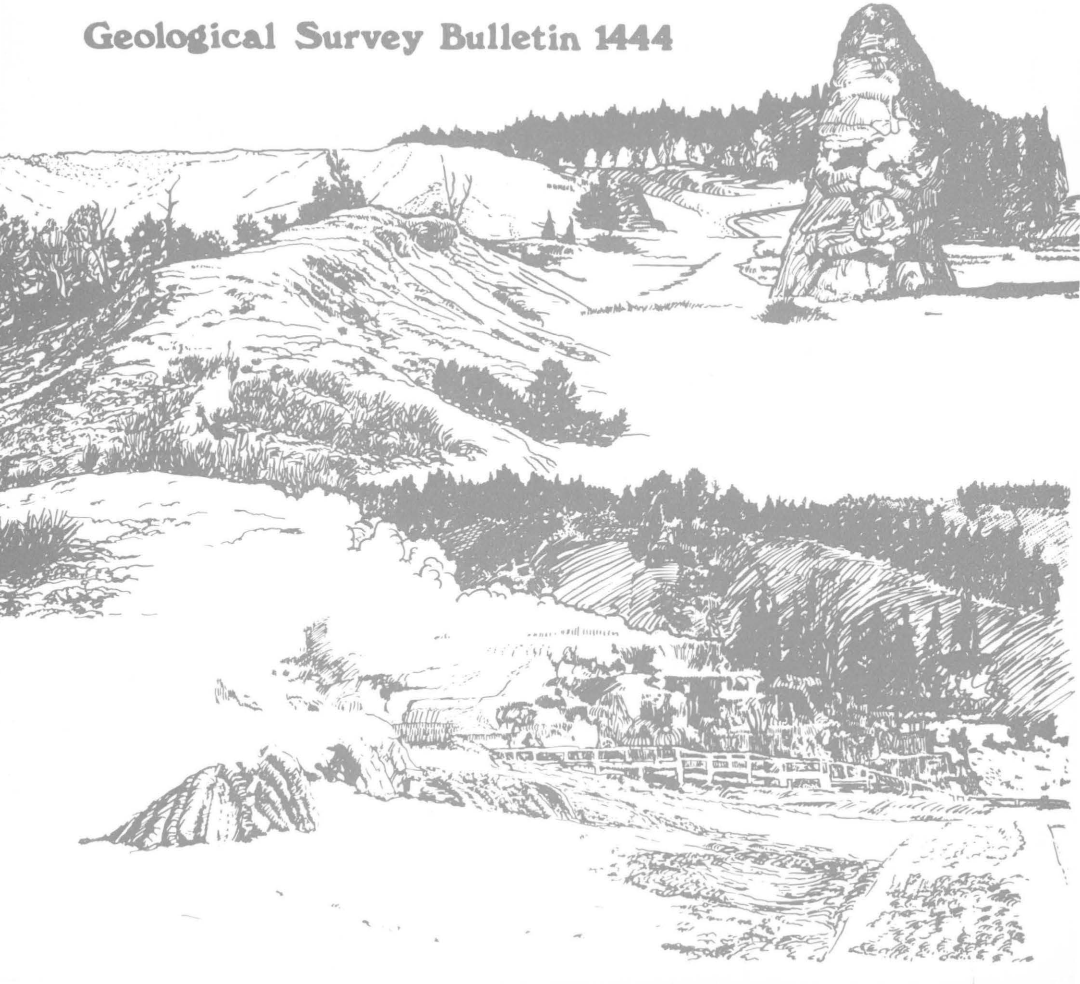
Geology and thermal history of MAMMOTH HOT SPRINGS, YELLOWSTONE NATIONAL PARK, WYOMING

Geological Survey Bulletin 1444



Geology and thermal history of Mammoth Hot Springs, Yellowstone National Park, Wyoming

Photograph: Stalactite curtain at end of Elephant Back Terrace

Geology and Thermal History of Mammoth Hot Springs, Yellowstone National Park, Wyoming

By KEITH E. BARGAR

GEOLOGICAL SURVEY BULLETIN 1444

Geology of travertine deposits and summary of hot-spring activity since 1871

1978

UNITED STATES DEPARTMENT OF THE INTERIOR

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Conversion Factors

Length

1 centimeter (cm)	= 0.3937 inches (in)
1 meter (m)	= 3.281 feet (ft)
1 kilometer (km)	= 0.6214 mile (mi)

Temperature

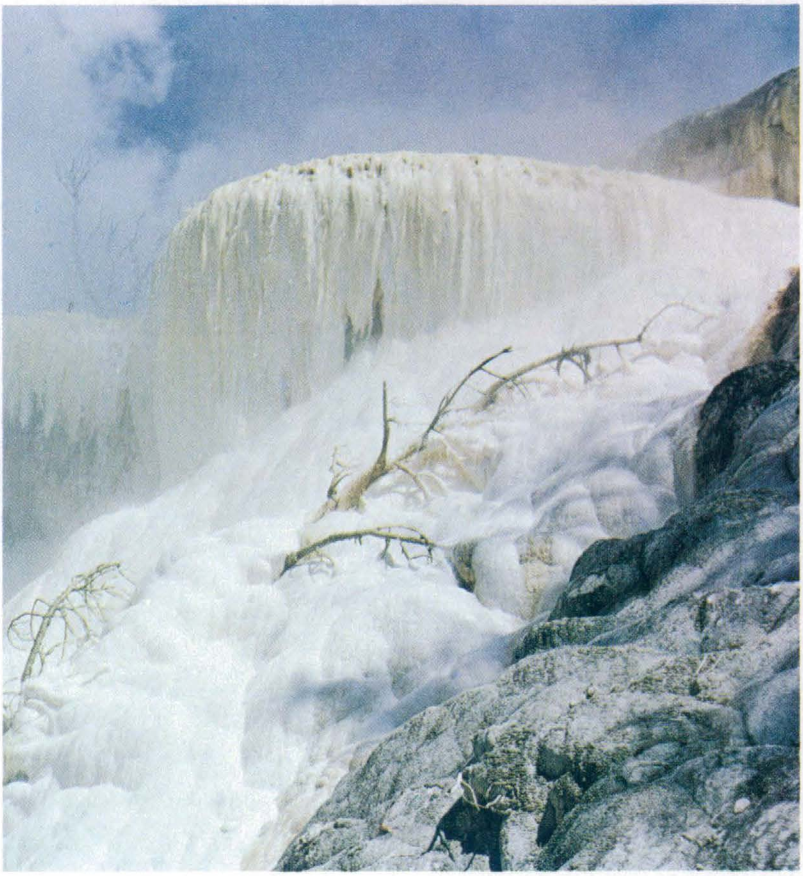
degrees Celsius (°C)	= (degrees Fahrenheit (°F) - 32)/1.8

Pressure

1 kilogram per square centimeter (kg/cm^2)	= 14.22 pounds per square inch (lb/in^2)

Volume Per Unit Time

cubic meter per minute (m^3/min)	= 264.2 gallons per minute (gal/min)
liter per minute (L/min)	= 0.2642 gallons per minute (gal/min)



New Highland Terrace

Geology and thermal history of MAMMOTH HOT SPRINGS, YELLOWSTONE NATIONAL PARK, WYOMING

By Keith E. Bargar

Mammoth Hot Springs, located about 8 km inside the north entrance to Yellowstone National Park, consists of nearly 100 hot springs scattered over a score of steplike travertine terraces. The travertine deposits range in age from late Pleistocene to the present. Sporadic records of hot-spring activity suggest that most of the current major springs have been intermittently active since at least 1871.

Water moving along the Norris-Mammoth fault zone is heated by partly molten magma and enriched in calcium and bicarbonate. Upon reaching Mammoth this thermal water (temperature about 73°C) moves up through the old terrace deposits along preexisting vertical linear planes of weakness. As the water reaches the surface, pressure is released, carbon dioxide escapes as a gas, and bicarbonate in the water is partitioned into more carbon dioxide and carbonate; the carbonate then combines with calcium to precipitate calcium carbonate, forming travertine. The travertine usually precipitates rapidly from solution and is lightweight and porous; however, dense travertine, such as is found in core from the 113-m research drill hole Y–10 located on one of the upper terraces, forms beneath the surface by deposition in the pore spaces of older deposits.

The terraces abound with unusual hot-spring deposits such as terracettes, cones, and fissure ridges. Semicircular ledges (ranging in width from about 0.3 m to as much as 2.5 m), called terracettes, formed by deposition of travertine around slowly rising pools. Complex steplike arrangements of terracettes have developed along runoff channels of some hot springs. A few hot springs have deposited cone-shaped mounds, most of which reach heights of 1–2 m before becoming dormant. However, one long-inactive cone named Liberty Cap attained a height of about 14 m. Fissure ridges are linear mounds of travertine deposited from numerous hot-spring vents along a medial fracture zone. The ridges range in height from about 1 to 6 m and in length from a few meters to nearly 300 m; width at the base of a ridge is equal to or greater than its height. In some places, such as along the northern border of Main Terrace, water from new hot-spring activity becomes ponded behind fissure-ridge barriers or dams and deposits travertine that eventually forms large flat terraces.

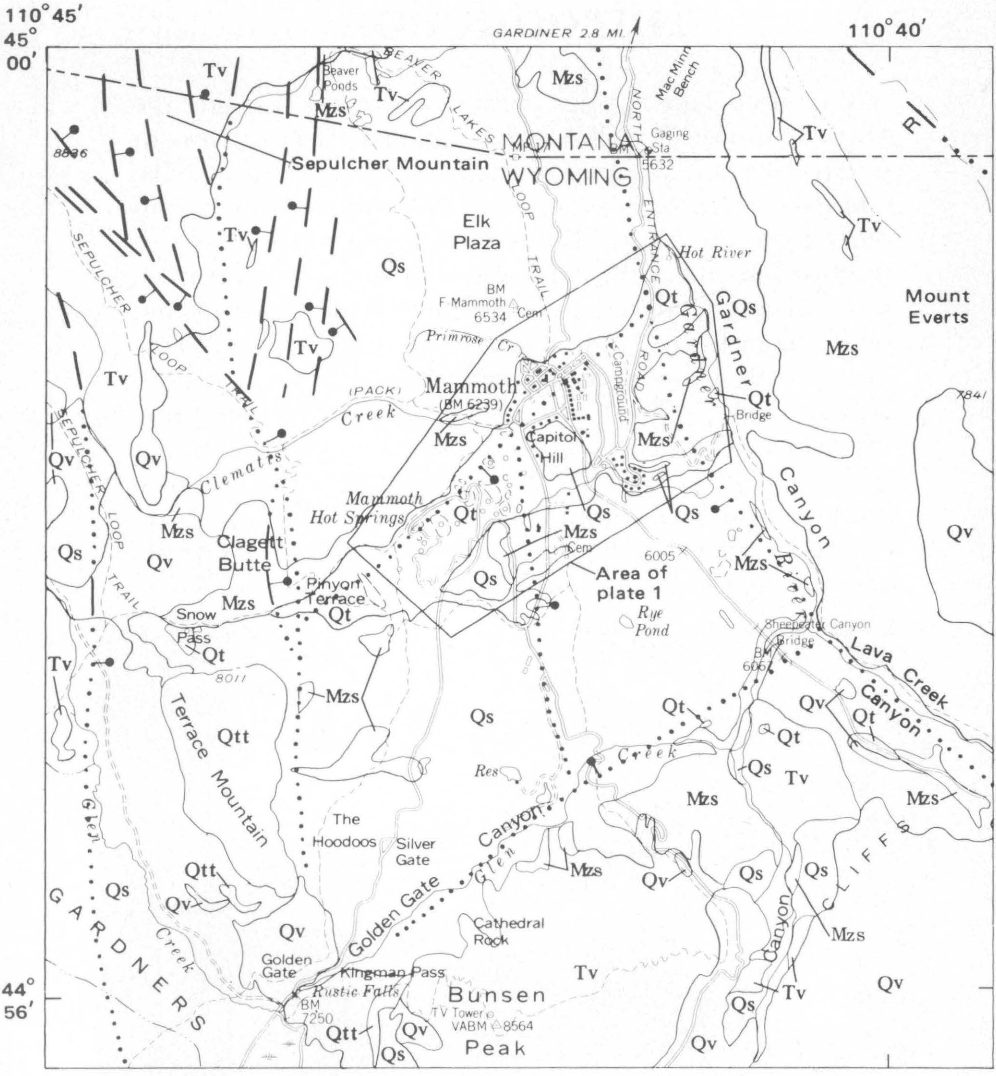
Introduction

Mammoth Hot Springs, located about 8 km inside the north entrance of Yellowstone National Park, consists of nearly 100 hot springs scattered over a score of steplike *travertine*[1] terraces (fig. 1), which descend almost continuously from the top of Terrace Mountain to the banks of the Gardner River (fig. 2). Several of the terraces contain unusual ridge- and cone-shaped hot-spring deposits, and other terraces are characterized by a myriad of colors owing to algae and bacteria that live in the hot springs and runoff areas. The natural beauty of these imposing travertine deposits, combined with the variegated hot springs, makes Mammoth Hot Springs one of the foremost attractions in Yellowstone Park.

