Surficial Geologic History of the Canyon Village Quadrangle, Yellowstone National Park, Wyoming, for use with Map I–652

By GERALD M. RICHMOND

GEOLOGICAL SURVEY BULLETIN 1427

A summary of the glacial and nonglacial history of the basin of Yellowstone Lake and the Grand Canyon of the Yellowstone in the Yellowstone caldera

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1976

UNITED STATES DEPARTMENT OF THE INTERIOR

THOMAS S. KLEPPE, *Secretary*

GEOLOGICAL SURVEY

V. E. McKelvey, *Director*

Library of Congress Cataloging in Publication Data
Richmond, Gerald Martin, 1914-
Surficial geologic history of the Canyon Village quadrangle, Yellowstone National Park, Wyoming.
(Geological Survey Bulletin 1427)
Bibliography: p.
Supt. of Docs. no.: I 19.3:1427
1. Geology, Stratigraphic—Quaternary. 2. Geology—Yellowstone National Park.
I. Title. II. Series: United States Geological Survey Bulletin 1427.
QE75.B9 no. 1427 [QE696] 557.3'08s [551.4'09787'52] 76-608357

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402
Stock Number 024-001-02899-9

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UNITS OF MEASURE USED IN THIS REPORT

To convert *English units*	*Multiply by*	*To obtain* *Metric units*
Feet (ft)	0.3048	Metres (m).
Miles (mi)	1.609	Kilometres (km).
Inches (in.)	2.54	Centimetres (cm).
Yards (yd)	.9146	Metres (m).
Feet/mile (ft/mi)	.1893	Metres/kilometre (m/km).

SURFICIAL GEOLOGIC HISTORY OF THE CANYON VILLAGE QUADRANGLE, YELLOWSTONE NATIONAL PARK, WYOMING

By GERALD M. RICHMOND

ABSTRACT

The Canyon Village quadrangle lies in central Yellowstone National Park. It includes the northern part of Yellowstone Lake and the spectacular sector of the Grand Canyon of the Yellowstone seen by most visitors. The oldest Quaternary event recognized in the quadrangle occurred about 600,000 years ago when a large caldera, covering most of the quadrangle, collapsed after eruption of vast quantities of tuff. Events prior to the Sacagawea Ridge Glaciation include primarily a lake in the caldera and the eruption from beneath the lake of a large rhyolite flow. Possible glaciolacustrine deposits but no till of the Sacagawea Ridge Glaciation were found in the quadrangle. However, Sacagawea Ridge Till derived from sources in Yellowstone National Park occurs just outside the park. During the Sacagawea Ridge–Bull Lake interglaciation, further eruptions of rhyolite flows and tuffs in the caldera constructed the present Central Plateau and thereby separated the eastern part of the lake from a former outlet to the west. As a result, the eastern lake rose, and its overflow to the north initiated erosion of a paleocanyon along the course of the present Grand Canyon of the Yellowstone. The subsequent history of the canyon and of the caldera lake consisted largely of a succession of major advances and recessions of Bull Lake and Pinedale glaciers, and eruptions of rhyolite flows during both glacial and interglacial or interstadial times. canyon, in this quadrangle, was partly filled with lake sediments deposited upstream from ice dams during both stades of the Bull Lake Glaciation. A major withdrawal of the ice occurred between the early and late stades of the Bull Lake Glaciation and during the Bull Lake–Pinedale interglaciation. A major shrinkage of the ice also took place between the early and middle stades of the Pinedale Glaciation; final wasting was very rapid and occurred between about 13,600 and 12,000 years ago.

INTRODUCTION

The Canyon Village quadrangle is in central Yellowstone National Park (fig. 1). Yellowstone Lake, in the southern part of the quadrangle, is bordered to the east by the foothills of the Absaroka Range which trends north across the Pelican Cone quadrangle, adjacent to the east, and is underlain by Eocene volcanic rocks. West of the lake, Elephant Back Mountain forms the east edge of the Central Plateau which is chiefly in the Norris Junction quadrangle, adjacent to the west. Pelican Creek flows into the north end of Yellowstone Lake from its broad valley to the east. A short distance to the west, the Yellowstone River flows from the lake northward across an east-trending fault at LeHardys Rapids and along a trench through the rolling terrain of Hayden Valley. East of Hayden Valley, a broad, high, broken, dome-shaped upland culminates in Stonetop Mountain (altitude 9,042 feet, or 2,756 m), the highest point in the quadrangle. North of Hayden Valley, the Yellowstone River flows through a narrows and then turns sharply northeast across Upper Falls (109 feet or 33 m high) and Lower Falls (319 ft, or 97 m high) into the Grand Canyon of the Yellowstone (750–1,600 ft or 228–488 m deep). The canyon, in this quadrangle, cuts across a large rhyolite flow which underlies the hills rising eastward to Broad Creek. The spectacular hues of yellow and red for which the canyon is so famous are the result of hydrothermal alteration of the rhyolite in the areas below Lower Falls and Inspiration Point, and north of the great elbow in the canyon 2.5 miles (4 km) downstream.

This report was originally planned as part of the text of U.S. Geological Survey Miscellaneous Geologic Investigations Map I–652, Surficial geologic map of the Canyon Village quadrangle (Richmond, 1976), and its organization parallels that of the surficial geologic history texts of other surficial geologic maps of Yellowstone National Park (fig. 1). However, the unusually large number of geologic units mapped in this quadrangle necessitated a descriptive text of such length that available space on the map would not permit inclusion of the surficial geologic history.

This report makes constant reference to places, features and deposits shown on map I–652, as well as to the descriptions of geologic units and stratigraphic sections on it. Map I–652 is thus essential to the use and understanding of this report. An index map of published Miscellaneous Geologic Investigations Maps in the park (fig. 1) and an index map of the Canyon Village quadrangle showing the distribution of Quaternary rhyolite flows (fig. 2) are included both on map I–652 and in this report.

QUATERNARY HISTORY

Yellowstone National Park was repeatedly glaciated by large icecaps during the Quaternary. Volcanic eruptions of rhyolite tuffs and flows occurred during both glacial and interglacial times. The Quaternary history of this quadrangle involves the sequence of these events. Three glaciations are recognized, from oldest to youngest: Sacagawea Ridge, Bull Lake, and Pinedale (Richmond, 1965). Evidence for Sacagawea

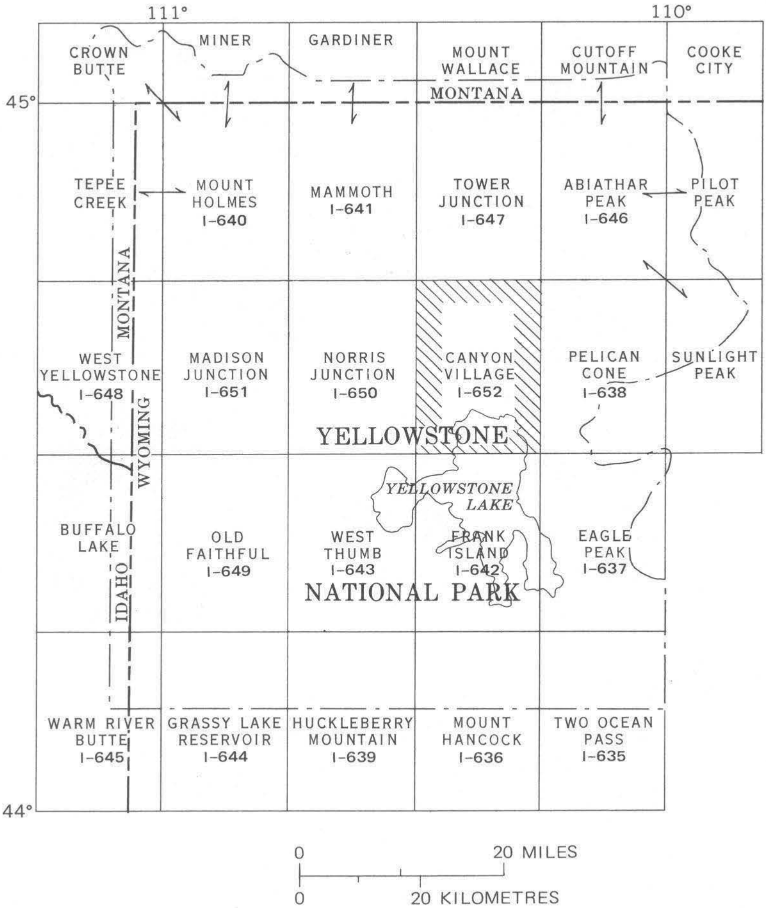
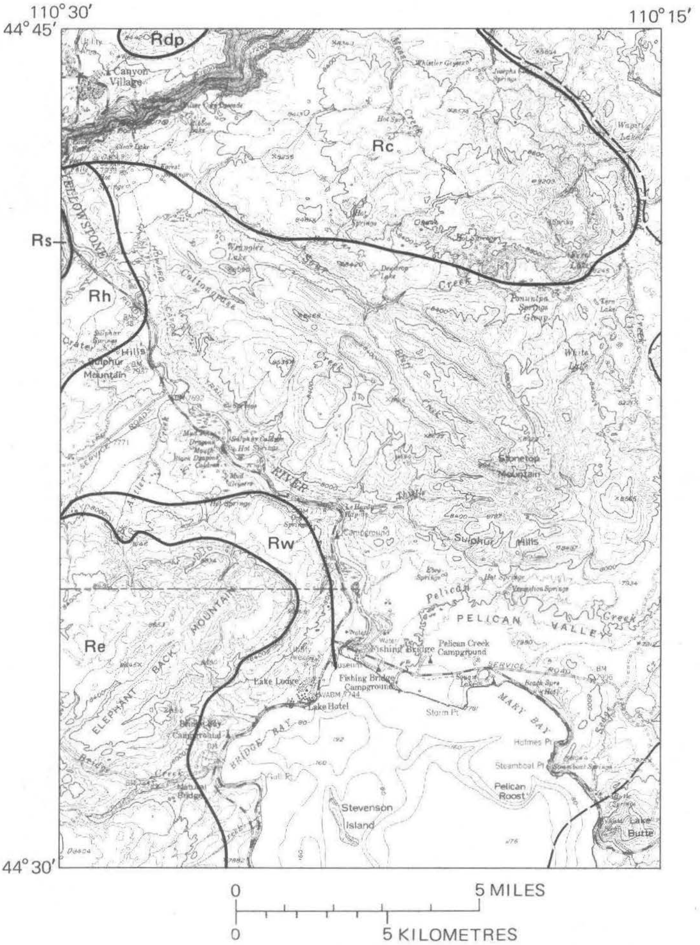


FIGURE 1. — Index map of Yellowstone National Park, showing location of Canyon Village quadrangle and published U.S. Geological Survey Miscellaneous Geologic Investigations Maps of the area.

Ridge Glaciation is sparse. Deposits of the Bull Lake Glaciation can be divided into informal early and late stades; deposits of the Pinedale Glaciation can be divided into informal early and middle stades. Deposits of an informal late stade of the Pinedale have been recognized in the Pelican Cone quadrangle (MI–638, Richmond and Waldrop, 1972), adjacent to the east.

