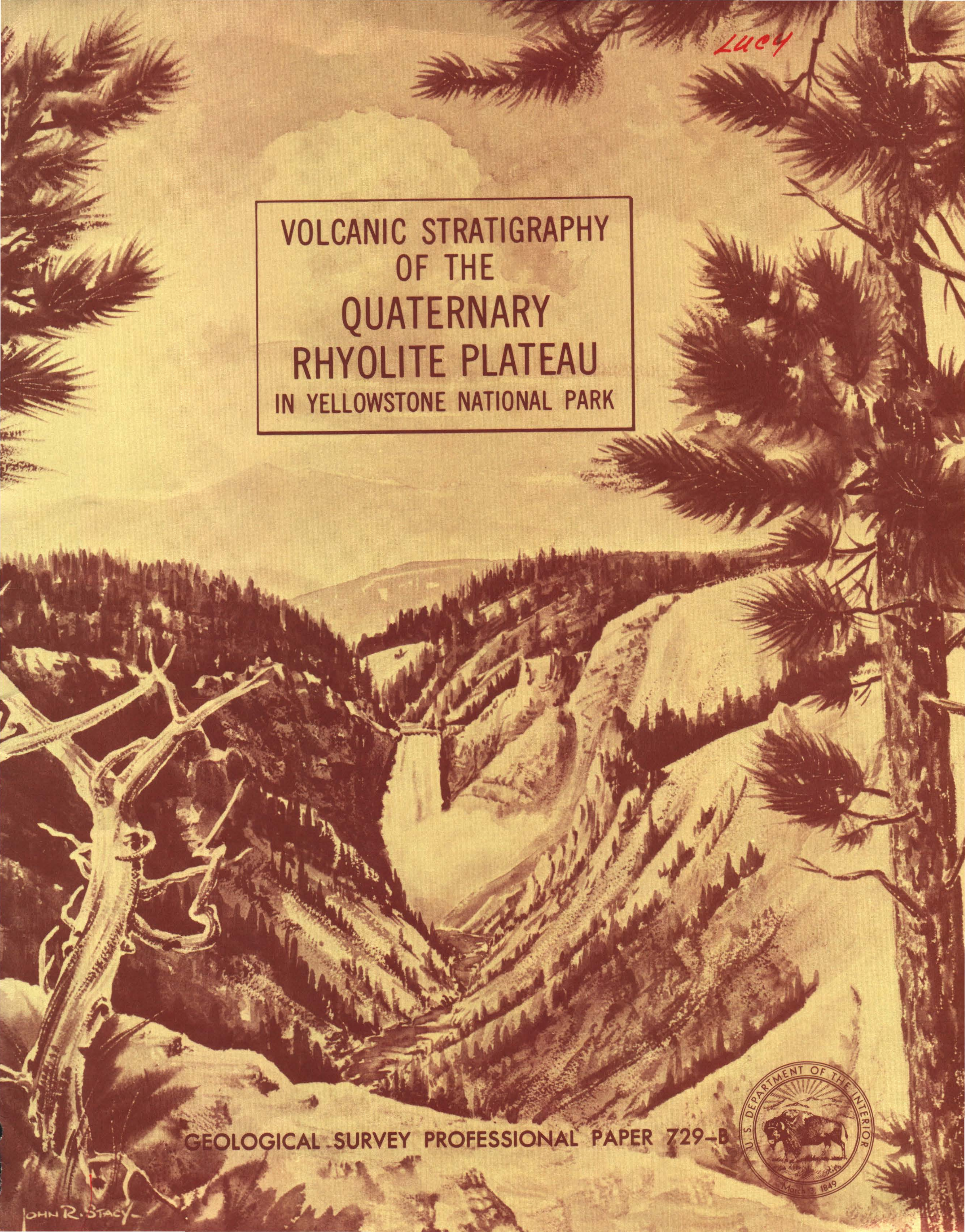
VOLCANIC STRATIGRAPHY OF THE QUATERNARY RHYOLITE PLATEAU IN YELLOWSTONE NATIONAL PARK



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Volcanic Stratigraphy of the Quaternary Rhyolite Plateau in Yellowstone National Park

By ROBERT L. CHRISTIANSEN *and* H. RICHARD BLANK, JR.

GEOLOGY OF YELLOWSTONE NATIONAL PARK

GEOLOGICAL SURVEY PROFESSIONAL PAPER 729-B

Nomenclature for Quaternary volcanic rocks of the Yellowstone rhyolite plateau is based upon recognition of three successive cycles of volcanism, only two of which are identified within the national park

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Yellowstone National Park, the oldest of the areas set aside as part of the national park system, lies amidst the Rocky Mountains in northwestern Wyoming and adjacent parts of Montana and Idaho. Embracing large, diverse, and complex geologic features, the park is in an area that is critical to the interpretation of many significant regional geologic problems. In order to provide basic data bearing on these problems, the U.S. Geological Survey in 1965 initiated a broad program of comprehensive geologic and geophysical investigations within the park. This program was carried out with the cooperation of the National Park Service, and was also aided by the National Aeronautics and Space Administration, which supported the gathering of geologic information needed in testing and in interpreting results from various remote sensing devices. This professional paper chapter is one of a series of technical geologic reports resulting from these investigations.

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VOLCANIC STRATIGRAPHY OF THE QUATERNARY RHYOLITE PLATEAU IN YELLOWSTONE NATIONAL PARK

By ROBERT L. CHRISTIANSEN and H. RICHARD BLANK, JR.

ABSTRACT

The volcanic sequence of the Quaternary Yellowstone plateau consists of rhyolites and basalts representing three volcanic cycles. The major events of each cycle were eruption of a voluminous ash-flow sheet and formation of a large collapse caldera. Lesser events of each cycle were eruption of precaldera and postcaldera rhyolitic lava flows and marginal basaltic lavas. The three major ash-flow sheets are named and designated in this report as formations within the Yellowstone Group. The lavas are assigned to newly named formations organized around the three ash-flow sheets of the Yellowstone Group to represent the volcanic cycles.

Rocks of the first volcanic cycle comprise the precaldera Junction Butte Basalt and rhyolite of Broad Creek; the Huckleberry Ridge Tuff of the Yellowstone Group; and the postcaldera Lewis Canyon Rhyolite and basalt of The Narrows.

Rocks of the second volcanic cycle do not crop out within Yellowstone National Park, and only the major unit, the Mesa Falls Tuff of the Yellowstone Group, is named here.

The third volcanic cycle is represented by the precaldera Mount Jackson Rhyolite and Undine Falls Basalt; the Lava Creek Tuff of the Yellowstone Group; and the postcaldera Plateau Rhyolite and five post-Lava Creek basaltic sequences. Collapse to form the compound and resurgent Yellowstone caldera was related to eruption of the Lava Creek Tuff. The Plateau Rhyolite is divided into six members — the Mallard Lake, Upper Basin, Obsidian Creek, Central Plateau, Shoshone Lake Tuff, and Roaring Mountain Members; all but the Mallard Lake postdate resurgent doming of the caldera. The basalts are divided into the Swan Lake Flat Basalt, Falls River Basalt, basalt of Mariposa Lake, Madison River Basalt, and Osprey Basalt.

Sediments are intercalated in the volcanic section below the Huckleberry Ridge and Mesa Falls Tuffs and within the Junction Butte Basalt, sediments and basalts of The Narrows, Undine Falls Basalt, Plateau Rhyolite, and Osprey Basalt.

INTRODUCTION

This paper summarizes the stratigraphy of volcanic rocks which form the Yellowstone rhyolite plateau, a volcano-tectonic feature of Quaternary age which lies at an average elevation of about 2,500 m (meters), largely within Yellowstone National Park. Rock units which form parts of the plateau sequence but which lie entirely outside the national park are not discussed here except for one major ash-flow tuff which bears directly on the regional stratigraphy. Volcanic rocks of the plateau and its outliers cover more than 6,500 square kilometers in Wyoming, Idaho, and Montana.

Early work on rhyolitic rocks of the Yellowstone region, especially that by Iddings (1888; and in Hague and others, 1899), attracted wide attention. These rocks, however, have received surprisingly little modern study, considering their volume, youth, and potential regional and volcanological significance. The only detailed work of recent years directed specifically toward the rhyolite plateau was the excellent study by Boyd (1961). Other modern studies that have borne importantly on the volcanic rocks of the plateau include those by Howard (1937), Love (1956a, b), Hamilton (1960, 1963, 1964), and Brown (1961). In addition, detailed mineralogic and petrologic studies of single volcanic units include those of Bowen (1935), Fenner (1938), and Wilcox (1944).

Potassium-argon ages referred to in this paper are based on work still in progress by J. D. Obradovich and are stated approximately only in order to aid visualization of the stratigraphy. These ages and the K-Ar analyses will be discussed in a later paper. Terminology used for the features and relations of ash-flow tuffs follows Smith (1960a, b) and Ross and Smith (1961). Figures 1 and 2 identify major features of the area. Most localities referred to in this paper are shown in these figures. Features not shown in the figures can be found on the U.S. Geological Survey's topographic map of Yellowstone National Park, published in 1961 (scale 1:125,000).