The Hayden Survey (one of the four precursors of the U.S. Geological Survey), charged by Congress with inves-

Steplike travertine terraces at Mammoth Hot Springs (fig. 1). Several large flat travertine deposits lie between Prospect Terrace (pt) on the right and Opal (ot) and Hymen Terraces (ht) on the left (see pl. 1). Photograph courtesy of D. E. White, U.S. Geological Survey.

[1] See "Glossary" at end of report for definitions of italicized geologic terms.

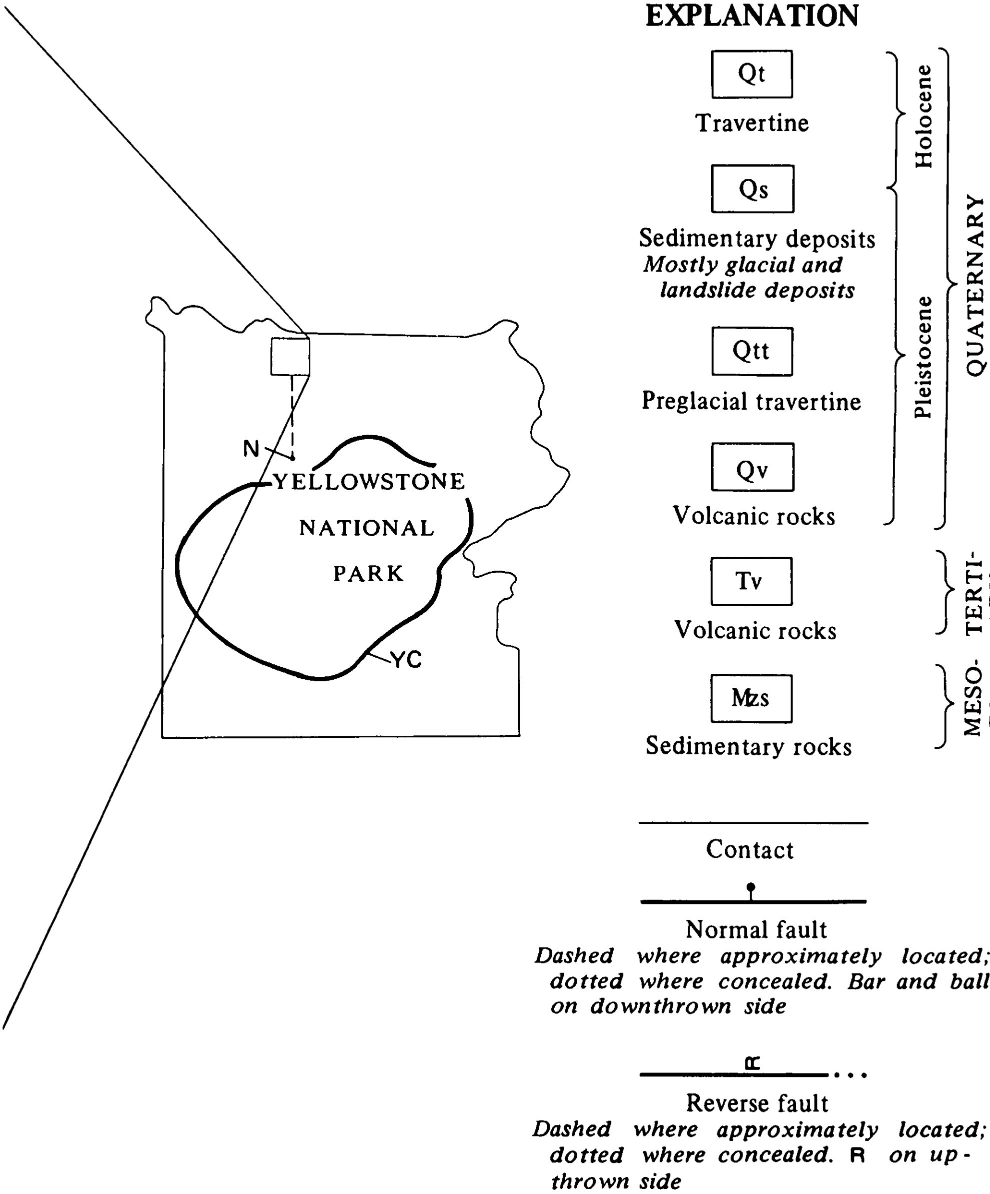


Base from U.S. Geological Survey,
1:62,500, Mammoth, 1958

0 1 2 MILES

0 1 2 3 KILOMETERS

Geologic map of Mammoth Hot Springs and surrounding area (fig. 2). Small index map shows location of Norris Geyser Basin (N), Norris-Mammoth fault zone (dashed line), and approximate outline of the rim of the Yellowstone caldera (YC). Geology



generalized from Ruppel (1972), U.S. Geological Survey (1972), Pierce (1973), Bargar and Muffler (1975), and unpublished geologic mapping of R. L. Christiansen, H. J. Prostka, E. T. Ruppel, and H. W. Smedes, all of the U.S. Geological Survey.

tigating the geology and natural history of the Yellowstone region, included in their reports (Hayden, 1872,1873,1883) the first published descriptions of the thermal feature they named "White Mountain Hot Springs."[2] During later years, numerous workers, notably Allen and Day (1935), contributed much information on the geology and thermal history of Mammoth Hot Springs; however, no attempt was made to correlate all of the available material. Accordingly, the purpose of this report is to summarize the relevant data concerning the geology of the travertine deposits and the history of hot-spring activity at Mammoth Hot Springs.

Acknowledgment—The author gratefully acknowledges the help of R. Alan Mebane, the Chief Park Naturalist of Yellowstone National Park, for providing access to the naturalists' files, which proved to be of great value in compiling the history of hot-spring activity at Mammoth.

Geologic history of Mammoth Hot Springs and surrounding area

The oldest exposed rocks in the immediate vicinity of Mammoth Hot Springs are Mesozoic (Jurassic and Cretaceous) marine and nonmarine sedimentary rocks (Ruppel, 1972). (See geologic time scale in table 1.) Mount Everts (fig. 3) contains an excellent exposure of part of the Cretaceous sedimentary section, and the hill opposite the entrance to the Terrace Loop Road (pl. 1) is composed of Jurassic rocks. Sediments and fossils in these rocks reveal a

[2] A. C. Peale, one of the members of the Hayden Survey, credits the name "Mammoth Hot Springs" to the residents and transient hot-spring bathers met by the first Hayden expedition (Peale, 1883). Earlier names for Mammoth Hot Springs were "White Sulphur Banks" on the 1839 map of Captain Washington Hood and "Sulphur Mountain" on the 1851 maps of the famous mountain man Jim Bridger and the Jesuit priest Father Pierre-Jean de Smet (Haines, 1974, p. 187–189).

Geologic time scale (table 1)

[From Cohee (1974)]

Era	Period	Epoch	Age (years)
Cenozoic	Quaternary	Holocene	
		Pleistocene	1,800,000
	Tertiary	Pliocene	5,000,000
		Miocene	22,500,000
		Oligocene	37,500,000
		Eocene	53,500,000
		Paleocene	65,000,000
Mesozoic	Cretaceous		136,000,000
	Jurassic		190,000,000 to 195,000,000
	Triassic		225,000,000
Paleozoic	Permian		280,000,000
	Pennsylvanian		320,000,000
	Mississippian		345,000,000
	Devonian		395,000,000
	Silurian		430,000,000 to 440,000,000
	Ordovician		500,000,000
	Cambrian		570,000,000
Precambrian			

history of widely fluctuating sea level that produced environments ranging from shallow oceans to swamps and river flood plains (Fraser and others, 1969).

Beginning in Late Cretaceous time, the area was subjected to intense compression that caused the existing rocks to be folded, faulted, and uplifted to form

Mount Everts and Main Terrace (fig. 3). The Cretaceous sedimentary rocks of Mount Everts are capped in the right half of the figure by Pleistocene volcanic rocks erupted from the Yellowstone caldera. Main Terrace (with Jupiter Springs on the left, the blue pool of Main Spring in the center, and Canary Springs, marked by vapor plumes, on the right) is the light-colored travertine terrace in the middle of the figure. Foreground shows part of tree-studded Prospect Terrace.

mountains (Keefer, 1971).[3] This disturbance in the Earth's crust, known as the Laramide *orogeny*, lasted until early Eocene time. The remainder of the Eocene Epoch was distinguished by voluminous outpourings of lava called the Absaroka Volcanic Supergroup. Near Mammoth Hot Springs, the Absaroka crops out on Sepulcher Mountain (fig. 2). Bunsen Peak, also shown in figure 2, is a small *intrusive* rock body related to this period of volcanism.

The Oligocene and Miocene Epochs were a comparatively quiet time during which the landscape underwent very little change. However, the region was once again

[3] Much of the geologic history of the Mammoth area given in this section is extracted from Keefer's paper, which provides an excellent account of the geologic history of Yellowstone National Park.

subjected to intense mountain-building forces in the Pliocene Epoch.

Large volumes of volcanic rocks flooded the Yellowstone region a second time during the Pleistocene Epoch. The yellowish cliffs of Golden Gate (fig. 2) and the top of Mount Everts (fig. 3) represent a very small part of the *extrusive* rocks erupted from the Yellowstone *caldera* (see index map of fig. 2) during this volcanic episode.

Three periods of glaciation, called pre-Bull Lake (180,000 to 300,000 years ago), Bull Lake (125,000 to 170,000 years ago), and Pinedale (10,000 to 50,000 years ago), also affected the Yellowstone region during the Pleistocene Epoch (Keefer, 1971; Pierce and others, 1976). The glacial deposits that form Capitol Hill and those shown elsewhere on plate 1 are of Pinedale age (Pierce, 1973).

The youngest geologic features found in the Mammoth area are landslides and travertine terraces deposited from hot-spring waters. The hot-spring activity, beginning in Late Pleistocene time and extending to the present, forms the subject matter for this report.

Origin and chemical composition of Mammoth Hot Springs water and travertine deposits

Chemical and *isotopic* analyses of hot-spring waters supply important information about the history of the thermal water. Cold, dilute meteoric water (rain or snow) has a distinctive hydrogen and oxygen isotopic composition that distinguishes it from water that comes from *magmas* deep in the earth. Such information suggests that over 95 percent of the hot-spring water emerging in Yellowstone Park probably originates as meteoric water (White, 1969).

Water from rain and snowmelt percolates into the ground and gradually descends to depths of a kilometer or more beneath the Earth's surface, where it is heated to very high temperatures and becomes enriched in several chemical constituents. The dissolved chemicals in the deep hot water change according to the composition and temperature of the surrounding rock. If the water remains in an *aquifer* at a uniform temperature for a relatively long period of time, a chemical equilibrium between the water and the rock will be reached. When the deep circulating water eventually moves back toward the surface, its temperature drops and its composition may undergo additional change by continued reaction with the surrounding rock and by mixing with shallow dilute meteoric water.

