# Geology of Prisoners Rock and The Peninsula

## Pleistocene Hydrovolcanism in the Tule Lake Basin, Northeastern California

ALEXIS LAVINE
Department of Earth and Planetary Sciences
University of New Mexico

Photo 1. View to the west over Prisoners Rock, lake sediments and Tule Lake, recent basalt flows, Medicine Lake shield volcano, and Mt. Shasta. *Photo by Grant Heiken.*

### INTRODUCTION

Prisoners Rock (also known as Petroglyph Point) and The Peninsula are two **tuff cones*** and a **tuff ring** at the northern end of Lava Beds National Monument (Photo 1; Figure 1). The monument lies within the Tule Lake Basin, which was formed by normal (extensional) faulting during the Pliocene and Pleistocene (Donnelly-Nolan and Champion, 1987). Extensional faulting in the basin has resulted in widespread magmatic activity, mainly in the form of basalt flows and cinder cones.

The tuff cones and tuff ring were formed by **phreatomagmatic or hydrovolcanic eruptions** approximately 270 thousand years ago (ka) when basaltic magma rising along a north-trending fault came in contact with abundant ground water and possibly shallow lake water. The magma superheated the ground water, resulting in violent steam explosions that fractured the surrounding rocks, and supercooled the magma, forming basaltic glass. Large clouds of steam and volcanic ash with pieces of subsurface rocks may have reached heights of 3 miles (5 km) during hundreds to thousands of pulsatory eruptions. Material from these **pyroclastic surges** fell layer upon layer, building cones around the craters.

Explosions resulting from varying degrees of water-magma interaction deposited material at the three vents studied. The amount of water involved in the eruptions and the mechanisms involved in depositing the layers can be determined by examination of the

*Terms in **boldface** type are in the glossary on page 102.

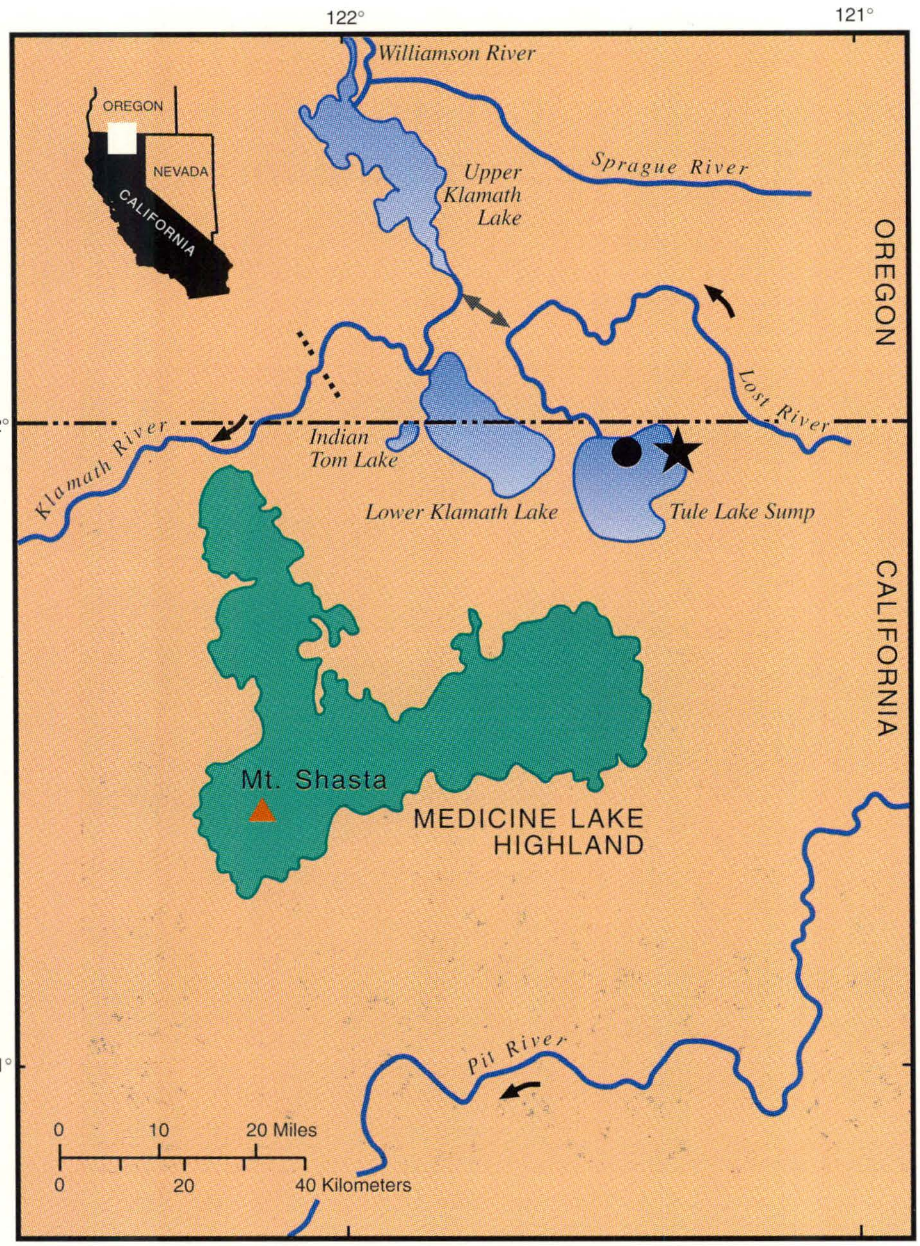


Figure 1. Location map of Tule Lake, and Prisoners Rock and The Peninsula (star). Shows historic lakes, paleodrainage patterns, and location of the Tulelake drill core site (black dot). Double-headed arrow indicates bidirectional flow between the Lost and Klamath rivers. Dotted line across the Klamath River indicates probable location of sill over which the ancient lake system first spilled into the Klamath drainage. Green area indicates portions of the Medicine Lake Highlands and Mt. Shasta region with elevations in excess of 5,000 feet (1,525 m). *Modified from Bradbury (1992).*