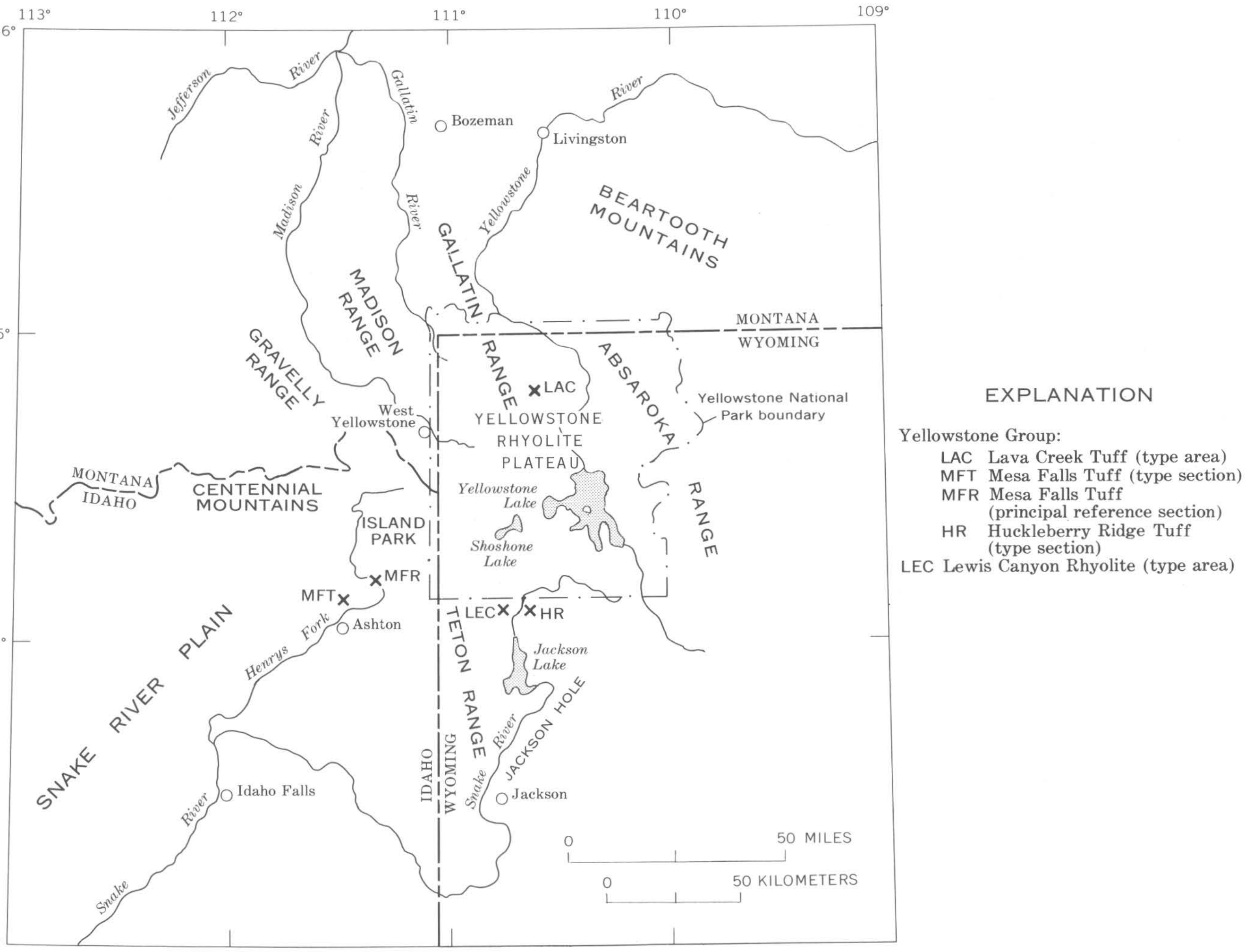


FIGURE 1.—Index map of region around Yellowstone National Park, showing locations of type sections of formations in the Yellowstone Group, type area of Lewis Canyon Rhyolite, and features outside the national park referred to in text.

GENERAL GEOLOGIC RELATIONS

Most previous workers considered the rhyolites and basalts of the Yellowstone plateau to be of Pliocene age. Richmond and Hamilton (1960) and Hamilton (1960) first called attention to relations which suggested a late Quaternary age for some of the youngest flows. Stratigraphic relations that we have worked out, together with extensive and continuing potassium-argon dating by J. D. Obradovich, show that virtually all of the plateau volcanism was younger than about 2 m.y. (million years) and that some was as young as about 70,000 years. We consider all of this time span to be within the Quaternary, and this seems to accord with the present thinking of most stratigraphers.

The volcanic rocks of the Quaternary rhyolite plateau are virtually all either rhyolites or basalts, and the rhyolites are greatly predominant. The rare rocks of intermediate composition are mixed lavas with rhyolitic and basaltic components. Areally, the plateau consists of two parts, as demonstrated by Boyd (1961)—an outer ring that consists largely of rhyolitic welded tuff but also lesser amounts of rhyolitic and basaltic lavas, and an inner area covered mainly by rhyolitic lava flows, some of them very large (fig. 2). The inner lavas partly filled an enormous elliptical caldera, 70 by 45 km (kilometers) across, and spilled over its margins in places, especially on its southwest side.

Although rimmed by mountains on its other sides, the Yellowstone rhyolite plateau along its southwestern margin overlooks the eastern Snake River Plain, a topographically lower area also covered largely by Quaternary volcanic rocks, principally basalts but including subordinate rhyolites. The transitional Island Park region lies between the plateau and the plain and was shown by Hamilton (1965) to be a large caldera. Our study extends to include the Island Park area, and although we do not discuss it here at length, its history is intimately related to that of the Yellowstone rhyolite plateau and is partly contemporaneous.

We have found that the ash-flow tuffs which largely constitute the outer part of the Yellowstone rhyolite plateau and its outliers comprise three major ash-flow sheets, each principally a single cooling unit separated from the others by major unconformities. These three ash-flow sheets form a basis for dividing the entire volcanic section into three parts, each of which represents a volcanic cycle in the evolution of its respective source area. The plan of the paper, therefore, is to describe first the three major ash-flow sheets and then to discuss the volcanic stratigraphy of the rhyolite plateau in terms of these cycles. Table 1 summarizes the stratigraphic nomenclature outlined here. Figure 3 shows some of the stratigraphic relations between the units outlined in table 1. Because the second cycle was completely confined to the Island Park region, it will not be discussed at length.

YELLOWSTONE GROUP

We recognize three cooling units of ash-flow tuff as the major stratigraphic units of the rhyolite plateau and establish them here as the Huckleberry Ridge, Mesa Falls, and Lava Creek Tuffs of the Yellowstone Group. Boyd (1961, p. 393–400) named and described the Yellowstone Tuff, but he did not provide a formal stratigraphic definition of the unit. The two exposures he described in most detail are sections of two of the three ash-flow sheets recognized in this paper. Since these three sheets, as discussed in the following paragraphs, are separated by unconformities representing time spans of 600,000–800,000 years and are associated in their source areas with overlying and underlying lavas, each is designated here as a separate formation. The name Yellowstone Group now replaces the Yellowstone Tuff of the literature (for example, Boyd, 1961; Brown, 1961; Fraser and others, 1969; Witkind, 1969) which clearly has been used to include at least two of our three formations. We define the Yellowstone Group here as the rhyolitic tuffs which constitute the three ash-flow formations designated in this paper. No single exposure shows all three formations in unbroken succession, but the stratigraphic relations are shown by mapping in the Island Park area and in the southern part of the Madison Range, or Henrys Lake Mountains.

The Yellowstone Group lies on rocks as old as Precambrian and as young as early Quaternary. In many areas, particularly in eastern Yellowstone National Park, the group overlies rocks of the Absaroka Volcanic Supergroup of Eocene age (Smedes and Prostka, 1972).

All three formations of the Yellowstone Group consist mainly of welded ash-flow tuff, predominantly devitrified, containing phenocrysts of quartz, sanidine, and sodic plagioclase. Common minor phenocrysts are opaque oxides, clinopyroxene, fayalite, zircon, hornblende, allanite, and chevkinite.

HUCKLEBERRY RIDGE TUFF

We name the Huckleberry Ridge Tuff, the oldest ash-flow sheet of the Yellowstone Group, for the topographic crest east of the Snake River just south of Yellowstone National Park and north of Jackson Lake. The type section (fig. 1) is designated as the cliff exposure at the head of a large landslide 1.8 km N. 10° E. of the Snake River bridge at Flagg Ranch on the highway about 3 km south of the South Entrance of Yellowstone National Park. The Huckleberry Ridge Tuff, locally as thick as 300 m, is exposed widely around the margins of Yellowstone National Park and in surrounding areas south to southern Jackson Hole, north down the valley of the Gallatin River as far as the West Fork, and west into the Island Park region to the edge of the younger lavas of the Snake River Plain. In central Yellowstone Park the formation is largely buried by younger rocks. The Huckleberry Ridge in various areas overlies eroded rocks of virtually every major older unit exposed in the Yellowstone region. West of Yellowstone Park the formation commonly is overlain by the Mesa Falls Tuff, but in most other areas it is most commonly overlain by the Lava Creek Tuff.

The type section of the Huckleberry Ridge is about 170 m thick and consists mainly of welded phenocryst-rich rhyolitic ash-flow tuff forming a single compound cooling unit. The tuff overlies sandstones and shales of Cretaceous age and is eroded at the top, but regional relations indicate that no more than a few meters has been removed along the present topographic surface. The section is divided into three widely mappable informal members on the basis of significant changes in welding

Figure 2. — Index map showing major localities in Yellowstone National Park referred to in text.

