GEOTHERMAL SYSTEMS OF THE YELLOWSTONE CALDERA

FIELD TRIP GUIDE

Duncan Foley
Dennis L. Neilson
Clayton R. Nichols

Work performed under contract number DE-AC07-80ID12079

EARTH SCIENCE LABORATORY
University of Utah Research Institute
Salt Lake City, Utah

Prepared for
U.S. Department of Energy
Division of Geothermal Energy

DISCLAIMER

GEOTHERMAL SYSTEMS OF THE YELLOWSTONE CALDERA

GEOTHERMAL RESOURCES COUNCIL
September 6, 7, 8, 1980

Field Trip Guide

Duncan Foley[1]
Dennis L. Nielson[1]
Clayton R. Nichols[2]

[1]Earth Science Laboratory
University of Utah Research Institute
Salt Lake City, UT

[2]Department of Energy
Division of Geothermal Energy
Idaho Falls, ID

TABLE OF CONTENTS

TABLES

FIGURES

INTRODUCTION

The starting point for this road log is the west entrance to Yellowstone National Park. To reach the entrance from the West Yellowstone Airport, drive out of the airport, turn right (south) on Hwy. 287, and proceed to the stop sign near the old railroad station (which is now a museum). Turn left (east) at this intersection, and proceed to the entrance. Daily routes and stops are outlined in Figure 1.

Geothermal studies are proceeding on two fronts in the West Yellowstone area. High-temperature resources for the generation of electricity are being sought in the Island Park area, and lower temperature resources for direct applications, primarily space heating, are being explored for near the town of West Yellowstone.

Potential electric geothermal development in the Island Park area has been the subject of widespread publicity over fears of damage to thermal features in Yellowstone Park. At the time of writing this guide (June, 1980), companies have applied for geothermal leases in the Island Park area, but these leases have not yet been granted by the U. S. Forest Service. The Senate is now discussing a bill that would regulate geothermal development in Island Park; outcome of this debate will determine the course of action on the lease applications.

The Island Park area was the site of two cycles of caldera activity, with major eruptions at 2.0 and 1.2 million years ago. The U.S. Geological Survey (Smith and others, 1978) estimates that 16,850 x 10^{18} joules of energy may remain in the system.

Geothermal resources suitable for direct applications are being sought in the West Yellowstone vicinity by the Montana Bureau of Mines and Geology, under funding from the U. S. Department of Energy. West Yellowstone has a mean annual temperature of 1-2°C. Research thus far suggests that basement rocks in the vicinity are at a depth of about 600 m and are probably similar to the rocks exposed north of Hebgen Lake, where Precambrian, Paleozoic and Mesozoic rocks have been mapped. A few sites with anomalously warm water have been identified near the town. Work is continuing on this project.

Our first stop will be at Virginia Cascades, about 30 miles east of the park entrance. Along this drive, there will be time to look at The Geologic Story of Yellowstone National Park (Keefer, 1971) and the geologic map of the park (U.S.G.S., 1972a), which are contained in this packet. A few copies of the surficial geologic map (U.S.G.S., 1972b) are also available for viewing. An article on the volcanic evolution of Yellowstone (Christiansen, unpub.) is in your packet. Geophysical data and interpretations for the Yellowstone area are presented in the report from Scientific American (Smith and Christiansen, 1980), which is also contained in your packet.

The road log is adapted primarily from U. S. Geological Survey Geologic and Surficial Geologic quadrangle mapping. Lithologic and outcrop descriptions have been drawn from these maps. To avoid repetitious citation of sources, Table 1 has been included in this log to allow readers to consult the original sources. Quotations not from map texts are referenced in the traditional manner.

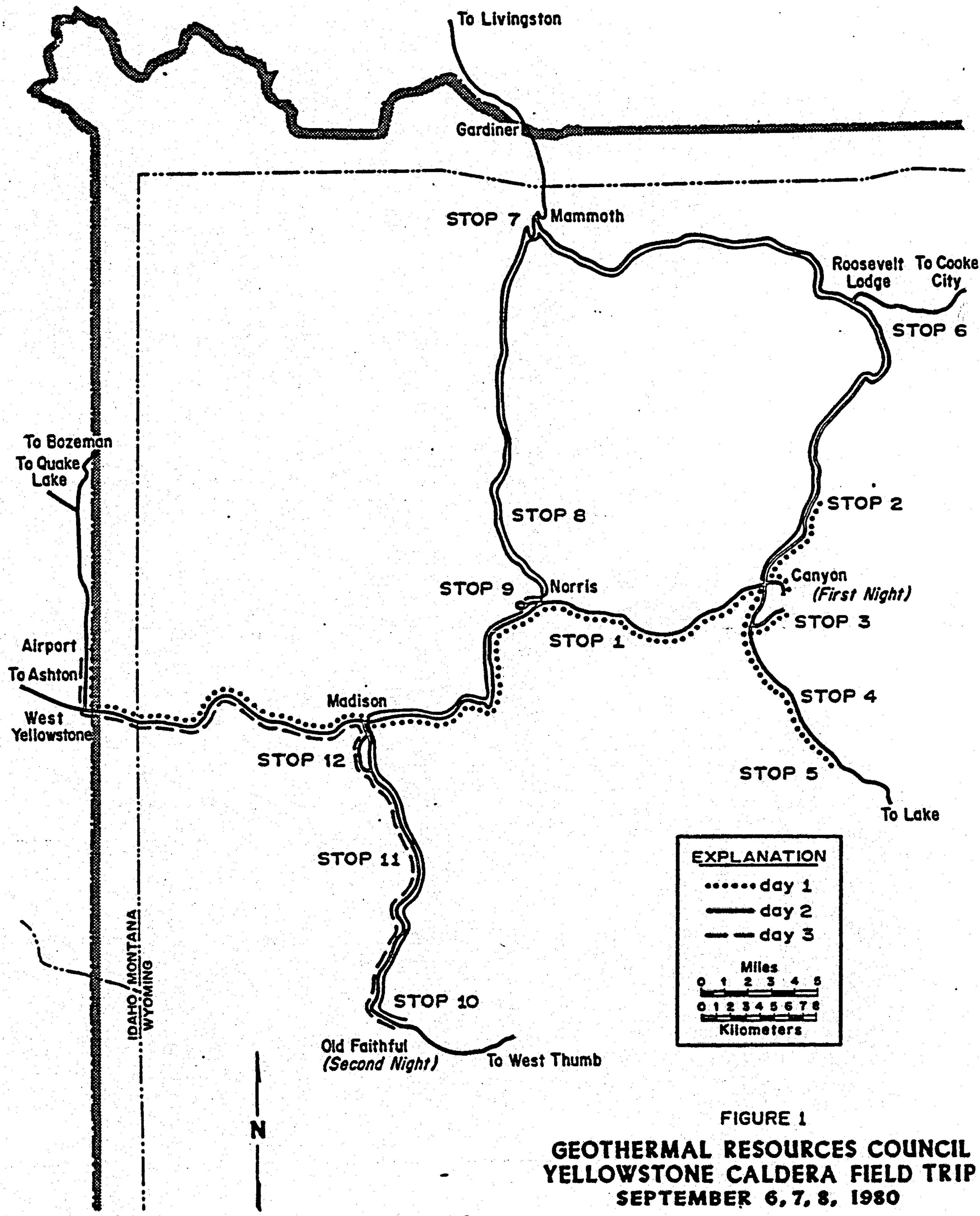


FIGURE 1

GEOTHERMAL RESOURCES COUNCIL
YELLOWSTONE CALDERA FIELD TRIP
SEPTEMBER 6, 7, 8, 1980

TABLE 1

Geologic and Surficial Geologic Map References

MILES	QUADRANGLE NAME	BEDROCK	SURFICIAL
all	---	USGS 1972a	USGS 1972b
Day 1			
0.0-4.1	West Yellowstone	---	Waldrop, 1975a
6.0-19.4	Madison Junction	Christiansen and Blank, 1974a	Waldrop and Pierce, 1975
20.7-38.4	Norris Junction	Christiansen, 1975	Richmond and Waldrop, 1975
39.4-40.4	Canyon Village	Christiansen and Blank, 1975	Richmond, 1977
41.0-48.0	Tower Junction	Prostka and others, 1975	Pierce, 1974
49.4-72.6	Canyon Village	see above	see above
Day 2			
5-24.0	Tower Junction	see above	see above
24.0-55.2	Mammoth	---	Pierce, 1973
59.3-67.1	Norris Junction	see above	see above
68.4-86.9	Madison Junction	see above	see above
86.9-89.7	Old Faithful	Christiansen and Blank, 1974b	Waldrop 1975b
Day 3			
0-2.9	Old Faithful	see above	see above
2.9-27.8	Madison Junction	see above	see above
27.8-33.8	West Yellowstone	---	see above

Potassium-Argon dates reported in this guide were calculated using pre-1977 decay constants. To compare with more recent dating, multiply the dates given herein by 1.025.

Glacial activity has been separated into Bull Lake and Pinedale times. Estimates for the ages of the ice are given in Table 2.

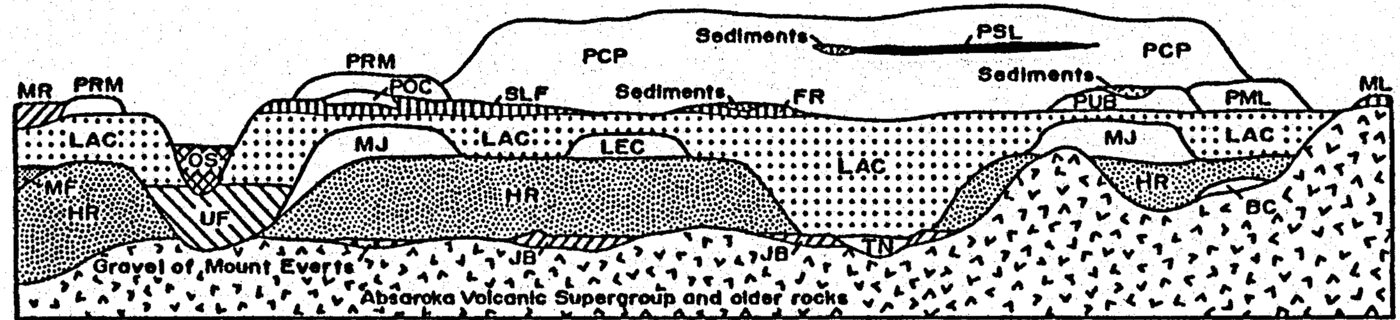
DAY 1 - WEST YELLOWSTONE TO CANYON

Distance	Cumulative Mileage	
0	0	Beginning at the west entrance to the Park, we drive across alluvial gravelly sand, deposited in the Pinedale-Bull Lake interglacial interval in the West Yellowstone Basin. The tremendous number of dead pine trees in this area is due to an infestation of the Mountain Pine Beetle, which kills the trees by cutting the circulation of sap. Many trees in the Island Park area to the south have been killed by the beetle, and the infestation is now moving northeast into Yellowstone National Park. Figure 2 illustrates the relations among the Quaternary volcanic units in the park. Although it is not comprehensive, the figure does illustrate some of the more important stratigraphic relations. More than 10,000 thermal features have been catalogued within Yellowstone Park. In addition to the heat phenomena associated with hot springs and geysers, the waters have a beneficial effect of increasing aquatic productivity. The Madison and Firehole rivers have some of the best trout fishing in the country. Many of the streams in the Park have normal productivity upstream from thermal features, but support a wider variety of aquatic life after the hot waters have mixed with the river waters. There are also a few sites where the opposite effect is true, thermal springs reduce stream productivity. Yellowstone is an area of general high elevation and high precipitation. This implies that, especially for areas to the west and south, it is an area of regional groundwater recharge.
2.2	2.2	The Madison River is visible on the north side of the highway. The river here flows along outwash sand and gravel from Pinedale glaciers. Pinedale outwash fans form the deposits away from the

