STATE OF OREGON
DEPARTMENT OF GEOLOGY AND MINERAL INDUSTRIES
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SPECIAL PAPER 7

PLUVIAL FORT ROCK LAKE, LAKE COUNTY, OREGON

1979

STATE OF OREGON

DEPARTMENT OF GEOLOGY AND MINERAL INDUSTRIES

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SPECIAL PAPER 7

PLUVIAL

FORT ROCK LAKE,

LAKE COUNTY, OREGON

Ira S. Allison

1979

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NOTICE

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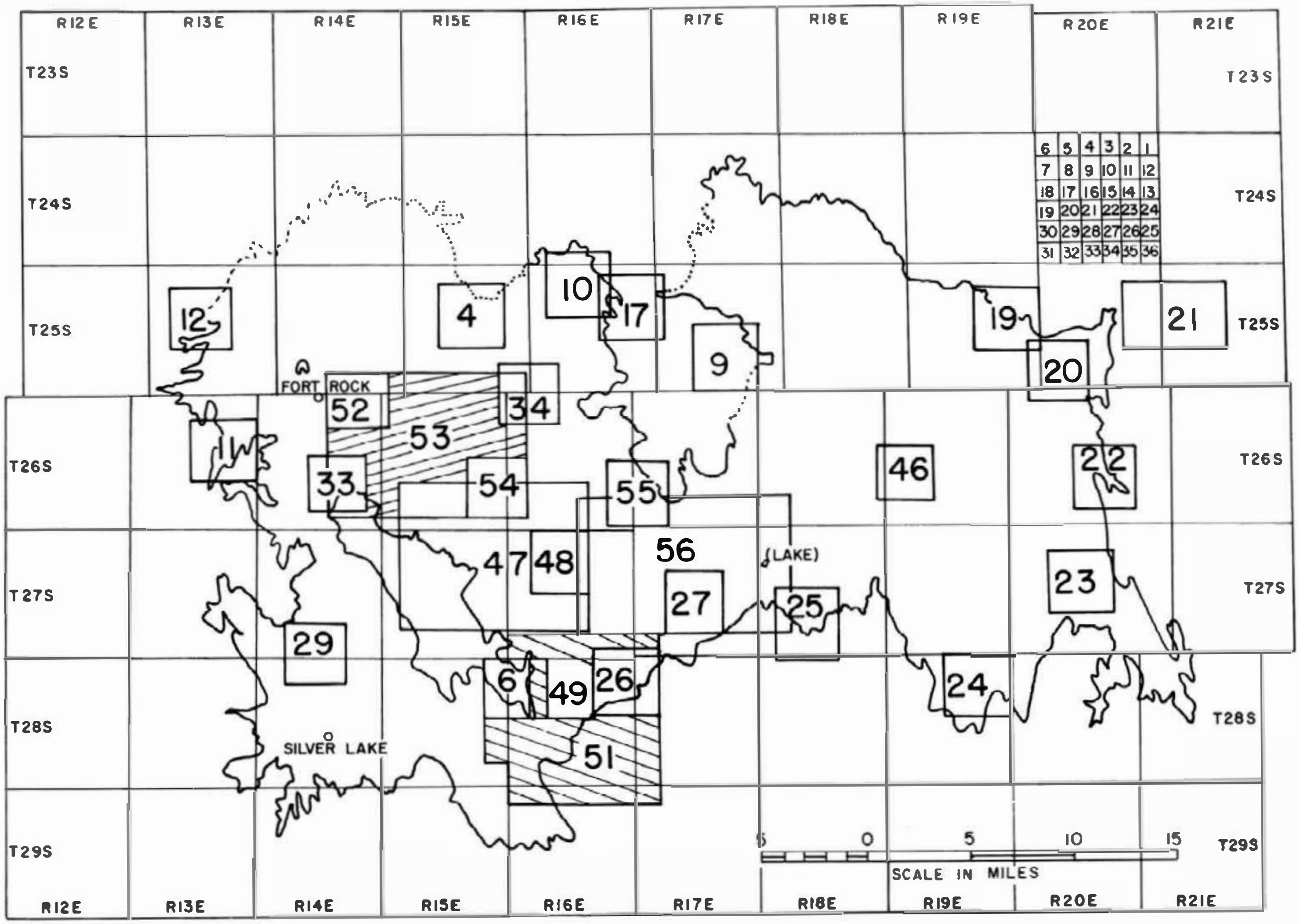

Map showing locations of areas covered by aerial photographs in correspondingly numbered figures.

PLUVIAL FORT ROCK LAKE

INTRODUCTION

Fort Rock Lake is an extinct pluvial lake that formerly occupied the complex Fort Rock-Silver Lake-Christmas Lake-Fossil Lake basin in northwestern Lake County, Oregon (Fig. 1). Its water scribed stillstand markings along its shores, developed beach ridges where suitable materials were available, and accumulated sediments over the floor of the basin. At its maximum stage the lake was more than 200 feet deep. The lake sediments at Fossil Lake in the eastern part of the basin have yielded abundant fossils of mammals, birds, fishes, and fresh-water mollusks. These sediments have been described separately (Allison, 1966a). Snail shells obtained about 10 feet below the top of the lake beds at Fossil Lake have a radiocarbon age of 29,000 years. The mammal bones come from a stratigraphic level a few feet lower in the section and so are older. Fort Rock Lake was terminated by evaporation probably about 10,000 years ago. It was first plotted by Russell (1884a, 1884b, 1905), and later by Waring (1908), Meinzer (1922), and Snyder (1964).

Name

Previous names for the lake were confusing. In the years soon after their discovery in 1876, the fossil bones, actually from the Fossil Lake area, were variously referred to Fossil Lake, Christmas Lake, Silver Lake, or the "Oregon desert" region near Silver Lake, but until 1939 no clear name had been applied to the former expanded lake. Meinzer (1922) referred to it as Silver and Christmas Lakes, and Brogan (1950) used the name Christmas Lake, but both names are duplications of modern features. Recognizing the need of a short convenient name for it, the present writer in 1939 began using the name Fort Rock Lake (Allison, 1940). Fort Rock itself (Fig. 2), standing well out in the middle of a large bay (herein called Fremont Bay) of the former lake, is a conspicuous wave-carved island remnant with wave-cut benches and grooves scribed against it, especially near the 4440-foot level. Multiple wave-cut cliffs and wave-deposited beaches, representing stillstands at both higher and lower levels, mark the former shores elsewhere. There is no modern lake of the same name. The hyphenated combination of Fort Rock-Silver Lake-Christmas Lake-Fossil Lake is awkward. Besides, the three lakes last mentioned are (or have been) modern lakes in depressions in the floor of the larger extinct lake, and so their use in reference to the previous large lake is unwarranted.

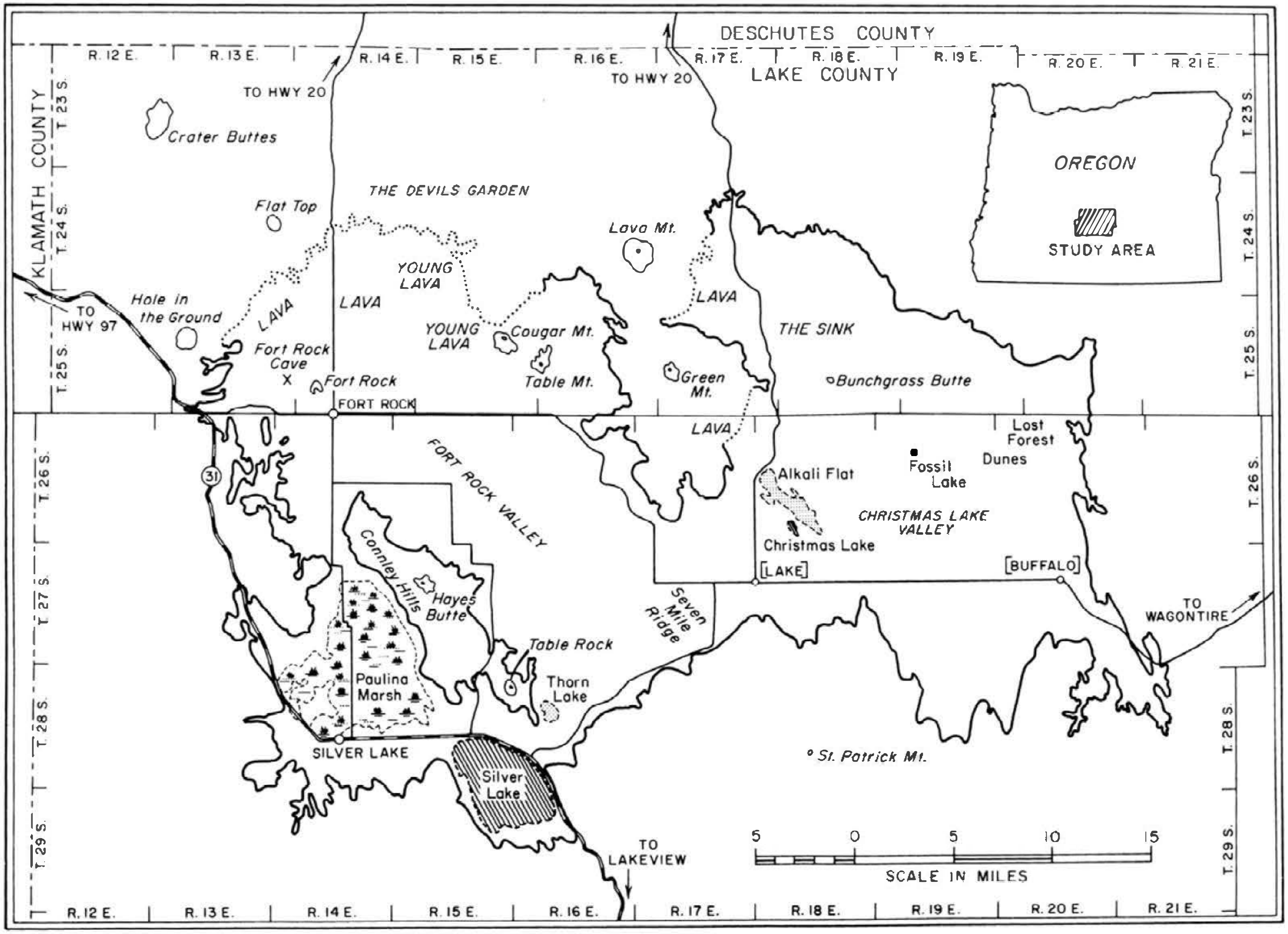

Figure 1. Map of the Fort Rock Lake Area.

GEOGRAPHY

The origin and history of Fort Rock Lake are necessarily related to the physiographic setting of the lake basin and the climate then prevailing. A climate of higher annual precipitation and cooler summers than those of the present was essential. So for a better appreciation of these factors, let us summarize the geomorphic position of the lake, the present climate, and the present vegetation.

Regional Setting

The Fort Rock Lake basin lies in the transition zone between the Basin and Range physiographic province on the south and the Harney High Lava Plains section of the Columbia Intermontane physiographic province on the north. The part of the Basin and Range province that extends into south-central Oregon is characterized by deep fault troughs, such as the basins of Summer Lake, Abert Lake, and Warner Valley, and by tilted fault-block mountains with precipitous rims, such as Winter Ridge, Abert Rim, and Steens Mountain. The Harney High Lava Plains area, adjoining the Great Basin on the north, has hundreds of faults also (Raisz, 1955), but the vertical displacement on most of them ranges from a few feet to a few tens of feet, or locally to a few hundred feet. So the dividing line between the two provinces was placed somewhat arbitrarily near the southern limits of the Fort Rock Lake basin (Allison, 1968). An alternative boundary is the Brothers Fault Zone situated farther north-northeast and trending N60°W (Lawrence, 1976). This puts Fort Rock Lake in the Basin and Range province.

The Harney High Lava Plains and the Fort Rock Lake basin are bordered on the west by the volcanic range of the High Cascades province, but the boundary is transitional, because many young volcanic cones stand well to the east of the Cascade divide. Of these outlying volcanic mountains, the chief one is Newberry Volcano, which borders Fort Rock Valley on the north.

Figure 2. Fort Rock, as seen from the south, a former wave-cut island, whence the name Fort Rock Lake

Local Setting

Fort Rock Lake, the most northwesterly of the large Pleistocene pluvial lakes in south central Oregon (Meinzer, 1922), occupied an irregular basin which extends about 40 miles east-west and about 30 miles north-south (Fig. 1). Its outer boundaries originated by faulting.

The lake basin has two main natural subdivisions, Fort Rock Valley on the west and Christmas Lake Valley on the east. As the Fort Rock Valley portion of the basin is open eastward to Christmas Lake Valley, the term Fort Rock Lake will readily be understood to include the water of the whole basin and not merely Fort Rock Valley. A former bay in the northwest part of Fort Rock Valley is designated Fremont Bay of Fort Rock Lake, named for the former postoffice site near the western shore of the lake.

The main body of Fort Rock Lake was connected with another bay in the modern Paulina Marsh-Silver Lake area by way of a strait southeast of Table Rock. For convenience this bay is here called Paulina Bay. It is separated from Fort Rock Valley by the Connley Hills, a ridge which extends about 12 miles northwesterly from Table Rock, and by unnamed volcanic hills farther west. Another bay occupied a lowland locally known as The Sink at the northeast extremity of Fort Rock Lake. An unnamed fourth bay occupied a triangular recess about 7 miles deep and 10 miles wide (on its north end) in the extreme southeastern part of the lake.

Young lavas encroach upon the Fort Rock Lake basin north of Fort Rock, at the Devils Garden near Cougar Mountain, and west of The Sink.

Climate

The present climate of the area is characterized by low but variable precipitation, low humidity, and large daily and annual ranges of temperature. According to the Climatic Summary, National Weather Service, and Climatological Data, U.S. Environmental Science Service Administration, a volunteer observing station was maintained at former Lake P.O. (NW corner Sec. 18, T. 27 S., R. 18 E.) from 1918 to 1945; an intermittent one at Silver Lake village, 1897 to 1924, and re-opened recently at the Silver Lake Ranger Station; one at Fremont (formerly situated at E quarter-corner, Sec. 28, T. 25 S., R. 13 E., until 1958 and now a few miles southwesterly) from 1914 to date; and one at the Poplars Ranch in the NE 1/4 Sec. 4, T. 27 S., R. 15 E., from 1940 to 1965.

The rainfall on the west (Fremont, Poplars Ranch, Silver Lake) is slightly more than at Lake and Cliff, a former postoffice in the northeastern part of the Fort Rock Lake basin (Table 1). Most of the precipitation falls as snow in November, December, and January, or as rain in May and June.

Table 1. Annual Precipitation Data (in inches)

	Years	Mean	Minimum	Maximum
Cliff	9	9.62	7.03	11.15
Fort Rock[a]	5	9.19	7.71	9.81
Fremont	51	9.78	4.45	19.38
Lake	28	6.92	4.00	17.45
Poplars Ranch	26	10.68	5.15	17.18
Silver Lake[a]	27	10.83	6.99	15.82

a Incomplete records, Silver Lake, 1889-1915;
Fort Rock, 1910-1914; J.H. Whistler and J.H. Lewis (1915)

The temperature ranges are large and variable. Hot days in midsummer are succeeded by cool nights, and hot summers are followed by cold winters. Extremes of temperature recorded at both Lake and Cliff were -40° and 107°F. The mean January temperature is about 26°, the July mean about 65°, the mean annual minimum -17° the mean annual maximum 102°, and the mean annual temperature about 45°F. Frost occurs nearly every month of the year. The ground elevation of more than 4300 feet above sea level is a factor. Wind records are not available.

These data on annual precipitation and summer temperatures clearly contrast with those needed in Pleistocene time to form and maintain Fort Rock Lake.

Vegetation

The vegetation in and around the Fort Rock Lake basin is largely dependent upon the amount of rainfall and subordinately upon the character of the soil. The lowland areas having less than 10 inches of annual rainfall support a modest growth of sagebrush, rabbit brush, bunch grass, salt grass, greasewood (in alkaline areas), and a number of short-season herbaceous plants. On high ground along the extreme west, where rainfall exceeds 15 inches, are open stands of western yellow pine. Other high places, such as Green Mountain (Fig. 3), Cougar Mountain (Fig. 4), and Connley Hills (Fig. 1), bear sparse stands of juniper trees. A tract of wind-blown sand on the eastern rim of the Fort Rock Lake basin has a disjunct stand of western yellow pine, the "Lost Forest" (Berry, 1963; Fig. 5). A similar band of wind-blown pumice sand on the faulted eastern boundary of the basin north of Buffalo (site of a former well at the common corner of Secs. 8, 9, 16, and 17, T. 27 S., R. 20 E.) also has enough moisture to support juniper trees. Rank sagebrush occurs similarly on some water-retaining beach ridges elsewhere.

Figure 3. Green Mountain, a juniper-covered basaltic lava cone on the middle north shore of Fort Rock Lake

Figure 4. Cougar Mountain and vicinity. The mountain (upper right), rhyolitic in composition, has wave-cut cliffs and caves (occupied by early man) on its west and south sides. A southward extension of the Devils Garden basaltic lava later flowed onto the wave-washed rocky lake plain

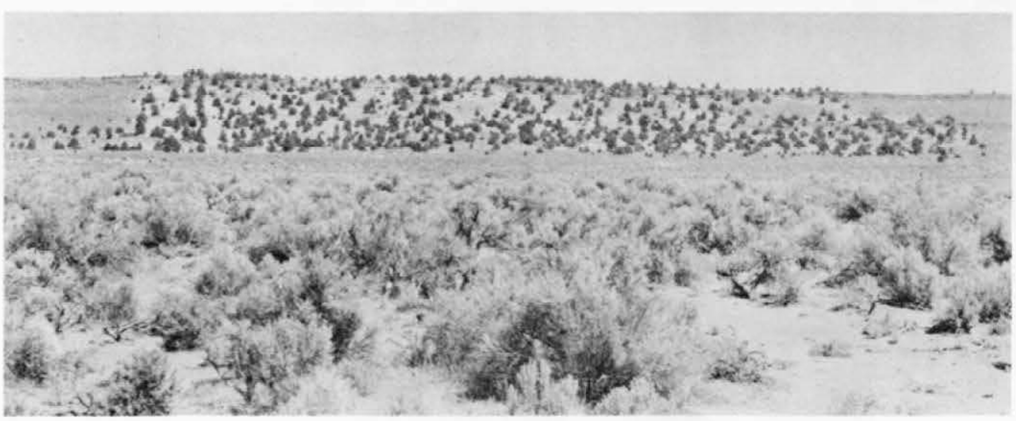

Figure 5. Juniper forest on pumice sand. The sand was blown off the lake floor (foreground) and up the eastern fault-scarp margin of the Fort Rock Lake basin

PRESENT STUDY

The writer's interest in the Fort Rock Lake area was first aroused in the 1930s by Dr. Earl L. Packard, then head of the Department of Geology at Oregon State University, who was puzzled by the strange occurrence of supposedly old fossils at Fossil Lake found at or near the surface of the nearly flat floor of an open basin. Although the paleontological evidence seemed to indicate an early Pleistocene age of the fossils, the geological setting appeared to favor a late Pleistocene age of the fossil-bearing deposits. This apparent discrepancy required study.

History

In the summers of 1939 and preceding years, Dr. Luther S. Cressman, professor of anthropology at the University of Oregon, and his students were engaged in archeological studies at Catlow Cave, Paisley Caves, Fort Rock Cave, and other prehistoric habitation sites of early man in south central Oregon. The cave sites were situated along the wave-cut shores of former pluvial lakes, so an integration of the archeological findings with the geological history of the lakes required more information about the lakes than was then available. The dating of the lakes and their deposits was needed to establish the time relations of the wave-cut caves and their enclosed archeological materials. Dr. Howel Williams, vulcanologist of the University of California (Berkeley), had already identified an unbroken layer of pumice sand separating two levels of human occupation of the Paisley Caves as of Mount Mazama (predecessor of Crater Lake) origin, so the Crater Lake history was also involved.

Consequently, Dr. John C. Merriam, then president emeritus and research associate of the Carnegie Institution of Washington, who was greatly interested in the Fossil Lake problem, Crater Lake, and the studies of early man, asked me in 1939 to undertake an investigation of the Pleistocene pluvial lakes of south central Oregon as one phase of a cooperative research project. He also named a group of consultants, including Earl L. Packard (paleontologist), Chester Stock (vertebrate paleontologist), Ralph Chaney (paleobotanist), Warren D. Smith (geologist), John P. Buwalda (geologist), Luther S. Cressman (archeologist), Ernst Antevs (glacial geologist), Howel Williams (vulcanologist), and Daniel Axelrod (paleobotanist), to confer on the geological, paleontological, climatological, and archeological aspects of the studies in the area extending from Crater Lake on the west to Catlow Valley on the east.

Following a preliminary reconnaissance of the Fort Rock, Summer Lake, and Goose Lake basins, as well as Warner, Catlow, and Alvord Valleys, in 1939, my detailed field studies were devoted thereafter mainly to the Fort Rock and Summer Lake basins. The work ceased during World War II, but field and laboratory investigations have been conducted intermittently since 1946.

Previous geologic work and the geology and paleontology of the Fossil Lake area in the eastern part of the Fort Rock Lake basin were described earlier (Allison, 1966a). Forbes (1973) later mapped and classified the peripheral shore line features of Fort Rock Lake.

Acknowledgements

Part of the expenses of this study were met by the Carnegie Institution of Washington (via Dr. John C. Merriam) and by General Research funds of Oregon State University. Aid in the field was supplied by numerous students and by several local residents, particularly by the late M. S. Buchanan of Lake and Merritt Y. Parks of the Poplars Ranch. Luther S. Cressman, the late Stephen F. Bedwell, and Laurence R. Kittleman of the University of Oregon also were helpful in supplying data and in discussing mutual problems.

Dr. Harold E. Enlows, Professor of Geology, Oregon State University, is responsible

for the portions of this report treating the petrography, chemical analyses, and correlation of tephra deposits at Ana River in the Summer Lake basin and the identification of corresponding deposits in the Fort Rock Lake basin. Dr. Ray Wilcox, U. S. Geological Survey, Denver Federal Center, also kindly supplied useful petrographic data.

Special thanks are extended to Therese Belden for her skill in devising the layout and typing this report.

Maps and Aerial Photographs

The only pertinent maps available in 1939 were the quarter-inch-to-the-mile maps of the U. S. Forest Service. Fortunately, however, U. S. Coast and Geodetic Survey bench marks had been placed at frequent intervals along the Fremont Highway, along the road from Fort Rock to Silver Lake village, and along a line running from Silver Lake past the former site of Lake P. O. and thence northeasterly beyond the limits of the basin. Aerial photographs of all of northern Lake County were made for the Soil Conservation Service in 1939 and were available for use in the field from 1940 onward. High-altitude photographs of the area were made in 1953. The regional topographic relations of the area are shown on the Crescent, Oregon, sheet (NK 10-3) of the 1:250,000 map series of the U. S. Geological Survey issued in 1958 and on the landforms map of Oregon by Raisz (1955).

Paulina Marsh and its environs in the southwest part of the Fort Rock Lake basin are shown in great detail on the Silver Lake and Hager Mountain topographic maps (1966) of the 7.5-minute series on a scale of 1:24,000 and contour intervals of 10 and 20 feet respectively. Several fault scarps are recognizable on these maps.