The chemical composition of water from Soda Spring, shown in table 2, is typical of cold, dilute, shallow ground water that has not been heated to high temperatures dur-

Average chemical composition of Mammoth Hot Spring water compared with acid chloride water from Norris Geyser Basin and cold spring water from Snow Pass (table 2)

[Analyses given in parts per million]

Chemical constituent	Chemical formula	Little Whirligig Geyser, Norris Geyser Basin[1]	Average Mammoth Hot Springs water[2]	Soda Spring, Snow Pass[3]
Silica	SiO_2	420	54	18.4
Aluminum	Al	2.1	.2	.4
Iron	Fe	1.0	.1	5.3
Manganese	Mn	----	.3	----
Calcium	Ca	2.5	323	80.8
Magnesium	Mg	.5	67	10.6
Sodium	Na	349	130	3.9
Potassium	K	83	54	2.7
Lithium	Li	5.3	1.6	----
Ammonia	NH_4	----	.6	.5
Bicarbonate	HCO_3	0	755	249.6
Carbonate	CO_3	0	0	----
Sulfate	SO_4	113	563	46.8
Chloride	Cl	607	163	4.4
Fluoride	F	3.3	2.5	----
Boron	B	9.2	4.1	----
Arsenic	As	----	.9	----
Hydrogen sulfide	H_2S	----	2.4	----
Temperature (°C)		91	69	6
pH[4]		3.2	7.2	----

[1]From Rowe, Fournier, and Morey (1973).

[2]Average of 15 analyses reported in Gooch and Whitfield (1888), Rowe, Fournier, and Morey (1973), and Thompson, Presser, Barnes, and Baird (1975).

[3]From Gooch and Whitfield (1888). Snow Pass is located just north of Terrace Mountain (fig 2).

[4]pH is a measurement of the degree of acidity or alkalinity (on a scale of 0 to 14 a value of 7 is neutral, 0 is most acid, and 14 is most alkaline).

ing deep circulation. In contrast, the chemical composition of water from Little Whirligig Geyser in Norris Geyser Basin is typical of water coming directly to the surface from a hot aquifer with little or no dilution during the ascent. Fournier, White, and Truesdell (1976) estimated that the aquifer feeding the Norris hot springs and geysers has a temperature of 270°C. Large amounts of dissolved chloride and silica and small amounts of calcium and bicarbonate are typical of high-temperature Yellowstone waters.

The distinctive chemical composition of Mammoth Hot Springs water shown in table 2 (very high calcium, bicarbonate, and sulfate, and moderate silica, chloride, and sodium) possibly results during movement of Norris Basin acid-chloride water along a fault between Norris Geyser Basin and Mammoth Hot Springs (A. H. Truesdell and R. O. Fournier, oral commun., 1976). Along the route, three major events may occur: (1) The water reacts with sedimentary rock that is rich in calcium carbonate, liberating carbon dioxide gas (CO_2), (2) the hot water is cooled and diluted by mixing with water similar to that coming from Soda Spring, and (3) the mixed water reaches a new chemical equilibrium with the surrounding rock in an aquifer at about 73°C.[4]

The source of heat that gives rise to the Yellowstone Park hot springs is partly molten rock in a gigantic *magma chamber* situated beneath the Yellowstone caldera with its top about 5–10 km below the surface of the ground (Eaton and others, 1975). Alinement of fairly young volcanic rocks along the Norris-Mammoth fault zone (see fig. 2) suggests that the thermal water that eventually reaches Mammoth may be heated by partly molten magma within the fault zone (D. E. White, oral commun., 1976).

The thermal water beneath the Mammoth travertine

[4]Research drill hole Y–10, one of 13 holes drilled in Yellowstone National Park by the U.S. Geological Survey in 1967 and 1968, lies just east of Bath Lake (pl. 1). Drill core recovered from the 113-m hole shows travertine (intermixed with glacial sediments in the middle part of the section) down to 77.3 m, below which are Mesozoic sedimentary rocks. Temperature measurements made during drilling of Y–10 show a remarkably constant temperature of about 73°C at all depths below 15 m (White and others, 1975).

deposits contains a large amount of dissolved gas, mainly carbon dioxide. Measurements (White and others, 1975) in research hole Y–10, drilled through the travertine terrace into thermal water, showed that the confining pressure necessary to keep the gas dissolved in the water is greater than 6 kg/cm^2. As the water flows upward through a labyrinth of channels in the old fractured terraces (fig. 4), the confining pressure gradually decreases, and hot gas, consisting mainly of CO_2 (table 3), separates and escapes at the surface. The effect is similar to removing the cap from a carbonated soft drink bottle. The escape of CO_2 causes the water to become supersaturated with cal-

Steeply dipping fractures cutting horizontally bedded travertine deposits of Highland Terrace (fig. 4). Numerous channels have been carved along the fractures by thermal water flowing toward the surface. Pencil (circled) is about 15 cm long.

Average chemical composition of gas exsolved from the Mammoth Hot Springs (table 3)

[----, values not reported]

Gas	Chemical formula	Percentage composition	
Carbon dioxide	CO_2	[1]98.48	[2]99.70
Oxygen	O_2	.23	.12
Carbon monoxide	CO	.00	----
Hydrogen	H_2	.00	<.40
Methane	CH_4	.03	<.04
Nitrogen	N_2	----	<.21
Nitrogen plus argon	N_2+Ar	1.27	----
Hydrogen sulfide	H_2S	.00	----
Total		100.01	100.47

[1]Average of six analyses reported in Allen and Day (1935)
[2]Average of four analyses reported in Gunter (1968)

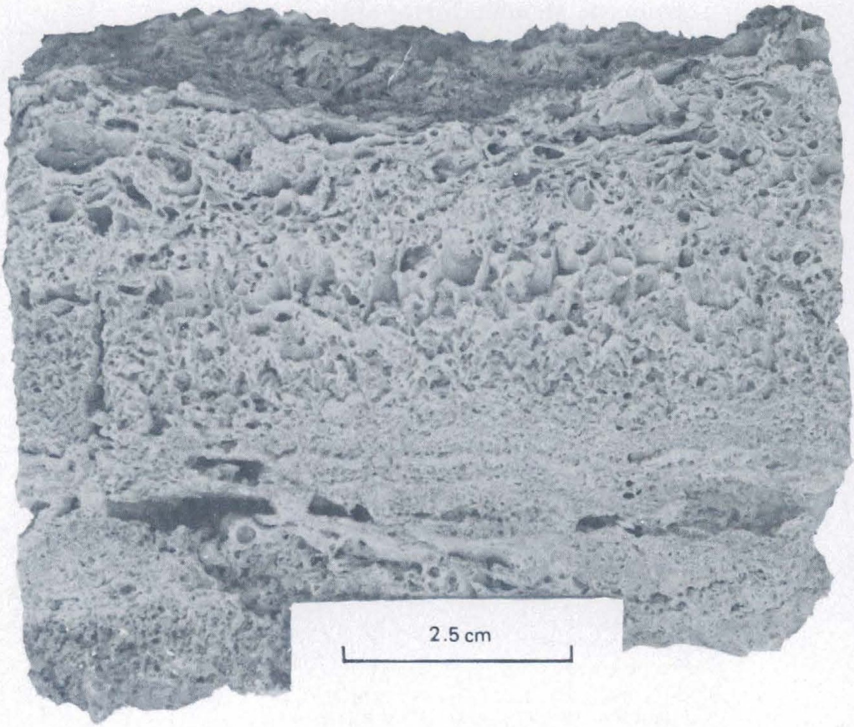
Average chemical composition of travertine from Mammoth Hot Springs (table 4)

[Average of ten analyses reported by Clarke (1904)]

Chemical constituent	Chemical formula	Percent composition
Silica	SiO_2	0.15
Aluminum oxide	Al_2O_3	.15
Iron oxide	Fe_2O_3	
Calcium oxide	CaO	54.20
Magnesium oxide	MgO	.46
Potassium oxide	K_2O	.20
Sodium oxide	Na_2O	.18
Water	H_2O	1.22
Sodium chloride	NaCl	.25
Potassium chloride	KCl	.08
Sulfur trioxide	SO_3	.89
Carbon dioxide	CO_2	42.25
Organic carbon	C (organic)	.20
Organic hydrogen	H (organic)	.02
Total		100.25

cium carbonate ($CaCO_3$), which precipitates out of solution to form travertine, mainly in the form of the mineral calcite. An average chemical analysis of the travertine is given in table 4.

Allen (1934) estimated that the travertine at Mammoth Hot Springs is being deposited at a rate varying from about 2.8 to 56.5 cm per year and averaging about 21.1 cm per year. According to Allen and Day (1935), the porous



Porous travertine of drill core (fig. 5). Specimen is from 73 cm below the surface, drill hole Y–10.

travertine (fig. 5) that forms the massive Mammoth terrace deposits is a product of rapid deposition. Allen and Day also suggest that the formation of denser travertine, found locally about a meter below the surface, may result from either slow deposition or precipitation of calcite into the pore spaces of older deposits. The cross-section through part of an old *fissure ridge* (fig. 6) also supports the idea that dense travertine is a product of slow deposition. The right half of the figure shows horizontally layered porous travertine that forms the bulk of the fissure-ridge deposit. Vertically banded layers in the left half of the figure are

Dense vertically banded travertine (fig. 6). Specimen lines an old channel in a partially collapsed fissure ridge of the Highland Terrace area. Coin (circled) is 1.8 cm across.

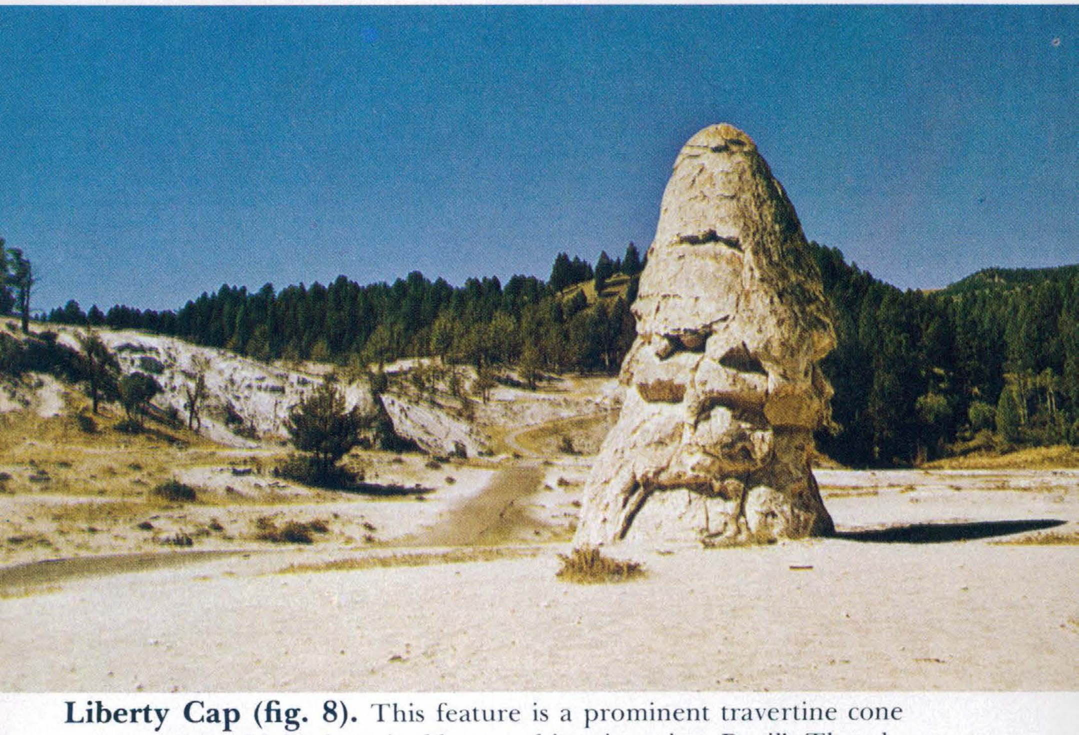
composed of nonporous dense travertine that precipitated (presumably over a long period of time) along the interior walls of the fissure ridge. Figure 7 shows a sample of porous travertine in which the pore spaces have been partially filled.

Dense travertine of drill core (fig. 7). Specimen is from 14.1 m below the surface, drill hole Y–10. Channel (c) is partly filled by younger lighter colored travertine (arrow).