TABLE 2

Age estimates for Glacial Activity in Yellowstone
(in thousands of years)

<table>
<tr><th></th><th>Keefer (1971)</th><th>Richmond (1976)</th><th>Pierce (1979)</th></tr>
<tr><td>Pinedale</td><td>25-8</td><td>70-12</td><td><70-13</td></tr>
<tr><td>Bull Lake, late stade</td><td rowspan="2">125-45</td><td>98-85</td><td rowspan="2">160-130(?)</td></tr>
<tr><td>Bull Lake, early stade</td><td>120-110</td></tr>
</table>



Second volcanic cycle
- MF Mesa Falls Tuff (1.2)

First volcanic cycle
- TN Sediments and basalts of The Narrows (1.6)
- LEC Lewis Canyon Rhyolite
- HR Huckleberry Ridge Tuff (2.0)
- BC Rhyolite of Broad Creek
- JB Junction Butte Basalt (2.0)

Third volcanic cycle
- PRM Roaring Mountain Member (0.4-0.075(?))
- PCP Central Plateau Member (0.2-0.07)
- PSL Shoshone Lake Tuff Member (0.18)
- POC Obsidian Creek Member
- PML Mallard Lake Member (0.6-0.53)
- PUB Upper Basin Member (0.6-0.53)
- OS Osprey Basalt
- MR Madison River Basalt
- SLF Swan Lake Flat Basalt
- FR Falls River Basalt
- ML Basalt of Mariposa Lake
- LAC Lava Creek Tuff (0.6)
- UF Undine Falls Basalt (<0.7)
- MJ Mount Jackson Rhyolite (0.79-0.64)

FIGURE 2. Diagrammatic relations among Quaternary volcanic units, Yellowstone National Park. Neither all stratigraphic units nor all possible stratigraphic relations are depicted. Numbers after units indicate approximate ages, in millions of years. Redrafted from Christiansen and Blank (1972), with modification of Christiansen and Blank (1974).

		river.
1.9	4.1	The roadbed is over an outcrop of Madison River basalt.
1.9	6.0	The low ridge on the north side of the river is composed of Pinedale age till which is near the margin of Pinedale glaciation.
0.7	6.7	Approximate entrance to Madison River Canyon. The road east of here received extensive damage from rockfalls and landslides during the August 1959 Hebgen Lake earthquake. The epicenter of the earthquake was 35 miles northwest of West Yellowstone; 26 people were killed near Hebgen and Earthquake lakes.

The rocks on the north side of the river are Member B of the Lava Creek Tuff, which has been described as:

> Gray, brown, or pinkish-gray ash-flow tuff. Devitrified throughout; generally densely welded exept for partially welded vapor-phase zones at top and bottom. Lithic inclusions are locally abundant. Abundant 1-5 mm phenocrysts of quartz, sanidine, and sodic plagioclase; some sanidine phenocrysts as much as about 1 cm; sparse opaque oxides, clinopyroxene, and fayalitic olivine phenocrysts. Thin basal zone of phenocryst-poor tuff grades downward from densely welded to partly welded.

This tuff was emplaced immediately prior to the formation of the Yellowstone Caldera, and has been dated at 600,000 years (Christiansen and Blank, 1972). This was the third major tuff eruption in the history of caldera formation in this vicinity. The Huckleberry Ridge Tuff at 2 million years, and the Mesa Falls Tuff, at 1.2 million years, were the earlier eruptions.

The rocks on the south side of the river are flows of the Mount Jackson Rhyolite, which in this area has been separated into the Mt. Haynes flow and the Harlequin Lake flow. The Mt. Haynes flow forms the cliffs south of the river. This rhyolite has been described as:

> Mainly gray crystalline rhyolite with local light-gray vitrophyric margins. Contains 1-3 mm phenocrysts of quartz, sanidine, plagioclase, and opaque oxides.

The Mt. Jackson Rhyolite has been dated at 790,000 and 640,000 years (Christiansen and Blank, 1972). Preservation of this unit outside the Yellowstone Caldera collapse area has helped define the caldera margin.

0.8	7.5	Bridge across the Madison River.

As we drive east, the Mount Jackson Rhyolite is exposed on the south side of the canyon. On the north slope, it is overlain by the upper part of Member A of the Lava Creek Tuff, which has been described as:

> Brown to bright pink. Densely welded throughout. Devitrified except for minor vitrophyric lenses in lower part. Contains abundant phenocrysts as much as 5 mm and larger of quartz, sanidine, and sodic plagioclase, moderately abundant opaque oxides and hornblende, and sparse allanite.

Pinedale till, talus, rubble, and sand and gravel mantle the bedrock outcrops along the river.

2.8	10.3	Mt. Haynes is the prominent peak to the south.
1.9	12.2	About here we cross the northwestern fault scarp of the Yellowstone Caldera. As we travel east, the road generally follows the Caldera margin. Detailed seismic studies were undertaken by University of Utah personnel and others in July to determine whether any shallow magma may exist in the Caldera. Eaton and others (1975) concluded on the basis of gravity, aeromagnetic, earthquake epicenter and seismic wave patterns that: "a body composed at least partly of magma underlies the region of the rhyolite plateau, including the Tertiary volcanics immediately to its northeast."

Further geophysical evidence of the anomalous nature of the Yellowstone Caldera is presented in Iyer (1979), where it is suggested that a body of low seismic velocity material extends beneath the caldera to a depth of 200-250 km. Morgan and others (1977) conclude, on the basis of heat flow data, that a cooling batholith, perhaps with some re-supply of magma, exists beneath the caldera. Smith and others (1977) present seismic, aeromagnetic, and gravity data, and agree with the conclusion that a cooling batholith exists beneath the caldera. Smith and Christiansen (1980) summarize all these data.

Heat supply for hydrothermal activity in the Park is undoubtedly related to the magmatic activity. Rhyolitic magmas typically occupy shallow chambers where their influence on the surface hydrothermal regime can be strong. Such magma, whether partially melted or solidified but still warm, could create the heat to drive Yellowstone hydrothermal systems. Basalts do not create large near-surface magma chambers; instead they come from much greater depth. This implies that basalts do not retain residual near-surface heat in the vast quantities found at Yellowstone (Fournier and others, 1976; Morgan and others, 1977), and a basalt eruption the same age as the Yellowstone rhyolite eruptions would not be able to maintain the hydrothermal systems.

The rhyolites exposed east of Mt. Haynes on the south side of the canyon are part of the Central Plateau rhyolite and have been described as:

> Large rhyolitic lava flows, each containing a wide variety of lithologies and distinguishable from one another only by topographic forms and zonal development of various textural features and emplacement structures. Most exposures are dark pitchstone or obsidian vitrophyres of flow-layered or flow-brecciated rhyolite, but gray to red pumiceous rhyolite and gray, brown, or varicolored crystalline rhyolite also are common; all varieties can occur within a single flow. All flows contain abundant 1-3 mm phenocrysts of quartz, sanidine, opaque oxides, and, in glassy zones, sparse clinopyroxene and fayalitic olivine; a few flows also contain minor sodic plagioclase phenocrysts.

The West Yellowstone flow, which is exposed from this point east to Madison Junction, has been dated at about 114,500 ± 7,300 years. North of the river, the Harlequin Lake flow of the Mt. Jackson Rhyolite is overlain by the lower part of Member A of the Lava Creek Tuff, which has been described as:

> Generally pinkish gray to light gray nonwelded to partly welded ash-flow tuff. Glassy to vapor-phase zone. Contains abundant lithic inclusions and some very large pumice blocks (some nearly 1 m). Contains moderately abundant small (generally 1 mm or less) phenocrysts of quartz,

sanidine, and sodic plagioclase, moderately abundant hornblende and opaque oxides, and sparse allanite.

Outcrops of Madison River Basalt, described as "gray to black containing abundant phenocrysts of plagioclase and olivine" have also been mapped on the north slope. Member B of the Lava Creek Tuff overlies member A on the hill north of the road.

1.7 13.9 Madison Junction, turn left (north). This is the confluence of the Gibbon and Firehole rivers, which form the Madison River. National Park Mountain, southwest of the intersection, commemorates the formation of the idea of a National Park to preserve Yellowstone's features. Cornelius Hedges, a journalist travelling with the Washburn expedition of 1870, is credited with suggesting, while camped at the site of the present campground, that the Yellowstone area should be set aside and preserved. The act setting aside the Park passed Congress on March 1, 1872.

0.8 14.7 Terrace Springs Complex. Bath Springs and Terrace Springs form the major outlets. Terrace spring is 62°C, and has a flow of about 1220 gpm. The apparent boiling of this spring is due to CO_2 gas. Terrace Springs is one of four sites in the park where silica and travertine have both been deposited (Marler, 1973, p. 599-600). Fournier and Truesdell (1974) used Terrace Spring as a demonstration of mixing of hot and cold waters without enthalpy loss from the hot water component.

The hills south of the river are composed of the Nez Perce Flow of the Central Plateau Rhyolite. This flow has been dated at about 160,000 years.

0.7 15.4 The Gibbon River flows along a bottom of humic alluvium, with Pinedale fan gravels, kame deposits, till and rubble forming the higher slopes.

0.3 15.7 The prominent cliff north of the road is composed of the lower and upper parts of member A of the Lava Creek Tuff. As we proceed east, we will be driving across the upper part of member A.

3.3 19.0 Gibbon Falls, which flows across the upper part of Member A of the Lava Creek Tuff, is east of the highway.