Accuracy of Elevations

Much of the time during the first field seasons was used to run lines of levels from bench marks to various shore features, to Fossil Lake, and to certain deflation basins elsewhere. Plane table and telescopic alidade were used; the alidade was generally used as a level, even on fairly steep shore line profiles. At each setup the striding level was reversed and double readings to hundredths of feet were recorded. Fully or nearly identical readings were required. If the differences were only a few hundredths of a foot, the readings were averaged. In this way it was generally possible to limit vertical errors of closure of traverses to less than a foot. On one long 35-mile traverse the difference in elevation upon closure was only 2.18 feet. So the elevations given in this report are thought to be accurate within a foot or two.

GEOLOGIC SETTING

The geologic setting of any area includes its stratigraphy, structure, and geomorphology. In this instance, the geologic setting of Fort Rock Lake may be summarized by calling it a structural basin in a region of volcanic rocks cut by numerous faults. Fault scarps form most of the margin of the basin.

Stratigraphy

The Fort Rock Lake basin lies within an area where nearly all the solid rocks are Cenozoic volcanic products. The stratigraphy has not been established in detail. A few townships of the area between Fort Rock and Silver Lake are included within the eastern border of the generalized geologic map of Oregon west of the 121st meridian, issued by the U. S. Geological Survey on a scale of 1:500,000 (Peck, 1961). Hampton (1964, Plate 1) gave local names to some of the stratigraphic units in or near the Fort Rock Lake basin. Part of the area near Silver Lake village is included on a reconnaissance map of eastern Klamath and western Lake Counties by Peterson and McIntyre (1970). Walker (1973a) in the area south of the Fort Rock Lake basin and east of Summer Lake distinguished four categories of bedrock: (1) Late Miocene(?) and early Pliocene basalt, (2) Pliocene tuffs, tuffaceous sandstone and siltstone, lapilli tuff, and tuff breccia, (3) Pliocene olivine basalt, and (4) patches of Tertiary and Quaternary volcanic rocks. Maps by Walker, Peterson, and Greene (1967) and Walker (1973a) supply further information. A generalized stratigraphic succession of units shown on Walker's 1973 map is listed in Table 2.

Table 2. Stratigraphic Units and Representative Areas
(After Walker, 1973)

Qd	Quaternary dune sand (Fossil Lake-Lost Forest area)
Qs	Quaternary lacustrine sedimentary rocks (lake flat and borders)
Qb	Quaternary basalt flows (Green Mountain)
QTb	Basalt (bench south of Cougar Mountain)
Tvs	Tertiary siliceous vent rocks (Cougar Mountain)
Tvm	Tertiary vent and near vent mafic rocks (Hayes Butte)
Ts	Tertiary tuffaceous sedimentary rocks and tuffs (Seven Mile Ridge)
Tob	Tertiary (Pliocene?) olivine basalt and andesite (much of the south border of the Fort Rock Lake basin)

Especially noteworthy rocks in or near the Fort Rock Lake basin are certain palagonitic tuffs and volcanic breccias, as in Fort Rock itself, in Seven Mile Ridge, in the benches near Table Rock (Fig. 6) at the southeast end of the Connley Hills, in part of the eastern rim of the basin, and in a few rocky knobs that protrude above the lake flat elsewhere. Much of the breccia has the form of tuff rings which resulted from under-water eruptions (Peterson and Grog, 1963; Heiken, 1971).

Tuffs and basaltic lava flows, probably of Pliocene age, make up the western border of the basin. Hayes Butte in the Connley Hills is a basaltic lava cone within the basin (Fig. 7). The south, east, and northeast sides of the Fort Rock Lake basin are composed almost entirely of basaltic lava flows with only local interflow sediments or volcanic breccias. Basalt flows of the Green Mountain lava cone (Fig. 3), probably Pliocene in age, make up the basin rim in T. 26 S., R. 16 and 17 E., and basalt supposedly Pliocene or early Pleistocene in age appears in the fault blocks south and west of Cougar Mountain also.

The youngest rocks in the area include: (1) lake sediments, (2) late Pleistocene or

Figure 6. Table Rock and vicinity. The Connley Hills ridge capped by this mesa (upper left) is surrounded by wave-eroded cliffs (as seen at middle left). Part of the Thorn Lake basin (a deflation product) is at the southeast corner

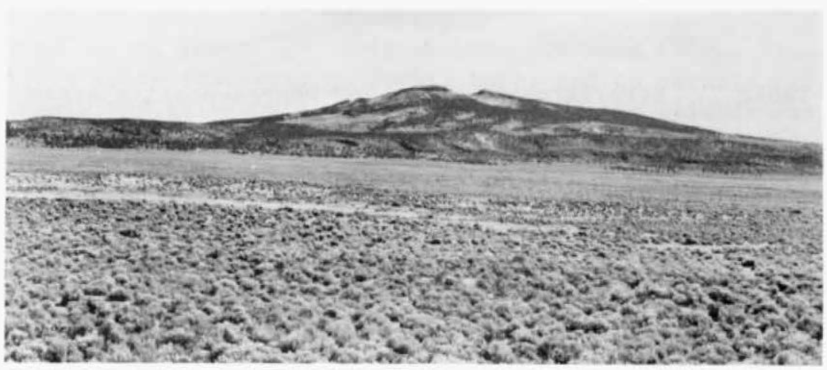

Figure 7. Volcanic Hayes Butte on Connley Hills ridge, as seen from east

Recent basalt flows north of Fort Rock, (3) Recent lavas of the Devils Garden lava field which extends into the basin west of Cougar Mountain (Fig. 4), (4) Lava Mountain (Fig. 8), which covers about 40 square miles north of Green Mountain, (5) Recent lavas and four small aligned cinder cones (Fig. 9) on the southeast slope of Green Mountain (Peterson and Groh, 1964), and (6) surficial pumice and Recent sediments, mainly wind-blown sand. Descriptions of these deposits, insofar as they are pertinent, are given at appropriate places on subsequent pages of this report.

Structure

The structure of the rocks of the Fort Rock Lake basin is partly constructional, as in the several lava cones and tuff rings, and partly deformational, owing to extensive regional faulting (Fig. 10). The region is disrupted by hundreds of high-angle faults with vertical displacements ranging from a few feet to hundreds of feet. The Fort Rock

Figure 8. Lava Mountain, a basaltic lava cone covering an entire township north of the Fort Rock Lake basin

Figure 9. Recent lava flows and three (of four) aligned cinder cones. The northwest-southeast lines (left and top) are low fault scarps

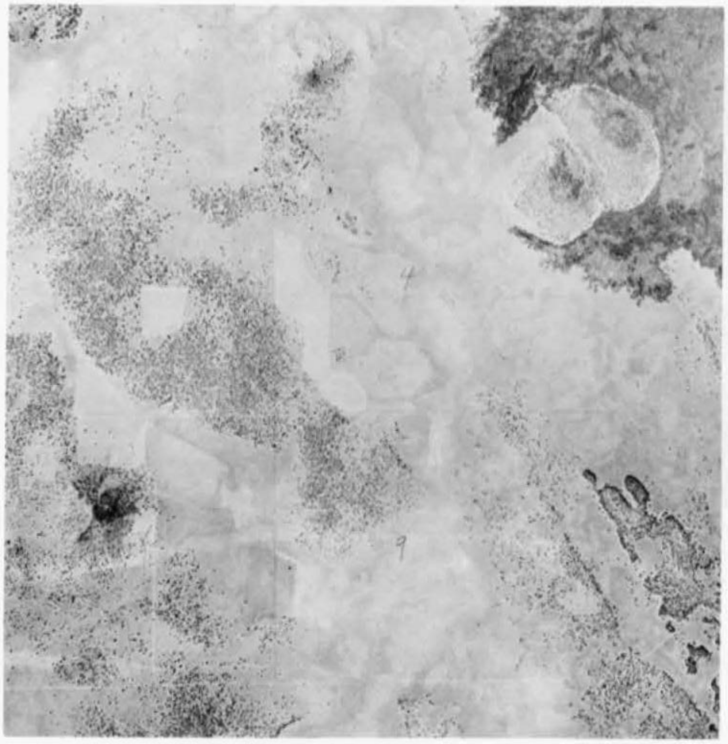

Figure 10. Minor fault scarps and young lava. One fault (northeast corner) split a previous volcanic cone and lowered the southwest side, on which later lava spread encircling tongues. The dark specks on high ground are juniper trees

Lake basin itself is of multiple fault-block origin. It lies south of the northwest end of the Brothers Fault Zone described by Higgins and Waters (1967), Higgins (1973), Walker and others (1974), and Lawrence (1976).

Scarps from these faults are conspicuous features of the landscape along the western, southern, and eastern parts of the basin, especially across T. 26 S., Ranges 16 to 20E., where the blocks are obliquely tilted. Many of the faults strike north-northwesterly or north-northeasterly in a crisscross pattern (Allison, 1949; Higgins, 1973), so in places the rocks are broken by two sets of faults into rhombic or diamond-shaped blocks (Fig. 11).

Faulting in the area between the Fort Rock Lake basin and the Summer Lake basin was studied by Donath (1958, 1962), who recognized a discrepancy between the rhombic pattern, which suggests strike-slip movement on conjugate shears, and the normal-fault scarps, which seem to lack any strike-slip component. He concluded that the high-angle normal faults may have followed fractures formed during an earlier deformation. Trauger (1958) also recognized the rhombic wrench-fault pattern, but he too considered the faults to be normal faults. Pease (1969) in a study of a comparable area in northeastern California attributed the normal faults to dynamic tension from deep-seated lateral shear. Walker (1969) conceived the normal faults to be an adjustment of surface and near-surface volcanic and tuffaceous sedimentary rocks to lateral displacement along a "deeply buried fault." He later (1973b) concluded that the crustal deformation that formed a "reticulate pattern of normal faults, broad warps, and areas of local crustal collapse" probably resulted from "deep-seated lateral shear and east-west crustal extension" related to plate tectonics.

Lawrence (1976) distinguishes the Brothers and other similar en echelon fault zones of right-lateral strike-slip from the normal faults in the blocks between these zones, and attributes the faults in the major zones to shear and the normal faults to east-west extension. The interaction of these movements caused the rhombic fracturing.

The association of shear and extension (Thompson and Burke, 1972) seems reasonable in the light of recently discerned crustal plate movements (Atwater, 1970; Christiansen and Lipman, 1972). When in its westward course the North American continental plate met the East Pacific Rise, the San Andreas rift began in California, and related tectonic movements and vulcanism occurred in the Great Basin.

Figure 11. Pattern of intersecting faults, southwest of Fort Rock. The area is about 3 by 3 miles. Clear angular patches are former homesteads

As the precise ages of the faulted lavas are not known, the exact age of the faulting is also uncertain. The principal movement probably took place in late Pliocene or early Pleistocene time, but minor displacements may have occurred intermittently later, though the shore lines within the Fort Rock Lake basin seem to have been disturbed very little, if any. One northeast-striking fault (Fig. 12), downthrown on the southeast, does cut the western edge of the late Pleistocene or Recent lava field a few miles east-northeast from Hole-in-the-Ground, and other faults occur elsewhere in this lava field. The Recent lavas of the Devils Garden are not known to be faulted.

Additional details concerning the stratigraphy, structure, and geomorphology, when relevant, are supplied in subsequent sections of this report.

Figure 12. Faulted northwestern boundary of Fort Rock Lake basin. The pine tree-covered lava plain (northwest corner) is separated from the lake basin by a fault, which continues northeasterly into lavas covered with Mount Mazama pumice. These lavas extend almost to Fort Rock

SHORE FEATURES OF FORT ROCK LAKE

Most of the rocks accessible to wave work in the Fort Rock Lake basin were very resistant to wave attack, and so wave-formed features were poorly developed along extensive stretches of the former shores. Here and there, however, relatively weak solid rock or a ready supply of previously loosened surficial material exposed to waves of long fetch permitted wave-cut cliffs, terraces, and grooves to form, or wave-built beaches and spits to be built. These will be described in clockwise order about the margin of the basin, beginning with Fort Rock and former Fremont Bay.

On Fort Rock

Fort Rock (Fig. 2) is a horseshoe-shaped residual mass of volcanic tuff and breccia, situated in the SW 1/4 Sec. 29, T. 25 S., R. 14 E. Its open side faces south-southeast. It is about 2,500 feet long along a transverse axis, and a little more than 200 feet high. The inside of the horseshoe and the outer rim are flanked with talus and other products of disintegration, but only to a moderate height. The upper part of the outer wall rises nearly vertically, whereas the inner wall can be climbed without much difficulty.

Waves on Fort Rock Lake carved benches and grooved nips on each of the tips of the horseshoe (Figs. 13 and 14). As these benches bevel the inclined layers of tuff and breccia, they are definitely the products of wave erosion and not merely effects of differential weathering.

The inner edge of the bench at the foot of the wave-cut cliff at the southwestern tip of Fort Rock has an elevation of 4431 feet above sea level, and its outer edge 30 feet away 4428 feet. Thus the bench has appreciable slope; moreover its surface is somewhat

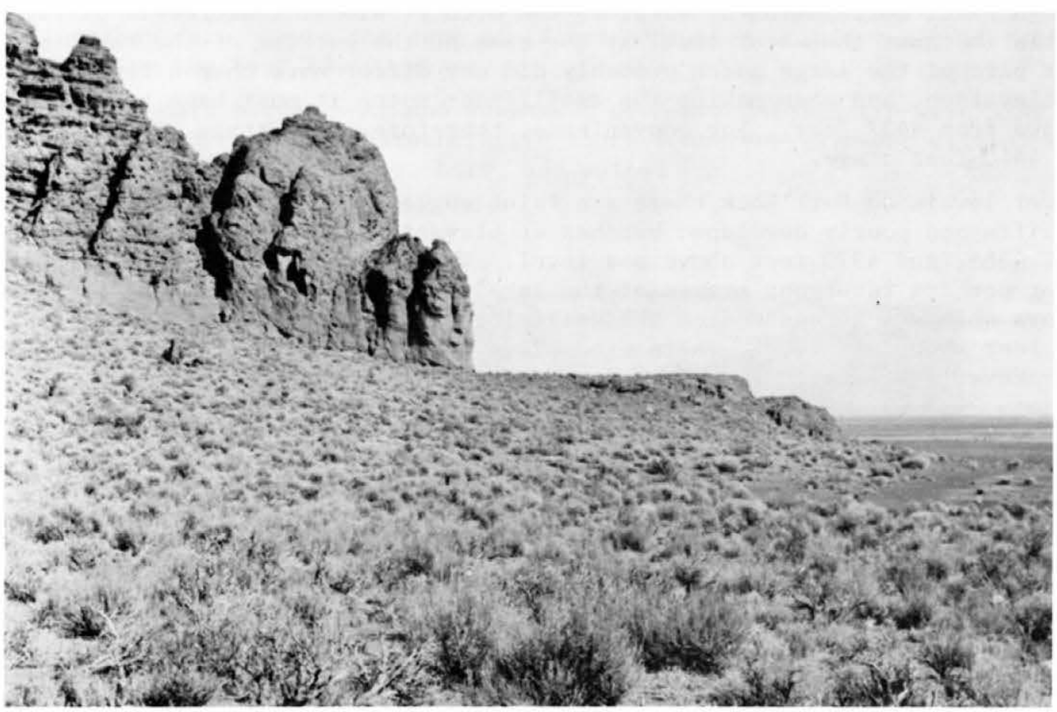

Figure 13. Wave-cut terraces on the southeast corner of Fort Rock

Figure 14. Wave-cut terraces on the southwest corner of Fort Rock

irregular, in part because of cavernous weathering subsequent to its planation. Immediately above the bench is a notch 12 feet high (between 4431 and 4443 feet) cut back into the rock to a depth of 3 feet. Within this notch, between the 4336- and 4339-foot levels, is a smaller wave-worn nip 3 feet high and 1 foot deep (Fig. 15).

Although exact correlation of water levels with erosional features is difficult at best, in this instance the water level at the time of the cutting of the bench and perhaps the greater part of the large notch probably did not differ more than a few feet from a 4440-foot elevation, and when making the small inner notch it must have been not more than a foot or two from 4437 feet. For convenience, therefore, this stage of the lake may be called the 4440-foot stage.

At lower levels on Fort Rock there are faint suggestions of stillstands represented by small cliffs and poorly developed benches at elevations (in round numbers) of about 4420, 4405, 4385, and 4370 feet above sea level. These probably were made during the declining or perhaps resurgent stages of the lake's existence. No ridging or other evidence of wave work was recognized on the still lower outer slopes, which decline gently to about 4225 feet above sea level, where wind-blown Mount Mazama pumice sand conceals or obscures whatever shore features may once have been formed there.

On Menkenmaier Butte and Vicinity

Menkenmaier Butte, situated in SW1/4NE1/4 Sec. 25, T. 25 S., R. 13 E., on the former Menkenmaier horse ranch, is about 1,500 feet long. The southern end of a rocky spur on its southwest edge was also terraced by waves on Fort Rock Lake. The southeast face was excavated by waves to form a large open cave or grotto (the "Fort Rock Cave," or "Cow Cave") about 15 feet high, 70 feet wide at its mouth, and 60 feet deep. Evidences of occupation by early man were found here and studied by Dr. L. S. Cressman and his associates (Cressman, 1942; Bedwell, 1973). Sandals woven from sagebrush-bark fiber, buried underneath pumice in the cave, were found by radiocarbon dating to be 9,053 ±350 years old (Arnold and Libby, 1951, p. 117). According to Bedwell, charcoal on top of gravel in front of the cave yielded a C-14 age of 13,200 ±720 years (Gak-1738). The pumice, originally thought to be from Newberry Crater, was identified by Randle, Goles, and Kittleman

Figure 15. Wave-cut groove on Fort Rock, at the 4436- to 4439-foot level

(1971) as pumice from former Mount Mazama (on the present site of Crater Lake).

Figure 16 shows a view of this bench and cave. The critical elevation of the rock floor of the cave is 4447 to 4449 feet above sea level--almost matching the erosional levels on Fort Rock. The top of the associated gravel is at 4445 feet. According to the second radiocarbon date above, the cave could not have been within reach of Fort Rock Lake waves again during the last 13,200 years.

Three other small buttes west and southwest of Menkenmaier Butte were also wave-washed and now are bordered by characteristic shore features--wave-cut cliffs, wave-cut terraces, stripped benches, beaches, bars, and spits.

Figure 16. Wave-cut bench (left) and Fort Rock Cave (right), at Menkenmaier Butte northwest of Fort Rock. The cave was inhabited by early man 13,200 ±720 radiocarbon-years ago

On the Western Shore of Former Fremont Bay

The western shore of Fremont Bay, within which Fort Rock and the abovementioned buttes stood for a time as islands, lay at or near the base of a basin-boundary fault scarp just west of the former site of Fremont postoffice at the east quarter-corner of Sec. 28, T. 25 S., R. 13 E. This scarp extends south-southwesterly from the east side of a prominent butte in the NW1/4SW1/4 Sec. 22, T. 25 S., R. 13 E., for a distance of at least 3 1/2 miles.

Lake shore features are barely discernible in this sector. A low cliff of lava that projects near the base of the scarp in the NE1/4 Sec. 28, T. 25 S., R. 13 E., near Fremont, at elevations between 4435 and 4465 feet above sea level, appears to have been freshened by wave-washing. Its level accords roughly with the 4440-foot shore features on Fort Rock and Menkenmaier Butte.

Water-rounded pebbles lie near the base of a cliff at the Menkenmaier well in the SW1/4 Sec. 22, T. 25 S., R. 13 E., at an elevation of about 4470 feet. The foot of the cliff, somewhat obscured by talus from the disintegration of rock pinnacles above it, stands 27 feet higher. This cliff and associated gravel alternatively may record a lake stage higher than the one graved on Fort Rock, indicate a subsequent uplift along the boundary fault, or denote sinking of the Fort Rock area. Since cliffs and beach gravels to be described later in this report have been found elsewhere at correspondingly high levels, a 4470-foot lake stage is authentic.

On the North Side of Former Fremont Bay

Few shore features are exposed in the long stretch from the butte at Menkenmaier well on the west to the vicinity of Cougar Mountain on the east, an airline distance of 13 miles. Instead, this sector has been flooded by late Pleistocene or Recent lava, which for most of the way effectually conceals the underlying topography and lacustrine materials.

The main mass of this lava encroached on the Fort Rock Lake basin from the north and northwest. It appears to be continuous with the constructional slopes of the lava cones of Crater Buttes on the south flank of Newberry Volcano, but part of the source vents may well have been fissures instead. The lava completely surrounds Flat Top Butte in Secs. 13 and 14, T. 24 S., R. 13 E. The flows reach as far south as Secs. 22, 23 and 24, T. 25 S., R. 13 E. Part of their southern edge is shown in Figure 12.

A smaller tract of Recent lava entered the Fremont Bay area from the northeast as the southerly extension of the Devils Garden lavas, which cover most of T. 24 S., R. 15 E. and about a third of T. 25 S., R. 15 E. This lava is banked against the north side of Cougar Mountain and reaches about 3 miles west and 1 mile south of it (Fig. 4), where the elevation is less than 4400 feet above sea level. On the northeast side of Cougar Mountain, the lava was flowing against a gentle adverse slope about 4480 feet above sea level at the present lava edge, and so it did not go far in that direction (Fig. 17).

In both areas the lavas seem to have spread as a succession of thin sheets. Their surfaces show typical flow structure, pahoehoe surfaces, pressure ridges, aa and surface brecciation, upturned blocks, and flow-unit tongues along the frontal edge--features characteristic of recent lava flows (Fig. 4). The lava field near Cougar Mountain appears to be fresher and hence younger than that north of Fort Rock. Neither of these lavas shows any visible effects of wave erosion.

The principal shore features in this part of the rim of Fort Rock Lake are two sets of beach ridges that are exposed in the gap between these two sheets of lava. One group lies in the southeast part of T. 24 S., R. 14 E. and the southwest corner of T. 25 S., R. 15 E. Another group lies mainly in Sec. 7, T. 25 S., R. 15 E. Both sets trend in a WNW-ESE direction. Their elevations were not determined.

At Cabin Lake Ranger Station, about 9 miles north of Fort Rock village, the log of a water well shows that the drill passed through 4 feet of pumice, 21 feet of dark lava, 5 feet of fine sand and silt, and several other lava flows and intervening beds of cinders and pumice before entering pumiceous sands between the depths of 90 to 109 feet, and other sands near the 120-foot depth which possibly are lacustrine in origin. As a nearby bench

Figure 17. Devils Garden lava (black), Cougar Mountain (left), and Cougar Gap (middle). Three beach ridges cross the road (below center) at 4483-, 4466-, and 4452-foot elevations. Wave-eroded cliffs surround Table Mountain (near east edge)

mark has an elevation of 4521 feet above sea level on an uneven lava surface, the elevation of most, if not all, of the beds penetrated in the well would fall below the known upper limit of the former Fort Rock Lake level. If these beds are truly lake-laid, their intercalation in the volcanic sequence would indicate that volcanic activity on this southeastern flank of Newberry Volcano took place during an early part of the lake's existence and not merely after Fort Rock Lake had declined to a low level or had disappeared.

A surface blanket of Mount Mazama pumice, thickening locally to the west and northwest, is of course later than both the lava north of Fort Rock and that near Cougar Mountain.

Because of these lava masses, the precise position of much of the boundary of Fort Rock Lake in this sector cannot be determined.