EXPLANATION

Plateau Rhyolite

Other rocks of third volcanic cycle

Rocks of first volcanic cycle

Plateau Rhyolite:
- Roaring Mountain Member:
  - RCS Crystal Spring flow
  - RO Obsidian Cliff flow
  - RCC Cougar Creek flow
  - RR Riverside flow
- Obsidian Creek Member:
  - OGR Mixed lavas of Gardner River
  - OGL Mixed lavas of Grizzly Lake
  - OW Willow Park dome
  - OA Apollinaris Spring dome
  - OL Landmark dome
  - OGH Gibbon Hill dome
  - OGC Geyser Creek dome
  - OPH Paintpot Hill dome

OS Osprey Basalt (type section)
MR Madison River Basalt (type area)
SLF Swan Lake Flat Basalt (type area)
LAC Lava Creek Tuff (type area)
- SC Upper member; Sheepeater Canyon (principal reference section)
- PM Lower member; Purple Mountain (principal reference section)

UF Undine Falls Basalt (type locality)

and minor variations in phenocryst content. The lowest member, about 45 m thick, consists of a few centimeters of nonwelded to partially welded glassy ash-flow tuff overlain successively by about 1 m of black vitrophyric welded tuff, about 2 m of dark-gray microspherulitic densely welded tuff, and a brown-weathering devitrified zone. The basal part of the member contains abundant (40–50 percent) phenocrysts. About 30 m above the base, phenocrysts become less abundant; from there upward they decrease in size and abundance for about 15 m. This widely mapped zone of relatively sparse phenocrysts contains a thin zone near the top in which the tuff is less densely welded than that below or above, and this zone is used to divide the lower two members. The middle member, about 30 m thick, has a thin basal phenocryst-poor zone; above, it has abundant large phenocrysts, and at the top it contains conspicuous dark-gray to brown crystallized pumice along with light-colored crystallized and collapsed pumice typical of the member as a whole. This two-pumice, large-phenocryst zone is overlain sharply by the third member, about 95 m thick, which is characterized by moderately abundant phenocrysts that are distinctly smaller than those in the underlying units. The upper member shows marked lineation of stretched pumice and alined phenocrysts and minor flowage folding of the compaction foliation.

Basal air-fall tuffs are as much as about 2 m thick north of central Yellowstone Park but are thin or absent to the south. The lower two members of ash-flow tuff of the type section of the Huckleberry Ridge, separated by a relatively phenocryst-poor zone and a partial welding break (a devitrified but less densely welded zone between two devitrified more densely welded zones), have been traced virtually everywhere the formation is found. The commonly lineated, upper member occurs only south of central Yellowstone Park. Although this upper member is demonstrably an ash-flow tuff, in many exposures it superficially resembles a rhyolitic lava flow. This characteristic of the member, which constitutes a large proportion of the highly altered exposures in the Red Mountains in southern Yellowstone National Park, in part led Boyd (1961) to regard the rocks there as mainly rhyolite flows which he designated the Red Mountains Rhyolite. The base of this upper member in many places overlies a thin crystal ash and grades southward from the type section into a separate cooling unit; the Huckleberry Ridge Tuff as a whole, therefore, is a composite sheet.

Potassium-argon dating of sanidine from the Huckleberry Ridge Tuff by J. D. Obradovich (written commun., 1970) indicates an age of 2 m.y.

MESA FALLS TUFF

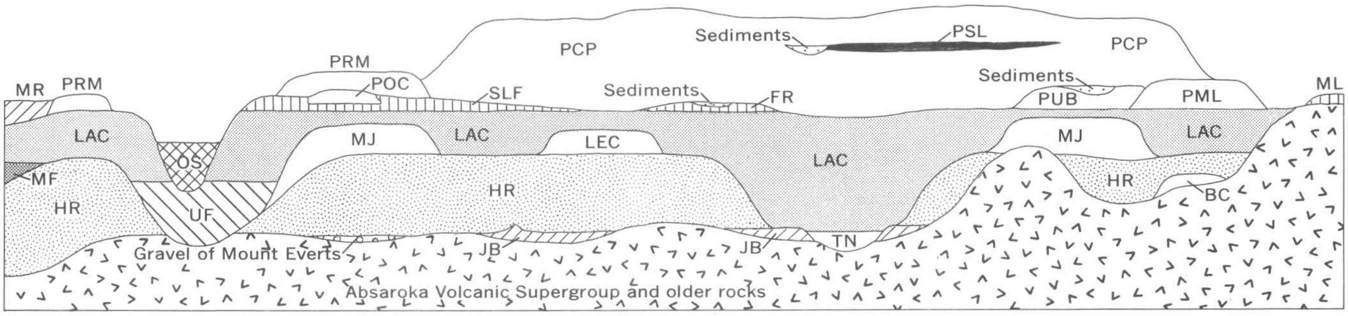
The Mesa Falls Tuff, the middle ash-flow sheet of the Yellowstone Group, does not crop out within Yellowstone National Park, but we name and briefly describe it in order to provide a complete summary of the Yellowstone Group and to help outline the Quaternary volcanic evolution of the Yellowstone region. The formation is named here for Upper Mesa Falls on the Henrys Fork of the Snake River in the Island Park area of eastern Idaho. The type section (fig. 1) is designated as the roadcut on U.S. Highway 20 about 6.8 km north of Ashton, Idaho.

TABLE 1. — *Summary of stratigraphic nomenclature*

Approximate age (million years)	Volcanic cycle	Rhyolites	Basalts and sediments
			Sediments of late Bull Lake through Holocene age
0.07	Third	Plateau Rhyolite: Roaring Mountain Member Central Plateau Member Shoshone Lake Tuff Member Obsidian Creek Member Upper Basin Member Mallard Lake Member	Osprey Basalt (includes gravels) Madison River Basalt Swan Lake Flat Basalt Falls River Basalt Basalt of Mariposa Lake Sediments of Potts Hot Springs, till of Bechler Meadows, sediments of Sevenmile Hole, sediments of Upper Falls, sediments of Lower Falls, sediments of Red Rock, sediments of Inspiration Point
0.6	Third	Lava Creek Tuff of Yellowstone Group	
	Third		Undine Falls Basalt (includes gravels)
<0.8	Third	Mount Jackson Rhyolite	
1.2	Second	Mesa Falls Tuff of Yellowstone Group	
1.6	First		Sediments and basalts of The Narrows
	First	Lewis Canyon Rhyolite	
2.0	First	Huckleberry Ridge Tuff of Yellowstone Group	
<2.4	First	Rhyolite of Broad Creek	Junction Butte Basalt (includes gravels) Gravel of Mount Everts

The Mesa Falls Tuff varies greatly in thickness but commonly is more than 100 m thick. It is present mainly in the Island Park area and on the lower slopes of the Centennial Mountains and the southern Madison Range. The Mesa Falls overlies the Huckleberry Ridge Tuff and older units, and in the Island Park area it overlies lavas of the second volcanic cycle that are not discussed in this report. The Mesa Falls most commonly is overlain by the Lava Creek Tuff, but in the Island Park area second-cycle volcanic units also overlie the Mesa Falls.

The type section of the Mesa Falls is shown in a photograph by Hamilton (1965, fig. 3). At that locality a thick basal air-fall pumice and a thin distal ash-flow tuff overlie a buried loess and a deeply weathered outcrop of the lower member of the Huckleberry Ridge Tuff. The basal 5–6 m of the type section of the Mesa Falls Tuff consists of well-sorted and well-bedded air-fall pumice and crystals, commonly several millimeters to a centimeter or more in grain size. This basal air-fall pumice is overlain by phenocryst-rich (about 40 percent) ash-flow tuff about 15 m thick with conspicuously large feldspar phenocrysts (some greater than 1 cm). The ash-flow tuff forms a simple cooling unit, nonwelded and glassy in the basal 1½ m, overlain by a pale-pink vapor-phase zone. The top of the section is eroded, but regional relations show that only the presumed original glassy nonwelded top of the cooling unit, probably never more than a few meters



EXPLANATION

Third volcanic cycle:
- PRM Roaring Mountain Member (Plateau Rhyolite)
- PCP Central Plateau Member (Plateau Rhyolite)
- PSL Shoshone Lake Tuff Member (Plateau Rhyolite)
- POC Obsidian Creek Member (Plateau Rhyolite)
- PUB Upper Basin Member (Plateau Rhyolite)
- PML Mallard Lake Member (Plateau Rhyolite)
- 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
- UF Undine Falls Basalt
- MJ Mount Jackson Rhyolite

Second volcanic cycle:
- MF Mesa Falls Tuff

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

FIGURE 3.—Diagrammatic relations between stratigraphic units outlined in table 1. Not all possible stratigraphic relations discussed in text are shown.

thick, is missing. The Mesa Falls has been traced continuously along the ridges and roadcuts to more densely welded tuff about 5 km north, where the formation is thicker and has a conspicuous pinkish-brown devitrified zone.