0.4	19.4	The small outcrop on the west side of the road has been mapped as part of the Lava Creek Tuff.
1.3	20.7	Bridge across the Gibbon River.
0.6	21.3	As we proceed north through Gibbon Canyon, the rocks on the west side of the river are member A of the Lava Creek Tuff, and the rocks on the east side of the river are the Gibbon River flow of the Plateau Rhyolites. The Gibbon River Flow has a reported K-Ar age of about 87,000 years; it erupted from a vent along the caldera rim, and flowed over pre-existing Nez Perce flows. The Nez Perce flows may be locally preserved on the west side of the canyon. They ponded a lake that may have extended as far north as the Norris Geyser Basin.
0.3	21.6	Bridge across the Gibbon River.
0.4	22.0	Sinter terraces on the east side of the river.
0.4	22.4	Beryl Springs. A steam vent blows behind the main springs. A large zone of alteration may be observed around the spring. Siliceous sinter deposits continue along the river to the north. These sinter deposits imply a base reservoir temperature above 180°C. The caldera margin is inferred through geologic mapping to be along or just east of the Gibbon River here. As we travel through the Park, the stress placed on vegetation by thermal activity may be easily noted. White (1978), while including other possible factors such as depth to water table, concluded that normal tree growth occurs in areas of less than 200 HFU (heat flow units, 10^{-6} cal/cm^2/sec) conductive heat flows, stunted growth of trees occurs in areas of 200-400 HFU, and no growth occurs in areas with greater than 500 HFU.
0.4	22.8	Bridge.
0.6	23.4	Enter Gibbon Meadow, a popular place to observe elk. The surface deposits in the meadow are primarily diatomaceous silt. Surface thermal activity is most evident along the margins of the basin. The rocks surrounding the north, west, and south margins of the basin are members A and B of the Lava Creek Tuff. Outcrops of rhyolite adjacent to the east side of the road at the south end of the basin have been tentatively correlated with the Nez Perce Creek flow of the Central Plateau Member.

Paintpot Hill is the prominent hill on the southeast side of the basin. It is part of the Obsidian Creek Member of the Plateau Rhyolite, which has been described as:

> Extrusive rhyolitic domes, each with a core of gray crystalline rhyolite and a shell of black vitrophyre or gray pumiceous flow breccia. Contains 1-2 mm phenocrysts of quartz, sanidine, sodic plagioclase, opaque oxides, and sparse clinopyroxene. Age relations between individual domes or between the Obsidian Creek and Upper Basin Members are uncertain.

The Gibbon Hill and Geyser Creek domes occur east of the basin. The domes were probably emplaced shortly after the extrusion of the Lava Creek Tuff and the collapse of the caldera at 600,000 years ago.

1.4	24.8	Enter the small canyon associated with the Gibbon River Rapids. Bedrock is member A of the Lava Creek Tuff. Chocolate Pots hot springs are along both sides of the river. One small spring issues from gravel fill used as a road base.
0.7	25.5	Enter Elk Park. Bedrock here is covered by humic alluvium along the rivers, with diatomaceous silt and siliceous sinter deposits comprising the rest of the basin. The hills around the basin are composed of Member B of the Lava Creek Tuff. A few small hot springs are presently active in the park.
1.1	26.6	We are now driving along the south edge of the Norris Geyser Basin, where we will be stopping tommorow.
1.1	27.7	Intersection; turn right (east) toward Canyon. From here until our first stop we will be traveling on Pinedale till and sand deposits. The sand is either stream or outwash and stream deposits. Humic alluvium is restricted to the vicinity of present streams. Bedrock beneath the surficial deposits has been mapped as Member B of the Lava Creek Tuff.
1.6	29.4	Stop 1.

Turn off for the Virginia Cascades Road. The narrow road precludes parking the busses at the outcrop, so we will have the busses drop us off and then walk up the road to the parking area.

The outcrops are Lava Creek Tuff, which show many of the features of ash flow tuff stratigraphy. We will see the contact between members A and B of the tuff.

2.0	31.3	Return to main highway and turn right (East).
0.6	31.9	Exposure of vitrophyre in new road cut. The rock is the Solfatara Plateau flow of the Central Plateau Member of the Plateau Rhyolite. This flow has a K-Ar age of about 100,000 years. The rhyolite is covered by Pinedale till. At approximately this point we are crossing the northern fault scarp of the Yellowstone Caldera.
3.6	35.5	Zone of hydrothermal alteration and hot ground
1.3	36.8	Forest fire area on north side of road.
1.6	38.4	At the break in the forest, we enter Cascade Meadows. Outwash and alluvial deposits, with humic alluvium along stream courses, cover bedrock in the meadow.
1.0	39.4	Intersection, turn left (North) toward Mt. Washburn and Tower. As we drive north from the intersection, the road is on the Canyon Flow of the Upper Basin Member of the Plateau Rhyolites. This flow has been described as:

> Rhyolitic lava flow. Most exposures are brown or dark-gray crystallized rhyolite, but black pitchstone vitrophyre and gray pumiceous rhyolite occur at the margins. Contains abundant 1-5 mm phenocrysts of quartz and sodic plagioclase, and, in glassy zones, clinopyroxene. No sanidine phenocrysts.

This flow is exposed above the Upper Falls of the Yellowstone River at Canyon. Pinedale till forms the surficial deposits.

1.6	41.0	Cross the mapped trace of the northern fault scarp of the Yellowstone Caldera. The bedrock changes from the Canyon flow to the Dunraven Road flow of the Upper Basin Member of the Plateau Rhyolites, which has been described as:

> Similar to rhyolites of Central Plateau Member but contains abundant phenocrysts of sodic plagioclase; clinopyroxene phenocrysts are more abundant.

0.5 41.5 The rock on the south side of the road is Dunraven Road flow, with andesite flows of the Lamar River Formation on the north side of the road. The Lamar River Formation is part of the Absaroka Volcanic Supergroup, which is preserved outside the caldera. We will view the Absaroka volcanic field from Mt. Washburn. Smedes and Prostka (1972) describe the Lamar River Formation as:

> "...well-bedded coarse alluvial facies volcanic conglomerates, breccias, and tuffs."

The andesite flows are described on the geologic maps as:

> Medium-gray and brown platy-jointed lava flows and flow breccias of hypersthene-hornblende andesite and dacite. This unit forms a small volcanic shield in the lower part of the Mount Washburn composite volcano. 0-1,400 feet (0-427 m) thick.

Smedes and Prostka (1972) considered the Lamar River Formation to be late Wasatchian or early Bridgerian age; this is about 49 m.y.

0.8 42.3 The road here crosses onto the Sepulcher Formation which has been described as:

> Light-brown to yellowish-gray and greenish-gray epiclastic volcanic breccia, conglomerate, sandstone, and tuffs. Clasts are a variety of colors--gray, green, purple, red, brown, and yellow--of hornblende- and biotite-bearing pyroxene andesite, quartz latite, and dacite. Fragments of Precambrian metamorphic rocks occur locally in lower 100 feet (30 m) of unit. Fossil trees are especially abundant in some horizons, and fossil leaves occur in thin porcelaneous tuff beds. Proportion of coarser beds increases eastward and southward as the unit grades into and interfingers with the alluvial facies of the Lamar River Formation. 0-1,400 feet (0-427 m) thick.

At this point, the road climbs out of plateau rhyolites and will remain in various facies of the Absaroka Volcanic Supergroup to Dunraven Pass. Pinedale till and rubble mantle the hillsides.

0.6 42.9 View east toward Washburn Hot Springs. These springs have the characteristics of a vapor dominated system. D. E. White (written comm.,

1980) points out, however, that the discharge of high chloride waters through the hot springs at Seven Mile Hole in the Grand Canyon of the Yellowstone indicates an underlying water dominated part of this hydrothermal system.

1.5 44.4 Stop 2.

Dunraven Pass Picnic area. We will hike the Chittenden Road to the overlook of the Yellowstone Caldera and the Absaroka Range. Schultz (1962) summarized the topography and volcanic history of Mt. Washburn by saying:

> "The cone associated with the vent of the Washburn volcano was broad and erosion-scarred, with dips up to 25° near the vent. Generally, slopes varied between 6° and 12° away from the vent area, but were only 3° to 4° in outlying areas. The cone was approximately 25 to 30 miles in diameter at the base and stood 3,000 feet above the general terrain. In relation to the present general elevation of the region and the height of Mt. Washburn (10,243), the maximum elevation of the cone was probably nearly 12,000 feet.' Eruptions from the vent were spasmodic, and were separated by relatively long periods of quiescence. During these periods, rapid erosion attacked the cone, causing the paleotopography and the cut-and-fill structures that occur in breccia outcrops of Mt. Washburn."
>
> "It is proposed that the vent or vents for the volcanic rocks in the Mt. Washburn region is [are] located two to three miles southeast to south-southeast of Mt. Washburn. The vent is now buried beneath the plateau formed by the Canyon (Plateau) flows and probably is situated on the northwest side of the Grand Canyon."

Mt. Washburn has many of the characteristics, such as extensive mud flow deposits, that are found on modern volcanos like Mt. St. Helens.

The rocks exposed along the trail we will hike are part of the vent facies of the Lamar River Formation, which has been described as:

> Medium- to dark-gray and brown laharic breccias, autoclastic flow breccias, thin discontinuous lava flows, and tuffs; all

variably altered to shades of red, purple, and light yellowish gray. Lava flows and rock fragments are of pyroxene andesite and pyroxene-hornblende andesite. These deposits have primary dips of as much as 30 degrees and form part of the Mount Washburn composite volcano centered in the southwestern corner of the quadrangle. This unit grades into and interfingers with the alluvial facies northward and northeastward away from the volcanic center. 0-3,000 feet (0-914 m) thick.

The relations between vent and alluvial facies Absaroka volcanic rocks are illustrated in Figures 3 and 4.

Return to vehicles. We will retrace our route to Canyon Village.

5.0 49.4 Canyon Intersection. Proceed straight (south). Immediately south of the intersection the road travels on Pinedale sand and till. The bedrock to the south is composed of the Canyon flow of the Upper Basin Member and the Hayden Valley flow of the Central Plateau Member; these are separated by sediments of the Upper Falls. The sediments are chiefly lacustrine sands and silts, with local gravels and pumiceous tuff, formed during the intra-Bull Lake interval.

7.5 51.9 Turn left (east) for Artists Point. The oldest known sinter deposits in the park are exposed in roadcuts on the way to the parking area; they are interbedded with caldera fill sediments (D. E. White, pers. comm., 1980).

1.7 53.6 Stop 3. Artists Point parking area. We will walk to the overlook of the Grand Canyon of the Yellowstone.

The canyon is cut in the Canyon Flow of the Upper Basin Member of the Plateau rhyolite. The Canyon Flow has been K-Ar dated at about 590,000 years. Christiansen and Blank (1972, p. 13) say:

> "In our interpretation, the rhyolite section in the upper Grand Canyon area consists of a basal, largely agglutinated air-fall tuff overlain successively by the Canyon flow proper and by a younger flow exposed near the Dunraven Pass Road."