On Cougar Mountain and Vicinity

Cougar Mountain, situated mainly in Sec. 24, T. 25 S., R. 15 E., is an eroded rhyolitic dome that rises abruptly to an elevation of about 5140 feet above sea level, or about 700 feet above the rock bench immediately south of it (Figs. 4 and 17). By isotopic potassium-argon dating, it is about 4 million years old (Walker and others, 1974). Cliffs on its nearly straight west and south sides meet at an angle of about 90° so as to suggest that they originated as fault scarps, but regardless of any such prior origin, they became sites of wave erosion in Fort Rock Lake. A shallow wave-cut cave at the foot of the cliff near the middle of the south side and two deep ones near the northwest corner of the mountain penetrate the base of the cliffs. Their elevations are near 4450 feet. A sandal fragment made of tule fiber, collected by Cowles (1960) from one of the caves, had a radiocarbon age of 8,510 ±250 years (Radiocarbon, vol. 4, 1962, p. 111). Another C-14 age obtained from charcoal was found to be 11,950 ±350 years old (Gak-1751; Bedwell, 1970).

An extensive rock bench south of Cougar Mountain, wave-washed but probably only slightly wave-cut, is strewn with rounded pebbles of black obsidian derived from the base of the mountain. The scarp at the southern edge of this rock bench was wave-battered at a lower lake stage, but it is primarily of fault origin.

Immediately southeast of Cougar Mountain is a gap through the hills about a half mile wide, across which waves and shore currents on Fort Rock Lake constructed a series of beach ridges or bars (Fig. 17). Their elevations in order from northeast to southwest descend as follows: 4483, 4466, and 4452 feet. Their profile along the road angling across the NW1/4 Sec. 24, T. 25 S., R. 15 E., is shown in Figure 18. The 4483-foot or uppermost of the three beaches is a bulky one, about 400 feet wide; it stands 11 feet above the swale behind it. It must represent a long-continued stand of Fort Rock Lake near the 4480-foot level. The 4466-foot beach ridge, 4 feet higher than the swale behind it, is 200 feet wide. The 4452-foot beach is narrow and only 2 feet high. Whether these two lower beaches of the group represent halts in a declining lake level immediately following the 4480-foot stand, or readvances considerably later, is not known.

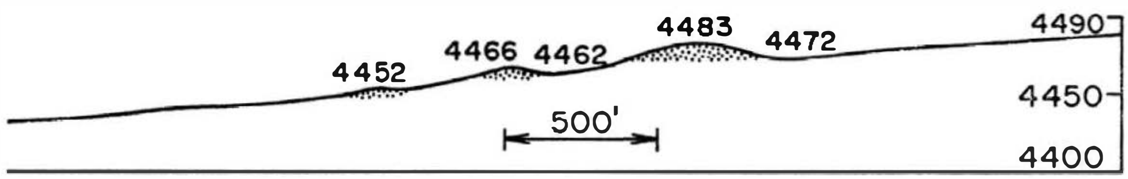

Figure 18. Profile and elevations of beach ridges in Cougar Gap, east of Cougar Mountain

In an alcove northeast of these beach ridges is a nearly flat tract covering more than a square mile, mostly 4480 to 4500 feet above sea level in elevation, which apparently was partly awash at the maximum stages of Fort Rock Lake, but because of resistant rock it was little modified by wave work. Only a few rounded pebbles are strewn over it; beaches are lacking or obscure.

In the E1/2 Sec. 24, T. 25 S., R. 15 E., and in the W1/2 Sec. 19, T. 25 S., R. 16 E., east and southeast of the above-mentioned beach-ribbed Cougar Mountain gap, is a ragged group of hills, of which Table Mountain is chief (Fig. 17). They are composed of basalt and volcanic breccia. Their lower reaches came within the range of wave activity on Fort Rock Lake, but their diversity of slopes and of basal elevations did not seem to warrant leveling to them to make measurements.

About a mile farther southeast, a small embayment apparently allowed the lake to reach to the SE1/4 Sec. 29, T. 25 S., R. 16 E.

In the Green Mountain Sector

Green Mountain is a large shield-type volcanic cone culminating at an elevation of 5190 feet in the southwestern part of T. 25 S., R. 17 E. (Fig. 3). Its upper slopes average about 4 degrees. Regional faulting subsequent to its construction left a large triangular extension of it projecting southward into the north side of the Fort Rock Lake basin. The southwest side of this triangle extends about 8 miles from a point near the NW corner, Sec. 32, T. 25 S., R. 16 E., into the N1/2 Sec. 32, T. 26 S., R. 17 E. The southeast side of the triangle extends nearly 7 miles northeasterly to the NW corner, Sec. 18, T. 26 S., R. 18 E., where it is cut off by a fault trending north-northwest. Cliffs along these two sides of the triangle are basically fault scarps running approximately parallel to the two main directions of regional faulting. Other fault scarps on the mountain within the triangle, especially those of the northwest-southeast set, have only small vertical displacement.

The height of the cliffs along these rims varies, but it commonly ranges between 50 and 100 feet. At certain places, however, as in Secs. 1, 2, 11, and 12, T. 26 S., R. 16 E. and in Secs. 27 and 28, T. 26 S., R. 17 E., the rim is embayed about a mile. These irregularities are thought to be the combined result of originally uneven surfaces of incompletely overlapping lava flows on the slopes of the lava cone, and slight subsequent wave erosion.

The elevation of the base of the cliffs is generally between 4350 and 4400 feet above sea level. Water-rounded stones in fair abundance are spread over a rock bench in the former strand zone below the cliffs.

Fort Rock Lake at its highest stages lapped beyond the cliffs onto the slopes of the Green Mountain lava cone, as shown by relative elevations and by scattered wave-worn pebbles, but no continuous strand lines are discernible above the marginal fault-determined rims.

In The Sink Area

An area locally called The Sink is a semi-detached basin of about 50 square miles situated northeast of Green Mountain. Its central point is in the north part of T. 25 S., R. 18 E. It receives the wet-weather drainage of several townships lying farther north and northeast. Its nearly flat floor has an elevation of about 4330 feet above sea level.

Lava Mountain, a magnificent basaltic shield-type lava cone apparently of recent age, covering about a township, borders The Sink on the northwest. Its fresh lavas reach down to 4445 feet on the southeast and to 4380 feet on the east, where one lava tongue protrudes about 2 miles beyond the base of the cone.

Older lavas surround the remainder of The Sink, except at a broad open gap on the southeast which connects The Sink with the Fossil Lake-Christmas Lake Valley portion of the greater Fort Rock Lake basin.

Bunchgrass Butte, a small gently sloping volcanic cone which rises to a little more than 4600 feet above sea level in the NE1/4 Sec. 28, T. 25 S., R. 18 E., south of The Sink, was an island in Fort Rock Lake, but its slopes were only moderately modified by wave work.

A reconnaissance of The Sink area did not discover any significant shore features about its margins, so no detailed study was made of it other than to run a line of levels across the western part of it along the Lake-Millican road. Elevations along the approach road from the south range from about 4300 feet near Alkali Flat to 4430 feet at a local divide, and to 4336 feet at the Fort Rock-Sink road junction. Much of this route is over a lava rock bench near the 4400-foot level, on which lie a thin sheet of pumice sand and a few apparently water-worn pebbles. At one point the road passes along the foot of a south-facing fault scarp about a half mile long, at the base of which are numerous water-worn pebbles and cobbles at or near the 4410-foot level.

On the Northeastern Margin

On the east side of The Sink in the extreme northeastern corner of the Fort Rock Lake basin, shore features are absent or dim. Beginning in the SE1/4 Sec. 7, T. 25 S., R. 19 E., however, and thence toward the southeast and south, the shore lines are distinct. The positions of these shore lines were controlled mainly by three northwest-southeast fault scarps arranged en echelon. The sandy gravel portions of these shore lines are only a foot or two high, but because of their moisture content they support a heavier growth of sagebrush than is found on the lavas elsewhere. Such lines show up on aerial photographs but are scarcely recognizable on the ground.

Three such high shore lines are found in this northeast sector (Fig. 19). The uppermost one crosses Secs. 8, 9, 10, and 11, T. 25 S., R. 19 E., where its elevation is at least 4525 and possibly 4540 feet above sea level; the former strand zone above 4500 feet is thickly strewn with basalt boulders, which make precision difficult. In Sec. 11 this shore line turns south and then follows a low fault scarp 2 miles southeastward to the

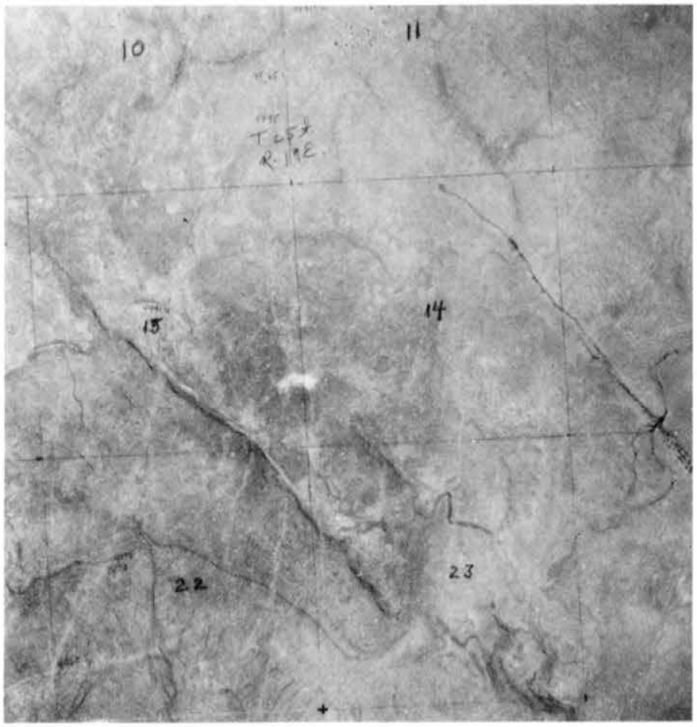

Figure 19. Low fault scarps and associated beaches in the northeast part of the Fort Rock Lake basin. The highest beach (4541 feet) crosses Secs. 10 and 11 (top), turns southeasterly, and continues along a fault scarp (middle right). A second beach (near 4440 feet) enters (middle left), follows a fault scarp more than a mile, and then loops into Sec. 23. A third beach at 4370 feet also crosses the area through Sec. 22 (southwest part)

north edge of a later field of sand dunes, which then mask the next 5 miles of the faulted margin of the basin (Allison, 1966a, Plate 10, p. 16).

A second shore line in this northeastern area follows a northwest-southwest fault scarp southeastward into the SE1/4 Sec. 17, T. 25 S., R. 19 E., where it tops the low fault scarp, swings easterly across Sec. 16 into Sec. 15 before turning southeast across the northeast corner of Sec. 22 and the western part of Sec. 23. It then loops northward in the north-central part of Sec. 23, before resuming a southeasterly course. Its elevation is approximately 4441 feet above sea level, about like the markings on Fort Rock.

A third shore line in this sector extends from the eastern part of Sec. 21, T. 25 S., R. 19 E., along a curved line across Sec. 22 into the SW1/4 Sec. 23. Then its course loops northeasterly across a dry valley before continuing southeasterly to the abovementioned dune field. Its elevation is 4376 feet above sea level.

A leveling traverse from bench mark B-91 (elevation 4408.128 feet) eastward along the north edge of the Lost Forest dune field crossed cobble beaches at 4450 and 4467 feet (Fig. 20).

On the Eastern Margin

The Lost Forest dune field covers part of the eastern margin of Fort Rock Lake with an accumulation of wind-blown sand (Fig. 21). Farther south the margin is complicated by a complex fault pattern and by the entrance of a dry stream bed which descends to an elevation of less than 4350 feet at the edge of the basin (Fig. 22). The lower reaches of this channel cut through a fault block, the otherwise smooth top of which rises in a 1-mile distance along the northeast-southwest road upon it from about 4400 feet to about 4450 feet at the foot of the next scarp. This next scarp rises 10 to 30 feet. Water-rounded cobbles and pebbles are found on the surface of the block at 4467-, 4473-, and again at 4467-foot levels along the road which goes around the south and east edges of the sand dunes (Fig. 21). The third of these occurrences of gravel definitely has the form of a low beach ridge. Along a northerly traverse reaching 1.1 miles farther, additional definitely water-worn pebbles or cobbles were found at 4505-, 4515-, and 4517-foot levels.

Southward from this reentrant of the shore near the south side of the dune field, the

Figure 20. Lost Forest area. Wind-blown sand from the Fossil Lake and Sand Springs deflation basins overtopped a northwest-southeast fault-scarp boundary of the lake basin and continued eastward on the upland. The forest is western yellow pine

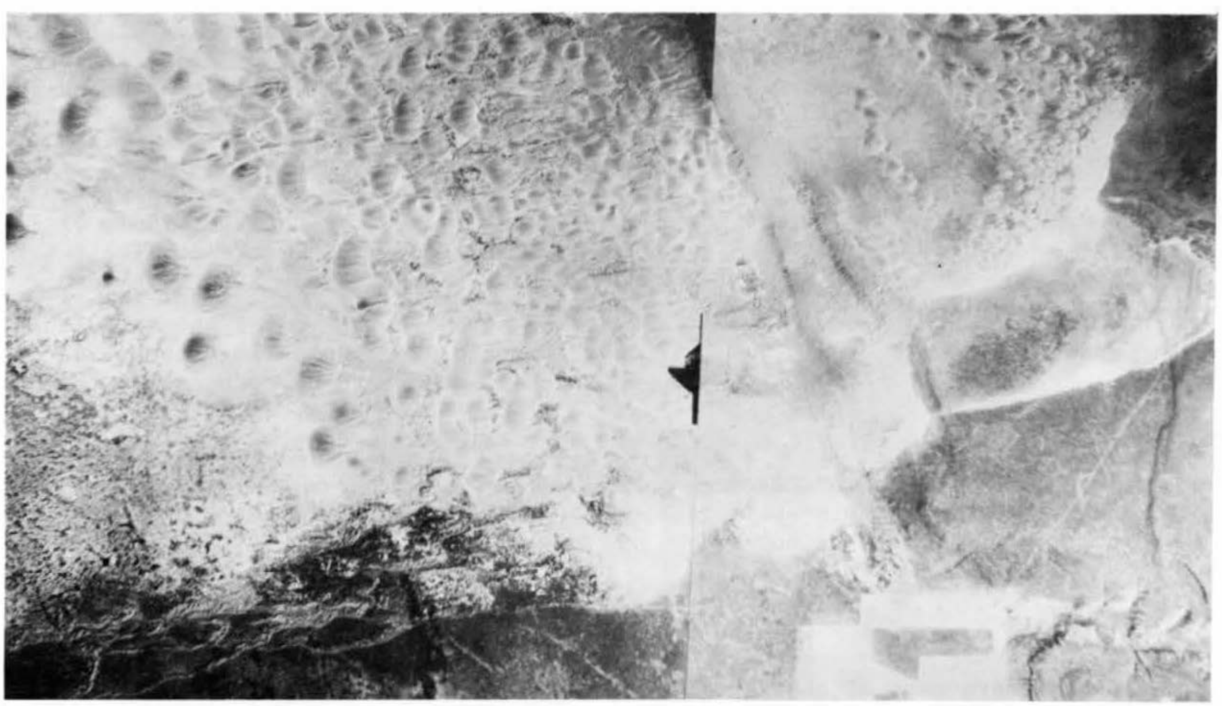

Figure 21. Tail of dune tract east of Fossil Lake

Figure 22. Tilted fault block and dry valley at east edge of Fort Rock Lake basin. Wind-blown pumice sand on fault scarp and upland (bottom) supports a stand of juniper trees

rim of the Fort Rock Lake basin along a 4-mile stretch is a continuously high wall caused by pre-lake faulting. It has a slightly zigzag trend because of intersecting or en echelon sets of faults. Its base is only a few feet higher than the offshore lake flat and shows only minor beach ridging. Evidently the basalt cliffs did not furnish much debris to the waves except large talus blocks. At one place pumice sands from the lake floor have been wind-driven up the side of the basin in a band 1/3 mile wide onto the high lava plain 1/4 mile beyond the rim (Fig. 22).

Southeast of Buffalo (Fig. 1, former site of a well) the marginal fault blocks are tilted diagonally, and so the shore lines, especially at high levels, swing around the sharp corners of the blocks in an irregular way onto a part of the high lava plain. The main result is a gap about 3 miles wide which reaches from about the middle of Sec. 15, T. 27 S., R. 20 E., to the NW1/4 Sec. 29, T. 27 S., R. 20 E. The Silver Lake-Wagontire road leaves the Fort Rock Lake basin through this gap.

A stream channel draining the wet-weather runoff of two townships (T. 27 S., R. 20 and 21 E.) enters the basin from the east also via this gap. The 4500-foot contour, not quite at the maximum high-water level of Fort Rock Lake, even reaches the middle of these townships. This channel also carried the overflow from the pluvial lake at Alkali Lake south of Wagontire, but presumably only when Fort Rock Lake also was at a high level.

Perhaps largely because of the availability of stream-borne gravel and sand, this sector of the Fort Rock Lake margin southeast of Buffalo displays a large number of minor beach ridges (Fig. 23). The most conspicuous beaches in descending order along this portion of the Silver Lake-Wagontire road are at levels of 4523, 4476, 4446, 4394, 4370, 4361, 4342, and 4332 feet. Pumice sand is abundant below 4330 feet.

The south end or tip of a tilted plowshare-shaped fault block was cut by wave action near the 4500-foot level. This shore line can be traced easterly about a mile within the gap and discontinuously farther on.

On the Southeastern Margin

The southeastern part of the Fort Rock Lake basin has a roughly triangular recess which extends about 8 miles south of the Silver Lake-Wagontire road. The southern edges of this recess are formed by a very striking series of obliquely tilted fault blocks which give the edge of the basin a zigzag or even a barbed form in plan view. So the shore patterns in this area are complicated by re-entrants between tilted blocks (Fig. 24).

Figure 23. Reentrant on southeastern shore. Special features are a fault-block shore (lower left), dry stream course (middle right), multiple beach ridges (right half), and lake flat (upper left)

Figure 24. Tilted fault-block shore lines. Several water-level lines appear along the main fault scarp and on the down-tilted side of the partially split block

The fault scarps were attacked by waves on Fort Rock Lake and the debris along them was ridged at several different levels (Fig. 24), but no measurements were made in this sector.

In the Lake Sector of the Southern Margin

That portion of the southern margin of the Fort Rock Lake basin situated between the northeast part of T. 27 S., R. 18 E. and the Seven Mile Ridge in T. 27 S., R. 17 E., may conveniently be designated the Lake sector, after the former postoffice site of Lake (NW corner, Sec. 18, T. 27 S., R. 18 E.). In this area the boundary fault blocks slope into the basin at moderate angles, against which multiple strand lines are moderately well scribed.

A leveling traverse was run from bench mark M-91 (4316.412 feet) at Lake southward to an elevation of 4545 feet above sea level. The main features met were a concentration of pumice sand at and below 4332 feet, basalt outcrops at 4350 to 4361 feet, pebble gravel at 4379 feet, minor beach ridges at 4417, 4440, and 4454 feet, a well-defined gravel beach at 4478 feet, and no appreciable beach deposit or shore cliff at any higher level.

Another southward traverse 2 miles east of Lake encountered pumice sands, partly wind-blown, at 4320 to 4333 feet, a beach of coarse basaltic sand at 4352 to 4355 feet, and beach ridges at 4363, 4393, 4408, 4419, 4430, 4440, 4460, 4473 to 4482, and 4534 feet above sea level. The three uppermost beaches were well developed (Fig. 25). Typically each beach ridge has a swale or furrow behind it. The pumice sands here and across the Silver Lake-Wagontire road southeast of Buffalo are thought to be of Mount Mazama origin.

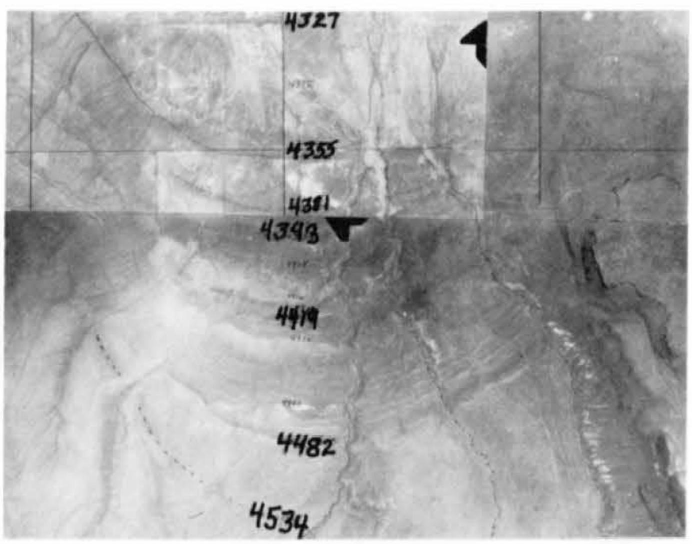

Figure 25. Series of beach ridges near Lake. These curved beaches range in elevation from 4534 feet (bottom) down to 4355 feet (above)

In the Seven Mile Ridge-Silver Lake Sector

The south shore of the Fort Rock Lake basin between Seven Mile Ridge and the east edge of the basin of modern Silver Lake consists of northerly-tilted fault blocks disposed in a steplike series which becomes progressively lower toward the southwest. A well-defined wave-cut cliff was developed at the high-water level, but shore features are only fair at lower levels. Because of the fault-block boundaries, the abandoned shore line has a pronounced offset from one block to the next.

A leveling traverse was run from bench mark S-91 (4318.836 feet), which is located near the west edge of NW1/4 Sec. 1, T. 28 S., R. 16 E., about 2 1/2 miles southward to the former high-level shore of Fort Rock Lake. This line crossed more than a mile of lake flat and then gradually rose along the northward dip slope (about 190 feet per mile) of a fault block of basalt. Owing to a dearth of available rock debris along the way, nearly all the beaches on this slope are very faint. Only the beach ridge at 4475 feet is at all prominent; it stands 6 feet above the furrow behind it. A cliff, traceable along the southern shore for miles, zigzags southwesterly across fault blocks uneven in height (Fig. 26). Interpretation of the maximum high-water level here is fraught with some uncertainty, because the waves were quarrying up-dip against a 40-foot cliff, but a maximum high-water level of about 4540 feet seems probable.

Figure 26. High south shore line on NW-tilted fault blocks. The wave-cut cliff (its base at 4546 feet) crosses one fault block (bottom) to a fault-based stream course (southeast corner), jogs northward, and then continues east-northeasterly across the next higher block on the right

Seven Mile Ridge itself (named by pioneers for a former road distance to it) was severely battered by waves of Fort Rock Lake, especially when its northern end was an island and later a peninsula in the lake (Fig. 27). It was planed to wide wave-cut terraces. Beach gravels occur at bench mark Q-91 (43.39.430 feet) where the old Silver Lake-Wagontire road formerly crossed the Ridge at Seven Mile Gap, and at other places along both sides of the Ridge.

The sides and north end of Seven Mile Ridge were effectively eroded by waves on Fort Rock Lake, so that embankments of gravel now flank the Ridge. Small molluscan shells picked from the gravel at an elevation of 4381 feet (Bedwell, 1970) were radiocarbon-dated at 12,980 ±230 years before the present (Gak-1752). The lake level at that time presumably was 4385 to 4390 feet above sea level. Caliche on the gravel was found to be 9780 ± 220 years old (Gak-1753).