K-Ar (potassium-argon) dates determined by John D. Obradovich (written commun., 1974, 1975) of rhyolite flows and pumice beds stratigraphically related to the sediments broadly place pre-Pinedale glacial and interglacial events in time. Carbon-14 dates by Meyer Rubin



EXPLANATION

Rs – Solfatara Plateau flow
Rh – Hayden Valley flow
Re - Elephant Back flow
Rw – West Thumb flow
Rdp – Dunraven Pass flow
Rc – Canyon flow
——— Margin of flow
– – – Inferred position of northwest rim of 600,000-year-old caldera

FIGURE 2. — Index map of Canyon Village quadrangle showing distribution of Quaternary rhyolite flows. Modified from "Geologic Map of Yellowstone National Park," U.S. Geological Survey Misc. Geol. Inv. Map I–711, 1972, and "Geologic Map of the Canyon Village Quadrangle, Wyoming," U.S. Geol. Survey Geol. Quad. Map GQ–1192, 1975.

serve a like purpose for events preceding and following the Pinedale Glaciation.

PRE-SACAGAWEA RIDGE GLACIATION EVENTS

A large caldera, 30–40 miles (48–64 km) in diameter, developed in the park in association with the eruption of a tuff (Boyd, 1961) of the Yellowstone Group (Christiansen and Blank, 1972), K-Ar dated as about 600,000 years old. The north rim of the caldera extends along the base of the Washburn Range, just north of the quadrangle. Broad Creek flows along the inside margin of its northeast rim (fig. 2). The large faulted elliptical dome east of the Yellowstone River is a resurgent dome underlain by two tuffs of the Yellowstone Group, one about 600,000 years and the other about 2 m.y. (million years) old (Christiansen and Blank, 1972).

Subsequent to formation of the caldera, the tuff of Uncle Toms Trail (Rut), which is exposed in the Grand Canyon of the Yellowstone between Lower Falls and Upper Falls, erupted, probably along the fault system just inside the caldera rim to the north. The tuff contains the oldest sediments in the caldera, recorded by sand and gravel masses several feet long and 1–3 feet (0.3–1 m) thick that are swirled upward in the tuff. The sediments were probably swept from a streambed by the force of the ash flow that descended the north slope of the caldera and formed the welded tuff. Pebbles of quartzite and gneiss in the sediments probably were transported by the stream southward from Eocene and early Pleistocene or Pliocene conglomerates[1] containing these rock types that are now exposed north of the caldera rim on the southeast slope of Hedges Peak, in the Washburn Range, just north of the quadrangle.

The oldest evidence of a lake in the caldera is the tuffaceous lake silt of the sediments of Lower Falls (lf) which overlies the tuff of Uncle Toms Trail in the wall of the canyon at Lower Falls (stratigraphic section 12). The lake rose over the tuff to an altitude of at least 7,650 feet (2,332 m), the highest altitude at which the lake sediments occur. Later, the diamicton of the sediments of Lower Falls was deposited over the lake silt. The genesis of this diamicton is not fully understood. It has been called till (De Martonne, 1915; Alden, 1928; Richmond, 1971; U.S. Geological Survey, 1972) and talus (Howard, 1937). The

[1]Schultz (1962, p. 43–57) believed these conglomerates and associated sandstones to be all of middle Eocene age on the basis of fossil leaves identified by Erling Dorf and the position of some of the beds beneath andesitic volcanic rocks. He described some beds as containing chiefly volcanic pebbles and others as chiefly of Precambrian crystalline and younger nonvolcanic rocks. Pollen analysis of silty interbeds in conglomerates composed chiefly of nonvolcanic rocks, exposed at the old Canyon Village water-intake dam along the Dunraven Pass road, revealed types and percentages of pollen showing that these particular beds are probably of Pliocene or early Pleistocene age (William Mullenders, Louvain la Neuve Univ., Belgium, written commun., 1973). The beds at this locality do not underlie andesitic volcanic rocks.

numerous subangular fragments of gray fine-grained biotite diorite in it are derived from an Eocene intrusive mass exposed in the area of Washburn Hot Springs, just north of the quadrangle (R. L. Christiansen, written commun., 1971). The massive nonbedded unsorted tuffaceous nature of the deposit and the shapes of its enclosed fragments suggest that although it may be a till, it more probably is a subaqueous tuffaceous mudflow or a subaqueous lithic tuff. It has been recognized in boring Y–3 at the picnic area along Yellowstone River south of Mud Volcano (Christiansen and Blank, 1975) about 10 miles (16 km) from Washburn Hot Springs. Such extent precludes its being a talus.

There followed an interval of erosion of the caldera wall during which the sediments of Lower Falls (lf) were stripped from the tuff of Uncle Toms Trail except in the area of the present canyon above Lower Falls. The lowest altitude at which evidence of this erosion — represented by a disconformity between the tuff and the overlying Canyon rhyolite flow (Rc) — was observed is 7,500 feet (2,286 m). Thus, at the time of erosion, the level of the caldera lake could not have been above that altitude.

The Canyon rhyolite flow (Rc) (K-Ar age about 590,000 years) and the associated tuff of Sulphur Creek (Christiansen and Blank, 1972) next erupted in the caldera lake in the northeastern part of the quadrangle (fig. 2), locally overlapping onto the north rim of the caldera. The upper limit of intense perlitization of the flow, indicative of rapid hydration and chilling in contact with water, is at an altitude of about 7,600 feet (2,316 m) beneath the next younger sediments of Cascade Creek (cc) (stratigraphic section 15). This altitude probably approximates that of the caldera lake immediately following eruption of the Canyon flow. Other evidence for the existence of the lake at the time of the eruption are inclusions of bedded lake silt in the tuff of Sulphur Creek along Broad Creek, north of Wapiti Lake Trail.

At the site of present Lower Falls, the western extremity of the Canyon flow encountered a steep prominence, nearly 600 feet (183 m) high, underlain by the sediments of Lower Falls and the tuff of Uncle Toms Trail. A near-vertical contact between the flow and the tuff of Uncle Toms Trail is exposed on the east wall of the canyon at Lower Falls, and a similarly steep contact between the flow and the diamicton of the sediments of Lower Falls is exposed opposite the mouth of Cascade Creek (between Lower Falls and Upper Falls), and upstream along the east wall of the canyon about 750 yards (686 m) below Upper Falls. The prominence divided the rhyolite flow into two lobes which flowed around its steep slopes and rejoined to the west in the vicinity of the present mouth of Cascade Creek. There, a depression about 100 feet (30.5 m) deep was left between the two lobes.

Subsequently, the mudflow and alluvial fan facies of the sediments of Cascade Creek (cc), composed chiefly of detritus from the Canyon flow, were deposited at the west edge of the depression, whereas in the depression itself, the tuffaceous lake facies of the sediments of Cascade Creek (cc) was deposited. The two facies intertongue abruptly, and both rest on the Canyon flow (stratigraphic sections 15, 16). Probably, the depression lay at the edge of the caldera lake. The altitude of the highest lake sediments (cc) in the depression is 7,600 feet (2,316 m), which is about the same as the highest intensely perlitized parts of the subjacent Canyon flow. This altitude is about 400 feet (122 m) below the pre-Grand Canyon drainage divide on the Canyon flow to the north, in which direction no similar sediments were found. It is therefore improbable that the caldera lake drained northward at this time. More likely, it drained west across the west rim of the caldera near or above the site of present Madison Canyon (Madison Junction quadrangle). This hypothesis is based on the probability that the caldera lake extended to the west rim of the caldera near Madison Junction because the rhyolite flows of the Central Plateau were not in existence at this time, as discussed below.

In the northwestern part of the quadrangle, the Dunraven Pass rhyolite flow (Rdp) may have erupted over the surface of the Canyon flow during deposition of either the sediments of Cascade Creek or the sediments of Inspiration Point. However, this is conjecture, inasmuch as the flow is not in contact with the sediments and could not be reliably K-Ar dated.

Probably after deposition of the sediments of Cascade Creek, but possibly at the same time, the sediments of Inspiration Point (ip) were deposited at higher altitudes in a broad swale on the surface of the Canyon flow along which the canyon itself was subsequently cut. The sediments crop out on both rims of the canyon northeast of Cascade Creek. Most have been intensely opalized and cemented by hydrothermal solutions (Christiansen and Blank, 1972). Howard (1937, p. 111) recognized these highly altered sediments between Grand View and Inspiration Point and near Artist Point, but included them with his "Rim Sediments" here called the sediments of Upper Falls (uf). Locally, they contain layers of chalcedonic sinter, evidence that the sediments were deposited near hot springs. The texture and bedding characteristics of the sediments suggest that they are of alluvial and shallow-lake origin, much like those forming in Norris Geyser Basin today. Their association with sinter at altitudes as low as 7,750 feet (2,362 m) indicates that the caldera lake could not have been that high, for hot springs cannot deposit sinter under water (Donald E. White, written commun., 1972). Such springs do, however, require a high water table, and the caldera lake probably lay to the west and south at about the same level as during deposition of the sediments of Cascade Creek.

The sinter deposits of hot springs are originally opaline. Their conversion to chalcedony requires subsequent burial for a long time under conditions of high temperature and high ground water (White and others, 1956). The sinter in the sediments of Inspiration Point may have been buried by any of four kinds of deposits or combinations thereof. Burial may have been accomplished by additional increments of the sediments themselves, by younger pumiceous tuff units described below, by ice-contact deposits or till of the Sacagawea Ridge Glaciation localized as a result of rapid melting of the glacier over the hot springs area, or by lake sediments of Sacagawea Ridge–Bull Lake interglacial age. Whatever the cover, it has now been stripped away by erosion.

Three pumiceous tuff beds exposed in the south wall of the canyon below the lookout at Uncle Toms Trail parking area (stratigraphic section 13, pumice beds uf–I, uf–II and uf–III of the sediments of Upper Falls, uf) were deposited at some time after deposition of the sediments of Inspiration Point. The oldest, pumice bed uf–I, rests disconformably on the diamicton of the sediments of Lower Falls. It is 22 feet (6.7 m) thick and its top is at an altitude of 7,640 feet (2,329 m). The upper 12 feet (3.6 m) of the pumice are stained bright orange by iron oxide. The color zone appears related to a long stand of the water table rather than to weathering. The source and age of the pumice are unknown. Pumice bed uf–II is about 8 feet (2.4 m) thick. It yielded a K-Ar age older than the caldera and, thus, must contain age contaminants. Pumice bed uf–III, about 12 feet (3.6 m) thick, yielded a K-Ar age of about 266,000 years. Between pumice beds uf–II and uf–III at stratigraphic section 13 is a pumiceous sandy diamicton (ufd), discussed below.

SACAGAWEA RIDGE GLACIATION

Though no distinct till of the Sacagawea Ridge Glaciation was found in the quadrangle, Sacagawea Ridge Till immediately south and southwest of Yellowstone National Park in the Huckleberry Mountain quadrangle (Richmond, 1973b), Grassy Lake Reservoir quadrangle (Richmond, 1973c), and Warm River Butte quadrangle (Richmond, 1973d) was deposited by cap ice flowing from the caldera. Sacagawea Ridge ice was therefore probably present in this quadrangle. Just west of the park, in the Buffalo Lake quadrangle, reddish, deeply weathered loess beneath a flow K-Ar dated as about 156,000 years old is considered to be of Sacagawea Ridge age. An older glacial advance, included in the Sacagawea Ridge Glaciation, is represented by a till-like diamicton exposed in the shore of Flat Mountain Arm of Yellowstone Lake in the Frank Island quadrangle (MI-642, Richmond, 1974). The till lies below lake silt that is overlain by a thick pumiceous tuff K-Ar dated as about 219,000 years old. I correlated the Tuff (Richmond, 1974) with the Shoshone Lake Tuff member (Christiansen and Blank, 1972), K-Ar dated as about 155,000 years old, but I now believe that the till-like diamicton at Flat Mountain is older than about 219,000 years. In the Canyon Village quadrangle, the diamicton exposed at stratigraphic section 13 between pumice beds uf–II and uf–III of the sediments of Upper Falls may represent a correlative deposit. The diamicton is a compact, massive, angular pumiceous sand containing scattered subangular to subround clasts, chiefly of local derivation but including a few quartzite erratics. Its poor sorting and local weak lacustrine bedding suggest a glaciolacustrine origin.

