcano does not directly threaten large population centers, it does pose a hazard to facilities and people at Crater Lake National Park and to the major transportation corridor east of the Cascades. The ultimate causes of volcanic activity at all Cascade volcanic centers are linked by common processes. However, Crater Lake is unique in many regards, and potential effects of future activity cannot be anticipated by analogy with past eruptions there or at other Cascade volcanoes. Profound changes occurred at Crater Lake about 7,700 years ago that affect the type of eruptions that can occur and the consequences of such events for the surrounding area. This report attempts to forecast what may happen in such future, but largely unprecedented events.

The caldera-forming or **climactic eruption** of Mount Mazama changed the landscape all around the volcano. **Pyroclastic flows** devastated the surrounding area, including all of the river valleys that drained Mount Mazama to as far as 70 km away, and a blanket of pumice and **ash** fell to the northeast of

the volcano at least as far as southern Canada. Erosion removed much of this material, feeding rivers that carried it far from its source, ultimately into the Pacific Ocean. Prior to the climactic event, Mount Mazama had a 400,000 year history of activity more like that of other Cascade volcanic centers such as Mount Shasta. Since the climactic eruption, there have been several less violent, smaller **postcaldera eruptions** within the caldera itself. In addition, many short-lived volcanoes have erupted at various times in the Crater Lake region, most recently about 10,000 years ago. We recognize that volcanic hazards at Crater Lake fall into two main categories: eruptions within the caldera, reflecting reawakening of the Mazama system, in which Crater Lake itself plays an important role in determining eruptive violence, and eruptions from new **vents** in the surrounding region.

Volcanic eruptions are not the only geologic hazards at Crater Lake. The Crater Lake region is cut by many faults, some of which are capable of producing damaging earthquakes (*e.g.*, Klamath Falls, September 1993). Not only do earthquakes pose direct hazards to people and structures but they also can cause rockfalls and landslides which, if they entered the lake rapidly, could produce life-threatening waves. Consequently, this report contains information about faults, seismicity, and possible effects of earthquake shaking in addition to an evaluation of volcano hazards.

GEOLOGIC SETTING OF CRATER LAKE

Mount Mazama and Crater Lake caldera lie at the intersection of the Cascade chain of volcanoes with the Klamath graben, a north-northwest trending basin bounded by faults whose displacement is mainly vertical (fig. 1). At this latitude, the western margin of the Basin and Range province, characterized by north-south to northwest-southeast trending faults, impinges upon the Cascades. Focusing of volcanism at Crater Lake and the development of the shallow **magma chamber** which fed the climactic eruption are linked to this regional tectonic situation.

North and south of Crater Lake are many **shield volcanoes** of modest size and many more **cinder cones** with associated lava flow fields. Both represent short-lived activity at isolated vents. These **monogenetic volcanoes** are manifestations of **regional volcanism** throughout the Oregon Cascades.

Mount Mazama is the name applied to the volcano in which Crater Lake caldera formed (fig. 2). Before the caldera-forming eruption, the summit of Mount Mazama stood at ~3,700 m (~12,000 feet) elevation. Mount Mazama was constructed during the last approximately 400,000 years by episodic growth of many overlapping shield and **composite volcanoes**, each of which probably was active for a comparatively brief period (Bacon, 1983). The erupted magma was mainly **andesite**. As the volcanic complex evolved, so did its eruptive style, such that the last ~70,000 years saw more highly explosive eruptions of **silicic magma (dacite and rhyodacite)**. In the last ~30,000 years, the only record of activity, prior to the caldera-forming climactic eruption of ~7,700 years ago, was limited to a small number of **preclimactic** pyroclastic eruptions and ensuing lava flows of rhyodacite. Subsequent to the climactic eruption, all volcanic activity has occurred within the caldera itself. Wizard Island is a cinder cone and lava flows of postcaldera andesite, erupted soon after the caldera formed. Several more postcaldera volcanoes are hidden by the lake (fig. 3).

The remainder of this report discusses volcano hazards¹, followed by those related to earthquakes². The most probable types of volcanic activity and their respective hazard zones are described first, namely, reawakening of Mount Mazama, eruptions in Crater Lake, **lahars**, and eruptions outside of the caldera. These are followed by the low probability, high consequence events of another caldera-forming eruption and sudden gas release from the lake. In subsequent sections, potential magnitudes of earthquakes are estimated and hazards of earthquake-induced landslides are evaluated. Suggestions for mitigation are given at the ends of both the volcano and earthquake hazard sections.

¹ The recent book by Scarpa and Tilling (1996) contains many papers on volcano monitoring, eruptive phenomena, hazards and risk assessment, and emergency management.

² See Wong and Bott (1995) for a useful overview of earthquakes in Oregon.

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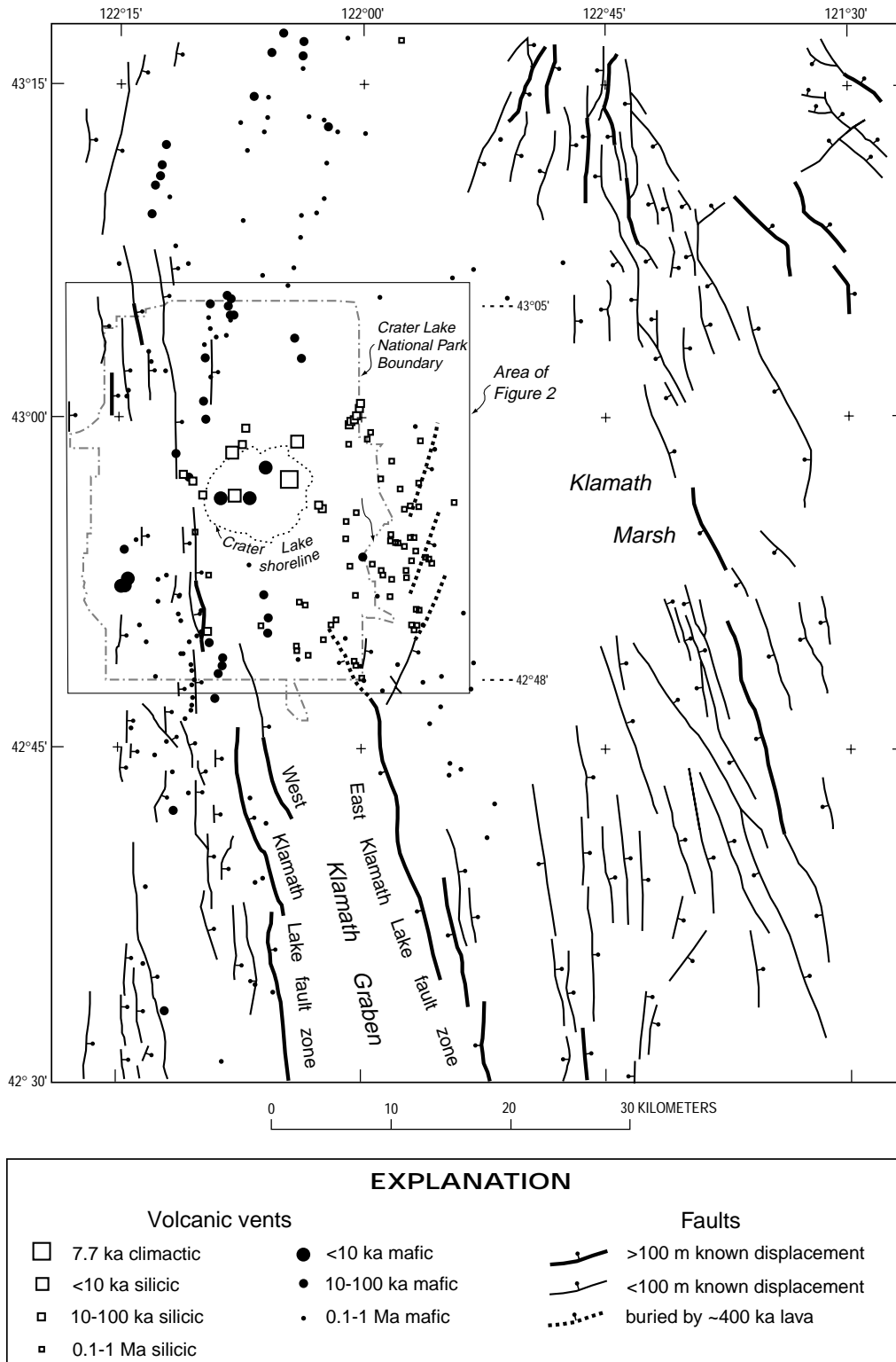


FIGURE 1.—Map showing faults and volcanic vents in the Crater Lake region (Plate 1 covers a slightly larger area at 1:100,000 scale and includes hazard zones). Data sources: Hawkins and others (1989), MacLeod and Sherrod (1992), Sherrod (1991), Sherrod and Pickthorn (1992), Smith (1988), Smith and others (1982), C. R. Bacon (unpublished mapping, 1996), and M. A. Lanphere (unpublished K–Ar ages, 1996).

REAWAKENING OF MOUNT MAZAMA

The long history of volcanism at Mount Mazama strongly suggests that this volcanic center will be active in the future. The record of past eruptions shows us how the volcano behaved before the system was perturbed by the climactic eruption and caldera formation. Eruptions of Mount Mazama were more frequent than those of the monogenetic volcanoes around it. As the volcano grew, the focus of activity migrated in a west-northwest direction. Some eruptive episodes were much longer and produced a far greater volume of materials than others. Likewise, the lengths of repose periods must have varied considerably. Most of the vents that produced the lavas of Mount Mazama were within the area circumscribed by the present caldera. Vents for silicic magma that tapped into the Mazama system are mainly within 2 km and all within 11 km of the caldera rim.

Wizard Island and the other postcaldera volcanoes (fig. 3) are evidence of renewed activity of Mount Mazama following its climactic eruption. Postcaldera volcanism is common at calderas worldwide (Newhall and Dzurisin, 1988). As all postcaldera volcanism was restricted to the caldera, and given the eruptive history of Mazama with its west-northwest vent migration, we anticipate that the most likely site of the next eruption probably will be within the western part of the caldera. We have no basis for estimating a finite probability of volcanic eruptions from a reawakened Mazama system because of the dramatic changes that occurred as a result of the climactic eruption. Judging from the overall eruptive history of Mount Mazama and the surrounding region, renewed volcanic activity within or very near to the caldera is at least as likely as the birth of a new volcano within Regional Hazard Zone RH (around one chance in 10,000, or 10^{-4} , or a 30-year probability of about one chance in 330, or 3×10^{-3} ; *see Probability of a future volcanic eruption*). We do not have sufficient information to evaluate the significance of the 5,000 year repose period since the last eruption in terms of its possible effect on the probability of future volcanic eruptions. Future eruptions within the caldera may be explosive (*see Potential hazards from an eruption beneath Crater Lake*). Eruptions outside of the caldera and fed by the Mazama system might produce andesite lava and *tephra* with hazards akin

to those of regional volcanism (*see Regional volcanism*). Alternatively, the Mazama system might generate slowly emplaced, viscous dacite to rhyodacite *domes* that may be preceded or accompanied by explosive eruptions (*see Hazards of silicic eruptions outside the caldera*).