deposits. Country rock fragments provide information about the subsurface geology, age of the deposits, paleolacustrine conditions, and depth and energy of the explosions. Magmatic activity continued at Prisoners Rock and The Peninsula after water-magma interaction ceased, forming basalt flows, dikes, spatter, and a lava lake in the central crater.

This paper discusses the geology of Prisoners Rock and The Peninsula, paleoenvironmental conditions, subsurface geology, and the unique processes that occurred when rising magma came in contact with external (non-magmatic) water and formed tuff cones and a tuff ring.

## GEOLOGIC SETTING

The Tule Lake Basin is part of the Modoc Plateau Province, an area composed principally of basaltic lavas that rose from the mantle along north- and northwest-trending extensional faults, with little or no contamination from crustal rocks (Hannah, 1977; McKee and others, 1983). The Tule Lake Basin is bounded on the south by the Medicine Lake shield volcano and on the north by northwest-trending normal faults. The west side of the basin is defined by the Gillem Bluff Fault, which extends beneath and is a major structural feature of the Medicine Lake volcano (Donnelly-Nolan and Champion, 1987). The east side of the basin is defined by Big Crack, a similar north-trending normal fault.

The modern day Tule Lake Sump, drained in 1905 for agricultural purposes, was part of pluvial Lake Modoc, situated over much of southeastern Oregon and northeastern California during the late Pliocene and Pleistocene. The lake covered the area now occupied by Upper and Lower Klamath, Tule, and Spring lakes, and Poe, Swan Lake, Yonna, and Langell valleys (Dicken, 1980). Interdisciplinary studies on a 1,096-foot- (334-meter-) long drill core taken in the town of Tulelake, near the center of the Tule Lake Basin, document at least 3 million years of lacustrine deposition and environmental change (Adam and others, 1989).

## GEOMORPHOLOGY

The cones rise 164 to 820 feet (50 to 250 m) above the lake-eroded surface. Lake bottom sediments between the tuff cones, found at a depth of 148 feet (45 m), mark the ground surface at the time of the eruptions (Hotchkiss, 1968). The tuff cones are subelliptical and elongated north-south, with a greater thickness of deposits and higher crater rims on the east and northeast, probably due to prevailing southwesterly winds at the time of the eruptions. This is especially noticeable at The Peninsula tuff cone, which is the central and largest of the three landforms (Figures 2a and 2b). More than half of the northernmost tuff ring, which can be seen along Highway 139, has been eroded, exposing the deposits and the crater. North-and northwest-trending faulting in the area was prevalent before, during, and after deposition of the cones (Figures 2a and 2b). Cooling of the deposits and crater collapse have caused further fracturing. Waves on Tule Lake undercut the deposits, which broke along fracture surfaces and formed cliffs on the east and west sides. Historic lake levels as much as 23 feet (7 m) above the present ground surface can be seen on the tuff cone at Prisoners Rock (Cleghorn, 1959; Photo 2).

## FORMATION OF THE DEPOSITS

The tuff cone deposits at Prisoners Rock (Photo 3) and The Peninsula derive from very wet mixtures of ash and steam. These deposits: 1) are in beds dipping 25 to 40 degrees radially outward from the vent, and up to 50 degrees toward the vent; 2) contain **armored lapilli** with **scoria** or glass cores; 3) show soft sediment deformation structures in the form of shear ripples (Lorenz, 1974) from downslope movement of wet deposits along bedding planes, and large slump folds (Photo 4); 4) are massive and vesicular with occasional pebble stringers and channels; 5) contain U-shaped channels (Fisher, 1977) from surge erosion of unlithified deposits; and 6) in places have most primary depositional structures overprinted by alteration to calcite, zeolites, and clays due to moisture and high temperatures at the time of emplacement.