SACAGAWEA RIDGE–BULL LAKE INTERGLACIATION

Eruption of a succession of rhyolite flows and tuffs within the caldera in the Norris Junction (MI-650, Richmond and Waldrop, 1975) and West Thumb (MI–643, Richmond, 1973a) quadrangles, west and southwest of this quadrangle, took place between about 160,000 and about 140,000 years ago, on the basis of K-Ar dating of the flows. These eruptions built up the Central Plateau, gradually divided the caldera lake into eastern and western parts, and eventually blocked the probable former westward drainage of the eastern part. In this quadrangle, the eruptions of the West Thumb rhyolite flow (Rw) (K-Ar age about 144,000 years), and of the overlying, slightly zounger Elephant Back rhyolite flow (Re) were a late phase of this volcanic activity (fig. 2). The West Thumb flow (Rw) erupted eastward across the caldera lake basin and impinged against the flank of the faulted resurgent dome east of the present Yellowstone River at an altitude of about 8,000 feet (2,438 m). It thereby divided the eastern caldera lake into two parts, one to the south and one to the north. The southern lake rose to an altitude of at least 8,000 feet or 2,438 m (overstated at 8,100 feet or 2,469 m in Richmond, 1973a, 1974) or about 270 feet (83 m) above present Yellowstone Lake. Its outlet was to the north around the outer margin of the West Thumb flow in the area of present LeHardys Rapids. Deposits of this lake are exposed in the Frank Island quadrangle (Richmond, 1974), adjacent to the south.

The northern lake also rose against surrounding divides. Its sediments include the lacustrine pumiceous silty sand exposed in the west bluff of the Yellowstone River in Hayden Valley (s–bsl in stratigraphic sections 29, 30), and possibly the lowest lake silt (s–bl) of the sediments of Upper Falls (uf) downstream from Upper Falls. Its highest sediments (mapped as uf) are at an altitude of 7,900 feet (2,408 m) in the southeastern part of Canyon Village. The lake is inferred to have attained an altitude of 8,000 feet (2,438 m) and to have been the first to drain northward across the divide of the Canyon rhyolite flow (Rc) at about the position of the great elbow in the present canyon 2 miles (3 km) downstream from Point Sublime. To the north, the outlet stream flowed into an ancestral Yellowstone River whose headward erosion to the elbow at that time is suggested by the abrupt doubling of the width of the present canyon both in the soft hydrothermally altered rock of the Canyon flow immediately downstream and in the hard rocks in the Tower Junction quadrangle to the north.

After overflow, the outlet stream cut a narrow canyon about 320 feet (97 m) deep from the elbow upstream past Red Rock as far as Lower Falls. Fragments of highly altered, silicified sediments derived from the sediments of Inspiration Point, well-rounded pebbles of biotite diorite derived from the diamicton of the sediments of Lower Falls upstream, and well-rounded pebbles of andesite derived from either upstream or downstream occur in the talus breccia at the base of the sediments of Red Rock (rr) (stratigraphic section 8). They show that the canyon was cut through both the sediments of Inspiration Point (ip) and the diamicton of the sediments of Lower Falls (lf) into the underlying Canyon rhyolite flow (Rc). This canyon lay entirely within the area of the present canyon. A remnant of it, now a paleocanyon filled with the sediments of Red Rock (rr), is preserved between Red Rock, a pinnacle jutting from the west wall of the present canyon, and the main canyon wall (Jones and Field, 1929; Howard, 1937). At Red Rock, the base of the paleocanyon is at an altitude of about 7,400 feet (2,255 m), 250 feet (76 m) above the present canyon floor and about 80 feet (24 m) below the present top of Lower Falls. An ancestral Lower Falls may therefore have existed at the head of the paleocanyon. If so, its crest was probably at an altitude of about 7,800 feet (2,377 m), and its height above the floor of the paleocanyon was probably between 350 and 400 feet (106 and 122 m). This ancestral falls would have been retained, as today, by a zone of hard rhyolite at the outer margin of the Canyon flow, in near-vertical contact with the tuff of Uncle Toms Trail (Rut) upstream. Upper Falls did not exist at that time.

BULL LAKE GLACIATION

The Bull Lake Glaciation in Yellowstone National Park comprised two stades of widespread icecap development, separated by an interval when the ice retreated from both Hayden Valley and the basin of Yellowstone Lake. During both stades, valley glaciers flowed west and north from the Absaroka Range into the basin of Yellowstone Lake where they merged as a single icecap. At their maximums, the icecaps of both stades were more than 3,000 feet (915 m) thick and extended south and west of this quadrangle to points within and beyond the boundaries of the park. North of the quadrangle the ice merged with another large glacier in the drainage of the Lamar River.

EARLY STADE

Glacial sediments here assigned to the early stade of the Bull Lake Glaciation are distinguished in stratigraphic sections of the sediments of Upper Falls (uf). In Hayden Valley (stratigraphic sections 29, 30) and in the area of the canyon (stratigraphic section 13), they consist of a thin layer of unsorted subangular to subround pebbles and cobbles in a silty sandy matrix (bgl) and contain erratics of basalt and andesite from the Absaroka Range. In the headwaters of Astringent Creek (stratigraphic section 55), they are composed of rhyolite, tuff, andesite, and basalt, are 30 feet (9 m) thick, and probably represent an outwash or ice-contact deposit, Locally (stratigraphic sections 29, 30), they overlie coarse gravelly lake sand (bsll) of possible proglacial origin; elsewhere (stratigraphic sections 13) they rest disconformably on laminated lake silt (s–bl) of the Sacagawea Ridge–Bull Lake interglacial interval. In the Frank Island quadrangle (MI–642, Richmond, 1974) lake silt of the Sacagawea Ridge–Bull Lake interglaciation is extensively exposed in the bluffs of Yellowstone Lake, locally beneath Bull Lake Till (bt). The silt contains a pumice bed K-Ar dated about 150,000 years old, and rests on the West Thumb rhyolite flow, more reliably K-Ar dated as about 144,000 years old. The early stade of the Bull Lake Glaciation is thus younger than about 144,000 years. In the Madison Junction quadrangle (MI–651, Waldrop and Pierce, 1975), Waldrop found erratics of basalt above and beyond the outer limit of Pinedale end moraines and 1,200 feet (365 m) above the nearby valley of the Madison River on the steep west-facing slope of the West Yellowstone rhyolite flow, K-Ar dated as 114,500±7,300 years old. Abnormal incurving basins along the margin of this flow indicate that it erupted around and in contact with something no longer there, and suggests to R. L. Christiansen (written commun., 1974) and myself that the flow erupted in contact with a glacier. The basalt erratics could only have been deposited at this time for they lie beyond the outer limits of Pinedale ice. I infer that they were deposited during the early stade of the Bull Lake Glaciation, for they are younger than deposits between 150,000 and 160,000 years old, correlated with the Sacagawea Ridge Glaciation. Presumably, deposition of these deposits was separated from that of the erratics by the interglaciation about 125,000 years ago that is widely recognized in other parts of the world.

In this quadrangle (stratigraphic sections 13, 30), glacial sediments (bgl) of the early stade of the Bull Lake are locally overlain by lacustrine gravelly sand (bsll), possibly related to the recession of early Bull Lake ice. Above this sand and directly above the glacial sediments elsewhere (stratigraphic section 29) are laminated lake silts (bil). In Hayden Valley (stratigraphic sections 18, 19, 29, 30), these silts are invaded by the Hayden Valley rhyolite flow (Rh) (K-Ar age about 100,000 years; fig. 2). In the canyon area the lake silts are overlain by lake sand containing a pumice bed K-Ar dated as about 99,000 years old (near stratigraphic section 13). The early stade of the Bull Lake Glaciation is thus older than about 99,000 or 100,000 years by an undetermined amount of time, the time of existence of this lake. I estimate that it began about 120,000 years ago and ended about 110,000 years ago.

Erratics of basalt and andesite from the Absaroka Range in glacial sediments of early Bull Lake age (stratigraphic sections 13, 29, 30) show that the ice advanced across the quadrangle from the southeast. In and north of Hayden Valley the ice flowed across older lake beds of the Sacagawea Ridge–Bull Lake interglacial interval (stratigraphic sections 29, 30). Beyond, to the west and north, it thickened against and probably overrode the divides of the Central Plateau and the Washburn Range. While this ice was advancing from the southeast, a large glacier was also developing in the drainage of the Lamar River, which is tributary to the Yellowstone River in the northern part of the park (Alden, 1928; Howard, 1937; Pierce, 1974). Lateral extension of this ice to the south was proposed by Howard (1937) as a means of impounding the lacustrine sediments of Red Rock (rr) in the paleocanyon of the Yellowstone River in this quadrangle. This hypothesis is still the most acceptable. One or more landslides downstream from Red Rock could have formed temporary dams as they have at later times, but such dams would hardly have lasted for sufficient time to permit deposition of over 200 feet (61 m) of the sediments of Red Rock. Movement along faults that cross the canyon downstream from Red Rock might have formed dams, but the precise age and extent of displacement of the faults are unknown.

The sediments of Red Rock (rr) have an original northeasterly downstream dip and in places a downstream deltaic structure. They were therefore derived from the south. None are varved and none contain erratics. This suggests that the ice both to the north and to the south was probably at a distance. Overflow of the lake across the ice to the north was at an altitude of at least 7,585 feet (2,312 m), the present top of the sediments, and probably higher. The sediments are believed to have been deposited during the advance of the early Bull Lake glaciers, rather than during their recession, because they rest on a talus breccia containing river gravel and sand (stratigraphic section 8), rather than on till. Pebbles of andesite and biotite diorite in the gravel could have been derived from sources to either north or south, but the fact that the gravel is well rounded indicates that it was transported from southern sources by the north-flowing ancestral Yellowstone River. I infer that after the sediments of Red Rock were deposited, they were overridden by early Bull Lake ice from the south because no erratics of northern derivation have been found in deposits of early Bull Lake age in this quadrangle.

Deposits associated with the recession of early Bull Lake ice include the gravelly sand (bsll) and silt (bll) immediately above the erratic-bearing glacial sediments (bgl) at stratigraphic section 13 and elsewhere just below the canyon rim (stratigraphic sections 9, 10, 14) at an altitude of about 7,900 feet (2,410 m). Along the highway, just south of the parking area at Artist Point (stratigraphic section 9), the sand is overlain by varved silt. These sediments therefore were deposited in a lake retained at an altitude of 7,900–8,000 feet (2,410–2,438 m) over the hydrothermally active section of the paleocanyon by ice of northern derivation northeast of Inspiration Point. The lake was probably short lived.