Form and structure of the hot-spring deposits

Hot-spring cones

Liberty Cap and the Devil's Thumb (fig. 8) are the two best examples of a cone-type hot-spring deposit at Mammoth Hot Springs. Hot-spring cones form by travertine deposition where water persistently emerges at a single point rather than along a crack in the terrace. As long as water flows up this point of weakness in the terrace, the cone continues to grow, but if the water finds a more con-



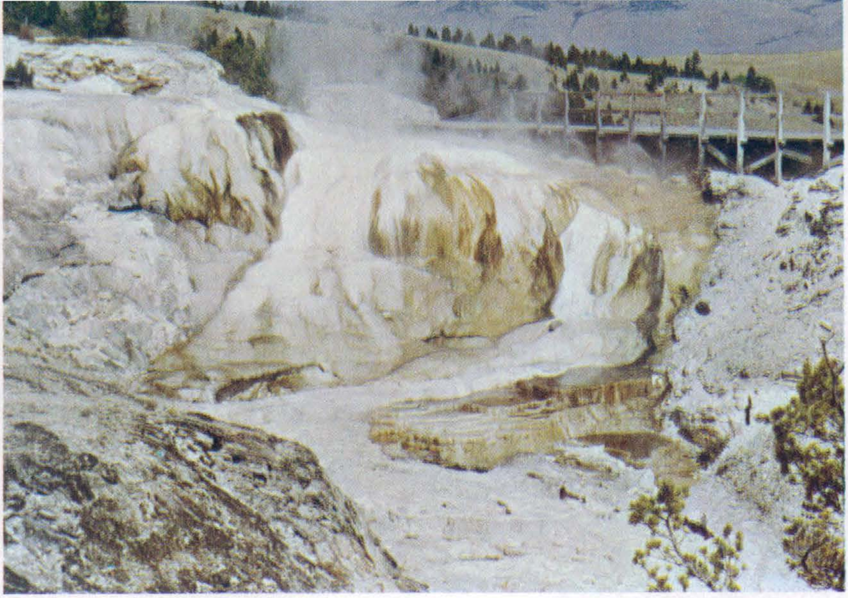
Liberty Cap (fig. 8). This feature is a prominent travertine cone (about 14 m high) deposited by a prehistoric spring. Devil's Thumb, a similar cone-shaped deposit, is partly obscured by tree in left background.

venient underground channel or if the orifice of the spring is sealed over by travertine, the cone becomes dormant. Also, as a tall cone such as Liberty Cap increases in height, the flow of water from the top may eventually stop, because there is insufficient *artesian pressure* to continue lifting the hot water over the newly deposited lip of the pool.

Terracettes

Hot-spring runoff over steep banks typically results in the formation of multitudes of small scalloped deposits. In places where the runoff slopes are gentle or where irregularities in the slope allow small pools to form, travertine precipitates around the edge of the slowly rising pool to produce larger scallop-shaped deposits called *terracettes* (figs. 9, 10). New Highland Springs are characterized by spectacular overhanging terracette deposits (fig. 11). Hot-spring water overflowing the lip of the deposit typically forms a mass of stalactites that gradually fills in the base of the projecting terracette.

Well-developed terracettes at Minerva Spring (fig. 9).



Cupid Spring (fig. 10). Small group of terracettes formed along break in slope of runoff area. Algae that grow in the runoff area of this spring impart a reddish-brown color. White travertine is freshly deposited; grayish areas are older travertine deposits from springs that are no longer active.

Terracettes and overhanging terracette deposits of New Highland Springs (fig. 11).

Collapse features

Collapse features are fairly common on most of the Mammoth terraces. Water flowing through near-surface channels weakens the overlying travertine until the undercut deposits collapse under their own weight (fig. 12). The surface expression of a collapse feature is commonly circular; however, several collapse or slump features may coalesce to produce a linear slump feature such as is found along the surface projection of the underground Hot River.

Collapse features usually range from 1 to 6 m in depth and width. The largest and most conspicuous ones occur on Hotel Terrace (pl. 1), one of them opening into McCartney's Cave. This cave is named after James C. McCartney, who in 1877 reportedly escaped from Nez Perce Indians by hiding in the cave for 3 days (Baggley, 1933). The walls of the cave, which extends about 50 m northeast down an average slope of about 40°, are composed of horizontally stratified travertine with lenses of soil and sand (Guptill, 1890; Condon, 1954).

Tension fractures

Three large tension fractures, one of which is shown in the lower left corner of plate 1, and several smaller subparallel fractures occur on Pinyon Terrace. Similar tension fractures probably gave rise to slumping that eventually resulted in large blocks of travertine cascading down the face of Terrace Mountain to form the landslide deposit at Silver Gate (see fig. 21).

Several parallel tension fractures occur southwest of and along the same trend as the White Elephant Back fissure ridge (pl. 1). Spring MHS–30 (fig. 13) is a small linear pool fed by several springs that reach the surface along a segment of one of the tension fractures. This relation between a fissure ridge and a tension fracture suggests that the many fissure-ridge deposits on the Mammoth terraces may have developed from hot-spring waters flowing to the surface along preexisting linear vertical planes of weakness.

Collapse feature in the Highland Terrace area (fig. 12). The approximately 1.2-m-deep depression is one of a series of collapsed areas that form a linear trend parallel to the group of tension fractures in the southwest corner of the area shown on plate 1.

White Elephant Back Terrace (background) and spring MHS–30 (fig. 13). The spring occurs along a tension fracture that coincides with the trend of the White Elephant Back Terrace. Length of the pool is approximately 3 m.

Fissure ridges

The most outstanding topographic features on the upper Mammoth terraces are the numerous fissure ridges (pl. 1). A few, such as the old inactive ridge located just north of the Devil's Kitchen Springs (fig. 14), stand out in bold relief above the surrounding terraces; others have been partially buried and nearly obscured by later travertine deposits (fig. 15).

In addition to their topographic relief, most fissure ridges are characterized by a fissure that extends along the top of the ridge for nearly its entire length (see fig. 15). Width of the crack ranges from a centimeter to as much as 0.3 m. Most of the cracks probably widen when a ridge becomes topheavy and pulls apart along the lubricated plane of weakness at the center. The width of some fissures, however, may depend on the thickness of the dense, vertically banded calcite layers (fig. 6) that are deposited on the interior walls of the fissures. Winkler and Singer

Terminus of fissure ridge about 3 m high located just north of Devil's Kitchen Springs (fig. 14).

Fissure ridge along part of the northern border of Main Terrace (fig. 15). The ridge forms a barrier to later travertine deposits of Main Terrace that are beginning to cover and obscure the ridge. A fissure extends along most of the top of the ridge.

(1972) calculated that salt, sprinkled on snow- and ice-covered marble steps in winter, is capable of exerting a pressure of up to 670 kg/cm^2 upon recrystallization (when oversaturated by a factor of two) and thus causing hairline cracks in the marble to widen. Similar calculations based on the average chemical analyses of Mammoth Hot Spring water from table 2 suggest that the thermal water may be oversaturated with calcium carbonate by a factor of three (J. M. Thompson, oral commun., 1975). With this amount of supersaturation, a pressure exceeding 770 kg/cm^2 could be exerted on the interior walls of a fissure ridge, forcing the fissure to widen gradually.

A few of the fissure ridges in the Highland Terrace area, such as the Devil's Kitchen Springs and Orange Spring Mound (fig. 16), appear to be composed of coalesced cone-shaped hot-spring deposits. Devil's Kitchen Springs contains 28 small cones rather than a fissure marking the axis of its ridge, whereas Orange Spring Mound, which

Orange Spring Mound (fig. 16). The small cone-shaped deposit behind and to the right of the mound is Tangerine Spring.

appears to be a large cone-type hot spring, has the medial fracture line of a fissure ridge extending along its longer axis; however, three distinct and partly coalesced hot-spring cones (one of which is named Tangerine) do occur along the projection of the fracture of Orange Spring Mound. This ill-proportioned fissure ridge undoubtedly results from the greater duration of hot-spring activity near its west end. A few other fissure ridges such as White Elephant Back Terrace (figs. 13, 18) display the same asymmetry to a lesser degree.

An important function of many fissure ridges is that they form dams or barriers behind which later travertine deposits accumulate. These may eventually overflow the ridge (fig. 15). Several of the large flat travertine terraces at Mammoth Hot Springs (pl. 1) apparently owe their origin to this mechanism, and deposits in areas such as the confined Glen Springs (fig. 17) may in the distant future build up to form a large flat terrace.

Glen Springs (fig. 17). White central ridge is shown nearly surrounded by two older subparallel fissure ridges. If Glen Springs remain active, enough travertine may eventually be deposited to form a flat terrace between the old bounding ridges.

Caves

White Elephant Back Terrace contains small cavelike openings along its northwestern side called "The Grottos" (H. M. Majors III, unpub. data, 1962) (fig. 18). Such caves develop because of the inverse solubility of calcium carbonate ($CaCO_3$). That is, a given volume of cold water can take more $CaCO_3$ into solution than the same amount of hot water. As hot water flows down the sides of a fissure ridge, it begins losing $CaCO_3$ through deposition, but more important, the temperature of the water decreases with increasing distance from the hot-spring orifice. Eventually the temperature and dissolved $CaCO_3$ content of the water reach a point at which the cooled runoff is able to dissolve the old travertine deposits and thus create an underground channel beneath the flank of the ridge. A larger solution cave, Stygian Cave, similar to the Grottos, lies at the base of the Squirrel Springs fissure ridge. In

One of the Grottos along the northwest flank of White Elephant Back Terrace (fig. 18).

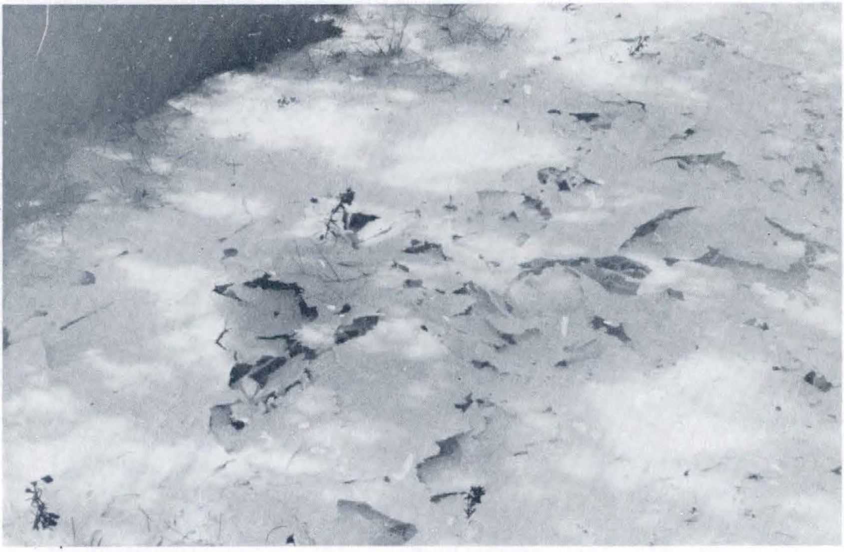
winter, the icicles formed by spring water dripping into the cave may be "beautifully colored with tints varying from white to light blue and amethyst" (N. W. Scherer, unpub. data, 1932) (apparently owing at least in part to algal growth). Stygian Cave also contained carbon dioxide gas; Joyner (1928b) once counted 53 asphyxiated birds in the cave during a 3-month period. No study has been made recently; however, such caves remain particularly dangerous.

A similar type of solution cave may occur in the center of a fissure ridge, giving the impression that part of the ridge is merely a shell with a hollow interior. One such cave, known as the Devil's Kitchen (pl. 1), has a 3-m-long entrance (along the crack of the ridge) through which early visitors to the park were able to descend 10 m by means of a ladder and explore the cavern for a distance of about 22 m. Unfortunately, the Devil's Kitchen had to be closed to the public in 1939 because of carbon dioxide gas and lack of oxygen (Haynes, 1949).

Calcite "ice" and fossiliferous travertine

A rare type of travertine deposit found on the Mammoth terraces is called calcite "ice." Calcite "ice," also called "hot-water ice" by Allen and Day (1935), is a thin crust of calcite that gradually forms on the surface of some stagnant hot-spring pools. Usually the delicate calcite layer breaks up and settles to the bottom of the pool; however, if the pool dries up, the calcite crust may persist for a short time (fig. 19).

Another unusual travertine texture results from the growth of microorganisms. The significance of microorganisms or algae in promoting precipitation of travertine was discussed by Weed (1889) and later by Allen (1934). Weed concluded that algae play a prominent role in travertine deposition. However, Allen indicated that the amount of calcium carbonate actually deposited by algal growth at Mammoth Hot Springs is very small. Samples containing microorganism fossils (fig. 20) are found at



Calcite "ice," now partly collapsed (fig. 19). Deposit is on the surface of the former pool of spring MHS–12.

only a few locations on the Mammoth terraces, which bears out Allen's conclusion.

