CALCAREOUS TUFA FORMATIONS

Searles Lake and Mono Lake

TED RIEGER, Writer and Photographer

Photo 1. Tufa spires at South Tufa Area, Mono Lake Tufa State Reserve. Narrowed diameters on two spires at left indicate a former lake surface where tufa was reduced, possibly by waves or solution in lake water. *Photos by author.*

INTRODUCTION

Tufa formations, while not unique to California, are represented here by some of the most picturesque and diverse examples known (front cover and Photo 1). Tufa, often called calcareous tufa, is a sedimentary rock composed of calcium carbonate (limestone) deposited as calcite, aragonite, or high-magnesium calcite. The hard, dense variety of tufa is travertine. Tufa has been quarried and cut for building stone, most notably from sources in Italy (Putnam, 1971), but extraction of tufa in California has been limited.

Tufa deposits occur in several forms, and the factors and variables involved in tufa formation may differ by location. Although substantial research has been done on the subject, particularly at Mono Lake, the specific mechanisms for tufa formation are still not fully understood. However, the basic process for the formation of tufa towers and pinnacles is discussed below.

Calcareous tufa forms underwater in saline or alkaline lakes when calcium-bearing spring water wells up from the lakebed. When the calcium-containing spring water comes in contact with carbonate in the lake water, precipitation into calcium carbonate, or the formation of tufa, occurs around the opening of the spring (Figure 1). Although springwater temperature may influence tufa formation, deposition can occur with geothermal or cold-water springs. Lake level fluctuation influences tufa formation by altering the mineral concentration in the lake water and can also change the rate and location of springwater discharge from a tufa formation. Receding lake levels eventually halt tufa deposition, leaving exposed formations appearing as towers, cones, domes, ridges, knobs, or more intricate shapes.

Tufa deposits also occur as pavements or concretionary deposits in sedimentary lakebeds, and along shorelines of alkaline lakes throughout the world. Tufa is sometimes found in terraces of former shorelines that have been exposed by evaporation or by receding lake waters. Calcium-bearing streams and rain runoff may also contribute to tufa precipitation in some locations. Another form, sand tufa, found at Mono Lake in intricate structures of calcite-impregnated columns, tubes, and other configurations, forms beneath and adjacent to the lake in sands and silts saturated with brine.

For many years, published research has discussed whether tufa is formed by physicochemical precipitation, biological precipitation, or a combination of these two processes. Algal remains in older exposed tufa, and the occurrence of algae with freshly formed tufa at Mono Lake, raise the issue of the role of algae in tufa formation. Researchers differ as to whether algae play a biological role, being required to form certain types of tufa, or if algae only affect tufa structure and texture, and possibly enhance tufa precipitation that would also occur without their presence. Although deposition of sand tufas and concretionary deposits appear to be purely physicochemical, there are indications of biological influences on the deposition of tufa towers, particularly in shallower lake water.

Ongoing research reveals potential influences on the formation of tufa, and there are indications that tufa, under certain conditions, can precipitate and build deposits faster than was previously known. The present understanding of tufa precipitation is perhaps best summarized by the observations of David Herbst (Sierra Nevada Aquatic Research Laboratory [University of California], Mammoth Lakes, California, oral communication, 1992) and Scott Stine (California State University, Hayward, oral communication, 1992) who have stated that it appears to be more complex than simply the mixing of spring water with lake water.

TUFA APPEARANCE AND STRUCTURAL TYPES

The exposed tufa formations discussed in this article generally have the surface appearance and texture of white, tan, light gray, or cream-colored porous limestone. Russell (1883, 1889) was one of the first to describe tufa types based on structural varieties and age of deposition, from his observations of weathered cross sections of formations at Pyramid Lake and Mono Lake. He described three basic types: lithoid, dendritic, and thinolitic. Lithoid tufa forms the inner core of a tufa formation, or the entire formation. It has been described as a stony variety, and may form as porous and tubular masses. Dendritic tufa has a structure of tightly packed columns of upward branching stems. Thinolitic tufa is made of thinolite (a variety of calcite) that appears as tetragonal pyramids that can form a lattice-work crystalline deposit. All three types can occur in layers of varying thicknesses to form a tufa tower. While the central core of a tower is always a lithoid variety, the subsequent order of dendritic and thinolitic layers can vary, and there may be more than one layer of each of the three varieties.

REGIONAL GEOLOGIC HISTORY

In California, tufa is associated with Pleistocene lakes and dry lakes of the Basin and Range province. Water levels of these lakes have fluctuated during geologic history due to variations in precipitation and glacial melt runoff from the Sierra Nevada during the Pleistocene ice ages. During wetter periods, these lake basins overflowed and fed one another from runoff flowing north to south from western Nevada through the Mono Basin and the Owens Valley, through China Basin and Searles Basin, then into Panamint Valley and Death Valley (Figure 2). These lakes, most of which are dry, are also associated with the former Lake Lahontan system of the Pleistocene that ranged across the Great Basin to the Great Salt Lake in Utah. During the ice ages, vast inland seas filled the troughs between mountain ranges. Without outlets, the basins accumulated saline and alkaline minerals that formed thick sedimentary deposits. Evaporation has concentrated saline and alkaline minerals in the remaining lakes, as in Mono Lake and the Great Salt Lake.