A similarly short-lived but smaller lake existed over a hydrothermally active area in the headwaters of Astringent Creek in the east-central part of the quadrangle. It was impounded between ice to the south and the Astringent Creek–Broad Creek divide to the north, over which it probably drained at an altitude of about 8,200 feet (2,500 m). At stratigraphic section 55, gravel (bgl) of early Bull Lake age is overlain by sand deposits (bsll) of the lake, beneath younger deposits of late Bull Lake and Pinedale age.

INTRA-BULL LAKE INTERSTADIAL

Following stagnation and recession of the early Bull Lake icecap, the Yellowstone River began to cut a new canyon below Lower Falls through the sediments of Upper Falls (uf, stratigraphic section 9, units bll and older) and the sediments of Red Rock (rr) into the underlying Canyon rhyolite flow (Rc). Lower Falls was probably exhumed. The course of this new canyon was within the limits of the present canyon. At the end of the interval, its depth may have been about 280 feet (85 m) at Inspiration Point, south of which a segment of its floor is preserved on the west wall of the canyon beneath sediments inferred to be of late Bull Lake age (gv, stratigraphic section 5).

Above Lower Falls, an open lake extended southwest and south across Hayden Valley. The highest deposits of this lake are cemented nearshore sands of the sediments of Upper Falls (uf) that are exposed around the hills south of the canyon at altitudes between 7,760–7,800 feet (2,365–2,377 m). In the Norris Junction quadrangle (MI–650, Richmond and Waldrop, 1975), along the upper part of the canyon of Cascade Creek at an altitude of 7,800 feet (2,377 m), some of these sands were injected into the base of, and were baked by, the overlying Hayden Valley rhyolite flow (Rh) (K-Ar age about 100,000 years). I infer that the lake was retained at this level by a dam formed of the nearly vertical hard rhyolite at the margin of the Canyon rhyolite flow (Rc) at the present position of Lower Falls. In Hayden Valley, as has been stated, massive and laminated offshore silt deposits (bil in stratigraphic sections 29, 30) of this lake locally overlie deposits of early Bull Lake age and underlie the Hayden Valley flow (Rh). The silt contains abundant pumice from the flow and is infolded into its lower part. Along the east side of the Yellowstone River (stratigraphic sections 18 and 19), the silt also was injected as much as 40 feet (12 m) up into the flow by its overriding weight. At the highway bend just south of Chittenden Bridge (Norris Junction quadrangle; MI–650, Richmond and Waldrop, 1975), a great fold of the silt extending up into the overlying perlitized flow is well exposed. In the canyon between Upper and Lower Falls, the silt (bil) and overlying pebbly sand (bslu) (the "Rim Conglomerate" of Howard, 1937, p. 110) are exposed along and below both rims (stratigraphic sections 13, 14). They form the uppermost part of the sediments of Upper Falls (uf). The upper part of the sand is extremely rich in pumice and obsidian. A pumice layer near its top yielded a K-Ar age of about 99,000 years and is probably related to the eruption of the Hayden Valley rhyolite flow, K-Ar dated at about 100,000 years. Intrusion of the Hayden Valley flow into the lake displaced its waters from Hayden Valley and the area northward to about the site of present Upper Falls. Displacement of the water may well have caused catastrophic erosion of the canyon downstream.

The Hayden Valley flow extended east of the present Yellowstone River (fig. 2). West of the river in the Norris Junction quadrangle (MI–650, Richmond and Waldrop, 1975), it extended north of the present site of Upper Falls. Outcrops of the flow overlying lake sand (uf, unit bsll) of early Bull Lake age occur within 220 yards (200 m) of Upper Falls. They suggest that the flow extended to the site of the falls and that it controlled their original position, now controlled by hard rhyolite at the north edge of a lobe of the Canyon rhyolite flow (Rc). Following eruption of the Hayden Valley rhyolite flow, a low-level lake, dammed by the flow, probably existed in Hayden Valley. From it, the ancestral Yellowstone River drained across the flow to the present confluence of Otter Creek (Norris Junction quadrangle). Beyond, it flowed along the margin of the Hayden Valley flow to Upper Falls which first came into existence at this time. Subsequently, the river cut a channel at least 50 feet (15 m) deep across the flow before eruption of the Solfatara rhyolite flow (Rs).

A lake also existed in the basin of Yellowstone Lake during the intra-Bull Lake interstadial. In this quadrangle, its sediments were found only at Steamboat Point (bisl, bil, stratigraphic section 65), where they underlie till of late Bull Lake age and younger deposits. The lake was impounded in the area of LeHardys Rapids, as was its predecessor during the Sacagawea Ridge–Bull Lake interglaciation, by the east margin of the West Thumb rhyolite flow (Rw), where it overlapped the flank of the dome of older tuffs of the Yellowstone Group to the east. The surface of the lake, as thus controlled, was probably at an altitude of about 7,980–8,000 feet (2,432–2,438 m). Its outlet was northward across the dam into the lake in Hayden Valley. That this lake was an extensive open lake is substantiated by the presence of lake silt containing a layer of pumice, K-Ar dated as about 103,000 years old, along Chipmunk Creek at the south end of Yellowstone Lake. Open water in that area must indicate withdrawal of the ice for climatic reasons. Neither rhyolite extrusion of this age nor hydrothermal activity capable of inducing local melting occurs in that area. However, glaciers may have existed in the Absaroka Range and in the valley of the Yellowstone River south of Yellowstone National Park.

LATE STADE

The icecap of the late stade of the Bull Lake Glaciation advanced from the southeast in the same manner as that of the early stade. Nowhere in the quadrangle were erratics of northern derivation, such as granite, gneiss, or quartzite, found in deposits of late Bull Lake age. However, while late Bull Lake ice was advancing from the southeast, another icecap developed in a drainage basin tributary to the Yellowstone River in the northern part of the park (Tower Junction quadrangle, MI–647, Pierce, 1974). Lateral buildup of this ice from the north is inferred to have impounded a lake west of Inspiration Point in the canyon existing at that time. Lake sediments derived from the south were deposited in this lake and are now exposed (stratigraphic section 5) beneath a younger landslide deposit on the northwest wall of the present canyon 0.4 mile (0.6 km) northeast of Grand View, from which their informal name, sediments of Grand View, is derived.

The sediments of Grand View (gv) are about 150 feet (45 m) thick. They consist of sand rich in obsidian and pumice, and varved silt. The obsidian and pumice were probably derived from the Hayden Valley flow (Rh) upstream. Their abundance is in marked contrast to their near absence in the sediments of Red Rock (rr) of early Bull Lake age and is a major reason for assigning them a late Bull Lake age. The base of the deposits is about 380 feet (115 m) below the rim of the canyon at Inspiration Point, a measure of the depth of the canyon in late Bull Lake time. These sediments were probably deposited during the advance of late Bull Lake ice from the north because they overlie talus rather than till. Following deposition, they are believed to have been overridden by ice from the south because of the absence of erratics from the north in deposits of late Bull Lake age in this quadrangle. The southern ice probably merged with the northern ice north of the quadrangle. However, no till or erratics were found between the sediments and the overlying landslide deposit.

Elsewhere in the quadrangle, till (bt) and glacial rubble (br) of late Bull Lake age occur on the higher part of the upland east of the canyon. They are mapped as late Bull Lake because they lie topographically higher than thick, hummocky Pinedale moraines to the west. The deposits contain erratics of Eocene basalt and andesite. Basalt erratics in the till have weathering rinds as much as one-fourth inch (0.6 cm) thick, and the profile of weathering on the till is locally 24–30 inches (60–75 cm) thick, in contrast to less than 12 inches (30 cm) on Pinedale Till.

Glacial sediments referred to the late stade of the Bull Lake Glaciation can be stratigraphically bracketed and restricted in age. At Steamboat Point (stratigraphic section 65) till (btu) and interlayered gravel, both containing erratics of Eocene basalt, andesite, and rhyodacite porphyry, overlie lake deposits of the intra-Bull Lake interstadial (bil, bisl) and are overlain by pumice-bearing lake silt and sand (bsl) of either late Bull Lake age or Bull Lake–Pinedale interglacial age. These units are steeply overlapped by Pinedale Till and kame gravel. In Hayden Valley (stratigraphic sections 29,30), sandy gravel (bgu) containing striated erratic cobbles of basalt and andesite overlies the Hayden Valley rhyolite flow (K-Ar age about 100,000 years); the gravel grades up into lake silt of late Bull Lake age which is overlain disconformably by Pinedale Till. Farther west in Hayden Valley, in the Norris Junction quadrangle (MI–650, Richmond and Waldrop, 1975), till, containing erratics of basalt and andesite, overlies the Hayden Valley flow and grades upward into varved silt of late Bull Lake age which is overlain disconformably by Pinedale Till. Between Upper Falls and Lower Falls (stratigraphic sections 11, 12, 14), sandy gravel containing subangular clasts and erratics of basalt and andesite disconformably overlies the cemented upper sand (bslu) of the sediments of Upper Falls. The sand contains a pumice bed K-Ar dated as about 99,000 years old whose eruption is probably related to that of the Hayden Valley flow (Rh). At a nearby temporary excavation (stratigraphic section 11), the zone of erratic-bearing gravel grades upward into pumice-rich silt that contains a layer of clean pumice and is overlain by sorted well-bedded sand. The sand is overlain by construction debris at this exposure, but nearby it is overlain by Pinedale Till containing erratics of granite and gneiss from the north. The lake deposits above the zone of erratics probably accumulated rapidly in an ice-dammed lake. The pumice is as yet undated. It is inferred to be associated with the eruption of the Solfatara Plateau rhyolite flow (Rs) (fig. 2), which yielded a K-Ar age of about 107,000 years but which overlies the Hayden Valley rhyolite flow (Rh) K-Ar dated at about 100,000 years. In the Norris Junction quadrangle (MI–650, Richmond and Waldrop, 1975), adjacent to the west, the incurvate shape of the Solfatara Plateau flow, the shattered and recemented nature of its glassy marginal breccia, and the intimate association of the breccia with glass-rich sediments of late Bull Lake age (sediments of Otter Creek, not exposed in this quadrangle) indicate that the flow probably erupted against advancing late Bull Lake ice. The zone of erratics and overlying pumice-bearing lake sediments at stratigraphic section 11 may have been deposited at this time.

In the western part of the Norris Junction quadrangle, the Gibbon River rhyolite flow, K-Ar dated as about 88,000 years old, was not glaciated by late Bull Lake ice, although it lies in the path of the ice and below its upper limit. However, the flow dammed a lake whose northern end was dammed by late Bull Lake ice from the north (MI–650, Richmond and Waldrop, 1975). The late Bull Lake glacial advance therefore began at some time after extrusion of the Hayden Valley flow about 100,000 years ago. I infer that it began about 98,000 years ago and that the Solfatara Plateau rhyolite flow (Rs) erupted against the ice about 95,000 years ago. The glacier had receded east of the western part of the Norris Junction quadrangle, but still lay to the north, about 88,000 years ago. Deglaciation was completed by 85,000 years ago. The total duration of the late stade of the Bull Lake Glaciation may therefore have been about 13,000 years, which is essentially the same as the duration of the last glaciation (late Wisconsin) as dated in other parts of the United States.