POTENTIAL HAZARDS FROM AN ERUPTION BENEATH CRATER LAKE

Although future eruptions could occur anywhere within Crater Lake caldera, all known postcaldera eruptions took place in the west half of the lake (fig. 3). Those eruptions produced andesite lava flows and tephra (Wizard Island, Merriam Cone, and the central platform), as well as a rhyodacite dome and minor ash fall. These events occurred between ~7,700 and ~5,000 years ago, most before the lake had risen to its present level. Any ash deposits above the shore of Crater Lake, which would have provided a record of associated explosive activity, evidently have been lost to erosion. Evaluation of hazards from eruptions beneath the lake must be based on historic eruptions elsewhere and knowledge of the general characteristics of volcanic eruptions in water.

FACTORS CONTROLLING EXPLOSIVITY OF ERUPTIONS IN BODIES OF WATER

The presence of Crater Lake creates potential hazards from future eruptions that had not existed prior to formation of the caldera ~7,700 years ago. One such hazard is the violent mixing of lake water with erupting magma to produce a *hydromagmatic* eruption. Some famous eruptions became explosive when magma apparently mixed with shallow sea or lake water (*e.g.*, Surtsey volcano, Iceland, 1964, described by Moore, 1985; Taal volcano, Philippines, 1965, described by Moore and others, 1966). In other eruptions, however, explosions caused by magma/water mixing have been less violent. Factors that determine how violently water and magma interact include the type of magma, its rate of extrusion, the degree to which the magma is fragmented by expanding internal gas bubbles, and water depth (Mastin, 1995).

Explosive water/magma mixing is most common in shallow water (a few meters to tens of meters deep)

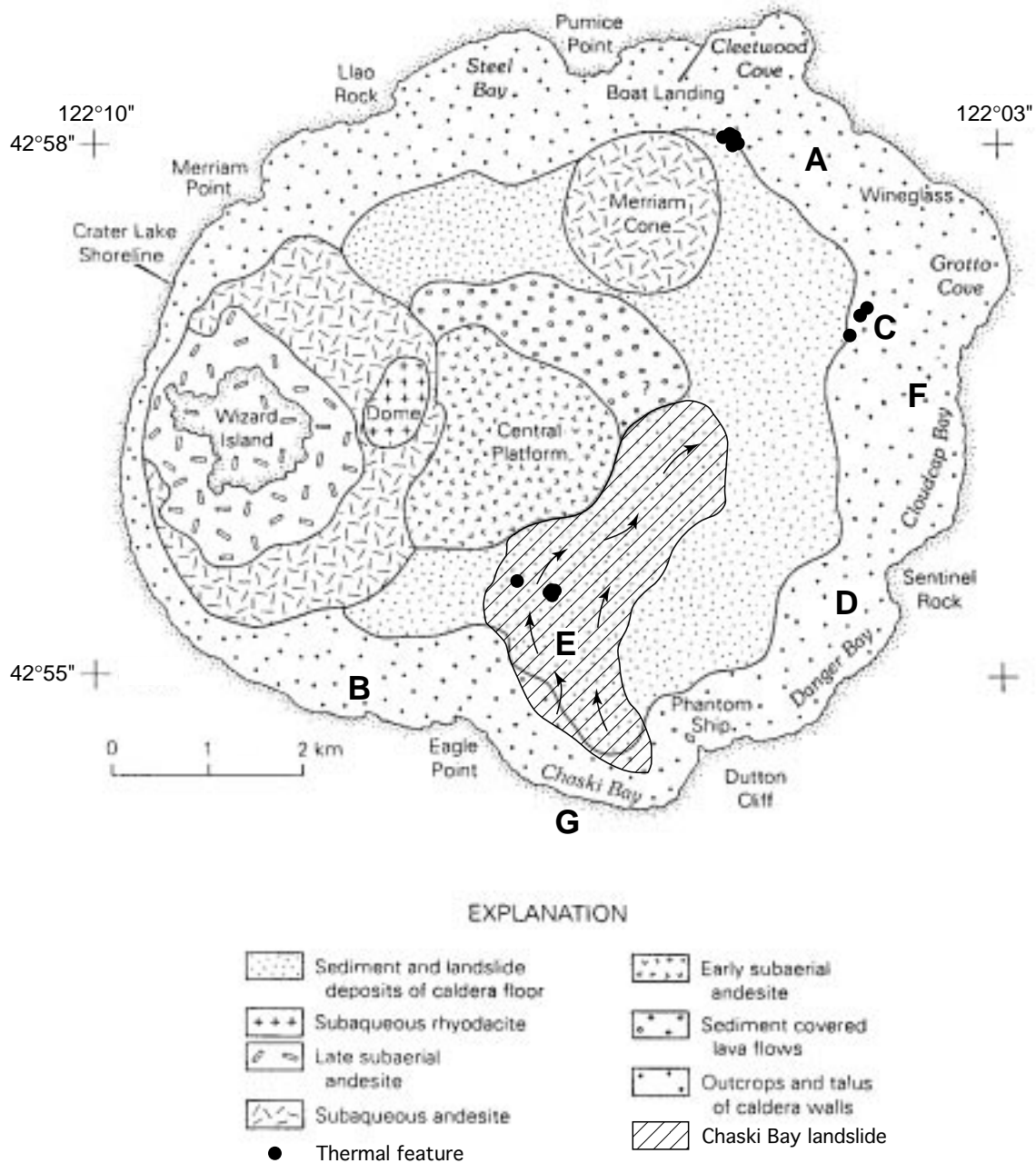


FIGURE 3.—Geologic map of Crater Lake caldera floor. Modified after Nelson and others (1994). Geology inferred from bathymetry (Byrne, 1962), traverses and sampling by manned submersible, video from remotely operated vehicle, and dredged samples. Letters refer to specific bathymetric features listed in table 6.

when magma extrudes rapidly and breaks apart into coarse particles before it is quenched. After contacting water, the magma can thermally fracture into micrometer-sized particles that transfer heat at explosive rates to generate steam (Wohletz, 1986). Eruptions into deep water, where the high pressure inhibits the expansion of steam, tend to be much less violent than those through shallow water. Except near the shoreline, the floor of Crater Lake is at depths that would inhibit explosions.

Slow rates of lava extrusion ($\sim 1 \text{ m}^3/\text{s}$), typical of lava flows or silicic domes, also inhibit violent mixing with water. For example, at Kilauea Volcano, Hawaii, **basalt** has flowed slowly into the ocean for more than a decade with relatively little explosive activity. Extrusion of silicic domes into lakes or in shallow marine environments has been known to have produced minor explosions. A lava dome extruded onto the floor of Crater Lake could grow to sufficient height that eruptions could become explosive. Because the possibility of magma/water interaction is the dominant factor in determining explosivity for an eruption within the caldera, we consider all magma compositions to be capable of producing explosive activity from an eruption of modest volume.

PYROCLASTIC SURGES

The most serious hazard posed by a hydromagmatic eruption is a **pyroclastic surge**. Surges are mixtures of air, volcanic gas, steam, and magma or rock fragments that move along the ground surface at high velocities (Waters and Fisher, 1971). Surges differ from pyroclastic flows in that they contain less solid debris, and are therefore less dense and more 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, they can destroy or incinerate most structures and living things in their path.

The distance that a surge travels from its source is greatly dependent on the type of eruption. Discrete explosions at well-observed volcanoes typically send surges only a kilometer or so from the vent, though

some larger explosions can produce surges that travel several kilometers. The most mobile surges are generated by the most violent hydromagmatic eruptions that combine an influx of water and high rate of magma discharge over sustained periods of time. Such eruptions generate columns of ash and debris extending several kilometers or more into the atmosphere. If all or part of the gas/magma mixture in those columns is heavier than air, it falls back to earth, in some cases from plumes that have drifted kilometers from the vent. Gravity-driven descent of particle-laden clouds can accelerate them to high velocities. Surges from such eruptions have extended more than 30 kilometers from their source vents.

BALLISTIC BLOCKS AND OTHER HAZARDS OF ERUPTIONS IN THE LAKE

A somewhat less serious hazard is the ejection of large **ballistic blocks**, tens of centimeters or more in diameter, to distances up to a few kilometers. Blocks have been ejected from hydromagmatic craters at velocities ranging from less than 100 m/s to nearly 250 m/s (Self and others, 1980; Lorenz, 1970). At Crater Lake, blocks ejected at these velocities could travel 1 to 4 km, and could easily overtop the caldera rim if the eruption vent were near the lake shore.

Other hazards include the development of water waves (seiches) during large explosions. Seiches at least a few meters in height accompanied the 1965 eruption of Taal volcano in the Philippines. Also, during an explosive eruption, surges might melt snow, or lake water might be ejected in sufficient volume, to mobilize surface debris and create lahars (volcanic debris flows) on the flanks of Mount Mazama (lahars are discussed below).

PROXIMAL HAZARD ZONES FOR EXPLOSIVE ERUPTIONS

The type of volcanic eruption considered most likely at Crater Lake would take place from a vent within the caldera, probably beneath the surface of the lake. We have defined Proximal Hazard Zone PA as the caldera itself, bounded by the caldera rim (plate 1). Proximal Hazard Zone PB is the maximum area we

judge likely to be affected by pyroclastic surges and ballistic ejecta, assuming an eruption that breaks the surface of the lake.

The outer boundary of Proximal Hazard Zone PB was drawn by assuming a maximum height of ejection of surge-forming material of 500 m above the lake surface and a ratio of height of drop to runout distance of 1:10, or $H/L = 0.1$, for vents within the lake and close to the shoreline (such a low ratio maximizes predicted runout). Surges would be funneled through low areas on the caldera rim and channeled into valleys. Although surges would not be expected on the higher ground, we have included the entire area within 1.5 km of the rim within zone PB because of a possible hazard from exceptionally energetic ballistic blocks. For the same conditions of height of origin, surges from vents near the center of the lake would not surmount the caldera walls and ballistics would fall within the caldera. Crater Lake Lodge, Rim Village, and structures in the park headquarters area are at highest risk from an eruption in the southwest quadrant of the lake. An eruption elsewhere in the caldera might not affect this area with pyroclastic surges but might result in tephra fall there if wind conditions were appropriate.

HAZARDS OF SILICIC ERUPTIONS OUTSIDE THE CALDERA

Silicic magma generated in a reawakened Mazama system might erupt outside of the caldera but within a few kilometers of the caldera rim. It is impossible to forecast this type of event or to determine where such an eruption would be most likely because of the drastic reorganization of the magmatic plumbing system that took place when the caldera formed. We believe the probability of such an eruption is less than for an eruption within the caldera. Nevertheless, it is worthwhile to describe the types of phenomena that could be expected.