In the Silver Lake Area

The present water body of Silver Lake occupies a sharply defined, down-faulted trough about 5 miles long and 4 miles wide. The long axis of the trough trends northwest-southeast. The northeastern and southwestern sides are each bounded by straight high scarps alongside fault blocks which decline in height to the northwest (Fig. 28). The southeast end of the basin is defined by a series of narrow depressed blocks which plunge northwestward beneath the lake basin. The northwest end is open.

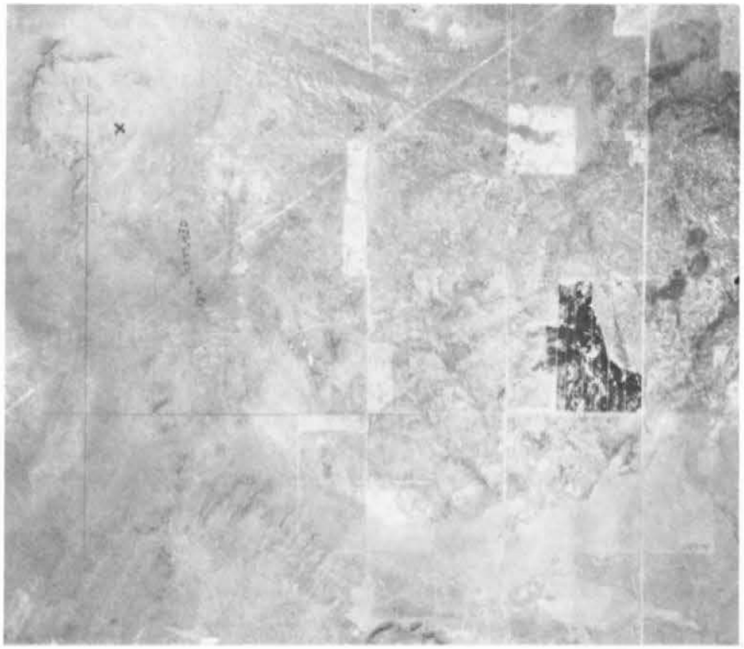

Figure 27. Seven Mile Ridge and vicinity. This wave-eroded ridge (middle bottom toward NW corner) yielded 13,000-year old mollusk shells (at x) from gravel at 4381 feet elevation. Ridges of Mount Mazama pumice cross the northern part of the area

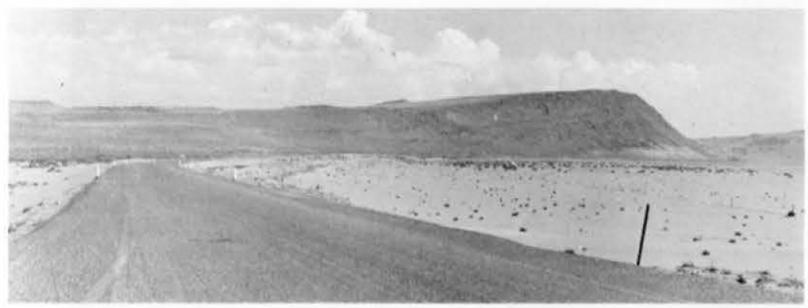

Figure 28. Silver Lake's dry bed (right), beach ridge (under road), and tilted-fault-block eastern border

Modern Silver Lake has a prominent pumice-sand beach ridge around its north shore. Its principal supply of water is the surface overflow from Paulina Marsh, which receives water from perennial streams near Silver Lake village. The depth of Silver Lake in recent decades has varied considerably. In the years near 1900 Silver Lake is said to have overflowed northward into Thorn Lake, whereas in 1940 the lake had dried up completely. The elevation of the dry floor of the lake was found to be just a few feet less than 4300 feet. In recent years a shallow lake usually covered a small part of the basin floor. As the overflow level is about 4315 feet, the maximum depth of Silver Lake is between 15 and 20 feet. Dunes on the beach ridge formerly reached 4335 feet.

The steep cliffs bordering two sides of the Silver Lake basin were wave-washed but not terraced in Fort Rock Lake. Only the sharp northern corners of the adjacent fault blocks bear much evidence of wave erosion; these clearly were trimmed near the 4520- and 4470-foot levels (by aneroid measurement). The southeastern end of the Silver Lake basin was a sheltered bay in Fort Rock Lake and so it shows only moderate alteration by former waves.

In the Former Paulina Bay Area

The southwestern part of the Fort Rock Lake basin is a nearly detached lowland. Its outline is nearly triangular, about 10 miles wide across the east-west base on the south and 10 miles long north-south. Silver Lake (proper) is at the southeast corner, and

Silver Lake village and postoffice near the southwest corner. The north-south Fort Rock-Silver Lake road roughly bisects the triangle. The central and eastern part of this lowland is the site of Paulina Marsh, whence the name for former Paulina Bay of Fort Rock Lake.

This lowland is separated from the remainder of the Fort Rock Lake basin by the bedrock Connley Hills-Table Rock ridge, except for (1) a low-level 1 1/2-mile gap (elevation 4310 to 4315 feet) immediately northeast of Silver Lake and (2) a high-level, 1-mile gap (height about 4455 feet) crossed by the Fort Rock-Silver Lake road north of Paulina Marsh (Fig. 29).

Three small perennial streams, Buck Creek, Bridge Creek, and Silver Creek, rising principally on the northern and eastern slopes of Yamsey Butte, an 8085-foot volcanic cone situated on the Klamath River drainage divide, enter the southwest corner of this triangular lowland and disappear in Paulina Marsh. Much of this stream water is now used for irrigation of pastures and hay fields. The overlow of Paulina Marsh in wet years goes on to Silver Lake.

When Fort Rock Lake was at or near its maximum stage, the Paulina March lowland was occupied by a large bay herein called Paulina Bay. Waves on Paulina Bay cut a distinct trace along the barren southwest side of the Connley Hills, and formed gravel bars in the Fort Rock-Silver Lake gap (Fig. 29). They less clearly washed certain basaltic fault blocks along the southern and western sides of the bay, and formed distinct beach ridges where gravels were available at appropriate levels.

Figure 29. Wave-cut cliff (on right) and associated gravel deposits on west side of the Connley Hills. A curved gravel ridge crosses the Fort Rock-Silver Lake road (north of middle)

On the Connley Hills-Table Rock Peninsula

This range of hills northeast of Paulina Marsh is about 15 miles long from northwest to southeast and 2 to 5 miles wide. One lava cone, Hayes Butte (Fig. 7), reaches an elevation of 5740 feet; another, 5570 feet; and Table Rock, above an area of volcanic breccia, 5630 feet (Fig. 6). This ridge formed an island during the high-water stages of Fort Rock Lake, but it was a long peninsula between Paulina Bay and the main body of the lake during much of the lake's later existence.

The tuffs and breccias surrounding Table Rock were especially vulnerable to wave attack, and so they were conspicuously terraced at several levels (Figs. 30 and 31). The main wave-cut terrace is generally 100 to 400 feet and locally 700 feet wide. Its outer edge was found to be about 4430 feet above sea level and its back edge at the foot of a wave-cut cliff about 4450 feet (Fig. 32). The lake stage represented is inferred to be approximately the same as that of the 4440-foot features on Fort Rock. Below the outer edge of this principal terrace stands a low wave-cut cliff. Other wave-cut cliffs, grooves, caves, and terraces appear at both higher and lower levels. The mouth of the

Figure 30. Wave-cut terrace at southeastern end of Connley Hills. Its elevation is 4430 to 4450 feet

Figure 31. Connley Hills shore near Table Rock. Wave-eroded shore (across middle) is continuation of Fig. 30, as seen from the east. Table Rock is on the right

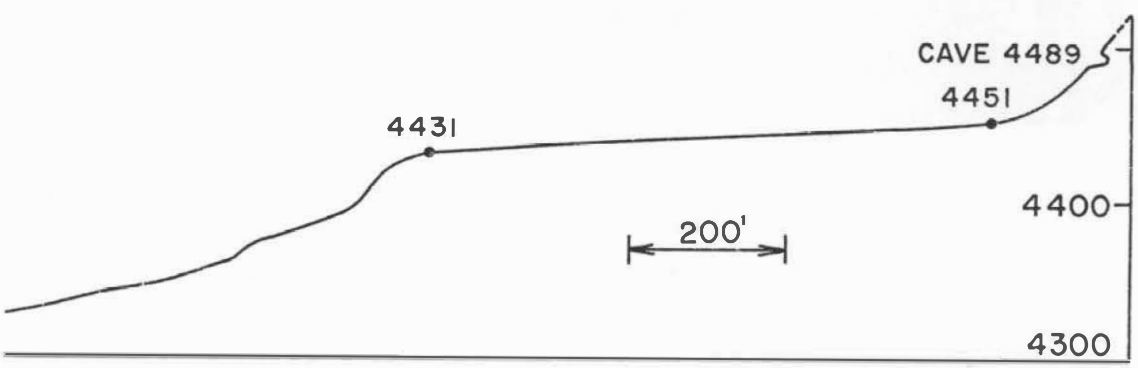

Figure 32. Profile of shore features east of Table Rock (vertical exaggeration 2x)

uppermost cave seen is at the 4489-foot level, and a horizontal groove 5 feet wide vertically occurs between the 4498- and 4503-foot levels. Minor cliffs rise above 4345, 4339, and 4381 feet, and a minor terrace is 4363 feet above sea level. These elevations though may have been determined in part by differences in the erosional resistance of the texturally variable volcanic breccia. Bedwell (1970) found rock-shelter occupation sites at 4449 and 4409 feet.

A wave-washed bench also surrounds the north end of the Connley Hills, and recurved gravel ridges flank it on both sides, as on a winged headland. The bench is partly structural, but wave work is plainly evident also (Fig. 33).

Figure 33. Wave-eroded north end of Connley Hills. The point is bordered by a wave-cut rock terrace and by gravel bars (lower left). The fan (middle) is younger

West of the Connley Hills, a saddle separates the western part of Fort Rock Valley on the north from Paulina Marsh on the south (Fig. 29). It is utilized by the Fort Rock-Silver Lake road. The pass itself is crossed by a gravel ridge which is plainly a bar. Pits for road material disclose its composition and structure. Occasional pebbles extend up the adjoining slopes 20 to 25 feet above the saddle.

North of this saddle and gravel bar is a fault-block hollow 50 feet deep, succeeded in turn northward by a stubby spit, a broad swale, and another prominent bar 4458 feet above sea level, 6 1/2 miles south of Fort Rock village. This bar (Fig. 29) declines in elevation and becomes compound to the southwest. A half mile farther north the lake-bed plain is about 4370 feet above sea level. To the east and northeast of these gravel bars is a rock bench flanking the north end of the Connley Hills, from which presumably the gravel for the bars was derived by waves and shore currents, hard-driven by northerly winds.

Several caves occur along a shore cliff near the 4445-foot level. Charcoal from one of them yielded a radiocarbon age of 10,000 ±400 years before the present (Gak 1742; Bedwell, 1970).

Southwest of Fort Rock village the boundaries of Fort Rock Lake are complicated by a complex array of variously disposed fault blocks. In this sector the shore lines had many re-entrants, peninsulas, and islands, along which erosional and depositional features were only moderately developed, because of resistant rocks and limited fetch of the waves.

Low-Level Shores

One occurrence of low-level shore lines deserves special mention. This is a set of beaches at low elevations which are found along the township-line road east of the former site of Fleetwood, or 9 miles east of Fort Rock village. Within a distance of one-half mile near the southeast corner of Sec. 36, T. 25 S., R. 15 E., the road crosses a swarm of beach or bar ridges (Fig. 34). Their elevations are 4373 feet (a cobble-shingled ridge, 7 feet above the swale behind it), 4365, 4363, and 4360 feet above sea level (Fig. 35). All are composed of particles of basalt, derived from a rocky ridge to the south. No additional beach ridges of basaltic material cross the road farther west. A pit 3 1/2 feet deep dug at the 4329-foot level in the NE1/4NE1/4 Sec. 1, T. 26 S., R. 15 E., revealed only hard basaltic sand.

At elevations below 4350 feet above sea level beside the road west of this beach swarm, the surface is disturbed by deflation and piling up of blow sand, derived in part from lower-lying land that had been cleared of sagebrush for farming. A sheet of Mount Mazama pumice is general below the 4330-foot level and is locally ridged in post-Fort Rock Lake beaches and dunes. The description of these and other Mount Mazama pumice deposits is deferred to subsequent pages of this report.

Figure 34. Shore cliff and beach ridges near Fleetwood, about 9 miles east of Fort Rock village

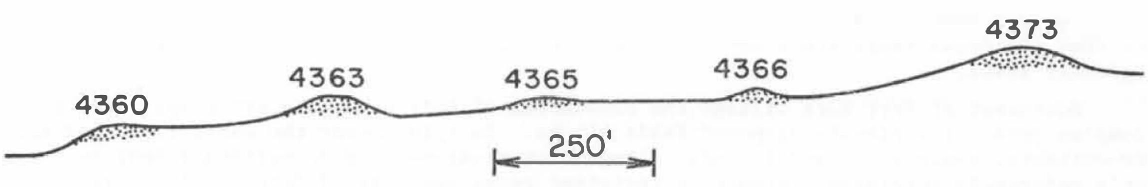

Figure 35. Profiles and elevations of five beaches near Fleetwood (vertical exaggeration 10x)

OUTLET OF FORT ROCK LAKE

The problem of a possible outlet to the former expanded lake in the Fort Rock Lake basin was raised by Hay (1927, p. 241-242) in the following words:

> "Notwithstanding the depth of the water Russell [his p. 459] concluded that the lake did not overflow. He was able to trace the ancient water-lines continuously around the basin. It is difficult to harmonize this view with the fact that Jordan had described from the vicinity of Fossil Lake bones of the king salmon (Onchorhynchus tschawytscha) . . . Whether the species of Onchorhynchus reached Fossil Lake by way of the Columbia River or by the Klamath, as did the fish found near Klamath Lake, is yet to be determined."

In the course of the field work on Fort Rock Lake a search was made for a possible outlet by overflow. The route to the Goose Lake basin to the south and thence via Pitt River in California is interrupted by (1) a 4830-foot divide at Picture Rock Pass between Silver Lake and the Summer Lake basin, and this in turn by (2) another divide at an elevation of about 4950 feet, separating the Summer Lake-Chewaucan Marsh-Abert Lake basin from the Goose Lake basin farther south. So a route southward is not possible. Routes to the Klamath River basin are likewise blocked by divides more than 5000 feet high. The lowest saddle across the high lava plain east of Newberry Volcano, i.e., on the divide between The Sink and Dry River (east of Bend), is more than 4800 feet above sea level. Similarly the lowest divide on the northwest toward the Deschutes River, tributary to the Columbia River, is nearly 4800 feet above sea level. Hence under present conditions overflow at the lake's upper limit of about 4540 feet would not be possible. Could past conditions have been different?

The last-named (Deschutes River) divide is formed by late Pleistocene or Recent flows of basaltic lava. These are the western and southwestern part of the great field of lavas that border Newberry Volcano on the south and flood the northern part of Fort Rock Valley almost to Fort Rock itself. These lavas are clearly younger than the high shores of Fort Rock Lake. They lap against the north slope of Hole-in-the-Ground cone, against the north side of Big Hole Butte, and continue to the northwest as far as the western part of Sec. 7, T. 24 S., R. 11 E., southwest of Moffitt Butte. Here a tongue of lava occupies the head of a shallow dry valley at an elevation of about 4350 feet. This dry valley can be traced northwesterly beyond the end of the lava into Sec. 22, T. 23 S., R. 10 E., and thence northerly via Long Prairie past Lapine to the Little Deschutes River in Sec. 10, T. 22 S., R. 10 E. Long Prairie is a swampy swale about a half mile wide, now irrigated for pasture by water diverted from Little Deschutes River, but it evidently was once the bed of a fair-sized stream, as was the now-dry valley tributary to it. If this channel is the distal portion of the overflow route from former Fort Rock Lake, as seems likely, then a span of about 15 miles of the former outlet of the lake, including the point of overflow on the rim, has been concealed by these lavas from Crater Buttes on the south flank of Newberry Mountain.

The only alternative to such a lava-covered outlet would be a lava-filled route at or near the base of Newberry Volcano, but this possible route lacks a distal channel equivalent to the tributary to Long Prairie, and so it is not a probable one.

If the outlet of Fort Rock Lake happened to be superimposed on volcanic tuff or breccia like that in certain nearby buttes which rise above the lava flows which presumably buried the outlet, then the outlet may conceivably have been cut down by tens of feet. On the other hand, if the outlet lay on lava flows, the deepening of the outlet channel may have been nil, or only a few feet at most. Inasmuch as an outlet is uncertain, any such downcutting is speculative. Because the shore features at the 4474- to 4480-foot level are so well developed, however, downcutting below this level, if ever reached at all by this method, is very unlikely.

Further evidence for an outlet to the Columbia River is furnished by the presence of the snail Limnaea, which today is restricted to the Columbia River drainage basin (D. W. Taylor, letter to L. S. Cressman, 1968). This snail is found at Fossil Lake and at a gravel pit near the north end of Seven Mile Ridge.

STRATIGRAPHY OF THE FORT ROCK LAKE AND OLDER SEDIMENTS

Reference has been made already to the surficial pumice deposits on the floor of former Fort Rock Lake and to the older beach gravels and sands at higher elevations around the periphery of the basin. The bulk of the lake sediments, however, underlies the floor of the basin. Fine-grained sediments of substantial thickness are not found even on broad-topped surfaces within the basin at elevations above 4400 feet above sea level. Either the sediments deposited at such places were removed pari passu with the lowering of lake levels in a single lake stage, or they were washed off during a protracted history of waxing and waning stages of the lake, or possibly they were blown off by the wind. On a terrain composed mainly of basaltic lava flows, except for air-laid falls of volcanic ash, they may never have been plentiful.

Exposures of lake sediments occur mainly where the wind has excavated deflation basins or where streams have incised channels into them. Drilling of water wells, digging of pits, and boring by soil auger have furnished further information regarding the lake sediments, but no studies have been made in the Fort Rock Lake basin comparable in detail to those made at Searles Lake, California (Flint and Gale, 1958; Roosma, 1958; Smith and others, 1969), or in the Lake Bonneville basin, Utah (Bissell, 1952; Hunt and others, 1953; Jones and Marsell, 1955; Eardley, 1956; Eardley, Gvosdetsky, and Marsell, 1957; Eardley and Gvosdetsky, 1960; Morrison, 1961a, 1965, 1968, 1970, 1975; Richmond, 1961, 1965; Shuey, 1972; and Eardley and others, 1973); except at Fossil Lake (Allison, 1966a).

Near former shores, as along the northwest edge of Thorn Lake basin, shore-derived gravels and sands of Fort Rock Lake are several feet thick. Noteworthy quantities flank the north end of the Connley Hills. Sands and silts compose the bulk of the sediments at Fossil Lake in the eastern part of the basin.

A special search was made in the Fort Rock Lake basin for a set of lake-laid tephra deposits correlative with those in the Ana River section in the Summer Lake basin. The most nearly complete section was found at Fossil Lake; the record elsewhere is meager. Because of the importance of these layers of sandy pumice or fine-grained volcanic ash in the geologic record, let us consider the petrography of these volcanic ejecta before proceeding with other aspects of the Fort Rock Lake stratigraphy, in which they form distinctive parts.

Tephra Deposits at Ana River
By H. E. Enlows

The pumice and volcanic ash deposits exposed in the banks of Ana River in the northwestern part of the Summer Lake basin are described here for their use in identifying correlative deposits made in Fort Rock Lake. They record several different explosive volcanic eruptions, so they serve as a standard reference set (Fig. 36). Their position near the top of the stratigraphic section indicates that they were formed at relatively late stages in the history of pluvial Winter Lake in that basin, as also do intercalated sand layers and minor disconformities in the section. Their description will be followed by a short treatment of later Mount Mazama pumice which is abundant in the Fort Rock Lake basin.

Samples from the five main layers of tephra in the Ana River section have been studied in expectation that they would assist in the identification of volcanic ash and pumice deposits in the Fort Rock Lake basin. They are numbered S 64-13 to 64-17. The first four of these samples correspond to layers 2, 8, 12, and 18 as described by Allison (1945, Fig. 3, p. 796; and 1966b) and by Kittleman (1973, p. 2968-2969). These beds are 1.5, 4.0, 4.0, and 2.5 inches thick, respectively. The fifth layer is 2 inches thick. Two minor layers of volcanic ash, each 1/4-inch thick, below the 64-14 layer are omitted.

Petrography

The first of these five main layers of tephra in the Ana River section, Sample 64-13,

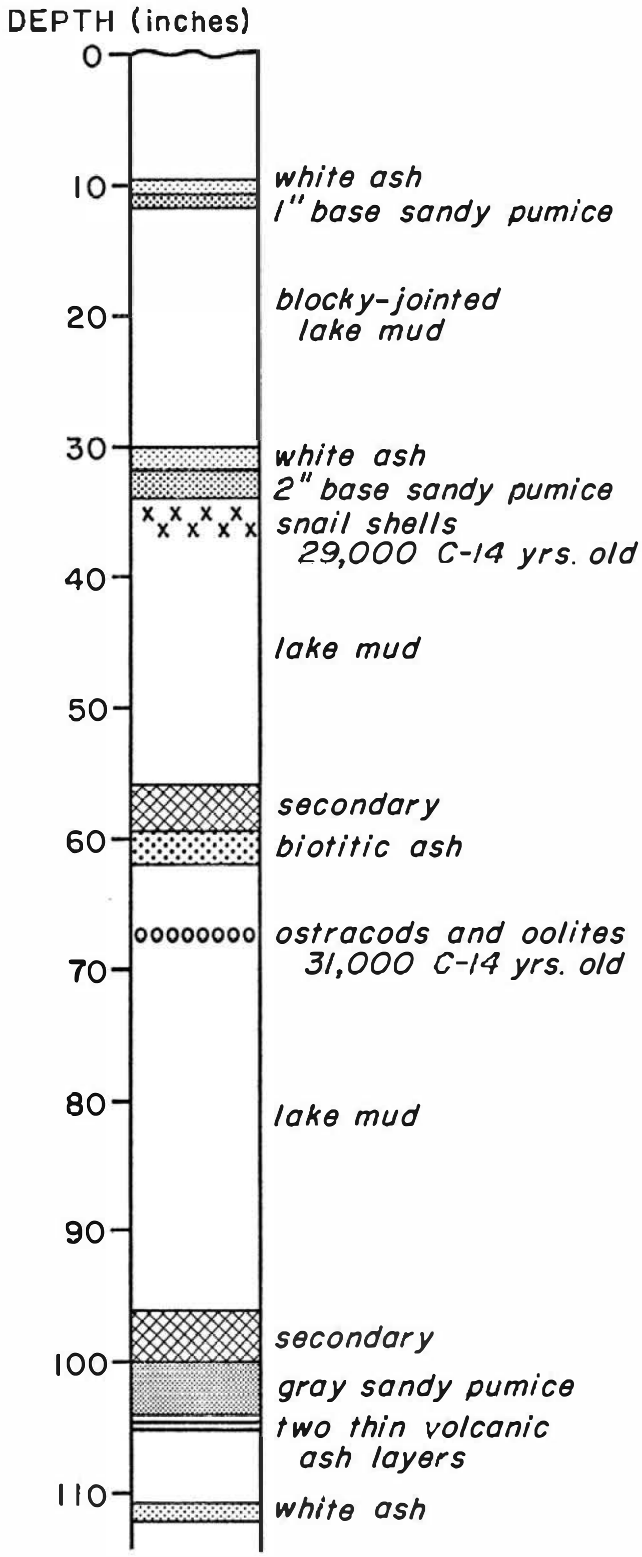

Figure 36. Partial stratigraphic section at Ana River near Summer Lake. It records seven layers of pumice or volcanic ash. The dated snail shells were from Fossil Lake, not Ana River. These volcanic layers form a standard refernce set for identification of correlative layers in Fort Rock Lake deposits

consists almost entirely of white, fine-grained, vesicular volcanic-ash particles. Tiny crystals of plagioclase (An_{30}), hypersthene (n 1.710), rare clinopyroxene, and opaque iron-titanium oxides, herein called magnetite, make up only about 1 percent by weight. Hornblende is absent.