During late Bull Lake deglaciation, large mounds of kame gravel (bkg, bksg) were deposited beneath or adjacent to the ice in areas of hydrothermal activity, owing to more rapid melting of the ice in these areas. The deposits, now hydrothermally altered and silica cemented, are partly overlapped by uncemented Pinedale Till or ice-contact deposits. They occur in Hayden Valley, south of Artist Point, at Josephs Coat Springs and on Sulphur Hills.

As deglaciation progressed, a lake opened in Hayden Valley. The silty sediments of the lake (bl) are mostly varved but in places are massive or laminated. They are commonly mantled by Pinedale Till or by erratics that, north of Crater Hills, include granite and gneiss of northern derivation. Beneath the till, the lake beds are locally disrupted, broken, and mixed with masses of the till throughout a zone a few feet thick. However, no erratics of northern derivation were found in the lake beds themselves. East of Yellowstone River the silt occurs at a maximum altitude of 8,120 feet (2,475 m). To the south, on both sides of the river in the area of Mud Volcano, the silt is as much as 7,960 feet (2,426 m) high. In the central part of the valley, it underlies ridges at about 7,940 feet (2,420 m). This distribution suggests that deposition began in high ice-marginal ponds, which gradually expanded and merged to become an open lake. Howard (1937, p. 94) inferred that the lake sediments comprised deposits of a proglacial "advance" phase overlain by deposits of a "retreat" phase of his "Hayden Lake," dammed during both phases by ice from the north. However, he was unable to demonstrate evidence of glaciation between the lake deposits. He concluded that these lakes were associated with the last glaciation (Pinedale). Because the lake deposits contain no erratics of northern origin, grade downward into till of late Bull Lake age containing erratics of southeastern origin, and, in the Norris Junction quadrangle (MI–650, Richmond and Waldrop, 1975), are crumpled, folded, and mixed beneath overlying Pinedale Till containing erratics of northern origin, I conclude that they were deposited during wasting of late Bull Lake ice.

North of Hayden Valley, the varved silt (bl) overlaps the slopes of the Solfatara Plateau flow (Rs) to an altitude of 8,080 feet (2,463 m) and is at about the same altitude northwest and southeast of the canyon where it is extensively overlain by Pinedale Till. Along the road just south of Artist Point (stratigraphic section 9), the varved silt (bl) overlies cemented and hydrothermally altered sediments of Upper Falls (uf). The lake must therefore have been dammed at an altitude of over 8,000 feet (2,438 m) by ice in and over the canyon, as postulated by Howard (1937), though in late Bull Lake time rather than during the Pinedale advance.

At about the same time that the lake existed in Hayden Valley, a lake was opening around stagnant ice in the basin of Yellowstone Lake. Its highest deposits (bsl, stratigraphic section 55), in the headwaters of Astringent Creek, consist of hydrothermally altered lake sand that rests on glacial gravel (bgu) of late Bull Lake age which overlies more altered deposits of early Bull Lake age. The lake sand (bsl) is overlain by unaltered kame sand (pks) of Pinedale age. The deposits lie 520 feet (158 m) above present Yellowstone Lake. Their position, 50 feet (15 m) above the divide to the north, suggests that the lake was dammed by ice both to the north and to the south. Varved silt (bl), overlapped by Pinedale Till just west of Natural Bridge and 320 feet (97 m) above Yellowstone Lake, may represent the locus of an ice-marginal pond.

One or more floods may have taken place during final disintegration of late Bull Lake ice. Such floods may have initiated erosion of the trench of the Yellowstone River through Hayden Valley and of the present Grand Canyon of the Yellowstone in the sediments of Grand View (gv).

BULL LAKE–PINEDALE INTERGLACIATION

During the Bull Lake–Pinedale interglaciation, as during previous interglacial intervals, a high-level open lake was impounded in the basin of Yellowstone Lake by a dam in the area where the West Thumb rhyolite flow (Rw) overlaps the dome of older tuffs near present LeHardys Rapids. Though the surface altitude of this lake cannot be determined in this quadrangle, huge silt deltas, overlain by Pinedale Till and gravel in the valley of the Yellowstone River and its tributaries south of Yellowstone Lake, are at an altitude of 7,980 feet (2,432 m) or 250 feet (76 m) above present Yellowstone Lake, in the Eagle Peak (MI–637, Richmond and Pierce, 1972), Two Ocean Pass (MI-635, Richmond and Pierce, 1971), and Frank Island (MI–642, Richmond, 1974) quadrangles. The silt deposits locally overlie a thin volcanic ash at the top of a compressed peat that rests on thick, weathered outwash gravel of late Bull Lake age. The ash has petrographic characteristics indicating a source within Yellowstone National Park (R. E. Wilcox, oral commun., 1972) and can therefore be no younger than about 70,000 years, the K-Ar age of the youngest rhyolite flow in the park. Wood from the middle part of the delta deposits yielded a radiocarbon age of >42,000 years (W–2197) and >45,000 years (W–2411, Meyer Rubin, written commun., 1970).

In this quadrangle, silt (pbl) and sand (pbsl) deposits of the lake are exposed in several places in the bluffs of present Yellowstone Lake. At Lake Hotel (stratigraphic section 80), they lie beneath Pinedale Till; at Fishing Bridge (stratigraphic sections 78, 79) they contain a layer of volcanic ash and underlie Pinedale lake deposits (pl, psl); at Steamboat Point (stratigraphic section 65), they contain a pumice-rich sand, overlie till and gravel of late Bull Lake age, and are overlain by ice-contact gravel of Pinedale age. Exposures of the silt along Sedge Creek are capped by Pinedale Till; others in Pelican Valley are overlain by Pinedale erratics of Eocene volcanic rocks. Along Bear Creek near Turbid Lake (stratigraphic sections 58, 59), a gravelly sand (pbgl) facies is overlain by Pinedale Till and younger deposits.

Drainage from the lake across the dam at LeHardys Rapids probably further deepened and widened the trench of the Yellowstone River through Hayden Valley. At some time during the interglaciation a shallow lake lay within the trench at an altitude of about 7,760 feet (2,365 m). At the great southward bend of Sour Creek, a deposit of cemented gravelly sand (bdgs), having long foreset bedding, represents a delta in this lake. The cemented delta deposits have been truncated, probably by Pinedale ice, and are overlapped by similar but uncemented Pinedale delta deposits (pdgs). No deposits of this lake occur along the Yellowstone River north of Hayden Valley, which suggests that the lake was dammed where the east margin of the Solfatara Plateau flow (Rs) overlapped the Hayden Valley flow (Rh) (fig. 2). To the north, the ancestral Yellowstone River deepened its valley as far as Lower Falls. Downstream, by the end of the Bull Lake–Pinedale interglaciation, the river had cut a canyon about 440 feet (135 m) deep through the sediments of Grand View, west of Inspiration Point (stratigraphic section 5), into the underlying Canyon flow (Rc). At the north edge of the quadrangle, this canyon was cut deeper than the bed of the present river.

PINEDALE GLACIATION

Early in Pinedale time, glaciers formed in the higher parts of the Absaroka Range east and southeast of Yellowstone Lake. The glaciers flowed into the lake basin where they coalesced to become a large icecap (Richmond and Pierce, 1972). The cap eventually attained a thickness of about 3,000 feet (915 m) in the southeastern part of the lake basin (Frank Island quadrangle; MI–642, Richmond, 1974) and may have been as much as 2,000 feet (610 m) thick in the southeastern part of this quadrangle. The beginning of Pinedale time cannot be precisely dated. In the Frank Island (MI–642, Richmond, 1974) and Eagle Peak (MI–637, Richmond and Pierce, 1972) quadrangles, Pinedale Till and ice-contact deposits disconformably overlie lake silt of the Bull Lake–Pinedale interglaciation that contains wood more than 40,000 years old and locally overlies volcanic ash not less than about 70,000 years old.

In this quadrangle, Pinedale Till overlies lake deposits of the Bull Lake–Pinedale interglaciation in the bluffs of Yellowstone Lake at a number of places (stratigraphic sections 64, 80, 81, and elsewhere). Erratics of Eocene basalt, andesite, and volcanic breccia in the till north and west of the lake show that the ice flowed northwestward across the southern, central, and northeastern parts of the quadrangle. It overrode the uplands of Elephant Back Mountain and Stonetop Mountain in the central part. In the northern part, the surface of the ice was lower, for the highest Pinedale deposits, represented by end moraines and embankments of thick till, lie at an altitude of 8,950 feet (2,728 m) on the eastern slope of the upland northwest of Fern Lake and at an altitude of 8,760 feet (2,670 m) on the western slope. The upland itself shows no evidence of having been crossed by the main icecap but may have supported a local cap or snow dome.

As the icecap was forming in the basin of Yellowstone Lake, a large glacier was also developing in the drainage of the Lamar and Yellowstone Rivers in the region north of this quadrangle (Howard, 1937; Pierce, 1974). That this northern ice spread laterally southwest to the canyon was first recognized by Holmes (1883), who discovered the now-famous large granite "glacial boulder" on the rim of the canyon near Inspiration Point. He concluded that it had been transported by a glacier from a source 20 miles (32 km) to the north. Later, Howard (1937, p. 89) showed, from the distribution of granite erratics, that the northern glacier not only advanced over the area in which the canyon lies but also spread westward across Hayden Valley. The present study fully supports Howard's conclusion. Erratics from northern sources are widespread north and south of the canyon in this quadrangle. These include large cobbles and boulders of granite and gneiss derived from far to the north, pebbles and small well-rounded cobbles of granite and quartzite from a conglomerate of probable Pliocene or early Pleistocene age on the southeast side of Hedges Peak (Tower Junction quadrangle), irregular fragments of an agglutinate phase of the tuff of Sulphur Creek from the canyon rim west of Sevenmile Hole, and fragments of obsidian from the Dunraven Pass rhyolite flow (Rdp), all to the north. South of the canyon, the erratics also include cobbles of biotite diorite from the diamicton at Lower Falls (possibly also from their original source in an Eocene stock exposed on the south slope of Mount Washburn in the Tower Junction quadrangle), and fragments of chalcedonic sinter from the area of Artist Point. All of these erratics must have been transported by southward-flowing Pinedale ice. That they are not reworked from older glacial or lake deposits is indicated by the absence of erratics of northern derivation in older deposits in this area.

The erratics of granite, gneiss, and quartzite extend to higher altitudes than the other erratics. Northwest of the canyon, in the Tower Junction quadrangle, a 2-foot (0.6-m) boulder of granite was reported by Howard (1937, p. 87) near the Dunraven Pass road at an altitude of 8,490 feet (2,588 m). I have found boulders of granite and gneiss at altitudes of as much as 8,760 feet (2,670 m) on the two ridges southeast and south of Hedges Peak (Tower Junction quadrangle). On both ridges and in the intervening stream gullies the erratics are moderately abundant. Few were found on ridge slopes, owing to a mantle of colluvium. To the west, erratics become increasingly sparse. The highest were found at altitudes which decrease westward from 8,760 feet (2,670 m) to 8,520 feet (2,597 m) northeast of Cascade Lake in the Mammoth quadrangle. The erratics consist of cobbles and boulders 6–14 inches (15–35 cm) in diameter and of smaller stones. Most are of gray hard unweathered Precambrian crystalline rock. However, some of the small crystalline stones are stained yellow or brown and some are rotted. Some small quartzite stones are also stained and have weathered rinds. These small stones are believed to be derived from a conglomerate of probable Pliocene or early Pleistocene age that is exposed locally southeast of Hedges Peak. Southeast of the canyon, the highest granite boulders lie at an altitude of only 8,080 feet (2,460 m), 2 miles (3.2 km) northeast of Point Sublime. The 420-foot (125-m) difference in maximum altitude of erratics northwest and southeast of the canyon suggests that the crystalline-bearing glacier from the north abutted ice bearing erratics of basalt and andesite from sources to the southeast. This suggestion is supported by evidence in Hayden Valley.

