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Reconnaissance Study of Pleistocene Lake and Fluvial Deposits In and Near Ancestral Yellowstone Lake, Wyoming

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C

Reconnaissance Study of Pleistocene Lake and Fluvial Deposits In and Near Ancestral Yellowstone Lake, Wyoming

By J.D. Love, John M. Good, and D.G. Browne

Chapter C *of*

Integrated Geoscience Studies in the Greater Yellowstone Area—Volcanic, Tectonic, and Hydrothermal Processes in the Yellowstone Geoecosystem

Edited by Lisa A. Morgan

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Foreword

This reconnaissance study of the Pleistocene lake and fluvial sediments in and near the ancestral Yellowstone Lake in Yellowstone National Park (the Park) was begun in 1956 by J.D. Love, joined by John M. Good, Chief Park Naturalist-Geologist of the Park, in a cooperative project in 1963, and completed in 1967. It then went through technical review by G.M. Richmond, K.L. Pierce, and H.E. Malde of the U. S. Geological Survey (USGS).

At the time the original report was completed, no modern topographic maps were available for this area so key localities were only approximately located. Coincidentally, near the end of the field work, the National Aeronautics and Space Administration (NASA) proposed and financed a major program that included (1) constructing modern topographic maps on which new geologic mapping was completed and (2) making related and adequately financed geological studies in the Park, with helicopter support and a staff of experienced field geologists. It seemed likely that our reconnaissance studies would be duplicated and (or) replaced by more sophisticated studies—so this report was withdrawn in 1968.

During the subsequent 30 years, seven chapters in the USGS/NASA Professional Paper 729 volume (Baker, 1976; Christiansen, 2001; Christiansen and Blank, 1972; Love and Keefer, 1975; Pierce, 1979; Ruppel, 1972; Smedes and Prostka, 1972), many 15-minute geologic quadrangle maps (Blank, 1974; Christiansen, 1974, 1975; Christiansen and Blank, 1974a, 1974b, 1975; Christiansen and others, 1978; Prostka, Ruppel, and Christiansen, 1975; Prostka, Smedes, and Christiansen, 1975; Prostka and others, 1975; Smedes and others, 1989) (fig. 1), one general geologic map of the Park (U. S. Geological Survey, 1972), and one general geologic map of the Park and surrounding areas (Christiansen, 2001, pl. 1) were published. However, none of these reports attempted to duplicate or expand on data on the Pleistocene lake deposits—so the authors have, for the present report, resurrected the stratigraphic, lithologic, and paleontologic data with little alteration. A modern study of the glacial history of the region was published by Pierce (1979) and his colleagues in the USGS, and the tectonic history was summarized in Pierce and Morgan (1992) and references cited by them and Christiansen (2001). Therefore, the original discussion of these topics has been deleted.

This manuscript might still have remained dormant, except for the fact that colleagues within the USGS and other institutions recently discovered a siliceous-spire field on the floor of Yellowstone Lake in Bridge Bay less than three miles south of our study area. These spires consist mainly of bacterial mats and diatoms bound into a hard rock by silica cement (Morgan and others, 2003; Shanks and others, this volume). Individual spires rise as much as 25 feet and most are located in hydrothermal craters (see Morgan and others, this volume). Even more interesting to us, these spires contain about the same assemblage of some trace elements as those in some of the lacustrine and fluvial strata in our study area (Krajick, 2001). Therefore, data on nearby diatom assemblages as well as our data on the geochemical and spectrographic composition of the sediments have been included.

In addition, the authors were faced with the problem of how to reconcile 35-year-old scientific observations and interpretations with more modern work (including that presented in the remainder of this volume). In most cases, the original stratigraphic descriptions and lists of biota have been retained.

Lisa A. Morgan

About the Author

In 1956, J. David Love began his reconnaissance studies of the Yellowstone Lake area and continued them through the late 1960s when he began collaborating with John Good, writing the first version of *Reconnaissance study of Pleistocene lake and fluvial deposits in and near ancestral Yellowstone Lake, Wyoming*. At the time, no modern topographic base map of the area was available to record their detailed observations. In anticipation of possible new mapping in concert with the National Aeronautics and Space Administration's efforts in Yellowstone National Park and perhaps new interest in Yellowstone Lake, Love and Good withdrew their manuscript from publication in 1968 thinking it would be incorporated in a renewed effort. Love's interest in Yellowstone Lake never languished, and efforts by the U.S. Geological Survey to complete a high-resolution bathymetric survey of Yellowstone Lake proceeded, and included many stimulating and helpful discussions with Dave.

We have included the following chapter, *Reconnaissance study of Pleistocene lake and fluvial deposits in and near ancestral Yellowstone Lake, Wyoming*, by J.D. Love, John M. Good, and D.G. Browne, originally written in the 1960s, in the current Professional Paper as a companion and historical paper to the chapters on Yellowstone Lake. It has been modified slightly since, but the main parts of the manuscript have not been changed. Hydrothermal explosions and their associated breccia deposits were not understood in the 1950s and 1960s. In this chapter, hydrothermal-explosion breccia deposits were identified as distinct units but were referred to as "beach rock." This term has been retained in the manuscript. Today, we understand the "beach rock" units to be products of hydrothermal explosions.

Reconnaissance study of Pleistocene lake and fluvial deposits in and near ancestral Yellowstone Lake, Wyoming, by J.D. Love, John M. Good, and D.G. Browne is a marvelous example of the detailed and solid work performed by geologists 50 years ago. While technology in the geological sciences has advanced remarkably over this same time frame allowing us to "see" images never previously imagined, the observations made in the field and the never-ending attention to fine detail were trademarks of David Love. This is obvious in his ancestral Yellowstone Lake work. We include this historical manuscript for clues into Yellowstone Lake's past and as an example of work few have ever replicated.

Lisa A. Morgan

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Reconnaissance Study of Pleistocene Lake and Fluvial Deposits In and Near Ancestral Yellowstone Lake, Wyoming

By J.D. Love,[1] John M. Good,[2] and D.G. Browne[3]

Abstract

Seven sequences of Pleistocene strata, five of them predominantly lacustrine, are described from outcrops north of Yellowstone Lake. These are (1) Turbid Lake sequence, 30–50 feet of white pumiceous claystone and tuff with carbonaceous partings and a distinctive compositional pattern of excesses and deficiencies of many elements; (2) Yellowstone Falls sequence, 75 feet or more of varved white claystone and tuff containing pollen and diatoms, overlain by gray conglomerate and sandstone; (3) Hayden Valley sequence, 200 feet or more of gray and white silt and claystone containing sparse diatoms; (4) Alum Creek sequence, 30 feet or more of bedded sand and gravel with lesser amounts of clay; (5) Mudkettle sequence, 150 feet or more of light gray to white, soft clay and claystone with lesser amounts of sandstone and conglomerate, moderately lithified in part, and containing some pollen and diatoms; (6) Astringent Creek Sand (newly named), a gray, commonly unlithified sand as much as 300 feet thick and containing abundant volcanic debris; and (7) Pelican Valley sequence, 120 feet or more of light gray to white, soft clay, silt, sand, and some pumice pebble conglomerate and shard beds; finer grained beds contain diatoms, pollen, and carbonaceous debris that has a radiocarbon date of 7,550±350 years.

Other localized deposits with radiocarbon dates and abundant diatoms consist of white carbonaceous tuffaceous clay and sand with an age of 9,440±300 years, in Gibbon Canyon, and a gray and white carbonaceous clay, silt, and sand with an age of 3,750±300 years at Bannock Ford in Yellowstone Canyon.

Slight arching of the Upper Basin Member of the Plateau Rhyolite caused the Yellowstone River to develop an antecedent course across it. Uplift of the Pelican Valley area during the last 7,500 years averaged about one foot in 50 years.

[1]U.S. Geological Survey

[2]National Park Service

[3]University of California

Introduction and Acknowledgments

During the program of geologic mapping in Jackson Hole in 1956 (fig. 2), directly south of Yellowstone National Park, several Pleistocene lacustrine deposits were differentiated. Their present maximum altitude is about 7,000 feet, which is approximately the same as that of Yellowstone Lake (7,733 feet above sea level). The drainage divide (the Continental Divide) that separates the Yellowstone Lake drainage from that of the Snake River on the Jackson Hole side is lower than 8,000 feet. It seemed possible that one or more Pleistocene lakes may have extended northward continuously from Jackson Hole to ancestral Yellowstone Lake. This possibility prompted the present investigation. Preliminary data on a few localities were published by Love (1961).

Figure 2 shows the regional relations of mountains to basins and the distribution of present-day lakes. Figure 3 is a portion of the geologic map of Yellowstone National Park and vicinity by Christiansen (2001) showing localities discussed in the text. Data on the 19 numbered localities and adjacent areas consisted of reconnaissance mapping; measurement of stratigraphic sections; and sampling, chiefly for diatoms, pollen, radiocarbon determinations, and some chemical and spectrographic analyses. The writers wish to acknowledge the valuable contributions by Estella B. Leopold, who made field collections in 1958 and 1962 and identified the pollen. K.E. Lohman and G.W. Andrews identified the diatoms and R.W. Brown identified the fossil leaves. Robert S. Houston made a petrographic study of thin sections.

We are most grateful to Lisa Morgan, who reviewed our original manuscript and helped to formulate an up-to-date revision that would be compatible with the ongoing research in the adjacent Yellowstone Lake area. We also are grateful to her colleague, W.C. Pat Shanks, for sharing the discussion of the potential application of their work on Yellowstone Lake with our adjacent studies.

Previous Work

The existence of Pleistocene lake deposits in the vicinity of the present Yellowstone Lake was recorded by several pioneer explorers and scientists. The first was Lieutenant Gustavus C. Doane, U.S. Army, who noted on September 1, 1870, upon entering Hayden Valley:

> "Six miles above the falls we entered a wide valley of calcareous formation, open and branching among timbered ridges on either side of the river, which runs through its centre in a northeast [sic] course an old lake bed, as are all the grassy sections of the basin" (Doane, 1870, p. 15).

Another remarkably astute observation was made in 1875 by Theodore B. Comstock who stated:

> "The deposits of the Yellowstone Lake Basin and in the valley of the main river and its tributaries, which may be regarded as Pliocene, are mainly the sediments of an ancient lake, of which the present body of water is the representative on a much reduced scale. Beautiful and highly instructive sections of the old beach formations are exposed in the valleys of the streams, particularly in the lower valley of Pelican Creek, and far down the Yellowstone River, where they become more complicated, but on that account all the more interesting. An examination of these shows that the lake formerly extended over a much larger area, and that it has held its place amid changes of great importance" (Comstock, 1875, p. 130–131).

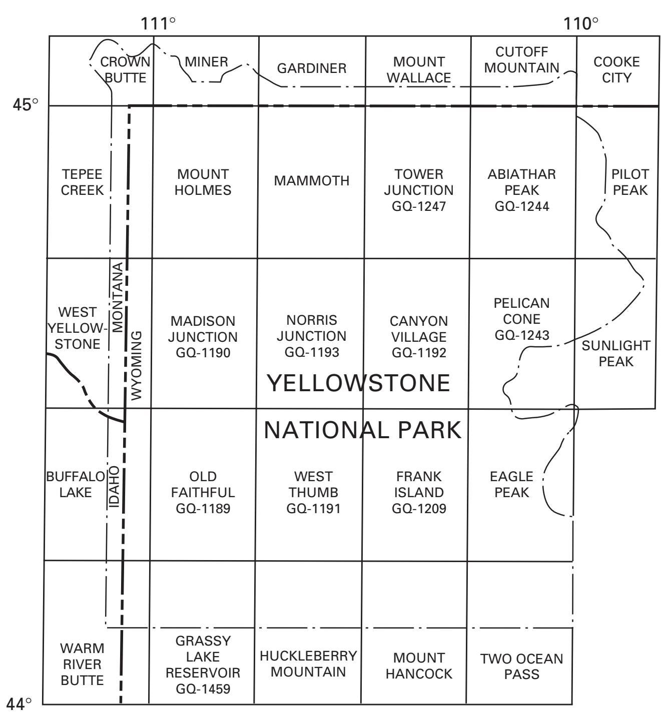


Figure 1. Index map showing 15′ quadrangles of Yellowstone National Park. Published USGS geologic quadrangle maps indicated by GQ numbers. From Christiansen (2001).

William Henry Holmes, in the final annual report of Ferdinand V. Hayden's Geological and Geographical Survey of the Territories, published a map of "Yellowstone Lake showing the dimensions of the ancient lake" (Holmes, 1883a, pl. 31). However, Arnold Hague, in his Yellowstone Park Folio (1896) and the Atlas accompanying USGS Monograph 32 (1904), apparently ignored these earlier descriptions and showed much of the area of lacustrine deposits as glacial drift or volcanic rocks on his folio maps. Howard (1937) made a superb study of the Grand Canyon of the Yellowstone River and included excellent descriptions of the associated fluvial and lacustrine sediments.

Chemical and Spectrographic Analyses

Rock analyses of selected samples were taken from measured sections of the Yellowstone Falls, Hayden Valley, Mudkettle, and Pelican Valley sequences (table 1). These indicate, in a general way, the variation in amount of common oxides within and between the sequences. The significance of these variations is not yet known, but they are probably not entirely random.

Figure 4 shows spectrographic analyses of selected groups of samples of strata from the Yellowstone Falls, Hayden Valley, Mudkettle, and Pelican Valley sequences and compares them with Pleistocene rhyolite from the Pitchstone Plateau in the southwestern part of the Park and with crustal abundance of these elements in the Earth (Mason, 1958, p. 44). The analyzed samples from the Yellowstone strata were, in general, well-sorted, highly tuffaceous sand and (or) clay. Each sample point on the graphs represents the average of five or more individual samples. These analyses represent an attempt to emphasize similarities and (or) contrasts in the composition of the stratigraphic sequence.

While the chemical and spectrographic data were collected and analyzed more than 30 years ago, we include this original data as a contribution that may provide leads to significant qualitative and quantitative associations of trace elements, not only in our exposed lacustrine and fluvial strata but also in some that may extend under Yellowstone Lake into the area of the spires and hydrothermal-explosion craters.

Stratigraphy

Seven sequences of Pleistocene lacustrine and fluvial strata are here discussed and given informal names. Formal names are undesirable until completion of detailed mapping and of paleontologic, geochemical, and petrographic studies and more age determinations. Such studies should demonstrate whether or not any of the sequences are lateral equivalents.