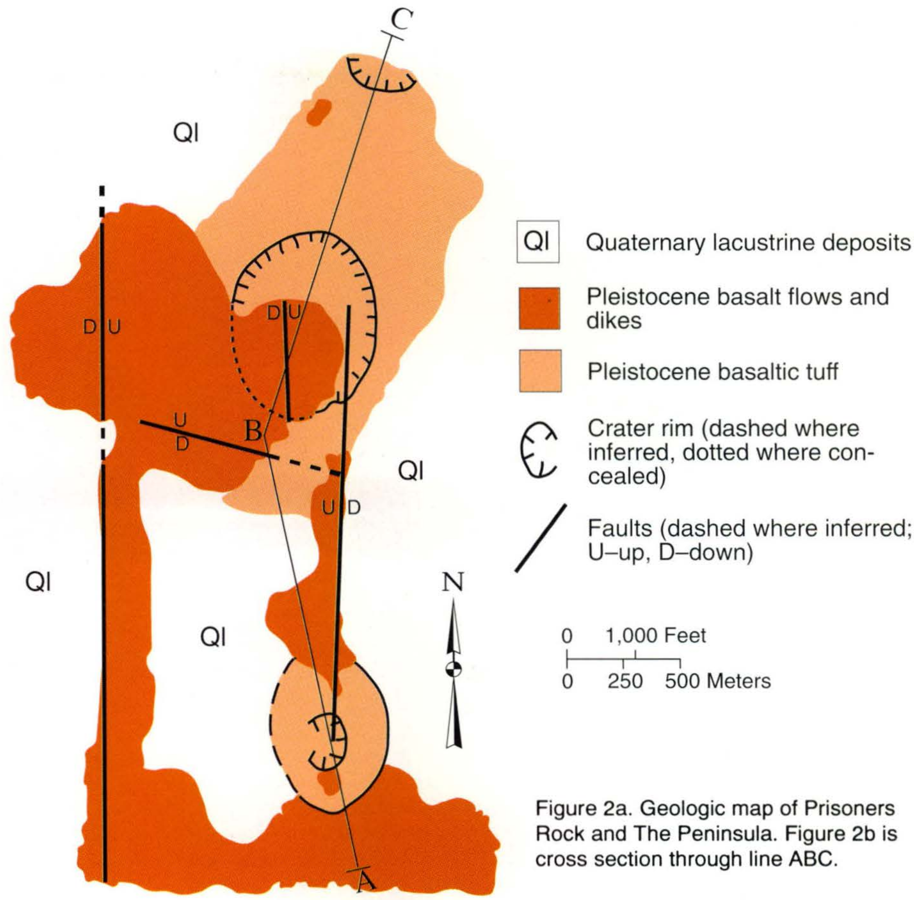


Figure 2a. Geologic map of Prisoners Rock and The Peninsula. Figure 2b is cross section through line ABC.

The amount of water-magma interaction decreased as the eruptions at both cones continued, culminating in the eruption of basaltic dikes, flows, and spatter. At Prisoners Rock this can be seen by an upward succession of massive deposits, inversely graded surge layers, and ash and lapilli fall beds.

Inverse grading in many of the planar bedded deposits is from upward migration of larger grains during emplacement, or from the decrease in energy of each eruptive pulse. This implies that the surges were in a deflated, highly concentrated state during the emplacement of the planar beds (Cas and Wright, 1987).

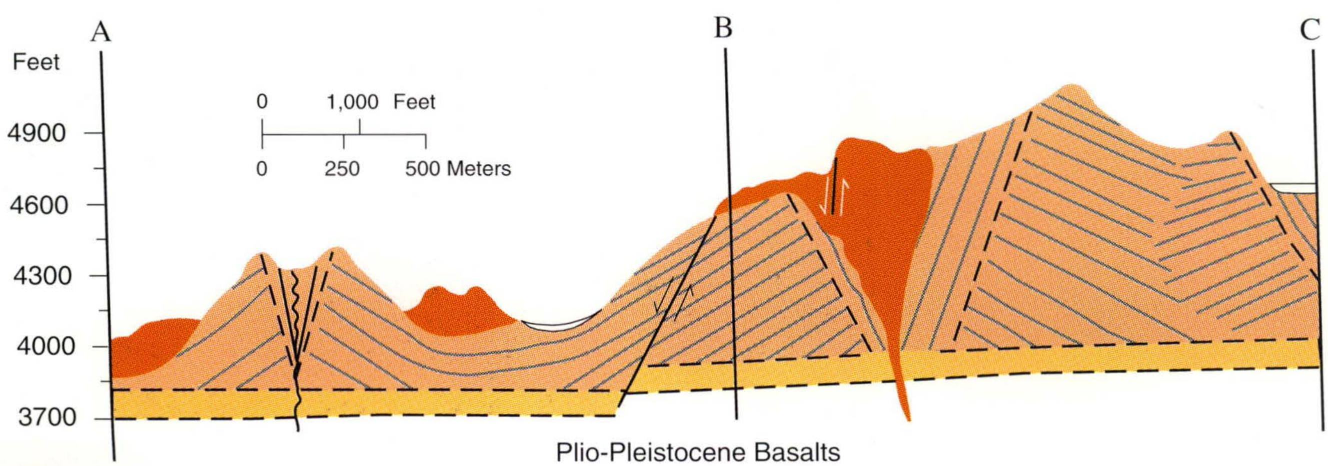


Figure 2b. Cross section of Prisoners Rock and The Peninsula. Light yellow deposits beneath the cones are Pleistocene lacustrine deposits. Vertical exaggeration is 3.3x.

Photo 2. View of Prisoners Rock tuff cone from wave-cut abrasion platform (Petroglyphs parking area) on the west side of the cone looking northeast. The fence is approximately 7 feet (2 m) high. The cliff face formed along north-trending fracture surfaces. Note bedding in the cliff face and on the abrasion platform. Differential erosion because of differences in grain size and weathering has accentuated bedding. Weathering pattern is from weathering of a cemented fracture surface. Behind the fence are wave-cut nips up to 23 feet (7 m) above the ground surface, and white calcite precipitate. *Photos by author unless otherwise noted.*

and asymmetrical impact sags beneath ballistically emplaced country rock fragments (Photo 7) indicate flow direction in many of the beds. These features also indicate the surges were highly inflated at the time of deposition. Alternation of fine-grained laminated units with lapilli beds and lithic rich beds in these deposits indicates pulses of explosive activity with varying degrees of water-magma interaction (Cas and Wright, 1987).