The type section is the only easily accessible good exposure of virtually the entire ash-flow sheet. Nevertheless, because the ash-flow tuff there is only a thin distal part of the sheet, the section is not representative in gross lithology of the formation as a whole. For this reason we designate the cliffs along the gorge of the Henrys Fork at Upper Mesa Falls as the principal reference section (fig. 1). Here the characteristic lithology of thicker sections of the formation is seen. A thick pinkish devitrified zone with abundant large phenocrysts forms the wall of the inner gorge of the river at the level of the falls. The base is not exposed but probably is not far beneath the level of exposures. A thickness of about 140 m is exposed. The devitrified zone grades upward into a vapor-phase zone that is poorly exposed on the east side of the upper canyon wall in roadcuts above the falls. Just below the rim of the upper canyon wall near the top of the road to the falls, the Mesa Falls Tuff is overlain by the Lava Creek Tuff, but the contact is not exposed. Basalts cap the section where the road crosses the canyon rim. A section of the Mesa Falls (complete except for the base) is well exposed on the nearly inaccessible west wall of the gorge at Upper Mesa Falls.

Sanidine from the Mesa Falls Tuff has been dated by the K-Ar method by J. D. Obradovich (written commun., 1970) as 1.2 m.y. old.

LAVA CREEK TUFF

The Lava Creek Tuff, the upper ash-flow sheet of the Yellowstone Group, is named here for a stream which enters the Gardner River about 3 km southeast of Mammoth. The formation is divided throughout its extent into two major informal members. They are exposed overlying the Huckleberry Ridge Tuff in a 210-m-thick section in the walls of the upper canyon of Lava Creek and its tributary, Arrow Canyon. This is designated the type area (figs. 1 and 2). Arrow Canyon and nearby parts of Lava Creek canyon are more than 13 km from the nearest roads or trails; there is no readily accessible exposure of the Lava Creek Tuff in which both of its members as well as its base and top are well exposed. We therefore designate a more accessible principal reference section for each of the members.

The Lava Creek Tuff is more than 300 m thick in several areas. The formation occurs widely in Yellowstone National Park and has been traced south to Jackson Lake, westward through much of the Island Park area to the southern foothills of the Centennial Mountains, and southwestward along the margin of the Snake River Plain to the south side of the Snake River about 25 km northeast of Idaho Falls. The Lava Creek in various areas overlies most of the older rock units exposed in the region. Around the margins of the Yellowstone plateau, the Lava Creek commonly overlies the Huckleberry Ridge Tuff. The Lava Creek is overlain by most of the younger units of the third volcanic cycle in and near Yellowstone National Park.

The principal reference section of the lower member is the south-facing cliff of Purple Mountain above an old gravel pit about 1 km east of Madison Junction (fig. 2). The section overlies the Mount Jackson Rhyolite and is overlain a few kilometers northeast by the upper member of the Lava Creek Tuff; a few patches of Madison River Basalt lie on the lower member on benches in the cliff southwest of Purple Mountain. In its basal 300 m the lower member has somewhat fewer and distinctly smaller phenocrysts and is less densely welded than above. Collapsed pumice in this less densely welded basal portion, though not particularly more abundant, is more conspicuous than above; rhyolitic lithic inclusions (including welded tuffs) are especially abundant. Boyd (1961, p. 393) called this basal part the Purple Mountain Pumice Breccia, but we regard it only as a unit of the lower member of the Lava Creek Tuff and do not believe that it warrants a separate formal name. This basal unit is overlain sharply by devitrified densely welded tuff with especially abundant large phenocrysts. This densely welded tuff, about 180 m thick here, is typical of the member in most localities and generally weathers to crumbly dark-brown crudely columnar outcrops or to steep grussy slopes. The lower member of the Lava Creek Tuff is the only part of the Yellowstone Group in which hornblende is more abundant than pyroxene.

Boyd (1961, p. 393) correlated outcrops of partially welded tuff containing abundant lithic inclusions in the Stonetop Mountain area, north of Yellowstone Lake, with the Purple Mountain Pumice Breccia. Our mapping, however, shows that these outcrops are in the upper, not the lower, member of the Lava Creek.

The principal reference section of the upper member is on the east wall of Sheepeater Canyon on the Gardner River 1 km northeast of Osprey Falls (fig. 2). This section was described by Boyd (1961, p. 395) as the only complete section of the Yellowstone Tuff, but it is not a stratigraphically complete section of either the Yellowstone Group or the Lava Creek Tuff. It is a well-exposed section 140 m thick with exposures of both the basal and the upper contacts of the upper member of the Lava Creek. The Lava Creek overlies the Quaternary Undine Falls Basalt, which in turn lies on lower Tertiary intrusive dacite and Cretaceous sedimentary rocks. The member is overlain by the Swan Lake Flat Basalt, which was erupted soon enough after emplacement of the Lava Creek to preserve the unconsolidated ashy and pumiceous top of the member. The basal few meters of air-fall pumice and ash is overlain by about 2 m of phenocryst-rich glassy welded tuff —nonwelded and gray tuff at the base but densely welded black vitrophyre at the top. Above this vitrophyre is about $4\frac{1}{2}$ m of dark-gray microspherulitic densely welded tuff alternating with vitrophyre. Farther above is devitrified generally pinkish brown densely welded tuff with abundant large phenocrysts (a few of them nearly 1 cm) that increase slightly in abundance upward, conspicuous large white collapsed crystallized pumice lenticles, and abundant reddish-brown rhyolitic lithic inclusions. The devitrified zone is almost 90 m thick. It is overlain by an orange-pink vapor-phase zone about 40 m thick. The vapor-phase zone is overlain in turn by $3\frac{1}{2}$ m of unconsolidated nearly white glassy ash-flow tuff of the original top of the cooling unit. This is one of the few known exposures of any of the three ash-flow sheets of the Yellowstone Group in which this frothy glassy top, presumed to have been present initially over the entire area of each ash-flow sheet, is preserved. Locally, where the overlying basalt does not have a rubbly basal breccia, the top of the frothy ash and pumice is reddened and even fused to a depth of a few centimeters.

Where the upper member overlies the lithologically very similar lower member, several meters of relatively phenocryst-poor welded tuff occur in the base of the upper member. This phenocryst-poor zone grades downward from densely welded into partially welded at the contact between the two units, and locally a sorted and bedded crystal ash several centimeters thick forms a parting between the two. A section containing this contact is exposed in roadcuts just downstream from Virginia Cascade on the loop road south of the main highway between Norris Junction and Canyon Village, although constant spalling of the cuts generally covers the contact itself.

The Yellowstone caldera formed by collapse of the magma-chamber roof as a result of eruption of the Lava Creek Tuff. The two members were erupted in immediate succession from adjacent but distinct source areas, each of which formed a discrete caldera segment with its own central resurgent dome.

Sanidine from the Lava Creek Tuff has been dated by the K-Ar method by J. D. Obradovich (written commun., 1970) as 600,000 years old. Richmond (1970b, p. 8, 21) noted that ash beds probably derived from the Lava Creek eruptions are slightly younger than deposits of the Cedar Ridge Glaciation (Rocky Mountains) and of the Kansan Glaciation (Great Plains).

ROCKS OF THE FIRST VOLCANIC CYCLE

The Huckleberry Ridge Tuff and the rhyolitic and basaltic lavas associated temporally and spatially with it are discussed here as the first volcanic cycle of the rhyolite plateau. The record of this cycle is quite incomplete because much of the source area of the Huckleberry Ridge and associated rocks was disrupted by later deformation and is now covered by younger rocks. Little else than marginal parts of the first-cycle volcanic fields can be observed within Yellowstone National Park. However, parts of a large caldera related to eruption of the Huckleberry Ridge Tuff are preserved in the southern Island Park area and between Grassy Lake Reservoir and the Red Mountains (figs. 1, 2).

JUNCTION BUTTE BASALT

The basalts of the Yellowstone rhyolite plateau, although not nearly as voluminous as the rhyolites, occur widely around the plateau margins. None of them, however, crops out within the source areas of the major ash-flow tuffs. Thus it is somewhat difficult to assign individual basaltic units confidently to the different volcanic cycles in a genetic sense. One can reasonably say that basaltic volcanism was intermittently active around the margins of the plateau before, during, and after each of the major rhyolitic cycles. Nevertheless, it is possible to show that certain basaltic units are time and stratigraphic relatives of the major rhyolitic units, and it is in this sense that the Junction Butte Basalt is discussed with the first volcanic cycle.

The name Junction Butte Basalt is given here to basalts in northern Yellowstone National Park that conformably underlie the Huckleberry Ridge Tuff. The name comes from the prominent butte between the Yellowstone and Lamar Rivers, but the type locality is designated as the west side of the Grand Canyon of the Yellowstone opposite the mouth of Deep Creek (fig. 2). Outcrops of Junction Butte Basalt occur in the valley of the Yellowstone River and on adjacent uplands from near Deep Creek to Blacktail Deer Creek and Mount Everts. The basalts unconformably overlie the Absaroka Volcanic Supergroup and Paleozoic and Precambrian rocks. The top of the Junction Butte commonly is an erosionally stripped surface, but locally the Huckleberry Ridge Tuff, the Mount Jackson Rhyolite, or the Lava Creek Tuff overlies it.