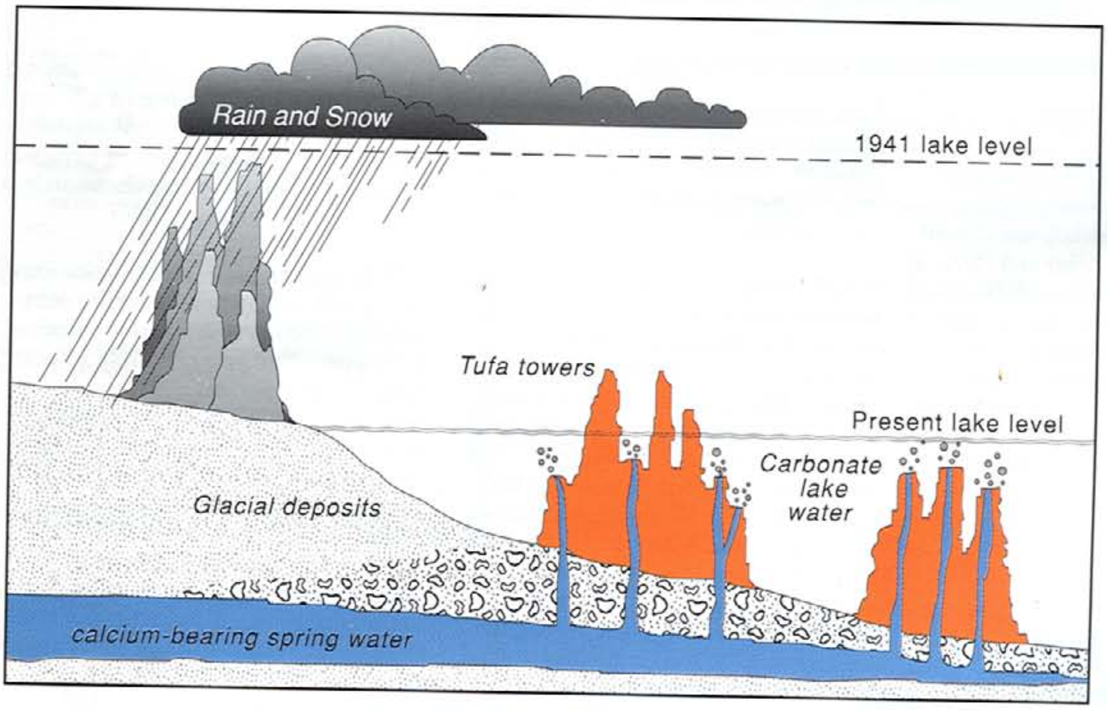

Figure 1. Stylized cross section of Mono Lake showing tufa deposition by interaction of lake and spring water. Tops of tufa spires at left mark the lake's level in 1941. *Courtesy of the California Department of Parks and Recreation.*

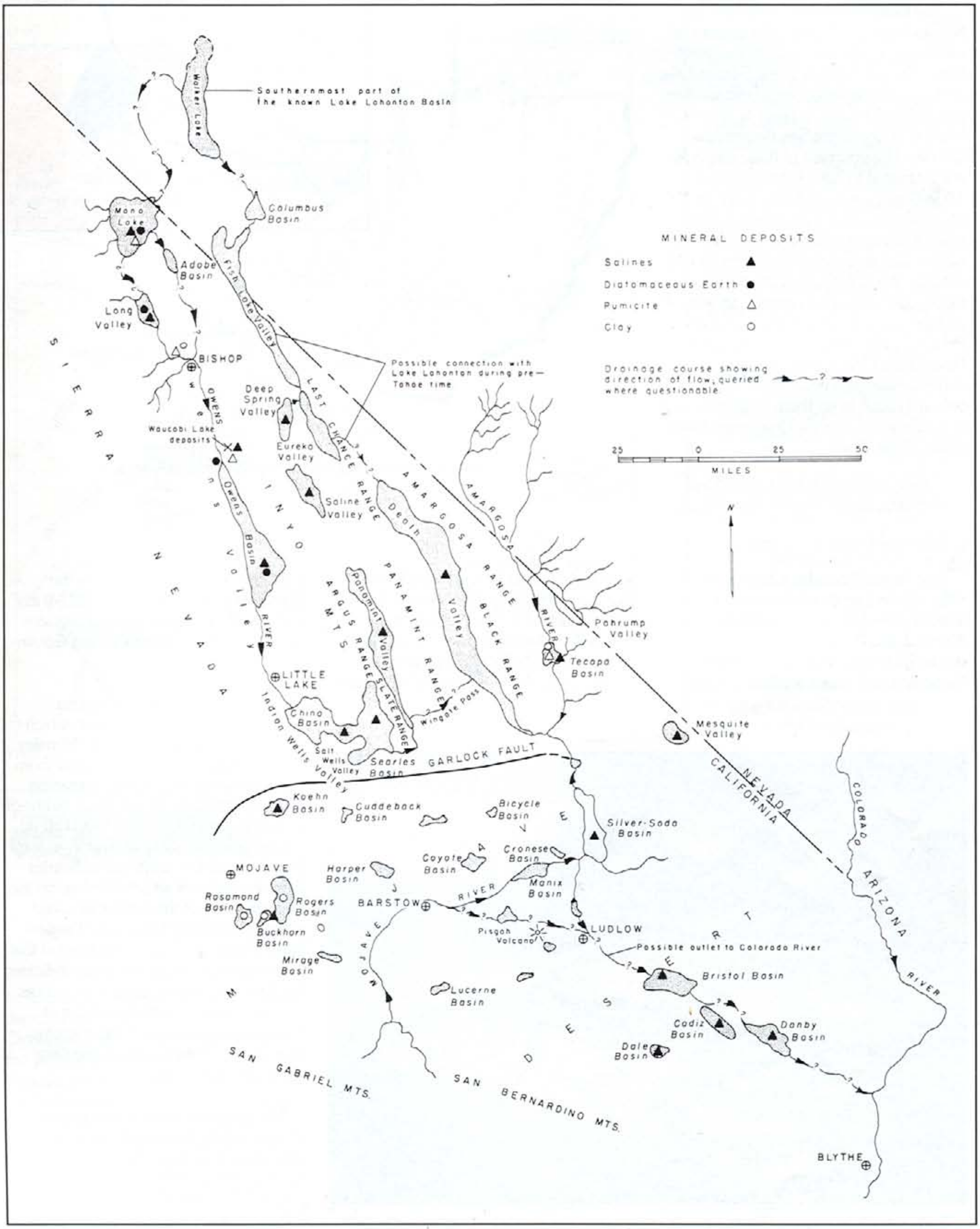

Figure 2. Map showing basins probably occupied by lakes during the Tahoe stage of the Pleistocene. *Modified from Blackwelder (1954).*

The locations of tufa formations at Searles Lake and Mono Lake present an interesting contrast in present-day conditions. The tufa known as the Searles Lake or Trona Pinnacles occurs at the southern end of Searles Lake, a playa or dry lakebed in northwest San Bernardino County. The youngest of these pinnacles are estimated to have formed at least 10,000 years ago. At Mono Lake, in Mono County near Lee Vining, which holds the largest volume of water of any natural lake entirely within California, the process of tufa formation still occurs. Good examples of tufa domes, towers, and terrace deposits are also found at Pyramid Lake, Nevada, another Great Basin lake of Pleistocene origin. Tufa deposits have also been found in the Salton Trough in southern California, and at a number of alkaline Quaternary lakes of the Great Basin.