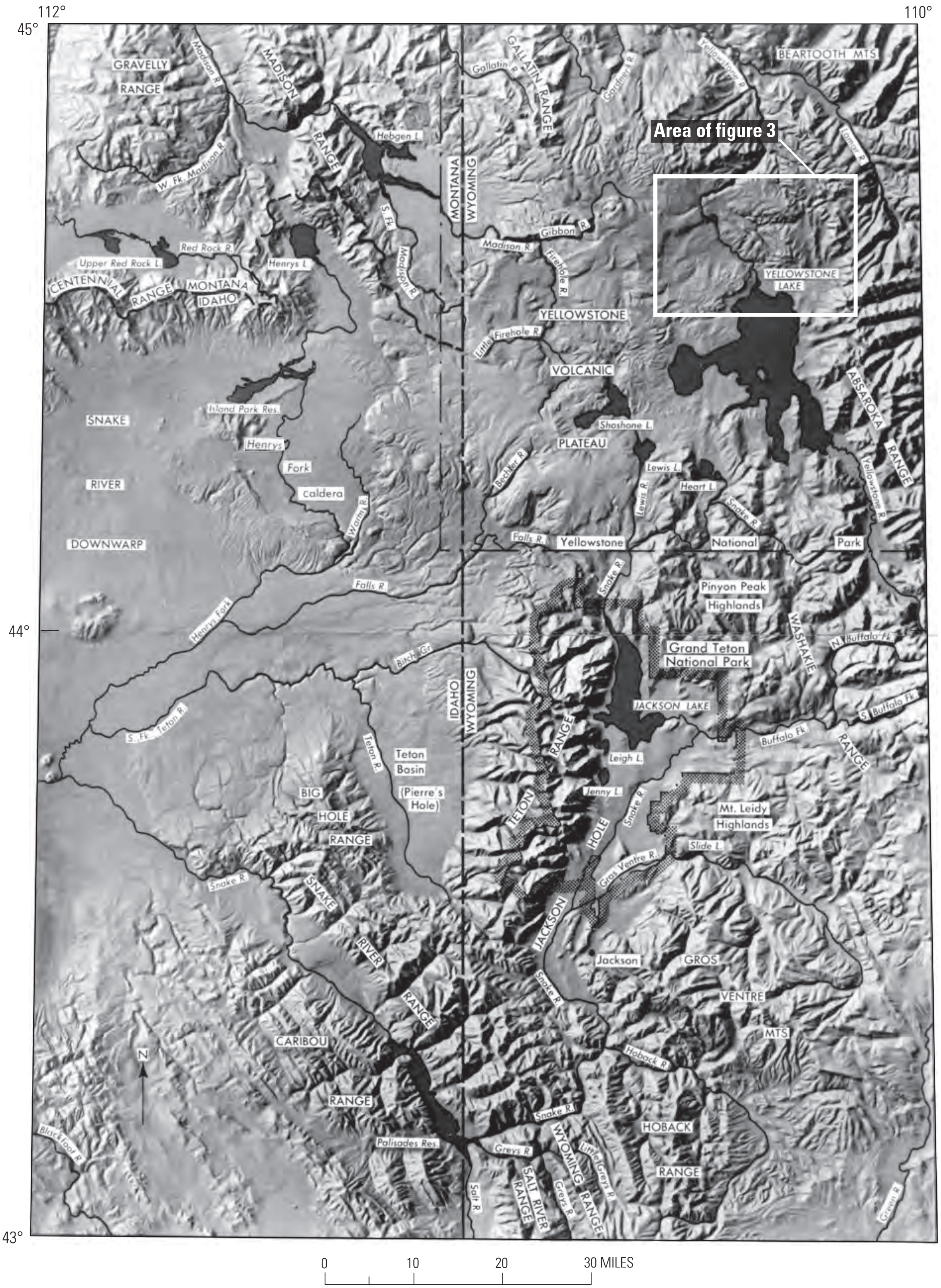


Figure 2. Index map and physiography of northwest Wyoming and adjacent areas showing the Yellowstone Plateau. From Christiansen (2001).

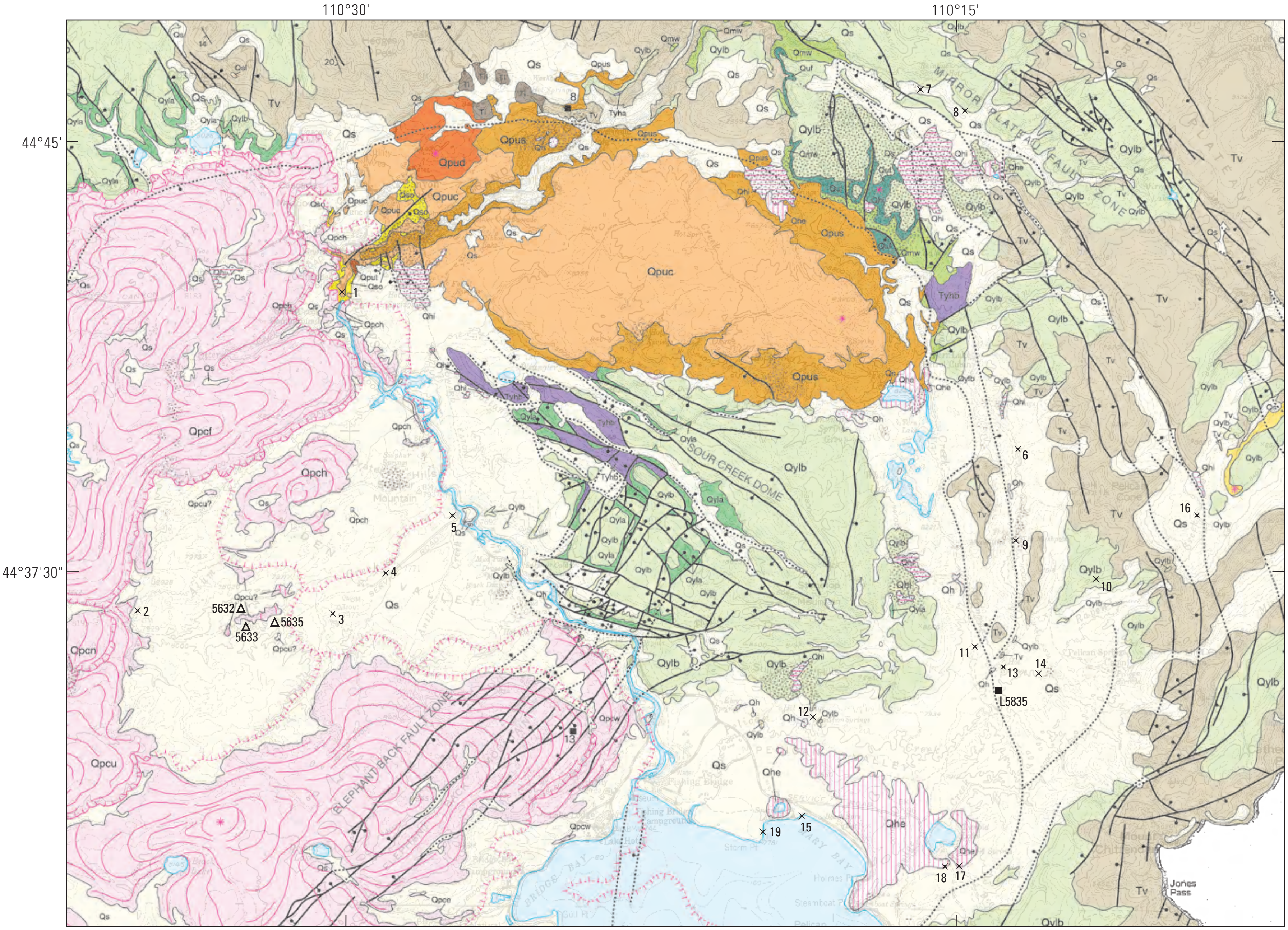
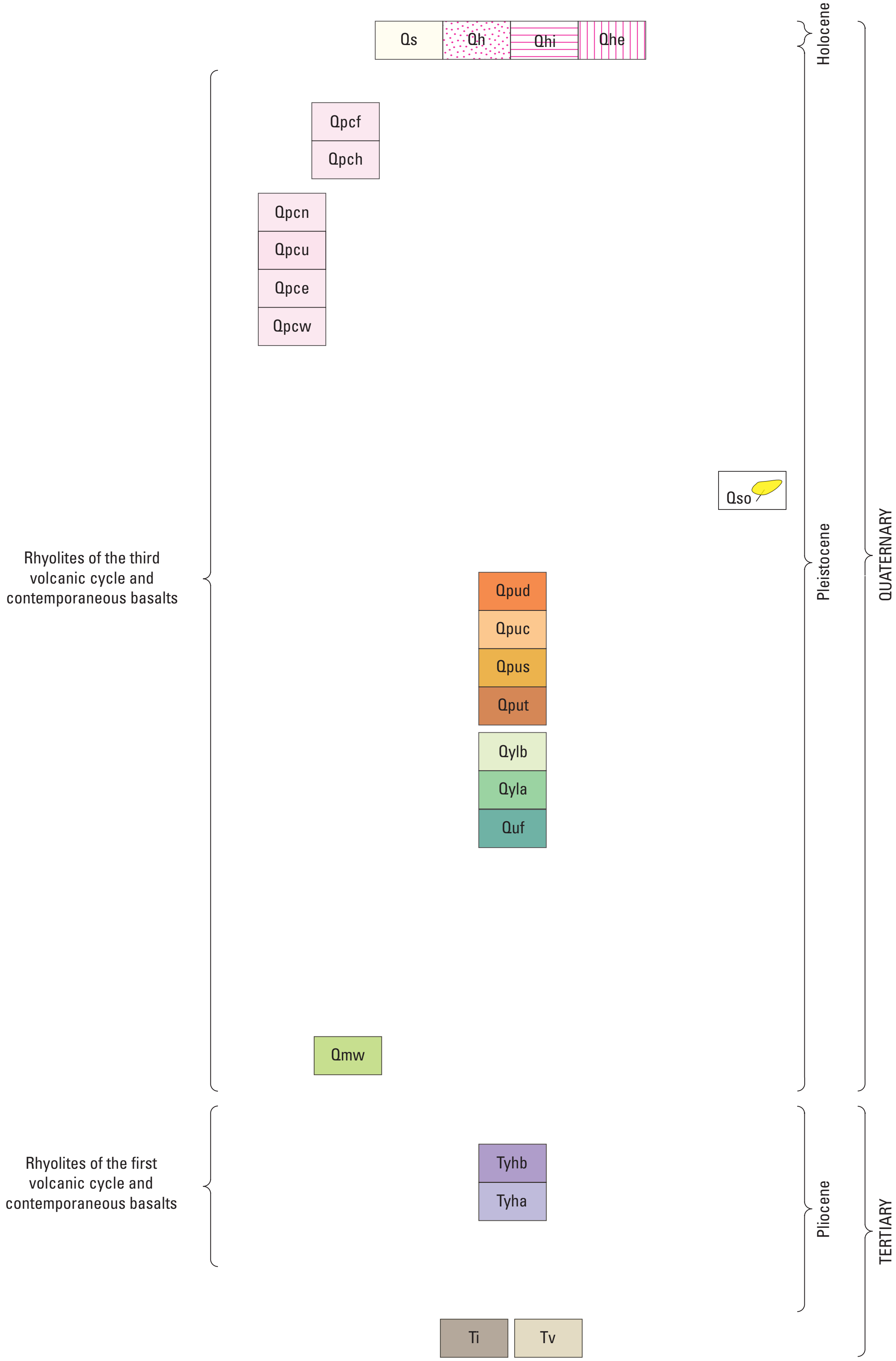


Figure 3. Geologic map of central Yellowstone National Park showing localities discussed in the text. After Christiansen (2001).

CORRELATION OF MAP UNITS



LIST OF MAP UNITS

Surficial deposits (Holocene and Pleistocene)—Age ranges of individual units overlap

Qs	**Detrital deposits**
Qh	**Hot-spring deposits**
Qhi	**Cemented ice-contact deposits localized by hot springs**
Qhe	**Hydrothermal-explosion deposits**
	Plateau Rhyolite (Pleistocene)
	Central Plateau Member
Qpcf	**Solfatara Plateau flow**
Qpch	**Hayden Valley flow**
Qpcn	**Nez Perce Creek flow**
Qpcu	**Spruce Creek flow**
Qpce	**Elephant Back flow**
Qpcw	**West Thumb flow**
	Upper Basin Member
Qpud	**Dunraven Road flow**
Qpuc	**Canyon flow**
Qpus	**Tuff of Sulphur Creek**
Qput	**Tuff of Uncle Tom's Trail**
Qso	**Sediments (Pleistocene)**—Interlayered with Plateau Rhyolite
	Lava Creek Tuff (Pleistocene)
Qylb	**Member B**
Qyla	**Member A**
Quf	**Undine Falls Basalt (Pleistocene)**—Includes some gravel
	Mount Jackson Rhyolite (Pleistocene)
Qmw	**Wapiti Lake flow**
	Huckleberry Ridge Tuff (Pliocene)
Tyhb	**Member B**
Tyha	**Member A**
Ti	**Intrusive rocks (Tertiary)**
Tv	**Volcanic rocks (Tertiary)**

EXPLANATION

- **Contact**—Dotted where concealed
- **Lava-flow front**—Hachures on side of younger flow; dotted where concealed
- **Lava-flow form lines**
- **Normal fault**—Bar and ball on downthrown side; dotted where concealed
- **Area of hydrothermal acid alteration**
- × 4 **Sample locality**
- * **Volcanic vent**
- △ **Diatom sample locality**
- ■ **Pollen sample locality**

Pleistocene(?) Strata Possibly Underlying Turbid Lake Sequence

About 125 feet of poorly stratified detritus of uncertain age and correlation are exposed along Bear Creek, south of Turbid Lake (loc. 17 on fig. 3; fig. 5). The lower part of this deposit consists of 40 feet of chocolate brown to gray compact claystone and siltstone with sporadic sand grains and small pebbles of felsic volcanic rock. The base of this unit is below creek level at the section studied. Overlying the claystone and siltstone is about 85 feet of stratified, rusty brown sandstone and conglomerate. Pebbles in the conglomerate are highly rounded, as much as 3 inches in diameter, and are composed of rhyolite, felsic, and mafic porphyries, and gray chert of unknown origin. Some parts of the conglomerate are indurated enough to stand as pinnacles (lower left part of fig. 5*A*). The sandstone, some of which is indurated, is most abundant near the base and top. Overlying the sandstone is 20 feet of blue-green, coarse-grained, poorly cemented, stratified sand. This sand is unconformably overlain by as much as 15 feet of glacial or hydrothermal-explosion debris from nearby Turbid Lake. This debris contains a 2-inch layer of charcoal with a ^{14}C age of 8,310±300 years (Meyer Rubin, written commun., 1966, USGS Lab No. W-1944; Love, 1989, p. 52–53, his figs. 58 and 59). Overlying it is about 10 feet of possible hydrothermal-explosion debris.

No fossils were found in these strata. Their relation to the nearby Turbid Lake sequence is obscured, but field relations suggest that the Turbid Lake sequence is younger and that they are separated by an unconformity with an erosional relief of 100 feet in a horizontal distance of 300 feet. Both sequences are much less indurated than the nearby Tertiary volcaniclastic rocks so are tentatively considered to be Pleistocene.

Turbid Lake Sequence

The Turbid Lake sequence was studied at locality 18 (figs. 3 and 6) where it consists of 30–50 feet of white, bedded pumiceous claystone and tuff. Rounded grains and pebbles of white, fibrous pumice and granules of black obsidian are common. Several horizons contained flattened brown twigs, fragments of leaves, and other plant material. The strata are locally altered chemically by intrusion of active sulfurous vents.

Preliminary spectrographic analyses show that the Turbid Lake sequence contains conspicuously different amounts of trace elements from those of other Pleistocene sedimentary sequences thus far analyzed in the region (fig. 4). For example, it is lowest in Fe, Mg, Ca, V, Mn, Sr, Cr, Y, Sc, and Co, and highest in Ti, Zr, B, and Nb. The source of the volcanic debris has not yet been established.

The Turbid Lake sequence dips 5–10 degrees north, probably in response to local crustal tilting. This movement is suggested by a beheaded drainage on the north side of Turbid Lake, in line with Bear Creek on the south side, by the aggrading character of the valley of Sedge Creek before it enters the Turbid Lake, and by the entrenched course of the stream after it leaves the lake.

Yellowstone Falls Sequence

Howard (1937, p. 108) first recognized the presence of the strata here called the Yellowstone Falls sequence. He measured a stratigraphic section and discussed the age of the strata and their origin and significance. Additional data were given by Love (1961). The maximum thickness is less than 100 feet. The following section describes the general lithology and was measured by J. D. Love along the old Savage Trail (abandoned) on the east side of Yellowstone Canyon (fig. 7), about 600 feet downstream from Upper Falls (locality 1, fig. 3). Because of the steep slope, slumping, poor exposures, and lenticularity of some beds, the section is generalized. Some of Howard's observations on the lower part of the section are paraphrased here. Top of section coincides with flat on east side of canyon.