At its type locality the Junction Butte lies in a paleovalley eroded in Eocene volcanic rocks of the Absaroka Supergroup and is overlain unconformably by the Wapiti Lake flow of the Mount Jackson Rhyolite and by the Lava Creek Tuff. The basalt section at the type locality is about 90 m thick and consists of three or four thick flows. A few kilometers downstream, below the mouth of Tower Creek, only a single flow of the Junction Butte Basalt is exposed. This flow, the Overhanging Cliff flow, is about 30 m thick where it forms the spectacular roadside cliff just north of Tower Creek. In this cliff and in other good exposures along the canyon rims downstream, the flow is characterized by well-developed two-tiered columnar jointing. The lower colonnade is commonly about 2½–3 m thick, and small blocks from the upper zone, or entablature, of irregularly intersecting prismatic joints generally form conspicuous black talus cones beneath cliff exposures. The basalt is black and aphanitic in hand specimen and contains only sparse plagioclase phenocrysts. In the valley of Tower Creek the Overhanging Cliff flow and a lithologically similar overlying flow lie topographically below the Huckleberry Ridge Tuff. Although the contact is not well exposed, parallelism of the respective outcrop bands along 2 km of a narrow canyon suggests that the basalts are concordant beneath the ash-flow tuff.

A few meters of gravel and associated sand and silt commonly lies at the base of the Junction Butte Basalt. Inasmuch as earlier workers had difficulty in determining age relations between certain outcrops of the Overhanging Cliff flow and the Yellowstone Tuff, we carefully searched the underlying gravels for clasts from ash-flow tuffs of the Yellowstone Group. We have failed to find any, although a few cobbles of welded tuff from the underlying Eocene Absaroka Volcanic Supergroup do occur. Howard (1937, p. 36–80) similarly noted the presence of less than 1 percent rhyolites in the same gravels. These gravels contrast with the younger sediments of The Narrows which contain moderately abundant (commonly 10–15 percent) welded tuff cobbles of the Yellowstone Group — although, for reasons not clear to us, Brown (1961, p. 1182–1183) stated that he could find no rhyolite clasts in either of the two gravels we distinguish in the Tower Creek area. These observations support the conclusion that the Overhanging Cliff flow is older than the Huckleberry Ridge Tuff.

Basalt which we regard as Junction Butte crops out conformably beneath the Huckleberry Ridge and above Cretaceous shales and sandstones on the southeast side of Mount Everts, on the steep slopes extending about 3 km west from just northwest of Blacktail Pond. The basalt ranges in thickness from a few meters to about 100 m. Two flows are present in the sequence, and the outcrops closest to Blacktail Pond form a buried mound of scoria and cinders, probably representing the source vent for the flows.

The Junction Butte Basalt has not been dated isotopically, but it probably is only slightly older than the 2-m.y.-old Huckleberry Ridge. Flows in the Tower Creek–Grand Canyon area all have stable reverse remanent magnetic polarities and, therefore, probably are less than about 2.4 m.y. old (Cox, 1969, fig. 4). The two flows on Mount Everts are normally polarized and may be older or younger, but preservation of a cinder cone conformably beneath the Huckleberry Ridge suggests that the basalt is barely older than the tuff.

RHYOLITE OF BROAD CREEK

The rhyolite of Broad Creek underlies the Huckleberry Ridge Tuff and crops out only in the area east of the Grand Canyon of the Yellowstone on the east side of Broad Creek between about ½ and 2½ km south of the Wapiti Lake Trail (fig. 2). A single flow about 60 m thick forms the unit as exposed. The flow forms the base of the exposure at this locality. The rhyolite contains about 30 percent quartz, sanidine, and plagioclase phenocrysts, and it has the steeply dipping flow layering typical of the upper portions of rhyolitic lava flows.

This early rhyolite of the first cycle has not been dated isotopically but appears to be conformable beneath the overlying welded tuff. We presume that the flow represents some of the earliest rhyolitic activity of the Yellowstone rhyolite plateau but that it is not much older than the 2-m.y.-old Huckleberry Ridge.

LEWIS CANYON RHYOLITE

The Lewis Canyon Rhyolite is named here for the excellent exposures in Lewis Canyon between Lewis Lake and the Snake River. The formation consists of several bulbous, nonstratiform rhyolitic lava flows, but we have recognized no more than one in any single section. The north side of Glade Creek, between the Snake River and the east end of Grassy Lake Reservoir, is designated the type area (fig. 1). In this area, the Lewis Canyon Rhyolite overlies the Huckleberry Ridge Tuff and Cretaceous sedimentary rocks and is overlain by the Lava Creek Tuff. The contacts in this area are not well exposed, but the relations are clear from mapping. The rhyolite is well exposed on the north side of Glade Creek along the meadows about 3 km southeast of Grassy Lake Reservoir. The flow is more than 200 m thick in the type area.

Exposures of the formation are excellent in Lewis Canyon, but the base is not exposed there. As in the Glade Creek area, the Lewis Canyon is overlain by the Lava Creek Tuff. The base of the Lewis Canyon Rhyolite is again poorly exposed above Paleozoic and Mesozoic sedimentary rocks about 7 km east of Lewis Canyon, at the east end of nearly continuous exposures along the north side of the Snake River between the Lewis River and Red Creek.

The rhyolite has 30–40 percent conspicuous phenocrysts, including abundant much-embayed sodic oligoclase, generally about 5 millimeters long, and less abundant, slightly smaller phenocrysts of quartz, sanidine, clinopyroxene, and opaque oxides. Despite the abundant plagioclase and relatively sparse sanidine, chemical analyses show the rocks to be rhyolites.

Boyd (1961, p. 392) regarded the Lewis Canyon Rhyolite as part of his Jackson flows, but we separate the Lewis Canyon from the Mount Jackson Rhyolite (as we call the remainder of his Jackson flows) on the basis of their different lithology, particularly the phenocryst assemblages, and on what appears to us to be a significantly different relation to the Huckleberry Ridge and Lava Creek Tuffs, despite the occurrence of both rhyolites between the two. The Mount Jackson Rhyolite is conformable beneath the Lava Creek and was erupted from vents around what was to become the third-cycle, Yellowstone caldera. By contrast, the Lewis Canyon

Rhyolite is overlain on an erosional unconformity by the Lava Creek and appears to be closer in age to the first-cycle Huckleberry Ridge Tuff, the Lewis Canyon filling a segment of the first-cycle caldera. The Lewis Canyon is petrographically similar to early postcaldera rhyolite lavas (the Upper Basin Member of the Plateau Rhyolite) similarly situated in the Yellowstone caldera. This suggests parallel roles in evolution of the first and third volcanic cycles for these similar rhyolites.

The age of the Lewis Canyon Rhyolite has not yet been determined isotopically.

SEDIMENTS AND BASALTS OF THE NARROWS

Gravels and basalts near The Narrows of the Grand Canyon of the Yellowstone, below Tower Creek (fig. 2), were included by Pierce, Christiansen, and Richmond (1970) in the Osprey Formation. K. L. Pierce and we have found in subsequent work that the sediments and basalts in the vicinity of The Narrows formerly included in the Osprey postdate the Huckleberry Ridge Tuff but predate the Lava Creek Tuff. The correlation with the Osprey, therefore, was in error. We will use informal terminology for this unit until the pertinent geologic relations can be discussed more fully in a later paper. For the present we note only that four basaltic lava flows, most of them very thick and with conspicuous two-tiered columnar jointing, are interlayered with the sediments of The Narrows. The four flows all contain plagioclase phenocrysts, and the upper flow is particularly coarse grained.

The sediments and basalts of The Narrows lie in a paleovalley cut through the Huckleberry Ridge Tuff and the underlying Junction Butte Basalt, and the gravels contain abundant clasts of the Huckleberry Ridge. The Lava Creek Tuff has not been found directly overlying these sediments and basalt but is judged to be younger on the basis of the reverse paleomagnetic polarities of all four basalt flows and on the basis of a K-Ar age of 1.6 m.y. for sanidine from an ash bed interlayered in the unit.

ROCKS OF THE SECOND VOLCANIC CYCLE

Because rocks related to the second eruptive cycle of the Yellowstone region are not exposed within the national park, we do not introduce formally any of these formations in this paper other than the Mesa Falls Tuff, already defined. However, in order to emphasize the cyclic nature of Quaternary volcanic activity in the region, we make brief reference to them here. The Mesa Falls Tuff was erupted from the area of the Island Park caldera, and late collapse of that area was related to that eruption. Basaltic and rhyolitic lavas were closely associated in space and time with this volcanism. As in the first and third cycles, some associated lavas predate and others postdate the major ash-flow tuff.

ROCKS OF THE THIRD VOLCANIC CYCLE

Most of the Quaternary volcanic rocks exposed in Yellowstone National Park are related to the third eruptive cycle of the rhyolite plateau. Eruption and emplacement of these rocks were major geologic events of the middle and late Pleistocene history of the Rocky Mountain region. The key event in this cycle was eruption of the Lava Creek Tuff 600,000 years ago and collapse of the roof of its source magma chamber to form the gigantic compound Yellowstone caldera. The stratigraphic succession and petrologic evolution of this volcanic cycle must ultimately serve as a model for interpreting the more fragmentary record of the first and second cycles.