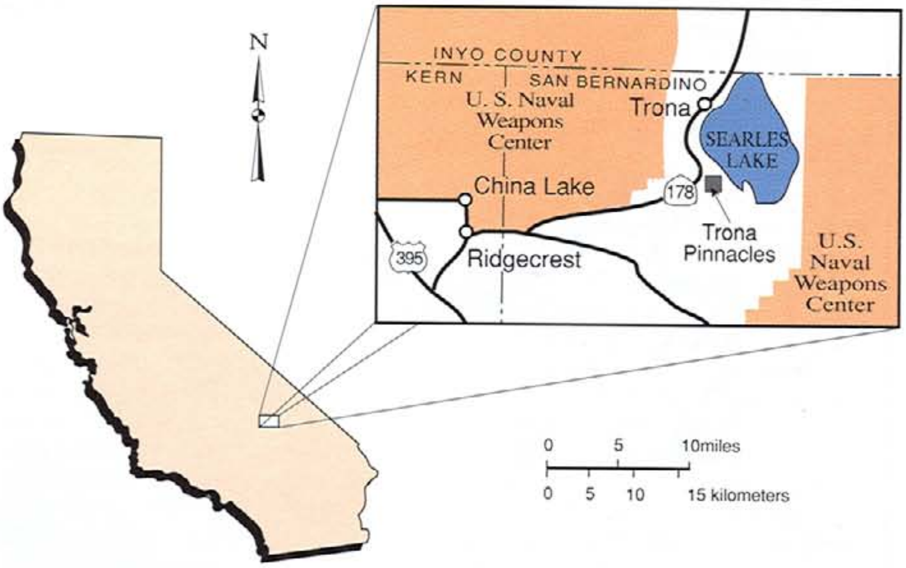

Figure 3. Location map of the Trona Pinnacles tufa area.

DISCUSSION OF SEARLES LAKE PINNACLES OR TRONA PINNACLES

Location and Distribution of Pinnacles

The Trona Pinnacles tufa area is 10 miles (16 km) south of the town of Trona and 20 miles (32 km) east of Ridgecrest (Photo 2 and Figure 3). The pinnacles are visible from State Highway 178 between Ridgecrest and Trona south of the highway, and reached by a graded dirt road that meets Highway 178 about 7.7 miles (12 km) east of its junction with the Trona-Red Mountain road. Trona Pinnacles, designated a National Natural Landmark by the U.S. Department of the Interior in 1968, is managed by the Bureau of Land Management (BLM) as an Area of Critical Environmental Concern within the California Desert Conservation Area.

There are about 500 tufa spires spread over the Trona tufa area, which is roughly 4 miles (6 km) wide by 10 miles (16 km) long. They range in height from 1 to 140 feet (0.3 to 43 m), averaging 10 to 40 feet (3 to 12 m). Basal widths or diameters range up to 500 feet (150 m), but average only 20 to 30 feet (6 to 9 m). They occur at the south end of Searles Basin in what was an arm-like bay on the southwest side of the former lake, and generally straddle what is now Teagle Wash (Figure 4). Scholl (1960) noted that the occurrence of tufa formation indicates that tufa precipitated around the orifices of springs issuing along the strikes of faults in the igneous and metamorphic rocks that underlie the lacustrine (lake-deposited) sediments.

The pinnacles occur in three separate groups varying in age and elevation. The southern group is the oldest and corresponds to the lake's highest elevation of 2,260 feet (690 m) during the Tahoe ice age (between 100,000 and 32,000 years ago) (Scholl, 1960). At this

Photo 2. Northern group of Trona Pinnacles with castellated summit of ridge pinnacle, and smaller tower pinnacles to the right.