Unit	Lithology	Thickness (ft)
5	Tuff, white, slabby, grading up to reddish-brown conglomeratic sandstone and tuff with clayey matrix	6
4	Obsidian conglomerate, dark gray, evenly-bedded; upper half is hard and forms ledges; lower half is poorly cemented; consists of angular fragments, rarely more than 1 inch in diameter, of black obsidian, gray and white fibrous pumice and black, red, and white rhyolite; matrix of soft part is white, decrepitating, noncalcareous clay; matrix of ledge is a silica cement with little clay; this unit is the "Rim Conglomerate" of Howard (1937)	30
3	Claystone, diatomite, and shale, light gray to white, light weight, smooth-feeling, nondecrepitating in water, noncalcareous; some sandy layers and some clayey beds with sparse quartz and feldspar grains; lower part laminated to varved in part; contains carbonized leaves (for pollen and diatom collections, see figure 8 and table 2)	25
2	Sandstone and conglomerate, gray, hard in upper part and soft in lower part, composed of obsidian and rhyolite fragments	7
1	Claystone, white to light gray, thin-bedded, soft, light weight	5+
Thickness of measured part of Yellowstone Falls sequence		73+
Underlying units are rhyolitic volcanic rocks.		

The strata here are much more completely lithified than any of the other Pleistocene sequences in this area. Thin sections of the hard part of the "rim conglomerate" show fragments of brown obsidian with diffused margin areas of alteration. Other fragments are of perlitic glass and welded rhyolite tuff with corroded quartz phenocrysts. Grains in the matrix include plagioclase, quartz, anorthoclase, biotite, and curved glass shards. The lower part

Table 1. Rock analyses of Pleistocene lake deposits north and northwest of Yellowstone Lake.

[All samples are arranged as nearly as possible in stratigraphic order. Rapid rock analyses are by P.L.D. Elmore, S.D. Botts, Gillison Chloe, Lowell Artis, and H. Smith, using methods similar to those described by Shapiro and Brannock (1956). Analyses are in percent]

Sequence	Locality on geologic map and unit in measured section described in text	Laboratory no.	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	H_2O^-	H_2O^+	CO_2	Volatiles other than H_2O and CO_2
Pelican Valley	14, unit 2	D123124	70.5	13.2	1.0	1.0	0.91	1.7	2.7	4.6	0.28	0.07	0.00	0.64	3.1	<0.05	
Do--	11, unit 7	D123136	60.3	17.2	2.4	.28	.47	.28	.31	1.8	.74	.26	.33	2.8	8.1	< .05	4.6
Do--	11, unit 4	D123126	53.4	19.7	2.6	.76	.52	.36	.65	2.0	.89	.31	.02	2.5	8.7	< .05	7.5
Do--	11, unit 2	D123120	58.1	16.4	3.5	.88	1.2	1.7	1.5	2.2	.71	.33	.00	2.1	5.5	< .05	5.4
Do--	2,000 ft S. of 11	D123131	60.0	15.4	4.0	1.5	3.3	2.6	2.1	2.3	.65	.35	.07	4.3	3.4	< .05	
Do--	1,500 ft SW. of 12	D123132	62.6	16.3	4.5	.20	3.5	2.8	3.2	2.0	.56	.19	.08	.91	3.0	< .05	
Do--	13	D123127	62.9	15.9	2.4	1.6	2.9	4.8	2.9	2.3	.50	.18	.06	.95	1.8	< .05	
Do--	12	D123125	61.0	15.3	4.4	.64	2.8	3.2	2.7	2.3	.62	.23	.11	3.3	3.4	< .05	
Mudkettle	Fossil loc. 5907	D123135	71.5	12.4	1.0	.32	.49	.13	.50	1.5	.74	.13	.00	2.1	5.7	< .05	2.9
Do--	7	D123121	67.0	15.1	3.1	.60	1.2	1.2	2.0	3.5	.45	.11	.00	1.8	3.4	< .05	
Do--	7	D123118	66.4	14.2	4.0	.48	.99	.98	1.5	3.0	.45	.13	.05	2.4	4.0	< .05	1.2
Do--	6, unit 5	D123133	64.1	16.2	3.0	.24	.95	1.4	1.2	2.2	.46	.06	.03	3.1	5.6	< .05	1.0
Do--	6, unit 3, top	D123128	64.6	15.2	3.2	.60	1.0	1.4	1.2	3.1	.48	.11	.02	3.5	5.3	< .05	
Do--	6, unit 3, upper middle	D123123	67.8	12.5	5.0	.24	1.0	.68	.52	2.3	.43	.17	.00	4.2	4.6	< .05	
Do--	6, unit 3, lower middle	D123130 B	66.4	13.8	3.0		1.5	.93	.50	2.6	.48	.16	.04	5.5	3.7	< .05	
Do--	6, unit 3, base	D123115	66.0	13.6	3.5	.60 .20	1.6	1.0	.45	2.8	.48	.13	.04	5.4	4.7	< .05	
Hayden Valley	2	D123117	63.7	14.5	4.0	.60	2.4	2.2	2.1	2.8	.53	.21	.07	3.4	3.2	.05	
Do--	2,500 ft SW of 2	D123122	61.0	15.2	4.8	.48	2.5	2.4	2.1	2.7	.58	.20	.32	3.6	3.8	< .05	
Hayden Valley?	15	D123116	61.0	15.6	3.7	1.1	2.9	3.4	2.7	2.1	.62	.26	.00	2.9	2.9	< .05	
Yellow-stone Falls	1, unit 3, upper part	D123119	73.8	10.0	3.5	.12	.55	.41	.85	1.8	.30	.04	.05	2.8	3.7	< .05	1.3
Do--	1, unit 3, middle	D123134	66.6	14.9	3.1	.44	.84	1.5	1.9	2.9	.43	.14	.00	2.5	4.4	< .05	

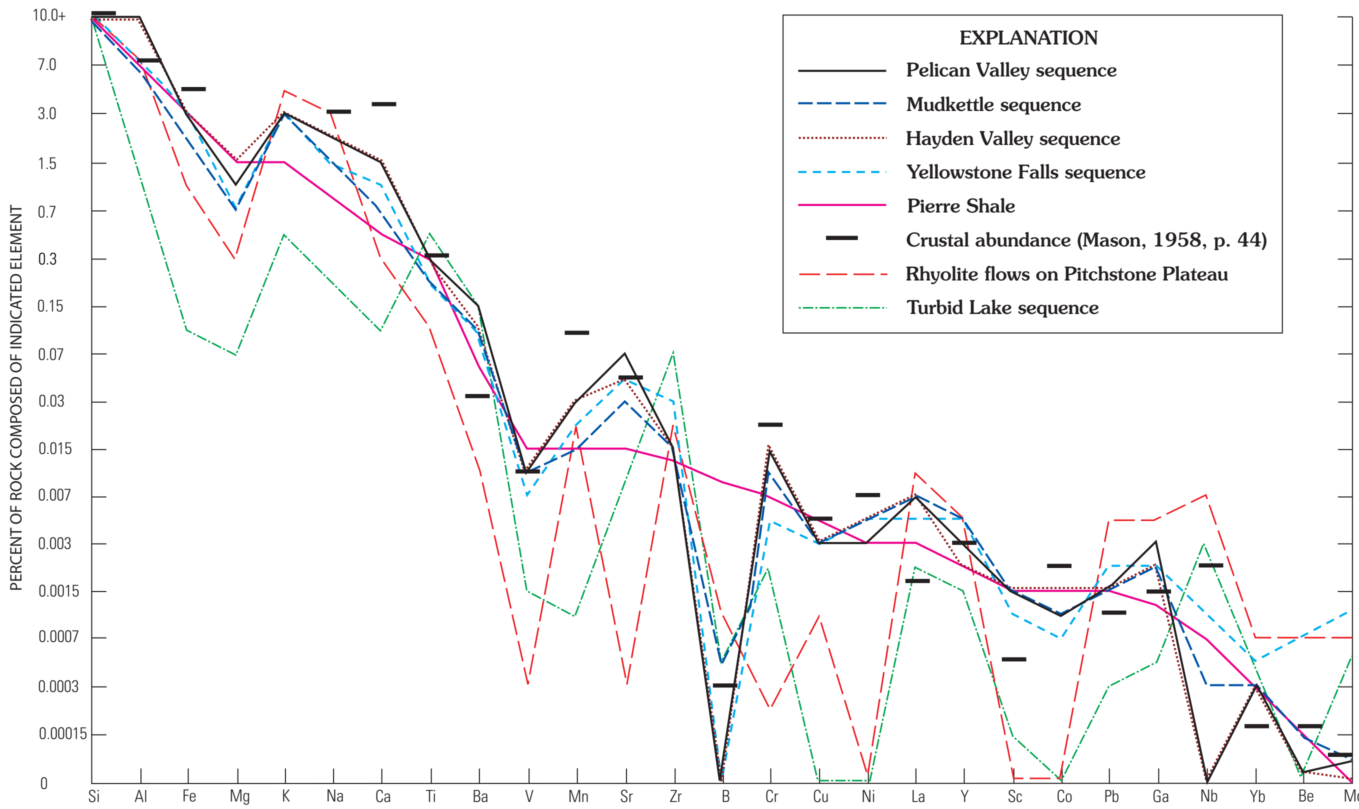


Figure 4. Semiquantitative spectrographic analyses of Pleistocene lake deposits north and northwest of Yellowstone Lake. Values of selected elements are graphed to show contrast in distribution with those in the Pierre Shale and other marine Cretaceous shales and with Pleistocene rhyolitic welded tuff on the Pitchstone Plateau. Quantities are reported in percent to the nearest number in the series (10 to 0:); at least 60 percent of results are expected to be in the correct range. Data on Cretaceous shales are by Tourtelot (1962). Numbers of samples: Pelican Valley sequence, 8; Mudkettle sequence, 8; Hayden Valley sequence, 3; Yellowstone Falls sequence, 3; rhyolite flows on Pitchstone Plateau, 6; and Turbid Lake sequence, 5.

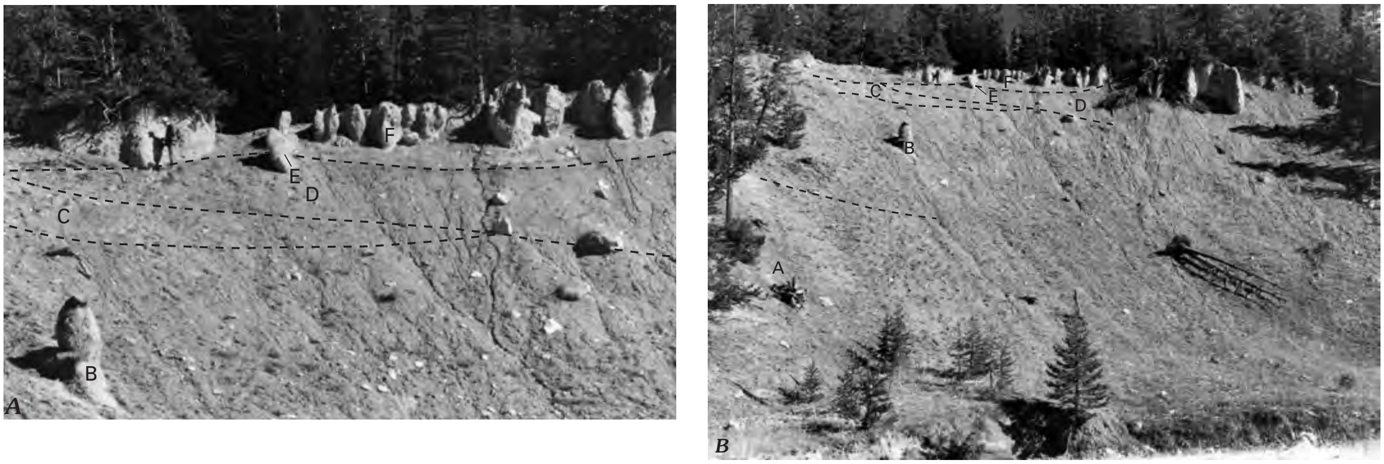


Figure 5. *A*, Telephoto view north across Bear Creek at locality 17. *B*, View north across Bear Creek at locality 17. Indicated are 40 feet of brown pebbly claystone (A); 85 feet of conglomerate and rust-brown sandstone (B); 20 feet of blue-green sand (C); lower till, 0–15+ feet (D); 2-inch charcoal horizon with 8,200 year ^{14}C date (E); and upper till, 10 feet (F).

of the unit contains rounded grains of welded rhyolite tuff, together with perlitic, spherulitic, brown, and clear glass. Crystals in the matrix include oligoclase(?), quartz, and sanidine-anorthoclase.

The strikingly laminated and varved clay in the lower part of unit 3 was determined by X-ray diffraction to contain about 75 percent montmorillonite or mixed-layer clay, 10 percent quartz, and 15 percent feldspar. Spectrographic analyses (fig. 4) show that the Yellowstone Falls sequence matches the average of the Pleistocene units, other than the Turbid Lake strata. Nevertheless, there are some variations in the general grouping. For example (again excluding the Turbid Lake sequence), the Yellowstone Falls sequence is the lowest in V, Cr, Sc, and Co and the highest in Zr, Pb, Nb, Yb, Be, and Mo. Among the scarcer trace elements, single samples show 0.015 percent Ce, 0.01 percent Nd, and 0.001 percent Sn. Although there are too few analyses of common oxides to be statistically valid, those available (table 1) suggest that the Yellowstone Falls sequence has a slightly higher content of SiO_2 and lower FeO, MgO, CaO, Na_2O, K_2O, TiO_2, and P_2O_5 than is present in the other sequences (none is available on the Turbid Lake sequence).

The Yellowstone Falls sequence was deposited on a rough topography developed on the Upper Basin Member of the Plateau Rhyolite of Christiansen and Blank (1972), and its lowest beds are therefore much more lenticular and less widespread than the upper. At locality 1, the strata are overlain by the Hayden Valley sequence and by till.

Howard found no diagnostic fossils in the Yellowstone Falls strata but considered them to be of Pleistocene age. A Pleistocene age is suggested by the discovery of abundant pollen and diatoms (table 2; Love, 1961) in unit 3. A series of pollen samples from bottom to top of unit 3 (fig. 8) shows a progressive change in vegetation types. In the lowest part, pine and spruce are dominant; in the middle is pine, spruce, and sage; in the upper part, sage dominates, with some greasewood, herbs, algae, and tree pollen. These data suggest that the local environment became drier and probably warmer during this interval of deposition, perhaps somewhat warmer than the present climate (E.B. Leopold, written commun., 1960). K.E. Lohman (written commun., 1960) discusses the diatoms from the upper part of unit 3 as follows:

"The following analysis of the assemblage indicates the percentage of the 64 species and varieties that also occur in several dated formations:

White marl associated with Pinedale glacial debris, Grand Teton National Park (Love, 1956) with a ^{14}C date of 9,580±350 yr B.P.	15%
Provo Formation, Utah, upper Pleistocene (11,650 to 13,000 yr B.P.)	27%
Hagerman [Glenns Ferry] Formation, Idaho, upper Pleistocene [upper Pliocene] (vertebrate fauna)	28%
Thousand Creek beds, middle Pliocene (vertebrate fauna)	15%
Esmeralda Formation, lower Pliocene (vertebrate fauna)	7.8%

Figure 6. Turbid Lake sequence composed of plant-bearing white pumiceous clay and tuff overlain by dark-colored till, with beveled upper surface; locality 18 on west bank of Bear Creek, south of Turbid Lake. Haze at left is stream from vents cutting through Turbid Lake sequence. Note beds dipping north (upper left to lower right) to left of man.