In the second main tephra layer, Sample 64-14, about half (by weight) of the basal 2 inches is composed of crystals of plagioclase (An_{46}), hypersthene (n 1.698), clinopyroxene (n 1.685), and magnetite, mostly in the size range of 1/4 to 1/2 mm. It lacks hornblende. The upper part of the layer is laminated volcanic ash, nearly all finer than a 200-mesh screen (0.074 mm). Partial sorting by differential settling in lake water is evident.

The third in this set of samples, Sample 64-15 from layer 12, is white, rich in biotite (much concentrated at the base), low in feldspar (An_{44}), contains hornblende (n 1.698), and cummingtonite (Wilcox, personal communication, 1964), and lacks both ortho- and clinopyroxene. It has a distinctive rare-earth lanthanum-ytterbium (La/Yb) ratio (Randle, Goles, and Kittleman, 1971). The basal portion, 2 inches thick, is primary; the upper part is thin-bedded from later settling out of suspension in pluvial Winter Lake. The source of this biotitic ash may have been in northeastern California, where dacites and rhyolitic pumice are common. Williams (1932) found biotite at Baker Peak, Crescent Cliffs, and elsewhere in Lassen Volcanic National Park, and Macdonald (1963) identified biotite in several volcanic rocks in the Manzanita Lake quadrangle. Wilcox (1965) also shows biotite as a constituent of Lassen Peak volcanic rocks. On the other hand, Anderson (1941, p. 397) found only one specimen in the Medicine Lake area to contain biotite.

The fourth tephra layer sampled at Ana River (S 64-16), from layer 18, is 2 inches thick, is white, contains about 6 percent crystals in the basal 1/2-inch--two-thirds plagioclase (An_{42}), and one-third hypersthene, and a trace of magnetite. About half of the early settled material has a textural range between 1/8 and 1/4 mm. Most of the remainder is finer than 200-mesh (0.074 mm).

A later white ash layer (not yet discovered by Allison in 1945) has 2 inches of direct fall material of sandy texture, Sample 64-17, followed by 4 inches of minutely cross-bedded and thinly laminated volcanic ash. It contains small quantities of plagioclase (An_{34}), hypersthene (n 1.720), and hornblende (n 1.672).

The indices of refraction of the volcanic glass in these five Ana River samples are 1.507, 1.515, 1.503, 1.503, and 1.503, respectively. In equivalents of the first four of these samples, Kittleman (1973) found nearly the same indices: 1.508, 1.518, 1.500, and 1.507. As indices of refraction of volcanic glass vary within different parts of a single sample, as well as from sample to sample from the same source, these numerical values have limited significance. The relatively high index, whether 1.515 or 1.518, in Sample 64-14, however, may have some usefulness.

The main differences in mineral content of these samples are: distinctive biotite in S64-15 only; absence of hornblende in S 64-13, S 64-14, and S 64-16; and the absence of both ortho- and clinopyroxene in biotitic and hornblendic S 64-15.

Chemical Composition

Silica (SiO_2) was determined by a visual light spectrophotometer. An atomic absorption spectrophotometer was used to determine magnesia (MgO) and soda (Na_2O). Alumina (Al_2O_3), iron (total as FeO), lime (CaO), titanium (as TiO_2), and potash (K_2O) were measured by means of x-ray fluorescence. The resulting percentages are shown in Table 3.

Table 3. Chemical Analyses of Ana River Tephra

Sample No.	64-13	64-14	64-15	64-16	64-17
SiO_2	71.00	61.50	64.80	70.00	71.00
TiO_2	0.42	0.77	0.59	0.41	0.43
Al_2O_3	14.92	17.60	16.10	15.50	14.80
FeO	2.70	5.10	3.90	2.70	2.60
MgO	0.30	2.30	2.00	9.80	0.40
CaO	1.50	5.50	5.70	2.70	1.90
Na_2O	5.50	4.70	4.60	5.00	5.00
K_2O	3.35	1.63	1.49	2.57	2.85

The table shows that Samples 64-14 and 64-15 are characterized by moderate quantities of silica; by high alumina, iron, magnesium, and lime; and by low potash, whereas Samples 64-13, 64-16, and 64-17 have high percentages of silica, low magnesia and iron, and high alkalies. Samples 64-14 and 64-15 are andesitic in chemical composition; the other three are rhyodacites. Apparently Sample 64-13 is not preliminary to the next succeeding major eruption, S 64-14; rather, it chemically resembles Samples 64-16 and 64-17, as though from a common source.

Fossil Lake Section

Details on the lake sediments in the Fossil Lake area, already given in a previous publication (Allison, 1966a) need not be repeated here. The stratigraphic section there is characterized by several different layers of volcanic ash, a series of intraformational gravels or breccias at minor disconformities (indicating repeated shoaling of Fort Rock Lake in its late stages), and a thickness of 12 feet of sediments above the major disconformity between pumiceous beds above and diatomaceous beds below. Snail shells obtained near the base of the upper sequence were found to have a radiocarbon age of about 29,000 years.

Sediments near Silver Lake Village

Streams entering the Paulina Bay area of former Fort Rock Lake deposited an extensive sheet of gravel near Silver Lake village. Some of this gravel may have been deposited as alluvial fans before the lake came into existence, but most of it probably is deltaic in origin. In any event, waves on the lake reworked the gravel surface to a smooth plain, and wind has removed most of any cover of Mazama or other pumice sand that may have fallen on it.

A road-cut on the Fremont Highway at the northwest edge of a terrace between Rock Creek and Bridge Creek exposes 12 feet of even-bedded, laminated silts and occasional sands, overlain by about 6 feet of wind-blown Recent sand (Fig. 37). A bench mark on this

Figure 37. Laminated lake beds and overlying sand in roadcut 2 miles northwest of Silver Lake village

terrace surface has an elevation of 4387 feet. One half mile southeast of this cut, a gravel pit in the terrace shows 20 feet of iron-stained pebble gravel. These two exposures give an impression of age, as though the materials antedate the late history of Fort Rock Lake. Similar gravel of granule texture is exposed in a road-cut near the middle of Sec. 21, T. 28 S., R. 14 E.; and laminated silts show at several places in the banks of Silver Creek nearby.

A gravel plain forms a nearly level surface for a distance of more than two miles east of Silver Lake village. Bench marks at the Silver Lake school and near the centers of Secs. 22 and 23, T. 28 S., R. 14 E., have elevations of 4345, 4347, and 4348 feet, respectively. A gravel pit in the NW1/4NW1/4SE1/4 Sec. 24, T. 28 S., R. 14 E. shows only even-bedded, poorly sorted pebble and granule gravel. Evidently this gravel, situated 1 1/2 to 2 miles from the former south shore of Paulina Bay, was washed in by streams from west and southwest. Its wide spread suggests a stillstand of Fort Rock Lake near the 4350-foot level over a considerable span of time. It may be related in time to a swarm of 4360- to 4373-foot beaches 9 miles east of Fort Rock village (Fig. 35). Several minor beach ridges cross the north-facing slopes above the gravel plain. Noteworthy quantities of pumice sand first appear at a somewhat lower elevation (about 4325 feet) near the east side of this same Sec. 24. The gravel plain apparently has been wind-swept of nearly all surface sand from pumice falls.

Sediments at Arrow Sink

The stratigraphic section of lake beds at a deflation basin informally called Arrow Sink, situated at the west quarter-corner, Sec. 30, T. 27 S., R. 16 E. is given in Tables 4 and 5. The fine-grained or silty lake beds consist mostly of volcanic ash and diatomite. The several layers of coarse pyroclastic fragments in the section show repeated volcanic explosions in the region during the period of sedimentation represented.

Table 4. Section of Lake Beds at Arrow Sink

Unit	Material	Thickness (feet)
16	Loose pumice sand	3.00
15	Pebble pumice	2.00
14	Pumice sands, other sands, silts	2.65
	- - - - - Disconformity, elevation 4306 feet - - - - - - -	
13	Compact silty lake beds	10.29
12	Dark sand	0.01
11	Silt	1.80
10	Dark gray sand seam	0.02
9	Silty lake beds	4.02
8	Brown volcanic ash	0.38
7	Yellow volcanic ash	3.29
6	Pebble pumice	1.30
5	Volcanic ash, silicified	0.40
4	Pumice, pebbly at base, grading upward to sandy	0.67
3	Silty lake beds	12.74
2	Pebble pumice	1.02
1	Silty lake beds (base concealed)	n.d.
		43.79

Whether the sediments below the disconformity (near the top of the section) should be ascribed to an early stage of Fort Rock Lake or to some previous lake, perhaps of middle or early Pleistocene age, is uncertain, but one of these alternatives seems likely.

Table 5. Details of the Upper Part of the Arrow Sink Section

Unit	Material	Thickness (inches)	Total
15	Loose pumice sand and silt	36	77
14	White pebbly pumice (maximum size 3 inches)	26	31
13	Pumice sand	1/2	15 1/4
12	Silt	1	14 3/4
11	Pumice sand	1	13 3/4
10	Silt	3 1/2	12 3/4
9	Coarse pumice sand	3 1/4	9 1/4
8	Silt	1 1/2	6
7	Basaltic sand	1	4 1/2
6	Silt	3/4	3 1/2
5	Sand	1/4	2 3/4
4	Silt	1/2	2 1/2
3	Sand	1/2	2
2	Laminated silt	1 3/4	1 1/2
1	Sand	1/4	1/4
	- - - - - - - - - - - Disconformity - - - - - - - - - - - - - - - - -		
0	Semiconsolidated lake beds of silt, volcanic ash, pumice sand, and pumice pebbles, approximately 36 feet thick as exposed.		

A cut dug with a shovel at the southwest edge of the Arrow Sink deflaction basin (Figs. 38 and 39) revealed the details near the top of the section reported in Table 5. Unit 9, the somewhat gray, coarse sandy pumice layer (Samples 64-19 and 65-14) above the banded portion of alternating silt and dark sand layers (above camera case) in Fig. 38, is correlated petrographically with Layer 8 (S 64-14) of the Ana River section in the Summer Lake basin. Unlike its counterpart there, this layer does not show a primary fall into water and subsequent settlings; instead, it appears possibly to have been reworked. Approximately two-thirds of it is coarser than a 60-mesh screen (0.250 mm). Its plagioclase is andesine (An_{42}); its glass has a refractive index of 1.514; but its heavy minerals make up less than 1 percent.

Figure 38. Layered lacustrine beds at Arrow Sink. Loose upper sediments are separated by a disconformity (near middle of camera case) from semiconsolidated and jointed older lake beds below.

Figure 39. Pebbly pumice at Arrow Sink, in upper part of Fig. 38. (Ruler is 1 foot long.)

The sand of unit 7 consists partly of particles of basalt. This and similar sands lower down in the section clearly record times of shallow water in Fort Rock Lake. Units 11 and 13 presumably represent two separate volcanic eruptions, but the record is incomplete, as the biotite-bearing volcanic ash present at Ana River and Fossil Lake is missing here.

Unit 14 contains an unsorted, apparently air-laid mixture of particle sizes ranging from dust to pumice pieces of pebble size, which have a satiny luster on freshly broken surfaces. The refractive index of the glass is 1.503. Crystals, mostly plagioclase (An_{30}) with a little hypersthene, make up less than 4 weight percent of crushed particles. The pebble-sized pieces appear to be too coarse for Mount Maxama pumice, and moreover clinopyroxene and hornblende are lacking. A more likely source is Newberry Volcano or one of its subsidiary vents.

Sediments at Four Mile Sink

This deflation basin, 40 feet deep, situated 4 miles east of Arrow Gap road and near the southeast corner of Sec. 21, T. 27 S., R. 16 E., shows the oldest beds here to be composed almost entirely of diatomite and volcanic ash (Fig. 40). A few layers of coarse pumice or volcanic cinders occur in the exposure. The top of the fine-grained beds has an elevation of 4308 feet. Cuts dug into the western and northwestern rims of the basin exposed 4 to 5 feet of pumice sand resting on a thin layer of flat-pebble breccia composed of fragments of the underlying fine-grained lacustrine beds. The contact immediately below this breccia evidently is a disconformity. Jointing is prominent in the lower beds, which may well be pre-Fort Rock Lake in age. The thin pumice on top is not resolvable into discrete layers or separate types, and so it cannot be correlated with certainty, but the bulk of it probably is Mount Mazama pumice.

Sediments at Other Deflation Basins

The southwest side of a deflation basin in the SE 1/4 Sec. 4, T. 28 S., R. 16 E., shows 4 feet of loose sandy pumice cover, 1 foot of stratified lake silts, and 1 1/2 inches of pebbly sand, including rounded pieces of diatomite, overlying several feet of diatomaceous lower lake beds. The pebbly sands show the former presence of shallow water and a pronounced change in sedimentation from that of the diatomite stage. The rounded fragments of reworked diatomite indicate a major disconformity, or break in the history of

Figure 40. Western part of Four Mile Sink deflation basin, as seen from the north. The white wall is composed of diatomite and occasional layers of volcanic ash or volcanic cinders. One dark cindery layer is broken by slumping off the wall

the lake (or lakes).

The edge of another basin in the SW 1/4 Sec. 28, T. 27 S., R. 16 E., at an elevation of 4312 feet, shows a similar sequence (in descending order) of 2 to 3 feet of surface sand and silt, apparently wind-blown; 1 to 2 feet of shaly lake beds; 1 foot of sand, pebbly sand, and somewhat cemented gravel; and about 20 feet of platy, white-weathering, diatomaceous lake beds.

A cut dug into the south side of another deflation basin situated on the south line of SW1/4NW1/4 Sec. 35, T. 26 S., R. 16 E., shows 3 feet of sandy pumice resting on compact older lake beds composed of diatomite, silty ash, and layers of granular pumice, but no stones. The contact between the two parts is marked by an accumulation of stones consisting of rounded pebbles of black volcanic glass and angular pebble-sized pieces of fine-grained basalt. A few sporadic stones are enclosed in the pumice beds on top. The basin has a salt-crusted mud bottom (Fig. 41).

Figure 41. Salt-crusted floor of former deflation basin. The sides are diatomite, volcanic ash, and granular pumice, overlain by 3 feet of pumice sand. (Auto on the far rim gives scale.)

Sections in Artificial Pits

Because of the inadequacy of natural exposures of the lake beds, pits were dug at many different places in the Fort Rock Lake basin. Stratigraphic sections observed in only a few of these pits are described below. Only a few were really fruitful in the search for identifiable volcanic ash layers.

A pit dug to a depth of 54 inches in the NE 1/4 Sec. 35, T. 26 S., R. 17 E., encountered 2 inches of loose pumice sand, 3 inches of spongy pumice sand (leached ?), 27 inches of hardpan of cemented pebbly sand (requiring use of a pick), 16 inches of loose basaltic sand, and 6 inches of very hard, well-cemented sand and gravel in alternating layers each about an inch thick. Some of the pebbles consist of reworked fine-grained lake beds like those found at disconformities elsewhere. The section lacks the sought-for layers of volcanic ash.

A pit dug at an elevation of 4311 feet above sea level, 200 feet west of the north quarter-corner, Sec. 14, T. 27 S., R. 16 E., penetrated 43 inches of pumice sand overlying tough, fine-grained lake beds. The pumice sand includes 1-inch pumice pebbles, small pieces of basalt, and a few snail shells. The nearby dump of a former dug well of unknown depth (now caved in) consists of slabby pieces of diatomaceous lake beds. A deflated field in the SE1/4SE1/4 of the same section has had 2 to 3 feet of pumice sand and silt blown away (Fig. 42). Pebbly lag stones are scattered over the present surface. Snail shells occur in the pumice here too.

Figure 42. Deflated farm field, cleared of sagebrush and later abandoned by a homesteader, has lost 2 to 3 feet of lake sediments. Scattered residual pieces of basalt lie on the wind-swept surface

Another pit dug at the NE corner of Sec. 1, T. 27 S., R. 17 E., 2 miles north of Lake, showed 3 inches of loose pebbly sand, 13 inches of lightly cemented sand, 14 inches of compact, fine-grained, flaky lake beds, 3 inches of sand cemented to sandrock, and 22 inches more of only locally cemented sandy lake beds in which the 55-inch-deep pit was stopped. A contrast in the degree of induration at a depth of 16 inches apparently denotes a disconformity.

A 30-foot boring with a soil auger equipped with extra couplings was made beside bench mark D-91, elevation 4306.090 feet, situated near the north edge of the SE1/4SW1/4 Sec. 21, T. 25 S., R. 19 E., in the northeastern part of the Fort Rock Lake basin. The top 19 feet of the material penetrated consisted mainly of medium-grained sand, water-bearing at the base. The material in the bottom 11 feet was dark blue (unoxidized) "mud." No layers of pumice were recognized in the auger test, so an 11 1/2-foot pit was dug by shovel. The section in the pit, as shown in Table 6, includes three beds of volcanic ash. On the basis of Samples 46-01 and 46-02, from the lowest two, these beds are correlated with the uppermost three layers of volcanic ash in the Ana River section. An auger boring to an additional depth of 3 1/2 feet at the bottom of the pit brought up only sands like those in the bottom unit of Table 6.

Table 6. Section of Lake Beds at Bench Mark D-91

Unit	Material	Thickness (inches)	Depth (feet and inches)
13	Surface silt	26	2 - 2
12	Silty lake beds, somewhat jointed	36	5 - 2
11	Volcanic ash, distinct white band at base, remainder reworked	4 1/2	5 - 6 1/2
10	Sand	9 1/2	6 - 3 3/4
9	Clay	6 3/4	6 - 10 1/2
8	Coarse sand	7 1/4	7 - 5 3/4
7	Reworked white volcanic ash	9 3/4	8 - 3 1/2
6	White volcanic ash	1	8 - 4 1/2
5	Fine sand	1	8 - 5 1/2
4	Coarse sand	2 1/2	8 - 8
3	Fine sand	4 3/4	9 - 0 3/4
2	Volcanic ash	1	9 - 1 3/4
1	Sands	28 1/4	11 - 6

In a further search for a complete record of the late volcanic ash falls, besides that at Fossil Lake, a 10-foot pit was dug beneath a white flat in the NW1/4NW1/4 Sec. 13, T. 27 S., R. 19 E., 500 feet south of the Silver Lake-Wagontire road, at an elevation of about 4300 feet above sea level. No identifiable ash layer was found, and an auger test to a total depth of 28 feet was also negative. The material was dry, yellowish brown, sandy silt, tough to dig. Apparently the surface materials here are deposits, probably of Little Pluvial age, brought in by an intermittent drainage course on the rim of Fort Rock Lake basin southeast of Buffalo, a few miles distant to the east.

Summary of Stratigraphy

The lacustrine deposits in the Fort Rock Lake basin consist of two disparate stratigraphic sections separated by a prominent disconformity. The older lake beds in the lower section consist mainly of diatomite and volcanic tephra. This material forms part of what Hampton (1964) called the Fort Rock Formation. Its thickness is variable because of a base of uneven fault blocks of basalt. Water wells have penetrated 200 to about 700 feet of it before reaching basalt.

The upper section is relatively thin and consists of gravel, sand, and silt, including a large fraction of pumice. At some places, especially Fossil Lake, other disconformities occur within these upper beds. Over much of the lake floor the top sediments have later been disturbed by wind and water. Air-laid Mount Mazama pumice is widespread across the area.

SAND DIKES AND JOINTING

Some of the deflation basins expose joint sets and sand dikes in the underlying lake beds. The main joints (Fig. 43) and sand dikes trend northerly, but locally they deviate both to north-northeast and north-northwest, in line with the regional faulting. Most of them at any particular locality are approximately parallel. In some of the stabilized deflation basins, the jointing is reflected by an alignment of dark sagebrush, scarcely recognizable in the field but easily seen on aerial photographs.

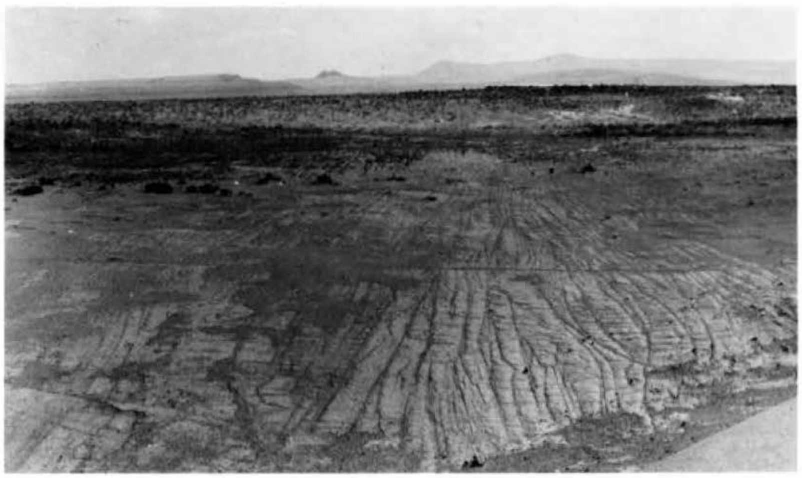

Figure 43. Jointing in older lake beds in eastern part of Four Mile Sink

The largest sand dike seen in the field is one that forms a median ridge that extends N20°E across Four Mile Sink (Fig. 44). The main mass of this dike is several feet wide near the middle but it tapers and branches to only an inch or two, especially toward the northeast. It is composed of sharply angular bits of basalt, wholly unlike any of the lake beds or surface materials exposed in the deflation basin. Hence the material must have come up from below, presumably by water transport or injection along a fracture during an episode of adjustment of the underlying fault blocks. Fault blocks plunging toward the site and bordered by north-northwesterly trending faults are exposed at a distance of only 4 miles to the south.

A second and smaller sand dike in Four Mile Sink, composed of bluish gray pumice sand, lies alongside the first one locally, turns away to the west for several tens of feet, and then turns sharply toward the north-northeast again before finally pinching out. It clearly came from a different underlying source.

As the present top of the large sand dike at Four Mile Sink is only 2 feet below the level of the lake plain outside the deflation basin, the fracture into which it was injected must have broken the surface and may well have created conditions favorable for the beginning of deflation. The liklihood of a connection between minor faulting and the injection of sand dikes on the one hand and later deflation on the other is supported by the presence of sand dikes, although generally small ones, in other deflation basins. Yet none has been seen in the well-exposed Fossil Lake-Sand Springs deflation area. So faulting and sand dikes may not have been necessary to break the surface and initiate deflation.