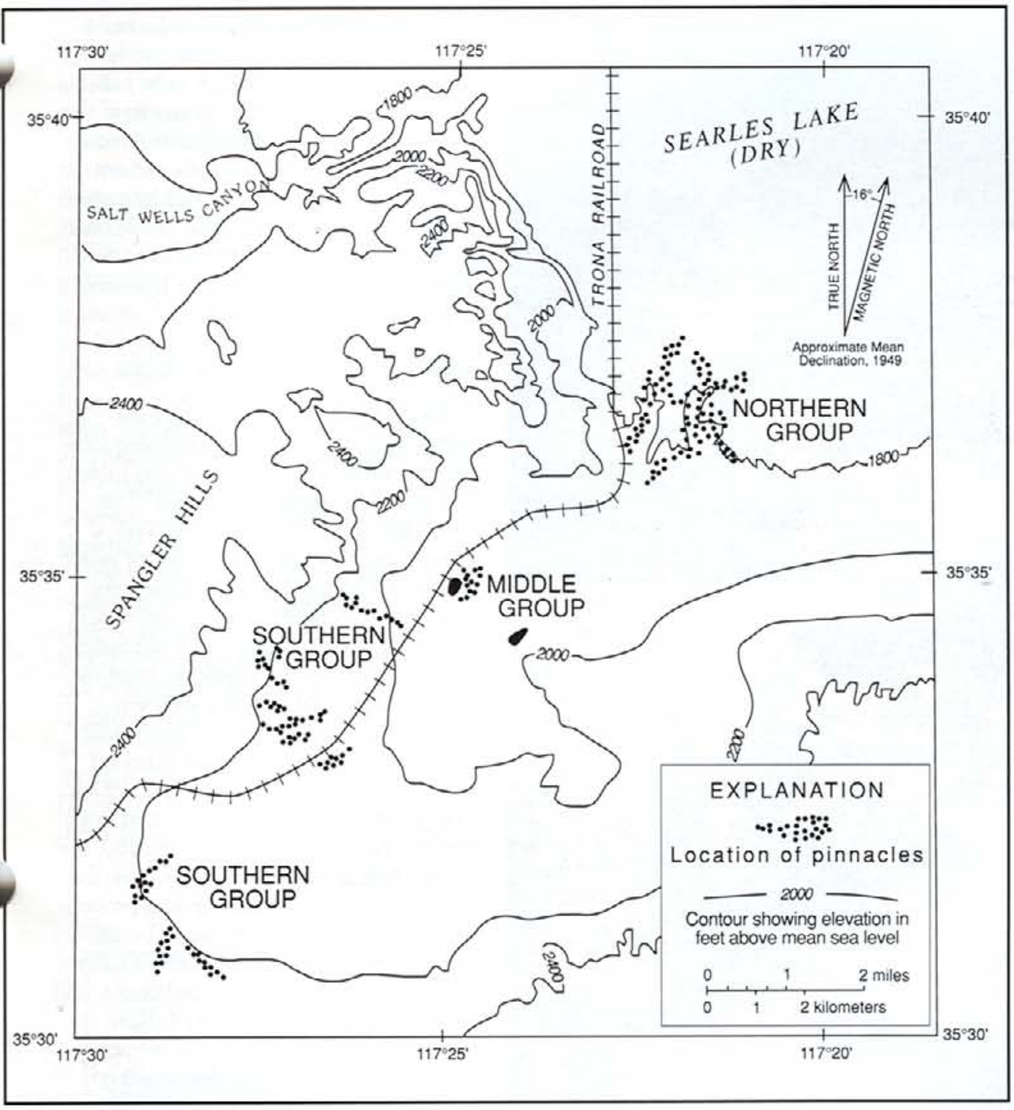

Figure 4. Sketch map showing distribution of most of the pinnacles at the southwest end of Searles Basin; however, less than half of the pinnacles in the southern group are shown. The two enlarged black areas in the middle group are the large limestone ridges. *From Scholl (1960).*

time, Searles Lake reached its maximum depth of 640 feet (195 m) (Blanc and Cleveland, 1961), and was connected to the west with waters of China Basin through Salt Wells Valley, where weathered tufa towers are also found at elevations of 2,200 to 2,260 feet (670 to 690 m). The southern group of Trona Pinnacles contains about 200 formations that range from 1 to 25 feet (0.3 to 8 m) high and 5 to 40 feet (1.5 to 12 m) in diameter. These are the most severely weathered and many are damaged from blasting activity (Scholl, 1960). They range in elevation from 2,100 to 2,260 feet (640 to 690 m).

The middle and northern groups are younger and more similar in age. They formed during the Tioga ice age between 25,000 and 10,000 years ago, when Lake Searles had a maximum depth of 460 feet (140 m) and lake level elevation of 2,000 feet (610 m). The middle group contains about 100 formations and the northern group about 200.

Pinnacle Shapes and Structure

Generally, the pinnacles rise vertically from gently sloping basal mounds composed of sublacustrine talus material and more recently eroded tufa talus. Scholl (1960) has classified the pinnacles into four general shapes—tower, tombstone, cone, and ridge (Photos 2 and 3). The tower structures occur in all three groups, and are among the most common and noticeable type, with roughly circular horizontal cross sections and summits that may be pointed, rounded, or flat. Their heights exceed their diameters. The tombstone pinnacles occur only in the northern group and are characterized as ellipsoidal in cross section. Scholl's cone type is actually a mound structure that occurs in all three groups and is the smallest and shortest type, commonly fewer than 10 feet (3 m) high. The ridge type of tufa is the most massive. Only three of these structures exist in the Trona area—one in the northern group and two in the middle group. One in the middle group is 800 feet (240 m) long, 500 feet (150 m) wide, and 140 feet (43 m) high, making it the tallest and largest tufa formation in the area.

Scholl (1960) states that the sizes and shapes of the pinnacles probably reflect the size, flow, and chemical composition of the springs, the spacing of the springs, the depth of lake water, and the rate of rise or fall of the lake level. Tombstone and ridge structures may have developed around a number of closely spaced springs of higher flow; tower and cone pinnacles developed around one or just a few springs.

While the Trona Pinnacles would primarily be classified structurally as lithoid, Scholl (1960) has adapted Russell's terms and added his own to list seven tufa classifications at Searles Lake. They are: 1) stony lithoid—a porous and somewhat cavernous cream-colored tufa; 2) cavernous lithoid—a highly porous cream-colored tufa; 3) massive lithoid—a light-gray somewhat porous