Texture produced by fossil microorganisms in travertine from Pinyon Terrace (fig. 20).

Age of the travertine formations and history of thermal activity at Mammoth Hot Springs

Perhaps the most outstanding characteristic of the hot springs at Mammoth is the rapidity of change. A hot spring may dry up at one location and a new spring begin flowing a short distance away within a few days. Also, a spring may have a large discharge one day, be completely dry the next day, and flow again the following week. Numerous detailed observations of rapid changes in thermal activity at Mammoth have been recorded by park naturalists and other observers through the years, but such detailed records are beyond the scope of this report. Instead, tables 5 and 6 and this section summarize the major changes in hot-spring activity that have been recorded since the Hayden Survey.

Terrace Mountain Travertine

The top of Terrace Mountain is capped by 15 to as much as 75 m (Hayden, 1872; Allen and Day, 1935) of horizontally bedded, dense travertine (fig. 21) which, according to Hayden, may have precipitated from hot springs in the bottom of a lake. A small patch of travertine on the west side of Bunsen Peak (fig. 2) is probably contemporaneous with the Terrace Mountain travertine (Allen and Day, 1935). The Hoodoos and Silver Gate (figs. 2, 21) are part of a landslide deposit that is composed largely of travertine from Terrace Mountain.

Schlundt and Moore (1909) calculated that the travertine from Terrace Mountain was deposited about 20,000 years ago. Their age calculation, based on the rate of decomposition of the radioactive element radium, is not now regarded as accurate, because of numerous possible errors of which they were unaware at the time. A more

Recorded history and temperatures of named thermal springs at Mammoth Hot Springs, 1870–1974 (table 5)

[See plate 1 for hot-spring locations. I=inactive, A=active at least during part of the year; missing years and dashes indicate that no records of hot spring activity were located. Thermometers used for obtaining temperature data were not standardized, and recorded temperatures in °C (Celsius) may be in error by as much as 2 or 3°C. Reference numbers correspond to the list of references at the end of table, p. 34. All unpublished references except 86–88 were obtained from the files of the Naturalists' office at Mammoth Hot Springs]

Spring name	1870	1871	1872	1873	1874	1875	1876	1877	1878	1883	1884	1886	1887	1889	1896	1906	1911	1917	1922	1923	1924	1925
Angel Springs	--	I	72	--	--	--	--	--	72	--	--	--	--	--	--	--	72	--	71	--	A	65
Baby Spring	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Bath Lake	--	--	--	--	--	--	--	--	33	--	--	A	--	--	--	46	--	--	--	--	--	47
Blue Springs	--	--	--	--	--	--	--	--	74	--	--	--	74	--	--	70	--	--	A	--	--	--
Canary Spring	--	66	--	--	--	--	--	--	62	--	--	--	--	--	--	--	--	--	--	--	--	65
Cavern Spring	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Cedar Tree Spring	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Cleopatra (Diana) Spring	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	71	--	--	--	--	--	71
Cupid Spring	--	72	72	A	--	--	--	--	74	--	--	--	--	--	--	--	--	--	--	--	--	--
Devil's Kitchen Springs	--	--	--	--	--	--	--	--	49	--	--	--	--	--	--	--	--	--	--	--	--	--
Fan Spring	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Glen Springs	--	--	72	--	--	--	--	--	I	--	--	--	--	--	--	--	--	--	--	--	A	--
Highland Spring	--	A	--	--	--	--	--	--	73	--	--	--	--	--	--	--	--	--	--	--	--	72
Hot River	--	56	--	--	--	--	--	--	--	--	58	58	--	--	58	51	51	--	--	--	--	49
Hymen Springs	A	72	72	A	A	A	A	A	72	--	--	--	--	--	--	71	--	A	--	--	A	72
Jupiter Springs	--	70	69	--	--	--	--	--	69	--	--	--	--	A	--	--	--	--	71	A	A	71
Little Joker	--	--	--	A	I	I	A	A	62	--	--	--	--	--	--	--	--	--	--	--	--	--
Main Springs	--	68	72	--	--	--	--	--	64	--	--	--	58	--	--	71	--	--	--	--	A	70
Minerva (Cleopatra) Spring	--	68	--	--	--	--	--	--	68	--	67	--	--	68	--	71	--	--	--	--	A	--
Naiad Spring	--	--	--	--	--	--	--	--	62	--	--	--	--	--	--	A	--	--	--	--	--	--
Narrow Gauge Springs	--	--	--	--	--	--	--	--	--	--	--	--	--	A	--	--	69	--	--	--	--	--
New Blue Springs	--	72	--	--	--	--	--	--	I	--	--	--	--	--	--	70	--	--	--	--	--	--
New Highland Springs	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
New Palette Spring	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Opal Spring	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Orange Spring Mound	--	61	64	--	--	--	--	--	64	63	--	--	64	--	--	64	63	--	--	--	--	60
Painted Pool	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Palette Spring	--	68	67	--	--	--	--	--	70	--	--	--	--	--	--	--	--	--	72	--	--	--
Poison Spring	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Prospect Springs	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Reservoir (Bath) Springs	--	33	--	--	--	--	--	--	46	--	--	--	--	--	--	--	--	--	--	--	--	--
Roadside Spring	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Soda Spring (Squirrel Springs Group)	--	--	--	--	--	--	--	--	A	--	--	--	--	--	--	32	--	--	--	--	--	--
Soda Spring	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	39	--	--	--	--	--	--
Squirrel Springs	--	--	--	--	--	--	--	--	62	--	--	--	--	--	--	--	--	--	--	--	--	--
Sulfur Spring	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Tangerine (Little Orange) Spring	--	61	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Trail Springs	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
White Elephant Back Springs	--	--	--	--	--	--	--	--	69	--	--	--	--	--	--	--	--	--	68	--	--	59
References	4	1 2 4	3 4	4	4	4	4	4	4	6	6	5 40	7	8	10	9	40	69	11 13 18	11	11 12	40

Recorded history and temperatures of named thermal springs at Mammoth Hot Springs, 1870–1974 (table 5)—Con.

Spring name	1926	1927	1928	1929	1930	1931	1932	1933	1934	1935	1936	1937	1938	1939	1940	1943	1944	1945	1946	1947	1948	1949
Angel Springs	--	74	A	63	--	A	73	A	A	--	A	--	A	--	--	--	--	--	--	73	--	--
Baby Spring	--	--	--	--	--	--	72	A	A	--	A	--	A	--	--	--	--	--	--	--	--	--
Bath Lake	I	I	I	--	--	--	A	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Blue Springs	--	--	--	A	--	A	74	A	A	--	--	--	A	A	--	--	--	--	--	--	A	A
Canary Spring	--	--	I	--	--	--	A	--	--	--	--	--	--	--	--	--	--	--	--	--	A	--
Cavern Spring	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Cedar Tree Spring	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Cleopatra (Diana) Spring	--	--	A	69	A	A	73	--	--	--	--	--	A	--	--	--	--	--	--	A	I	--
Cupid Spring	--	--	--	--	--	A	69	A	A	--	--	--	A	--	--	--	--	--	--	--	73	A
Devil's Kitchen Springs	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Fan Spring	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Glen Springs	--	--	A	A	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Highland Spring	--	--	--	72	--	A	A	--	--	--	--	--	--	A	--	--	--	--	--	--	--	--
Hot River	--	--	52	46	--	55	55	--	--	--	54	--	--	--	--	--	--	--	--	--	--	--
Hymen Springs	I	--	A	71	--	A	73	--	--	70	I	I	--	--	--	--	--	--	--	--	--	--
Jupiter Springs	--	73	57	71	--	A	59	--	A	--	--	--	A	--	--	--	--	--	--	--	--	--
Little Joker	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Main Springs	--	72	71	73	--	A	--	A	A	--	--	--	A	--	--	--	--	--	--	--	A	A
Minerva (Cleopatra) Spring	A	A	A	70	A	A	63	A	A	--	--	--	A	--	--	--	--	--	--	--	--	--
Naiad Spring	--	--	--	--	--	--	--	--	--	--	--	--	A	--	--	--	--	--	--	--	--	--
Narrow Gauge Springs	--	--	A	75	--	A	57	--	--	--	--	--	--	--	--	--	--	--	--	--	62	--
New Blue Springs	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
New Highland Springs	--	--	A	A	--	A	72	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
New Palette Spring	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	A	A	--	--	A	A
Opal Spring	A	--	--	--	--	A	A	A	A	69	A	--	A	--	A	A	--	--	A	72	72	--
Orange Spring Mound	--	--	A	60	--	A	61	--	--	--	--	--	A	--	--	--	--	--	A	--	--	--
Painted Pool	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Palette Spring	--	--	--	72	A	A	72	A	A	--	--	--	--	--	--	--	--	--	--	--	73	A
Poison Spring	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	A	--	--	--
Prospect Springs	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Reservoir (Bath) Springs	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Roadside Spring	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Soda Spring (Squirrel Springs Group)	--	--	--	22	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Soda Spring	--	--	A	--	--	--	31	--	--	--	--	--	--	A	--	--	--	--	A	--	--	--
Squirrel Springs	--	--	--	A	--	--	A	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Sulfur Spring	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Tangerine (Little Orange) Spring	--	--	A	--	--	--	59	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Trail Springs	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
White Elephant Back Springs	I	I	I	67	--	A	A	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
References	16 20 65 69	14– 16 19 20	15– 21 40	22– 27 40	28 65	29– 32	33– 37	38 65	39	41	42 44 48	48	43 44	45– 47	48	49	65	65	48– 50	51 52	52 53 65	54

Angel Springs	A	--	71	--	I	--	I	I	I	--	I	I	I	I	I	I	--	I	--	I	I	I
Baby Spring	--	--	--	--	--	--	--	--	--	--	--	65	70	66	64	I	--	I	--	I	I	I
Bath Lake	--	--	--	--	--	--	--	--	--	61	59	48	52	44	63	54	--	57	--	64	56	38
Blue Springs	--	--	--	71	71	71	--	76	76	76	71	69	72	71	67	I	--	40	--	I	I	I
Canary Spring	--	--	--	A	73	--	A	67	68	71	71	65	A	58	54	73	--	I	A	A	71	A
Cavern Spring	--	--	--	--	71	71	68	66	64	66	69	68	66	68	67	68	--	56	72	68	68	62
Cedar Tree Spring	--	--	--	--	--	--	--	--	--	--	--	71	72	71	53	67	A	74	A	74	73	70
Cleopatra (Diana) Spring	--	--	--	A	71	70	70	71	71	69	63	61	60	66	66	60	--	I	--	--	68	50
Cupid Spring	A	--	--	A	A	--	A	69	69	72	73	74	70	64	72	73	A	71	73	72	73	72
Devil's Kitchen Springs	--	--	--	--	--	--	--	--	--	--	--	61	61	60	61	57	A	54	--	55	57	50
Fan Spring	--	--	--	--	--	--	--	--	--	--	61	50	49	42	49	51	--	32	A	--	31	--
Glen Springs	--	--	--	--	--	--	--	59	58	60	58	A	53	59	62	62	--	71	--	61	64	64
Highland Spring	--	--	A	A	74	--	62	76	72	A	A	68	69	68	59	I	--	71	--	I	I	I
Hot River	--	--	--	--	--	--	53	--	--	--	--	--	--	--	--	53	--	--	--	--	60	46
Hymen Springs	--	--	--	--	--	--	--	I	I	--	--	I	I	I	I	I	--	--	--	I	I	I
Jupiter Springs	--	--	--	A	70	--	69	72	71	74	74	70	70	70	70	71	--	69	68	A	73	A
Little Joker	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	I	I	I
Main Springs	--	--	--	--	66	--	--	--	--	72	71	I	I	I	73	74	--	--	--	A	A	I
Minerva (Cleopatra) Spring	A	A	--	A	73	74	74	74	74	74	76	74	74	A	72	72	--	67	72	72	A	A
Naiad Spring	--	--	--	--	70	--	69	71	71	70	70	70	A	A	69	70	--	69	--	--	70	I
Narrow Gauge Springs	A	--	--	--	I	--	I	I	I	71	73	67	70	66	72	64	--	53	--	59	63	62
New Blue Springs	--	--	--	--	--	--	74	--	--	--	--	I	I	I	I	I	--	74	59	70	73	A
New Highland Springs	--	--	--	--	--	--	74	75	74	--	A	73	73	74	74	74	--	74	74	73	75	75
New Palette Spring	A	--	--	A	71	--	60	64	64	63	61	63	63	62	62	55	--	57	--	--	A	60
Opal Spring	A	--	--	A	73	--	73	69	66	71	71	70	68	68	71	71	--	71	A	A	71	A
Orange Spring Mound	A	--	--	--	71	66	61	61	61	62	62	61	54	51	63	63	A	54	--	66	63	64
Painted Pool	--	--	--	--	--	--	--	--	--	--	67	66	66	67	65	66	--	66	--	A	61	64
Palette Spring	A	A	--	--	66	--	51	57	54	63	63	61	60	64	64	63	--	63	--	--	63	58
Poison Spring	--	--	--	A	--	--	--	--	--	A	--	37	43	42	42	40	A	39	--	43	32	32
Prospect Springs	--	--	--	A	A	--	A	I	I	--	I	I	58	59	60	59	--	--	--	I	I	I
Reservoir (Bath) Springs	--	--	--	--	--	--	--	A	A	63	56	53	53	53	51	60	--	23	48	--	32	27
Roadside Spring	--	--	--	--	--	--	--	--	73	72	--	I	68	68	71	--	--	--	--	--	I	I
Soda Spring (Squirrel Springs Group)	--	--	--	--	--	--	--	--	--	--	--	--	--	--	42	--	--	--	--	57	57	56
Soda Spring	--	--	--	--	38	--	32	--	--	A	31	35	51	41	31	34	A	39	--	32	33	32
Squirrel Springs	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	62	64	71
Sulfur Spring	--	--	--	--	49	--	49	--	--	A	33	33	49	32	28	31	A	29	--	A	A	A
Tangerine (Little Orange) Spring	--	--	--	--	--	--	--	--	--	--	--	59	64	63	63	61	--	--	--	--	61	A
Trail Springs	--	--	--	--	--	--	--	--	--	--	--	75	73	75	70	74	--	53	A	--	--	A
White Elephant Back Springs	--	--	--	--	70	--	66	56	57	--	62	61	63	63	64	66	--	57	--	66	57	69
References	55	65	57 60	56 59	57 58	60 61	61 87	63 64	65	66 67 83	67	68	70	71	72 74	73 74 88	77	75– 77	78– 80	81 82 85 86	84 84– 86	86