Silicic eruptions typically begin with hydromagmatic explosions as the slowly rising magma heats groundwater in the shallow subsurface. Such explosions will be most likely in poorly-drained areas. Commonly, explosive magmatic eruptions follow the vent-clearing, hydromagmatic phase. Both phases can produce pyroclastic surges, flows, and falls. Factors

controlling the runout distances of surges and pyroclastic flows are described above (*see Proximal hazard zones for explosive eruptions*). Heavy rainfall on fresh pyroclastic deposits may feed lahars (*see Hazards of lahars (volcanic debris flows) and their runout flows*). Viscous magma that has lost its original gas may eventually extrude from the vent to form a lava dome or slowly-moving flow. Relatively small pyroclastic surges or flows may form as hot lava blocks fall from the unstable dome or flow front. The smallest domes are only a few tens of meters in diameter. Larger silicic lava flows are exemplified at Crater Lake by the preclimactic rhyodacite flows such as Cleetwood, Llaoc Rock, Grouse Hill, and Redcloud Cliff. They were preceded by *plinian eruptions* that resulted in tephra fall as far as several hundred kilometers from their vents. These eruptions were fed by the climactic magma chamber, which contained a large volume of silicic magma at the time. The present magma system is unlikely to have accumulated such a large volume of eruptible magma in the 7,700 years since the climactic eruption (*see Another large volume or caldera-forming eruption?*). Consequently, we do not consider eruptions of this magnitude to be likely in the next few thousand years. A smaller silicic eruption within a few kilometers of the caldera cannot be ruled out. We have not designated a specific hazard zone for this type of eruption on plate 1 because it would approximately coincide with Proximal Hazard Zone PB.

HAZARDS OF LAHARS (VOLCANIC DEBRIS FLOWS) AND THEIR RUNOUT FLOWS

Lahars are rapidly flowing mixtures of water and rock debris that originate from volcanoes. They can range from dense, viscous slurries resembling wet concrete (containing about two thirds sediment and one third water by volume) to turbulent muddy floods that carry relatively little sediment. Lahars can develop from (1) water-saturated debris avalanches or (2) originate from erosion and incorporation of sediment or rock debris by large, rapidly released volumes of water. Although a major concern at Cascade volcanoes such as Mount Rainier, the first type of lahar is not considered possible at Crater Lake because the

main volcanic edifice of Mount Mazama, which would have been the potential source for a debris avalanche, was engulfed 7,700 years ago by collapse of Crater Lake caldera. The second type of lahar would be possible if lake water were rapidly ejected from the caldera during a volcanic eruption or if hot volcanic deposits melted a large amount of snow.

Lahars are channeled into valleys as they move downhill under the force of gravity. They can get bigger as they move downstream by incorporating additional sediment and water en route (called bulking), commonly increasing in volume by a factor of 3 to 5. The amount of water available limits the potential size of a lahar. Lahars travel faster than water in channels of similar depth and slope. Their velocities may be as great as 20 m/s (45 mph) in steep channels close to a volcano but diminish to 5 to 10 m/s (about 10 to 20 mph) in the broader, more gently inclined channels farther away. In relatively narrow canyons, lahars may be many tens of meters deep. As they get farther from a volcano, lahars spread out in the wider, flatter river valleys, often burying roads, bridges, and buildings with their deposits. Lahars commonly travel tens of kilometers (tens of miles), and the largest have travelled 100 km (60 miles) or more from Cascade Range volcanoes.

POTENTIAL FOR LAHARS AT CRATER LAKE

Lahars could be generated as ejected lake water or melted snow mobilized the poorly-consolidated parts of the climactic eruption deposits in the drainages radiating from Mount Mazama. The mantle of climactic eruption deposits is up to ~100 m thick and forms an ample source of sediment for lahars. These deposits include (1) poorly-consolidated, sandy pyroclastic-flow veneer and coarse lithic breccia (rocky debris) on upland surfaces and in the heads of valleys, (2) pumiceous pyroclastic-flow deposits partially filling valleys below ~1,800 m (~6,000 feet) elevation, and (3) well-sorted pumice-fall deposits on hills east of the caldera. These materials are porous and permeable, and the unsaturated portions of such deposits probably would rapidly absorb substantial amounts of water emplaced upon them. If water is supplied faster than it can be absorbed, the excess will run off. Moreover,

the deeper portions of these deposits commonly are water saturated, limiting their ability to absorb additional water.

There are many cases of volcanic melting of snow or ice, expulsion of water from a crater lake during a volcanic eruption, failure of a natural dam, or storm runoff causing lahars on the flanks of volcanoes in which volcanic deposits have been the source of sediment. Mount Pinatubo, Philippines, is a recent example where spectacular damage was wrought by such lahars on agricultural land, communities, and infrastructure. These granular (noncohesive) lahars begin as water flows over new pyroclastic deposits. The water entrains sediment until a debris flow is formed. Farther downstream, the flow wave is progressively diluted and transforms into hyperconcentrated flow (20 to 60 percent sediment by volume) and, finally, into normal streamflow with sediment concentrations below 20 percent. The granular nature of the flow reflects the entrainment sediment that has few particles in the clay (<0.004 mm) and silt (0.004-0.0625 mm) size fractions. These flows characteristically attenuate rapidly downstream, but the hyperconcentrated phase can persist for tens of kilometers.

DEFINITION OF LAHAR HAZARD ZONE

The boundaries of the Lahar Hazard Zone (LA on plate 1) were determined as in flood-hazard mapping in arid and semi-arid regions. The Lahar Hazard Zone includes any area potentially inundated by flows of the magnitudes estimated below. A lahar generated on the upper slope of Mount Mazama would be expected to quickly bulk to a debris flow but would attenuate continuously with decreasing slope as flow is lost through deposition of sediment and is not replaced by tributary inflows. Meteorologic flood hazards would surpass those of lahars from Mount Mazama at low elevations where flow spreads on broad alluvial reaches of low and decreasing slope and tributary inflow adds to the flow wave. Thus, areas farther from Crater Lake, where exceptional meteorologic floods will be a more significant hazard than floods and lahars related to volcanic activity, are excluded from the Lahar Hazard Zone.

POTENTIAL SIZE AND FLOW VELOCITY OF LAHARS AT CRATER LAKE

We can make an educated guess of the size and properties of potential lahars at Crater Lake by analogy with documented events at other volcanoes. The analysis presented in table 1 is based on a 1982 lahar at Mount St. Helens (Scott, 1988) and several lahars from Ruapehu Volcano, New Zealand (Nairn and others, 1979; Ruapehu Surveillance Group, 1996; S.J. Cronin, written commun., 1996).

Ruapehu is an andesite composite volcano with a crater 0.5 km in diameter. A $9 \times 10^6 \text{ m}^3$ (cubic meters) lake (also called Crater Lake) occupied the active vent at 2,540 m altitude prior to 1995. Numerous past eruptions have catastrophically displaced lake water, which probably transformed to debris flows and their hyperconcentrated runouts. At least $1.6 \times 10^6 \text{ m}^3$ of water and lake deposits were ejected by hydromagmatic explosions in a 1975 eruption, resulting in an 8 m fall in lake level (Nairn and others, 1979). Recorded discharges in downstream drainages reached $5,000 \text{ m}^3/\text{s}$ and flow velocities as high as 12 m/s were estimated (Nairn and others, 1979). Estimated flow volume indicated substantial bulking of the flow. From data for the 1953, 1975, and 1995 flows at Ruapehu Volcano and the 1982 flow at Mount St. Helens, we can synthesize the dynamics and behavior of a flow appropriate for planning and design purposes at Crater Lake (table 1). The greater size of Crater Lake, Oregon, (~9 km, Oregon, vs. 0.5 km diameter, New Zealand) may represent a greater hazard, but more probably the greater volume and depth would absorb a significant part of the energy of an explosive event. There should be ample warning to prepare for noncohesive lahars because any plausible scenario for their generation at Crater Lake is linked to renewed volcanic activity that should be preceded by detectable seismicity.

REGIONAL VOLCANISM

The Cascade Range is known for large volcanoes that have been active for periods of tens to hundreds of thousands of years, among them Mount Mazama, the volcano in which Crater Lake caldera formed. Far more numerous in northern California, Oregon, and southern Washington, however, are smaller shield

volcanoes, cinder cones, fissure vents, and lava domes that are manifestations of regional volcanism. Each of these erupted for brief periods in geologic terms, generally in a single episode. Compositions include the entire range from basalt to andesite, with a corresponding variety of eruptive styles and products; the most common lava type is basalt. Hazards arise mainly from tephra falls and lava flows. Lava flows may travel tens of kilometers downslope but travel sufficiently slowly that they pose a threat only to structures and property. Life-threatening pyroclastic eruptions are possible when magma interacts with shallow ground water in wet areas, producing surges or pyroclastic flows. Areas affected by such pyroclastic activity tend to be limited to a few square kilometers. In addition, the region downwind may experience tephra fall.

Crater Lake lies in a part of the Cascades where the belt of Quaternary volcanoes is comparatively narrow, about 30 km from west to east (fig. 1, plate 1; Guffanti and Weaver, 1988). For purposes of hazard assessment for the immediate Crater Lake area, consider the region between approximately latitudes $42^\circ 48'$ and $43^\circ 05'$, that is, ~11 km north and south of the caldera rim (~1,100 km^2 ; ~1,040 km^2 excluding the caldera). It is important to appreciate that Mount Mazama itself, dacite and rhyodacite vents related to Mazama, and vents within the caldera are excluded from table 2. Some eruptive episodes are represented by several approximately coeval, nearby vents. For example, the three postglacial vents at Castle Point lie in close proximity to one another. They produced related basaltic lava and were active during a single period of at most a few years (age bracketed between 8 and 13 ka; considered to be <10 ka in table 2). The three vents thus represent a single eruptive episode. In addition, *paleomagnetic studies* and *K-Ar dating* have established that eruptive episodes have not been uniformly spaced in time. We have given estimates of the average number of episodes per 1,000 years in table 2. The episodes varied widely in volume of products and number of vents. Because younger lava flows tend to obscure older ones, the record is much less complete for vents and episodes 100-1,000 ka in age. The average number of known episodes per 1,000 years is much smaller for this age range than for the <10 ka and 10-100 ka intervals.

Table 1.— *Volume and flow properties of a hypothetical lahar at Crater Lake based on events at Mount St. Helens, Washinton, and Ruapehu Volcano, New Zealand*[m³, cubic meters; m³/s, cubic meters per second; km, kilometers; -do-, ditto]

| | Values for hypothetical flow at Crater Lake | Remarks |
|--|--|--|
| Volume | 6 x 10 ⁶ m ³ | Value of 1975 flow, Ruapehu (Nairn and others, 1979) |
| Peak Discharge | 5,000 m ³ /s | Value of 1975 flow, Ruapehu (Nairn and others, 1979) |
| Velocity on edifice (0-6 km) | 15-20 m/s | Velocity estimated for 1995 flow on flank— Whakapapaiti Stream, Ruapehu (Ruapehu Surveillance Group, 1996) |
| Velocity of runout (6-16 km) | 10 m/s | Based on velocities of 1953, 1975, and 1995 flows at Ruapehu and 1982 flow at Mount St. Helens |
| Velocity of runout (16-40 km) | 6 m/s | Based on velocities of 1953, 1975, and 1995 flows at Ruapehu and 1982 flow at Mount St. Helens |
| Distance for bulking to debris flow | <3 km | Based on behavior of 1995 flows at Ruapehu and 1982 flow at Mount St. Helens |
| Lahar-runout distance as hyperconcentrated flow | 40 km | Based on behavior of 1995 flows at Ruapehu and 1982 flow at Mount St. Helens |

PROBABILITY OF A FUTURE VOLCANIC ERUPTION

Estimating the probability of a volcanic eruption occurring within a hazard zone requires not only knowledge of eruptive frequency in the past but also assumptions about the regularity of eruptions in time and their distribution within the area in question. Lacking age information for every vent, we treat the opening of new regional volcanic vents as a random process. We assume that regional volcanism has no memory of previous events such that the process has a Poisson distribution. This may not be true of large, central-vent volcanoes such as Mount Rainier or ancestral Mount Mazama, which have erupted many times from the same conduit system. The probability of an eruption occurring somewhere in the stated region at a new vent during a specified number of years, an exponential function, reduces to simply the average recurrence rate times the length of the period of interest for time periods that are short (tens of years) relative to the average recurrence interval (thousands of years).