The Canyon flow probably erupted into a lake

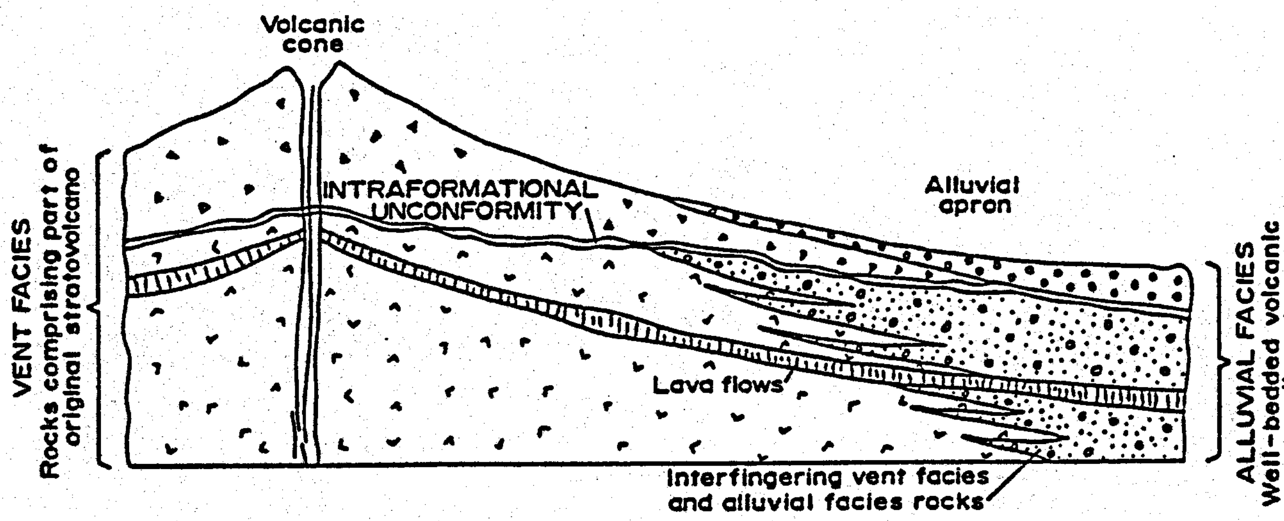


FIGURE 3. Hypothetical cross section, showing relationships of vent facies and alluvial facies rocks. From Smedes and Prostka, 1972.

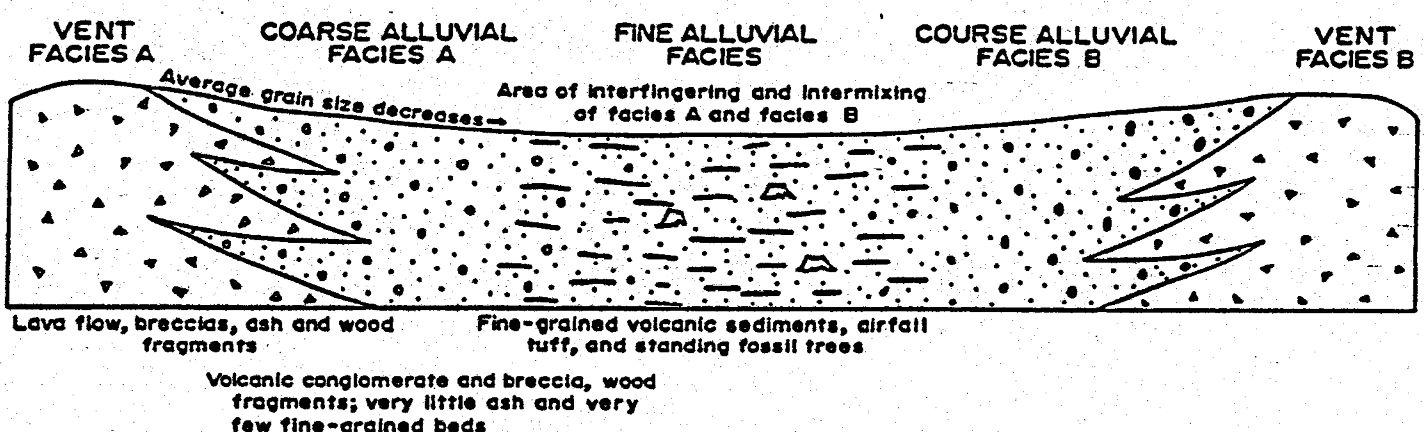


FIGURE 4. Hypothetical cross section, showing facies relationships of two vent complexes (A and B) and the intervening volcanic sediments derived from them. From Smedes and Prostka, 1972.

ponded by the collapse of the caldera following the eruption of the Lava Creek Tuff (Richmond, 1976, p. 6).

The colors of the rocks are primarily due to the formation of iron oxides and hydroxides from hydrothermal activity. Hot springs may still be seen near river level both upstream and downstream from Artist's Point.

The canyon itself has been cut in successive stages, related to interglacial meltwaters, floods produced by volcanic eruptions into lakes, and catastrophic lowering of lakes by sudden melting and hydrothermal explosions (Richmond, 1976).

1.7	55.3	Return to main road and proceed right (south) toward Mud Volcano.
1.3	56.6	The Solfatara Plateau flow forms the hill west of the river; the Hayden Valley flow forms the hill east of the river.
0.7	57.3	Enter Hayden Valley. Glacial lake, kame, and till deposits form the valley floor. The earliest lake was older than the 100,000 year Hayden Valley flow of the Central Plateau Member of the rhyolites. Three younger lakes also formed during Bull Lake late stade, Bull Lake-Pinedale interglacial, and Pinedale glacial times. These lakes also existed in the present area of Yellowstone Lake. The youngest glaciation in Hayden Valley was probably about 12,600 to 12,000 years ago (Richmond, 1976).
1.0	58.3	The road climbs a small hill of Hayden Valley flow, Pinedale till, Bull Lake sediments, and flood deposits.
0.6	58.9	Stop 4.

Turn out for a view of the Sour Creek Dome, Hayden Valley, the Absaroka and Washburn Ranges.

This stop provides a view of the Sour Creek resurgent dome to the east across the Yellowstone River. The resurgent phase of the caldera followed collapse and is produced by magma pressure from beneath. This is a structural dome in contrast to extrusive lava domes exposed elsewhere in the park. As a structural uplift, older portions of the stratigraphy are exposed with both members A and B of the Lava Creek Tuff and small areas of Huckleberry Ridge Tuff present. The surface of the resurgent dome is broken into discrete blocks by numerous normal faults forming an orthogonal pattern. An apical graben often forms as part of this faulting which is produced by extension associated with uplift. The topographic expressions of the faults can be observed although the faults themselves are mantled by till. Numerous hot springs and areas of altered ground can be found on the margins of the resurgent dome although the central portion of the structure contains no thermal manifestations.

1.1	60.0	Hydrothermally altered sediments and landslide topography are visible on the west side of the highway.
2.7	62.7	Stop 5.

Mud Volcano - Sulphur Cauldron area. We will park in the Mud Volcano parking lot and walk the trail to the southwest. If there is time, you may wish to walk the several hundred yards north along the highway to the overlook of Sulphur Cauldron.

This stop will provide the opportunity to observe the surface manifestations of a vapor-dominated system. Numerous acid sulfate springs and mud pots are present. Note the small amount of actual run off from the entire area. The sulfur cauldron area has been mapped in detail by White and others (1971) and is the area of research drill hole Y-11. Christensen and Blank (1975) have mapped siliceous hot spring deposits along the Yellowstone River indicating that the geothermal system at one time was water dominated. The change from a water dominated to a vapor dominated system is thought to result from the development of impermeable margins, which restricts recharge of water and leads to the lowering of the water table through boiling.

The transitory nature of thermal phenomena is illustrated at Mud Volcano. A series of earthquakes in early 1979 led to greatly increased thermal activity here. Many trees have since been killed, and new mudpots are developing. A chemical analysis from this area is included on Table 3.

Smith (pers. comm., 1980) reports uplift rates in the Mud Volcano area of approximately 14 mm/year.

It is important in thermal areas to remain on the walkways provided. In particular, hydrothermal sinter deposits often form a thin crust on the

TABLE 3
Chemical Analyses of Yellowstone Waters
(see references for sampling and analytic details)

	Norris Basin Echinus Geyser[1]	Upper Basin Interchange Sp[1]	Upper Basin Old Faithful[2]	Mud Volcano Churning Cauldron[2]	Mammoth E. Jupiter Terrace[2]
Temp (^{o}C)	93	74	85	55	72
pH	3.01	8.6	9.1	1.7	6.25
SiO_2	256	275	390	325	52
Fe	2.2	<.02	.1	38	<.1
Mn	0.19	<.02			
Ca	1.87	0.27	.7	152	339
Mg	0.488	<.01	<.1	73	67
Na	160	290	326	77	130
K	50.2	21	22	46	56
Li	0.8	2.9	5.3	0.1	1.8
HCO_3	0	183		0	816
CO_3	0	90	0	0	
SO_4	289	18	18.5	1066	479
Cl	114	226	451		165
F	5.1	165		2	3.0
B	2.15	3.55		0.4	4.2
As	nd	0.993			0.60
Zn	0.03	nd			

1. Thompson and Yadav, 1979
2. Rowe and others, 1973

edges of pools, which will collapse under the weight of a person. Many people have been burned by breaking through such thin crusts.

Return to buses and drive north toward Canyon.

9.9	72.6	Canyon Junction; turn right (east) to hotel.

END OF DAY 1

DAY 2 - CANYON TO OLD FAITHFUL

From Canyon to Dunraven Pass is along the same route as yesterday, from miles 39.4 to 44.4.

5.0 5.0 As we cross Dunraven Pass, the road is on vent facies of the Lamar River Formation that we looked at yesterday. For the next several miles toward the north, the breccias of this facies are well exposed on the east side of the highway.

The high peaks west of the pass are also composed of Absaroka volcanic rocks.

1.9 6.9 The valley of Tower Creek is visible to the north and northwest. The northeast-sloping benches in the valley are Member B of the Lava Creek Tuff.

As we proceed, the road passes from vent facies to alluvial facies of the Lamar River Formation. The alluvial facies of the Langford Formation is also present along the road; this has been described as:

> Light-gray to medium-gray well-sorted, massively bedded alluvial-facies volcanic breccia and conglomerate consisting of dark-gray subangular to subrounded clasts of pyroxene andesite and hornblende andesite in a light- to medium-gray ash-rich matrix. 2,000 feet (610 m) thick.

The Langford Formation has been dated at about 48 m.y. (Smedes and Prostka, 1972).