"Two of the three extinct species (indicated by asterisks) in this assemblage were first described from the Provo Formation and one from the Hagerman [Glenns Ferry] Formation. These are not known from beds older than early Pleistocene [late Pliocene]. Based on the above analysis, the best estimate of age is somewhere in the Pleistocene. I say somewhere for the reason that statistically the correlation is about the same for the late Pleistocene (Provo) and the early Pleistocene [late Pliocene] Hagerman [Glenns Ferry], although the fact that it contains two extinct species from the Provo and only one from the Hagerman [Glenns Ferry] suggests upper Pleistocene rather than lower. The paleoecology indicated by this assemblage is that of a temperate, shallow lake of fresh to somewhat saline water."

The leaves are of the pondweeds *Myriophyllum* or *Proserpinaca* (R.W. Brown, written commun., 1956).

The Yellowstone Falls sequence apparently was deposited before the adjacent part of the present Yellowstone Canyon was cut. Likewise, prior to modern canyon development, the area was glaciated by ice that moved at least 35 miles southwestward from the Beartooth Mountains (fig. 2) and left huge granite erratics. Figure 7 shows the broad open valley along which the ice moved southwestward (the direction in which the camera was pointed). The ice also overrode the Hayden Valley sequence, which, in turn, overlies the Yellowstone Falls strata. Therefore, it seems likely that the Yellowstone Falls sequence is of early or middle Pleistocene age.

Figure 7. Air oblique view southwest showing Upper and Lower Falls of the Yellowstone River cut in Canyon Rhyolite. Fossiliferous strata of Yellowstone Falls sequence at locality 1 are exposed in white cut at left of Upper Falls. Treeless area at top of photo is underlain by Hayden Valley sequence. Photo by H.M. Cowling, 116th Photograph Section, Washington National Guard.

Hayden Valley Sequence

The presence of Pleistocene strata in Hayden Valley was first recognized by Hayden in reports for 1871 and 1872 (Hayden, 1872, 1873) but they were not described. Holmes (1883a, p. 56) gave a cursory mention of lake beds in Hayden Valley and presented two maps (Holmes, 1883a, pl. 31 and Holmes, 1883b) that included this area in ancestral Yellowstone Lake. On the latter map he used the name “Lake Hayden” for the ancestral Yellowstone Lake. Weed (1896) mapped the deposits as glacial drift and stated: “In Hayden and Pelican valleys extensive morainal deposits occur whose clays and loosely cemented sands closely resemble lake beds.” Howard (1937) was the first to recognize and describe two sets of strata, the “divide sediments” and the “plains sediments,” separated by an unconformity. He described the former as having abundant sand and gravel in the lower part, grading up to lacustrine deposits, and the latter as varved clay-rich silts. The “divide sediments” of Howard are here called the Hayden Valley sequence.

Figure 3 shows the described localities 2 and 3 of the Hayden Valley sequence, and figure 9 shows its characteristic treeless low rounded hills. The Hayden Valley sequence is at least 200 feet thick at several places.

Along Alum Creek at locality 2, the sequence consists of nearly 200 feet of soft, gray and white, noncalcareous, remarkably homogeneous silt and clay and some gravel beds. The latter contain abundant rounded granules of black obsidian, colorless angular crystals of quartz and feldspar, and conspicuous fresh shards. In the lower part of this exposure, laminae of silt alternate with clay, giving the strata a varved appearance. This laminated deposit lies between two knobs of obsidian nearly 100 feet high and 800 feet apart, thus indicating the amount of local relief on which the fine-grained strata were deposited.

At locality 3 is about 150 feet of well-exposed strata, chiefly light gray clay and silt in the lower part, interbedded with gravel of rounded rhyolite and obsidian fragments in the middle, and fine-grained silt and clay in the upper part. Elsewhere gravel and sand are common on the highest hills, but whether or not they are more closely related to the Hayden Valley sequence or to younger glacial debris remains to be determined.

Flooring the channel of Yellowstone River at the outlet of Yellowstone Lake and exposed farther east in a wave-cut scarp along the north edge of Mary Bay at localities 15 (fig. 10) and 19 are strata tentatively considered by us to be part of the Hayden Valley sequence. At locality 15, a composite section is 25–50 feet thick (fig. 11). The lowest beds are varved and laminated light-gray to brown (blue-gray when wet) clay (fig. 12), of which as much as 20 feet is exposed above lake level. The section at this locality was first described by Comstock (1875, p. 131). Overlying the varved unit, with a gradational contact, are light gray to rusty brown fine-grained sand beds alternating with thin silt and clay beds. At locality 19 (fig. 13), some one-fourth-inch laminae of silt and clay can be traced continuously for more than 25 feet along the outcrop. Local ripplemarks and cross-bedding are present in many layers. Coarser sands and pebble lenses contain abundant black obsidian. At locality 15, these strata are overlain by till (fig. 11). [*The “till” noted here is now interpreted as hydrothermal-explosion breccia, a concept not yet in the “working*

Table 2. Diatoms in Pleistocene strata north and northwest of Yellowstone Lake.

[YFs, Yellowstone Falls sequence; ACS, top of Astringent Creek(?) Sand; GCd, Gibbon Canyon deposit (this assemblage, although from beds from outside the map area, is included for comparison because it is dated by radiocarbon); BFd, Bannock Ford deposit. Sample localities are denoted by bold 4-digit number near top of columns—these localities are described at end of table. R, rare; F, frequent; C, common; A, abundant. Identified by K.E. Lohman and G.W. Andrews]

Genera and species	YFs	Hayden Valley sequence				Mudkettle sequence		ACS	Pelican Valley sequence			GCd	BFd
	4618	**5632**	**5633**	**5635**	**5636**	**5589**	**5907**	**5637**	**5904**	**5905**	**5906**	**5596**	**5639**
Achnanthes cf. *A. calcar* Cleve	R	--	--	--	--	--	--	--	--	--	--	--	--
flexella (Kützing) Brun	--	--	--	--	--	--	--	--	--	--	--	F	--
lanceolata (Brébisson) Grunow	--	--	--	--	--	--	--	--	--	R	R	--	R
lanceolata var. *rostrata* Hustedt	--	--	--	--	--	--	--	--	--	--	--	--	F
Amphora ovalis (Kützing) Kützing	F	--	--	--	--	--	--	--	R	--	R	--	R
ovalis var. *pediculus* Kutzing	--	--	--	--	--	--	--	--	--	--	--	--	R
Caloneis bacillum (Grunow) Mereschkowsky	F	--	--	--	--	--	--	--	--	--	--	--	--
schumanniana var. *biconstrica* Grunow	--	--	--	--	--	--	--	--	--	--	--	--	R
silicula (Ehrenberg) Cleve	F	--	--	--	--	--	--	F	--	--	--	--	--
trinodis (W. Smith) Boyer	--	--	--	--	--	--	--	--	R	--	--	--	--
cf. *C. trinodis* (W. Smith) Boyer	--	--	--	--	--	--	--	R	--	--	--	--	--
sp.	--	--	--	--	--	--	--	--	R	--	--	--	--
Campylodiscus sp.	F	--	--	--	--	--	--	--	--	--	--	--	--
Cocconeis pediculus Ehrenberg	--	--	--	--	--	--	--	--	R	--	--	--	--
placentula Ehrenberg	--	--	--	--	--	--	--	--	--	--	--	--	A
placentula var. *euglypta* (Ehrenberg) Grunow	F	--	--	--	--	--	--	--	--	--	--	--	A
Cyclotella americana (Ehrenberg) Kützing	C	--	--	--	--	--	--	--	--	--	--	--	--
comta (Ehrenberg) Kützing	--	F	R	F	F	F	R	--	F	--	R	--	F
kutzingiana var. *planetophora* Fricke	--	--	--	--	--	--	--	--	--	R	--	--	--
cf. *C. operculata* (Agardh) Kützing	--	--	--	--	--	F	--	--	--	--	--	--	F
sp.	--	--	--	--	--	F	--	--	--	--	--	--	F
Cymatopleura cf. *C. elliptica* (Brébisson) Wm. Smith	F	--	--	--	--	--	--	--	--	--	--	--	--
Cymbella affinis Kützing	F	--	--	--	--	--	--	--	--	--	--	--	F
arcus Gregory	R	--	--	--	--	--	--	--	--	--	--	--	--
cistula var. *maculata* (Kützing) Van Heurck	--	--	-- --	--	--	--	--	R	--	--	--	R	--
ehrenbergii Kützing	--	--	--	--	--	--	R	R	--	--	--	--	--
gracilis (Rabenhorst) Cleve	F	--	--	--	--	--	--	--	--	--	--	--	--
hybrida Grunow	--	--	--	--	--	--	--	--	--	--	--	--	F
mexicana (Ehrenberg) Cleve	--	--	--	--	--	--	--	--	--	--	--	--	R
naviculiformis Auerswald	F	--	--	--	--	--	--	--	F	F	R	--	--
cf. *C. sinuata* var. *antiqua* (Grunow) Cleve	R	--	--	--	--	--	--	--	--	--	--	--	--
turgida (Gregory) Cleve	F	--	--	--	--	--	R	F	--	R	--	--	F
cf. *C. turgida* (Gregory) Cleve	--	--	--	--	--	--	--	--	--	--	--	R	--

Table 2. Diatoms in Pleistocene strata north and northwest of Yellowstone Lake—*Continued*.

Genera and species	YFs	Hayden Valley sequence				Mudkettle sequence		ACS	Pelican Valley sequence			GCd	BFd
	4618	5632	5633	5635	5636	5589	5907	5637	5904	5905	5906	5596	5639
ventricosa Kützing	F	--	--	--	--	--	--	--	--	--	--	R	C
sp. A*	F	--	--	--	--	--	--	--	--	--	--	--	--
Denticula elegans Kützing	--	--	--	--	--	--	--	--	--	--	--	--	R
Diatoma anceps (Ehrenberg) Grunow	--	--	--	--	--	--	--	--	--	--	R	--	--
Diatomella balfouriana Greville	--	--	--	--	--	--	--	--	--	--	--	R	--
Diploneis elliptica (Kützing) Cleve	F	--	--	--	--	--	--	A	--	--	--	--	R
ovalis (Hilse) Cleve	--	--	--	--	--	--	--	--	R	R	F	--	--
Epithemia cf. *E. argus* (Ehrenberg) Kützing	F	--	--	--	--	--	--	--	--	--	--	--	--
sorex Kützing	--	--	--	--	--	--	--	--	--	--	--	--	F
turgida (Ehrenberg) Kützing	F	--	--	--	--	--	R	---	R	--	--	--	F
zebra var. *porcellus* (Kützing) Grunow	--	--	--	--	--	--	--	R	--	--	--	--	--
zebra var. *proboscidea* Grunow	--	--	--	--	--	--	--	--	R	--	--	--	--
zebra var. *saxonica* (Kützing) Grunow	--	--	--	--	--	--	--	R	--	--	R	R	--
sp. A*	F	--	--	--	--	--	--	--	--	--	--	--	--
sp.	R	--	--	R	--	--	--	--	--	--	--	--	R
Eunotia arcus Ehrenberg	--	--	--	--	--	--	--	--	--	--	--	--	C
lunaris (Ehrenberg) Grunow	R	--	--	--	--	--	--	--	--	--	--	--	--
monodon Ehrenberg	R	--	--	--	--	--	--	--	--	--	--	--	--
paludosa Grunow	--	--	--	--	--	--	F	--	R	F	F	--	--
cf. *E. parallela* Ehrenberg	--	--	--	--	--	--	--	--	--	--	--	--	R
praerupta Ehrenberg	--	--	--	--	--	--	R	R	--	--	--	--	--
praerupta var. *bidens* Grunow	--	--	--	--	--	--	--	F	--	--	--	--	--
praerupta var. *minor* (Kützing) Rabenhorst	--	--	--	--	--	--	--	--	--	--	--	R	--
sudetica (Müller) Hustedt	R	--	--	--	--	--	--	--	--	--	--	--	--
valida Hustedt	--	--	--	--	--	--	--	F	--	--	--	R	--
sp.	--	--	--	--	--	--	--	--	R	--	--	--	--
Fragilaria capucina Desmazieres	--	--	--	--	--	--	--	--	--	--	--	R	--
construens var. *subsalina* Hustedt	--	--	--	--	--	--	--	F	--	--	--	--	--
construens var. *binodis* (Ehrenberg) Grunow	--	--	--	--	--	--	--	--	--	--	--	--	F
leptostauron (Ehrenberg) Hustedt	--	--	--	--	--	--	--	--	--	R	--	R	F
leptostauron var. *rhomboides* Grunow	C	--	--	--	--	--	--	--	--	--	--	--	--
pinnata Ehrenberg	A	--	--	--	--	--	--	--	--	--	--	--	--
virescens Ralfs	A	--	--	--	--	--	--	--	--	--	--	--	--
sp.	F	--	--	--	--	--	--	--	--	--	--	--	--

Table 2. Diatoms in Pleistocene strata north and northwest of Yellowstone Lake—*Continued.*

Genera and species	YFs	Hayden Valley sequence				Mudkettle sequence		ACS	Pelican Valley sequence			GCd	BFd
	4618	5632	5633	5635	5636	5589	5907	5637	5904	5905	5906	5596	5639
Frustulia rhomboides (Ehrenberg) De Toni	--	--	--	--	--	--	--	--	--	--	--	--	F
rhomboides var. *saxonica* Rabenhorst) De Toni	--	--	--	--	--	--	R	--	--	--	--	--	--
sp.	R	--	--	--	--	--	--	--	--	--	--	--	--
Gomphoneis herculanea (Ehrenberg) Cleve	--	--	--	--	--	--	--	--	--	--	--	--	F
herculanea var. *clavata* Cleve	--	--	--	--	--	--	--	--	--	--	--	--	C
Gomphonema acuminatum var. *coronata* (Ehrenberg) W. Smith	--	--	--	--	--	--	--	--	--	--	R	--	--
cf. *G. acuminatum* Ehrenberg	--	--	--	--	--	--	--	--	--	--	--	--	R
intricatum Kützing	F	--	--	--	--	--	--	--	--	--	--	--	--
"*lanceolatum*" Cleve non Ehrenberg	--	--	--	--	--	--	--	--	--	--	R	--	--
lanceolatum var. *insignis* (Gregory) Cleve	C	--	--	--	--	--	--	--	--	--	--	--	F
longiceps var. *subclavata* Grunow	--	--	--	--	--	--	--	F	--	--	--	R	--
olivaceum (Lyngbye) Kützing	--	--	--	--	--	--	--	--	--	--	--	--	F
sphaerophorum Ehrenberg	--	--	--	--	--	--	--	--	--	--	--	--	F
subclavatum Grunow	R	--	--	--	--	--	--	--	--	--	--	--	--
ventricosum Gregory	--	--	--	--	--	--	--	--	--	--	--	--	F
sp.	R	--	--	--	--	--	--	R	--	--	--	--	--
Hannaea arcus (Ehrenberg) Patrick	--	--	--	--	--	--	--	--	--	--	--	--	C
Hantzschia amphioxys (Ehrenberg) Grunow	R	--	--	--	--	--	F	C	C	F	C	R	F
Melosira distans var. *lirata* (Ehrenberg) Bethge	R	--	--	--	--	--	--	--	--	--	--	--	--
cf. *M. distans* (Ehrenberg) Kützing													
italica (Ehrenberg) Kützing	C	R	R	R	R	--	--	A	F	F	F	--	C
cf. *M. italica* (Ehrenberg) Kützing	--	--	--	--	--	F	--	--	--	--	--	--	--
italica var. *tenuissima* (Grunow) O. Müller	--	--	--	--	--	--	--	--	--	F	--	--	--
sp.	--	--	--	--	--	R	R	--	--	--	--	R	F
Meridion constrictum Ralfs	--	--	--	--	--	--	R	F	R	--	R	F	R
Navicula amphibola Cleve	--	--	--	--	--	--	R	R	--	--	--	--	--
bacillum Ehrenberg	--	--	--	--	--	--	--	--	--	--	R	--	--
cincta (Ehrenberg) Kützing	--	--	--	--	--	--	--	--	--	--	--	--	R
cryptocephala Kützing	--	--	--	--	--	--	--	--	--	--	--	R	--
cuspidata Kützing	--	--	--	--	--	--	R	--	--	--	--	--	--