The zone of granite-bearing drift in the area of the canyon is about 4 miles (6.5 km) wide. South of the canyon, this drift is present on the upland immediately east of the Yellowstone River as far south as the confluence of Sour Creek. Immediately west of the Yellowstone River, it extends as far south as the north slope of Crater Hills. Farther west, granite erratics occur sparingly in a band of drift about 8 miles (13 km) wide that extends across the Norris Junction quadrangle (Richmond and Waldrop, 1975) between the south flank of the Washburn Range in the Mammoth quadrangle, adjacent to the north, and the central axis of Hayden Valley at elevations of as much as 8,520 feet (2,600 m). Howard (1937, p. 87) reported an erratic of granite on Mary Mountain (Norris Junction quadrangle) at an altitude of about 8,500 feet (2,590 m). The glacier-bearing crystalline erratics were therefore at least 720 feet (220 m) thick in Hayden Valley and must have been in contact along the axis of the valley with ice from the southeast. Such a confluence of the two ice masses was suggested by Howard (1937, p. 92) for other reasons.

Though the existence of Pinedale Till in Hayden Valley has been debated, there is no doubt that Pinedale glaciers traversed the lake sediments (bl) of late Bull Lake age in that area. Hague, Weed, and Iddings (1896) and De Martonne (1915) failed to recognize the lake sediments and considered all of the deposits to be moraine. Howard (1937, p. 93) found that varved and laminated lake sediments underlay the broad high divides and denied the existence of moraine. Both conclusions are, in part, correct. As stated, lake silt of late Bull Lake age, in which I found no erratics, underlies the divides. However, there is clear evidence that these deposits were deeply eroded during the Bull Lake–Pinedale interglaciation by ravines graded to the trench of the Yellowstone River, and that Pinedale glaciers from both northeast and southeast subsequently left their deposits on this dissected terrain. Pinedale Till as much as 15 feet (4.6 m) thick mantles the walls of the trench and the southeast slopes of divides in the southeastern part of Hayden Valley. Thin till locally mantles the divides and northwest slopes. In the western part of Hayden Valley (Norris Junction quadrangle; MI–650, Richmond and Waldrop, 1975), a veneer of glacial stones, including erratics, mantles the dissected lake silt. Along the highway south from Upper Falls (Norris Junction quadrangle), crumpling, folding, and mixing of the upper few feet of the silt beneath Pinedale Till indicate overriding by Pinedale ice.

STAGNATION OF THE PINEDALE ICECAP

After the Pinedale icecaps had begun to recede, several secondary readvances of the ice took place in middle Pinedale time. The terminal moraines of the younger of these advances lie in the Norris Junction quadrangle (MI–650, Richmond and Waldrop, 1975) west of this quadrangle.

In the Canyon Village quadrangle, the upper limit of one middle Pinedale readvance (PM) is recorded by discontinuous lateral moraines, morainal embankments, and ice-marginal drainage outlets around the upland extending northwest from Fern Lake to the Grand Canyon of the Yellowstone. These features lie about 400 feet (120 m) below the maximum upper limit of Pinedale ice northwest of Fern Lake and slope northwest to the canyon where they are about 700 feet (215 m) below the maximum upper limit 5 miles (8 km) east of the canyon.

Following the readvance, both the southern and northern ice masses wasted rapidly. As uplands appeared from beneath the ice, ice-contact gravelly sand (pkgs) was deposited around, or upvalley from, the ice. The highest deposits are northwest of Stonetop Mountain at an altitude of 8,400 feet (2,560 m), 670 feet (204 m) above present Yellowstone Lake. They extend down the valleys northwest of Stonetop Mountain and the melt waters which deposited them probably drained across ice in Hayden Valley and westward into the Norris Junction quadrangle. A small deposit, also at an altitude of 8,400 feet (2,560 m), on the south side of Sulphur Hills owes its location to melting of the ice over local hot springs. Other deposits related to local hydrothermal activity are the ice-dammed lake silt in the area of Hot Springs Basin Group, also at 8,400 feet (2,560 m) altitude, and probably some of the ice-contact gravelly sand mapped as Bull Lake in age (bkgs) at Josephs Coat Springs. A Pinedale hydrothermal explosion deposit (phe) and crater near Josephs Coat Springs suggest that area may have been the locus of a small ice-marginal lake in Pinedale time. Muffler, White, and Truesdell (1971) proposed that some hydrothermal explosions may be caused by the sudden release of water from a lake overlying an area of hot springs. Another hydrothermal explosion deposit (phe) forms a ridge around a crater at Fern Lake, 5 miles (8 km) to the southeast.

After further downwasting of the icecap, ice-contact gravelly sand (pkgs) was deposited on and adjacent to the ice in the valley of Astringent Creek, on the slopes around Yellowstone Lake, and in the area of LeHardys Rapids. In the valley of Astringent Creek the deposits lie between altitudes of 8,500 feet (2,590 m) and 8,040 feet (2,450 m), or between 770 feet (235 m) and 310 feet (94 m) above present Yellowstone Lake. They contain small pebbles of pumice derived from outcrops of the tuff of Sulfur Creek at the margin of the Canyon rhyolite flow (Rc) to the north, indicating that the local drainage was to the south. The deposits show unusually well-developed ice-contact slopes. The basins of White Lake and Fern Lake are huge kettles formed when buried ice masses melted. An esker (peg) at the narrows of White Lake marks the former position of a subglacial stream. On the east side of Yellowstone Lake, ice-contact sandy gravel (pkgs) mantles the slopes south of Lake Butte between altitudes of 8,240 feet (2,510 m) and 7,840 feet (2,390 m), or between 510 feet (155 m) and 110 feet (33 m) above present Yellowstone Lake, and extends upslope to higher altitudes in the Pelican Cone quadrangle (MI–638, Richmond and Waldrop, 1972), adjacent to the east. On the west side of Yellowstone Lake, ice-contact gravelly sand (pkgs) extends from an altitude of 8,200 feet (2,500 m), or 470 feet (143 m) above present Yellowstone Lake, down to 7,840 feet (2,390 m), or 110 feet (33 m) above the lake. The deposits form a series of broad discontinuous kame terraces. In the valley of the Yellowstone River near present LeHardy's Rapids, thick ice-contact deposits of gravelly sand (pkgs) extend from river level upslope over ridges of tuff of the Yellowstone Group (through which the river had cut its course during the Bull Lake–Pinedale interglaciation) and form a sequence of terraces at altitudes of 8,040, 7,880 and 7,840 feet (2,450, 2,402, and 2,390 m) or 310, 150, and 110 feet (94, 46, and 33 m) above present Yellowstone Lake. The highest of these terraces, which is at the same altitude as the lowest ice-contact deposits around Yellowstone Lake, is a kame terrace formed when ice lay both in Hayden Valley to the north and in the area of Yellowstone Lake to the south. The lower two are erosion terraces cut in the deposits of the highest terrace. In the southern part of Hayden Valley, at the west edge of the quadrangle, ice-contact gravel underlies an irregular surface that slopes northward from an altitude of 8,000 feet (2,438 m) to 7,800 feet (2,377 m).

As downwasting continued in the basin of present Yellowstone Lake, silt (pkl) was deposited in small lakes marginal to the ice. One such lake, ancestral to Yellowstone Lake, first developed at an altitude of 8,360 feet (2,548 m) in an area of thermal activity on the west side of the basin of Astringent Creek. Further downwasting of the ice extended the lake eastward and southward toward Pelican Valley at gradually decreasing surface levels. At about the same time, another ice-marginal lake developed at an altitude of 8,240 feet (2,511 m) in the headwaters of Pelican Valley in the Pelican Cone quadrangle (MI–638, Richmond and Waldrop, 1972) adjacent to the east. In like manner, this lake opened southward and westward down Pelican Valley into this quadrangle at gradually decreasing surface levels until it merged with the lake in the valley of Astringent Creek at an altitude of 8040 feet (2,450 m), or 310 feet (94 m) above present Yellowstone Lake. At this altitude the lake was probably retained by ice in the basin of Yellowstone Lake at about the position of the present north-west trending ridge north of Mary Bay. Its outlet was through a channel at an altitude of 8,040 feet (2,450 m) north of Ebro Springs. From the channel it drained along the edge of the ice (at about the position of the present unnamed stream south of Thistle Creek) into melt waters flowing on a gradient of about 40 feet/mile (7.6 m/km) from the ice front east of Ochre Springs across the kame terrace gravel (pkgs) at an altitude of 8,040 feet (2,450 m) southwest of LeHardys Rapid onto and around ice in Hayden Valley. From this ice it probably drained westward through a large channel, recognized by Howard (1937, p. 99), which extends westward from moraines in the headwaters of Cascade Creek (Mammoth quadrangle;

MI–641, Pierce, 1973) at an altitude of about 8,040 feet (2,450 m) through Cascade, Grebe, and Wolf Lakes (Norris Junction and Mammoth quadrangles) into the drainage of the Gibbon River. The channel marks the last westward flow of water from the drainage of the Yellowstone River.

Subsequently, the ancestral lake was lowered 200 feet (60 m) to an elevation of 7,880 feet (2,402 m) or 150 feet (46 m) above present Yellowstone Lake. The lowering was probably caused by wasting of the ice from the hills south of the unnamed stream south of Thistle Creek and was probably sudden and extraordinarily rapid. It was not caused by movement on the east-trending fault across LeHardys Rapids because Pinedale Till (pt) and overlying ice-contact gravelly sand (pkgs) extend unbroken across the fault (stratigraphic sections 38 and 39).

Lowering of the lake reduced its confining pressure on the hydrothermal area around Mary Bay and triggered a hydrothermal explosion or group of closely spaced explosions in that area. According to Muffler, White, and Truesdell (1971), hydrothermal explosions are commonly caused by the rapid fall of a lake. The explosion deposit (phe), the largest known in the park, forms a broad hemi-elliptical ridge around the north and east sides of Mary Bay. The ridge is about 200 feet (60 m) high and ½–1½ miles (0.8–2.4 km) wide. The inside long dimension of its arc is about 3 miles (4.8 km). An elliptical depression shown in Mary Bay on an unpublished reconnaissance map of the floor of Yellowstone Lake by the U.S. Fish and Wildlife Service may be a remnant explosion crater. It is nearly 1 mile (1.6 km) long and has a maximum depth of more than 160 feet (49 m).

The explosion deposit (phe) is well exposed along the service road to Turbid Lake. In places it is 140 feet (43 m) thick (stratigraphic section 71). In the bluff east of Mary Bay it rests on lake sand (pksl) (stratigraphic sections 69, 70) which overlies Pinedale Till (pt) (stratigraphic section 71). In the bluff southeast of Squaw Lake (stratigraphic sections 73, 75, 76) it disconformably overlies varved silt (pl), is locally contorted, and is overlain by fine lake sand (psl) or varved silt (pl). At stratigraphic section 76, the outer edge of the hydrothermal explosion deposit (phe) intrudes a dark, richly organic lake deposit, carbon-14 dated as 13,650±600 years old (W–2894) (Meyer Rubin, written commun., 1973), which lies in finely laminated lake sand immediately above varved silt (pl).