After water-magma interaction ceased, basaltic magmatism continued at all three vents forming dikes, flows, and spatter cones (Figure 2). The basalts are mainly **porphyritic**, with clusters of olivine and plagioclase. The main north-trending dike exposed in the crater walls fed a glassy basalt flow on the northeast flank of the tuff cone. The largest volume of basalt erupted from the crater of The Peninsula, formed a lava lake, and flowed out of the cone to the west (Photo 8; Figure 2a). Inward-dipping **tuff** beds were baked by the heat of the overlying lava lake basalt. Erosion of the tuffs has exposed the base of the lava lake. Load

At The Peninsula the lowermost deposits are extremely altered, making primary depositional structures almost impossible to see. The decrease in saturation of subsequent deposits caused them to be less altered. The extremely high-energy explosions deposited laminated, fine-grained surge beds with dune and antidune structures. Pervasive desiccation cracks, probably due to shrinkage from clay formation, facilitated erosion (Heiken, Los Alamos National Labs, New Mexico, oral communication, 1992). Large-scale slump folding followed deposition of inversely-graded planar beds (Photo 4; Figure 3).

More-explosive eruptions that formed the tuff ring to the north were caused by a lower water:magma ratio. Dryer, less-concentrated ash clouds deposited beds with angles ranging from 10 to 15 degrees outward from the crater and 25 to 50 degrees inward (Photo 5). Dune structures (Photo 6)

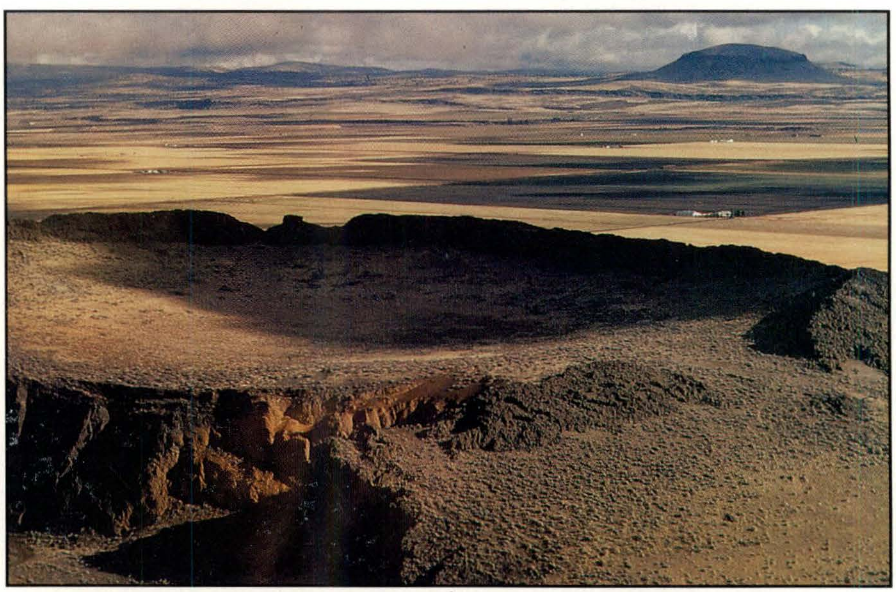

Photo 3. Aerial view of Prisoners Rock tuff cone from the southwest, showing crater rim, fumerolic alteration, and enhanced erosion (red-orange area in lower middle of photo). Big Crack and Horse Mountain are seen in the distance to the northeast of the cone. *Photo by Grant Heiken.*

Photo 4. Slump fold caused by soft-sediment deformation in inversely graded planar surge beds of The Peninsula tuff cone. A slip surface can be seen at the base of the fold, and the uppermost portion has been eroded by surges.

or flute casts radiating from the center of the crater, and pahoehoe-like crinkles at the base of the lava lake indicate a bowl shaped crater was filled passively, making reconstruction of the original crater rim possible (K.R. Aalto, Humboldt State University, unpublished data, 1993). Load folds in the underlying tuffs indicate that the phreatomagmatic deposits were unlithified during emplacement of the lava lake. The lava lake basalt flowed out of the crater at least 1,640 feet (500 m) to the west, where flows are 16 to 33 feet (5 to 10 m) thick. A small spatter cone near the center of the crater probably marks the source of the lava lake basalt. The flow west of the cone has been faulted down to the west indicating that faulting continued after magmatic activity ceased at Prisoners Rock and The Peninsula.

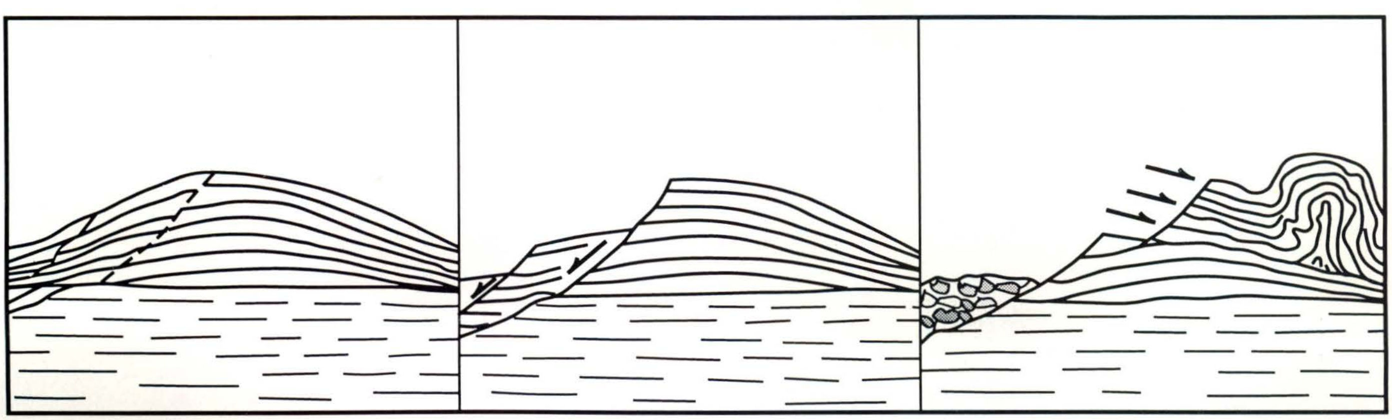

Figure 3. Diagrammatic sketch showing how slump folding was caused by crater collapse with subsequent downslope movement of saturated deposits. *Modified from Heiken (1992).*