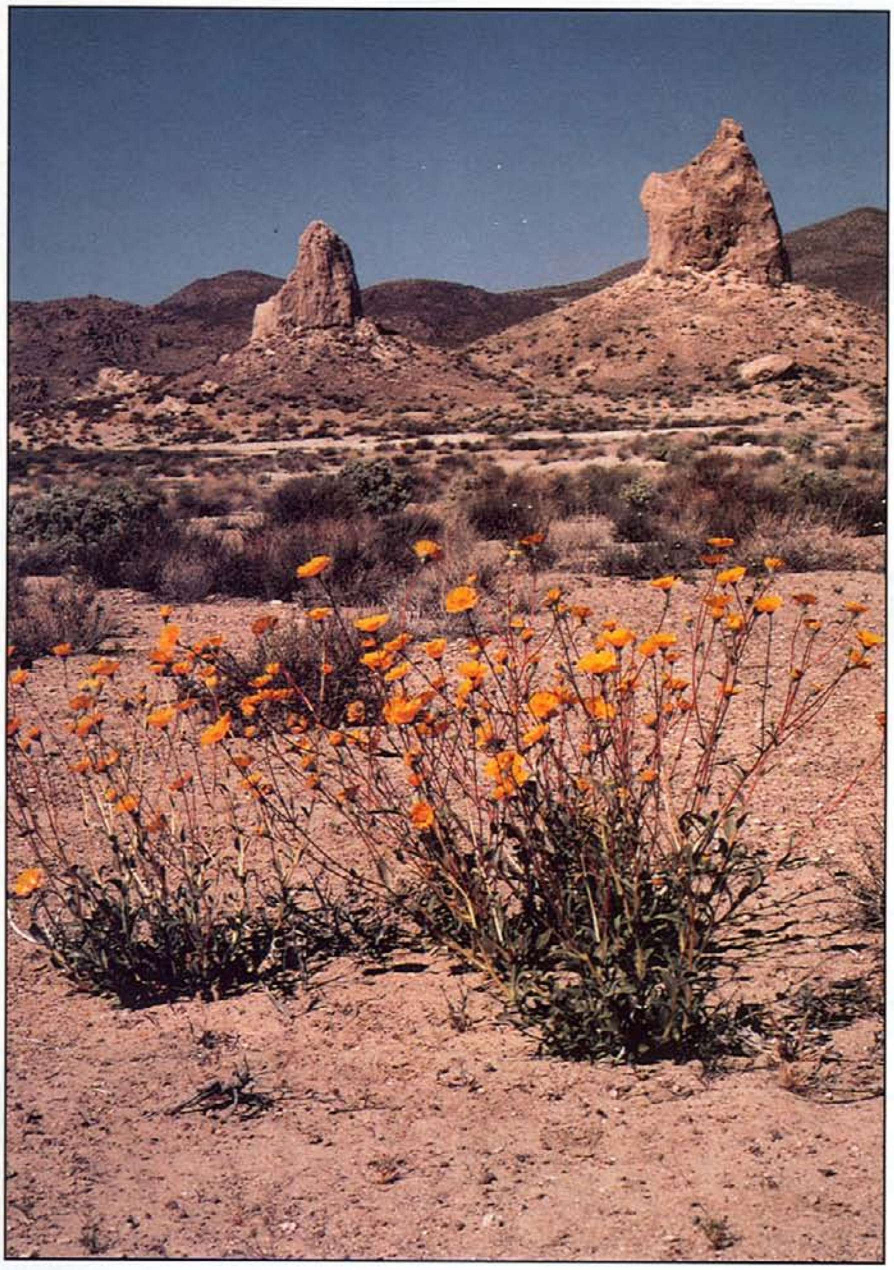

Photo 3. Tombstone pinnacles in northern group of Trona Pinnacles.

compact tufa; 4) dendritic—a rather dense branching or arborescent tufa; 5) nodose—a cream-colored tufa; and 6) tubular—a chalk-white to cream-colored tufa which grades upward into 7) lobate—a banded tufa.

Buried tufa deposits within fine-grained to gravelly lacustrine sediments are also exposed on the northern side of the northern pinnacles as bedded lens-shaped deposits 5 to 15 feet (1.5 to 5 m) thick. They are composed of stony lithoid tufa. While there have been no reports of thinolitic tufa in the Searles Lake area, Cloud and Lajoie (1980) report that sand tufa structures have been observed in older deposits in the Searles Valley that were interpreted as older shoreline indicators.

Scholl maintains that algae were principal agents causing deposition of tufa at the Trona Pinnacles (1960) and at Mono Lake (Scholl and Taft, 1964). Based on microscopic examinations of pinnacle tufa sections, Scholl found abundant small ellipsoidal to polygonal bodies that he believed to be molds of algal cells. He noted that these occurred primarily in the stony and cavernous lithoid tufas which constitute between 50 and 95 percent of most of the pinnacles. While he concludes that calcium carbonate would have probably accumulated without the aid of algae, it may not have been in the form of pinnacles (Scholl, 1960).

Uses of Trona Pinnacles, Searles Lake

Trona Pinnacles, in particular the northern group, have been a filming location for science fiction and fantasy movies because of the bizarre landscape. The pinnacles were seen in the Star Trek V movie, and have also been used for music videos, TV commercials, and magazine modeling layouts. BLM personnel report that shafts have been drilled at the bases of some pinnacles for unknown reasons, but it appears that only the southern group, which shows signs of weathering and blasting activity, has been quarried commercially for limestone (BLM, 1972). The pinnacles tufa is now protected from mining and collecting activity. Nearby, the dry lakebed of Searles Lake has been the site of commercial extraction and processing of mineral brines—including borax, potash, sodium carbonate, sodium sulfate, potassium chloride, lithium carbonate, and bromine—dating back to 1874. Kerr-McGee Chemical Corporation extracts lake deposits and operates processing facilities at Trona.

The northern group is the most accessible by a dirt road suitable for 2-wheel drive vehicles. However, the road should not be used in wet weather. A 1/2-mile loop trail takes hikers through this group of pinnacles. BLM's Ridgecrest office can be contacted for further information on visitation and recreation at the pinnacles.

DISCUSSION OF MONO LAKE TUFA FORMATIONS

Location, Age, and Former Levels of Mono Lake

Mono Lake is in a basin below the eastern escarpment of the Sierra Nevada (cover photo, Photo 4). The lake and basin area is bordered roughly on the west by Highway 395, on the north by Highway 167, and on the south by Highway 120 (Figure 5).