In Pelican Valley, the explosion debris (phl) is silty and weakly bedded, as if deposited in or reworked by the lake. The deposit (phl) rests disconformably on lake-bottom silts (stratigraphic sections 49, 50, 51, 52, 53). Beyond the limits of the debris (phl), a distinct though slight disconformity separates silts deposited before and after the explosion (stratigraphic section 45). The water in Pelican Valley, displaced violently by the explosion and construction of the ridge, flooded across the hills south of the unnamed stream south of Thistle Creek, where it produced a local scabland topography. Backwash of the waters flooded through four distinct channels across the ridge of explosion debris into the explosion crater. The lake in Pelican Valley settled at an altitude of 7,880 feet (2,402 m) for a short time, draining through the area of LeHardys Rapids across the kame terrace deposit (pkgs) at that altitude. It was then lowered by erosion of its outlet through the ridge west of Vermilion Springs to an altitude of 7,840 feet (2,390 m), 110 feet (33 m) above present Yellowstone Lake, and merged with water ponded in front of and around the margin of the ice in the basin of Yellowstone Lake. The upper limit of the lake at this altitude is marked by two terraces; one, underlain by lake-reworked explosion debris (phl), is on the southwestern slope of the ridge of hydrothermal explosion debris, and the other, underlain by beach gravel (pklb), is on the slopes northwest of Yellowstone Lake. In the southern part of the quadrangle and farther south around Yellowstone Lake, a 110-foot (33-m) terrace is also well developed but has ice-contact features, indicating that only a narrow irregular strip of water, ponded between stagnant ice in the basin and the adjacent hill slopes, lay in these areas. The northern limit of the ice was probably along the abrupt lobate slope shown by contours on the floor of Yellowstone Lake east of Stevenson Island (from U.S. Geological Survey topographic map of Yellowstone National Park, 1961). Stevenson Island is underlain largely by ice-dammed lake sand (pksl). The outlet of the lake was at the level of the erosional terrace cut in ice-contact sandy gravel (pkgs) at an altitude of 7,840 feet (2,390 m), 110 feet (33 m) above present Yellowstone Lake, at LeHardys Rapids.

South of this quadrangle, other strand lines and terraces, 90 and 80–75 feet (27 and 24–23 m) above present Yellowstone Lake, are believed to have been controlled by pauses in the erosion of the outlet, which, in turn, were probably controlled by stagnation of the ice in Hayden Valley. Their discontinuous nature and, for the most part, poor development suggest that they represent ony minor and short-lived stands during a time of falling water level. These strand lines were not noted in this quadrangle. Lake sediments younger than the hydrothermal explosion deposit at Mary Bay contain evidence for the time when Yellowstone Lake became fully open. Thinly laminated wavy beds of fine lake sand, exposed in the bluffs of the lake southeast of Squaw Lake, immediately overlie the explosion deposit (stratigraphic sections 73, 74, 75, 76). At stratigraphic section 75, a thin layer of volcanic ash, identified by R. E. Wilcox (written commun., 1972) as probably the Glacier Peak ash but possibly the Mount St. Helens J ash, was found in the sand, 2 feet (0.6 m) above the explosion deposit. The Glacier Peak ash is 12,000 or 12,600 years old and the Mount St. Helens J ash is probably about the same age. Both are from sources in the Cascade Range in Washington. Either would be about 1,000 years younger than the explosion deposit (carbon-14 age, 13,600±600 years). Charcoal found at a point 4.4 feet (1.34 m) above the ash yielded a carbon-14 age of 10,720±350 years (W–2738, Meyer Rubin, written commun., 1972). An ash bed, identified by Wilcox as the same as that at stratigraphic section 75, occurs in laminated silt in the bluff of Yellowstone Lake south of Gull Point (stratigraphic section 92), and, in the Frank Island quadrangle (Richmond, 1974), at the entrance to Flat Mountain Arm and along Grouse Creek. At the latter locality, the ash is 4 feet (1.2 m) above the base of the laminated silt which, in turn, overlies varved silt. Organic matter 4 feet (1.2 m) above the ash yielded a carbon-14 age of 9,060±300 years (W–2041; Sullivan and others, 1970). In the Canyon Village quadrangle, just north of the ridge of hydrothermal explosion debris (phe) in Pelican Valley at stratigraphic section 45, a pair of thin ash beds, 6 inches (15 cm) apart, occur in the thinly laminated foreset-bedded silt of a delta which disconformably overlies varved silt. These ash laminae have not been identified but may be the Glacier Peak or Mount St. Helens J ash bed.

The broad distribution of the ash around northern, western, and southwestern parts of Yellowstone Lake and its position in nonvarved sediments overlying varved sediments indicate that by 12,000 or 12,600 years ago the lake was free of ice. The relatively small amount of sedimentation, 2–4 feet (0.6–1.2 m), during the 1,200 to 2,000 years following deposition of the ash contrasts markedly with the underlying thickly varved beds and further suggests that the lake was fully ice free at the time the ash fell.

In Hayden Valley the ice from both northern and southern sources appears to have remained intact for some time and then to have downwasted very rapidly. Discontinuous ice-contact deposits of gravelly sand (pkgs) as high as 8,000 feet (2,438 m) altitude east and west of the southern part of Hayden Valley and the absence of lake deposits of Pinedale age at this level suggest that melt-water streams flowed north both on and marginal to ice in Hayden Valley and in the basin of Sour Creek. They probably drained through an outlet channel at an altitude of about 7,980 feet (2,432 m) 2 miles (3.2 km) northeast of Silver Cord Cascade and onto ice in the Grand Canyon of the Yellowstone. The surface of the ice in Hayden Valley was probably eroded by floodwaters resulting from the hydrothermal explosion and concurrent rapid fall of the lake in Pelican Valley to a level 110 feet (33 m) above present Yellowstone Lake. In the southern part of Hayden Valley, lake sediments (pkl) at and below an altitude of 7,840 feet (2,390 m) show that a lake 110 feet (33 m) above present Yellowstone Lake also occupied this area. These sediments are the "plains sediments" of Howard (1937, p. 94) in Hayden Valley. The level of this lake probably controlled that of the lake at the same altitude in the basin of Yellowstone Lake. The two may have been essentially continuous across the erosional terrace cut on ice-contact sandy gravel (pkgs) at an altitude of 7,840 feet (2,390 m) in the area of LeHardys Rapids. The lake in Hayden Valley was dammed by the front of ice from the north, which lay along the slopes north of Crater Hills and to the northeast, east of the Yellowstone River. For a time, it probably drained north across ice in the lower valley of Sour Creek and through successively lower well-marked outwash channels cut in rock at altitudes of 7,840 to 7,800 feet (2,390 to 2,377 m) between Ribbon Lake and Clear Lake, onto ice or into a lake in the Grand Canyon of the Yellowstone.

A thick basal sand and an overlying succession of five conformable sequences of varved silt were deposited in the lake. These sediments are exposed in the bluff of Trout Creek at stratigraphic section 35. Each varved sequence grades from megavarves at its base to thin varves at its top, and each is separated from its successor by a very thin layer of fine sand. No erosion seems to have taken place between sequences. The succession probably was the result of minor changes in lake regimen, but its precise meaning is obscure.

Subsequently, the ice in the basin of Sour Creek and in northern Hayden Valley deteriorated, and the drainage shifted to a course over ice in the sheltered canyon of the Yellowstone River north of Hayden Valley. At this time the lake level was lowered gradually about 100 feet (30 m) to an altitude of 7,700 feet (2,347 m). As the lake was lowered, a thin sheet of gravel (pgs), possibly a recessional beach deposit, was spread out over the lake deposits (pl). The level of the lake at 7,700 feet (2,347 m) is marked by the surface of a large delta of gravelly sand (pdgs) well exposed at stratigraphic section 21 in the basin of Sour Creek.

Final deterioration of the ice in the canyon of the Yellowstone River north of Hayden Valley and drainage of this lake was probably catastrophic. Ragged scablike pillars of rock in the Yellowstone River below Chittenden Bridge (Norris Junction quadrangle) suggest flood scour of the river channel. A flood also took place along the trench of the Yellowstone River at the head of the lake at this time. A deposit of this flood (pfd) at least 60 feet (18 m) thick is exposed in a highway cut at stratigraphic section 34. The deposit appears to be a flood bar, the top of which is at an altitude of 7,760 feet (2,365 m). The deposit is banked in near-vertical contact against Pinedale Till and underlying lake deposits of late Bull Lake and intra-Bull Lake age. To the west, in the bluff north of Trout Creek, thin layers of older flood deposits, possibly related to the flood immediately preceding the 110-foot (33-m) lake level, are interbedded in the basal sandy deposits of that lake. To the east, a younger alluvial terrace deposit (pgs) lies in steep contact against the flood deposit. The flood was probably associated with one of the drops in the level of Yellowstone Lake after its stand at the 110-foot (33-m) level, but no specific relation can be established.

In the Grand Canyon of the Yellowstone, wasting of the ice was probably rapid owing to the local extensive hydrothermal activity. A small deposit of lake silt, first noted by Howard (1937, p. 106) on the west wall of the canyon below Lower Falls, has steeply dipping laminae and appears to have formed in water ponded by ice in the canyon. Talus deposits on the east wall of the canyon below Lower Falls contain abundant well-rounded cobble gravel, chiefly of rhyolite but including unaltered obsidian, basalt, andesite, diorite, granite, gneiss, and red and white quartzite. This gravel is traceable upslope to a bed of gravel, mixed with, and mostly covered by, talus, that is perched on the canyon wall about 200 feet (60 m) above the river. The gravel was probably deposited by a stream marginal to ice in the canyon.

Lakes probably existed in the hydrothermal areas below Lower Falls and in Sevenmile Hole at least by the time of the flood caused by the giant hydrothermal explosion and catastrophic lowering of the lake in the basin of Yellowstone Lake to its 110-foot (33-m) level about 13,650 years ago. Erosion by this and other floods probably deepened the canyon and undercut its walls. Howard (1937, p. 106) described a sandstone block, about 50 feet (15 m) above river level on the east side of the canyon along the trail downstream from the observation platform below Lower Falls, which he believed had fallen from the canyon rim. The block is 30–40 feet (9–12 m) long, and the bedding of the sandstone strikes N. 25° W. and dips 25° S. Its lithologic characteristics are identical to those of silica-cemented sand (uf, unit 1) on the rim of the canyon upslope. Such blocks could easily have fallen during or shortly after undercutting of the canyon wall by a flood.

Just north of this quadrangle, near the south edge of the Tower Junction quadrangle, varved lake silt at an altitude of 7,400 feet (2,255 m) in a reentrant on the west slope of the canyon records the locus of an ice-marginal pond 800 feet (244 m) above the river. In this quadrangle, varved silt, overlying Pinedale gravel and till (stratigraphic section 1) at an altitude slightly less than 6,800 feet (2,073 m), formed in a lake dammed in the canyon at that altitude by an ice margin downstream north of Tower Fall. The lake was first recognized and its deposits described by Howard (1937, p. 127–134), who named it Retreat Lake. It is further discussed by Pierce (MI–647, 1974).