1. Hayden (1872)
2. Peale (1872)
3. Peale (1873)
4. Peale (1883)
5. Wingate (1886)
6. Gooch and Whitfield (1888)
7. Weed (1889)
8. Guptill (1890)
9. Schlundt and Moore (1909)
10. U.S. National Park Service (1916)
11. Albright (1924a)
12. Albright (1924b)
13. Van Orstrand (1924)
14. Lindsley (1928a)
15. Lindsley (1928b)
16. Lindsley (1928c)
17. Lindsley (1928d)
18. Arnold (1928a)
19. Jones (1928)
20. Arnold (1928b)
21. Joyner (1928a)
22. Yeager (1929a)
23. Joyner (1929a)
24. Yeager (1929b)
25. Joyner (1929b)
26. Joyner (1929c)
27. N. F. Joyner (1929, unpub. data)
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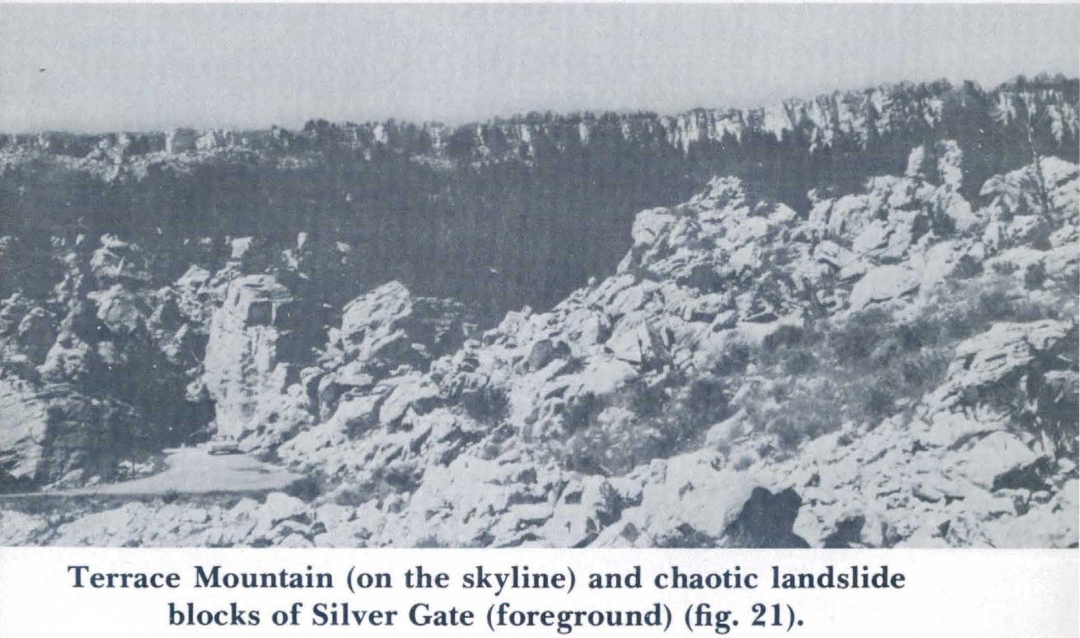
38. Crowe (1933)
39. W. B. McDougall (1934, unpub. data)
40. Allen and Day (1935)
41. J. W. Emmert (1935, unpub. data)
42. Bauer (1936)
43. G. D. Marler (1938, unpub. data)
44. Schlundt and Breckenridge (1938)
45. Brady (1939)
46. Condon (1939)
47. Oberhansley (1939)
48. C. M. Bauer (1946, unpub. data)
49. D. D. Condon (1946, unpub. data)
50. Ericson (1946)
51. D. E. White (1947, unpub. data)
52. Ericson (1948)
53. Rentchler (1948)
54. Alleman (1949)
55. Alleman (1950)
56. C. C. Alleman (1954, unpub. data)
57. Condon (1955)
58. C. C. Alleman (1955, unpub. data)
59. White, Brannock, and Murata (1956)
60. Alleman (1957a)
61. Alleman (1957b)
62. C. C. Alleman (1957, unpub. data)
63. Condon (1958)
64. C. C. Alleman (1958, unpub. data)
65. C. C. Alleman (1959, unpub. data)
66. C. C. Alleman (1960, unpub. data)
67. C. C. Alleman (1961, unpub. data)
68. Unpub. Naturalist Reports (1962)
69. D. P. Merrill (1963, unpub. data)
70. Unpub. Naturalists' Reports (1963)
71. Unpub. Naturalists' Reports (1964)
72. Unpub. Naturalists' Reports (1965)
73. Unpub. Naturalists' Reports (1966)
74. Friedman (1970)
75. G. T. Morrison (1970a, unpub. data)
76. G. T. Morrison (1970b, unpub. data)
77. R. C. Townsend (1970, unpub. data)
78. Follett and Schroeder (1971, unpub. data)
79. G. T. Morrison (1971, unpub. data)
80. J. J. Whitman and Downing (1971, unpub. data)
81. Follett (1971, unpub. data)
82. Milliken and J. J. Whitman (1971, unpub. data)
83. Rowe, Fournier, and Morey (1973)
84. J. J. Whitman (1973, unpub. data)
85. Thompson, Presser, Barnes, and Baird (1975)
86. K. E. Bargar and L. J. P. Muffler (1972–1974, unpub. data)
87. D. E. White (1957, unpub. data)
88. R. O. Fournier (1966, unpub. data)

Recorded history and temperatures of unnamed thermal springs at Mammoth Hot Springs, 1954–1974 (table 6)

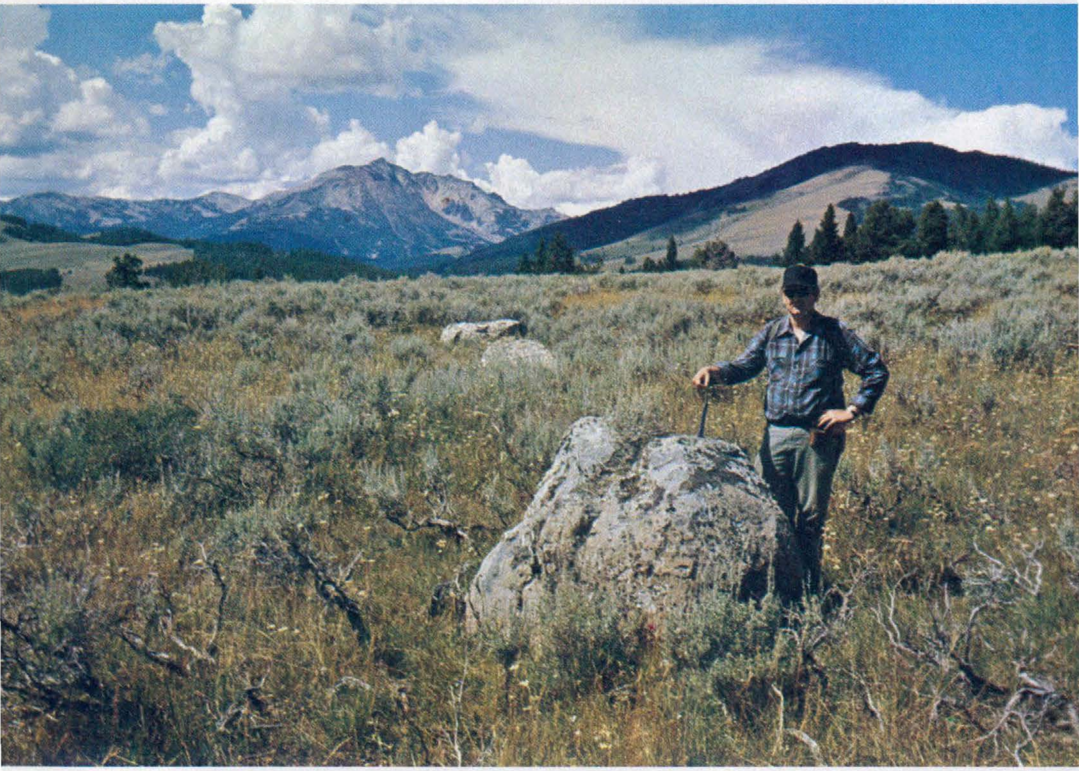
[See table 5 for explanation of symbols and reference list]

Spring No.	1954	1959	1962	1963	1964	1965	1966	1969	1970	1971	1972	1973	1974
MHS–1	--	--	--	--	--	--	--	--	--	--	--	--	46
MHS–2	--	--	56	--	--	--	--	--	--	--	--	--	53
MHS–3	--	--	--	--	--	--	--	--	68	--	--	70	67
MHS–4	--	--	--	68	64	I	I	--	--	--	--	--	65
MHS–5	--	--	--	--	--	--	--	--	--	--	--	29	26
MHS–6	--	--	--	--	--	--	--	--	--	--	72	59	I
MHS–7	--	--	I	I	72	68	64	--	--	--	I	A	A
MHS–8	--	--	I	I	68	63	64	--	--	--	--	52	58
MHS–9	--	--	--	60	62	61	60	--	--	--	I	I	A
MHS–10	--	--	--	--	--	--	--	--	--	--	I	60	68
MHS–11	--	--	--	--	--	--	--	--	--	--	I	I	67
MHS–12	--	--	--	--	--	--	--	--	--	--	74	69	68
MHS–13	A	A	71	75	72	72	74	A	A	--	I	73	61
MHS–14	--	--	--	--	--	--	--	--	--	--	--	--	62
MHS–15	--	--	--	--	--	--	--	--	--	--	55	--	59
MHS–16	--	--	--	--	--	--	--	--	--	--	51	--	51
MHS–17	--	--	--	--	--	--	--	--	--	--	60	--	I
MHS–18	--	--	--	--	--	--	--	--	--	--	--	67	64
MHS–19	--	--	--	--	--	--	--	--	--	--	71	--	69
MHS–20	--	--	I	57	58	53	49	--	51	46	47	45	42
MHS–21	--	--	--	--	--	--	--	--	--	--	63	58	56
MHS–22	--	--	--	--	--	--	--	--	--	--	--	18	39
MHS–23	--	--	--	--	--	--	--	--	--	--	38	--	35
MHS–24	--	--	--	--	--	--	--	--	--	--	--	68	70
MHS–25	--	--	--	--	--	--	--	--	--	--	--	--	50
MHS–26	--	--	--	--	--	--	--	--	--	--	53	--	55
MHS–27	--	--	--	--	--	--	--	--	--	--	--	54	50
MHS–28	--	--	--	--	--	--	--	--	--	--	--	50	44
MHS–29	--	--	--	--	--	--	--	--	--	--	59	61	61
MHS–30	--	--	--	--	--	--	--	--	--	--	65	66	65
MHS–31	--	--	--	--	--	--	--	--	--	--	A	A	40
References	56,59	65	68	70	71	72,74	73,74	77	75,76 77	78,79 80	81,82 86	84,86	86



Terrace Mountain (on the skyline) and chaotic landslide blocks of Silver Gate (foreground) (fig. 21).

recent age determination, based upon thorium-uranium isotope ratios, yielded a date of 63,000±9,000 years for travertine from Terrace Mountain (Rosholt, 1976). The latter date is in good agreement with the geologic evidence, in that Terrace Mountain is clearly older than the Pinedale glacial deposits (10,000–50,000 years ago) that mantle it (fig. 22). In any case, both lines of evidence point to the fact that the hot springs that deposited the travertine have been inactive for many thousands of years.