On the basis of the total number of eruptive episodes in the past ~100,000 years, exclusive of Mount Mazama, the average recurrence interval is about 10,000 years. The annual probability of an eruption occurring near Crater Lake, then, is around one chance in 10,000, or 10^{-4} , and the 30-year probability is about one chance in 330, or 3×10^{-3} . These estimates are, at best, very approximate because volcanic eruptions are triggered by the interplay of complex processes and there is no guarantee that events occurring in the future will adhere to the simplistic model used to estimate probabilities.

HAZARD ZONES FOR REGIONAL VOLCANOES

Hazard zones delineated on plate 1 are defined on the basis of locations of volcanic vents active during the past one million years. Zone boundaries are drawn ~3 km outboard of the region of known vents on the assumption that new vents are unlikely to erupt farther than 3 km from existing volcanoes. Note that the

Table 2.—Numbers of known basalt, basaltic andesite, and andesite volcanic vents and eruptive episodes outside Crater Lake caldera and exclusive of Mount Mazama between approximately latitudes 42° 48' and 43° 05'

| Age range ka* | Number of vents | Number of episodes | Episodes per 1,000 years |
|------------------|--------------------|-----------------------|-----------------------------|
| < 10 | 3 | 1 | 0.1 |
| 10 – 100 | 23 | 13 | 0.14 |
| 100 – 1000 | 41 | 28 | 0.03 |

*1 ka = 1000 years Before Present (1950 AD).

hazard zones represent likely vent locations. The extent of lava flows or tephra falls will vary depending on eruption location (local topography), rate, and duration. Lava may flow beyond the limits of the hazard zones. The transportation corridor east of Crater Lake National Park could be disrupted by even a small tephra eruption because prevailing winds probably would carry tephra in that direction. Boundaries are straight lines because there are insufficient vents to justify more irregular shapes. Likewise, some boundaries have been drawn to coincide with county lines or to include cultural features (*e.g.*, parts of highway 97) to minimize ambiguity in application.

Regional Hazard Zone RH contains all vents <100,000 years in age. In the vicinity of Crater Lake, as described above, the annual probability within this zone is thought to be roughly 10^{-4} or a 30-year probability of 3×10^{-3} . North of latitude 43°05' and south of latitude 42°48' within Zone RH there is less information on the history of volcanism but, nevertheless, the annual probability of an eruption is believed to be lower than in the immediate Crater Lake area. East of Zone RH is Regional Hazard Zone RL, a zone where eruption probability is considered lower than in Zone RH because it contains only vents believed to be between 100,000 and 1,000,000 years in age. Here the annual probability of an eruption occurring between latitudes 42°48' and 43°05' is judged to be of order 1 in 100,000, or about 10^{-5} , or a 30-year probability of 3×10^{-4} . Presumably, the annual probability is no greater in the parts of Zone RL north

or south of the 42°48' to 43°05' band. Outside of these hazard zones there are no known volcanic vents younger than 1,000,000 years old and the probability of an eruption is believed to be negligible.

The probabilities quoted above are for an eruption *somewhere* in a regional hazard zone. As any eruptive episode will cover only a small part of the zone with lava or tephra, the probability of *a given area* within the zone being affected in a particular time interval is substantially less than the probability of an eruption occurring somewhere within the zone.

EVENTS OF HIGH CONSEQUENCE BUT LOW PROBABILITY

Three types of events that may be considered possible at Crater Lake but very unlikely in the next few centuries are a large pyroclastic eruption, sudden release of lethal CO₂ from the lake, and catastrophic draining of the lake. These are discussed below for completeness and because the consequences of any one of them would be significant.

ANOTHER LARGE VOLUME OR CALDERA-FORMING ERUPTION?

The climactic eruption of Mount Mazama, during which Crater Lake caldera collapsed, took place ~7,700 years ago (calendar years, based on radiocarbon age of

6,845±50 ¹⁴C years B.P.; Bacon, 1983). This was the largest eruption in the Cascades in the last ~400,000 years, explosively venting ~50 km³ of magma during perhaps only a few days. The products of the climactic eruption are dominantly rhyodacite pumice and ash. Perhaps 10 percent of the total is andesite and crystal-rich "scoria" largely ejected late in the eruption. The compositionally-zoned eruption products indicate that relatively low-density rhyodacitic magma overlay hotter, denser andesitic magma and accumulated crystals deeper in the climactic magma chamber.

Tephra fall from the climactic eruption reached into southern Canada and pyroclastic flows traveled down the Rogue and Umpqua Rivers, and other drainages, as much as 70 km from Mount Mazama. The maximum extent of the pyroclastic-flow deposits of the climactic eruption, not to be confused with a modern hazard zone boundary, is shown on plate 1. The area devastated as a result of the eruption exceeds that bounded by the limit of pyroclastic-flow deposits shown on plate 1. The eruption began with hydromagmatic explosions leading shortly thereafter to a high plinian column from a single vent in what is now the northeast quadrant of the caldera, north of the summit of old Mount Mazama. A major pumice fall deposit extended in a northeast direction, downwind at the time. As the eruption proceeded, the eruption rate increased, causing the high column to eventually collapse as it ceased to be buoyant in the atmosphere. At this time, at least four valley-hugging pyroclastic flows descended the north and east flanks of Mount Mazama and left a deposit known as the Wineglass Welded Tuff. This phase of the eruption ended as the caldera began to collapse and multiple vents opened around the subsiding block. From these vents, eruption columns fed highly-mobile pyroclastic flows that descended on all sides of Mount Mazama, partially filling all valleys and spreading out across lowlands (plate 1). The result of the climactic eruption was transformation of the volcano from a large, snow-capped composite cone to a 1,200-m-deep caldera basin, drastic modification of all drainages nearby, and annihilation of all life forms for at least 30 km in all directions from Mount Mazama.

In the 200 years prior to the climactic eruption, there had been two smaller rhyodacitic plinian

eruptions, each followed by sluggish emplacement of a thick rhyodacitic lava flow (Llao Rock and Cleetwood flows). The younger of these flows, Cleetwood, was still hot when the climactic pumice fell on its surface. Although there would have been vigorous seismicity before each of these eruptions and the climactic eruption, the magnitude of the climactic event might not have been anticipated at its onset. The stage was clearly set for a voluminous eruption, however, as the geologic record indicates only rhyodacitic eruptions from the general area of Mount Mazama in the preceding 20,000-25,000 years. The eruptive history thus records growth of the shallow magma chamber approximately beneath the present caldera.

Is a shallow magma chamber still present and is another caldera-forming eruption likely in the next few centuries? The geologic evidence suggests that most of the gas-charged rhyodacitic magma was ejected in, or crystallized following, the climactic eruption. Virtually all of the postcaldera lava is andesite which probably would not have been able to erupt had a large amount of lower density rhyodacite remained molten in the subsurface. The small postcaldera rhyodacite dome appears to be related to cooling and crystallization of the magma batch which had earlier produced the postcaldera andesites of the central platform, Merriam Cone, and Wizard Island (fig. 3) rather than being left over from the climactic chamber. Rhyodacitic magma apparently accumulated in the climactic magma chamber at a rate of ~2 km³/1,000 yr. If the postcaldera rhyodacite reflects the cooling of the last magma emplaced in the upper 10 km of the crust, then sufficient magma for a voluminous, explosive eruption will not accumulate for many thousands of years. A less likely situation would be that the postcaldera rhyodacite represents the onset of silicic magma accumulation, in which case as much as 10 km³ of magma might have accumulated in the last ~5,000 years. This amount would be sufficient to feed a major pyroclastic eruption (*e.g.*, Mount Pinatubo, 1991) but probably would not lead to caldera collapse. In conclusion, we consider the annual or 30-year probability of a major silicic pyroclastic eruption to be low and the probability of a caldera-forming eruption to be negligible.

SUDDEN GAS RELEASE FROM CRATER LAKE

The August 12, 1986, sudden release of $\sim 1 \text{ km}^3$ of CO_2 gas from Lake Nyos in Cameroon resulted in death of at least 1,700 people by asphyxiation (Kling and others, 1987). The source of CO_2 at Lake Nyos was prolonged degassing of subsurface magma. This event drew attention to the potential for dissolved lethal gas to accumulate in the deepest parts of volcanic crater lakes. Depressurization of this water if the lake overturns suddenly results in rapid exsolution of the gas and its liberation to the atmosphere. The high density of cold CO_2 relative to ambient air allows the gas cloud to flow down topographic depressions and accumulate locally.

Crater Lake does not appear capable of producing a disastrous release of CO_2 . The input of thermal fluid through the floor of Crater Lake carries with it dissolved CO_2 in the form of carbonic acid, but most of the added carbon is in bicarbonate (Collier and others, 1991). Carbon and helium isotope studies indicate a magmatic source for the CO_2 input. The added carbonic acid is mixed with lake water in the deeper part of lake, reducing concentrations to fairly low levels. The upper 200 m of Crater Lake overturns and equilibrates with atmospheric gases twice a year. Any excess dissolved CO_2 (as carbonic acid) comes out of solution but does not accumulate in lethal concentration. Between 200 m and maximum depth, lake water has been shown to mix completely with the upper portion of the lake over a period of 2.5 to 3.5 years (McManus, 1992). In this process, the bottom part of the lake becomes re-oxygenated by equilibrating with oxygenated surface water. At the same time, higher concentrations of dissolved CO_2 are lowered by mixing with water containing only atmospheric concentrations of dissolved CO_2 . Thus, Crater Lake has a source of elevated CO_2 , but the possibility of buildup of large amounts of dissolved CO_2 is prevented by the mixing processes in the lake. The mixing process in the deep lake is driven by heating of lake water through input of the thermal fluid that carries the dissolved CO_2 . Any change in the thermal fluid input could affect the mixing processes in the deep lake. The state of the deep lake should continue to be monitored to detect if the mixing process changes.

CATASTROPHIC FLOOD OR LAHAR FROM DRAINAGE OF CRATER LAKE

Crater Lake contains 17 km^3 of water (Phillips and Van Denburgh, 1968). Should the caldera wall fail and allow the lake to drain, the ensuing flood of water, rock, and remobilized pyroclastic debris would be devastating. In order for Crater Lake to breach its walls the water level would have to rise dramatically or the wall would have to fail. At its lowest elevations at Kerr Notch, Wineglass, and northwest of Round Top, the caldera rim is $\sim 165 \text{ m}$ above the lake. Nothing short of major volcanic activity or drastic change in climate is likely to cause such a rise in lake level. The amount of rock that would have to be removed by wall failure in order for the lake to overflow into one of the valleys on the flanks of Mount Mazama, assuming a minimum width of 500 m, is on the order of 0.1 km^3 . Even if the lake should overflow, whether outflow becomes catastrophic would depend on the rate of downcutting and breach enlargement. A range of possible maximum discharges varying by two orders of magnitude (1.3×10^5 to $3.9 \times 10^7 \text{ m}^3/\text{s}$) can be estimated as theoretically possible by analogy with catastrophic drainage of a prehistoric lake in Aniakchak caldera, Alaska (Waythomas and others, 1996). However, there does not appear to be a mechanism by which breach of the walls of Crater Lake caldera could be accomplished. An extremely low level of risk from catastrophic lake drainage is understood to exist throughout all downstream lowlands around Mount Mazama.