Sand dikes in the eastern part of the dry floor of Thorn Lake basin are generally only a fraction of an inch to a few inches wide. They are composed of dark grit resemb-

Figure 44. Sand dike in middle of Four Mile Sink, injected from below, here several feet wide. Material on upper right was excavated by deflation from basins on each side of sand dike

ling the volcanic tuff that is exposed in the wave-cut benches to the west and that presumably underlies the site. Occasional pieces of light-colored, silty lake beds are incorporated in the dikes. These sand dikes are more resistant to erosion than the white, fine-grained lake beds which they intrude, and so they stand in relief to an extent of a few inches to about a foot. Locally they form two intersecting sets, so that in fancy they somewhat resemble the remains of walls of mortar. Hence one of the pioneer ranchers dubbed the area the "Sunken City," an intriguing name occasionally still carried on maps of the region. These sand dikes are only about 1 mile from an obvious fault line that trends directly toward the site from the south-southeast. A causal connection is therefore suspected.

MOUNT MAZAMA PUMICE

The basin of Fort Rock Lake was well within the range of the fallout of pumice from Mounta Mazama on the present site of Crater Lake. Fort Rock village is 60 miles beeline from Crater Lake. Kittleman (1973) identified Mazama pumice at Fort Rock Cave and Connley Cave, both near Fort Rock. Fort Rock Valley, the northwestern part of the basin, received the most and coarsest material. Although the bulk of the air-laid Mazama pumice in the Fort Rock Lake basin is sandy, numerous granules and occasional pieces of pebble size make up part of the pumice near Fort Rock, whereas the deposits near Silver Lake on the southwest and in Christmas Lake Valley on the east are almost entirely sandy.

Mount Mazama pumice has been described by many observers, especially by Moore (1934), Williams (1942), Powers and Wilcox (1964), Wilcox (1965), Randle, Goles, and Kittleman (1971), and Kittleman (1973). It is a "glassy hypersthene-augite dacite with accessory hornblende" (Williams, 1942). It contains large but highly variable quantities of minerals, usually 10 to 15 percent by volume, but locally about twice as much. By count (not weight) of enclosed crystals, Kittleman (1973) found its minerals to be about 73 percent plagioclase, 10 magnetite, 9 hypersthene, 4 hornblende, and 3 percent clinopyroxene. The feldspar is alternately zoned from labradorite at the centers of the crystals to oligoclase on the outside (Williams, 1942, p. 145-146).

In the wooded area 4 miles outside the northwest part of the basin, the sheet of Mazama pumice is 38 inches thick. Because of later redistribution by wind and water, its original thickness within most of the Fort Rock Lake basin is not measurable. Wind-blown pumice sand, carried mainly to the east and northeast, is thickest in a belt through T. 26 S., R. 15, 16, and 17 E. That reworked by water is treated on subsequent pages. Much of the disturbed surficial material on the floor of the basin probably is of Mount Mazama origin.

ALTITHERMAL CLIMATIC EFFECTS

Studies of mountain glaciers and of pollen records in peat bogs have established that a climate warmer and drier than the present prevailed about 6,000 to 4,000 years ago. Some glaciers in the mountains were shortened and others melted away completely. Vegetation changed in places from a humid type to one adapted to a semiarid climate, or from a semiarid type to a definitely xeric sort. This stage of warm dry climate is called the Altithermal Interval.

This change of climate also affected the dry bed of former Fort Rock Lake, mainly by increasing the geologic work of the wind. Wind activity excavated numerous deflation basins and piled up sand dunes.

Deflation Basins

Deflation formed many enclosed depressions in the sediments on the floor of the Fort Rock Lake basin (Allison, 1941). They are locally called sinks. It also stirred up deposits of Mount Mazama pumice, piled up dunes in the lee of deflation basins and sandy tracts, and in Recent time hollowed out blowouts in the dunes. Where early homesteaders, especially between 1890 and 1910, cleared sagebrush from part of the land in order to raise wheat, rye, or other crops, the wind in many places has removed 2 to 3 feet of the surficial material (Allison, 1966a, Plates 4 and 8). The most severe deflation took place, however, in the Altithermal Interval.

The deflation basins occur in four main areas: (1) Fossil Lake, (2) Sand Springs area, (3) Christmas Lake-Alkali Flat belt, and (4) an irregular belt about 15 miles long between Fort Rock village and Thorn Lake. The Fossil Lake deflation effects are described in the 1966 publication cited above.

Sand Springs Basin

The Sand Springs basin, northeast of Fossil Lake, extends east-northeasterly from the N 1/2 Sec. 3, T. 26 S., R. 19 E., for a distance of about 2 miles. Its northern rim, like that at Fossil Lake, has been undergoing recent undercutting (Fig. 45), whereas its southern edge and most of its floor has been stabilized be vegetation. Its sides flare

Figure 45. Part of Sand Springs deflation basin, northeast of Fossil Lake. The far side (across middle) is presently retreating by continued wind erosion. The depth of the basin is 20 to 25 feet

out downwind at an angle of 50°, so the basin rapidly widens eastward to about 1 1/2 miles. It coalesces with the Fossil Lake deflation tract in the western part of Sec. 2, T. 26 E., R. 19 E. The elevation of a flat in the western part of the basin is 4285 feet above sea level, and that of the surrounding lake plain (somewhat uneven because of wind-blown pumice cover) is about 4305 feet on the west and 4310 feet on the north. A leveling traverse southward across the basin from bench mark C-91 (elevation 4340.821 feet) reached a low of 4285 feet. So this deflation basin is 20 to 25 feet deep.

Christmas Lake-Alkali Flat Deflation Belt

A series of shallow deflation basins occurs in the Christmas Lake-Alkali Flat area northeast of Lake. They lie in a belt trending northwest-southeast, about 6 miles long and 1 to 3 miles wide. Christmas Lake, about 2/3 mile long and 1/3 mile wide, lies mostly in the NE 1/4 Sec. 12, T. 26 S., R. 18 E. Alkali Flat, about 3 miles long and nearly 1 mile wide, lies at the northwest end of the belt (Fig. 46). The other basins toward the southeast are smaller.

Figure 46. Alkali Flat, a deflation basin now coated with evaporites, 5 miles north of Lake. Its elongation is in line with a fault and cinder cones shown in Fig. 9. Spring-fed Christmas Lake is at bottom right

Alkali Flat has an elevation of 4289 feet above sea level. A bench mark (L-91) on an extensive flat 1 1/2 miles west of the southeastern end of Alkali Flat is 4317.826 feet above sea level, so the depth of the Alkali Flat basin does not exceed 29 feet.

Although considerable wind-blown sand is piled up around the margins of the deflation basins in the Christmas Lake-Alkali Flat tract, the basins may not be due entirely to deflation. Rather, they may have been formed partly by post-Fort Rock Lake faulting. The belt in which they lie is exactly in line with a row of four Recent volcanic vents (Fig. 9), situated 2 1/2 to 5 miles northwest of Alkali Flat. These vents in turn are parallel to the main direction of the fault traces in the vicinity (Peterson and Groh, 1964). Their lavas look fresh and young. A slight vertical movement on one or more of the faults, related to the volcanic eruptions, would be expected. If any down-sinking occurred as a result of such faulting or lava extrusion, the nearby Alkali Flat area presumably would also be depressed. Such a connection is speculative. Even though faulting may merely have broken the surface only slightly, such a break would favor deflation by providing ready access to deflatable lacustrine sediments.

Wave work on lakes and ponds which formed later in these deflation basins modified the basin outlines and formed sandy beaches, and these beaches in turn provided additional sand for further transport by the wind.

Fort Rock-Thorn Lake Deflation Belt

The deflation basins in this belt are most numerous in T. 26 S., R. 14 and 15 E., in T. 27 S., R. 16 E., and in the northern part of T. 28 S., R. 16 E. (Fig. 47). They range in area from a small fraction of an acre to hundreds of acres, and in depth from less than a foot to 44 feet. Only a few of them will be described here.

One is an elliptical basin about 1 1/2 miles long and 1/2 mile wide, which extends from the southern part of Sec. 9, T. 27 S., R. 16 E. southeasterly across the NE 1/4 Sec. 16 into the western part of Sec. 15 (Fig. 48). Most of its bottom lies 10 to 15 feet below the surrounding lake plain, which is itself somewhat uneven because of wind work. The northeast side of the basin is bordered by a conspicuous ridge of sand that rises 20 feet above the floor of the basin. This ridge apparently began as a dune ridge on the leeward side of the deflation basin, grew as beach dunes when the basin subsequently became the site of a lake, and later was subjected to blowouts and other modifications in very recent time. Most of the floor of the basin has been stabilized by a cover of sagebrush; low barren spots become mudholes or shallow pools in wet weather.

The heart-shaped basin of Thorn Lake (now dry) presumably began by deflation also, but the modern lake by means of its wave work settled into its bed, rounded out its form, and developed a beach ridge on its rim (Fig. 49). Wind-blown sand derived from the basin, partly no doubt via the beach, extends northeasterly as much as a half mile beyond the northeastern rim. The floor of the basin has an elevation of 4279 feet above sea level. The basin rim is breached on the east by a stream channel near the 4300-foot level. This channel is said to have carried the overflow of Silver Lake into Thorn Lake during exceptionally wet years several decades ago. A circuitous channel (Fig. 49) also connects Thorn Lake with several other shallow basins situated farther north within the 4310- to 4320-foot range of elevations on the Fort Rock Lake plain.

Arrow Sink is a deflation basin situated at the western edge of Sec. 30, T. 27 S., R. 16 E. It is 1/4 mile long, 44 feet deep, and bordered by a 22-foot ridge of wind-deposited material on its northeastern rim (Fig. 50). A nearby deflation basin, extending more than 1/2 mile through the NW 1/4 of this same section into Sec. 19, is approximately 32 feet deep.

A striking deflation basin lies in the SE1/4SE1/4 Sec. 21, T. 27 S., R. 16 E., and adjacent parts of Secs. 22, 27, and 28 (Figs. 40 and 43). As it is located 4 miles east of the Arrow Gap road, which crosses the Connley Hills, it is conveniently referred to as Four Mile Sink. The nearly flat, unmodified, sagebrush-covered lake plain adjacent to Four Mile Sink on the windward west side has an elevation of 4313 feet above sea level. The east side has a dune-crested embankment of material blown out of the basin. The floor of the northwestern part, 30 feet deep, is now covered by slope-wash material and sagebrush. Most of the remainder of the basin has been undergoing renewed deflation in recent years. The southwestern part of the basin is 41 feet below the western rim; the eastern part, beyond a dividing ridge, is 31 feet deep. The walls of the basin expose a high proportion of easily removed diatomite and volcanic ash and a few layers of dark cinders in the lake sediments in which the basin developed.

Lag Materials

The removal of fine particles from the deflation basins by the wind tended to concentrate coarse particles that were too heavy for the wind to remove. These coarse particles remain on the surface of the ground--pieces of basalt, fossil bones at Fossil Lake, and fossil snail shells. Widespread angular fragments of basalt, ranging in size from granules to boulders, presumably were ice-rafted far offshore on Fort Rock Lake. They are numerous on the surfaces of deflation areas.

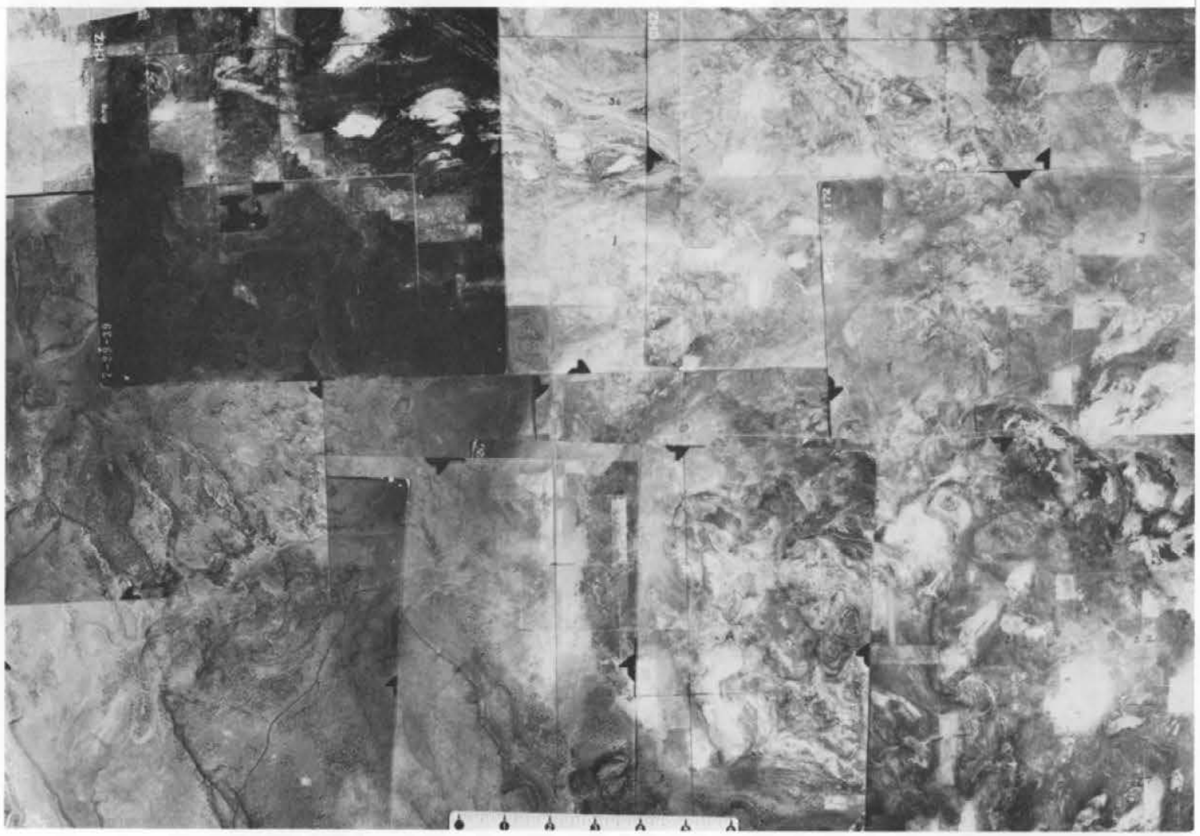

Figure 47. Deflation basins in Fort Rock Valley. The light-colored oval north of the 5-inch mark on the scale is Arrow Sink. A long basin is nearby on the north-northeast. The round patch (fogged picture) near the southeast corner is Four Mile Sink, 40 feet deep. Most other light areas are deflation basins, deflated fields (rectangular), or burnt-sagebrush areas (extreme right). The 6-inch scale corresponds to approximately 2 miles

Figure 48. Deflation basin (bottom) in Fort Rock Valley, bordered by a beach and dune ridge on the northeast. Dark lines within it are growths of sagebrush favored by joints in the underlying lake beds

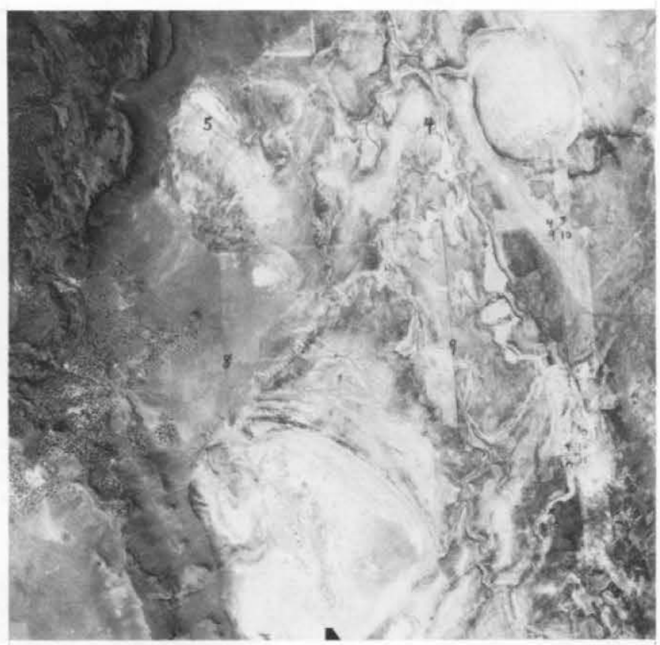

Figure 49. Thorn Lake deflation basin (heart-shaped; bottom), beach ridge, and wind-blown products to the northeast. An oval basin (upper right) and Thorn Lake are joined by crooked stream channel. Wave-eroded eastern side of Connley Hills-Table Rock peninsula is on the left

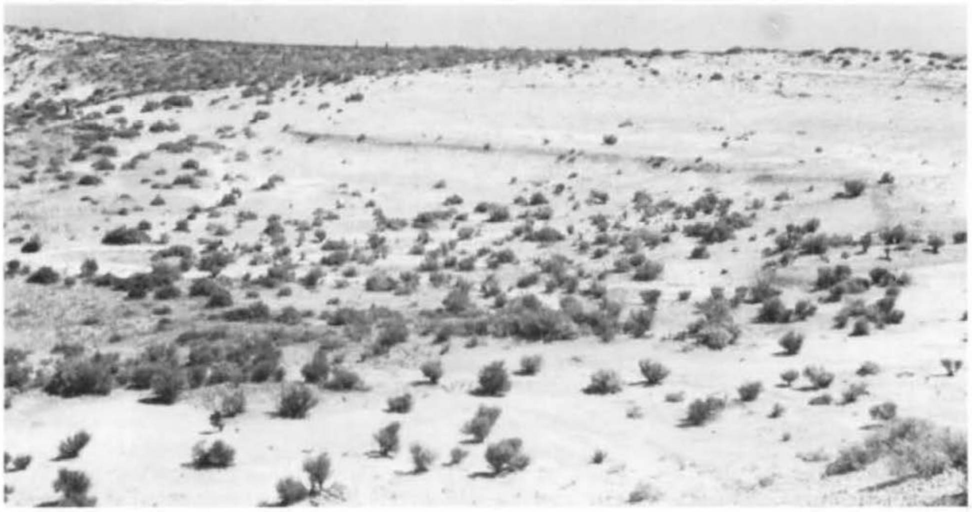

Figure 50. Arrow Sink deflation basin, 44 feet deep

Dunes

Accumulations of wind-blown sand occur at many places in the Fort Rock Lake basin. Some of them merely surround bushes or they form thin patches of sand which lack distinctive forms; others are classical dunes in shape. Many of the dunes had their origin in deposits of sandy Mount Mazama pumice. Other dunes are associated with each of the deflation basins, especially with the Fossil Lake-Sand Springs deflation tract (Figs. 20 and 21). They commonly form transverse ridges or detached hillocks leeward of the deflation basins, or leeward of the shores of shallow water bodies which later occupied these basins.

LITTLE PLUVIAL CLIMATIC EFFECTS

The Altithermal Climatic Interval was succeeded by a climate which was a little wetter and cooler than the present. Existing mountain glaciers grew larger and new ones formed in valleys previously empty of ice. This climatic episode is called the Little Ice Age. The term used for the time equivalent of the Little Ice Age in nonglacial areas is the Little Pluvial Age. It began somewhat more than 3,000 years ago and lasted until about 2,000 years ago. The principal effect in nonglacial areas was increased rainfall and corresponding changes in vegetation, as shown by pollen records.

Significant changes occurred in Fort Rock Lake basin in Little Pluvial time. Deflation basins previously excavated during the Altithermal Interval became ponds and a thin sheet of water covered a considerable part of the lake floor. Wave work on these water bodies piled up Mount Mazama pumice as beach ridges. Some previous deflation basins probably were partly filled. Since the end of the Little Pluvial Age, the wind has resumed deflation and has further modified the pumice and other fine-grained materials within its reach.

Accumulation of Water

The Silver Lake area offers a clue to one possible source of extra water. The late M. S. Buchanan, a former resident of Lake, reported orally that modern Silver Lake overflowed into Thorn Lake near the turn of the century (Fig. 51). The entrance elevation to Thorn Lake is not precisely known, but roughly it is between 4300 and 4310 feet. The lowest point found on a traverse between the southeast end of the Connley Hills ridge and the sloping fault blocks east of Thorn Lake was 4308 feet above sea level in a drainage channel. A shallow channel 1700 feet nearer Thorn Lake is at 4311 feet, and a point on an old road east of Thorn Lake is also at 4311 feet. So the modern high-water level of Silver Lake may well have been on the order of 4310-4315 feet in order to reach Thorn Lake.

The Summer Lake basin provides an analogous Little Pluvial rise of water level. Summer Lake, situated beyond a surface drainage divide to the south of the Fort Rock Lake basin, has a modern high-water stage of 4178 feet, according to a U.S. Forest Service map. Its level is highly variable; in 1944 it was 4146.3 feet. A beach at 4190 feet at its north end, considered to be Little Pluvial in age, seems to indicate a modest rise of Summer Lake at that time. So a similar rise of water in the Fort Rock Lake basin, presumably in large part via the Silver Lake route, would have flooded a substantial part of the flattish floor of the basin, much of which is less than 4320 feet above sea level. Detailed topographic maps are not available, so the best guide to a renewed lake level in Little Pluvial time is furnished by shore lines involving Mount Mazama pumice. Let us examine some representative localities.