MOUNT JACKSON RHYOLITE

The Mount Jackson Rhyolite is defined here to include rhyolitic lava flows essentially conformable beneath the Lava Creek Tuff of the Yellowstone Group in areas near the wall of the Yellowstone caldera. The formation takes its name from the summit on the cliffs forming the north wall of the Madison Canyon 5½ km west of Madison Junction (fig. 2). The Madison Canyon near Mount Jackson is the type area of the formation. The base of the Mount Jackson Rhyolite is not exposed in the type area, but the formation is overlain by the Lava Creek Tuff along the steeply sloping original surfaces of the flows. Little erosion occurred along this contact before emplacement of the Lava Creek, for the chilled glassy tops of the flows are everywhere preserved at the contact. Two rhyolite flows are present in the Madison Canyon area; the section there is as much as 450 m thick. The upper flow forms the summits and cliffs of Mounts Haynes and Jackson and is separated from the underlying flow by a thin fused tuff exposed near Harlequin Lake.

Rhyolite flows situated similarly with respect to the Lava Creek Tuff are exposed in the vicinity of Big Bear Lake, south of the Madison Canyon; near Wapiti Lake, west of the Mirror Plateau; on Flat Mountain, southwest of Yellowstone Lake; and in one small outcrop on Stonetop Mountain, north of Yellowstone Lake. Each of these flows is correlated with the Mount Jackson Rhyolite, and Boyd (1961, p. 392–393) included most of these localities in his Jackson flows.

The Mount Jackson Rhyolite flows are quite varied in general appearance, as is typical of rhyolitic lavas, but all contain 30–50 percent large phenocrysts of quartz, sanidine, plagioclase, and minor opaque oxides and clinopyroxene. These flows lithologically resemble younger rhyolitic lava flows of the third volcanic cycle and are distinguished mainly by their stratigraphic and structural positions.

J. D. Obradovich (written commun., 1970) has dated sanidine from the two flows in the Madison Canyon area as about 790,000 and 640,000 years old. This accords with the magnetic polarity time scale (Cox, 1969, fig. 4); remanent polarities of the two flows are, respectively, reverse and normal.

UNDINE FALLS BASALT

Basalts underlie the Lava Creek Tuff conformably in two areas. These basalts are named here the Undine Falls Basalt for the waterfall on Lava Creek near the Mammoth–Tower Junction Road just south of Mount Everts. The cliff on the north side of Lava Creek canyon just west of the falls is designated the type locality (fig. 2). The section there is about 6 m thick and consists of several thin basaltic flows overlying Cretaceous shales and sandstones and underlying the Lava Creek Tuff. Similar basalts, regarded as the same sequence of flows, occur as far northeast as Oxbow Creek and as far southwest as Obsidian Creek south of Winter Creek.

Probably correlative basalts occur north of Broad Creek, east of the Grand Canyon of the Yellowstone. Basalt, judged from mapping to be a single flow, occurs in that area between a flow of the Mount Jackson Rhyolite and the Lava Creek Tuff. The source vent is marked by a small scoria and cinder cone 3 km north of the Broad Creek crossing of the Wapiti Lake Trail. We believe this basalt north of Broad Creek to be at least approximately correlative with the type Undine Falls, inasmuch as both are conformable beneath the Lava Creek Tuff and have normal remanent magnetic polarities. We thus presume them both to be younger than 700,000 years.

PLATEAU RHYOLITE

Boyd (1961, p. 403–409) called the rhyolitic lavas younger than his Yellowstone Tuff, other than a few small rhyolite domes and mixed-lava complexes, the Plateau flows. He did not define them formally, but he clearly regarded them as a formation and named them as a composite of the flows of the Madison, Pitchstone, Central, and Solfatara Plateaus and nearby areas. We here name and define the Plateau Rhyolite in an essentially parallel way to include the rhyolitic lava flows of the Yellowstone rhyolite plateau that are younger than the Lava Creek Tuff. Inasmuch as we designate six new members of the formation, each with its own type area, the Plateau Rhyolite is defined here as the rock units that constitute the six named members.

Mallard Lake Member

The Mallard Lake Member of the Plateau Rhyolite is defined here to include rhyolite erupted within the Yellowstone caldera after it formed but before the rise within it of its two resurgent structural domes. The member consists of a single rhyolitic lava flow at least 120 m thick. It is named for a small lake near the center of its outcrop area, about 5 km northeast of Old Faithful (fig. 2). The area around Mallard Lake is designated the type area. The base of the member is nowhere seen in outcrop, but a drill hole near Rabbit Creek, just beyond the edge of the flow at the northwest end of the Mallard Lake resurgent dome, penetrated the underlying Lava Creek Tuff at a depth of only 10 m (White and others, 1969). The Mallard Lake flow is broken by northwest-trending normal faults that form a complex graben along the axis of the dome. The Mallard Lake Member and the graben system are overlain by the Upper Basin and Central Plateau Members of the Plateau Rhyolite. No complete sections of the Mallard Lake Member are exposed, and most of the original glassy shell of the flow has been eroded away. Most exposures are crystallized rhyolite with 20–30 percent phenocrysts of quartz and sanidine. Most mafic phenocrysts are altered to iron oxides. Flow layering is well displayed, and the rocks commonly are thinly flow-laminated.

The Mallard Lake Member is younger than the 600,000-year-old Lava Creek Tuff and is overlain by a flow about 530,000 years old (J. D. Obradovich, written commun., 1970). Structural reasoning suggests that the Mallard Lake is only very slightly younger than the Lava Creek.

Upper Basin Member

The Upper Basin Member, named here, is defined to include early postcaldera rhyolitic lava flows and associated pyroclastic deposits that were erupted within the Yellowstone caldera after resurgent doming. The Upper Basin Member is characterized by abundant plagioclase phenocrysts, commonly oligoclase that is highly embayed.

The type area of the Upper Basin Member is in the Upper Geyser Basin (fig. 2), where outcrops of the member are scattered widely among the sediments and hydrothermal deposits that floor the basin. Four drill holes in the Upper Geyser Basin all bottomed in rhyolite of the Upper Basin Member. These outcrops and drill cores from the Upper Geyser Basin, as well as many outcrops north along the Firehole River nearly to Tangled Creek in the Lower Geyser Basin, are interpreted to belong to a single flow. The steep front of a younger flow of the member forms the south end of the Upper Geyser Basin; the same flow forms the topographic surface around Scaup Lake. Both flows in the type area of the member overlie the Mallard Lake Member and underlie the Central Plateau Member of the Plateau Rhyolite.

Other than in the geyser basins of the Firehole River, rhyolites of the Upper Basin Member are exposed only in the upper Grand Canyon of the Yellowstone and in the area southeast from it to Fern Lake. Boyd (1961, p. 405-406) discussed the Canyon flow, named for the Grand Canyon of the Yellowstone, and relations of that flow along the rim to pyroclastic rocks deeper in the canyon. The flow and tuffs seem to be gradational from one to the other, which led Boyd to suggest tentatively that the Canyon flow is an example of a froth flow, an eruptive mechanism proposed by Kennedy (1955, p. 495) to explain some features of welded tuffs. We disagree with this explanation, but discussion of the mechanisms of eruption is deferred to a later paper. 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 older Mallard Lake Member and the younger intracaldera members of the Plateau Rhyolite generally have little or no phenocrystic plagioclase. The Upper Basin Member, by contrast, has considerably more plagioclase than sanidine phenocrysts, and in some flows the feldspar phenocrysts are exclusively plagioclase. Clinopyroxene too is considerably more abundant in the Upper Basin than in the other members.

Potassium-argon dating, by J. D. Obradovich (written commun., 1970), of sanidine, plagioclase, and nonhydrated glass from rhyolites of the Upper Basin Member shows that most of the flows are only slightly younger than the Lava Creek Tuff, ranging from about 600,000 to 530,000 years old. One flow, however, which we correlate on the basis of its phenocryst mineralogy with the Upper Basin Member, is about 260,000 years old.

Obsidian Creek Member

The Obsidian Creek and Roaring Mountain Members of the Plateau Rhyolite each comprise a series of isolated rhyolitic lava flows and domes that lies wholly outside the Yellowstone caldera and is, therefore, particularly difficult to define in traditional stratigraphic terms. In a sense they are extracaldera parallels of the intracaldera Upper Basin and Central Plateau Members. With this parallel in mind, we here define the Obsidian Creek Member as early post-Lava Creek rhyolitic domes and flows outside the Yellowstone caldera in which plagioclase is a common phenocrystic constituent. In terms both of age and of the petrography of their rhyolitic components, two lava flows of mixed rhyolite and basalt can reasonably be included in the member. The following bodies constitute the member (and thus, by definition, its type area): The mixed lavas of Gardner River (Fenner, 1938, 1944; Wilcox, 1944; Hawkes, 1945) and Grizzly Lake (Boyd, 1961, p. 403); and the Willow Park, Apollinaris Spring, Landmark, Gibbon Hill, Geyser Creek, and Paintpot Hill eruptive domes (fig. 2). The mixed lavas and the domes occur in a north-trending belt between the Norris Geyser Basin area and the Gardner River. Obsidian Creek, for which they are named, parallels much of this belt.

The mixed lava of Gardner River lies partly between flows of the Swan Lake Flat Basalt and partly on the Lava Creek Tuff. All the other bodies can be observed, or can be inferred with considerable confidence from map relations, to lie on the Lava Creek. The mixed lava of Grizzly Lake forms the top of its local stratigraphic section, but the Gardner River, Willow Park, and Apollinaris Spring bodies are overlapped by flows of the Swan Lake Flat Basalt, and the Landmark, Gibbon Hill, Geyser Creek, and Paintpot Hill bodies are overlain by younger flows of the Plateau Rhyolite.