Boulders on top of Terrace Mountain (fig. 22). Boulders were deposited by a glacier of Pinedale age. (Photograph courtesy of L. J. P. Muffler, U.S. Geological Survey.)

Pinyon Terrace

The remainder of the travertine deposits, which extend continuously from Pinyon Terrace to the Gardner River, as well as a few scattered outcrops found in Snow Pass and near the Sheepeater Canyon Bridge (fig. 2), are all younger than Pinedale age (Allen and Day, 1935). Young, horizontally bedded travertine deposited on top of Pinedale glacial deposits can be seen along part of the north-south tensional fracture near the east edge of Pinyon Terrace (a small section of the fracture is shown in the lower left corner of pl. 1).

The only record of hot-spring activity on the densely forested Pinyon Terrace is a spring (with a temperature of 41.8°C in 1925) labeled simply Pinyon Terrace in Allen and Day's (1935) table of hot-spring temperatures for Mammoth Hot Springs. They also mention "a few oozing springs" (presumably cold) but do not indicate the location of any of the springs.

There are no active hot springs on this terrace now. However, hot gases escape through underground channels near the east edge of the terrace, and acid alteration is in progress there (near the vapor vent in southwest corner of area shown on pl. 1). Native sulfur (S) and gypsum ($CaSO_4 \cdot 2H_2O$) are precipitated there as a result of *fumarole* activity. Vapor vents are quite common on the travertine terraces; however, acid-altered areas occur at only a few locations (Bargar and Muffler, 1975) where the hot vapors contain enough hydrogen sulfide to form gypsum and sulfur deposits.

Old terraces between Hotel Terrace and the Gardner River

The region of major hot-spring activity is between Pinyon Terrace and Hotel Terrace; the area between Hotel Terrace and the Gardner River has few thermal springs (pl. 1). One spring with a very large rate of discharge is the source of Hot River, which emerges from beneath an old, partly collapsed travertine ledge near the level of the Gardner River (fig. 23). The discharge channel is about 2.7 m wide and 0.6 m deep, and the stream flows for about 130 m before emptying into the river. Its undergound route can be followed upstream for an additional 140 m

Hot River (fig. 23). Hot carbonated spring water undercut the old horizontally bedded travertine deposits until individual blocks collapsed under their own weight. Direction of flow is toward viewer.

through a series of collapse features (pl. 1), one of which (MHS–1) contains visible flowing water.

The spring which feeds Hot River has the greatest discharge of any hot spring in Yellowstone National Park. Several discharge measurements reported by Allen and Day (1935) show that the flow of Hot River ranges from about 33 to 40 m^3/min, with the average flow being slightly greater than 38 m^3/min. A more recent measurement by R. O. Fournier and D. E. White (U.S. Geol. Survey, 1967) is about 41 m^3/min. Much of the flow of this thermal spring probably consists of water that previously issued from other hot springs and trickled down into underground channels feeding Hot River. Allen and Day also suggest that the variation in temperature of Hot River at different times of the year may be caused by dilution with cold meteoric water.

Derivation of the name Hot River is uncertain; however, H. M. Majors III (unpub. data, 1962) indicates that the name probably originated with a group of U.S. Geological

Survey scientists, headed by Arnold Hague, who studied the geology of Yellowstone Park in the 1880's. Hot River has also been called "Boiling River" (H. M. Majors III, unpub. data, 1962), "Warm-Stream Creek," and "Chestnutville" (Haines, 1974).[5]

Early maps of Mammoth Hot Springs (Hayden, 1872; 1883) show three or four hot springs (temperatures less than 49°C) near the level of the Gardner River 100 m or so upstream from Hot River and two thermal spring areas (temperatures about 60°C) between the base of Hotel Terrace and the road to Gardiner. The only subsequent reference to hot-spring activity at either location was Majors' (unpub. data, 1962) description of a spring on the riverbank about 100 m above Hot River. In May 1974, one small spring (MHS–2) was found near the location Majors described, but there were only a few vapor vents between Hotel Terrace and the road to Gardiner (pl. 1).

Hotel Terrace

The only recognizable hot-spring orifice on Hotel Terrace is the defunct fissure ridge on the east edge of the terrace (pl. 1). No hot-spring activity has ever been recorded on this terrace, but two vapor vents can often be seen on cold mornings.

An age determination by Prof. Herman Schlundt (reported in Bauer, 1933) indicates that the travertine of Hotel Terrace was deposited about 3,200 years ago. This age and the one for Liberty Cap are not regarded as numerically accurate but are probably of the right order of magnitude.

Hymen Terrace

Hymen Terrace is a small inactive terrace at the southwest edge of Hotel Terrace. An extinct hot-spring cone,

[5]According to Majors (unpub. data, 1962), many of the thermal features at Mammoth were named by members of the Hague expedition or by early visitors and residents of the area, and several of the hot springs and terraces have borne more than one name, as did Hot River.

about 14 m high and 6 m in diameter at the base (Allen and Day, 1935; H. M. Majors III, unpub. data, 1962), dominates the setting of Hymen Terrace (fig. 8). Indeed, this long-dead hot-spring orifice, named Liberty Cap by the 1871 Hayden expedition (Hayden, 1872), reigns supreme over the entire Mammoth Hot Springs Landscape.[6]

Hymen Springs, inactive since about 1936 (C. M. Bauer, unpub. data, 1946) was evidently a major attraction on Hymen Terrace from the time of the earliest recorded observation in 1870 (Peale, 1883) until the 1930's. In recent years, the only active thermal spring on this terrace (Roadside Spring) was located near the north end of the Liberty Cap parking lot (C. C. Alleman, unpub. data, 1962); however, its vent is not discernible at the present time.

Opal Terrace

Opal Spring and Terrace lie at the base of Capitol Hill just across the Grand Loop Road east of Liberty Cap (pl. 1). Evidently Opal Spring was inactive at the time of the Hayden Survey; however, Crowe (1933) indicated that it may have been active during the early 1890's. After being dormant for a number of years, Opal Spring began flowing again in about 1926 (D. P. Merrill, unpub. data, 1963) and has remained intermittently active to the present time.

During the 1940's, travertine deposited by Opal Spring began encroaching upon a tennis court in the northern part of the terrace. The spring eventually won the battle for space. In 1947 the tennis court was removed in compliance with the park's policy of not interferring with natural processes (J. S. Desanto, unpub. data, 1962).

Two small hot springs on Opal Terrace were active in 1974 (pl. 1). Spring MHS–3 began flowing about 1970 (G. T. Morrison, unpub. data, 1970), and spring MHS–4 has apparently been intermittently active since 1963 (W. R. Phillips, unpub. data, 1963). A third spring (MHS–5), situated on the grassy bank south of Opal Terrace, is

[6]According to Schlundt's age dating, Liberty Cap was formed about 2,500 years ago (reported in Bauer, 1933).

merely a warm seep with very little flow; however, travertine is being deposited along its runoff channels.

Palette Terrace

The two principal hot springs on Palette Terrace are Palette Spring (also known as Old Palette Spring) and New Palette Spring (sometimes referred to as Palette Extension). Palette Spring has been intermittently active at least since 1878 (Hayden, 1883), while the recorded activity of New Palette Spring dates back to about 1944 (D. P. Merrill, unpub. data, 1963).

Hot-spring activity occurs at three other locations on or near Palette Terrace. Spring MHS–6, situated at the base of the terrace below New Palette Spring, discharged a minor amount of hot water in 1972 and 1973 but was dormant in May 1974. The other two springs (MHS–7 and –8) apparently have had recurrent activity since 1964 (W. R. Phillips, unpub. data, 1964).

Cavern and Reservoir Springs

Cavern and Reservoir Springs lie southeast of and at or slightly below the level of Palette Terrace (pl. 1). Cavern Spring's recorded activity dates back to 1955; however, this spring probably discharged for some time prior to 1955. Condon (1955) indicated that the large cavern (evidently the source of the name Cavern Spring) previously located here was nearly sealed by travertine deposition.

Reservoir Springs have been intermittently active since the days of the Hayden Survey. Originally these springs were named Bath Springs because the tepid water was channeled into nearby bath houses (Peale, 1883).

Peale (1883) provided the only record of a hot spring known as Little Joker, which apparently was located east of the Grand Loop Road across from spring MHS–6. On the west side of the road, a spring called Fan or Little Spouter evidently was active between 1961 and 1973; however, this spring was not found in May 1974. C. C. Alleman (unpub. data, 1961) indicated that the spring was about halfway between Cavern and Reservoir Springs, and J. J. Whitman (unpub. data, 1973) placed it directly east of Cavern Spring.

Minerva Terrace

Minerva Terrace contains two currently active hot springs. Minerva Spring (fig. 9), originally named Cleopatra (Hayden, 1883), issues from a fissure ridge (see pl. 1) and is depositing a well-developed series of terracettes. Although dormant for short periods of time (N. W. Scherer, unpub. data, 1932; G. C. Crowe, unpub. data, 1932), Minerva has discharged almost continuously since the days of the first Hayden expedition and has been one of the most colorful and popular attractions at Mammoth Hot Springs.

The spring now named Cleopatra has been active at least since 1906 (Schlundt and Moore, 1909) and was originally called Diana Spring (a name that apparently persisted until sometime in the 1920's). According to D. P. Merrill (unpub. data, 1969), Cleopatra was one of the most active and popular springs at Mammoth during the 1930's; however, since the 1940's, this spring has been characterized by only minor intermittent discharge.

Main Terrace

Main Terrace (fig. 3) contains some of the largest and most consistently active hot springs at Mammoth, including Blue, Canary, Jupiter, Main, Naiad, New Blue, and Trail Springs. Large amounts of water discharging from these springs and the colorful algae living in the hot springs and their runoff channels have made this terrace an outstanding attraction since the days of the Hayden Survey.

Hayden's (1872) first map of Mammoth Hot Springs shows a thermal spring named Blue Spring[7] near the northwest corner of Main Terrace. Apparently when the

[7]Blue Spring was named for the apparent blue color of the water; however, it should be pointed out that the water is clear rather than blue. This spring and a few other deep thermal pools at Mammoth only appear blue because of scattering and absorption of light rays (Allen and Day, 1935).

spring ceased flowing, the name "Blue Springs" was given to the hot springs that subsequently appeared near the center of the terrace (Weed, 1889). Later renewal of discharge near the former site of Blue Spring led to the name New Blue Springs, which has been retained to the present time. Schlundt and Moore (1909) indicated that both springs were active in 1906; however, very little information on the activity of New Blue Springs was found except for recent years. On the other hand, several observations through the years suggest that Blue Springs have been characterized by persistently recurrent discharge.

The southwest corner of Main Terrace is the site of relatively recent (since 1962) thermal activity originating from a group of hot springs collectively known as Trail Springs (evidently from their position near the old trail in that part of the terrace). The volume of water discharging from these springs has varied considerably. In 1971, the flow from Trail Springs covered nearly an acre (G. T. Morrison, unpub. data, 1971), whereas in May 1974, there was only minor discharge from a single vent.