PROTECTING CRATER LAKE NATIONAL PARK AND SURROUNDING COMMUNITIES FROM VOLCANO HAZARDS

The National Park Service, local communities, businesses, and citizens can undertake several actions to mitigate the effects of future eruptions at and near Crater Lake. Long-term hazards mitigation includes 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. Development can (1) avoid areas judged to have an unacceptably high risk, (2) be planned in

such a way as to reduce the level of risk, or (3) include engineering measures to mitigate risk. Limits on development and land use within Crater Lake National Park and the ability of the National Park Service to control access simplify volcanic risk mitigation. In addition, the relatively low probability of lahars originating on Mount Mazama and flowing down the surrounding valleys limits the degree to which communities outside the park need to prepare for such unlikely events. Note that in the Crater Lake region, seismic risk may be as significant as volcanic risk (*see Preparing for an earthquake affecting the Crater Lake region*).

When volcanoes erupt or threaten to erupt, short-term emergency responses are needed. Such responses will be most effective if citizens and public officials have an understanding of volcano hazards and have planned the actions needed to protect communities. Because the time can be short between onset of precursory activity and an eruption (days to months), and because some hazardous events can occur without any warning, suitable emergency plans should be made beforehand. Public officials need to consider such issues as public education, communications, and evacuation planning. The last deserves special consideration at Crater Lake because of the limited road access to the heavily used south rim of the caldera. Although the number of people located there at any given time is not great, disruption of the road system could make rapid evacuation challenging.

Business owners, school officials, and individuals should also make plans to respond to volcano emergencies. Planning is not only prudent, it is vital. Once an emergency begins, public resources can often be overwhelmed, and citizens may need to provide for themselves and make their own informed decisions. The Red Cross recommends that certain basic items be kept in homes, cars, and businesses in case of emergency, such as portable radios, flashlights, first-aid kits, emergency food and water, etc. These items may prove very valuable in a volcano emergency. Two important additional items are (1) knowledge about volcano hazards and (2) an emergency plan of action. If you work or reside within the proximal hazard zone, know how to get safely out of the zone quickly and be aware that hazard zone boundaries are not sharp lines on the ground. Once an eruption begins, the proximal

hazard zone can be affected by a pyroclastic surge so rapidly that escape may not be possible. If you are located within a hazard zone for lahars, know how to move safely to high ground rapidly realizing that moving quickly on foot to the highest ground in the vicinity may be the best strategy. A safe height above a river channel depends on several factors: size of the flow, distance from the volcano, and shape of the valley. If you decide to evacuate downvalley, realize that these flows can travel as fast as 20 m/s (45 mps). Be sure that you don't move into a more hazardous area. Be aware that others also may be trying to evacuate at the same time as you are, and escape routes on roads may become dangerously congested. For example, if highway 97 becomes closed for any reason (such as tephra fall), highway 62 can become choked with redirected traffic.

EARTHQUAKES

Ground shaking from earthquakes on local faults and on the distant Cascadia subduction zone poses a hazard to structures at Crater Lake. Earthquakes may trigger landslides and rock falls that may not only threaten roads and trails but also may cause destructive waves on Crater Lake itself. Below we consider the historic record and the geologic evidence for the types of earthquakes likely to affect the Crater Lake area.

SEISMICITY

There is a significant variation in rates of modern seismicity along the Cascade Range, with the area south of Mount Hood in Oregon being quiet compared to other parts of the Cascades (Weaver, 1989). For example, a four station array along with an ultraportable outlier station operated in the summer of 1970 at Crater Lake found that there were fewer small events at Crater Lake than at Mount Hood and that no recorded events were deeper than 12 km (Westhusing, 1973). Prior to the 1993 Klamath Falls earthquakes (see below), seismometers have been too few and too distant from Crater Lake to detect and accurately locate small earthquakes. There is, however, a sparse record of seismicity at Crater Lake and its vicinity (fig. 4 and table 3). The largest event took place in 1920 before there were many seismometers in Oregon. It is known

Table 3.—*Seismicity in the vicinity of Crater Lake, Oregon.*

| Date | Time UTC | Latitude (degrees) | Longitude (degrees) | Depth (kilometers) | M | Comment |
|----------|-------------|-----------------------|------------------------|-----------------------|-----|---------------------------------------|
| 20/04/14 | 11:45 | 42.92 | 122.10 | | 4+ | 3 shocks. Intensity V at Fort Klamath |
| 47/10/11 | 16: | 42.75 | 122.00 | | 3.7 | |
| 47/10/12 | 19: | 42.67 | 122.08 | | 1+ | |
| 47/10/14 | 03:30 | 42.67 | 121.92 | | 1+ | |
| 82/06/19 | 08:23 | 42.904 | 122.083 | 0.02* | 1.7 | Felt |
| 93/09/21 | 12:50 | 42.575 | 122.181 | 0.02* | 1.9 | |
| 94/01/26 | 12:33 | 42.850 | 122.295 | 42.07 | 2.0 | Low frequency event |
| 94/01/28 | 07:37 | 42.533 | 122.058 | 4.55 | 1.3 | |
| 94/05/19 | 03:22 | 42.673 | 122.047 | 6.28 | 1.7 | |
| 94/05/19 | 14:35 | 42.662 | 122.054 | 9.29 | 1.6 | |
| 94/05/20 | 20:05 | 42.524 | 121.680 | 0.02* | 2.4 | Explosion? |
| 94/05/27 | 18:56 | 42.554 | 121.614 | 17.82 | 2.1 | |
| 94/12/29 | 00:21 | 42.886 | 122.120 | 1.48 | 2.3 | |
| 94/12/29 | 00:22 | 42.904 | 122.113 | 1.11 | 2.6 | Felt |
| 94/12/29 | 00:40 | 42.892 | 122.116 | 1.87† | 2.4 | Felt |
| 95/08/13 | 14:36 | 42.657 | 122.056 | 9.00† | 2.0 | |
| 95/08/13 | 16:18 | 42.661 | 122.047 | 4.28 | 2.1 | |
| 95/08/13 | 16:22 | 42.666 | 122.040 | 0.76† | 2.0 | |

Time is Coordinated Universal Time (UTC). For Pacific Standard Time, subtract 8 hours. For Pacific Daylight Time, subtract 7 hours.

* Depth fixed to an arbitrary value.

† Maximum number of iterations exceeded. Location and depth are arbitrary.

M – An estimate of the local Richter magnitude. For events after 1982, M is the coda-length magnitude M_c . For more information see Bacon and Nathenson (1996, table 2)

to have been felt at Intensity V³, and had an estimated magnitude of 4+. The earthquake's location is quite uncertain, though it is thought to have been near Crater Lake. In 1947 there was an event with estimated magnitude of 3.7 south of Crater Lake near the town of Fort Klamath. One felt event in 1982 occurred near Crater Lake while a temporary array of seismic stations was deployed in Oregon (Kollmann and Zollweg, 1984). Relocation of this event by

R.S. Ludwin (written commun., 1996) places it closer to Crater Lake and reduces its magnitude to 1.7 from the 2.5 calculated by Kollmann and Zollweg (1984).

South of the area of figure 4 and ~60 km south of Crater Lake, two strong earthquakes, $M = 5.9$ and 6.0 , occurred September 20, 1993, followed by hundreds of aftershocks during the succeeding weeks (the "Klamath Falls" earthquakes). The main events had hypocentral depths of ~9 km and apparently took

³ Modified Mercalli Intensity Scale V: "Felt outdoors; direction estimated. Sleepers wakened. Liquids disturbed, some spilled. Small unstable objects displaced or upset. Doors swing, close, open. Shutters, pictures move. Pendulum clocks stop, start, change rate."

place on a north-northwest-trending normal fault inclined $\sim 45^\circ$ to the northeast (Braunmiller and others, 1995). These earthquakes caused rock falls and small landslides (largest $\sim 300 \text{ m}^3$) from road cuts, quarries, and steep bluff faces as far as 29 km from the epicentral area (Keefer and Schuster, 1993). Subsequent to the Klamath Falls earthquakes of 1993, telemetered instruments were added to monitor ongoing seismicity (University of Washington, 1993), and locations and detection limits for earthquakes in the vicinity of Crater Lake improved. The 1993 event 38 km south of Crater Lake (fig. 4) took place a few hours after the second Klamath Falls earthquake (a magnitude 6.0) and still has a considerable uncertainty of location. The map of earthquakes in Washington and Oregon from 1872-1993 (Goter, 1994) shows a scattering of seismicity stretching northward from Klamath Falls to Crater Lake. The catalogue for these earthquakes (R. S. Ludwin, written commun., 1996) shows that they are preliminary locations of aftershocks from the 1993 Klamath Falls earthquakes as located by the Northern California Seismic Network. Subsequent work has shown that the aftershocks did not extend as far north as shown on Goter's map (Qamar and Meagher, 1993).

In 1994 and 1995, there was a significant amount of seismicity near Crater Lake. Detection of the earthquakes of 1994 and 1995 may be partly a result of improved instrumentation, as the prior detection threshold for earthquakes that were not felt was probably at least $M=3$. The event of 1 January 1994, west of Crater Lake is noteworthy in having a depth of 42 km and low-frequency wave form, properties atypical of **tectonic earthquakes**. In May, there were two events in the vicinity of the 1947 events near Fort Klamath. In December, there were three events (two felt) just south of Crater Lake. In August of 1995, there were three more events near Fort Klamath. It is possible that the recent $M=2-3$ earthquakes represent a regional increase in seismicity related to the Klamath Falls earthquakes of 1993 because the number of events per year has declined each year since 1993. The area around Klamath Falls in the Klamath graben has had significantly more seismicity in the last 50 years than has Crater Lake (see list in Sherrod, 1993).

Faults with normal (mainly vertical) displacement abound in the Crater Lake region and the contiguous

Basin and Range province to the east of the Cascades (fig. 1 and 4; plate 1; Pezzopane and Weldon, 1993). Most of these faults trend north-south to north-northwest-south-southeast. Faults are more easily recognized by topographic expression in the eastern half of the area where no relatively young volcanic rocks occur. Faults cutting the youthful lava flows of the forested Cascades are less obvious because fault offsets are smaller than in the older rocks of the sparsely vegetated landscape to the east where fault scarps can be dramatically seen, as along the east side of Upper Klamath Lake (Sherrod, 1993). Young lava flows and glacial deposits in the Cascades provide an opportunity for testing whether faults are potentially active, as these materials may be datable. Offset lava flows in Crater Lake National Park and glacial moraines at the mouths of valleys on the west side of the Upper Klamath Lake basin are described below as evidence for the recent activity of a major, through-going fault zone. Little is known about the state of faults immediately east of the Cascades and we are unaware of any detailed paleoseismic studies of faults (*i.e.*, trenching) depicted in plate 1.