No radiometric age determinations have been made on the Obsidian Creek Member. Stratigraphic relations just cited, however, suggest that at least most of the member is only slightly younger than the Lava Creek Tuff.

Central Plateau Member

The Central Plateau Member of the Plateau Rhyolite is defined here to include late postcaldera rhyolitic lava flows, some of them very large, erupted from vents within the Yellowstone caldera. Eighteen separate flows and domes have been mapped as parts of the member, but seldom can one find more than three flows superposed in a single stratigraphic succession. The type area is designated as the Central Plateau (fig. 2), located in the middle of the Yellowstone caldera between its two separately identified collapse segments. The flows of the member form the Madison, Pitchstone, Central, and Solfatara Plateaus and a few lower areas nearby. There may be other flows in the sequence that are entirely buried. The member constitutes by far the greatest part of the total volume of the Plateau Rhyolite.

The Central Plateau Member overlies the Obsidian Creek, Upper Basin, and Mallard Lake Members of the Plateau Rhyolite; the Lava Creek Tuff; and a few older units. Only surficial sediments of late Pleistocene age overlie the Central Plateau Member. Glacial and nonglacial sedimentary deposits have been identified locally within the member, as is noted in the final section of this report.

Some individual flows of the member are 300 m or more in thickness, and a few extend more than 20 km from their source vents. The flows have abundant phenocrysts, generally 30–50 percent. Most of them have mainly quartz and sanidine with no plagioclase; a few have minor plagioclase. All of them contain in their glassy portions minor clinopyroxene, opaque oxides, and fayalitic olivine.

Potassium-argon age determinations on sanidine from the Central Plateau Member range from about 200,000 to about 70,000 years (J. D. Obradovich, written commun., 1970).

Shoshone Lake Tuff Member

A single rhyolitic ash-flow tuff crops out within the Plateau Rhyolite sequence. We name it here the Shoshone Lake Tuff Member for exposures on the steep slopes west of Shoshone Lake. The type section is in the gully north of Fall Creek (fig. 2), west of the Shoshone Lake Geyser Basin, where the member is about 180 m thick and lies between two flows of the Central Plateau Member.

The member is widespread between West Thumb and Shoshone Lake. Elsewhere, the tuff is largely covered by younger rhyolite flows, but small exposures occur between various flows of the Central Plateau Member in the Bechler River area, near Little Firehole Meadows, and in the upper drainage of Nez Perce Creek. In the area of Shoshone Lake the ash-flow tuff has an irregular distribution which is hard to explain by erosion but which suggests the possibility that it was emplaced on a lobe of glacial ice that occupied the lake basin. The distribution and the pattern of welding and crystallization zones of the member indicate that its source area was in the vicinity of West Thumb, which may, in fact, be a caldera lake formed by collapse after eruption of the tuff.

Most of the type section consists of glassy nonwelded to partially welded tuff, but local vapor-phase and devitrified zones a few meters thick occur in the upper part. The degree of welding varies vertically between more and less densely welded tuff. By contrast, the Shoshone Lake Tuff Member near West Thumb, the deep western basin of Yellowstone Lake, commonly is more densely welded and contains a much thicker vapor-phase zone in proportion to glassy welded tuff. The basal part of the member is well exposed in the roadcut above Bluff Point, along the northwest shore of West Thumb. The basal glassy zone there is less than 5 m thick and rests against a flow of the Central Plateau Member. A specimen from the vapor-phase zone at the Bluff Point locality was illustrated by Ross and Smith (1961, fig. 11, p. 27). The upper part of the section at Bluff Point probably is repeated by faulting, but exposures are poor and do not allow determination of the stratigraphic thickness. The tuff appears to be overlain by a higher flow of the Central Plateau Member. About 2½ km southwest of Bluff Point, in a gravel pit northwest of Potts Hot Springs, the Central Plateau Member overlies gravels containing boulders and cobbles of the Shoshone Lake Tuff Member.

The Shoshone Lake Tuff Member contains 20–30 percent phenocrysts of quartz, sanidine, subordinate plagioclase, and minor clinopyroxene and opaque oxides. It contains more abundant pumice than tuffs of the Yellowstone Group and generally has a coarser matrix. Inclusions of older rhyolite, mainly black vitrophyre, are abundant throughout the member.

The age of the Shoshone Lake Tuff Member is bracketed by the ages of two flows of the Central Plateau Member, sanidine from which has been dated as about 200,000 and 150,000 years old respectively; sanidine from a bedded tuff in the Potts Hot Springs gravel pit, probably a part of the Shoshone Lake, is 180,000 years old (J. D. Obradovich, written commun., 1970).

Roaring Mountain Member

We name the Roaring Mountain Member here for four young phenocryst-free or phenocryst-poor extracaldera rhyolitic lava flows that occur as isolated bodies north of the Yellowstone caldera. The member comprises the Crystal Spring, Obsidian Cliff, Cougar Creek, and Riverside flows (which, by definition, constitute its type area, fig. 2); Roaring

Mountain is in the vicinity of the Crystal Spring and Obsidian Cliff flows, which occur in the same belt as the Obsidian Creek Member. The Cougar Creek and Riverside flows are in the area west and northwest of Madison Canyon. The four flows overlie the Lava Creek Tuff, the Swan Lake Flat Basalt, and parts of the Obsidian Creek Member of the Plateau Rhyolite. The Cougar Creek and Riverside flows are overlain by flows and cut by dikes of the Madison River Basalt. The other flows are overlain only by surficial deposits of late Pleistocene and Holocene age.

All the flows are phenocryst-free or very phenocryst-poor rhyolites which contain abundant fresh black obsidian as well as crystallized and partly crystallized material. Phenocrysts, where present, are quartz, sanidine, plagioclase, and opaque oxides.

Obsidian from three of the four flows has been dated by the K-Ar method by J. D. Obradovich (written commun., 1970) ; the dates seem to indicate a considerable age span for the member. The Crystal Spring and Obsidian Cliff flows yielded young apparent ages (about 160,000 and 75,000 years respectively) ; the Cougar Creek flow gave an age of 400,000 years. However, the reliability of these obsidian dates is uncertain.

POST-LAVA CREEK BASALTS

Basalts younger than the Lava Creek Tuff occur around the margins of the rhyolite plateau surrounding the caldera. Because different relations are displayed in several widely separated areas, these basalts have been grouped into five named formations.

Swan Lake Flat Basalt

Basalts younger than the Lava Creek Tuff but older than an unconformity that represents the first major period of canyon cutting into the Lava Creek occur widely in the area north of Obsidian Cliff, nearly to Mount Everts. We here name these lavas the Swan Lake Flat Basalt after a valley partly surrounded and largely underlain by them about 8 km southwest of Mammoth. The type area (fig. 2) is designated as the Sheepeater Cliffs, on the east side of the canyon of the Gardner River southeast of Bunsen Peak. Flows of the lower part of the sequence are well exposed there and are conformable on the Lava Creek Tuff, whose easily eroded nonwelded glassy cap is locally preserved. Flows of the Plateau Rhyolite locally overlie the Swan Lake Flat Basalt. No single section, however, exposes well both the base and the top of the formation. East of the Sheepeater Cliffs, basalts form a rounded hill that probably marks one of the source vents for the flows; the formation totals nearly 200 m in thickness in that area. Other cinder cones that probably mark vents for the Swan Lake Flat Basalt occur near Horseshoe Hill, northeast of Obsidian Cliff.

Boyd (1961, p. 402) observed that basalts of two ages occur in the Bunsen Peak area, one conformable on the Yellowstone Tuff (our Lava Creek Tuff) and the other filling a younger canyon. We recognize the former as the Swan Lake Flat Basalt and the latter as the Osprey Basalt.

The Swan Lake Flat Basalt generally is 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. Outcrops of a lithologically distinctive basalt in the area near Geode Creek (Howard, 1937, p. 19–21) probably represent a mixed lava dominated by basalt and have therefore been mapped separately. A faint streakiness, a few xenocrysts, and considerable textural heterogeneity show the mixing in hand specimen. Extremely large plagioclase phenocrysts, as much as 5 cm across, occur rarely in the rock. At least one flow near Geode Creek appears to have been fed through a vent now preserved as a low scoria mound above an exposed dike about midway between the main Mammoth–Tower Junction Road and the unpaved Crescent Hill Road, 1¼ km east of Geode Creek.

The age of the Swan Lake Flat Basalt is suggested by its stratigraphic relations. The Swan Lake Flat is conformable on the middle Pleistocene Lava Creek Tuff, which probably is somewhat younger than the Cedar Ridge (Kansan) Glaciation of the Rocky Mountains (Richmond, 1970b, p. 8, 21). The Swan Lake Flat is older than canyon cutting that predated the Osprey Basalt. Post-Lava Creek canyon cutting in the drainage of the Yellowstone River predated a till of probable Sacagawea Ridge (Illinoian) age in the Grand Canyon area (Richmond, 1970a; 1970b, p. 21). Thus the episode of canyon cutting between the Swan Lake Flat and Osprey Basalts probably was contemporaneous with the Yarmouth Interglaciation of the Great Plains. Richmond (1957) noted that the episode of deepest canyon cutting during the Pleistocene occurred in many parts of the Rocky Mountains during this same interglaciation.