Table 2. Diatoms in Pleistocene strata north and northwest of Yellowstone Lake—*Continued.*

Genera and species	YFs	Hayden Valley sequence				Mudkettle sequence		ACS	Pelican Valley sequence			GCd	BFd
	4618	5632	5633	5635	5636	5589	5907	5637	5904	5905	5906	5596	5639
cuspidata var. *heribaudi* Peragallo and Héribaud	--	--	--	--	--	--	--	R	--	--	--	--	--
cf. *N. cuspidata* Kützing	--	--	--	--	--	--	--	--	--	--	R	--	--
dicephala (Ehrenberg) Wm. Smith	--	--	--	--	--	--	--	R	F	R	F	--	F
dicephala Ehrenberg var.	--	--	--	--	--	--	--	--	--	R	--	--	--
cf. *N. dicephala* (Ehrenberg) Wm. Smith	F	--	--	--	--	--	--	--	--	--	--	--	--
halophila (Grunow) Cleve	--	--	--	--	--	--	--	--	--	--	F	--	--
cf. *N. hassiaca* Krasske	--	--	--	--	--	--	--	--	--	--	--	--	R
mutica Kützing	--	--	--	--	--	--	--	C	--	--	--	--	--
mutica var. A	--	--	--	--	--	--	--	R	--	--	--	--	--
mutica Kützing var.	--	--	--	--	--	--	R	--	--	--	--	--	--
peregrina (Ehrenberg) Kützing	R	--	--	--	--	--	--	--	--	--	--	--	--
pseudoscutiformis Hustedt	F	--	--	--	--	--	--	--	--	--	--	--	--
pupula Kützing	F	--	--	--	--	--	--	--	--	--	--	--	--
pupula var. *capitata* Hustedt	--	--	--	--	--	--	--	--	--	--	--	--	F
pupula var. *rectangularis* (Gregory) Grunow	--	--	--	--	--	--	--	--	R	--	--	--	--
radiosa Kützing	F	--	--	--	--	--	--	--	--	R	--	--	--
aff. *N. reinhardtii* Grunow	F	--	--	--	--	--	--	--	--	--	--	--	--
scutiformis Grunow	F	--	--	--	--	--	--	--	--	--	--	--	--
semen Ehrenberg	--	--	--	--	--	--	--	R	--	--	--	--	--
cf. *N. verecunda* Hustedt	--	--	--	--	--	--	--	--	--	--	--	--	R
sp. A	--	--	--	--	--	--	--	F	--	--	--	--	--
sp. B	--	--	--	--	--	--	--	F	--	--	--	--	--
sp.	F	--	--	--	--	--	--	--	--	--	R	--	--
Neidium affine (Ehrenberg) Cleve	--	--	--	--	--	--	--	R	--	--	--	--	--
bisulcatum (Lagerstedt) Cleve	--	--	--	--	--	--	--	--	--	F	--	--	--
iridis (Ehrenberg) Cleve	F	--	--	--	--	--	--	R	--	--	--	--	--
iridis var. *vernalis* Reichelt	--	--	--	--	--	--	--	--	--	R	R	--	--
Nitzschia denticula Grunow	F	--	--	--	--	--	--	--	--	--	--	--	--
cf. *N. dissipata* (Kützing) Grunow	--	--	--	--	--	--	--	--	--	--	--	--	F
recta Hantzsch	--	--	--	--	--	--	--	--	--	--	R	--	--
sp. A	--	--	--	--	--	--	--	F	--	--	--	--	--
spp.	F	--	--	--	--	--	--	--	R	R	--	--	--
Pinnularia acrosphaeria Brébisson	--	--	--	--	--	--	--	R	--	--	--	--	--
appendiculata (Ehrenberg) Cleve	--	--	--	--	--	--	--	--	R	--	--	--	--
appendiculata (Agardh) Cleve	--	--	--	--	--	--	--	--	--	--	--	--	R
borealis Ehrenberg	--	--	--	--	--	--	F	--	C	F	F	F	R
brebissonii Kützing	--	--	--	--	--	--	--	R	--	--	--	--	--
cf. *P. brevicostata* Cleve	C	--	--	--	--	--	R	--	--	--	--	--	R

Table 2. Diatoms in Pleistocene strata north and northwest of Yellowstone Lake—*Continued.*

Genera and species	YFs	Hayden Valley sequence				Mudkettle sequence		ACS	Pelican Valley sequence			GCd	BFd
	4618	5632	5633	5635	5636	5589	5907	5637	5904	5905	5906	5596	5639
cf. *P. divergentissima* (Grunow) Cleve	--	--	--	--	--	--	--	--	--	--	--	R	--
gibba Ehrenberg	--	--	--	--	--	--	R	--	--	--	R	--	--
cf. *P. gibba* Ehrenberg	--	--	--	--	--	--	--	--	--	--	--	R	--
gibba var. *linearis* Hustedt	--	--	--	--	--	--	--	--	--	--	--	--	R
hemiptera (Kützing) Cleve	R	--	--	--	--	--	--	--	--	--	--	--	--
interrupta Wm Smith	-	--	--	--	--	C	--	--	F	F	A	--	--
interrupta var. *minutissima* Hustedt	--	--	--	--	--	--	--	--	--	--	F	--	--
aff. *P. interrupta* Wm. Smith	--	--	--	--	--	--	--	--	--	R	--	--	--
lata (Brébisson) Wm. Smith	--	--	--	--	--	--	--	C	--	--	--	--	--
major (Kützing) Cleve	--	--	--	--	--	--	--	--	--	R	--	--	--
mesolepta (Ehrenberg) Wm. Smith	C	--	--	--	--	--	--	--	R	R	--	--	--
mesolepta var. *angusta* Cleve	--	--	--	--	--	--	--	R	--	--	R	--	--
nodosa Ehrenberg	R	--	--	--	--	--	--	--	--	--	--	--	--
streptorapha Cleve	--	--	--	--	--	--	--	F	--	--	--	--	--
viridis (Nitzsch) Ehrenberg	--	--	--	--	--	--	--	R	R	R	R	--	--
cf. *P. viridis* var. *sudetica* (Hilse) Hustedt	R	--	--	--	--	--	--	--	--	--	--	--	--
sp. A*	R	--	--	--	--	--	--	--	--	--	--	--	--
spp.	F	--	--	--	--	--	R	R	--	R	R	--	--
Rhoicosphenia curvata (Kützing) Grunow	R	--	--	--	--	--	--	--	--	--	--	--	C
Rhopalodia gibba (Ehrenberg) Müller	C	--	--	--	--	R	--	--	--	R	R	R	R
gibba var. *ventricosa* (Kützing) Van Heurck	--	--	--	--	--	--	--	--	--	--	--	--	F
gibberula (Ehrenberg) Müller	--	--	--	--	--	--	R	--	F	F	F	R	F
parallela (Grunow) Müller	--	--	--	--	--	--	--	--	--	--	R	--	--
Stauroneis acuta Wm. Smith	--	--	--	--	--	--	--	F	--	--	--	--	--
anceps Ehrenberg	--	--	--	--	--	F	--	--	R	--	--	--	F
phoenicenteron Ehrenberg	F	--	--	--	--	--	--	--	R	R	R	--	--
sp. A	--	--	--	--	--	--	--	F	--	--	--	--	--
sp.	R	--	--	--	--	--	--	--	--	--	--	--	--
Stephanodiscus astraea (Ehrenberg) Grunow	--	R	R	R	F	F	--	--	--	--	--	--	C
astraea var. *minutula* (Kützing) Grunow	--	F	R	R	F	F	R	--	R	R	R	--	C
Surirella angustata Kützing	F	--	--	--	--	--	F	--	--	--	--	--	F
cf. *S. turgida* Wm. Smith	F	--	--	--	--	--	--	--	--	--	--	--	--
utahensis Grunow	--	--	--	--	--	--	--	--	--	--	--	--	R
Synedra ulna (Nitzsch) Ehrenberg	--	--	--	--	--	--	--	--	R	--	--	R	F
cf. *S. ulna* (Nitzsch) Ehrenberg	F	--	--	--	--	--	--	--	--	--	--	--	--

Table 2. Diatoms in Pleistocene strata north and northwest of Yellowstone Lake—*Continued*.

Genera and species	YFs	Hayden Valley sequence				Mudkettle sequence		ACS	Pelican Valley sequence			GCd	BFd
	4618	5632	5633	5635	5636	5589	5907	5637	5904	5905	5906	5596	5639
Tabellaria fenestrata (Lyngbye) Kützing	F	--	--	--	--	--	--	--	--	--	--	--	--
Tetracyclus emarginatus (Ehrenberg) Wm. Smith	R	--	--	--	--	--	--	--	--	--	--	--	--
cf. *I. emarginatus* (Ehrenberg) Wm. Smith	F	--	--	--	--	--	--	--	--	--	--	--	--
rupestris (A. Braun) Grunow	--	--	--	--	--	--	--	--	--	R	--	R	--

* Extinct species.

SAMPLE LOCALITIES

4618. Yellowstone Falls sequence at locality 1; varved tan claystone in upper part of unit 3 in measured section (see text) on east side of Yellowstone Canyon about 600 feet downstream from Upper Falls.

5632. Hayden Valley sequence at fossil locality 5632; thin-bedded dark-brown silt on top of hill 130 feet above contact with underlying rhyolite.

5633. Hayden Valley sequence at fossil locality 5633; brown structureless clay from south bank of creek 12 feet above contact with underlying rhyolite.

5635. Hayden Valley sequence at fossil locality 5635; thin-bedded ripple-marked silt and clay about 80 feet above contact with underlying rhyolite.

5636. Hayden Valley sequence at fossil locality 5635 but 20 feet stratigraphically below collection 5635; dense brown blocky clay.

5589. Mudkettle sequence at locality 8; white to blue-gray claystone and siltstone about 50 feet below top of sequence in big exposure 1,000 feet west of forks of Wrong Creek and on south side of creek.

5907. Mudkettle sequence at fossil locality 5907; chalky white tuffaceous soft claystone on east side of Pelican Creek, 5–10 feet above water level.

5637. Top of Astringent Creek? Sand at fossil locality 5637, 5,000 feet east-northeast of locality 16; gray structureless clay at about the same topographic elevation as the top of a 100-foot section of Astringent Creek Sand directly overlying basalt at locality 16. Faulting and poor exposures in the intervening area make stratigraphic relation of diatomaceous beds to the sand somewhat uncertain.

5904. Pelican Valley sequence at locality 11; gray to drab tough clay in unit 2 of measured section (see text). A radiocarbon age of 7,550 years was obtained from overlying bed.

5905. Pelican Valley sequence at locality 11; creamy gray dense clay in unit 4 of measured section (see text).

5906. Pelican Valley sequence at locality 11; creamy gray dense clay in unit 7 of measured section (see text).

5596. Gibbon Canyon deposits in highway cut 800 feet upstream from right angle bend in Gibbon Canyon and 7 miles west of geologic map area. Sample is split of carbonaceous white and black clay from which a radiocarbon age of 9,440 years was obtained.

5639. Bannock Ford deposits 3,000 feet east-northeast of Tower Falls, on east side of Yellowstone River, about 8 miles north of geologic map area. Sample is evenly bedded gray-green silty clay 12 feet above river level. Basal 3 feet of overlying sand bed contains carbonized wood from which a radiocarbon age of 3,750 years was obtained.

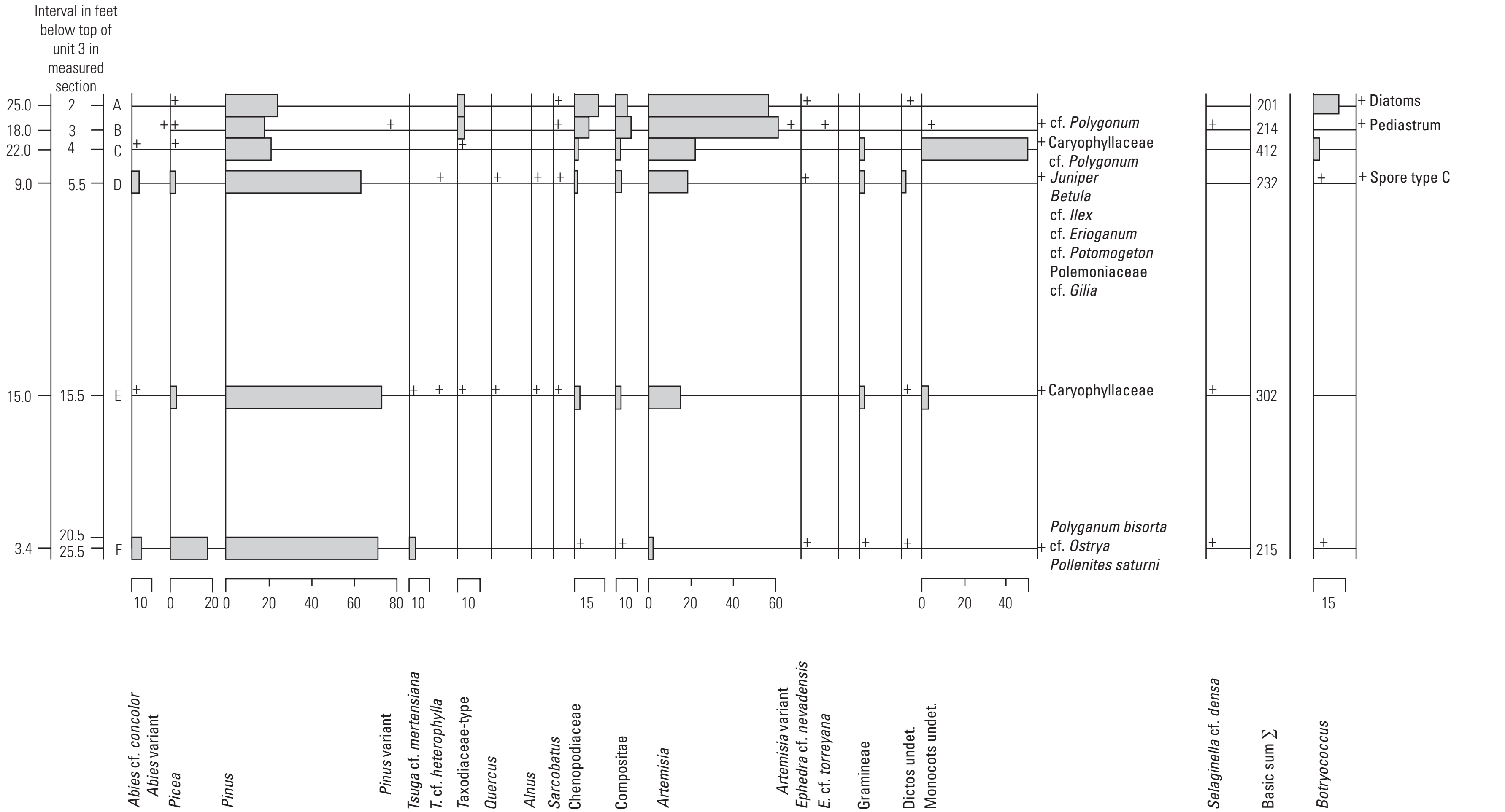


Figure 8. Pollen distribution in Yellowstone Falls sequence at locality 1. Identification and arrangement prepared by E.B. Leopold; samples from USGS paleobotany locality D1212, unit 3 of measured section (see text). Lithology: A, white light-weight clay with carbonized plant fragments; B, plant-bearing brown clay; C, white light-weight clay with brown plant fragments; D, brown clay; E, varved light-gray clay; F, laminated gray clay. Data are plotted in histogram form, showing percent composition of total pollen count. Spores and algae are not included in the basic sum, but are shown as number of specimens encountered per 100 pollen grains tallied. The basic sum Σ, which is entered on the right, represents a significant sample and is the basis for percentages. Pollen of tree forms are plotted on left, shrub and herbs in the middle, and spores and algae are plotted on the right of the basic sum column.

toolbox" of geologists in 1956; see Morgan and others, 1998; Pierce, Cannon and others, this volume—Editor.]