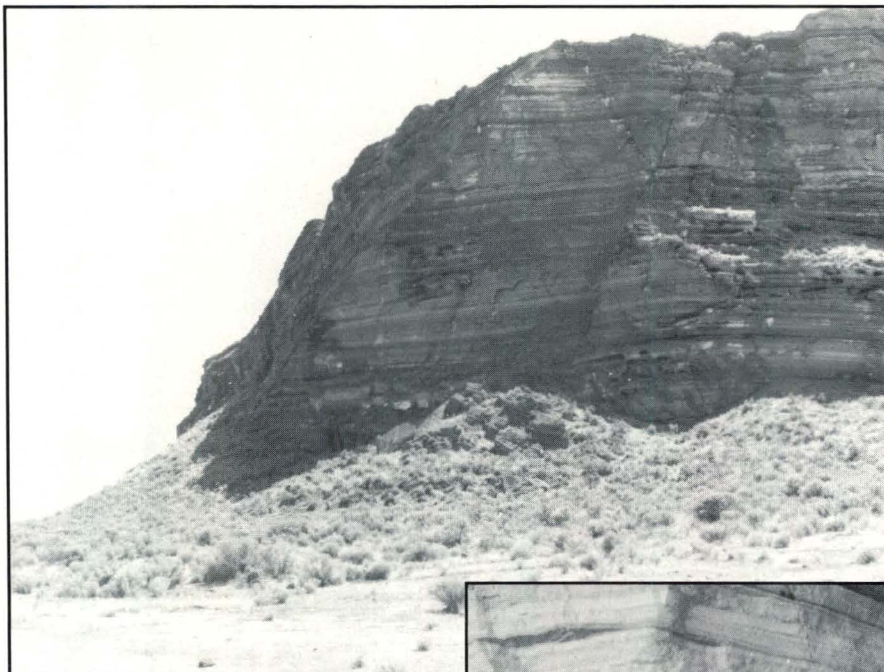

Photo 5. Preserved crater rim of the North Crater tuff ring from the west (visible from Highway 139). Beds on the left were plastered onto the inside of the crater wall and underwent minor slumping back into the crater, causing drag on the lowermost outward dipping beds. Beds on the right are dipping out of the crater.

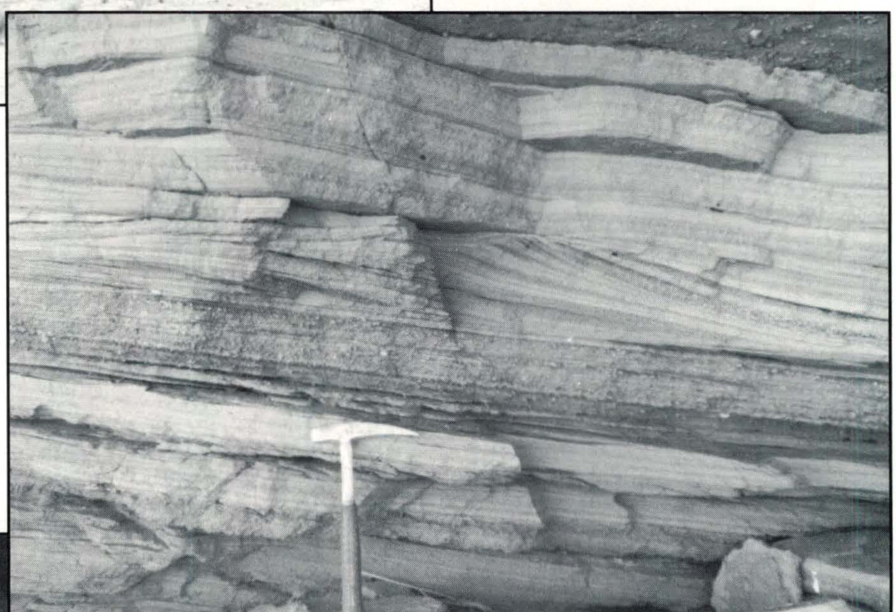

Photo 6. Dune structure in sandwave facies surge deposits of North Crater tuff ring. Flow direction is from left to right.