Falls River Basalt

The Falls River Basalt is named here to include basalts younger than the Lava Creek Tuff and older than the Central Plateau Member of the Plateau

Rhyolite in the region of the southwest corner of Yellowstone National Park. The formation takes its name from the major stream draining that area. The type locality is the west rim of the valley of Falls River just below Cave Falls (fig. 2), where the formation overlies the Lava Creek and is overlain by upper Pleistocene glacial deposits. In the drainage area of the Bechler River about 8 or 9 km north of its confluence with Falls River, just above Cave Falls, the Falls River Basalt is overlain by several flows of the Central Plateau Member.

The Falls River Basalt is very similar in lithology to the Swan Lake Flat Basalt, commonly containing sparse phenocrysts of plagioclase about ½–1 cm across. The basalts generally are moderate gray and form dense thin flows with vesicular tops. Just west of the southwest corner of the national park these flows make up a low shield, Rising Butte (fig. 2), which probably was the source of at least some of the flows in the park.

The age of the Falls River Basalt is bracketed by the ages of the 600,000-year-old Lava Creek Tuff and the overlying Plateau Rhyolite flows, probably about 100,000 years old. Apparent conformity of the Falls River and the Lava Creek suggests that the basalt is closer in age to the underlying tuff than to the overlying lavas.

Basalt of Mariposa Lake

A few scattered outcrops of basalt southeast of the rhyolite plateau are discussed in this section even though their stratigraphic position relative to the plateau sequence is unknown. These outcrops of basalt all occur on Two Ocean Plateau and are underlain by Eocene rocks of the Absaroka Volcanic Supergroup. These basalts have been mapped by our colleagues H. W. Smedes and H. J. Prostka, and the following discussion is based mainly on their observations. The basalts are as thick as 50 m and lie on an erosional surface of considerable relief. They are overlain by upper Pleistocene glacial deposits. Their age is unknown, but their lithologic and general petrographic characteristics are quite unlike those of the Absaroka volcanic rocks and much like those of upper Cenozoic basalts of the region. They are very similar to the Swan Lake Flat and Falls River Basalts in lithology and in their spatial relations to the rhyolite plateau except that no ash flows of the Yellowstone Group, our regional stratigraphic framework, were emplaced on the surface of Two Ocean Plateau. These relations suggest the possibility that the basalts of this area are stratigraphic relatives of other post-Lava Creek basalts, but the basalts on Two Ocean Plateau could be older.

The upper Cenozoic basalts of Two Ocean Plateau are designated here as the basalt of Mariposa Lake; they partly fill an old valley in which that lake lies (fig. 2). These basalts also occur on the flat ridge about 4 km northwest of Mariposa Lake and in two patches on the ridge west of the Yellowstone River between Badger and Phlox Creeks. Other isolated patches may be present beneath the widespread mantle of glacial debris in the area.

Madison River Basalt

Post-Lava Creek basalts which occur in widely scattered patches in the area south and west of the Gallatin Range to the vicinity of the Madison Canyon and the eastern part of the Madison Valley near West Yellowstone are named here the Madison River Basalt. We designate the basalt-covered uplands west of the south end of the Gallatin Range, south of upper Maple Creek, the type area. The lavas lie on an eroded surface on the Lava Creek Tuff but predate deeper canyon cutting in the area. Locally they overlie the Cougar Creek and Riverside flows of the Roaring Mountain Member of the Plateau Rhyolite. Some outcrops in the type area are deeply mantled by upper Pleistocene glacial deposits, and till of Bull Lake (early Wisconsin) age south of West Yellowstone contains abundant clasts of Madison River Basalt. Some flows are so small that it is difficult to show them on maps at a scale of 1 : 62,500. Other outcrop areas contain two or more flows, cover several square kilometers, and represent sections more than 50 m thick. Like the Swan Lake Flat and Falls River Basalts, the Madison River Basalt contains moderately abundant plagioclase phenocrysts and relatively rare olivine phenocrysts, and it generally is moderate gray to light gray. Chemically, however, these basalts are different. Although the chemistry of the rhyolite plateau volcanic rocks has not been used in defining the formations, it is worthy of note that the other basalts of the region are all olivine tholeiites with very low potassium contents. The Madison River Basalt, however, contains markedly more potassium, iron, titanium, phosphorus, fluorine, rubidium, lead, and uranium and contains less calcium and magnesium, even when compared with the other basalts of the area of similar silica content.

The Madison River Basalt is at least partly younger than the Roaring Mountain Member of the Plateau Rhyolite. Relations just noted suggest that the Madison River is younger than at least part of the Swan Lake Flat and Falls River Basalts, but it is entirely older than glacial deposits of early Wisconsin age and may be largely older than the canyon cutting contemporaneous with the Yarmouth Interglaciation. (See discussion of the age of the Swan Lake Flat Basalt.)

Osprey Basalt

The Osprey Formation was defined by Pierce, Christiansen, and Richmond (1970) to include basalts and minor interlayered gravels in the northern Yellowstone National Park area that are younger than the Swan Lake Flat Basalt. Subsequent work by K. L. Pierce and by us has shown inclusion of the Tower Creek Gravel Member in the Osprey to be erroneous. As a result, we now exclude the sediments and basalts of The Narrows and change the name from Osprey Formation to Osprey Basalt.

The flows and interlayered gravels of the Osprey Basalt partly fill deep canyons eroded into the Lava Creek Tuff and the Swan Lake Flat Basalt. As discussed in the section on the Swan Lake Flat Basalt, the valleys in which the Osprey was deposited may be of the same age as the Yarmouth Interglaciation; the formation is overlain by glacial deposits of late Pleistocene age.

SEDIMENTS ASSOCIATED WITH THE YELLOWSTONE RHYOLITE PLATEAU

G. M. Richmond, K. L. Pierce, and H. A. Waldrop are studying upper Pleistocene surficial deposits which overlie the plateau volcanic rocks as well as sediments interlayered with the volcanics. Their studies will be reported in forthcoming publications. For this reason, the sedimentary stratigraphy of the rhyolite plateau is not treated at length in the present report; however, deposits intercalated with the volcanic units are mentioned briefly in this section.

Gravels and associated minor sands and silts in the Junction Butte Basalt, the sediments and basalts of The Narrows, and the Osprey Basalt have already been noted. All of these sediments originally were included in the Tower Creek Conglomerate as mapped by Hague, Iddings, and Weed in the Yellowstone monograph atlas (Hague, 1904) and by Brown (1961, p. 1182–1183). Deposition of these sediments was separated by emplacement of ash-flow sheets of the Yellowstone Group and by episodes of valley cutting, and the gravels contain different assemblages of coarse clasts. Pierce, Christiansen, and Richmond (1970), therefore, restricted the term "Tower Creek" to the canyon-filling sediments which contain Yellowstone Group clasts and used the name as a member of the Osprey. Because subsequent separation of the type Tower Creek Gravel Member from the Osprey introduces further confusion into the term, we no longer use it but regard the gravels informally as associates of the various basalts. Minor gravels also are interlayered with the Undine Falls Basalt.

On the south side of Mount Everts an alluvial channel gravel about 2 m thick, composed almost entirely of debris of the Absaroka Volcanic Supergroup, underlies the Huckleberry Ridge Tuff and overlies Cretaceous sedimentary rocks. A wedge of loess lies between the Huckleberry Ridge and Mesa Falls Tuffs in the type section of the Mesa Falls.

Howard (1937) noted and described sediments in and near the upper Grand Canyon of the Yellowstone. In the area of the Grand Canyon, the Canyon flow is overlain by highly altered well-bedded sandstones and siltstones along the canyon rims; perhaps the best exposure of these sedimentary rocks is in cliffs about one-half kilometer northwest of Inspiration Point. Just above Lower Falls, sediments including a possible till of pre-Wisconsin age occupy a paleovalley cut in the Canyon flow and in the sediments of Inspiration Point and are overlain in turn near Upper Falls by clays, silts, sands, and partly cemented pumiceous sandstone (Richmond, 1970a; 1970b, p. 10). Sanidine from pumice in the basal beds of the sediments of Upper Falls has a K-Ar age of about 290,000 years; the sediments are overlain by a flow of the Central Plateau Member, sanidine from which has been dated as about 110,000 years (J. D. Obradovich, written commun., 1970). Two sediment-filled segments of a high-level channel cut off from the subsequently deepened main channel are stranded on the north wall of the Grand Canyon near the trail to the Red Rock overlook and about two-thirds kilometer west of Inspiration Point. These sediments of Red Rock are similar to those of Upper Falls but may be older. Sands, gravels, and tuffs in the Grand Canyon at Sevenmile Hole, about 8 km downstream from Lower Falls, may be partly equivalent in age to those in the area of Upper and Lower Falls and Red Rock (G. M. Richmond, oral commun., 1971).

At a gravel pit two-thirds kilometer northwest of Potts Hot Springs a flow of the Central Plateau Member is underlain by gravels and sands containing abundant clasts from the Central Plateau and Shoshone Lake Tuff Members. The sediments also appear to overlie the Shoshone Lake on a steep paleoslope.

A thin till just north of Bechler Meadows in southwestern Yellowstone National Park, about 2 km east of Boundary Creek, lies between the Falls River Basalt and a rhyolite flow of the Central Plateau Member.

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