POSTGLACIAL HISTORY OF THE GRAND CANYON OF THE YELLOWSTONE

Since drainage of Retreat Lake, 40–80 feet (12–24 m) of its sediments and older deposits have been stripped from the canyon floor, and the canyon walls have been eroded by mass-wasting processes associated with the development of landslides, mudflows, and talus. A mudflow deposit (pmf) containing wood, carbon-14 dated as 10,900±350 years old (W–2736) (Meyer Rubin, written commun., 1973), rests on gravel (pg) and till (pt) of Pinedale age about 15 feet (4.6 m) above river level at stratigraphic section 2. At the same locality, laminated silt of a landslide-dammed lake contains logs, one of which yielded a carbon-14 age of 2,430±250 years (W–2735) (Meyer Rubin, written commun., 1973). The logs were coated with sulfur and completely carbonized by local hydrothermal activity. Downstream, in the southern part of the adjacent Tower Junction quadrangle, logs from the same bed are altered to white splintery silicified wood. At another locality, at river level in the southern part of the Tower Junction quadrangle, a log from soft lake silt immediately upstream from a large landslide yielded a carbon-14 age of 540±250 years (W–2766) (Meyer Rubin, written commun., 1973). In June 1971 a landslide developed in hydrothermally altered talus and underlying rock on the east wall of the canyon in the Canyon Village quadrangle opposite stratigraphic section 3. The slide raised the floor of the river, bringing Pinedale Till and overlying deposits to the surface in the channel. The slide dammed the river to a height of approximately 40 feet (12 m) above its normal level, as shown by the presence of flood trash and boulders around the toe of the slide and upstream. Damming was probably brief, for the river broke across the eastern part of the slide deposit, cutting a new channel and leaving a deep pool, informally known as Threemile Hole, upstream from the western part of the deposit.

POSTGLACIAL HISTORY OF YELLOWSTONE LAKE

Since disappearance of the icecap from the basin of Yellowstone Lake about 12,000 or 12,600 years ago, the lake has existed as a body of open water at successively lower levels. A prominent terrace and associated well-sorted lacustrine deposits extend almost continuously around the lake at a level 60–65 feet (18–20 m) above it. The deposits of this terrace differ from those at higher levels in that they are characterized by numerous large spits, bars, and lagoonal depressions, indicative of strong longshore currents found only in a large body of open water. The presence of large deltas at the 60- to 65-foot (18- to 20-m) level along Pelican Creek, Sedge Creek, and Bridge Creek, as well as the width and continuity of the terrace, suggests that the lake maintained itself at this level for a fairly long time. No evidence of the age of the terrace was found in this quadrangle. However, along Grouse Creek in the Frank Island quadrangle (MI–642, Richmond, 1974), foreset-bedded sand deposits of a prograding delta at the 60- to

65-foot (18- to 20-m) level overlie lake silts containing organic matter that was carbon-14 dated as 9,060±300 years old (W–2041; Meyer Rubin, written commun., 1972). The 60- to 65-foot (18- to 20-m) terrace is therefore younger than 9,060±300 years.

The outlet waters of the lake probably flowed across the silica-cemented lake sand (pbsl) of Bull Lake–Pinedale interglacial age that underlies the area between Pelican Creek and the Yellowstone River and served to retain the lake in the same way that compact silt (pbl) of the same age retains present Yellowstone Lake at Fishing Bridge. The outlet at the time of the 60-foot (18-m) lake level is estimated to have been about 1.5 miles (2.4 km) north of Fishing Bridge. It might be imagined that the lake extended north to the outlets cut in rock (mentioned above) southeast of the canyon at an altitude of about 7,800 feet (2,377 m), approximately 60 feet (18 m) above present Yellowstone Lake. However, this seems impossible because those outlets show no evidence of long-term use. Furthermore, there is no gravel terrace and no lake silt at the 60-foot (18-m) level in the valley of the Yellowstone River south and west of LeHardys Rapids.

Although no glacial deposits of late Pinedale age are present in this quadrangle, outwash of late Pinedale age is graded to the 60-foot (18-m) terrace at the southeast end of Yellowstone Lake (MI–637, Richmond and Pierce, 1972). Late Pinedale time is therefore included in the time of formation of the 60-foot (18-m) terrace.

A hydrothermal explosion deposit (he) forms a ridge around Turbid Lake, the site of the crater from which the material was ejected. The deposit rests on a layer of subaerial organic matter carbon-14 dated as 8,000±500 (W–2486; Meyer Rubin, written commun., 1969) and 8,310±300 years old (W–1944; Marsters and others, 1969). The explosion does not seem to have been related to a falling lake level, because the preexisting terrain was 100–125 feet (30–38 m) above the 65-foot (20-m) terrace.

Lake terraces and associated lake deposits, 50–55, 40–45, and 30–35 feet (15–17, 12–14, and 9–11 m) above Yellowstone Lake are considered to have formed during the "altithermal" interval. A stream terrace entrenched about 8 feet (2.5 m) below the floor of the drained lake in Pelican Valley is itself entrenched 15 feet (4.5 m) by the modern flood plain. The terrace is probably related to the 40- to 45-foot (12- to 14-m) lake terrace, though this cannot be proven. Twigs from a boggy sand layer beneath the stream terrace gravel yielded a carbon-14 age of 5,900±300 years (W–2580) (Meyer Rubin, written commun., 1969). Organic matter from a lagoonal deposit of the 40-foot (12-m) terrace in the Frank Island quadrangle (MI–642, Richmond, 1974) is older than a minimal date of 5,590±250 years (W–2286) (Meyer Rubin, written commun., 1969). Lowering of the lake from the 30- to 35-foot (9- to

11-m) level to the 25-foot (7.6-m) level touched off a hydrothermal explosion, the crater of which is at Squaw Lake (Canyon Village quadrangle). In the bluff of Yellowstone Lake southeast of Squaw Lake, the hydrothermal explosion deposit (he) overlies thinly laminated wave beds of fine sand (psl) (stratigraphic sections 73, 74, 75, 76) that appear to represent offshore deposits of the lake at the 60-foot (18-m) terrace level. To the east, at stratigraphic section 74 where the modern bluff has cut inland from the 25-foot (7.6-m) terrace, the explosion deposit is overlain by limonite-stained sandy silt and organic-rich clay, carbon-14 dated as 3,500±250 years old (W–2734) (Meyer Rubin, written commun., 1972). Where the bluff crosses the 25-foot (7.6-m) terrace, the terrace is cut on the explosion deposit and its associated beach gravel is overlain by younger colluvium and dune sand.

Terraces 25, 15, and 10 feet (7.6, 4.6, and 3 m) above the lake are probably all of post-Altithermal age. Charcoal under colluvium overlying beach gravel of the 10-foot (3-m) terrace has a radiocarbon age of 620±250 years (W–1999; Meyer Rubin, written commun., 1968).

OTHER POSTGLACIAL EVENTS

Very few postglacial solifluction or mass-wasting deposits were recognized in the quadrangle, though such activity probably occurred on till-covered slopes, especially where the till overlies lake silts. A block landslide on the south slope of the valley of Sour Creek probably formed during recession of the ice. A few small slump landslide deposits were mapped, for example, at Turbid Lake.

Postglacial stream erosion and alluviation have been remarkably slight. Postglacier-related deposits are dissected 15–30 feet (4.5–9 m). Much of this was probably accomplished during floods or drops in lake level. Pelican Creek meanders in thin alluvium (fa) in a broad shallow trench only about 8–10 feet (2.5–3 m) deep. Underlying lake silts are exposed in the creek in several places. The outlet of Yellowstone Lake at Fishing Bridge is on compact lake silt (stratigraphic sections 78, 79). In the Grand Canyon of the Yellowstone, the river has eroded through as much as 40 feet of soft sediments but has cut only 10-15 feet (3–4.5 m) into hydrothermally altered rhyolite. Postglacial gullies on hillsides are mostly only 15–20 feet (4.5–6 m) deep. Alluvial fans (fa) at the foot of slopes are small. Changes in the shoreline of Yellowstone Lake may have been considerable. Large spits and bars in the lake denote extensive modern longshore transport. Storm waves have been observed to strip away as much as 4 feet (1.2 m) of the bluff southeast of Squaw Lake in less than an hour. Such catastrophic erosion, though perhaps rare, has probably effected significant changes in the shoreline over the years.

HYDROTHERMAL ACTIVITY

The hydrothermal activity in the park is being studied by D. E. White and others. Acid alteration of the rhyolite in the Grand Canyon of the Yellowstone is probably old, although many small thermal springs and gas vents lie between Lower Falls and Inspiration Point, and north of the great bend of the Yellowstone River near the north edge of the quadrangle. Other areas where acid alteration of bedrock is widely associated with hot springs or fumaroles include Sulphur Hills, the area west of Astringent Creek, and several areas north of Sour Creek on the southern slope of the Canyon rhyolite flow (Rc). The area of alteration, including Sulphur Springs, west of Crater Hills, is in ice-contact gravel (bkgs) and ice-dammed lake silt (bl) of late Bull Lake age. It includes at least one geyser. Other hot springs occur in ice-contact gravels at and near Josephs Coat Springs (including Whistler Geyser), along the Wapiti Lake Trail at Moss Creek, at Ochre Springs, in the Sulphur Hills, and at Steamboat Point. Hot springs and mud pots in lake silts are characteristic of the Mud Volcano area, Ebro Springs, Vermilion Springs, the Ponuntpa Springs Group, the Hot Spring Basin Group, and along the valleys of Pelican Creek, Astringent Creek, Sour Creek, and Cottongrass Creek. Hot springs occur in beach deposits around Mary Bay and westward to Pelican Creek, and beach deposits of older high stands of the lake have been cemented by silica-bearing waters in many places. Hot springs are also common in the hydrothermal explosion deposits around Mary Bay, Turbid Lake, Squaw Lake, Fern Lake, and near Josephs Coat Springs.

QUATERNARY FAULTING

Most of the quadrangle lies within a caldera whose collapse followed eruption of a widespread tuff of the Yellowstone Group about 600,000 years ago (Christiansen and Blank, 1972). The wall of the caldera trends northeast across the quadrangle east of Broad Creek. The faults shown on the map (I–652) are chiefly from R. L. Christiansen and H. R. Blank Jr. (1975). All are normal faults. Two sets trend northwest and northeast respectively across the elongate domelike hill in the central part of the quadrangle. The northwest-trending set was first recognized by Love (1961). Christiansen and Blank (1972) have shown that the domelike hill is the resurgent dome of the caldera and that both sets of faults are related to its uplift, shortly after 600,000 years ago. North- and northwest-trending faults in the northeast corner of the quadrangle record postcaldera movements along the caldera wall. Faults trending north-northwest in the area of the Grand Canyon of the Yellowstone cut the Canyon rhyolite flow (Rc), about 590,000 years old. The northeast-trending fault in that area appears to displace the sediments of Inspiration Point (ip). The group of faults trending northeast across Elephant Back Mountain transects the Elephant Back rhyolite flow (Re) and the underlying West Thumb rhyolite flow (Rh) (K-Ar age about 144,000 years). They are, in turn, displaced by later movement on the east-trending fault, downthrown to the north, that crosses the Yellowstone River at LeHardys Rapids. None of the faults in the quadrangle cut Pinedale or younger deposits.

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