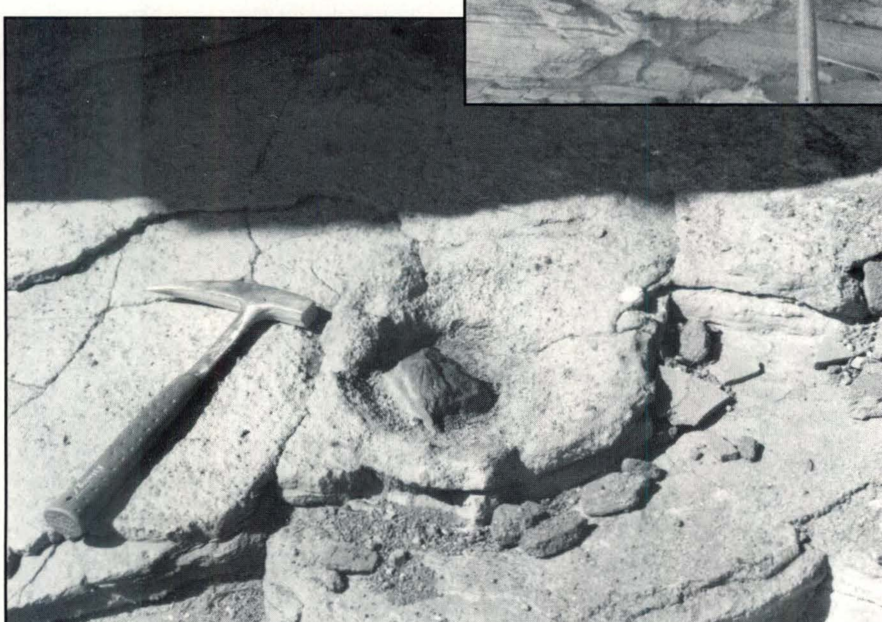

Photo 7. Asymetrical impact sag in deposits of North Crater tuff ring, indicating flow direction from upper right to lower left.

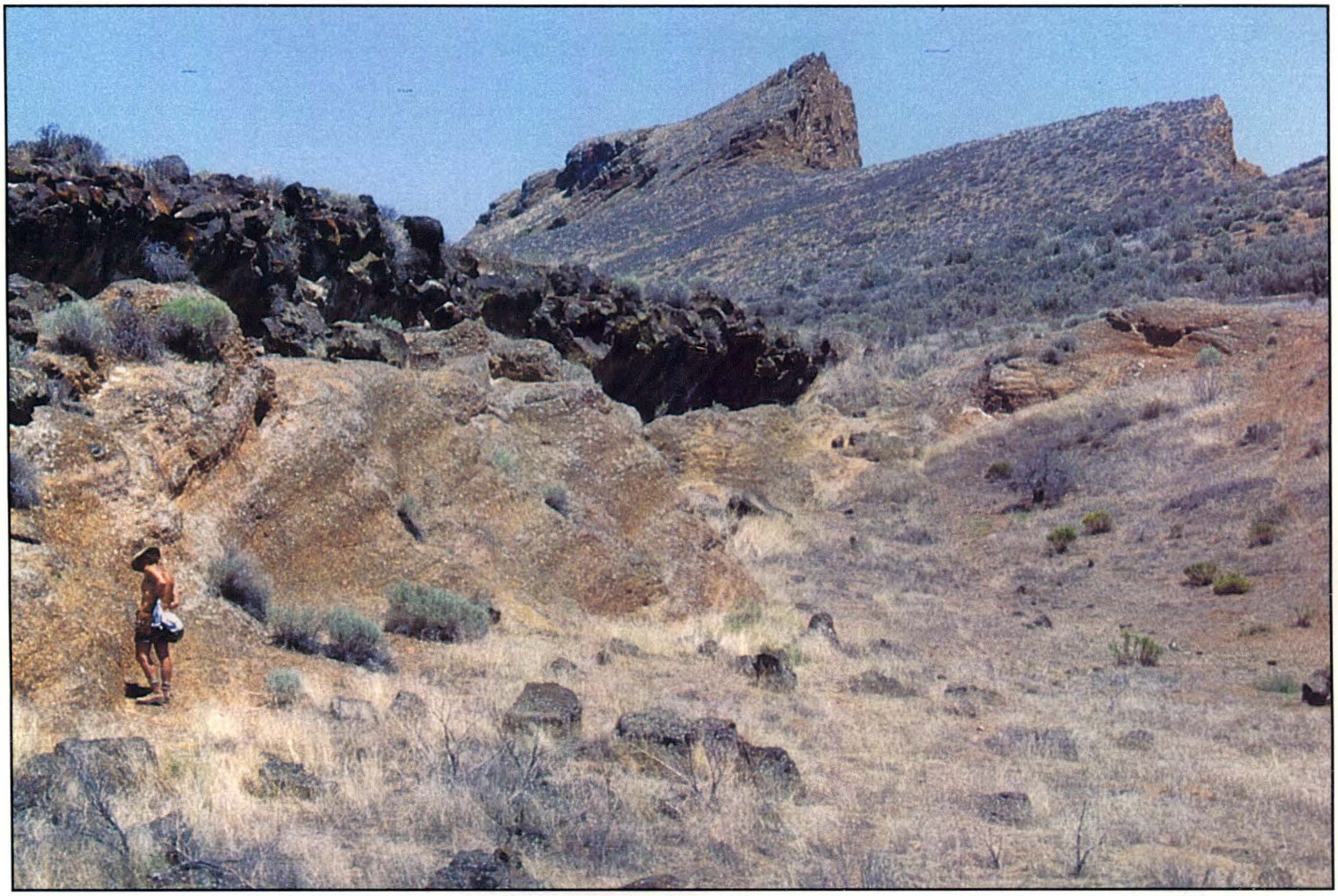

Photo 8. Basaltic lava lake overlying phreatomagmatic tuffs in The Peninsula tuff cone crater.