Mound, Pulpit, and Jupiter (Marble) Terraces top the steep scarp along the eastern face of Main Terrace. Algae living in the fluctuating runoff channels of Canary, Main, Jupiter, and Naiad Springs usually decorate parts of these slopes with an array of splendid colors. As the runoff channels change course along the face of the terraces, the algae die and the dry travertine deposits soon become white and then dingy gray.

Canary Spring, near the southeast corner of Main Terrace (fig. 3) has had intermittent discharge since the 1870's (table 5). Originally called "Sulphur Spring" (Hayden, 1883), this hot spring probably owes both names to filamentous sulfur-depositing bacteria commonly found growing in the waters of some thermal springs.

The two large depressions near the east edge of Main Terrace (pl. 1) were named Main Springs by the first Hayden expedition because that was the site of the principal hot-spring activity at that time (Hayden, 1872). Through the years, the two pits have been alternately full and empty (table 5). In 1972, the larger of the two was filled with hot water (fig. 3) but was dry again in May 1974.

Mound Terrace, in the northeast corner of Main Terrace, is a fissure-ridge deposit. The line of hot springs along the southern part of the fissure, called Jupiter Springs, evidently has been intermittently active since the 1870's. Naiad Spring, perched on the eastern face of Mound Terrace and apparently having a subterranean channel independent of the fissure ridge, has had recurrent discharge since at least 1878.

Prospect Terrace

Prospect Terrace (fig. 3), an old travertine terrace with only minor recorded hot-spring activity, probably was named for the scenic view of the lower terraces from a section of its eastern rim called The Esplanade (H. M. Majors III, unpub. data, 1962) (pl. 1). The part of the rim that protrudes peninsulalike out over Main Terrace is an old defunct hot-spring deposit, named Fissure Ridge by the Hayden Survey (Hayden, 1883). The only record of thermal activity on this ridge is Peale's (1872) observation that the fissure, extending along the entire length of the rounded linear mound, was lined with sulfur crystals deposited by vapor escaping from the gurgling waters far below.

Cupid Spring, in the notch between Fissure Ridge and the mass of Prospect Terrace (fig. 10), has a recorded history of fluctuating but nearly continuous discharge since about 1931, when the spring deposits began sealing a cave called Cupid's Cave (W. B. McDougall, unpub. data, 1931). The only other prior records of hot-spring activity at this location describe geyserlike discharge, in which two small springs intermittently spurted hot water to a height of about 1 m (Peale, 1872). There are no true geysers at Mammoth Hot Springs; however, if gas comes out of solution in sufficient volume and rate, the water can be ejected to a height of several centimeters or more.

A vapor vent located just across the Terrace Loop Road west of Cupid Spring marks the former site of Baby Spring (pl. 1). This hot spring, possibly named for its small size, was intermittently active during the years 1932–65 (table 5). Three other currently active hot springs on Prospect Terrace are Prospect Springs (intermittently active since about 1954 (C. C. Alleman, unpub. data, 1954)), spring MHS–9 (having recurrent discharge since about 1963 (unpublished data from the naturalists' files)), and spring MHS–10 (minor flow in 1973 and 1974).

Narrow Gauge Springs and Cheops Mound

One of the best examples of an active fissure ridge is Narrow Gauge Springs (fig. 24), which apparently was named for the ridge's resemblance to an old-time narrow-gauge railroad track bed (H. M. Majors III, unpub. data, 1962). Narrow Gauge Springs, intermittently active since about 1890 (Guptill, 1890), may have had its greatest recorded activity in the late 1920's, when Joyner

Narrow Gauge Terrace (fig. 24). This feature is a fissure ridge that is intermittently active (table 5).

(1928c) counted 180 hot springs and 70 vapor vents along the top of the ridge.

Cheops Mound, another fissure ridge located just south of Narrow Gauge Terrace, has no recorded activity; however, it is shown as a hot spring on one of the old maps of Mammoth Hot Springs (Hague, 1904). The north side of the mound has an excellent series of well-preserved old terracette deposits.

Angel Terrace and Glen Springs

Angel Terrace, intermittently active from the 1870's until about 1953 (table 5), was periodically a very popular attraction when large volumes of water inundated the terraces, allowing the colorful algae to grow profusely. In fact, H. M. Majors III (unpub. data, 1962) indicated that this terrace was apparently named for the delicate, celestial imagery of the pink microorganisms that lived in the hot springs and runoff areas.

One of the smaller active fissure-ridge formations, named Glen Springs, lies in a hollow between two older nearly parallel fissure ridges just north of Angel Terrace (fig. 17). This spring is somewhat hidden from view, which may account for the scanty record of its activity; however, the available data (table 5) suggest that Glen Springs has been intermittently active since the 1870's.

Highland Terrace area

The Highland Terrace area, as defined by Peale (1883) and later by G. D. Marler (unpub. data, 1961), includes all the travertine deposits in the southwestern part of the area shown on plate 1. The northeastern part of this area is known as Highland Terrace. No hot-spring activity has been recorded on the old fissure ridge called The Buttress. New Highland Springs have been intermittently active since at least 1928 (Arnold, 1928b), and from the late 1950's to the present this group of springs has been one of the most spectacular areas at Mammoth.

Highland Spring was intermittently active from 1871 until about 1970 (table 5). The remaining springs on Highland Terrace proper (Cedar Tree Spring and springs MHS–11, –12, and –13) all have very short records of activity (tables 5, 6). Spring MHS–11 currently discharges only a trickle of water from a few vents along a rather small, slightly rounded fissure ridge, whereas the rate of flow of the other three springs has ranged from less than 4 L/min to about 40 – 80 L/min during the years of observation (1972–74).

Several of the remaining hot springs in the Highland Terrace area are small pools ranging from a meter to about 50 m in diameter. Bath Lake, the largest of the pools, has completely dried up at least twice during its recorded history, once during the 1920's (Arnold, 1928b) and again in the 1950's (G. D. Marler, unpub. data, 1961). The supply of hot water that feeds Bath Lake began flowing again after the 1959 Hebgen Lake earthquake; the earthquake is not known to have been directly responsible (G. D. Marler, unpub. data, 1962).[8]

Evidently the name Bath Lake originates from this warm pool's early popularity as a bathing spot (H. M. Majors III, unpub. data, 1962). Early tourists who swam in Bath Lake probably viewed the experience with mixed emotions: Wingate (1886) indicated that, although he enjoyed the warm soothing water, his skin became encrusted with calcium carbonate to the extent that his body appeared to be whitewashed.

Another hot-spring pool, about 25–28 m in diameter and known as Painted Pool, is located just south of Bath Lake (pl. 1). Apparently the name Painted Pool was originally given to a smaller pool (Hague, 1904; now MHS–18), but probably when the small pool became dormant, the name was switched.

Several additional small pools, most of which are unnamed (pl. 1), occur in the Highland Terrace area; the

[8] In the past, numerous earthquakes have been felt at Mammoth Hot Springs, some of which caused landslides at Golden Gate and structural damage to roads and buildings in the area (Fischer, 1971). While such disturbances in the Earth's crust probably caused changes in hot-spring activity at Mammoth, few such changes have been recorded, perhaps because the thermal-spring activity is so variable.

only named pools are Sulfur Spring, Soda Spring, and Poison Spring. The exact location of Sulfur Spring, which first appears on the 1871 map of Hayden (1872), is uncertain, but the spring with this name on plate 1 is in a strongly acid-altered area that contains gypsum and sulfur (Bargar and Muffler, 1975).

The name Soda Spring has at various times been applied to at least three springs, most often to a warm spring in a grassy area about 180 m west of Painted Pool (pl. 1). However, a cold spring in Snow Pass (fig. 2) and the spring in a marshy area 30 m north of Squirrel Springs also have had this name (Gooch and Whitfield, 1888; Allen and Day, 1935).

Poison Spring, located about 150 m southwest of

Spring MHS–24 (fig. 25). Pencil above small stick (circled) protruding from lower part of deposit is about 15 cm long. When first observed in September 1972, the height of the spring was exactly equal to the level of the stick. In September 1973, the cone was about 74 cm high, and by the following May, the date of this photograph, it had grown to a height of nearly 94 cm. Reddish-brown color is due to algae. Yellowish fibrous material surrounding the orifice of the spring is bacteria.

Painted Pool (pl. 1), has a cavelike cavity at its southern terminus. W. R. Phillips (unpub. data, 1962) indicated that numerous birds have been asphyxiated by carbon dioxide gas in the cave.

One of the few active isolated cone-type hot springs (spring MHS–24, fig. 25) occurs about 30 m southwest of Poison Spring. This spring is particularly notable as representing an early stage in the development of a cone such as Liberty Cap (fig. 8).

The Highland Terrace area also contains several active and numerous inactive fissure ridges. Devil's Kitchen Springs, Orange Spring Mound (including Tangerine Spring) (fig. 16), Squirrel Springs, and White Elephant Back Springs and Terrace (figs. 13, 18) have all been intermittently active since the 1870's.

Summary

Thermal water is heated by partly molten magma in a fault zone under the Norris-Mammoth corridor. During transport along the fault, the water is enriched in calcium and bicarbonate, the two ingredients necessary for the formation of travertine.

The trend of White Elephant Back Terrace and the tension fractures to the southwest of this fissure ridge suggest that the thermal water moves up through the old terrace deposits along preexisting vertical linear planes of weakness. As the water reaches the surface, pressure is released, carbon dioxide escapes as a gas, and bicarbonate in the water is partitioned into more carbon dioxide and carbonate; the carbonate then combines with calcium to precipitate calcium carbonate, forming travertine. Most travertine has precipitated rapidly from solution and is lightweight and porous; however, a few fissure ridges contain denser, vertically banded travertine layers that line the fissure. These vertical bands were apparently deposited over a long period of time. Dense travertine also forms beneath the surface of the terraces by deposition in the pore spaces of older deposits.

Some hot springs are pools with little or no deposition of travertine, whereas others form magnificent arrays of terracettes, cone-shaped deposits, or linear mounds called fissure ridges. Minerva Spring consists of an intricate collection of terracette deposits that are greatly enhanced by variegated algal growth. Terracette deposits of New Highland Springs occur as spectacular overhanging ledges. A few hot-spring cones are active on the upper terraces, but the best example of this type of deposit is the long-inactive Liberty Cap. Fissure ridges occur in numerous sizes and shapes. In some places water from new hot-spring activity becomes ponded behind fissure-ridge barriers or dams, with the result that travertine deposits eventually form large flat terraces.

Sporadic records of hot-spring activity at Mammoth suggest that most springs have been intermittently active at least since 1871. Another characteristic of the hot springs is the colorful algae and bacteria that thrive in the thermal springs and their discharge areas. When discharge of a hot spring ceases, the microorganisms die and the travertine deposits become white and then dingy gray. With the passage of time, the surface travertine deposits develop a loose soil capable of supporting the growth of small plants and eventually large trees, such as occur on Pinyon Terrace.

Glossary

Aquifer. Body of rock containing substantial water in its fractures and open spaces.

Artesian pressure. Pressure exerted by the weight of a vertical column of water extending up to the surface of the water table.

Caldera. Large depression, commonly many kilometers in diameter, formed by collapse of the ground surface after violent eruption of gas-charged volcanic rocks; near-surface ground collapses into the space vacated by the erupted rock.

Extrusive rocks. Rocks originating from volcanic activity.

Fissure ridges. Linear mounds of travertine deposited from hot-spring vents along a medial fracture zone that may be partly concealed under the travertine.

Fissure ridges range in height from 1 to 6 m and in length from a few meters to nearly 300 m; width at the base of a ridge is equal to or greater than its height. The term fissure ridge was first used by Hayden (1883) to describe the travertine ridge at the east edge of Prospect Terrace.

Fumarole. A vent from which vapors are emitted.

Intrusive rocks. Rocks formed from magma that moved from its place of origin but solidified before reaching the surface.

Isotopic. Pertaining to isotopes, which are different species of the same chemical element that differ in atomic weight.

Magma. Molten rock contained in a magma chamber.

Magma chamber. A reservoir of molten rock that supplies the material composing volcanic rock on the Earth's surface.

Orogeny. Process of mountain building.

Terracettes. Semicircular travertine ledges formed by deposition of travertine around slowly rising pools; usually are from about 0.3 to as much as 2.5 m wide.

Travertine. Calcium carbonate ($CaCO_3$) precipitated from hot-spring waters.

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