Little Pluvial Lake Shores

The "Hand" Area

A peculiar array of low ridges and shallow swales occurs in Secs. 1 and 2, T. 26 S., R. 14 E., 3 miles east-southeast from Fort Rock village. The arrangement in fancy resembles part of a human hand, with thumb and slender fingers (Fig. 52). A leveling traverse westward from the north quarter-corner of Sec. 1 (south of the township-survey correction lot) and extending to the northwest corner of Sec. 1 crossed three ridges and intervening swales having elevations between 4311 and 4318 feet. The northwest corner is at 4313 feet. Three wind-modified ridges within a distance of 1/4 mile south from the northwest corner of Sec. 1 have elevations of 4312, 4308, and 4310 feet. The "index finger" ridge, little torn by wind, stands at 4312 to 4314 feet, while the flats immediately north and

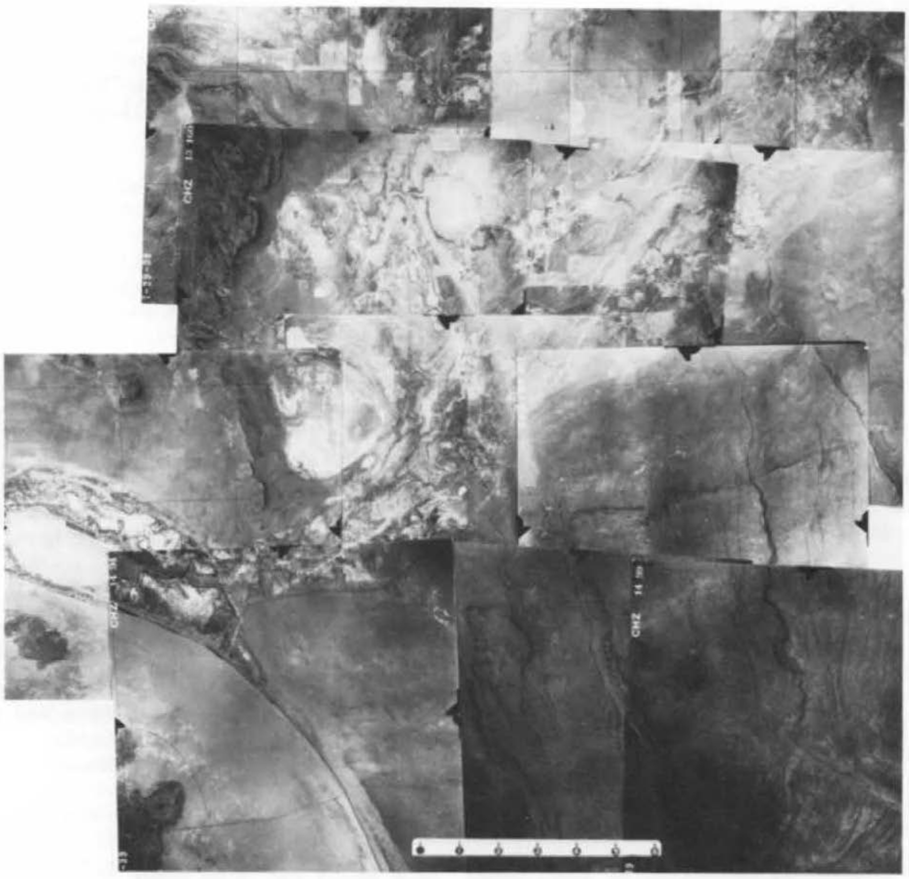

Figure 51. Silver Lake-Thorn Lake connection. Silver Lake (nearly dry, southwest corner), bordered by a beach ridge (bearing Fremont Highway), is said to have overflowed into Thorn Lake (middle left, now dry) many decades ago. A shallow Little Pluvial lake covered the north central area and points farther north. A high Fort Rock Lake shore line on a basaltic fault block is shown near the middle right. The 6-inch scale represents about 2 miles

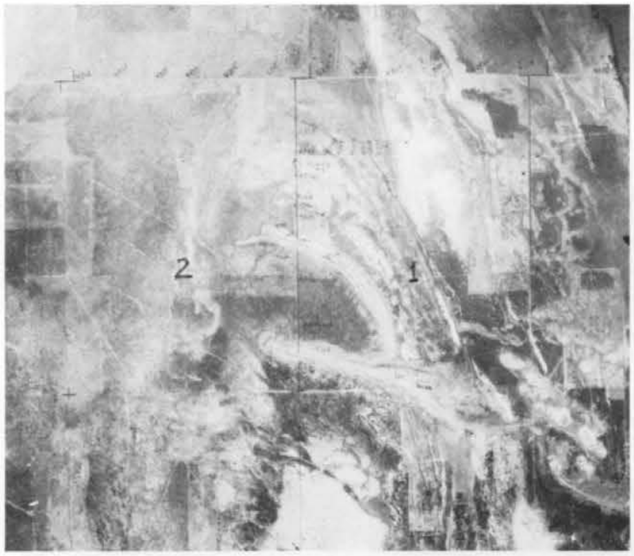

Figure 52. Little Pluvial pumice ridges in the "hand" area near Fort Rock village

south of it are at 4307 and 4306 feet, respectively. Most of the "thumb" ridge stands at 4323 to 4326 feet, and the flat at the southwest corner of Sec. 1 is at 4302 feet. A bulky dune of pumice sand in a down-faulted trough near the base of the "thumb" reaches 4332 feet in elevation. The pumice in all these ridges is identified as of Mount Mazama origin.

The arrangement of these low ridges in the "hand" area is not the usual arrangement of sand dunes. Rather, it resembles that of bars and spits made along the shore of a small bay of a lake, while the water level was declining, say from about 4315 to less than 4310 feet above sea level.

The "hand" area is at the north end of an oval basin about 4 miles long and 2 miles wide, with a mile-wide opening on the southeast (Fig. 53). The former shallow lake, responsible for the "hand" shore features, younger than the eruption of Mount Mazama about 7,000 years ago, must have occupied the basin during Little Pluvial time. The southeast end of this oval basin also has a beach ridge of pumice. The western or windward shore is indistinct.

A southeasterly extension of the "thumb" is a beach and dune ridge broken by a gap near the NE corner, Sec. 12, T. 26 S., R. 14 E. A patch of wind-blown pumice sand with several blowouts occurs in the lee of this 4312-foot pumice ridge in the NW 1/4 Sec. 7, T. 26 S., R. 15 E.

A mile-wide down-faulted depression (a graben) just east of the "hand" is bordered by a scarp only 4 feet high on the west side where crossed by the township-line road east of Fort Rock village, and 19 feet high on the east side. Some pumice lies in this graben, especially in the eastern part of Sec. 1, T. 26 S., R. 14 E.

The fault block on the east side of this graben slopes gently toward the southeast. Its surface near the north line of the township is covered with granule gravel composed mostly of rounded basaltic rock particles. Whatever cover of Mount Mazama pumice it once held has been almost completely removed by wind. A low ridge of pumice sand on this fault block crosses the NW 1/4 Sec. 5, T. 26 S., R. 15 E., continues northerly beyond the survey-correction lot and the township line, and then swings eastward.

A pit in this ridge in Sec. 5 revealed the stratigraphic section shown in Table 7. The top layer is considered to be a wind-laid layer of Mount Mazama pumice. More than 90 percent of the clean-looking basal pumice exceeds 0.125 mm in particle size. Pumice granules from unit 3 may be part of the initial fall of Mount Mazama pumice, as may also be the faintly stratified material. On the other hand, it may have been washed downslope

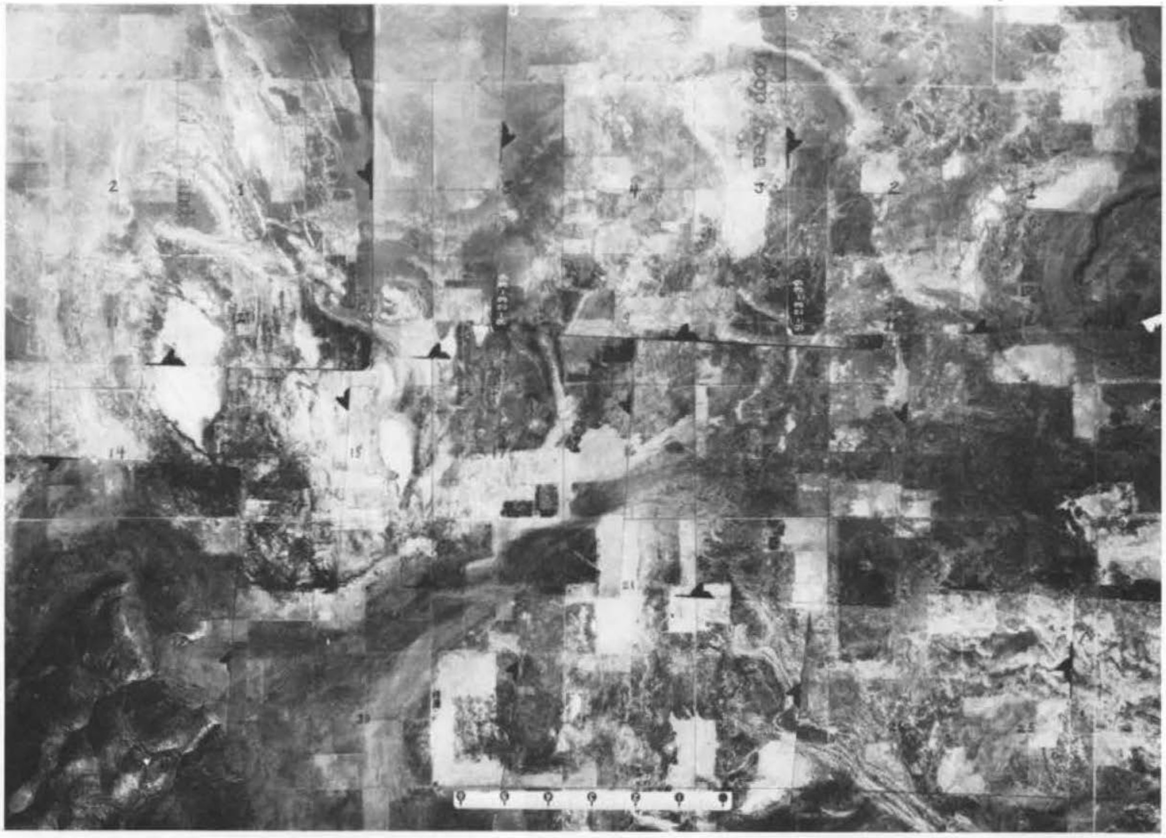

Figure 53. Little Pluvial lake sites in Fort Rock Valley. Four interconnected, shallow subsidiary basins appear here: (1) from the "hand" south to the Connley Hills (on left) and a northeast-projecting rock ridge, (2) the "loop" area (upper right), (3) at middle bottom, and (4) in the southeast quarter. The marginal ridges are beaches and associated dunes of redistributed Mount Mazama pumice. The 6-inch scale corresponds to about 2 miles

into water. At an elevation of 4326 feet, if entirely air-laid, it must have escaped erosion by Little Pluvial water, possibly because it was protected then as now by wind-laid sand. If not thus protected, the 4326-foot figure may set an upper limit on the depth of the Little Pluvial submergence of the Fort Rock Lake basin floor.

Table 7. Section exposed in pit in Sec. 5, T. 26 S., R. 15 E.
(In low ridge, surface elevation 4329 feet)

Unit	Material	Thickness (inches)
5	Loose structureless pumice, mostly sand-size, presumably wind-blown	33
4	Loose pumice, mostly coarse sand and granules, partly pebbly, with a faint bedding	29
3	Clean pumice granules; apparently a primary fall	4
2	Mixed basalt granules, basalt pebbles, and volcanic ash; cemented	8
1	Basaltic granule gravel	n.d.

The Pumice "Loop" Area

A well-developed looping ridge of pumice sand lies across the township line about 5 miles east of Fort Rock village (Fig. 53). Immediately west of the loop the elevation of the ground is 4321 feet; east of the loop, 4317 feet. The western part of the loop in dune form rises to a little more than 4330 feet; the east side to 4346 feet. As the interior of the loop at 4315 to 4318 feet is the site of a temporary pond in wet weather now, it surely must have been the locus of a lake during the Little Pluvial climatic stage. The present loop is a combination of beach and dune deposits. The pumice in this loop is also of Mount Mazama origin.

The loop is open to the south into a larger Little Pluvial lake basin. The beach ridge on the east side of the loop runs south through Sec. 2, T. 26 S., R. 15 E., and then swings southeasterly through Sections 11 and 12 and beyond. At the north quarter-corner, Sec. 11, the western or strand side of the ridge has an elevation of 4319 feet; on the east side, dune sand is piled onto a rocky ridge to more than 4350 feet.

Another shallow semi-detached basin lies in the southern part of T. 26 S., R. 14 E. It has a concentration of pumice sand attached to a low rocky rise in the east half of Sec. 27 of that township (Fig. 53). High ground southeast of this rocky point formed a divide between two Little Pluvial lake basins, upon which multiple pumice ridges were built from both southwest and northeast sides in Sec. 26, 35, and 36 (Fig. 54). These ridges continue southeastward.

Figure 54. Little Pluvial pumice beach ridges

The Y-Bar Area

This locality is in the SE 1/4 Sec. 24, T. 26 S., R. 16 E., where a cuspate Y-shaped gravel bar about 5 feet high juts out southwestward from a basalt cliff (Fig. 55). Pits dug into this bar at an elevation of 4347 feet showed only basaltic gravel and sand, but no pumice. Hence it is considered to be older than the pumice falls. Whatever pumice fell upon it has been blown or washed off.

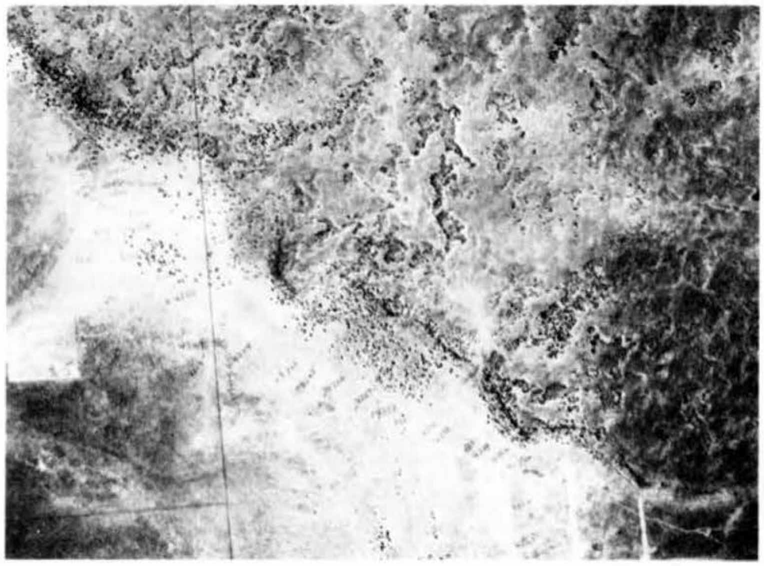

Figure 55. The Y-bar area, below the basalt cliff in upper left. Abundant wind-blown Mount Mazama pumice supports juniper trees. Road elevations decline from 4354 feet on the right to 4324 feet at the township range line. Rounded pebbles of pumice form a low ridge at 4328 feet elevation (south of the trees, left) and other apparently wind-rolled pumice pebbles occur slightly higher farther north. A Little Pluvial shore line curves across the southwest corner

At a distance of 960 feet south of the Y-part of the bar, is a narrow, sharply defined, arcuate ridge cresting at 4338 feet. A hand-dug pit revealed its composition. To a depth of 1 foot, this ridge contains granules and small pebbles of basalt, possibly mixed in by frost action or rodents. Below this gravel is a 20-inch structureless layer of pumice sand lying on dark-colored basaltic gravel. About 35 percent of the material is between 1/8 and 1/4 mm in particle size. Its feldspars are mixed; its heavy minerals--mainly hypersthene and hornblende with a little clinopyroxene--constitute 5.6 percent by weight. The minerals in crushed glass particles (n 1.507) are plagioclase (An_{42}) and hypersthene (n 1.720). Many grains are rounded, hence detrital. As the aggregate also contains rounded rock particles, it is not an air-fall. Instead, the mixture, largely of Mount Mazama pumice, forms a dune ridge.

At a distance of 880 feet farther south, at an elevation of 4328 feet, is another ridge about 3 feet high composed almost entirely of small rounded pumice pebbles. The material resembles the pebbly pumice at Arrow Sink. This pumice probably was put ashore when the Little Pluvial lake was at about a 4325-foot level.

Seven Mile Ridge-Green Mountain Gap

The gap between the north end of Seven Mile Ridge on the south side and the lavas of Green Mountain on the north divides the Fort Rock Lake basin into two main parts--Fort Rock Valley on the west and Christmas Lake Valley on the east (Figs. 1 and 56). The gap is about 3 miles wide. A leveling traverse across the gap found more than 2 miles of the way to lie between 4314 and 4320 feet above sea level. The lowest spot found was at 4312 feet. For miles both east and west of this gap, the ground is nearly flat and generally between 4315 and 4320 feet above sea level. The flat surface extends eastward beyond Lake (BM 4316.412 feet) to Buffalo (4318 feet), and even descends to between 4300 and 4310 feet

Figure 56. Seven Mile Ridge-Green Mountain gap. The flattish floor of Fort Rock Lake between Seven Mile Ridge (below center) and Green Mountain (at top) connects Fort Rock Valley on the west with Christmas Lake Valley to the east. Little Pluvial Age lake water extended through this gap. Light-colored rectangular areas are abandoned homesteads cleared of sagebrush and later stripped of soil by wind. The 6-inch scale represents about 2 miles

over part of this stretch. So any water that crossed the Seven Mile Ridge-Green Mountain gap in Little Pluvial time would connect Fort Rock Valley with Christmas Lake Valley and spread water to the base of the fault-scarp rim of Fort Rock Lake basin north of Buffalo.

Confirmation of such a wide sheet of a shallow Little Pluvial lake is furnished by pumice beaches and associated dunes around the periphery of Christmas Lake Valley as well as those already mentioned in Fort Rock Valley. Examples may be seen for instance beside Seven Mile Ridge; south and southeast of Lake; and south, southeast, and north of Buffalo.

AGE OF PLUVIAL FORT ROCK LAKE

Geologists generally agree that the pluvial lakes of the Great Basin were formed during the Pleistocene Epoch or Ice Age. A direct relation of the expanded lakes to glacial stages elsewhere was accepted by Russell (1883, p. 435-464; 1885, p. 288; 1889, p. 269-394), Gilbert (1890, p. 438), Antevs (1925, p. 74; 1945, p. 26; 1952, p. 98), and many others later.

Pleistocene Time Scale

The standard North American Pleistocene time scale, into which the pluvial lake histories must be fitted, is as follows:

Wisconsinan glacial stage
  Sangamon interglacial
Illinoian glacial stage
  Yarmouth interglacial
Kansan glacial stage
  Aftonian interglacial
Nebraskan glacial stage

These four main glacial stages find common acceptance, but opinions differ mainly as to their duration. Using a time scale based on paleomagnetic reversals of the earth's magnetic field, the relative abundance of certain foraminifera, changes in species, right and left coiling of shells, and extinction of some of them, Ericson and Wollin (1968) estimated the total Pleistocene time to be about 2 million years, of which the Wisconsinan glacial stage took about 100,000 years. The subdivisions and duration of the Wisconsinan glacial stage have been in controversy. Recent changes in the stratigraphy of the Wisconsinan stage take account of glacial deposits of post-Sangamon age that are older than the "classical" Wisconsin glacial drift sheets (Iowan, Tazewell, Cary, and Mankato) recognized prior to 1950 (Flint, 1963).

Frye and Willman (1960, 1963) describe the development of the classification of the Wisconsinan glacial stage in Illinois, based as far as possible, on a radiocarbon time scale. The Pleistocene stratigraphy of Illinois is given at length by Willman and Frye (1970). According to their chart, the Wisconsinsn in Illinois and Wisconsin may be subdivided as in Table 8.

Table 8. Subdivisions of the Wisconsinan Glacial Stages in Illinois
(After Willman and Frye, 1970)

7,000 years ago - - - - - - - - - - - - - -
  Valderan substage
11,000 years ago - - - - - - - - - - - - - -
  Two Creekan substage
12,500 years ago - - - - - - - - - - - - - -
  Woodfordian substage
22,000 years ago - - - - - - - - - - - - - -
  Farmdalian substage
28,000 years ago - - - - - - - - - - - - - -
  Altonian substage
75,000 years ago - - - - - - - - - - - - - -

In their scheme the Woodfordian replaces the former Iowan (of Illinois), Tazewell, and Cary substages; the "classical" Wisconsinan is shortened to 28,000 years; and a long preclassical substage, the Altonian, extends back to about 70,000 years.

The reconciliation of differences in the classification of the Wisconsinan glacial stage is not critical to our present study of the dating of the pluvial lakes of the West. It is enough for us to recognize that the Pleistocene as a whole was a time of multiple continental and alpine glaciation, and that the Wisconsinan itself in the Great Lakes region and in the mountains of the West had several substages.

Glacial Stages in the Rocky Mountains

Many references to glaciation in the Rocky Mountains are given by Richmond (1962, 1965, 1970), and by several others earlier. Richmond's fivefold sequence is summarized in Table 9. He correlated the Washakie, Cedar Ridge, and Sacagawea (sic) Ridge Glaciations with the Nebraskan, Kansan, and Illinoian stages of the mid-continent region. The Bull Lake (with 3 ice advances) and Pinedale (with 3 glacial advances) were considered equivalent to Wisconsinan, but Bull Lake Glaciation possibly may be Illinoian instead.

Table 9. Glacial Sequence in the Rocky Mountains
(After Richmond, 1965)

Approximate Age	Divisions	
	Neoglaciation (Temple Lake and Gannet Peak Stades)	
6,500 to 4,000 yrs	Altithermal Interval	
11,800 yrs		
		Late stade
		Interstade
	Pinedale Glaciation	Middle stade
		Interstade
		Early stade
25,000 yrs		
	Interglaciation	
32,000 yrs		
		Late stade, 2d episode
		Nonglacial interval
	Bull Lake Glaciation	Late stade, 1st episode
		Nonglacial interval
		Early stade
About 80,000 yrs		
	Interglaciation	
	Sacagawea Glaciation	
	Interglaciation	
	Cedar Ridge Glaciation	
	Interglaciation	
	Washakie Glaciation	

Glacial Stages in the Far West

Alpine glaciation also occurred in multiple stages in the mountains of the Far West. Matthes (1930) recognized the Glacier Point, El Portal, and Wisconsin (with two maxima) glacial stages in Yosemite Valley, California. Blackwelder (1931, 1934) named a fourfold glacial sequence in the Sierra Nevada as follows: (1) McGee, (2) Sherwin, (3) Tahoe, and (4) Tioga. The Sherwin stage was thought to be equivalent to the Kansan of the Mid-West, while the Tahoe and Tioga appeared to represent Early and Late Wisconsin stages, respectively.

Sharp and Birman (1963, p. 1079; Birman, 1964) expanded the Sierra Nevada sequence by adding Tenaya and Mono Basin glaciations to the series as follows:

	Tioga
Wisconsin	Tenaya
	Tahoe
Illinoian	Mono Basin
Kansan	Sherwin
Nebraskan	McGee

Morrison (1965, chart, p. 268) correlates a 2-stade Tahoe glaciation in the Sierra Nevada with the Bull Lake glaciation of the Rocky Mountains, and tentatively correlates the Tenaya, Tioga, and a later Hilgard (Wahrhaftig and Birman, 1965) as stades equivalent to the threefold Pinedale glaciation in the Rocky Mountains. Thus he recognizes at least five glacial advances in Wisconsinan time.

Burke and Birkeland (1976) studied the soil development and weathering of late Pleistocene tills under like environmental circumstances on the eastern Sierra Nevada. They conclude that separate designation of post-Sherwin glaciation other than Tahoe and Tioga is not justified.

The sequence in the Cascade Range of Oregon, so far as known, is similar to that of the Sierra Nevada by Blackwelder. Thayer (1939) found evidence of three glacial stages in the North Santiam River Valley. He named them the Mill City, Detroit, and Tunnel Creek stages, and tentatively correlated them with the Sherwin, Tahoe, and Tioga stages of California.

The late part of the Pleistocene sequence in the Puget Sound area of Washington (Armstrong and others, 1965; Crandell, 1965; Crandell and others, 1965b; Easterbrook, 1966, 1974; Easterbrook and Hansen, 1971; Hansen and Easterbrook, 1974; Mullineaux and others, 1955) is shown in Table 10. The Salmon Springs Glaciation is considered to be possibly early to middle Wisconsinan, and the Fraser Glaciation late or "classical" Wisconsinan, or more specifically, the equivalent of Pinedale in the Rocky Mountains.

Table 10. Late Pleistocene Glacial Stages in Northwest Washington

	Sumas Stade (ice readvance in Fraser River Valley, B.C., about 11,000 to 10,000 years ago)
Fraser Glaciation	Everson Interstade (marine and glaciomarine sediments; 13,500 to 11,000 years ago)
	Vashon Stade (advance of Puget lobe of Cordilleran ice sheet between 18,500 and 13,500 years ago)
Olympic Interstade (between more than 27,000 and 18,500 years ago)	
	Younger glacial episode
Salmon Springs Glaciation	Nonglacial interval
	Older glacial episode

Correlation of Pluvial Lakes with Glaciation

Regarding the relation of pluvial Lake Mono, California, to glaciation, Antevs (1925, p. 74) states: "The highest stage of Lake Mono was reached after, probably shortly after, the maximum extensions of the glaciers in the adjacent Sierra Nevada (Russell, 1889, p. 369; Gilbert, 1890, p. 314). This is shown by shore-lines on the inner as well as the outer sides of the moraines left by glaciers and by deltas formed between the embankments." In Antevs' view (1925), the pluvial lakes were contemporaneous with glaciers in the mountains, inasmuch as both lakes and glaciers required heavier precipitation and lower summer temperatures than now.