## COUNTRY ROCK INCLUSIONS

The subsurface geology of much of the Tule Lake Basin is largely unknown because Holocene basalt flows and lacustrine sediments cover most of the basin floor. Although drill cores have been taken in several locations within the basin, and older units are exposed at the Gillem Bluff Fault, where as much as 525 feet (160 m) of displacement has occurred (Donnelly-Nolan and Champion, 1987), many of the basalt flows are of unknown lateral extent, making subsurface correlations difficult. Country rock fragments in the pyroclastic deposits of Prisoners Rock and The Peninsula consist mainly of basalts and minor lacustrine diatomite and argillite. Country rock fragments at Prisoners Rock are vesicular and non-vesicular basalts ranging in size from less than 0.04 inch to 5 feet (1 mm to 1.5 m) The fragments are largest in the areas proximal to the vent and occur throughout the deposits. Fragments of vesicular basalt constitute approximately 50 percent of country rock inclusions and were derived from an underlying flow that may have served as an aquifer for the water involved in the explosions.

Fragments of the basalt of Scorpion Point, 2 miles (3 km) southeast of the Prisoners Rock tuff cone, are found in deposits of the North Crater tuff ring. The Scorpion Point basalt flow is truncated to the west by a normal fault, which has approximately 164 feet (50 m) of displacement down to the west (Donnelly-Nolan, USGS, Menlo Park, oral communication, 1992). Fragments of Scorpion Point basalt and lacustrine sediments incorporated in the tuff ring indicate a shallower explosion depth involved in the formation of the North Crater tuff ring. Two inclusions of diatomite, analyzed by J.P. Bradbury (USGS, Denver, unpublished data, 1992), contain diatom species indicating a shallow, periodically saline lake about the time of the eruptions. One diatomite inclusion is dominated by *Fragilaria* and *Cocconeis placentula*, indicating a shallow, freshwater marsh. The second sample is slightly calcareous (from altered ostracodes) and contains *Cyclotella meneghiniana, Anomoeoneis costata, Stephanodiscus oregonica,* and *Cocconeis placentula*. These diatoms are indicative of saline to alkaline open, but not necessarily deep, environments (Bradbury, USGS, Denver, written communication, 1992). The abundance of *Anomoeoneis costata* and *Cyclotella meneghiniana* after 300 ka at a depth of approximately 164 feet (50 m) (Bradbury, 1991) helps constrain the age of the eruptions and may be useful in interpreting changes in lacustrine conditions (Figure 4).

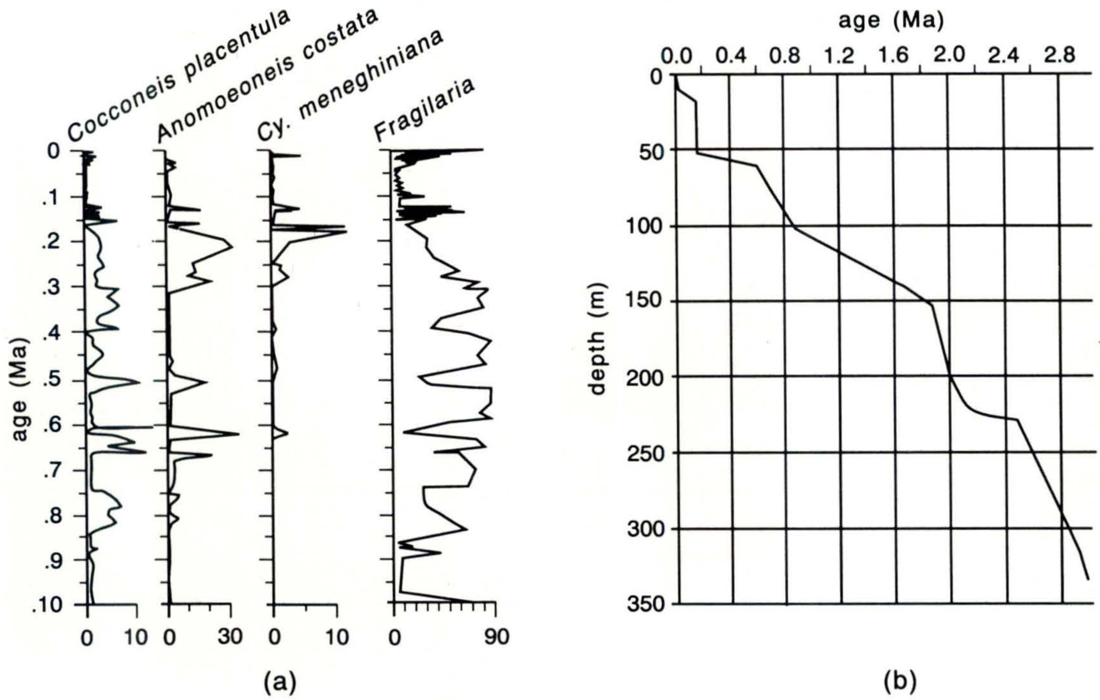


Figure 4.

(a) Abundances of diatom species found in diatomite inclusions in the Tule Lake drill core plotted against age for four species found in country rock inclusion from the North Crater tuff ring.

(b) Plot of age vs. depth for the Tule Lake drill core. *Modified from Bradbury (1991).*

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## GLOSSARY

**Armored lapilli:** Wet ash plastered around a crystal, lithic, or pumice nucleus (Fisher and Schmincke, 1984).

**Phreatomagmatic or hydrovolcanic eruptions:** Explosive eruptions of steam and volcanic ash that occur when magma comes into contact with ground water, lake water, or shallow ocean water.

**Porphyritic:** A texture term for an igneous rock with larger crystals or phenocrysts contained in a fine-grained or glassy matrix.