Mono Lake, dated to 730,000 years ago, is one of the oldest continuously existing lakes in North America. While the lake level has fluctuated throughout its existence, it reached its maximum depth of over 900 feet (275 m) when Mono Basin was filled by Pleistocene Lake Russell to an elevation of 7,180 feet (2,190 m), covering 338 square miles (875 km^2). This level may have occurred more than once during glacial advances of the Tioga ice age, 12,500 to 22,000 years ago (Mono Basin Ecosystem Study Committee, 1987). The lake is believed to have reached its lowest level (6,365 feet or 1,941 m) during the past 5,000 years, but it probably contained a higher volume of water than it would today at the same elevation. Since first recorded in 1857 at an elevation of 6,407 feet (1,954 m), lake levels have reached a high of 6,428 feet (1,960 m) in 1927 and a low of 6,372 feet (1,943 m) in 1982. Fluctuations are due to water diversions from tributary streams by the Los Angeles Department of Water and Power, wet winters, and drought. The lake level is 6,374.5 feet (1,944.2 m) (April 1992) with a maximum depth of about 150 feet (45 m).

Tufa Types and Locations in Mono Basin

Russell (1889) reported that compact stony tufa (lithoid) occurred as a cement in the gravel of some of the terraces and beaches around the lake basin, ranging from the present lake level to former water lines. According to Dunn (1953) the greatest quantity of tufa deposits occurs as a thin crust on the Sierran fault scarp that bounds the west side of the lake. He described it as light gray, tan to white, a very porous lithoid variety, and rather typical of that found in many parts of the world. Remnants of tufa deposits can be seen north of Lee Vining on the mountainside west of Highway 395. Scott Stine (California State University, Hayward, oral communication, 1992) reports tufa plasters and crusts at elevations up to 7,070 feet (2,150 m) in Mono Basin. While some of the highest deposits of tufa are about 13,000 years old, tufa deposits older than 40,000 years have been found within the Mono Basin (Scott Stine, University of California, Hayward, oral communication, 1992).

Thinolitic tufa deposits along an ancient shoreline nearly 6,800 feet (2,075 m) in elevation and over 400 feet (120 m) above the present shoreline are relics of some of the highest-elevation tufa towers, formed about 13,000 years ago. They can be found just south of State Highway 167, about 1.3 miles (2 km) east of its junction with Highway 395 and just inside the Mono Basin National Forest Scenic Area boundary.

The more spectacular tufa formations described by various sources as towers, crags, knobby spires, castle-like structures, pillared ruins, and toadstool-like masses occur at Mono Lake (Photos 4, 5, and 6). Towers may have single or multiple trunks, and range in height from a few inches to about 30 feet (9 m). They tend of be clustered in "groves," most notably along the northwest, western, and southern shores of the lake (Figure 6). Towers also protrude from the surface of the lake in these areas. The groves tend to be where water flows underground along faults, or at the sides of "deltas" within the lake where tributary streams provide

Photo 4. Exposed tufa formations at shoreline and in lake at South Tufa Area, Mono Lake Tufa State Reserve.

sources of fresh water to feed and charge lake-bottom springs. Two of the largest groves occur along the southern shore of the lake—South Tufa Grove and Lee Vining Grove. Exposed towers in the South Tufa Area are estimated to be 200 to 900 years old.

The towers in the lake and near the present shoreline tend to be of the lithoid variety of tufa. Dendritic and thinolitic tufa can be found in older towers at higher elevations, and in some cases, all three varieties may occur in the same formation.

When Russell visited the area in 1883, he explored the lake by canoe, and described tufa towers and domes in the Black Point area near the northwest shore of the lake: "They rise in water that is ten or twelve feet deep, to a height of about twelve feet above the lake surface.... The tops of several are hollowed out so as to form basins, and in a few instances these depressions are filled with clear, fresh water that rises through the porous and tubular tufa composing the submerged shaft of the structure. These are typical specimens of sublacustral spring deposits, which have been left partially exposed by a recession of the lake waters, but are still points of discharge for the springs that built them." Russell (1889) further described one that contained water of "exceptional purity," saying, "This spring fills a bowl three or four feet in diameter, in the top of a tufa dome which rises about three feet above the lake surface and overflows, fountain-like, into the surrounding alkaline waters. The interior of the basin, and portions of its exterior, are coated with white, calcareous tufa, which is still being precipitated from the outflowing waters." Russell (1889) also talked of canoeing over the tops of submerged towers that were releasing spring water into the lake in flows that were "sufficiently strong to deflect a boat when allowed to float over them."

Scholl and Taft (1964) confirmed the presence of tufa with summit springs, but more commonly found spring water seeping from cracks in the sides of formations, or from the bases of exposed formations. Lithoid towers near the shoreline and those in the lake sometimes have circular openings in their summits from which spring water has flowed or continues to flow (Scholl and Taft, 1964). Today, these springwater features are associated more with the tufa of Black Point and the north shore than with that of other areas.

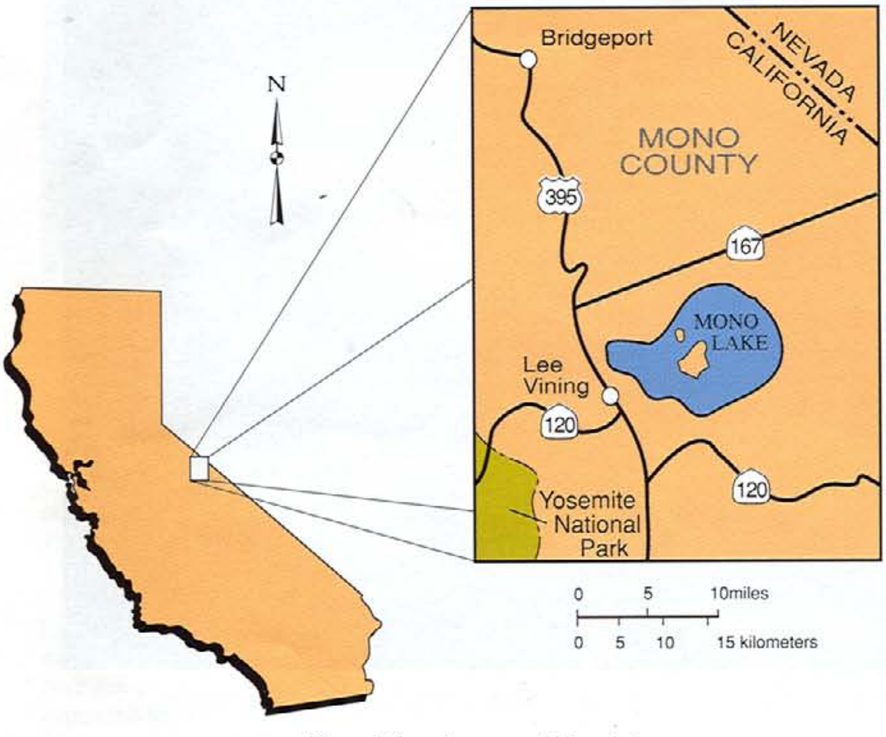

Figure 5. Location map of Mono Lake.