3.1 10.0 Turn off to Chittenden Road parking area. Proceed along main highway. The tight switchback immediately east of the turn off is in the alluvial facies of the Lamar River Formation, which has been described as:

> Medium- to light-brown, yellow, and green, well-bedded alluvial-facies volcanic conglomerate sandstone, tuff and well sorted breccia; fragments are subangular to subrounded clasts of pyroxene andesite and pyroxene-hornblende andesite; lower 100 feet (30 m) of unit locally contains sporadic Precambrian metamorphic rock fragments. Fossil trees, common throughout this unit, are especially abundant in the finer grained beds. This unit grades into and interfingers with the Sepulcher Formation to the west, and with the vent facies of the Lamar River

Formation to the southwest. 80-1,400 feet (24-427 m) thick.

Pinedale till and rubble mantle the slopes.

1.1	11.1	View toward the northeast of the Absaroka volcanic pile. The near hills across the river are Specimen Ridge, where extensive Eocene forests have been preserved. Dorf (1960) described these forests as covering more than 40 square miles, having hundreds of upright trees, identifiable parts of over 100 plants, and a vertical succession of up to 27 forests. Fritz (1980a, 1980b) has re-examined these concepts, and prefers a two-part model. Trees from high Absaroka volcanic slopes could have been transported downslope by mud flows, which then would have been re-worked by braided streams. This model could explain the mixing of cooler and warmer climate trees found on Specimen Ridge. The forests are in part of the Lamar River Formation.
1.7	12.8	Lamar River alluvial facies crop out on the west side of the road. Pinedale kame deposits form the slope toward Antelope Creek.
1.3	14.1	Member B of the Lava Creek Tuff is exposed in the outcrop along the road.
1.4	15.5	Junction Butte Basalt (approximately 2 m.y. old) exposed in road cut. This unit has been described as:

> Dark-gray basalt lava flows characterized by well-developed two-tiered columnar jointing. Basalt is dense, aphanitic, and contains sparse plagioclase phenocrysts; locally overlies gravel, sand, and silt that are mapped with the basalt.

The road passes better outcrops between Tower Falls and Calcite Springs.

0.7	16.2	Tower Falls turn out, proceed north on main road.
0.1	16.3	Cross Tower Creek. The falls and creek are in the Sepulcher Formation. Off-trail hiking in this area is particularly dangerous as the rocks of the Sepulcher Formation are loose.
0.2	16.5	The overhanging cliff flow of the Junction Butte Basalt is exposed in the spectacular roadcut. The basalt here is about 30 m thick, and shows

two-tiered jointing (Christiansen and Blank, 1972, p. B9).

0.5	17.0	Stop 6.

Turnout for Calcite Springs overlook. Good exposures of the sediments and basalts of the Narrows are present in the canyon walls. These have been described as:

> Yellowish-brown well-sorted gravels and interlayered dark-gray columnar-jointed lava flows of dense aphanitic basalt containing plagioclase phenocrysts; unit occupies pre-Lava Creek Tuff paleovalley.

The mountains to the north are composed of Precambrian rocks, while those to the east are Absaroka volcanic rocks. Calcite Springs is visible along the Yellowstone River at the base of Bumpus Butte. Pinedale till mantles the ridgetops on both sides of the river.

Return to vehicles, proceed north toward Tower Junction. As we drive north, Junction Butte Basalt forms the cap on Bumpus Butte, Member B of the Lava Creek Tuff forms the hill behind Rainey Lake, and hot spring travertine deposits form the last hill before dropping down to the junction.

1.6	18.6	Tower Junction. Proceed straight (west). The road to the right (north) leads to the northeast entrance of the park, Cooke City, and the Beartooth highway (regarded by some as the most spectacular road in the U. S.). Precambrian rock of the Beartooth Plateau has been extensively studied for field evidence of granitization. The surficial deposits at the intersection are Pinedale kame and fan gravels, with recent gravel and fine-grained alluvium along stream courses.

As we proceed west from the junction, we will be driving over various facies of Absaroka volcanic rocks which are covered by Pinedale till and rubble.

0.6	19.2	The road climbs the hill approximately along the contact of the main body of the Sepulcher Formation in the hills south of the road and the Lost Creek Tuff member of the Sepulcher Formation which covers the flats north of the road. The main body of the Sepulcher has been described as:

> Light-brown to yellowish-gray and

greenish-gray epiclastic volcanic breccia, conglomerate, sandstone, and tuffs. Clasts are a variety of colors--gray, green, purple, red, brown and yellow--of hornblende- and biotite-bearing pyroxene andesite, quartz latite, and dacite. Fragments of Precambrian metamorphic rocks occur locally in lower 100 feet (30 m) of unit. Fossil trees are especially abundant in some horizons, and fossil leaves occur in thin porcelaneous tuff beds. Proportion of coarser beds increases eastward and southward as the unit grades into and interfingers with the alluvial facies or the Lamar River Formation.

Good exposures of the Lost Creek Tuff Member will be mentioned below.

0.9	20.1	Road to Petrified Tree. We will proceed west, as no turn-round suitable for buses exists. The tree is in the Sepulcher Formation, immediately below strata mapped as interbedded Lamar River Formation alluvial facies. Small exposures of Pliocene siltstone and sandstone are also present on the hill with the Petrified Tree (Richmond and others, 1978).
1.0	21.1	The ridge east of the highway is formed of the Lost Creek Tuff member of the Sepulcher Formation. This member has been described as:

Gray, green, purple, and yellow welded ash-flow tuff of trachyte-rhyodacite, locally contains fragments of Precambrian metamorphic rocks and pieces of charred wood. Central densely welded zone has platy and columnar joints. Unit is interlayered with lower part of Sepulcher Formation and thins eastward and pinches out near west end of Lamar Canyon.

0.7	21.8	Floating Island Lake. The main body of the Sepulcher Formation with interbedded Lamar River Formation forms the hillside south of the lake. The Lost Creek Tuff forms the hills north and west of the lake.
0.6	22.4	Elk Creek Basalt Member of the Lamar River Formation is the bedrock at the trailhead road. This basalt has been described as:

Medium- to dark-gray and brown columnar-jointed lava flows and reddish-brown scoriaceous flow breccias of shoshonite. Phenocrysts of plagioclase, pyroxene, and olivine occur in highly variable amounts and sizes from flow to flow. Unit is at different localities a member of the Sepulcher or the Lamar River Formation and is interlayered with lower parts of both formations. 0-400 feet (0-122 m) thick.

1.9	24.3	The road climbs along the contact between the Lost Creek Tuff on the north side and the main body of the Sepulcher Formation on the south side.
1.3	25.6	Exposures of Crescent Hill Basalt on both sides of the road. The Crescent Hill Basalt:

> "... consists of two flows of scoriaceous, partly pillowed trachybasalt which have an aggregate thickness of about 250 feet." (Smedes and Prostka, 1972, p. C23)

Smedes and Prostka (1972) consider the Crescent Hill Basalt to have an early Bridgerian Provincial age (approx. 48 m.y.).

1.0	26.6	Phantom Lake on the south side of the highway.
0.4	27.0	The Undine Falls Basalt is exposed along the road. This basalt is estimated to be between 700,000 and 600,000 years old; it conformably underlies the Lava Creek Tuff (Christiansen and Blank, 1972, p. B12).
0.5	27.5	Blacktail Plateau Drive (not recommended for buses).
1.3	28.8	As we round the corner, the Gallatin Range becomes visible on the skyline to the west. The road at this point has traveled near Mississippian Mission Canyon Limestone and Pennsylvanian Quadrant Sandstone, which are brought to the surface along Gardner Fault Zone (Ruppel, 1972).

The Gardiner Fault Zone is discussed in detail by Fraser and others (1969). The fault has been mapped from Cinnabar Mountain, north of the park, southeastward to Mt. Washburn, but Fraser and others (1969) cite evidence that the fault may be 140 miles long, from the vicinity of Cody, Wyoming to the Madison Range in Montana. It is a high-angle reverse fault, with more than 10,000 feet of displacement. Most of the movement took place during Laramide tectonism, but Pliocene (?) basalt has been offset 400 feet, and Pleistocene deposits have been offset a few tens of feet along the fault. The Gardiner Fault forms the southwest margin of the Beartooth Block; in the vicinity of Gardiner, Precambrian rocks are adjacent to Paleozoic and Mesozoic rocks.

Isolated exposures of Huckleberry Ridge Tuff, which will be discussed below, are also preserved.

The Gallatin Range is an uplifted horst of Precambrian to Eocene metamorphic, sedimentary, and intrusive rocks. The intrusions in the Gallatin Range are Eocene and are a postulated source for some of the Absaroka volcanic rocks. (Smedes and Prostka, 1972).

As we drive west, the road crosses Pinedale till, with kame deposits near the creeks.

1.8	30.6	The low hills to the north are Lava Creek Tuff.
0.4	31.0	Outcrop of Lava Creek Tuff on the southside of the road. A low outcrop of this tuff continues west into the valley on the north side of the highway.
1.2	32.2	Turn off for Wraith Falls where Lava Creek Tuff is well exposed. The Swan Lake Flat Basalt is found to the west. This unit is younger than the Lava Creek Tuff, but was erupted soon enough after the emplacement of the Lava Creek Tuff that in many places it preserves the non-welded ashy top of the Lava Creek cooling unit. The Swan Lake Flat Basalt has been described as:

> "...Generally...light gray to moderate gray and contains sparse to abundant large phenocrysts of plagioclase, as much as 1 cm across, and locally some olivine phenocrysts." (Christiansen and Blank, 1972, p. B15)

0.4	32.6	Lupine Creek
0.5	33.1	Turn out for Undine Falls parking area. We will continue toward Mammoth.
0.1	33.2	Exposure of Swan Lake Flats Basalt.
0.1	33.3	Exposure of Undine Falls Basalt.

For the next several miles, Mt. Everts is visable north of Lava Creek Canyon. Prevolcanic rocks on Mt. Everts are, in ascending order, the Cretaceous Mowry Shale, Frontier Sandstone, and Cody Shale. Further west, the Telegraph Creek Formation, Eagle Sandstone, and Everts Formation are also exposed

(Ruppel, 1972).

0.1	33.4	Mammoth Hot Springs is visible to the west.
0.2	33.6	The cap of Huckleberry Ridge Tuff is easily visible on Mt. Everts. This unit is the oldest of the ash flow tuffs in the Yellowstone group, at 2 m.y.

It was erupted in the first caldera cycle. Smith and Christiansen (1980) draw the southern boundary of the caldera from which this tuff erupted. The northern and eastern boundaries of the caldera have been obscured by later volcanic activity.