The rock floor on which the Hayden Valley strata were deposited is at an altitude of about 7,820 feet at locality 2 as well as along Trout Creek a mile west of locality 3. Farther north and east, the base is not exposed even though the altitude decreases to 7,680 feet at the Yellowstone River. This fact plus the distribution of the next younger sequence suggests that there was northeastward tilting after deposition of both sets of strata. The peculiar course of Alum Creek northeastward across Hayden Valley, all the way to the edge of the bounding volcanic rocks, likewise suggests tilting.

Howard recognized the high elevation of the youngest part of the Hayden Valley sequence and postulated that the lake in which it was deposited could not have been connected with Yellowstone Lake because southern outlets of the latter are much lower. He suggested, instead, that there may have been a high level "retreat lake" in Hayden Valley, between his "Lamar glacier" to the north and ice occupying Yellowstone Lake to the south. The presence of extensive Pleistocene faults and evidence of crustal warping as may be related with the active and ongoing deformation of the Yellowstone caldera (see Pierce, Cannon and others, this volume), however, suggests to us that there was only one lake at this time, as postulated by Holmes, and that the relation of elevation of sediments to lake outlets has not remained constant.

Spectrographic analyses of the Hayden Valley sequence in Hayden Valley show that it contains slightly more magnesium and cobalt and less yttrium and molybdenum than the Yellowstone Falls, Mudkettle, and Pelican Valley sequences. The varved clay at locality 15 is spectrographically almost identical to that of the Hayden Valley sequence in Hayden Valley. There is likewise a close similarity in amount of common oxides (compare, for example, D123116 with D123117 and D123122 in table 1). For these reasons, plus the lithologic similarity, the outcrops at localities 15 and 19 are tentatively correlated with the Hayden Valley sequence.

Diatoms were collected from four horizons in the Hayden Valley sequence (table 2). Concerning this assemblage (and those from the Mudkettle, Pelican Valley, and Bannock Ford deposits), K.E. Lohman and G.W. Andrews stated (written commun., 1966):

> "All of these species are still represented in living assemblages elsewhere, although some of them have geologic ranges extending back to the Miocene; a larger number do not go back beyond the Pliocene, and some, particularly the most abundant species in the assemblage, such as *Stephanodiscus astreaea* and its variety *minutula*, are not known from rocks earlier than Pleistocene. Thus the age of the beds from which these collections came cannot be older than Pleistocene, and probably not older than middle or late Pleistocene.
>
> "The environment in which these diatoms lived, was probably a cool to cold, fairly shallow, clear lake, very near neutral, as the rare species usually preferring slightly acidic water are balanced by those usually preferring slightly alkaline water, and many are indicative of water of low mineral content."

Figure 9. Air oblique view west-southwest up Alum Creek showing treeless exposures of Hayden Valley sequence in western part of Hayden Valley.

Figure 10. View east at locality 15 along cliff cut by storm waves; surface bevels till and underlying lake sediments of Hayden Valley(?) sequence, north edge of Mary Bay, Yellowstone Lake. Foreground is site of figs. 11 and 12. Indicated are varved clay (dark because it is wet) (A), sand and silt (B), till (C), and beach or dune sand (D). Units A and B are probably part of Hayden Valley sequence.

Figure 11. Wave-cut cliff at locality 15, north edge of Mary Bay, Yellowstone Lake.

Figure 12. Varved clay at base of exposure shown in figure 11, locality 15.

Alum Creek Sequence

The Alum Creek sequence is here described from exposures along Alum and Trout Creeks in Hayden Valley, and comprises the "plains sediments" of Howard (1937). It is present only in the topographically low parts of the valley. The maximum thickness is unknown, but a section, locally as much as 125 feet thick, is poorly exposed on broad treeless grassy slopes.

At locality 4 in a large gravel pit (fig.14), the basal 20 feet is dark-gray, sugary, fine-grained, remarkably homogenous sand with abundant tiny magnetite crystals, shards, pumice

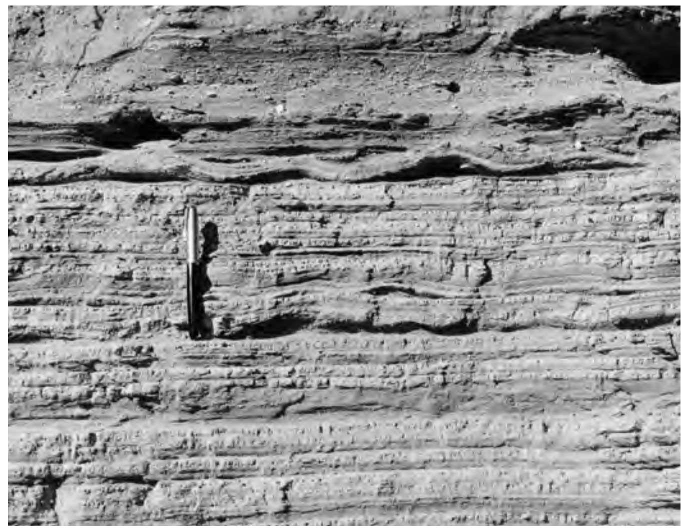


Figure 13. Silt beds in Hayden Valley(?) sequence at locality 19 on the northwest margin of Mary Bay, Yellowstone Lake. In nearby exposures, this unit overlies varved clay and underlies till.

Figure 14. Alum Creek sequence at locality 4. About 15 feet of strata can be seen; basal part is fine-grained gray sand; middle is dark gray obsidian sand and gravel interbedded with light gray sandy silt; upper part is dark brown soil. Origin of contorted zone has not been determined but may be due to frost wedges.

chunks, and black obsidian. The bed is overlain by 10 feet of dark-gray obsidian sand and loose gravel composed of rounded to angular fragments of rhyolite, obsidian, and basalt. Above this is 5 feet of sand, boulders, and weathered soil.

Along Trout Creek near the highway at locality 5 are broad natural exposures of the Alum Creek sequence. The basal 4 feet is a dark-gray, coarse-grained obsidian sand and gravel. Above this is 25 feet of gray, slightly clayey and silty sand. Some of it is crossbedded, but other parts have even layers as much as an inch thick with graded bedding from sand to thin clay laminae, which resemble coarse varves. The top 5 feet is a mixture of sand, gravel, and clay.

After retreat of the ice that overrode the Hayden Valley beds, broad northeast-trending valleys 100 to 200 feet deep were cut and in them the Alum Creek sequence was deposited. A few striated erratics, possibly reworked from the post-Hayden Valley till, are present in gravel pits, but no evidence of glacial debris with morainal form was found on the present surface.

The Alum Creek sequence has yielded no fossils as yet. A few tiny fragments of carbonized wood, not enough for a ^{14}C determination, were observed. The close coincidence of the down-valley part of these beds to the present level of the Yellowstone River suggests that they are of late Pleistocene age.

Mudkettle Sequence

The Mudkettle sequence is the oldest of the three lacustrine and fluvial sediment units recognized along and north of Pelican Valley, northeast of Yellowstone Lake. On Hayden's first trip through the area in 1871 (Hayden, 1872, p. 131), he not only recorded the presence of lake deposits but observed that they extended northward nearly to the head of the Pelican Creek drainage. These relations were not mentioned by subsequent workers. The strata are exposed in the bottoms of re-excavated stream valleys that separate hard ridges of Tertiary volcanic rocks. By far the best and most extensive exposures are near The Mudkettles, between localities 6 and 10 (fig. 3), along Pelican Creek. The Mudkettles, from which the name of the sequence is derived, are a series of hydrothermal vents that cut through these strata, and mud in the kettles is reworked from them.

The maximum thickness of the sequence is not known, although it appears the unit thickens from the north to the south. At locality 8, about 75 feet is visible in a continuous exposure (fig. 15), at locality 6 (fig. 16) about 85 feet, and farther south near The Mudkettles, 150 feet.

In the type area, east of The Mudkettles, the Mudkettle sequence consists of light-gray, soft claystone and siltstone with lesser amounts of sandstone and conglomerate that weather to rounded treeless badland hills. Vertical cuts show intricate depositional features (fig. 16 at locality 6) that are not readily apparent in more rounded exposures. The following section describes typical lithology:

Measured Section of Mudkettle Sequence

This section was measured by J.D. Love at locality 6 (fig. 16) on the east bank of Pelican Creek.

Unit	Lithology	Thickness (ft)
Top of section; younger beds eroded		
5	Claystone and siltstone, gray, with some pale-green spots, soft, crumbly, fine-grained, noncalcareous, highly tuffaceous	10+
4	Conglomerate and sandstone, gray, with green siliceous concretions, lenticular, cross-bedded; rock fragments are red and brown rhyolite ranging in size from cobbles to grit; sandstone is thin-bedded, with green fine-grained clay pellets and pumice chunks in limonitic hard siliceous matrix, noncalcareous, with sporadic angular grains of quartz and feldspar; forms prominent ledge at upper left in figure 16	15
3	Siltstone and sandstone with thin claystone partings, thin-bedded, moderately lithified. Upper part is noncalcareous, very tuffaceous, pale purplish-white, with texture of fine-grained bread; pink and clear sand grains are typical and very small; matrix contains enough clay to decrepitate rapidly in water. In the middle are beds of hard brittle, pale bluish-green to white noncalcareous, fine-grained, pure claystone. These are underlain by chalky, white colloidal, fine-grained blocky noncalcareous claystone. The basal beds are light gray mudstone interbedded with white, fine-grained, noncalcareous, hard to brittle claystone containing sporadic angular grains of quartz or sanidine; rock is limonite-stained along fractures; impregnated in places with a conspicuous blue stain of unknown composition.	40–50
Local unconformity		
2	Sandstone, greenish-gray to tan, chiefly a crystal tuff, pyritic, iron-stained, cross-bedded, moderately soft but sufficiently lithified to form conspicuous ledge (at lower right in fig. 16); middle part contains pumice breccia and conglomerate, dark gray, hard, a mass of altered pumice chunks and large shards in a silicified sandstone matrix; sporadic rounded pebbles of dense dark gray volcanic rock and quartz and feldspar grains; maximum dip of foreset beds is 25°N.	15–25
1	Conglomerate, mudstone, and claystone, pale green to brown, hard; forms ledge at water level of Pelican Creek; conglomerate is composed of coarse, rounded, rhyolite pebbles; claystone and mudstone are pale green, dense, hard, with layers of pumice chunks, shards, and angular quartz and feldspar grains	3
Thickness of measured part of Mudkettle sequence		73–93+

Underlying beds are not exposed here.

The north dip of foreset beds in unit 2 is of special interest. It suggests that this part of Pelican Valley may have been an outlet channel that drained northward from ancestral Yellowstone Lake at the time the Mudkettle sequence was being deposited.

The northernmost exposures of the Mudkettle sequence that have been examined are at localities 7 and 8, north of the present divide that separates southward drainage into Yellowstone Lake from northward drainage into Yellowstone River. About 75 feet of dull bluish-gray claystone and mudstone is exposed at locality 8 (fig. 15). It is blocky, soft, noncalcareous, limonite-stained, and interbedded with gray, fine- to medium-grained, poorly cemented volcanic sandstone containing abundant shards.

Perhaps the most unusual outcrop of any Pleistocene unit in the northern Yellowstone area is the Mudkettle sequence at locality 7. The rock here is impregnated with a volatile, extremely fluid, light-brown, paraffin-base oil, described and photographed elsewhere (Love and Good, 1970). The rock is a bright to dull, blue-gray claystone and mudstone. It is dense, hard, noncalcareous, blocky, and peppered with tiny black specks. Sporadic angular grains of clear quartz and feldspar are characteristic. Interbedded with the mudstone are partings of gray, fine-grained, homogeneous, "pepper and salt" volcanic sandstone that contains black magnetite grains, abundant tiny clear shards, and larger clear angular quartz and feldspar grains. The mudstone has a persistent acrid odor. Analysis of a representative sample shows 76 ppm arsenic, 0.5 ppm selenium, 0.10 percent fluorine, and 1.1 percent sulfur (determined by A.J. Bartel, G.T. Burrow, W.D. Goss, and I.C. Frost, respectively). In August 2004, a sample of similar description—a volatile, paraffin-base oil in a bright to dull, blue-gray claystone and mudstone that is dense, hard, noncalcareous, blocky, and peppered with tiny black pyrite crystals—was collected near active sublacustrine hydrothermal vents from the northern basin of Yellowstone Lake (L.A. Morgan and others, written commun., 2004).

Spectrographic analyses of the Mudkettle sequence shows that it contains less Fe, Ca, Mn, Sr, and Ni than the Yellowstone Falls, Hayden Valley, and Pelican Valley sequences (fig. 4) and no excessive amounts of any of the other elements listed in the figure. It is the highest of them all, however, in individual analyses (in percent) of yttrium (0.007), niobium (0.003), ytterbium (0.0007), cerium (0.02), neodymium (0.015), and tin (0.015). Common oxides in the Mudkettle sequence are given in table 1. They show no conspicuous excesses or deficiencies.

The Mudkettle sequence laps across Tertiary and pyroclastic rocks on the east and west sides of Pelican Valley and is correlated northward into areas that now drain directly into the lower part of Yellowstone Canyon. The presence of these lacustrine beds at localities 7 and 8 and the north-dipping foreset beds at locality 6 suggest that ancestral Yellowstone Lake extended around the east end of the Upper Basin Member of the Plateau Rhyolite. Perhaps this part of the Mudkettle sequence was deposited in sluggish outlet lagoons like those now present between Yellowstone Lake and the Upper Falls.

In some places the Mudkettle strata are overlain by moraines whose form has not been entirely destroyed; therefore, these moraines may be younger than the glacial debris overlying the Hayden Valley sequence. Elsewhere, glacial debris is missing and Astringent Creek Sand (a newly named unit described in the next section) rests directly on the Mudkettle sequence.

The Pleistocene age of the Mudkettle sequence is based on diatoms (table 2) and pollen. Only 3 of 30 species of diatoms are common to both the Mudkettle and Hayden Valley sequences, but, because of the paucity of collections, the significance of this difference is not known. The age and environmental interpretation by Lohman and Andrews is the same as for the Hayden Valley deposits.