WEST KLAMATH LAKE FAULT ZONE

Mount Mazama lies at the north end of the fault bounded basin known as the Klamath graben. North of Klamath Falls, highway 97 skirts Upper Klamath Lake along the base of fault scarps of the east side of the graben (Sherrod and Pickthorn, 1992; Sherrod, 1993). The west side is bounded by the active West Klamath Lake fault zone (WKLFZ; Hawkins and others, 1989). The surface expression of the WKLFZ consists of a series of normal faults trending approximately north-south. Individual faults have lengths of 10-15 km and displace late Quaternary lavas and glacial deposits tens of meters, generally down-to-the-east. For example, highway 62 ascends the Annie Spring fault scarp of the WKLFZ immediately north of the junction with the road to Crater Lake. The Annie Spring fault originates at least as far south as Pumice Flat, passes through Annie Spring, and continues nearly to The Watchman (fig. 2).

The consistency in age and amount of displacement on its various faults suggests that the WKLFZ merges at depth into a single through-going

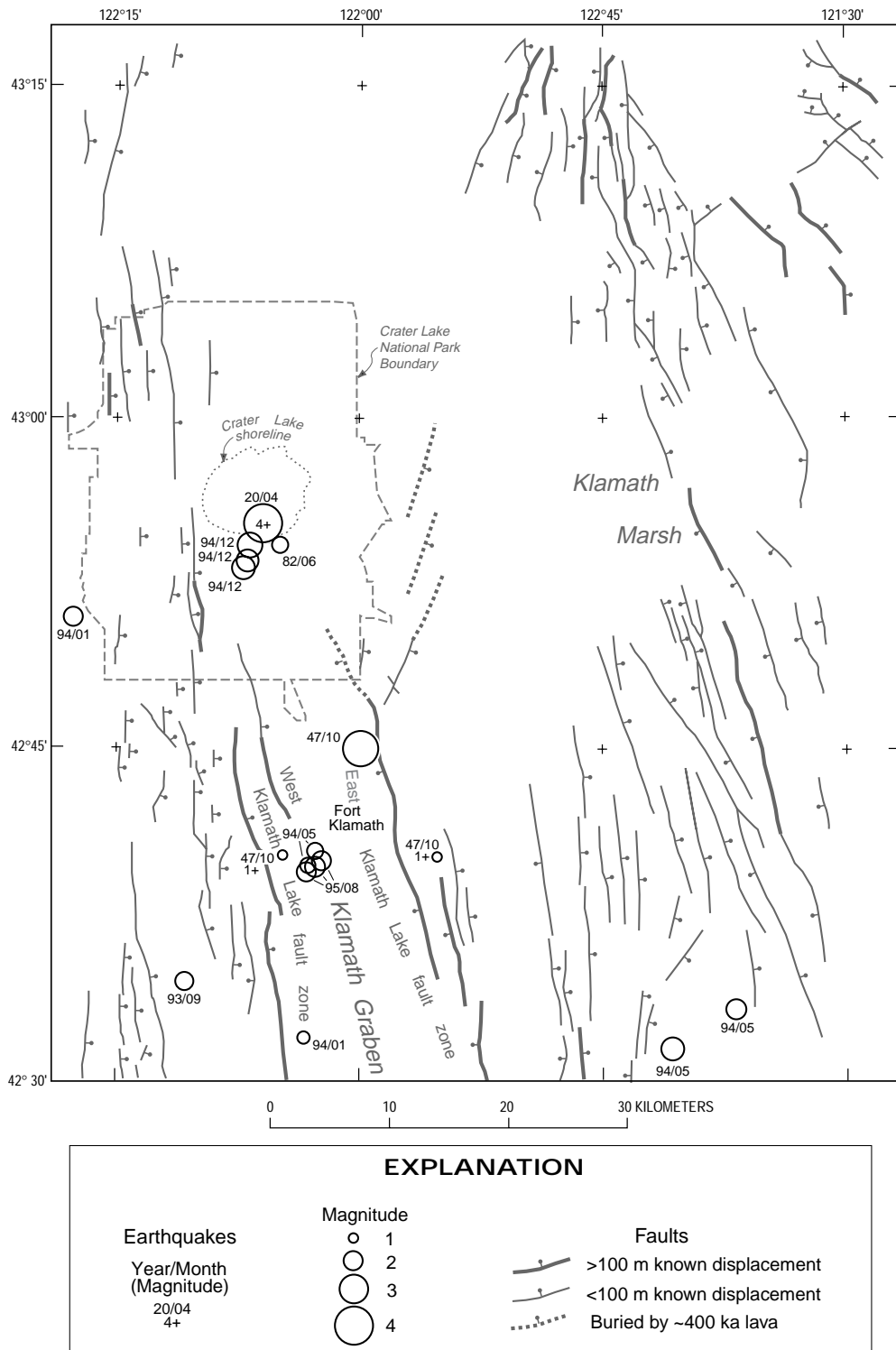


FIGURE 4.—Map showing earthquake epicenters and magnitudes. Base from figure 1. See Bacon and Nathenson (1996, table 2) for data sources. Note that accuracy of epicentral locations varies widely. Earthquakes occurring in 1993 and subsequent years are more accurately located than prior events. Depths of earthquake hypocenters also vary significantly and are not precisely known for most events. Because faults are inclined, earthquake epicenters that do not coincide with specific mapped faults nevertheless may have occurred on a known fault zone.

structure. The subparallel Sky Lakes fault zone cuts older lavas ~6–8 km west of the WKLFZ. Both of these fault zones pass through Crater Lake National Park and emerge on the north as a ~10-km-wide zone of faulting that has been mapped as far as Mount Bailey (plate 1). The southern boundary of the WKLFZ is marked by a change in strike of faults from north–south to north–northwest–south–southeast (south of the area of fig. 1 and 4, plate 1). The total length of the WKLFZ and its northward continuation, between approximately the latitudes of Pelican Butte and Mount Bailey, is ~70 km, ~50 km if the northern section is not included. Scarp heights in young lavas and moraines suggest that motion on the WKLFZ has occurred in events of a few meters vertical displacement and that large sections of the zone may have moved at once. The WKLFZ is analogous to other active normal fault zones of the Basin and Range province and is capable of producing large earthquakes (*e.g.*, Crone and others, 1991).

Many of the located earthquakes shown in figure 4 occurred within the Klamath graben. Fault planes exposed by quarrying in the Klamath Basin have steep dips (inclinations of ~60° from horizontal) and appear to record mainly vertical (dip slip) displacement. Earthquake epicenters shown in figure 4 may be associated with slip at depth on specific mapped faults, given the direction of dip of the faults, focal depths of earthquakes, and imprecision of earthquake locations. The earthquakes south of Crater Lake National Park and west of latitude 122° may have occurred along the WKLFZ, except the September 21, 1993 event which may have been on the Sky Lakes fault zone (plate 1).

SLIP RATE AND RECURRENCE INTERVAL OF THE WKLFZ

An estimate of the long-term slip rate on the WKLFZ near Crater Lake can be obtained from geologic mapping of offset lava flows that have been dated by the K–Ar method. For example, a dacite flow dated at 50 ± 6 ka appears to be offset ~15 m vertically, down to the east, along the Annie Spring fault ~750 m west of Rim Village. This result implies an average rate of vertical displacement of 0.3 mm/yr. This rate is corroborated by vertical offsets of older lava flows along the same fault up to 10 km south of The Watchman (table 4). In addition, a minimum displacement on

the related Red Cone Spring fault northwest of the caldera (fig. 1 and plate 1) suggests a similar rate (“A” in table 4). Should the fault dip 60° and have a purely normal sense of motion, the east–west tectonic extension rate would be 0.17 mm/yr and the slip rate in the plane of the fault would be 0.35 mm/yr. This result is similar to long-term average slip rates of 0.1–0.6 mm/yr determined by Pezzopane and Weldon (1993) for faults at the west edge of their Central Oregon fault zone ~100 km east of Crater Lake.

Estimates of slip rates on faults of the WKLFZ south of Crater Lake are consistent with our data for the Annie Spring and Red Cone Spring faults. Hawkins and others (1989, table 3) measured offsets in ~130–150 ka and ~10–30 ka glacial moraines and in early Holocene deposits at the mouths of the canyons of Dry, Sevenmile, Threemile, and Cherry Creeks where they enter the Klamath graben and reported an average slip rate of 0.17 mm/yr for the last ~130,000 years. They noted that at least one 1–2 m surface displacement event has occurred in the last 10,000 years.

Recurrence intervals are unknown for earthquakes that cause surface displacement on the WKLFZ. If all of the displacement on these faults occurred in events with, say, 1–3 m of vertical offset, significant earthquakes would be expected to recur at an average rate of one event in ~3,300–10,000 years. This inference is consistent with paleoseismic data for the Ana River fault ~100 km east-southeast of Crater Lake (Pezzopane and others, 1996). We cannot give a more rigorous estimate of the probability of a large earthquake on the WKLFZ without knowledge of the time and amount of co-seismic displacement of the last event (Working Group on California Earthquake Probabilities, 1990), such as might be obtained by trenching across the fault trace.

MAXIMUM EARTHQUAKE ON THE WKLFZ

The maximum earthquake likely to occur on a fault or fault zone can be estimated from fault characteristics such as surface rupture length and downdip rupture area. Critical to this analysis is rupture length, which depends on fault zone segmentation (Schwartz and Coppersmith, 1986). Crater Lake appears to be adjacent to a segment boundary in the

Table 4.—*Fault offsets (down to the east) and average long-term slip rates along Annie Spring and Red Cone Spring faults*[m, meters; ka, kilo-annum (10^3 years); mm/yr, millimeters per year]

| Unit | Locality | Offset m | Age ka | Avg. slip mm/yr |
|-------------------------------------|------------------------|-------------|-----------|--------------------|
| A: Basaltic andesite of Red Cone | NW of Red Cone | >11 | 35±4* | >0.31 |
| B: Dacite of The Watchman | W of Rim Village | ~15 | 50±6† | ~0.30 |
| C: Dacite north of Castle Creek | W of Rim Village | >50 | 205±3† | >0.24 |
| D: Dacite of Garfield Peak | W of Mazama Campground | >67 | ~240# | >0.28 |
| E: Andesite of Applegate Peak | W of Rim Village | >76 | 250±8† | >0.30 |
| F: Dacite of Munson Ridge | W of Annie Spring | >45 | 276±11† | >0.16 |
| G: Andesite of Arant Point | Arant Point | <160 | 297±12† | <0.5 |
| H: Basaltic andesite W of Arant Pt. | S of Arant Point | >100 | >300# | ~0.3 |

* $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age of whole rock sample by M.A. Lanphere.

† K–Ar age of whole rock sample by M.A. Lanphere.

Constrained by K–Ar age(s) of contiguous unit(s).

greater WKLFZ within which there is no recognized displacement of ~50 ka lava flows (fig. 2, plate 1). The southern boundary of this segment may be coincident with the end of the WKLFZ where the faults change trend from north-south to north-northwest–south-southeast in the epicentral area of the 1993 Klamath Falls earthquakes. This suggests a maximum possible rupture length of ~50 km. Consideration of the empirical relation between earthquake magnitude and surface rupture length (SRL) for normal faults given by Wells and Coppersmith (1994, table 1A) and a maximum SRL of 50 km suggests a maximum earthquake of $M_W = 7.1 \pm 0.3$ ($M_W = 7.3 \pm 0.3$ for SRL = 70 km; M_W = magnitude based on seismic moment, the total energy released in an earthquake). This result is similar to the conclusion of Hawkins and others (1989, 1992) who evaluated the potential shaking at dam sites 50–85 km south-southeast of Crater Lake and reported a maximum earthquake for the West Klamath Lake fault zone of $M_S = 7^{1/4}$ (M_S = surface wave magnitude).