The Huckleberry Ridge Tuff has been described and separated into three members (Christiansen and Blank, 1972; Christiansen and others, 1978):

> Compound cooling unit of ash-flow tuff. Gray to brown generally densely welded and devitrified but locally glassy or partly welded. Most parts contain abundant phenocrysts of quartz, sanidine, and sodic plagioclase; sparse opaque oxides, clinopyroxene, and fayalitic olivine.
>
> Member C - Entirely devitrified; commonly shows strong lineation of stretched welded pumice and aligned phenocrysts; compaction foliation commonly deformed by flowage folding. Abundant lithic inclusions. Phenocrysts abundant but generally smaller (less than 1 mm) than in members A and B. Thickness, 0-300 feet (0-90 m).
>
> Member B - Entirely devitrified. Phenocrysts abundant and particularly large (as much as 5 mm) in upper part, sparse in lower part. Two types of welded pumice in upper part: one very dark and scoriaceous, the other light-colored and compact. Thickness 0-500 feet (0-150 m)
>
> Member A - Mainly devitrified, but black vitrophyre at base. Phenocrysts, abundant in lower part, become progressively less abundant upward. Thickness, 0-700 feet (0-210 m)

Christiansen (1979) has estimated the combined volume of the three members of the Huckleberry Ridge Tuff at 2,450 km^3

1.6	35.2	View toward northwest of Gardiner River Canyon. This area was the site of a wikiup village occupied by Sheepeater Indians and one of the last native American inhabitations in Yellowstone Park.
0.1	35.3	Gardiner River. From here to Mammoth, the road travels on Pinedale Till. Travertine deposits of Mammoth Hot Springs and on Terrace Mountain are visible to the west.
2.3	37.6	Enter Mammoth, the park headquarters. Continue straight on road; turn left at hotel, and proceed south.
0.6	38.2	Stop 7.

Parking area at lower terrace. We will walk through the Main Terrace, and meet the buses at the Upper Terrace parking area.

Mammoth Hot Springs is a carbonate-depositing thermal system, and as such is different from the vapor-dominated system at Mud Volcano and the silica-depositing systems at Norris and the Upper and Lower Geysers basins.

Individual thermal features at Mammoth vary in their level of activity from year to year. Carbonate-depositing hydrothermal systems are transitory in their surface expression, as are the vapor-dominated systems, such as at the Mud Volcano, and the siliceous sinter-depositing systems, as at Norris Geyser Basin and Old Faithful.

A wide variety of features may be seen on the walk through Mammoth. These include hot-spring cones, terracettes, collapse features, tension fractures, fissure ridges, caves, calcite ice, and micro-organism deposited travertine (Bargar, 1978).

Although Mammoth Hot Springs is lower temperature than some other springs in the Park, the waters are postulated to have circulated through limestones, and picked up their carbonate load by reacting with the bedrock. If the waters had not circulated through limestones, their mineral load would be much different. Bargar (1978) quotes Allen (1934) as recording rates of travertine deposition that range from 2.8-56.5 cm/yr, with an average of 21.1 cm/yr. Color variations in hot spring pools are due to not only the reflection of the sky, but also to several kinds of bacteria and algae. Two bacteria found in thermal waters in the park, thermoanerobacter ethanolicus and thermoanerobium brockii, have been found to be very efficient at producing ethanol from carbohydrates. Iron and manganese oxides also strongly color some hot springs.

Travertine deposits on the top of Terrace Mountain, southwest of the present hot springs, have been dated at 63,000 ± 9,000 years (Rosholt, 1976). Travertine on Terrace Mountain is overlain by Pinedale till.

Research drilling by the U. S. Geological Survey encountered 253.5 feet of travertine, which was porous near the surface but cemented at depth (White and others, 1975). Jurassic (?) rocks were encountered beneath the travertine. A maximum temperature of 73°C was encountered, and White and others (1975, p. 64) conclude:

> "Evidently all of the water of the system is heated to this temperature or only a little higher, and it rises as liquid water and dissolved gases with no significant change until total vapor pressure has decreased to a few atmospheres."

A water analysis from Mammoth Hot Springs is presented in Table 3. Truesdell and Fournier (1976) suggest that Mammoth Hot Springs waters may be waters from Norris Geyser Basin that have moved north and reacted with limestone.

Corwin Springs, LaDuke Hot Springs, and Bear Creek Warm Springs are other travertine depositing springs north of Mammoth Hot Springs. Water circulation for these hydrothermal systems is postulated to involve deep circulation in the Madison Limestone, heating by the earth's thermal gradient, and circulation to the surface along the Gardiner Fault zone (Struhsacker, 1976).

1.7 39.9 Upper parking lot. Return to main road; proceed right (south). The road is on Pinedale till, kame, and landslide deposits to the south. Some landsliding is still active, as evidenced by the breaks in the highway.

1.7 41.6 The Hoodoos. This is a landslide of travertine springs deposits which has slumped to its present position from the top of Terrace Mountain.

Bunsen Peak is the mountain east of Golden Gate Canyon. It is composed of an intrusive dacite

		considered to be related to the Absaroka Volcanic Supergroup, but older than the Sepulcher Formation.
1.6	43.2	Entering Golden Gate. Excellent exposures of the Huckleberry Ridge Tuff. The 1959 Hebgen Lake earthquake caused much damage to the bridge and road here.
0.5	43.7	Enter Swan Lake Flat. The Gallatin Range is the prominent mountain chain to the west. Pinedale kame, till, and fan deposits, and recent alluvium cover bedrock in the flats. An extensive drumlin field covers the western portion of the flats (Pierce, 1979).
		The Sepulcher Formation is mapped west of Swan Lake, and the Swan Lake Flat Basalt is mapped east of the highway. We will drive south, along the Norris-Mammoth fracture zone which lies east of the Gallatin Horst. The Norris-Mammoth zone is an approximately 22-mi long zone of north-south-trending faults, rhyolite and basalt vents, and gravity and magnetic anomalies (Eaton and others, 1975). The zone has much hydrothermal activity.
3.2	46.9	Road to Sheepeater Cliffs. Rocks that are the products of mixing of basalt and rhyolite magmas are preserved in these cliffs (not visible from the highway). Struhsacker (1978) presents a detailed summary of the history of scientific investigation of these rocks, and interprets the mixed magmas in a regional context.
0.1	47.0	Gardiner River. The road crosses Swan Lake Flats Basalt to the south.
0.4	47.4	Indian Creek Campground. The hill on the east side of the highway south of the campground is composed of Lava Creek Tuff, with a mantle of Pinedale till and scree.
2.7	50.1	Appolinaris Spring.
0.9	51.0	Outcrops of Lava Creek Tuff on the west side of the highway.
0.6	51.6	Obsidian Cliffs on east side of road; Lava Creek Tuff on west. Obsidian Cliffs are formed of the Obsidian Cliff flow of the Roaring Mountain Member of the Plateau Rhyolite. Christiansen and Blank (1972, p. B15) described the unit as:

> Phenocryst-free or very phenocryst-poor

rhyolite which contains abundant fresh black obsidian as well as crystallized and partly crystallized material. Obsidian Cliff flow yielded a young apparent age (75,000 years); the reliability of the date is uncertain.

Obsidian quarried by indians from this locality was both worked locally and traded extensively throughout the region.

3.0	54.6	Clear Water Springs.
0.2	54.8	Hydrothermally altered alluvium.
0.4	55.2	Stop 8.

Roaring Mountain. Since early observation Roaring Mountain has declined in the intensity of its fumarolic activity. It is impressive on cool mornings when the condensate is most apparent. The decline of the "roar" is typical of the everchanging nature of surface hydrothermal phenomena.

Roaring Mountain is a hydrothermal explosion deposit overlying the Lava Creek Tuff. The explosion took place during deglaciation in Middle Pinedale time. Roaring Mountain shows the character of a near-surface vapor-dominated system. Manifestations of an active water-dominated system, which probably represents the associated boiling water table can be seen along Obsidian Creek to the west of the road.

Between Roaring Mountain and Norris, the amount of hydrothermal activity and alteration increases. Bedrock is member B of the Lava Creek Tuff.

4.1	59.3	Gibbon River.
0.8	60.1	Stop 9.

Norris Junction. Turn right (west) into parking area (loop road not included in mileage log). Norris Basin is a large seismically active system of silica depositing hot springs and geysers. We will walk the Back Basin, where Steamboat Geyser, the largest geyser in the world (recorded eruptions to 380 feet; Bryon, 1979) and Echinus Geyser, which in June 1980 is erupting every 40 minutes, can be seen.

Echinus Geyser presents a good opportunity to observe the full cycle of geyser activity described by White (1967). In particular, the draining of the geyser after an eruption, as water levels in the geyser tube equilibrate with the surrounding ground water, a rise in water level prior to the eruption, initiation of eruption with the unloading of cooler water from the top of the pool, an early water phase to the eruption, which is followed by a predominantly steam phase, which tapers as the eruption dies out, can be seen. White (pers. comm., 1980) reports that pyrite and marcasite are among the materials ejected during vigorous eruptions of Echinus.

Figure 5 is a temperature profile, with geologic units indicated, of the Norris area from U. S. Geological Survey drilling (White and others, 1975). The Carnegie Hole and Nuphar Lake are located on the tourist map of Norris; Y-9 is east of the museum, and Y-12 is north of the Porcelain Terrace. A chemical analysis of water from the Norris Basin is presented in Table 3.

Drive out to Norris Junction. Turn right (south). The road log from Norris Junction to Madison Junction was covered the first day.

13.8	73.9	Madison Junction. Proceed straight (south). The road log between Madison Junction and Old Faithful will be covered as part of day 3.
15.8	89.7	Entrance to Old Faithful
		End of Day 2