Scant pollen assemblages from oil-saturated claystone at locality 8 consist of the following forms (identified by E. B. Leopold, written commun., 1964 and 1966):

	Rainbow Springs (pollen colln. D3310)	**0.25 mi upstream from Rainbow Springs and stratigraphically a few feet higher (pollen colln. D3366)**
Pinus	42	57
Artemisia	35	12
Picea	2	12
Ephedra and *Ephedra(?)*	1	1
Botryococcus	1	7
Quercus	—	1
Juniperus	—	1
cf. *Acer*	—	1
Erigonum	1	—
Polygonum cf. *bistortoides*	1	—
Sarcobatus vermiculatus	1	—
Gramineae	1	1
Compositae	2	—
Cyperaceae	1	2
Dicot, undet.	10	1
Chenipodiaceae, undet.	3	—
Total count	101	98

Essentially the same pollen assemblage as that at Rainbow Springs (locality 7) was found in a claystone directly above the unconformity shown in figure 16. Below the unconformity, 2 feet above creek level, another claystone yielded a similar flora except that the pine pollen count increased to 50 percent and spruce to 5 percent. These collections represent pollen rains that are nearly identical to local modern accumulations.

Astringent Creek Sand

The Astringent Creek Sand is here named for exposures on Astringent Creek at locality 9 (fig. 17). It has not been previously recognized or described. The sand was deposited along Pelican Valley and its tributaries and across drainage divides to the east (loc. 16) and north (loc. 8) (fig. 15). The thickness of eroded remnants is commonly about 100 feet; it is nearly 200 feet thick at the type locality and more than 300 feet at locality 10.

The basal beds at the type locality are very coarse gray sand with some pebble gravel but little or no silt or clay matrix. These beds grade up to coarse, loose, homogeneous, gray, unlithified sand. In the upper 100 feet, a few thin lenticular silt and impure clay beds are present. Highly rounded pebbles, up to 1 inch in diameter, of volcanic rocks become more numerous near the top. The sand throughout most of the section is gray-brown, coarse grained, and loose with rounded grains of black and gray obsidian, gray pumice, clear quartz and feldspar, red and black volcanic rocks, and sparse shards up to one-sixteenth-inch long. The more clay-rich beds contain yellow and brown clay balls that quickly disaggregate in water. At the top of the section are highly rounded pebbles and cobbles and sparse boulders of hard volcanic rocks of various types. No striations were found on them, and they apparently are part of a fluviatile deposit rather than morainal debris.

At locality 8, the Astringent Creek Sand is exposed in a continuous, 125-foot-thick section (fig. 15). The basal bed is a hard, rounded, pebble conglomerate. It is overlain by a sandstone that is sufficiently lithified to form a weak ledge about 15 feet thick. The remainder of the sequence is crudely stratified, uncemented, coarse- to fine-grained sand; much of the sand consists of clear shards and white pumice fragments. Black obsidian shards, clear angular quartz and feldspar grains, and some rounded granules of pink rhyolite are present also. The volcanic material is much more abundant and less waterworn than that at locality 9 and may be closer to a source vent. [*See Foreword and About the Author, this chapter.*]

The thickest section (more than 300 feet) is at locality 10 where the strata consist largely of brown-gray, coarse- to fine-grained, nonintegrated volcanic sand. The grains are chiefly shards, pumice, quartz, feldspar, black obsidian, and brown and red volcanic rocks. Magnetite is common as very small crystals.

The farthest eastern section measured, at locality 16 along Raven Creek (fig. 3), is composed of 100 feet of sand that overlies basalt. At the base is 5 feet of dark blue-gray cross-bedded sandstone, then 30 feet of ledge-forming sandstone with a brown iron cement. The remainder is brownish-gray unconsolidated “pepper and salt” sand. Shards are present but not abundant.

East of locality 16, the Astringent Creek Sand thins but apparently was deposited continuously across the drainage divide that separates Raven Creek (fig. 2) from Willow Creek, a tributary to Lamar River (figs. 2 and 3). The occurrence on the drainage divide is of special importance because at this site a distinctive collection of diatoms was obtained (colln. 5637, table 2).

As much as 150 feet of sand is exposed on the northeast side of Broad Creek, 1 mile west-southwest of Wapiti Lake (because of lack of field time, not mapped separately at this locality on fig. 3). Additional outcrops of the sand are present for several miles down Broad Creek.

One of the conspicuous features of the Astringent Creek Sand is that it supports a thick growth of trees, whereas the older and younger lacustrine beds are almost treeless.

The conditions of deposition of the Astringent Creek Sand are not fully understood. It is a well-sorted, water-lain sand with remarkably little clay, silt, or other bonding cement. It overlies the Mudkettle sequence and has buried the moraines that rest on those beds. It may represent an ice-marginal deposit that accumulated in valleys to the north and east of a static mass of ice occupying the Yellowstone Lake basin. If so, deposition of sand across the drainage divides to the north and east demands an explanation. On the other hand, if this is not an ice-marginal deposit, what happened to it in the vicinity of Yellowstone Lake?

The sand extends from Rainbow Springs at locality 7 down Wrong Creek toward Yellowstone Canyon. If it was deposited as far west as the present brink of the canyon, this would suggest that the canyon is younger than the sand.

The source of the abundant pumice and shards at localities 8 and 10 is not known but the angularity, freshness, and volume suggests that the source was one or more vents in the Yellowstone area. [*See Foreword and About the Author, this chapter.*]

No fossils have been found within the Astringent Creek Sand except at its probable top on the Raven Creek–Willow Creek

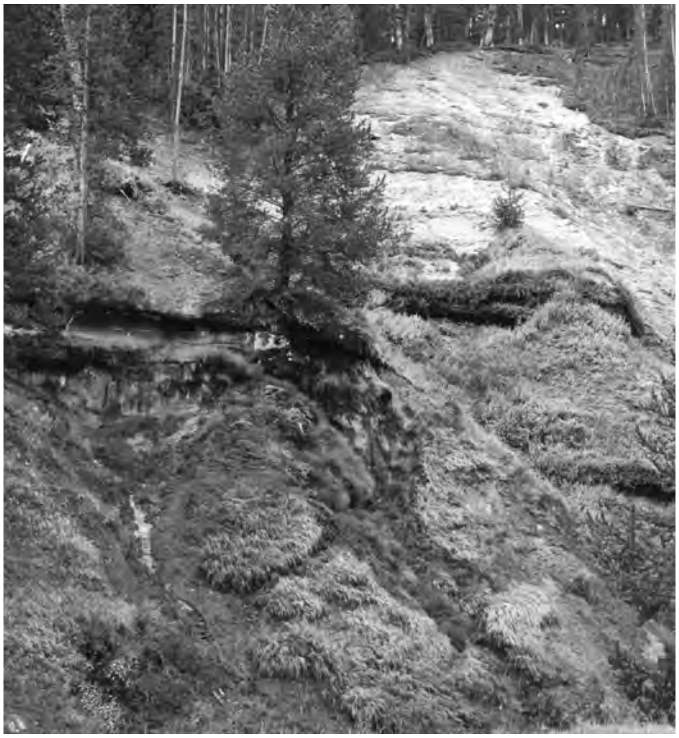


Figure 15. View south across Wrong Creek at locality 8, showing 200-foot scarp of Astringent Creek and Mudkettle sequences. About 75 feet of claystone in Mudkettle sequence is exposed in ravine below ledge at lower left. Ledge and overlying 125 feet of section is newly named Astringent Creek Sand.

Figure 16. Local unconformity in Mudkettle sequence at locality 6. View is east across Pelican Creek at cliff composed of 85 feet of strata, chiefly sandstone below unconformity and light greenish-gray claystone, siltstone, and sandstone above it. All ledges are highly tuffaceous sandstone.

Figure 17. Astringent Creek Sand (newly named) on east side of Astringent Creek, 2.5 miles north of Pelican Valley at locality 9. View is north at outcrop of nearly 200 feet of gray unconsolidated sand overlying white sulfurous thermal deposits that crop out in irregular areas.

drainage divide, 5,000 feet east-northeast of locality 16. Here abundant diatoms were found in a gray structureless clay (colln. 5637, table 2). This collection comprises an assemblage that is distinct from those in all the other sequences in the area. Concerning it, Lohman and Andrews stated (written commun., 1960):

> "The assemblage from locality No. 5637 suggests deposition in a cool, slightly saline, but fairly fresh water of low mineral content, and probably near the margin of a lake. This is indicated by a number of distinctly fluviatile species mixed with a larger number of species now living in lakes. All of the species in this assemblage are still represented in living assemblages elsewhere, so an age of Pleistocene (and probably late Pleistocene) is indicated. Although many of the species have long geologic ranges extending from Miocene to Recent, a few are not known from rocks earlier than Pleistocene in age."

Pelican Valley Sequence

The Pelican Valley sequence is named after Pelican Valley (fig. 18) where in the lower 10 miles it is exposed in broad treeless outcrops. These strata were recognized as representing a deposit in ancestral Yellowstone Lake by nearly all the earlier workers in the Park region, but they made no attempt to describe, measure, or date the beds.

The exposed thickness is commonly about 120 feet, but there is no information as to how much more underlies the valley floor. One of the best sections is in a bluff along Pelican Creek, one-half mile southwest of locality 12, where more than 100 feet can be seen (figs. 19 and 20). The lower part of this section is relatively massive, fine-grained, sparsely pebbly sandstone and siltstone; the middle is light-gray to white, thick-bedded siltstone with a velvety sheen; the upper 30 feet is finely layered white siltstone. At the top is 5 to 10 feet of hard, pale mustard-yellow, nodular porous sandstone and siltstone composed largely of tiny altered shards.

About halfway between localities 12 and 13, lenses of pebble gravel are interbedded with the siltstone. One rhyolite boulder three feet in diameter was observed in place in the siltstone. A thin but significant section is exposed at locality 11 (fig. 21).

Figure 18. Phototheodolite view southwest from Pelican Cone. White treeless area is Pelican Valley, underlain by the Pelican Valley sequence. Yellowstone Lake is gray expanse to right of upper center; Teton Range and Grand Teton Peak are on center skyline, 70 miles away.

Section of Pelican Valley Sequence Along Astringent Creek

The following section was measured on the east bank of Astringent Creek at locality 11:

Unit	Lithology	Thickness (ft)
Top of section		
8	Clay, rich rusty brown at base, gray and tan in middle, and greenish-brown at top, silty, crumbly; top of unit is horizon of soil at meadow surface	2.5
7	Clay and silt, light gray, with limonite stain in lower half; some grit and fine-grained sand partings; some creamy gray clay that is plastic when wet	4.0
6	Sand, gray, coarse-grained, loose with abundant shards	0.5
5	Clay, light gray, with rusty splotches, plastic massive, lenticular, sparse carbonized vegetal trash	2.0
4	Clay and silt, dull gray in lower part, becoming more carbonaceous near top, clay is creamy gray, fine-grained, noncalcareous, homogeneous; abundant twigs, rushes, blossoms, and seeds; sample collected for ^{14}C determination	2.3
3	Granule gravel, rusty brown, with 2 inches of clay in upper part, poorly cemented; abundant black obsidian, shards, and rhyolite fragments; brightly colored sand grains of many lithologies; pockets of carbonized trash, one of which contains a tree stump one foot in diameter dated as 7,550+350 yr B.P. (W-1684)	1.0
2	Clay and sand, deep indigo blue and green tinges when wet, dull gray to olive drab when dry; clay is massive, tough, dense, silty, noncalcareous; decrepitates in water after drying; contains abundant tiny white grains of pumice; sandy part is almost uncemented, with silty shard-bearing matrix; contains rounded pebbles up to one inch in diameter of gray previously silicified conglomerate, and pumice; highly carbonaceous, with abundant twigs, rushes, and tree branches as much as two inches in diameter; sample collected for ^{14}C determination	2.0
1	Conglomerate, blue gray, loose to moderately cemented, forms ledge at creek level; composed of highly rounded pea gravel to pebbles three inches in diameter in a shard-bearing matrix; most fragments are rhyolite but some are mafic rocks	3.0+
Total thickness of measured part of Pelican Valley sequence		17.3

Intermittent outcrops of velvety gray clay and silt are present along Astringent Creek between localities 11 and 14. Along the bank of Pelican Creek at locality 14 (fig. 22) is an exposure of the Pelican Valley sequence with a distinctive lithology.

Section of Pelican Valley Sequence at Locality 14

The following section was measured on the east bank of Pelican Creek about 100 yards downstream from the mouth of Astringent Creek.

Unit	Lithology	Thickness (ft)
Top of section		
7	Sand, dark gray, silty, loose	5
6	Sand, light gray, silty, pumiceous; forms slope back of creek bank	10
5	Conglomerate, dark brown, manganese-stained, hard, with striated boulders of volcanic rocks as much as 5 feet in diameter apparently reworked from a moraine to the south	5
4	Sandstone, gray, evenly bedded to cross bedded, slightly lithified (near top of right center in fig. 22)	8
3	Conglomerate, dark brown, with boulders of basalt and rhyolite in a course-grained ferruginous sand matrix; stratified in horizontal layers, in contrast with underlying unit	2
2	Pumice conglomerate composed of white fibrous, light-weight, rounded pumice pebbles up to 1-1/2 inches in diameter in a matrix of dark gray and clear shards, black obsidian, and clear angular quartz and feldspar grains; foreset beds strike N.40°E., dip N.25°W.	5
1	Sandstone, blue-gray, medium- to coarse-grained; grades up to overlying unit; base below creek levels	5+
Total thickness of measured part of Pelican Valley sequence		40+

Embedded in the glassy finer grained matrix of the pumice pebbles are numerous clear crystals of quartz and feldspar. The pebbles float in water; they are so abundant, yet so fragile that it is unlikely they could have survived transport over long distances.

At locality 13, about 300 feet upstream from the old Pelican Creek Service Road bridge, a bluish-gray shard-bearing claystone (Glacier Peak? ash) and siltstone 6 feet thick is

Figure 19. View southeast across Pelican Creek (not visible; between horses and cliff), 1,500 feet southwest of locality 12, showing 100 feet of white silt and lesser amount of sand in Pelican Valley sequence. Figure 20 shows detail in upper cliff at far left.

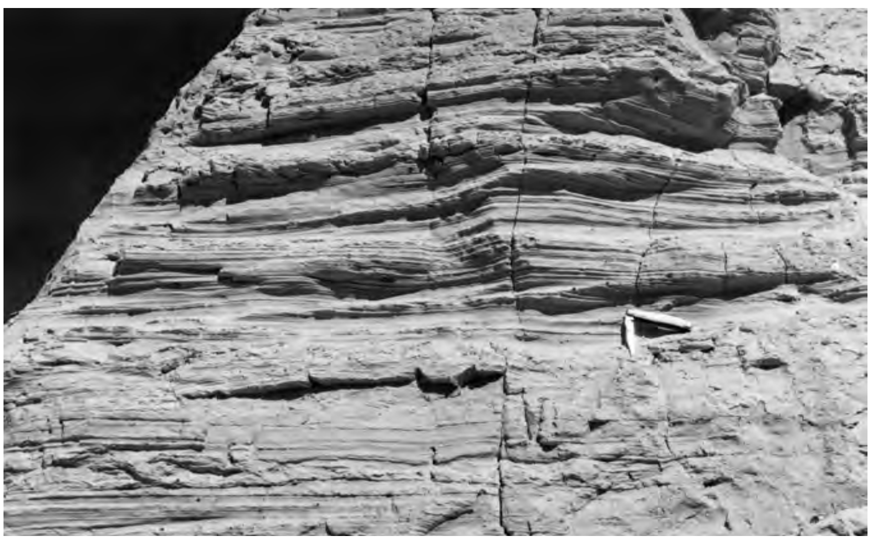


Figure 20. Bedding in white siltstone cliff of Pelican Valley sequence shown in Figure 19, 1,500 feet southwest of locality 12.