If the hypocentral depths of the 1993 earthquakes are typical of the fault zone, another estimate of the maximum event can be obtained from the empirical

relation between downdip rupture area and magnitude (Wells and Coppersmith, 1994, table 1A). This suggests a maximum magnitude of 7.0 ± 0.2 for a maximum depth of 12 km, dip of 60° , and length of 50 km (7.1 for SRL = 70 km). Increasing depth to 15 km raises the calculated magnitude to 7.1 (7.3 for SRL = 70 km). In light of the uncertainties in the above calculations we consider our best estimate of the maximum earthquake likely to occur near Crater Lake to be $M_L = 7^{1/4}$ (table 5; M_L = local magnitude).

CASCADIA SUBDUCTION ZONE

The Juan de Fuca and Gorda oceanic plates move beneath the North American plate along the Cascadia subduction zone. This process generates earthquakes, such as the $M_I = 6.7$ earthquake (M_I = magnitude based in Intensity) that occurred near the California–Oregon State line on November 23, 1873, and was felt from San Francisco to Portland (Ellsworth, 1990). Geologic evidence indicates that there have been very large Cascadia subduction zone earthquakes in the recent past (Atwater and others, 1995), apparently most recently in 1700 A.D. (Satake and others, 1996). The

Table 5—*Maximum earthquakes magnitudes in the Crater Lake region (modified after Hawkins and others, 1989).*
 [M_L = local magnitude; M_S = surface wave magnitude; M_W = magnitude based on seismic moment]

| Fault | Assumed rupture length, km | Assumed focal depth | Epicentral distance from Crater Lake, km | Magnitude |
|---------------------------------|----------------------------|---------------------|--|--|
| A: Random earthquakes | | 2-5 | 10 | M _L 6 |
| B: Sky Lakes fault zone | 17 | 5-10 | 50 | M _S 6 ³ / ₄ |
| C: West Klamath Lake fault zone | 50-70 | <12 | 0 | M _L 7 ¹ / ₄ |
| D: Cascadia subduction zone | | 35 | 100 | M _W ≥ 8 |
| E: Volcanic earthquake | | 1-5 | 0 | M _L 5 |

maximum magnitude of a great earthquake on the Cascadia subduction zone is certainly M_W ≥ 8 (table 5) and evidence is mounting that the event in 1700 A.D. had M_W ≥ 9 (*e.g.*, Satake and Tanioka, 1996). Probabilities of large earthquakes could be estimated if recurrence intervals were known but data are currently insufficient (Nelson and others, 1996). Probabilistic assessments of earthquake hazards in Oregon are described in detail by Geomatrix Consultants (1995)⁴.

VOLCANIC EARTHQUAKES

Renewed volcanic activity would be preceded and accompanied by earthquakes. Ground motion from volcanic earthquakes (*i.e.*, earthquakes associated with a volcano's plumbing system or occurring within the volcano itself) would be qualitatively similar to that caused by tectonic earthquakes but the maximum magnitude from a volcanic source would be expected to be considerably smaller than those estimated for purely tectonic earthquakes. For example, the largest earthquake recorded at Mount St. Helens prior to the eruption of May 18, 1980, was the event that triggered

the failure of the mountain. This earthquake had a magnitude of 5.1 and a hypocentral depth of 1.5 km (Endo and others, 1981). We consider M = 5 to be a reasonable maximum value for Crater Lake volcanic earthquakes (table 5). This is a significant potential source of ground shaking as volcanic earthquakes might occur beneath Crater Lake itself and could have very shallow hypocenters.

LANDSLIDES MAY CAUSE LARGE WAVES ON CRATER LAKE

Many park visitors descend to Crater Lake along the Cleetwood trail, from whence they may travel to Wizard Island and around the lake on tour boats operated by Crater Lake Lodge. Four tour boats and a NPS research boat are on the lake. Structures used for boat maintenance and to house the boats during the winter are located on Wizard Island. These facilities, and the people who use them, would be at risk if there were a major disturbance of the lake surface. An event that could result in such a disturbance would be failure of part of the caldera wall causing a rapidly-moving

⁴ Available from The Nature of the Northwest Information Center, Suite 177, 800 NE Oregon Street, Portland, OR 97232-2162.

landslide or rock fall into the lake or beneath its surface and which could result in one or more large waves that would travel rapidly across Crater Lake and impact its shore. Landslides or rock falls could be triggered within the caldera by earthquake shaking.

SUBAQUEOUS LANDSLIDES

Geologic evidence for the rapid formation of Crater Lake caldera by catastrophic collapse during the climactic eruption of Mount Mazama indicates that most of the caldera wall dates from that time. However, the bench on the south wall, informally known as Chaski slide, wall-parallel lake-facing scarps near Garfield Peak, and similar faults mapped in the Sun Notch to Eagle Point area suggest that large blocks of the south wall have the potential to fail. Nelson and others (1988, 1994) described a landslide deposit (fig. 3 and table 6) on the lake floor from Chaski Bay to the center of the lake that apparently formed soon after the caldera collapsed and the central platform volcano erupted but before a deep lake was present. Although other probable landslide deposits in the caldera also are thought to have been subaerially deposited and overlain by lacustrine deposits (Nelson and others, 1988), there are a number of bathymetric features that may be subaqueous slide deposits (fig. 3 and table 6). Early lake deposits (c. 7,000 years ago) are thought to be gravity-flow deposits derived from landslides triggered by seismicity associated with postcaldera volcanism (Nelson and others, 1994). We have no evidence from bathymetry or seismic profiling of large subaqueous slide deposits having formed on the caldera floor since volcanism ceased; *i.e.*, within the last ~5,000 years.

Extensive talus deposits form much of the caldera wall, particularly beneath the lake surface, and these might be prone to failure by sliding. Movement of debris down the subaqueous walls is ongoing and feeds

sediment to the deep portions of the lake (Nelson and others, 1988). It appears unlikely that rapid mass movements of sufficient volume to displace the lake surface have occurred in at least the last few hundred years. There does not appear to be unequivocal evidence of high stands of the lake, or destruction of lichen or trees that might be caused by large waves (Nelson and others, 1994). Williams (1942, p. 129), however, states that "Several years ago, Gordon Hegeness, then on the ranger-naturalist staff, discovered diatomaceous earth [lake sediment] on Wizard Island, approximately 50 feet above the surface of the lake." Assuming this report is correct, it is unclear whether this deposit formed during a high stand of the lake or was ripped up from the lake floor and deposited by a wave.

HOW LARGE MUST AN EARTHQUAKE BE TO TRIGGER LANDSLIDES?

A possible trigger for a landslide that might generate dangerous waves would be ground shaking during an earthquake on the WKLFZ, especially the Annie Spring and Red Cone Spring faults. In order to cause a wave, the avalanche or slide must travel rapidly into or beneath the lake. There are many types of "landslides" that may be triggered by earthquake shaking. Those considered possible at Crater Lake include disrupted falls, slides, and avalanches of rock, soil (broadly defined as a loose, unconsolidated, or poorly cemented aggregate of particles), or snow and coherent slumps and block slides (as defined by Keefer, 1984). Subaqueous slides are likely to consist of the same kinds of rock or soil as in subaerial slides, rather than sand or finer-grained sediments, so that we will not differentiate between the two environments for purposes of this report. Moreover, because we are concerned with falls and slides that may displace sufficient lake water to cause damaging waves, we only consider large volume landslides that move very to extremely rapidly. This eliminates coherent slides and

⁵ Modified Mercalli Intensity IV: "Hanging objects swing. Vibration like passing of heavy trucks; or sensation of a jolt like a heavy ball striking the walls. Standing motor cars rock. Windows, dishes, doors rattle. Glasses clink. Crockery clashes. In the upper range of IV wooden walls and frame creak." Modified Mercalli Intensity VI: "Felt by all. Many frightened and run outdoors. Persons walk unsteadily. Windows, dishes, glassware broken. Knickknacks, books, etc., off shelves. Pictures off walls. Furniture moved or overturned. Weak plaster and masonry D [poor quality] cracked. Small bells ring(church, school). Trees, bushes shaken (visibly, or heard to rustle)."

Table 6.—*Approximate minimum areas, thicknesses, and volumes of probable landslides at Crater Lake*
[m², square meters; m, meters; m³, cubic meters]

| Slide | Area 10 ⁶ m ² | Mean thickness, m | Volume 10 ⁶ m ³ |
|---|--|----------------------|--|
| A: South of Palisade Point | 0.066 | 20 | 1.3 |
| B: North of Castle Crest | 0.16 | 20 | 3.2 |
| C: Northwest of Skell Head | 0.23 | 30 | 6.9 |
| D: West of Sentinel Rock | 0.83 | 40 | 33 |
| E: Chaski Bay (Nelson and others, 1988) | 4.65 | 20 | 93 |
| F: Southwest of Skell Head | 0.044 | 3 | 0.13 |
| G: Chaski Bay block above lake level | 0.19 | 80 | 15 |

snow avalanches from our analysis.

Keefer (1984) provides guidelines for evaluating the potential of earthquakes of a given magnitude and epicentral distance to induce the various kinds of landslides. In terms of Modified Mercalli Intensity (MMI), a measure of local shaking, disrupted slides and falls would be expected to be common at $MMI \geq VI$. However, the minimum intensity for such occurrences would be IV^5 . The smallest local earthquake in Keefer's study that triggered rock falls and slides had $M_L = 4.0$. Thus, the maximum volcanic earthquake, with epicenter at Crater Lake, would be expected to cause rock falls and slides both above and beneath the lake. Plots of maximum distance from earthquake epicenter to landslides for earthquakes of different magnitudes (Keefer, 1984, fig. 2) provide a guide to the likely effects at Crater Lake of earthquakes with epicenters at a distance of 60 km, such as the September 1993, events. In this case, disrupted falls, slides, or avalanches could occur for $M \geq 5.7$. The effect of a large earthquake on the Cascadia subduction zone can be evaluated from plots of magnitude versus maximum distance from the fault-rupture zone (Keefer, 1984, fig. 3), which we consider to be more relevant than the epicenter of a large, distant event. Here, we assume a minimum distance of 100 km from the gently inclined fault-rupture zone and determine that disrupted falls or slides may occur for an earthquake

of $M \geq 6.5$. Clearly, the maximum event (table 5) is more than adequate to induce disrupted falls and slides at Crater Lake. A great earthquake on the Cascadia subduction zone would result in a longer duration of shaking, perhaps one to several minutes (Wong and Silva, 1996), than would a smaller local event and this undoubtedly would increase the probability of slides.