Fluctuating water levels at Mono Lake have been found to affect the formation and shape of tufa in several ways. Russell (1889) noted that partially submerged tufa columns and towers would have circular contractions, or reduced diameters where the water's surface level was in contact with the tufa. He speculated that this was caused by the dash of waves, or by solution of the tufa's calcium carbonate by lake water. In some mushroom-shaped towers, spring water continued to flow from the top and down the flanks of a partially exposed formation. Upon contact with the lake surface, calcium carbonate precipitated to form flat-bottomed shelves on the sides of the formation.

A drop in lake level can alter the flow rate as well as the location from which spring water flows from a formation. Towers near the shoreline can be found with spring water bubbling from the base of the formation. At the South Tufa Area, what appear to be "oily upwellings" (Mono Lake Committee, 1980) just offshore are the locations of fresh water rising through brine from lakebed springs. Tufa towers that become completely exposed eventually cease to "grow." Some exposed shoreline towers have toppled due to fluctuating lake levels that undermine the formations, or waves that erode their bases. Scuba divers who have explored submerged tufa groves report the existence of many fragile tufa columns and formations whose weight could not be supported on land.

Sand Tufa

Sand tufas occur primarily along the southern and southeastern shores of the lake, but have also been found in Mill Creek stream cuts above the northwest shore of the lake (Figure 7). They range in height from a few inches to 6 feet (2 m). The sand tufa figures consist of tubes, columns, and associated structures of calcite-impregnated pumice sand, formed in beach and lake-bottom sediments near the shore of the lake. The carbonate-cemented sand is exposed by a drop in lake level and subsequent wind erosion of loose sand around the formation. Cloud and Lajoie (1980) state that the younger sand structures may have formed within the past century. Sand tufas are found between elevations of 6,374 feet (1,944 m) and about

6,432 feet (1,962 m). They can be observed at Navy Beach near the South Tufa Area. Because of their fragile structure, they are probably more susceptible to erosion and toppling from rising lake levels and wave action than are the lithoid tufa formations.

Biological Influences on Tufa Formation

The remains of filamentous and spherical algal cells occur in lithoid tufa of dry towers at Mono Lake. Scholl and Taft (1964) have reported calcareous mat-forming algae on the surface of, and partially embedded in, lithoid tufa that is beneath spring water cascading from the summits of pinnacles above the lake surface. They also determined that the algal mat is calcareous due to an abundance of microcrystalline calcite accompanied by calcite pellets, immeshed in the filamentous algae. The mat-forming algae in Mono Lake are primarily filamentous green algae, diatoms, and blue-green algae. Scholl and Taft (1964) believed that due to the close association of algae and freshly-deposited tufa, precipitation of lithoid tufa could be botanically induced. Precipitation results from the photosynthetic withdrawal of carbon dioxide, which lowers the solubility of calcium carbonate near the algae.

Divers in Mono Lake have found that underwater tufa formations provide rocky substrates for the attachment of organisms such as blue-green algae, and for alkali fly larvae and pupae that have specialized lime gland tubules capable of precipitating carbonate/bicarbonate with calcium (Herbst and Bradley, 1989). While chemical precipitation could theoretically occur at depth in Mono's waters under the right conditions, the biological influences of algae, or insects, would have to take place within a photic zone of probably no more than about 30 feet (9 m) below the lake surface. The complexity of tufa formation continues to be investigated, but research at Mono Lake indicates that biological processes influence at least the morphology of some types of tufa formations.

Historic Tufa Uses and Current Tufa Area Management

Historically, the extraction of Mono Basin tufa for human use has been very limited. Stone lime kilns that date to the 1870s have been found in the Cedar Hill area northeast of the lake where it is believed that tufa extracted from older lakeshore terraces may have been calcined to form lime (Mono Lake Committee, 1980). Individuals have collected tufa chunks for souvenirs and for ornamental use in gardens, but collection for any purpose is now prohibited.

The Mono Lake Tufa State Reserve encompasses state-owned lakebed lands below the elevation of 6,417 feet (1,957 m)—the lake's surface elevation in 1941. This includes about 17,000 acres (6,900 hectares) that have been exposed since that year by the diversion of fresh water from tributary streams by the Los Angeles Department of Water and Power.

Photo 5. Lithoid tufa tower at South Tufa Area, Mono Lake Tufa State Reserve.

Photo 6. Tufa formations at South Tufa Area, Mono Lake Tufa State Reserve. Mushroom-shaped tufa (center) formed by spring water that continued to flow from the exposed summit and down the sides of the formation to interact with lake water and form the flat-bottomed "shelf" at lake surface.

The reserve, established in 1982, is managed by the California Department of Parks and Recreation (CDPR) to preserve the tufa formations and other natural shoreline features of Mono Lake.

The Mono Basin National Forest Scenic Area, encompassing 116,000 acres (46,800 hectares) was designated by Congress in 1984 to protect the natural, cultural, and scenic resources of the Mono Basin. The U.S. Forest Service operates the recently opened Mono Basin Scenic Area Visitor Center 1/4 mile (400 m) north of Lee Vining on the east side of Highway 395. The center has exhibits about the Mono Basin, and personnel can provide information on tufa groves, nature programs, and tours.