Figure 21. Upper part of Pelican Valley sequence at locality 11 on east side of Astringent Creek. This is site of detailed measured section and ^{14}C date of 7,500 years. Conspicuous units are shown by number used in section; horizons of wood collected for ^{14}C dating are indicated.

overlain by 2 feet of bluish-gray and brown, fine-grained, tuffaceous, soft sandstone. This locality is notable in three respects: the abundance of pollen, the unusual petrography of the rock, and the southwest dip of the beds. The rock is a pyroxene andesite tuff with abundant ortho- and clinopyroxene and andesine. This contrasts sharply with the felsic nature of the debris a mile upstream at the pumice pebble locality. The beds along a 50-foot outcrop strike N.60°W., and dip 9°SW. It is not known if this is an initial dip or the result of slumping or post-Pelican Valley warping. These beds are overlain by a brown hard conglomerate locally known as "beach rock" (fig. 23). [*For further discussion, see Foreword and About the Author, this volume.*]

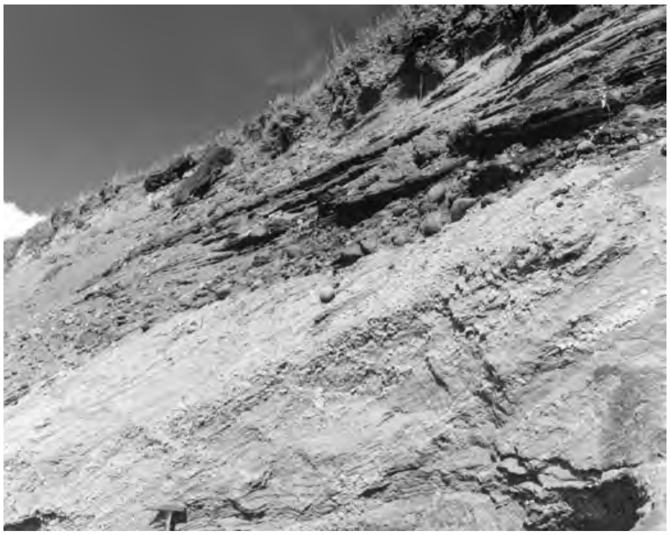


Figure 22. White pumice pebble conglomerate with steep foreset beds overlain by gravel and sand, all in upper part of Pelican Valley sequence at locality 14. Pumice pebbles will float on water.

Figure 23. Cliff of "beach rock" along north shore of Mary Bay, Yellowstone Lake. Rock is a conglomerate of silicified claystone, siltstone, sandstone, and volcanic rock fragments in a siliceous matrix. Black cap in foreground shows scale.

The Pelican Valley sequence laps across the lower part of the Astringent Creek Sand that forms the bordering hills to the north and northeast and buries part of the morainal deposits that lie between Pelican Valley and Yellowstone Lake. At locality 12 (fig. 24), the relations of rhyolite tuff, glacial deposits, and the Pelican Valley sequence are well exposed. At the base is 50 feet of white rhyolitic crystal tuff with abundant bipyramidal quartz crystals and obsidian fragments. This is overlain by 15 feet of till, chiefly of rounded to angular, striated erratics up to 3 feet in diameter, of rhyolite, basalt, and coarse porphyry with white euhedral phenocrysts. The top of the till has been reworked into the white velvety silt in the basal part of the Pelican Valley sequence. Above this contact is 50 feet or more of white silt. Sparse lag boulders of locally derived volcanic rocks are on the silt, but no evidence was found that these are of glacial origin.

Spectrographic analyses of the clays and silts in the Pelican Valley sequence are shown in figure 4. The composition is so similar to that of the older Hayden Valley sequence that it suggests the possibility of the younger deposit having been derived in part from the Hayden Valley or a lateral equivalent to the southwest. Transport would probably have been by wind. Of all the sedimentary units (excluding the Turbid Lake), the Pelican Valley sequence is highest in barium, strontium, and gallium, but does not have any record of low values in other trace elements. An especially interesting fact, the significance of which is not known, is that a spectrographic analysis of pumice pebbles in unit 2 of the measured section at locality 14 (fig. 22) shows almost the same composition as that of the silts and clays. A few elements in the pumice are at the top or bottom of the range for the silts and clays, but most fall within the span and none have excessively high or low concentrations. This composition pattern is in marked contrast with that of the similar-appearing pumiceous beds in the Turbid Lake sequence (fig. 4).

A rock analysis (D123124, table 1) of common oxides in the pumice pebbles in the Pelican Valley sequence shows slightly higher SiO_2 and K_2O and lower Al_2O_3, Fe_2O_3, and TiO_2 as compared with those for the clays and silts. With respect to clays and silts in other sequences, the Al_2O_3 content of those in the Pelican Valley sequence is high consistently, with values as high as 19.7 percent.

The age of the wood-bearing strata at locality 11 (fig. 21) has been determined by ^{14}C as 7,550±350 years B.P. (Meyer Rubin, written commun., 1965; USGS Lab No. W-1684). Diatom assemblages are listed in table 2. The quote of Lohman and Andrews regarding age and environment of deposition cited in connection with the Hayden Valley sequence applies equally well to the Pelican Valley.

Identification and evaluation of the following scant pollen collections (locations shown on fig. 3) were made by E.B. Leopold (written commun., 1960):

	L-5835	Loc. 13
Pinus		16
Populus	1	
Picea cf. *pungens*		3
Ephedra	1	
cf. *Tsuga*		1
cf. *Quercus*		1
Alnus	1	
cf. *Salix*	1	
Compositae undet.	14	6
Artemisia (primary)	62	89
Artemisia (secondary?)		2
Chenopodiaceae undet.	5	6
dicots undet.	15	6
monocots undet.	3	1
Umbelliferae		1
Selaginella cf. *densa*		13
Polypodiaceae(?)		
fern spores undet.	2	1
Redeposited:	4	
Foveotriletes	1	
Monosulcites	1	2
cf. *Quercus*	2	2
Total grains counted	111	111

> "Both assemblages are primarily composed of *Artemisia* pollen and neither contains much tree pollen. Both contain small amounts of rebedded pollen which may be of Mesozoic origin (*Foveotriletes, Monosulcites*) and perhaps some reworked Upper [sic] Cenozoic material (dark brown grains of *Artemisia* and cf. *Quercus*). The virtual lack of trees among the primary pollen assemblage and the excellent representation of low growing forms leaves the question of environmental interpretation unanswered. We can suppose that extensive sagebrush in the absence of trees might be attributed to a drier-than-present environment, but whether the environment was cold and dry or warm and dry, cannot be inferred from the present assemblage."

The occurrence in unit 2, locality 14, of pumice pebble conglomerate (fig. 22) composed of very fragile unaltered fragments that could not have been transported far in addition to the presence of shard beds at the top of the section at the site of figures 19 and 20 (analysis D123132, table 1; spectrographic analysis incorporated in figure 4) may indicate a Holocene episode of felsic volcanism. As mentioned in connection with the Turbid Lake sequence, the composition of the volcanic debris is not the same as that on the Pitchstone Plateau.

Other Deposits

Deposits at two localities outside the map area (fig. 3) bear on the late Pleistocene history of the region because they (1) are dated by ^{14}C, (2) contain abundant diatoms, and (3) are at the bottoms of steep-sided canyons of major rivers.

Gibbon Canyon Deposits

A local accumulation of stratified white pumiceous clay and sand with black carbonaceous partings is present near the bottom of the narrow steep-walled Gibbon Canyon 7 miles west of the geologic map (at the "R" on Gibbon River, fig. 2). The locality is 800 feet upstream from a right-angle bend in the canyon and along the highway, 1.4 miles south of Beryl Spring and 2.3 miles north of Gibbon Falls. It is exposed in a 20-foot cut on the east side of the highway. The finer grained strata consist of several layers of white, thin-bedded clay, silt, and ash containing mats of white, partly silicified stems of rushes and other plants and abundant black carbonized twigs and stems. The coarse-grained beds are white to gray, soft sands and gravels composed of black and red, rounded to angular fragments of obsidian, rhyolite, quartz, and white, fibrous pumice and large and small, smoky gray, angular, fresh shards. The carbonaceous beds contain abundant diatoms (table 2) and have a ^{14}C age of 9,440±300 years B.P. (Meyer Rubin, written commun., 1964; USGS Lab No. W-1364).

Figure 24. View north across Pelican Creek one-fourth mile east of Vermilion Springs at locality 12. Indicated are 50 feet of white clayey rhyolite crystal tuff (A), 15 feet of till (B), 50 feet of light gray silt in Pelican Valley sequence (C).

Bannock Ford Deposits

A section of about 30 feet of beds is preserved in the bottom of Yellowstone Canyon, 3,000 feet east-northeast of Tower Falls, on the east side of the Yellowstone River, at Bannock Ford, Tower Junction quadrangle, about 8 miles north of the geologic map (fig. 3). They comprise a local sequence that is much younger than, and was deposited against the base of Howard's 400-foot section of Pleistocene deposits in Alden Valley (Howard, 1937, his fig. 27).

Extending up from the river level is 12 feet of bedded, silty, gray-green clay containing some pebbles and carbonaceous debris. Diatom collection 5639 (table 2), which yielded 58 forms, came from the upper part of this unit. Overlying it is 10 feet of bedded gray sand containing a vegetal trash and wood horizon 3 feet above the base. Some wood fragments are more than 1 inch thick and 1 foot long. They gave a ^{14}C age of 3,750±300 years (Meyer Rubin, written commun., 1964; USGS Lab No. W-1367). The sand is overlain by 8 feet of cobble conglomerate of volcanic rock fragments overlain by sand. The Bannock Ford deposits are especially significant because they record one of the latest events in the complex history of the Yellowstone Canyon.

"Beach Rock"

"Beach rock" is the name used locally to describe a brown, hard, ferruginous conglomerate that crops out in ledges along Pelican Creek and forms a widespread slope cover along the southern part of Pelican Valley. [*See Foreword and About the Author, this chapter.*] It also is present in many places along and near the shore of Yellowstone Lake (fig. 23). "Beach rock" is of several ages ranging from that which is older than the last glaciation to deposits now being formed near thermal areas. Much of it apparently accumulated along the ancient beaches of Yellowstone Lake as the water level rose and fell. This would account for its position extending from the present level of Pelican Creek near locality 13 to the top of the divide directly west of Turbid Lake and its presence at water level of Yellowstone Lake as well as on top of wave-cut cliffs 50 feet or more above the lake. It is one of the common rock types in local morainal debris.

Deposits of "beach rock" are commonly very irregular and 5–10 feet or more in thickness. They consist of rounded to angular poorly to well oriented fragments of volcanic rocks and silicified shale chips tightly cemented with silica and iron oxide. They are porous and contain little unaltered clayey matrix.

Glacial Deposits

Glacial deposits are present in many parts of the map area (fig. 3). Their relation to various Pleistocene sedimentary sequences is important to the present study but other aspects are beyond the scope of this paper. Pierce (1979) and Pierce and Morgan (1992) summarized the regional geologic history.

Tectonic Significance of Pleistocene Strata

The foregoing discussion of Pleistocene stratigraphic units demonstrates the complexity of depositional history involving the northern part of ancestral Yellowstone Lake during this epoch. Inasmuch as 5 of the 7 described sequences accumulated in or near the northern part of the ancestral lake basin, they give us some fragmentary clues as to the origin, extent, and tectonic history of this section of the Park, as well as to the age of its most conspicuous feature, the Grand Canyon of the Yellowstone River. Several suggestions regarding the relations of the stratigraphic sequences to cutting of the Yellowstone Canyon are presented here.

The Pelican Valley sequence apparently accumulated in the northeastern arm of Yellowstone Lake about 7,500 years ago and "drowned" older moraines. The lineations in the moraines, the relation of the Pelican Valley sequence to them, and the fine-grained nature and elevation of the westernmost, and topographically lowest part of the sediments make the possibility remote that they were deposited in a perched lake trapped against an ice cap in the Yellowstone Lake basin. These sediments have a close lithologic and chemical similarity to the Hayden Valley sequence. This suggests that some of the Pelican Valley deposits may have been derived by wind erosion from the uplifted and newly-exposed Hayden Valley sequence. Volcanism somewhere in the immediate vicinity contributed fresh felsic pumice pebbles and shard deposits.

The most recent event in the study area was the rapid rise of the land northeast of Yellowstone Lake, in and near the vicinity of Sour Creek Dome, one of two resurgent domes in the 0.640-Ma Yellowstone caldera. Deformation and faulting associated with the Yellowstone caldera (see Pierce, Cannon and others, this volume) have uplifted the lacustrine and fluvial sediments of the Mudkettle sequence along the abandoned postulated northern outlet channel of ancestral Yellowstone Lake, 10–15 miles north of the present lake and east of the Upper Basin Member of the Plateau Rhyolite, nearly 700 feet above the present lake level. The lacustrine strata of the Pelican Valley sequence at locality 12 radiometrically dated at 7,500 years old, in the Pelican arm of ancestral Yellowstone Lake, are now 150 feet above the lake. Inasmuch as no other such broad areas of recently emerged correlative sediments are known elsewhere along the shore of the lake, it is assumed that this emergence is not the result of lowering of the general lake level but that Pelican Valley was actually tectonically uplifted at a rate averaging 1 foot in 50 years.

The anomalous downstream terminal course of Pelican Creek likewise suggests uplift northeast of Yellowstone Lake. For several miles the creek flows westward along Pelican Valley and then, rather than continuing an unobstructed course west into the Yellowstone River, it makes an abrupt right-angle bend and flows south into the lake (fig. 3). The creek is incised in bedrock (fig. 24) upstream from the change in course and downstream is on a broad flood plain.

Spires and Craters in Yellowstone Lake

In 1997, David Lovalvo of Eastern Oceanics, Inc. discovered a siliceous-spire field in the northern basin of Yellowstone Lake. Subsequent high-resolution mapping of this area between 1999 and 2004 by the U. S. Geological Survey show 12–18 conical structures up to 26 feet tall in crater-like depressions (see discussion in Morgan and others, this volume; Shanks and others, this volume). The spires are hydrothermal in origin, occur in the shallow photic zone less than ~45 feet in depth, and are limited in their distribution in the lake, identified only in the Bridge Bay area. Subsequent examination and analyses of several samples reveal the spires are composed of nearly pure silica, much of it taken up by bacteria and diatoms (Morgan and others, 2003; Shanks and others, this volume). While they are present in the lake, they are not common, are geologically young (~11,000 years old), and are relatively fragile. These are discussed briefly here because they are or may be related to Pleistocene lakes.

It would be worthwhile to compare the diatom assemblages in the spires with the 180 forms listed by areas in table 2, especially in terms of climate and environment and trace element content.

Conclusions

Seven sequences of lacustrine and fluvial strata were deposited in shallow topographic depressions of tectonic, volcanic, and (or) glacial origin, west, north, and northeast of the northern part of Yellowstone Lake. Our study was limited in scope to a reconnaissance overview of the lithology, geochemistry, and microfossils in these strata. It became apparent that these sequences were complexly interrelated with several volcanic units, and that, if the study was expanded, it could help fill the gaps in the complex Quaternary history of lake development in the Yellowstone–Jackson Hole region. In addition, the topographic position of some of the lacustrine and fluvial strata had both tectonic and geomorphic significance relative to the time of cutting of the Yellowstone Canyon. The interpretations presented in our reconnaissance report must be considered simply as a guide to, and suggestions for, more detailed work on all aspects of this study of the lacustrine and fluvial strata.

Currently data are not available regarding the thickness of deposits in Hayden and Pelican Valleys, nor their extent under the adjacent part of Yellowstone Lake. Similarly, data are not available on how these deposits may be hydrothermally altered or what their relation might be to the spires and explosion craters on the lake floor. Future, more detailed investigations on the fluvial and lacustrine sediments in the areas now identified as ancestral Yellowstone Lake are warranted and hold great promise in further unraveling the complex Holocene tectonic and depositional history of the Yellowstone caldera.

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