Another way to look at the potential for earthquake-induced rock falls and slides is in relation to the critical ground acceleration ($A_c = 0.05g$; Wilson and Keefer, 1985) necessary to cause motion of incoherent materials. The peak ground acceleration for sites on "soil" (any unconsolidated material; "rock" sites experience smaller accelerations) is given as a function of earthquake magnitude and distance from source in a relation developed specifically for extensional tectonic regimes, such as the Crater Lake area, by Spudich and others (1997). The distance is that to the nearest point on the surface projection of the area that slips in the earthquake. A peak horizontal acceleration of $0.05 g$ (+65%/-40%) would be expected to occur for a $M = 5$ earthquake at a distance of 23 km, $M = 6$ at 42 km, and $M = 7$ at 73 km. Earthquakes rupturing an area beneath Crater Lake, such as on the Annie Spring or Red Cone Spring faults projected downdip, could produce peak horizontal accelerations of $0.20 g$ for $M = 5$, $0.34 g$ for $M = 6$, and $0.57 g$ for $M = 7$ (all g values +65%/-40%). Recognizing the significant

uncertainties inherent in empirical relations such as the one used to calculate acceleration, these results are consistent with volcanic, local tectonic, or distant Cascadia subduction zone earthquakes all having the potential to trigger failure of the fractured and poorly consolidated rock of the caldera walls and talus slopes.

In a different type of analysis, Geomatrix Consultants (1995, plate 3a) indicates a peak horizontal acceleration of $\sim 0.14 g$ for sites on rock near Crater Lake and a return period of 500 years (mean annual frequency of exceedance of 0.002). This value takes earthquakes from all sources into consideration and includes estimates of the probability of earthquake occurrence. Increased return period (decreased mean annual frequency of exceedance) results in larger accelerations. Although not strictly comparable to our analysis, the Geomatrix study also indicates that peak horizontal accelerations at Crater Lake can significantly exceed A_c .

WAVES GENERATED BY LANDSLIDES INTO THE LAKE

There are many examples of large waves caused by landslides. 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 where the submarine slope has failed. A spectacular example of a seismically related rockfall and ensuing wave is the July 9, 1958, event at Lituya Bay, Alaska, described by Miller (1960). Lituya Bay is an ice-scoured, nearly landlocked tidal inlet adjacent to the Fairweather Range and Fairweather fault in the Gulf of Alaska. It has a maximum depth of 220 m. In the 1958 event, $30 \times 10^6 \text{ m}^3$ of rock plunged into a 1.2-km-wide inlet of the bay from an elevation of up to ~ 900 m, causing water to surge over the opposite wall of the inlet to an elevation of 530 m, and generating a wave that moved down the bay 11 km to its mouth at a probable velocity of 160 to 210 km/hr. Miller (1960) presents evidence for several lesser events at Lituya Bay caused by a variety of phenomena. Waves generated by landslides in Norwegian fjords and lakes are described by Jørstad (1968). The catastrophic waves induced by a rock slide at Tafjord (8–9 km long x 1–1.5 km wide x 200–220 m deep), Norway, April 7, 1934, traveled at between 20 and 100 km/hr,

were 1–16 m in height 3–11 km from the slide, and reached a maximum of 62 m in height 200 m from the slide. In this event, a total of $2\text{--}3 \times 10^6 \text{ m}^3$ of rock plus scree entered the water from a maximum elevation of 730 m. The Lituya Bay and Tafjord events are comparable in magnitude to a worst case scenario for Crater Lake. Rough calculations of minimum volumes of bathymetric features that may be landslides at Crater Lake are presented in table 6. The Chaski Bay slide (fig. 3) has a minimum volume of $93 \times 10^6 \text{ m}^3$. The minimum volume of rock in the block forming the prominent bench at Chaski Bay is $15 \times 10^6 \text{ m}^3$. A far greater volume of fractured and altered rock of the caldera wall above this feature might be presumed to be capable of failure. We stress that in order for such a slide to pose a significant wave-generation hazard, the slide mass would have to move rapidly into the lake.

The closed basin of Crater Lake caldera (Proximal Hazard Zone PA) is ~ 8 by 10 km at the rim and ~ 7 by 9 km at the shoreline. The maximum depth is 589 m, a large part of the lake is at least 450 m deep, and the high points on the rim are ~ 600 m above the lake. Postcaldera volcanoes form hills on the caldera floor, including the edifice capped by Wizard Island. Three-dimensional numerical models have been developed that simulate the effects of landslides entering bodies of water. Although the detailed propagation and character of waves induced by a landslide at Crater Lake, initiated subaerially or subaqueously, cannot be predicted directly from published numerical models of other landslides in fjords (*e.g.*, Harbitz and others, 1993) or in bodies of water adjacent to volcanoes (*e.g.*, Kienle and others, 1987), the numerical models lend credence to our concerns about Crater Lake. Initial waves likely would be followed by seiche effects caused by reflection of waves off of the caldera walls. Interference of waves could result in amplification.

The substantial depth of Crater Lake would cause a wave to travel at great speed. A common approach to determining the velocity of propagation is

$$v = (g \times h)^{1/2}$$

where v = velocity, g = gravitational acceleration, and h = water depth. For $h = 450$ m, $v = 66$ m/s. For example, a wave initiated at Chaski Bay would reach the boat dock at Cleetwood Cove in about two minutes.

The amplitude of the wave would diminish in the deep part of the lake but would increase on approach to the shore. Consequently, at the onset of shaking, perhaps as indicated by abundant, sudden rockfalls, it would be advisable for boats to head toward the center of the lake.

WAVES GENERATED BY EARTHQUAKES

Large waves or seiche effects caused by motion of the lake floor during an earthquake would require that the natural period of free oscillation of the lake be similar to the period of seismic waves. Surface waves responsible for motion of the lake floor would have maximum periods of about 20 seconds. The first mode of stationary oscillation of the lake is approximated by

$$t = 2L \times (g \times h)^{-1/2}$$

where L = length, which gives $t = 4$ minutes for Crater Lake, an order of magnitude longer than the maximum period of seismic waves. It is thus unlikely that earthquake shaking alone would cause dangerous waves on the lake.

PREPARING FOR AN EARTHQUAKE AFFECTING THE CRATER LAKE REGION

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. More frequent may be large, distant earthquakes on the Cascadia subduction zone for which shaking might be less violent but of much longer duration. Residents may wish to maintain supplies of food, water, clothing, flashlights, and first-aid materials (*see Protecting Crater Lake National Park and surrounding communities from volcano hazards*), such as recommended for people living in earthquake-prone areas elsewhere, and minimize the chances of large objects falling in their homes. Businesses and Crater Lake National Park should be aware of possible damage to structures, utilities, communication facilities, and transportation systems, in addition to the potential for rockfalls and dangerous waves on Crater Lake described above. Communities should develop plans for responding to

the effects of an earthquake. A relevant local example of moderate earthquake damage is provided by the $M \approx 6$ "Klamath Falls" earthquakes of September 1993 (Wiley and others, 1993; Dewey, 1993).

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GLOSSARY

andesite—magma containing about 57 to 63 percent SiO_2 ; intermediate in eruptive characteristics between basaltic and silica-rich magma.

ash—(volcanic) sand-sized or finer tephra; fragments are smaller than 2 mm (0.08 in) in diameter.

ballistics, ballistic blocks—rock fragments explosively ejected from the vent on a ballistic arc.

basalt—low-silica magma (containing about 45 to 57 percent SiO_2), which is the hottest and least viscous.

caldera—a large, basin-shaped volcanic depression, more or less circular in form, with a diameter generally greater than 1 to 2 km (a mile or more).

cinder cone—a conical hill formed by accumulation of solidified bubble-rich droplets and clots of lava that fall around the vent during a single basaltic to andesitic eruption.

climactic eruption—(Crater Lake) the catastrophic, highly explosive eruption of Mount Mazama about 7,700 years ago during which Crater Lake caldera collapsed.

composite volcano—volcanic edifice formed by accumulation of lava and fragmental volcanic material from repeated eruptions from a central vent or closely spaced vents; commonly forms a high, steep-sided, volcanic cone which may be referred to as a stratovolcano.

dacite—(Crater Lake) silica-rich magma containing 63 to 68 percent SiO_2 ; see also *silicic magma*.

dome—volcanic domes are masses of solid rock that are formed when viscous lava is erupted slowly from a vent and piles up over it. The sides of most domes are very steep and typically are mantled with unstable rock debris formed during or shortly after dome emplacement.

hydromagmatic—said of an explosive eruption caused by heating of water by magma or by physical mixing of magma and water.

lahar—a watery flow of volcanic rocks and mud that

surges downstream like rapidly flowing concrete; also called mudflow or debris flow.

K-Ar dating—the potassium (K) – argon (Ar) method of radiometric data of rocks and minerals. The radioactive isotope of potassium (^{40}K) decays to stable argon (^{40}Ar) at a known rate. Measurement of the amounts of K and radiogenic ^{40}Ar present in a rock or mineral specimen allows calculation of the elapsed time since the material was sealed to Ar loss. For unaltered volcanic rocks, the time since crystallization of the magma is determined.

magma—molten rock, which may also contain suspended crystals and(or) gas bubbles; forms lava or tephra upon eruption at the Earth's surface.

magma chamber—a reservoir of magma beneath the Earth's surface.

monogenetic volcano—a volcano built up by a single eruption or series of like eruptions closely spaced in time.

paleomagnetic studies—investigations of the orientation and(or) intensity of the Earth's magnetic field in the past, as recorded in geologic materials. The magnetic poles wander about the Earth's axis of rotation and the paleomagnetic pole position at the time of cooling of a volcanic rock is "frozen in" by magnetic minerals. An empirical calibration of this "secular variation" over time allows eruption ages to be constrained and isolated outcrops to be correlated with one another.

plinian eruption—an explosive eruption in which a steady, turbulent stream of fragmented magma and magmatic gas is released at high velocity from a vent producing a towering eruption column that rises buoyantly into the atmosphere.

postcaldera eruption—volcanic eruption occurring after caldera formation.

preclimactic eruption—(Crater Lake) volcanic eruption of rhyodacite occurring in the approximately 20,000 years before the climactic eruption of Mount Mazama.

pyroclastic flow—dense, hot mixture of volcanic rock fragments (pyroclasts) and gases that, driven by gravity, flows down a volcano's flank at high speed.

pyroclastic surge—turbulent, relatively low-density mixture of gas and rock fragments that, driven by gravity, flows above the ground surface at high speed.

regional volcanism—(Cascades) volcanic activity represented by widespread, generally basaltic to andesitic monogenetic volcanoes, including cinder cones and shield volcanoes, forming a background for the larger centers of the Cascades (composite volcanoes).

rhyodacite—(Crater Lake) silica-rich magma containing 68 to 72 percent SiO_2 ; see also *silicic magma*.

shield volcano—a broad, gently sloping mound composed of numerous overlapping and superimposed lava flows; resembles the shape of a

warrior's shield or an inverted shallow bowl; typically basaltic in Cascades but may be andesite.

silicic magma—magma that contains more than 63 percent SiO_2 and is generally the most viscous and gas-rich; includes dacite, rhyodacite, and rhyolite (the last not present at Crater Lake).

tectonic earthquake—an earthquake caused by sudden slip on a fault rather than by subsurface movement of magma or a volcanic eruption.

tephra—collectively, all fragmental rock material, including magma, ejected during a volcanic explosion or eruption.

vent—the opening at the Earth's surface through which volcanic materials are ejected.