**Pyroclastic surge:** A low-particle-concentration, high-velocity flow of tephra (erupted material) that occurs as a pulse or pulses in which the kinetic energy rapidly decays with each surge. Base surges are a type of pyroclastic surge consisting of condensed steam thoroughly mixed with particles, in a ring-shaped cloud moving, as a turbulent density current, horizontally outward from the base of a vertical eruption column (Wohletz and Sheridan, 1979; Fisher and Schmincke, 1984).

**Scoria:** Highly vesicular basalt.

**Tuff:** Lithified volcanic ash.

**Tuff cone:** Volcanic crater above the ground surface resulting from phreatomagmatic activity. Tuff cones are characterized by bedding angles between 15 and 30 degrees, highly indurated deposits, planar and massive bedding, and alteration of glass to calcite, zeolites, and clays. Tuff cones result from deep explosions and are deposited by poorly inflated, cold (<212° F or 100° C), wet pyroclastic surges (Wohletz and Sheridan, 1983).

**Tuff ring:** Volcanic crater at or above the ground surface resulting from phreatic and phreatomagmatic activity. Tuff rings are characterized by bedding angles smaller than 12 degrees, poorly indurated deposits, and sandwave (dune and antidune) and planar bedforms. Tuff rings usually result from shallow explosions (Heiken, 1992) and are emplaced by highly inflated, hot (>212° F or 100° C), poorly indurated pyroclastic surges with minor ash fall.

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**Alexis Lavine** received her Bachelor of Science degree in geology from Humboldt State University, California. She is a graduate student in geology at the University of New Mexico, Albuquerque. Her Master's thesis addresses the controls and record of volcaniclastic sedimentation around Miocene composite volcanoes in the Jemez Mountains, New Mexico.


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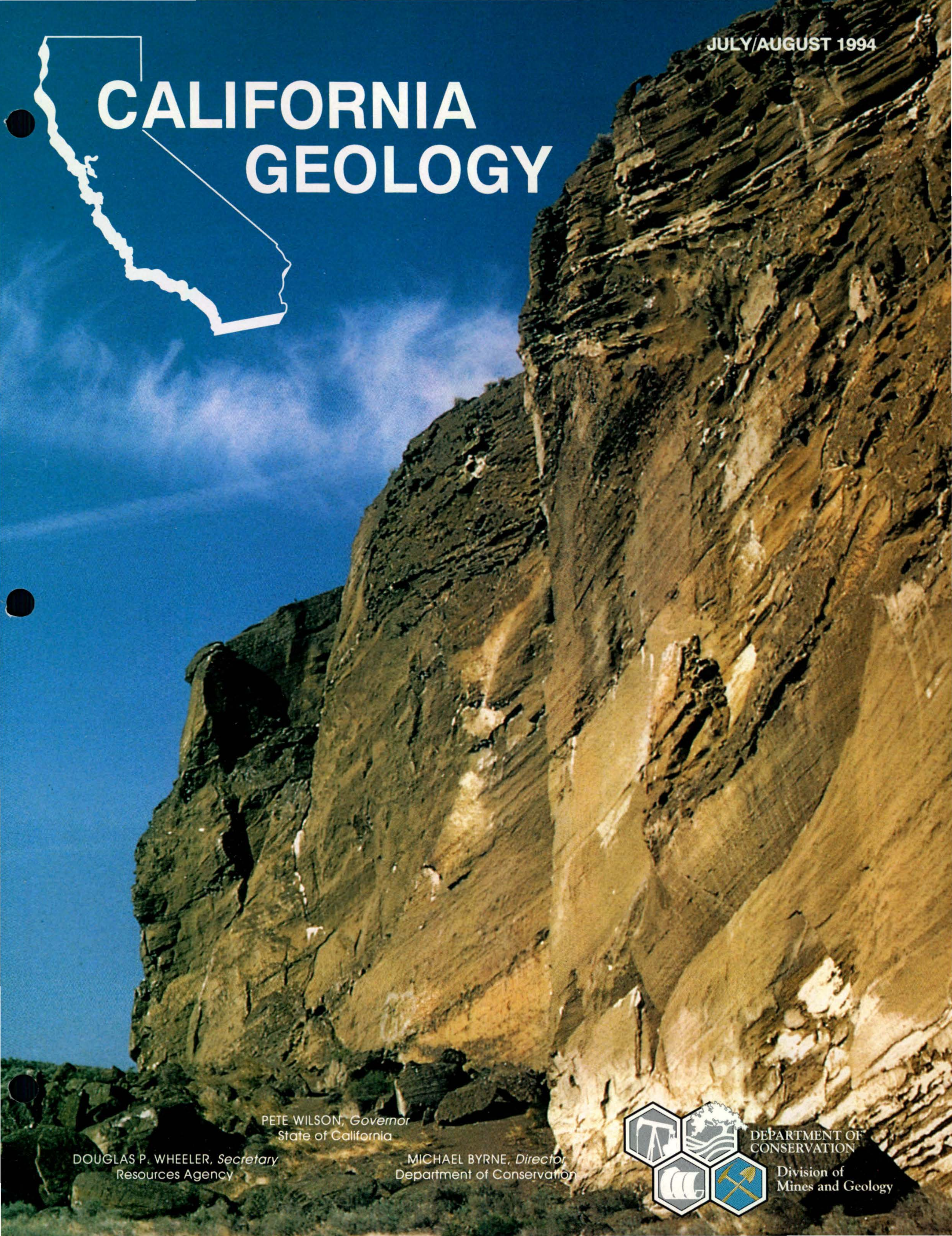

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