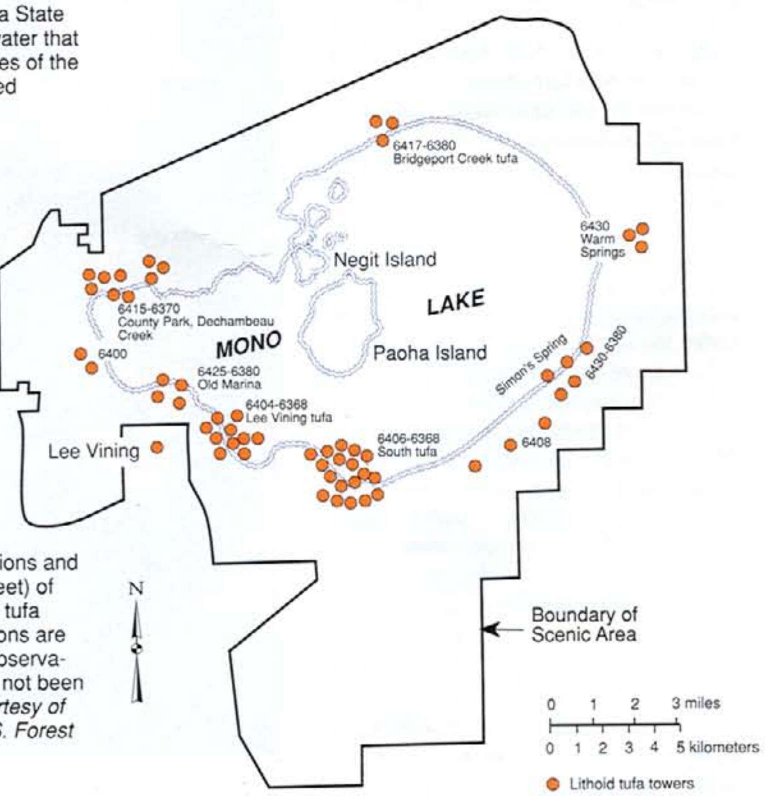

Figure 6. Locations and elevations (in feet) of bases of lithoid tufa towers. Elevations are estimated by observations and have not been surveyed. *Courtesy of N. Upham, U.S. Forest Service.*

The Mono Lake Committee operates the Mono Lake Visitor Center in Lee Vining which has exhibits and information about the Mono Lake and Basin area.

Observing Tufa at Mono Lake

The South Tufa Area, managed by CDPR, is one of the most easily accessible locations for tufa observation. It is reached by a one-mile dirt road that turns north from Highway 120, about 5 miles east of the Highway 395 junction south of Lee Vining. There is a self-guided trail through the tufa formations, and CDPR regularly conducts naturalist-led tours. At Mono Lake County Park, about 4 miles north of Lee Vining on the east side of Highway 395, there is a boardwalk trail through the tufa grove.

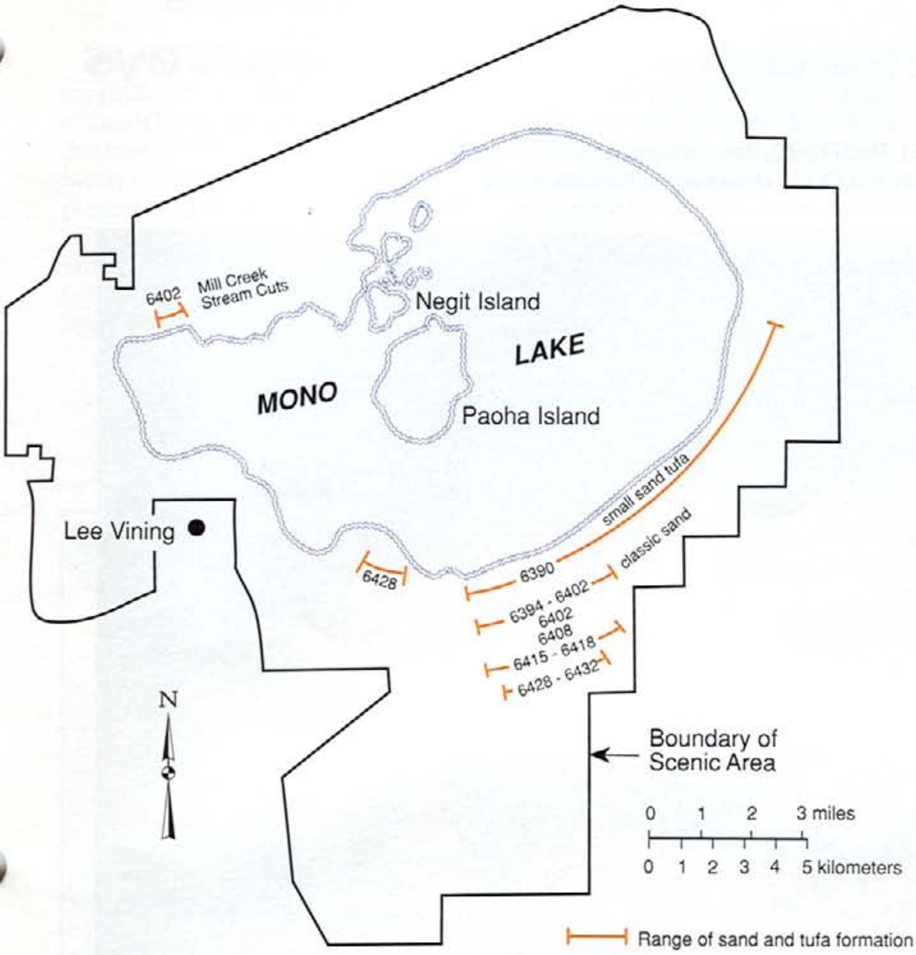

Figure 7. Locations and elevations of bases of sand tufa. Elevations are estimated by observations and have not been surveyed. *Courtesy of N. Upham, U.S. Forest Service.*

Ted Rieger is a freelance writer and photographer in Sacramento, California. He specializes in natural history, geology, and historical subjects, and produces technical and business articles for trade publications. Ted has varied experience in outdoor recreation and resource management with federal and State agencies.

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