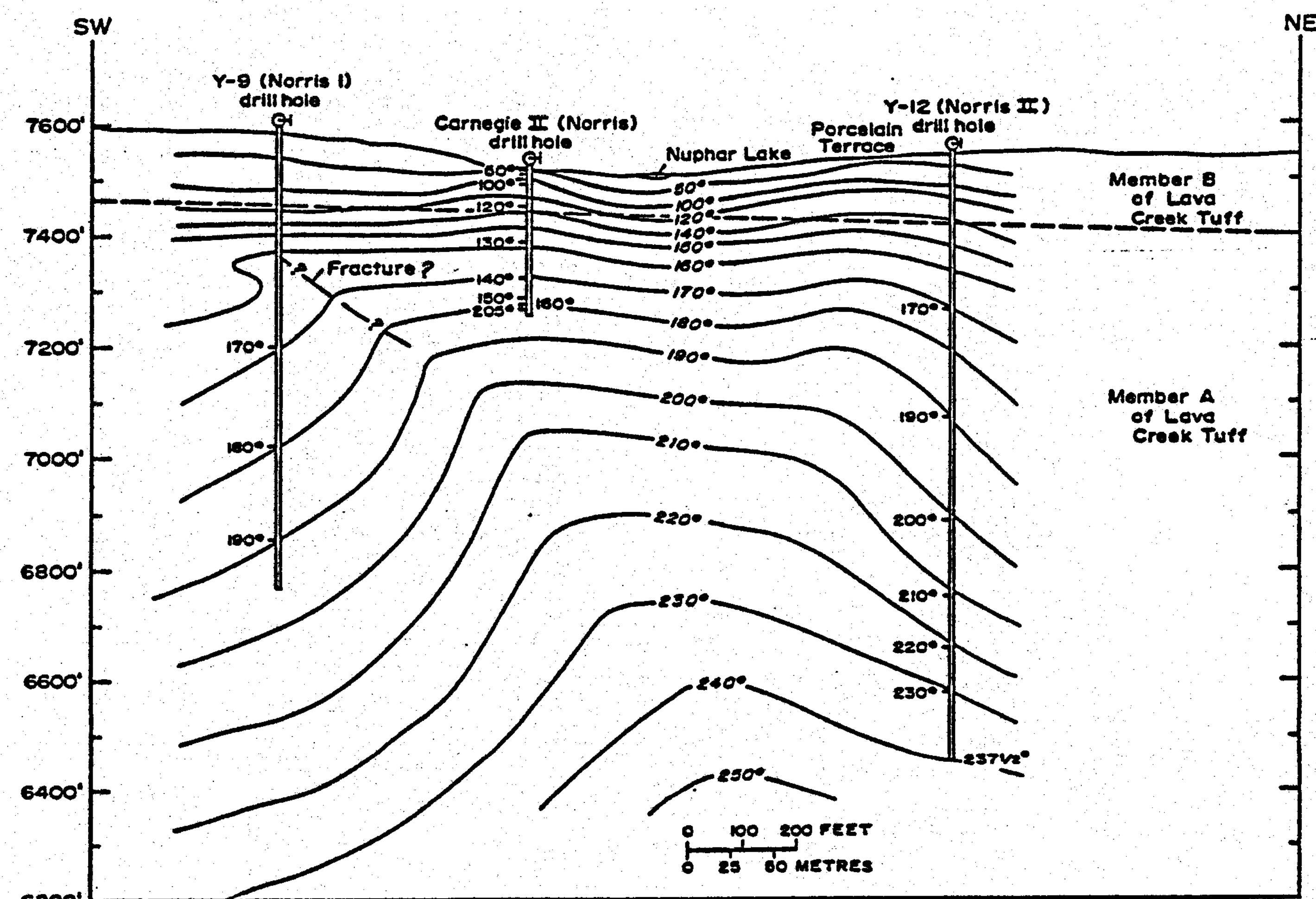


FIGURE 5. Vertical section through Norris Basin drill holes Y-9, Carnegie II, and Y-12, showing bedrock, measured bottom-hole temperatures, and inferred temperature contours. Note contrast between measured and inferred temperatures in Carnegie II drill hole. The inferred fracture near Y-9 presumably connects with others (not shown) that account for the activity near Carnegie II and Congress Pool. Redrafted from White and others, 1975.

DAY 3 - OLD FAITHFUL TO WEST YELLOWSTONE

Stop 10.

Old Faithful visitor center. The day will begin with two options. For those who desire, a 2.5 mile walk through the Upper Geyser Basin to Biscuit Basin is possible. Those who do not wish to walk may instead tour the Upper Geyser Basin and ride the buses to Biscuit Basin.

The Upper Geyser Basin contains more than 25% of the world's geysers in a one square mile area. Marler (1973) contains an extensive catalogue of geyser and spring features and cycles. Bryan (1979) presents a popularized edition of geyser descriptions.

Geyser cycles, a variety of sinter morphologies, siliceous deposits, a range of hot spring conditions, and thermophyllic algae will be observable on either walk. For those who choose to walk to Biscuit Basin, we will visit Seismic Geyser, which has been extensively discussed (Marler and White, 1975; Marler, 1964), and Artemesia Geyser, which has a large crater and intricate sinter deposits.

A chemical analysis of Old Faithful geyser is given on Table 3.

The U. S. Geological Survey and the Carnegie Institute have drilled in the vicinity of the Upper Basin. Results of these holes are summarized on Table 4. Lone Star Geyser is about three miles south of Old Faithful, and may be part of the same convection system. Black Sand Basin is approximately one mile west of Old Faithful Inn.

Looking northeast from the visitor center, extensive deposits of sinter form the foreground. The hill is in the background is the Mallard Lake resurgent dome, composed of the Mallard Lake Flow of the Plateau Rhyolites. It is mantled by Pinedale till. The Mallard Lake Dome is a resurgent dome of the caldera similar to the Sour Creek Dome seen on Day 1.

0 0 Old Faithful intersection. Interchange springs, at the turn off for Old Faithful, was created during road construction. Fournier and Truesdell (1974) used this spring as a demonstration of their model of mixing after steam loss. An

TABLE 4
Drilling Results, Upper Geyser Basin and Vicinity
(After White and others, 1975; Keith and others, 1978)

SITE	DEPTH (in ft)	MAX. TEMP. (^{o}C)	STRATIGRAPHY interval (in ft)	description
USGS Lone Star (Y-6)	500	181	0-69.5	uncemented sand and gravel
			69.5-500	Scaup Lake Rhyolite Flow
USGS Black Sand (Y-1)	215	171	0-11.5	sinter
			11.5-211.5	zeolitized and cemented obsid. rich seds.
			211.5-215	Biscuit Basin rhyo flow
USGS Biscuit (Y-7)	242	143	0-5.5	sinter
			5.5-173	partly altered and cemented sand gravel
			173-242	Biscuit Basin pumiceous flow breccia
USGS Biscuit (Y-8)	503	170	0-5	sinter
			5-181	cemented sand and gravel
			181-206	Biscuit Basin flow breccia
			206-503	Biscuit Basin pumiceous tuff
Carnegie I (Myriad)	406	180	0-7	sinter
			7-220	cemented sand and gravel
			220-406	Biscuit Basin rhyolite flow

analysis of this spring is given in Table 3. 200-208°C water apparently rises, cools adiabatically giving off steam to approximately 110°C; this cooled water then mixes with ground water to give the 76°C spring water.

0.3	0.3	Black Sand Basin on west side of Highway. This is a group of about 12 geysers and springs.
1.6	1.9	Stop 10 (continued)

Biscuit Basin. Note the thermal activity in the parking lot. The lower slopes to the west are composed of the Biscuit Basin flow of the Upper Basin Member of the Plateau Rhyolite. This unit has been described as:

> Generally exposed as black perlitic vitrophyre of flow-brecciated rhyolite. Contains abundant phenocrysts, as much as 5 mm, of deeply embayed and sieved plagioclase, moderately abundant quartz and clinopyroxene, and sparse sanidine and opaque oxides.

The upper hills to the southwest are formed of the Summit Lake Rhyolite flow, and the hills to the northwest are composed of the West Yellowstone flow. These units are both members of the Central Plateau rhyolites. Ubiquitous Pinedale till covers the bedrock.

3.7	5.6	Midway Geyser Basin. The Biscuit Basin flow is exposed on the east side of the highway. From the Midway Geyser Basin north to the north edge of the Lower Geyser Basin, the West Yellowstone flow forms the western skyline.
1.0	6.6	South junction, Firehole Lake Drive. Biscuit Basin flow forms the hill northeast of the intersection. East of the Highway, the Elephant Back flow of the Central Plateau Member of the Plateau Rhyolite forms the hill. The Mallard Lake Dome is the hill to the southeast of the intersection. The surficial deposits along the road from the point north to the next stop are composed of siliceous sinter.
1.1	7.7	North junction, Firehole Lake Drive.
0	7.7	Stop 11

Fountain Paint Pots parking area. This area presents a small but vivid demonstration of the effect of topographic control on water- and vapor-

		dominated hydrothermal systems.
0.6	8.3	The road climbs a small hill of the Elephant Back flow.
0.1	8.4	The road travels across a flat of largely diatomaceous silt. The hills to the north are composed of Bull Lake and Pinedale Kame deposits. The Bull Lake deposits have been described as:

> "Gray to brownish-gray sandstone and conglomerate composed almost entirely of rhyolite clasts. Firmly cemented with opal and zeolites by hydrothermal action. At Porcupine Hills in Lower Geyser Basin the conglomerate is characterized by great variation in texture, sorting, stratification, and local post-depositional slumping typical of ice-contact deposition."

Twin Buttes are the hills to the southwest, in front of the West Yellowstone flows as viewed from the highway. These hills are also composed in part of cemented kame gravels. The lower eastern and southern slopes of Twin Buttes, as well as the low hills surrounding Pocket Basin, which is just west of the highway at this point, are composed of hydrothermal explosion deposits. These deposits have been described as:

> Rubble formed by steam explosion in surficial deposits triggered by abrupt decrease in confining pressure.

An extensive discussion of the Pocket Basin area, as well as other hydrothermal explosion features, is contained in Muffler and others (1971).

1.3	9.7	Nez Perce Creek. The creek follows a course toward the northeast which marks a zone associated with the ring fracture system of the Yellowstone Caldera. The Elephant Back flow is present south of the creek, and the Nez Perce flow is found north of the creek.
2.2	11.9	The Nez Perce Creek flow is east and the West Yellowstone flow is west of the road. The level area north of this point is composed of Pinedale alluvial sands and gravels.
0.6	12.5	The Nez Perce Creek flow is on both sides of the highway. This spot is marked by a conspicuous talus slope of West Yellowstone flow on the west side of the river.

2.5	15.0	Cliffs of the West Yellowstone flow are visible across the Firehole River.
0.3	15.3	Stop 12.
		North entrance, Firehole River Drive. We will stop if parking is available. The Nez Perce Creek flow is on the east side of the river, and the West Yellowstone flow is on the west side. Spectacular rhyolite breccias are exposed in a road cut part way up the canyon.
2.3	17.6	South exit; turn left (north).
2.0	19.6	Gibbon River
0.2	19.8	Picnic area entrance
0.1	19.9	Intersection. Turn left (west). The road log to the west entrance is covered in day 1.
13.9	33.8	West entrance. END OF TRIP.

ACKNOWLEDGEMENTS

The authors would like to thank several people for their aid and assistance in compiling this guidebook. Donald White, of the U. S. Geological Survey, was particularily helpful by his willingness to share many years of experience in researching Yellowstone hydrothermal systems. Wayne Hamilton, of Yellowstone National Park, provided information on current research in the park. John Sonderegger and Charles Wideman, of the Montana Bureau of Mines and Geology, provided data and an update of the status of low-temperature geothermal resource exploration in West Yellowstone.

REFERENCES CITED

Allen, E. T., 1934, The agency of algae in the deposition of travertine and and silica from the thermal waters: Am. Jour. Sci., v.28, p. 373-389.

Bargar, K. E., 1978, Geology and thermal history of Mammoth Hot Springs Yellowstone National Park, Wyoming: U. S. Geol. Surv. Bull. 1444, 55p.

Bryan, T. S., 1979, The Geysers of Yellowstone: Colo. Assoc. Univ. Press, 225p.

Christiansen, R. L., 1975, Geologic map of the Norris Junction Quandrangle, Yellowstone National Park, Wyoming: U.S. Geol. Surv. Map GQ-1189.

Christiansen, R. L., 1979, Cooling units and composite sheets in relation to caldera structure, in Chapin, C. E. and Elston, W. E., (eds.), Ash-Flow Tuffs: Geol. Soc. America Special Paper 180, p. 29-42.

Christiansen, R. L., unpub., Quaternary and Pliocene volcanism of the Yellowstone Plateau volcanic field of Wyoming, Idaho, and Montana: Unpub. manuscript, 7p.

Christiansen, R. L., and H. R. Blank, 1972, Volcanic Stratigraphy of the Quaternary Rhyolite Plateau in Yellowstone National Park: U. S. Geol. Surv. Prof. Prof. Paper 779-B, 18p.

Christiansen, R. L., and H. R. Blank, 1974a, Geologic Map of the Madison Junction Quadrangle, Yellowstone National Park, Wyoming: U. S. Geol. Surv. Map GQ-1190.

Christiansen, R. L. and H. R. Blank, 1974b, Geologic Map of the Old Faithful Quadrangle, Yellowstone National Park, Wyoming: U. S. Geol. Surv. Map GQ-1189.

Christiansen, R. L., and Blank, H. R., 1975, Geologic Map of the Canyon Village Quadrangle, Yellowstone National Park, Wyoming: U. S. Geol. Surv. Map GQ-1192.

Christiansen, R. L., H. R. Blank, Jr., J. D. Love, and J. C. Reed, Jr., 1978, Geologic Map of the Grassy Lake Reservoir Quadrangle, Yellowstone National Park and Vicinity, Wyoming: U. S. Geol. Surv. Map GQ-1459.

Dorf, E., 1960, Tertiary fossil forests of Yellowstone National Park Wyoming, in West Yellowstone-Earthquake area, Billings Geological Society Guidebook, 11th Annual Field Conference, 1960, p. 253-260.

Eaton, G. P., R. L. Christiansen, H. M. Iyer, A. M. Pitt, D. R. Mabey, H. R. Blank, Jr., I. Zietz, and M. E. Gettings, 1975, Magma beneath Yellowstone National Park: Science, v. 188, p. 787-796.

Fournier, R. O., and A. H. Truesdell, 1974, Geochemical indicators of subsurface temperature - Part 2: estimation of temperature and fraction of hot water mixed with cold water: Jour. Res. U. S. Geol. Surv., v.2, no.3, p. 263-270.

Fournier, R. O., D. E., White and A. H. Truesdell, 1976, Convective heat flow in Yellowstone National Park: Second United Nations Symposium on the Development and Use of Geothermal Resources, p.731-739.

Fraser, G. D., H. A. Waldrop, H. J. Hyden, 1969, Geology of the Gardiner Area Park County Montana: U. S. Geol. Surv. Bull. 1277, 118p.

Fritz, W. J., 1980a, Stratigraphic framework of the Lamar River Formation in Yellowstone National Park: Northwest Geology, v.9, p. 1-8.

Fritz, W. J., 1980b, Reinterpretation of the depositional environment of the Yellowstone "fossil forests": Geology, v.8, no.7, p. 309-313.

Iyer, H. M., 1979, Deep continental structure under Yellowstone National Park, U.S.A.: A continental "hot spot": Tectonophysics, v. 56, p. 165-197.

Keefer, W. R., 1971, The geologic story of Yellowstone National Park: U. S. Geol. Surv. Bull 1347, 92p.

Keith, T. E. C., D. E. White, and M. H. Beeson, 1978, Hydrothermal alteration and self-sealing in Y-7 and Y-8 drill holes in northern part of Upper Geyser Basin, Yellowstone National Park, Wyoming: U. S. Geol. Surv. Prof. Paper 1054-A, 26p.

Marler, G. D., 1951, Exchange of function as a cause of geyser irregularity: Am. Jour. Sci., v. 249, p. 329-342.

Marler, G. D., 1964, Effects of the Hebgen Lake earthquake of August 17, 1959, on the hot springs of the Firehole Geyser Basin Yellowstone National Park: U. S. Geol. Surv. Prof. Paper 435-Q, p.185-197.

Marler, G. D., 1973, Inventory of thermal features of the Firehole River Geyser Basins and other selected areas of Yellowstone National Park, NTIS PB-221 289, 639p.

Marler, G. D., and D. E. White, 1975, Seismic Geyser and its bearing on the origin and evolution of geysers and hot springs of Yellowstone National Park: Geol. Soc. of America Bull., v. 86, p. 749-759.

Morgan, P., D. D. Blackwell, and R. E. Spafford, 1977, Heat flow measurements in Yellowstone Lake and the thermal structure of the Yellowstone Caldera: Jour. Geophys. Res., v. 82, p. 3732.

Muffler, L. J. P., D. E. White, and A. H. Truesdell, 1971, Hydrothermal explosion craters in Yellowstone National Park: Geol. Soc. of America Bull., v.82, no.3, p. 723-740.

Pierce, K. L., 1973, Surficial geologic map of the Mammoth Quadrangle and part of the Gardiner Quadrangle, Yellowstone National Park, Wyoming and Montana: U. S. Geol. Surv. Map I-641.

Pierce, K. L., 1974, Surficial Geologic Map of the Tower Junction Quadrangle and part of the Mount Wallace Quadrangle, Yellowstone National Park, Wyoming and Montana: U. S. Geol. Surv. Map I-647.

Pierce, K. L., 1979, History and dynamics of glaciation in the northern Yellowstone National Park Area: U. S. Geol. Surv. Prof. Paper 729F, 90p.

Prostka, H. J., H. R. Blank, Jr., R. L. Christiansen, and E. T. Ruppel, 1975 Geologic map of the Tower Junction Quadrangle, Yellowstone National Park, Wyoming and Montana: U. S. Geol. Surv. Map GQ-1247.

Richmond, G. M., 1976, Surficial geologic history of the Canyon Village Quadrangle, Yellowstone National Park, Wyoming, for use with Map I-652: U. S. Geol. Surv. Bull. 1427, 35p.

Richmond, G. M., 1977, Surficial geologic map of the Canyon Village Quadrangle, Yellowstone National Park, Wyoming: U. S. Geol. Surv. Map I-652.

Richmond, G. M., and H. A. Waldrop, 1975, Surficial geologic map of the Norris Junction Quadrangle, Yellowstone National Park, Wyoming: U. S. Geol. Surv. Map I-650.

Richmond, G. M., W. Mollenders, and M. Coremans, 1978, Climatic implications of two pollen analyses from newly recognized rocks of latest Pliocene age in the Washburn Range, Yellowstone National Park, Wyoming: U. S. Geol. Surv. Bull. 1455, 13p.

Rosholt, J. N., 1976, $^{230}Th/^{234}U$ dating of travertine and caliche rinds, Geol. Soc. of Am. Abs. with Progs., v.8, no.6, p.1076.

Rowe, J. J., R. O. Fournier, and G. W. Morey, 1973, Chemical analysis of thermal waters in Yellowstone National Park, Wyoming, 1960-65: U. S. Geol. Surv. Bull. 1303, 31p.

Ruppel, E. T., 1972, Geology of pre-Tertiary rocks in the northern part of Yellowstone National Park, Wyoming: U. S. Geol. Surv. Prof. Paper 729-A, 66p.

Schultz, C. H., 1962, Petrology of Mt. Washburn, Yellowstone National Park, Wyoming: unpub. PhD dissertation, The Ohio State University, 225p.

Smedes, H. W., and H. J. Prostka, 1972, Stratigraphic framework of the Absaroka volcanic supergroup in the Yellowstone National Park Region: U. S. Geol. Surv. Prof. Paper 729-6, 33 p.

Smith, R. B., R. T. Shuey, J. R. Pelton, and J. P. Bailey, 1977, Yellowstone Hot Spot: contemporary tectonics and crustal properties from earthquake and aeromagnetic data: Jour. Geophys. Res., v. 82, p. 3665-3676.

Smith, R. L., H. R. Shaw, R. G. Luedke, and S. L. Russell, 1978, Comprehensive tables giving physical data and thermal energy estimates for young igneous systems of the United States: U. S. Geol. Surv. Open File Report 78-925, 15p.

Smith, R. B. and R. L. Christiansen, 1980, Yellowstone Park as a window on the earth's interior: Scientific American, v. 242 , p. 104-117.

Struhsacker, D. W., 1978, Mixed basalt-rhyolite assemblages in Yellowstone National Park the petrogenetic significance of magma mixing: unpub. M.S. Thesis, Univ. Montana, Missoula, Montana, 112p.

Struhsacker, E. M., 1976, Geothermal systems of the Corwin Springs-Gardiner Area, Montana: possible structural and lithologic controls: unpub. M.S. thesis, Montana State Univ., Bozeman, Montana, 93p.

Thompson, J. M., and S. Yadav, 1979, Chemical Analyses of Waters from geysers, hot springs and pools in Yellowstone National Park Wyoming from 1974 to 1978: U. S. Geol. Surv. Open File Report 79-704.

Truesdell, A. H., and R. O. Fournier, 1976, Conditions in the deeper parts of the hot springs systems of Yellowstone National Park, Wyoming: U. S. Geol. Surv. Open file report 76-428.

U. S. Geological Survey, 1972a, Geologic map of Yellowstone National Park: U. S. Geol. Surv. Map I-711.

U. S. Geological Survey, 1972b, Surficial geologic map of Yellowstone National Park: U. S. Geol. Surv. Map I-710.

Waldrop, H. A., 1975a, Surficial geologic map of the West Yellowstone Quadrangle, Yellowstone National Park and adjoining area, Montana, Wyoming, and Idaho: U. S. Geol. Surv. Map I-648.

Waldrop, H. A., 1975b, Surficial geologic map of the Old Faithful Quadrangle, Yellowstone National Park, Wyoming: U. S. Geol. Surv. Map I-649.

Waldrop, W. A., and K. L. Pierce, 1975, Surficial geologic map of the Madison Junction Quadrangle, Yellowstone National Park, Wyoming: U. S. Geol. Surv. Map I-651.

White, D. E., 1967, Some principles of geyser activity, mainly from Steamboat Springs, Nevada: Am. Jour. Sci., v. 265, p. 641-684.

White, D. E., L. J. P. Muffler, and A. H. Truesdell, 1971, Vapor-dominated hydrothermal systems compared with hot-water systems: Econ. Geol. v. 66, p. 75-97.

White, D. E., R. O. Fournier, L. J. P. Muffler, A. H. Truesdell, 1975, Physical results of research drilling in thermal areas of Yellowstone Nationa Park, Wyoming: U. S. Geol. Surv. Prof. Paper 892, 70p.

White, D. E., 1978, Conductive heat flows in research drill holes in thermal areas of Yellowstone National Park, Wyoming: Jour. Research, U.S. Geol. Survey, v. 6, p. 765-774.