Blackwelder (1941) thought that the former pluvial lakes of two distinct ages in the Searles Lake basin of eastern California "may be correlative with the Tahoe and Tioga glacial stages in the Sierra Nevada."

Putnam (1950) described the relationships between the Pleistocene glacial sequences and shore lines of Lake Russell, the forerunner of modern Mono Lake, California. He mapped about 30 Tioga terminal and recessional moraines tributary to the basin and correlated groups of these moraines with certain stillstands among the 38 recognized shore lines of Lake Russell. His map shows four closely spaced clusters of moraines, two of them especially prominent, one in the terminal reaches and a second one about two miles up-valley in each of three tributary canyons. As the Tioga terminal moraine reaches to the highest shore line, 655 feet above modern Mono Lake, and is complemented by a delta, Putnam concluded (p. 121) "that the high stand of the lake was essentially synchronous with the advance of Tioga ice, and that, as the ice withdrew, the lake level was accordingly lowered. When the ice front was relatively stationary, the lake waves cut broad terraces; when retreat was rapid, only narrow benches were carved." A similar history occurred at Lake Tahoe (Hyne and others, 1972).

The synchroneity of pluvial Lake Bonneville with glaciation is well shown near the mouth of Little Cottonwood Canyon, south of Salt Lake City, Utah (Morrison, 1961a, 1965; Richmond, 1965). At that site glaciers of Bull Lake age extended a mile beyond the canyon mouth and deposited morainic material in direct association with high-level, fine-grained lake deposits.

Lake Bonneville and Lake Lahontan as Analogs

The history of pluvial Fort Rock Lake in Oregon is apt to be analogous to the history of Lake Bonneville and Lake Lahontan, and like that of Lake Russell and similar but smaller pluvial lakes in California.

Lake Bonneville, Utah, was a pluvial lake having an area of 19,950 square miles and a maximum depth of about 1100 feet. Its history has been studied by Gilbert (1890), Bissell (1952, 1963), Hunt and others (1953), Jones and Marsell (1955), Eardley (1956), Feth and Rubin (1957), Eardley, Gvosdetsky, and Marsell (1957), Antevs (1945, 1948, 1952, 1955), Eardley and Gvosdetsky (1960), Richmond (1961), Morrison (1961a, 1965, 1970, 1975), Williams (1962), Broeker and Kaufman (1965), Shuey (1972), and Eardley and others (1973).

Because of the late Pleistocene diversion of Bear River into the Lake Bonneville drainage basin, according to Morrison, Lake Bonneville overflowed into Snake River via Red Rock Pass as late as middle Pinedale time, about 14,000 years ago, whereas Lake Lahontan never did overflow its rim.

Using volcanic ash layers, repeated soil zones, and paleomagnetic reversals as stratigraphic markers in two drill cores and exposed lake deposits, Eardley and others (1973) and Morrison (1975) have extended the Lake Bonneville history back many thousand years, during which the lake level rose and fell tens of times.

Lake Bonneville is thought by Morrison (1965, 1975) to have had five expansions in Bull Lake time and three main rises in Pinedale time during the late Wisconsinan glacial stage, and to have been preceded by twenty or more other deep lakes during the Kansan and Illinoian glacial stages.

The principal Lake Bonneville shore lines are named Bonneville, Provo, and Stansbury. The Bonneville shore line at Red Rock Pass is 5085 feet above sea level (nearly 900 feet above Great Salt Lake), 5090 to 5200 feet (differing because of later warping) along the front of the Wasatch Range, and as much as 5300 feet above sea level in the middle of the basin, where isostatic rebound resulted from removal of the weight of the water (Crettenden, 1963). Downcutting during overflow between 15,000 and 12,000 years ago (Morrison, 1965, p. 276), or about 12,000 years ago (Broeker and Kaufman, 1965) reduced the outlet to approximately 4820 feet. The type Provo shore line is at 4800 to 4825 feet. The Stansbury level is a complex of multiple shore lines at 4450 to 4550 feet (Eardley, 1956), but especially about 4530 feet above sea level. They record several stillstands. Part of the Stansbury shore is possibly late Pinedale in age.

About 50 radiocarbon dates relate to Lake Bonneville (Libby, 1955; Crane, 1956; Broeker and Orr, 1958; Rubin and Alexander, 1958, 1960; Broaker, Ewing, and Heezen, 1960; Olson and Broeker, 1961; Broeker and Kaufman, 1965). According to Broeker and Kaufman (1965, p. 546-547), Lake Bonneville had relatively high water levels about 9500 years ago, 12,000 years ago, and 14,000 to 18,000 years ago, separated by stages of low water levels about 11,000, 13,500, and from 18,000 to at least 22,000 years ago. They think that two high rises and two declines took place rapidly between 13,500 and 8,000 years ago. However, wave-cut Danger Cave (Jennings, 1957) near Wendover, Utah, at the 4310-foot level (only about 110 feet above Great Salt Lake), dated by four radiocarbon samples of wood and dung to be about 11,000 years old (determinations are G 609: 11,450; C 610: 11,150; M 118: 11,000; M 119: 10,400 years) casts serious doubt on any high stand of the lake reaching or exceeding the cave level as late as 9500 years ago. This conflict is yet to be resolved.

Lake Lahontan, as much as 700 feet deep, covered about 8,665 square miles in western Nevada (Russell, 1885; Antevs, 1945, 1948, 1952, 1955; Morrison, 1961b, 1961c, 1964, 1965; Broeker and Kaufman, 1965). Its history is recorded in sediments. According to Morrison (1965), these sediments comprise the Eetza Formation and the Seehoo Formation, separated by the eolian and alluvial Wyemaha Formation and the strongly developed Churchill Soil. The Seehoo Formation interfingers with largely subaerial Indian Lakes Formation and is overlain by the nonlacustrine Turupah Formation. The Eetza Formation records five to eight (?) expansions of Lake Lahontan, the Seehoo five or six more. These two formations are correlated with the Bull Lake-Tahoe and Pinedale-Tioga glacial stages, about 75,000 to 34,000 and 25,000 to 8,000 years ago, respectively (Morrison, 1965, chart, p. 268).

In a tabulation of radiocarbon ages of samples from Lake Lahontan sediments, Broeker and Kaufman (1965, p. 540-542) list 36 ages in the range of 8,000 to 14,000 years, 30 ages between 14,000 and 20,000 years, a gap between 20,000 and 28,000 years, and 8 ages of more than 28,000 years. They interpret these ages as substantiating the same history of fluctuations of level as those reported in the Bonneville basin, with three high levels of Lake Lahontan about 18,500 to 14,500; 11,600; and 9,700 years ago, respectively. They correlate eight samples having an average age of 11,700 years and two samples having ages of 8,600 and 8,850 years with the last two lake stages in which the Seehoo Formation of Morrison was deposited. The postulated high level of the lake less than 10,000 years ago is an unsettled problem here too.

Stanley (1949), in his study of Lake Lahontan shore lines, found several groups of beaches. The highest beach has an elevation of 4374 to 4389 feet, whereas the present Pyramid Lake, situated in the bottom of the basin and shrunken from its 1870 shore line, lies about 3810 feet above sea level. The older beaches have more dirt and soil in the gravel and show darker shades of desert varnish on the surface pebbles. The area surrounding Pyramid Lake shows demarcations up to 120 feet above the lake. To Stanley the general relations "indicate a considerable period of general decline in lake level punctuated by upward resurgence."

Possible Age Correlations

The several stages of Lake Bonneville and Lake Lahontan probably have time equivalents in Fort Rock Lake, but their exact correspondence is not clear at this time. The high-water limit of Fort Rock Lake is judged to be about 4540 feet above sea level and of unknown age. The well established shore line at the 4475- to 4480-foot level represents a protracted stillstand in the lake's history, but its age is also indeterminate. One guess might place it in one of the Tahoe glacial stades. If a Tahoe age is accepted, then the prominent 4440-foot level (only about 40 feet lower) recorded on Fort Rock and elsewhere may also be of Tahoe age. In that case, the much lower 4373-, 4365-, 4363-, and 4360-foot and still lower beaches almost surely would have to be of Tioga-Pinedale-Fraser age.

One alternative is that all recorded lake levels are Tiogan in age and that they form a series of intermittently rising levels separated by low stages, with each maximum lower than the previous one. Such a history would resemble the Tioga Glaciation--Pluvial Lake Russell sequence described by Putnam (1950), who correlated two main clusters of end moraines in Lee Vining Creek Canyon, California, with corresponding water levels in Lake Russell. Putnam though did not envision intervening low-water stages. However, some of the four mapped clusters of end moraines may represent repeated advances of the ice in separate Tioga stades and not merely halts in recession of the ice front in one continuous episode of glaciation. The late Wisonsinan Pinedale Glaciation had three such stades. If separate stades in Tioga time are accepted, then a comparable sequence of alternately rising and falling lake levels may well have occurred three or four times in both Lake Russell and Fort Rock Lake during the Tioga glacial stage. Such an analogy of Fort Rock

Lake with the Tioga-Lake Russell regime seems reasonable. The question remains, though, whether any of the uppermost lake levels are Tahoe (pre-Tioga) in age. The writer is inclined to think they are Tahoe or even pre-Tahoe in age.

A radiocarbon (C-14) date from ostracodes and calcareous oolites obtained from a thin layer 5 inches below the biotite-bearing volcanic ash exposed in the banks of Ana River in the northwestern part of the Summer Lake basin were found to be 30,700 (+2,500 or -1,900) years old. Another C-14 date based on snail shells hand-picked from pumice sand immediately underneath the first of two white volcanic ash layers at Fossil Lake was 29,000 (+2,000 or -1,600) years. Accordingly the last two ash layers must be less than 29,000 years in age, but by unknown quantities. If all the sediments later than the biotite-bearing ash are Tiogan in age, then the Tioga Glaciation began more than 30,000 years ago.

These Ana River and Fossil Lake radiocarbon dates (30,700 and 29,000 years) would seem to fall near the beginning of Pinedale-Tioga Glaciation, when appropriately the level of Fort Rock Lake would be expected to be low, as the field relations suggest. Intraformational breccias in the Fossil Lake area signify the occurrence of shallow water at least twice after the arrival of the less than 30,700-year-old biotite-bearing volcanic ash. These low-water levels probably are related to interstades in Pinedale-Tioga time.

Molluscan shells in near-shore gravel at an elevation of 4381 feet near the north end of Seven Mile Ridge have a radiocarbon age of 12,980±230 years (GaK-1752), or when corrected for fractionation, 13,380±230 years (Bedwell, 1973). This age corresponds to the middle stade of Pinedale-Tioga Glaciation. It implies at least a moderate stage of the lake level later than all the pre-Mount Mazama pumice falls, except possibly the last two, which so far are known only to be younger than 29,000 years. The 7,000-year old Mount Mazama pumice is younger than Fort Rock Lake.

The 12,980±230 or 13,380±230 years old material on Seven Mile Ridge and the 13,200±720, 11,950±350, and 10,100±400 years ages on charcoal from the Fort Rock, Cougar Mountain, and Connley Caves impose restraints on any hypothetical high rise of Fort Rock Lake in late Pleistocene time. Even so, a number of rises below the 4440-foot limit may have occurred in Pinedale time.

The overlap of archeological dates with the late part of the geological time scale seems to indicate that occupation of these cave sites may well have begun before Fort Rock Lake vanished.

REFERENCES CITED

Allison, I. S., 1940, Study of Pleistocene lakes of south-central Oregon: Carnegie Inst. Washington Yearbook, v. 39, p. 299-300.

_ _ _ 1941, Work of wind in northern Lake County, Oregon (abs.): Geol. Soc. Am. Bull., v. 52, p. 1943.

_ _ _ 1945, Pumice beds at Summer Lake, Oregon: Geol. Soc. Am. Bull., v. 56, p. 789-807.

_ _ _ 1949, Fault pattern of south-central Oregon (abs.): Geol. Soc. Am. Bull., v. 60, p. 1935.

_ _ _ 1966a, Fossil Lake, Oregon, its geology and fossil faunas. Corvallis, Oregon, Oregon State University Press, 48 p.

_ _ _ 1966b, Pumice at Summer Lake, Oregon--a correction: Geol. Soc. Am. Bull., v. 77, p. 329-330.

_ _ _ 1968, Landforms, in Atlas of the Pacific Northwest, resources and development, R. M. Highsmith, Jr., ed., 4th ed., p. 27-30.

Anderson, C. A., 1941, Volcanoes of the Medicine Lake highland, California: Calif. Univ. Dept. Geol. Sci. Bull., v. 25, p. 347-422.

Antevs, Ernst, 1925, On the Pleistocene history of the Great Basin: Carnegie Inst. Washington, Pub. no. 352 (Quaternary climates), p. 51-114.

_ _ _ 1945, Correlation of Wisconsin glacial moraines: Am. Jour. Sci., v. 243A, Daly Volume, p. 1-39.

_ _ _ 1948, The Great Basin, with emphasis on glacial and postglacial times; 3, Climatic changes and pre-white man: Univ. Utah Bull., v. 38, p. 168-191.

_ _ _ 1952, Cenozoic climates of the Great Basin: Geol. Rundschau, Band 40, Heft 1, p. 94-108.

_ _ _ 1955, Geologic-climatic dating in the west: Am. Antiquity, v. 20, p. 317-335.

Armstrong, J. E., Crandell, D. R., Easterbrook, D. J., and Noble, J. B., 1965, Late Pleistocene stratigraphy and chronology in southwestern British Columbia and northwestern Washington: Geol. Soc. Am. Bull., v. 76. p. 321-330.

Arnold, J. R., and Libby, W. F., 1951, Radiocarbon dates: Science, v. 113, p. 111-120.

Atwater, Tanya, 1970, Implications of plate tectonics for the Cenozoic tectonic evolution of western North America: Geol. Soc. Am. Bull., v. 81, p. 3513-3536.

Bedwell, S. F., 1973, Fort Rock basin; prehistory and environment. Eugene, Oregon, Univ. Oregon Books, 159 p.

Berry, D. W., 1963, An ecological study of a disjunct Ponderosa pine forest in the northern Great Basin in Oregon: Oregon State Univ., Ph.D. thesis, 291 p.

Birman, J. H., 1964, Glacial geology across the crest of the Sierra Nevada: Geol. Soc. Am. Spec. Paper 75, 80 p.

Bissell, H. J., 1952, Stratigraphy of Lake Bonneville and associated Quaternary deposits in Utah Valley (abs.): Geol. Soc. Am. Bull., v. 63, p. 1358.

_ _ _ 1963, Lake Bonneville; geology of southern Utah Valley: U. S. Geol. Survey Prof. Paper 257-B, p. 101-130.

Blackwelder, Eliot, 1931, Pleistocene glaciation in the Sierra Nevada and Basin Ranges: Geol. Soc. Am. Bull., v. 42, p. 865-922.

_ _ _ 1934, Supplementary notes on Pleistocene glaciation in the Great Basin: Washington Acad. Sci. Jour., v. 24, p. 217-222.

_ _ _ 1941, Lakes of two ages in Searles basin, California (abs.): Geol. Soc. Am. Bull., v. 52, p. 1943-1944.

Broeker, W. S., and Orr, P. C., 1958, Radiocarbon chronology of Lake Lahontan and Lake Bonneville: Geol. Soc. Am. Bull., v. 69, p. 1009-1032.

Broeker, W. S., Ewing, W. M., and Heezen, B. C., 1960, Evidence for an abrupt change in climate close to 11,000 years ago: Am. Jour. Sci., v. 258, p. 429-448.

Broeker, W. S., and Kaufman, W. J., 1965, Radiocarbon chronology of Lake Lahontan and Lake Bonneville II: Geol. Soc. Am. Bull., v. 76, p. 537-566.

Brogan, P. F., 1950, Vanished lakes and ice-age weather: Geol. Society Oregon Country, News Letter, v. 16, p. 44-45.

Burke, R. M., and Birkeland, P. W., 1976, Re-evaluation of the late Pleistocene glacial sequence along the eastern escarpment of the Sierra Nevada, California: Geol. Soc. Am. Abstracts with Programs, v. 8, no. 6, p. 796.

Christiansen, R. L., and Lipman, P. W., 1972, Cenozoic volcanism and plate tectonic evolution of the western United States, II Late Cenozoic: Royal Soc. London Philos. Trans., v. 271, p. 249-284.

Cowles, John, 1960, Cougar Mountain Cave. Privately printed, Rainier, Oregon, Daily News Press, 50 p.

Crandell, D. R., 1965, The glacial history of western Washington and Oregon: In The Quaternary of the United States, H. E. Wright, Jr., and D. G. Frey, eds., Princeton, N. J., Princeton University Press, p. 341-353.

Crandell, D. R., Mullineaux, D. R., and Waldron, H. H., 1965, Age and origin of the Puget Sound trough in western Washington: U. S. Geol. Survey, Research B, p. 132-136.

Crane, H. R., 1956, University of Michigan radiocarbon dates, 1: Science, v. 124, p. 669.

Cressman, L. S., 1942, Archeological researches in the northern Great Basin: Carnegie Inst. Washington Pub. 538, 158 p.

Crittenden, M. D., Jr., 1963, New data on the isostatic deformation of Lake Bonneville: U. S. Geol. Survey Prof. Paper 454-F, p. 1-31.

Donath, F. A., 1958, Faulting in central Lake County, Oregon (abs.): Geol. Soc. Am. Bull., v. 69, p. 1681.

_ _ _ 1962, Analysis of basin-range structure, south-central Oregon: Geol. Soc. Am. Bull., v. 73, p. 1-15.

Eardley, A. J., 1956, Basin expansions and stability of levels of Lake Bonneville, Utah (abs.): Geol. Soc. Am. Bull., v. 67, p. 1689.

Eardley, A. J., Gvosdetsky, V., and Marsell, R. E., 1957, Hydrology of Lake Bonneville and sediments and soils of its basin: Geol. Soc. Am. Bull., v. 68, p. 1141-1201.

Eardley, A. J., and Gvosdetsky, V., 1960, Analysis of Pleistocene cores from Great Salt Lake, Utah: Geol. Soc. Am. Bull., v. 71, p. 1323-1344.

Eardley, A. J., Shuey, R. T., Gvosdetsky, V., Nash, W. P., Picard, M. D., Grey, D. C., and Kukla, G. J., 1973, Lake cycles in the Bonneville Basin, Utah: Geol. Soc. Am. Bull., v. 84, p. 211-216.

Easterbrook, D. J., 1966, Radiocarbon chronology of late Pleistocene deposits in northwest Washington: Science, v. 152, p. 764-767.

_ _ _ 1974, Late Pleistocene glacial and paleomagnetic events (abs.): Geol. Soc. Am. Abstracts with Programs, v. 6, p. 170-171.

Easterbrook, D. J. and Hansen, B. S., 1971, Palynology and stratigraphy of Early Wisconsin to Recent sediments in the Puget Lowland, Washington (abs.): Geol. Soc. Am. Abstracts with Programs, v. 3, p. 551-552.

Ericson, D. B., and Wollin, G., 1968, Pleistocene climates and chronology in deep sea sediments: Science, v. 162, p. 1227-1234.

Feth, J. H., and Rubin, Meyer, 1957, Radiocarbon dating of wave-formed tufas from the Bonneville Basin (abs.): Geol. Soc. Am. Bull., v. 68, p. 1827.

Flint, R. F., 1963, Status of the Pleistocene Wisconsin Stage in central North America: Science, v. 139, p. 402-404.

Flint, R. F. and Gale, W. A., 1958, Wisconsin stratigraphy and radiocarbon dates at Searles Lake, California: Am. Jour. Sci., v. 256, p. 689-714.

Forbes, C. F., 1972, Pleistocene shoreline morphology of the Fort Rock basin, Oregon: Univ. Oregon, Ph.D. thesis (Geog.).

Frye, J. C., and Willman, H. B., 1960, Classification of the Wisconsinan Stage in the Lake Michigan glacial lobe: Illinois State Geol. Survey Div., Circ. 285, 16 p.

_ _ _ 1963, Development of Wisconsinan classification in Illinois related to radiocarbon chronology: Geol. Soc. Am. Bull., v. 74, p. 501-506.

Gilbert, G. K., 1890, Lake Bonneville: U. S. Geol. Survey Monograph 1, 438 p.

Hampton, E. R., 1964, Geologic factors that control the occurrence and availability of ground water in the Fort Rock Basin, Lake County, Oregon: U. S. Geol. Survey Prof. Paper 383-B, 29 p.

Hansen, B. S., and Easterbrook, D. J., 1974, Stratigraphy and palynology of late Quaternary sediments in the Puget Lowland, Washington: Geol. Soc. Am. Bull., v. 85, p. 587-602.

Hay, O. P., 1927, The Pleistocene of the western region of North America and its vertebrated animals: Carnegie Inst. Washington Pub. 322B, 346 p.

Heiken, G. H., 1971, Tuff rings: Examples from the Fort Rock-Christmas Lake Valley Basin, south-central Oregon: Jour. Geophys. Res., v. 76, p. 5615-5626.
Higgins, M. W., and Waters, A. C., 1967, Newberry Caldera, Oregon; a preliminary report: Oregon Dept. Geol. and Min. Ind., Ore Bin, v. 29, p. 37-60.
Higgins, M. W., 1973, Petrology of Newberry Volcano, Oregon: Geol. Soc. Am. Bull., v. 84, p. 455-488.
Hunt, C. B., Varnes, H. D., and Thomas, H. E., 1953. Lake Bonneville--geology of northern Utah Valley, Utah: U. S. Geol. Survey Prof. Paper 257-A, 99 p.
Hyne, N. J., Chelminski, P., Court, J. E , Gorsline, D. S., and Goldman, C. R., 1972, Quaternary history of Lake Tahoe, California-Nevada: Geol. Soc. Am. Bull., v. 83, p. 1435-1448.
Jennings, J. D., 1957, Danger Cave: Utah Univ. Anthropological Papers, no. 27, p. 85-98.
Jones, D. J., and Marsell, R. E., 1955, Pleistocene sediments of lower Jordan Valley, Utah: In Utah Geol. Soc., Guidebook no. 10, p. 85-112.
Kittleman, L. R., 1973, Mineralogy, correlation, and grain-size distribution of Mazama tephra and other postglacial pyroclastic layers, Pacific Northwest: Geol. Soc. Am. Bull., v. 84, p. 2957-2980.
Lawrence, R. D., 1976, Strike-slip faulting terminates the Basin and Range province in Oregon: Geol. Soc. Am. Bull., v. 87, p. 846-850.
Libby, W. F., Jr., 1955, Radiocarbon dating, 2nd ed. Chicago, Illinois, Chicago Univ. Press, 175 p.
Macdonald, G. A., 1963, Geology of the Manzanita Lake quadrangle, California: U. S. Geol. Survey Quad. Map, GQ-248.
Matthes, F. E., 1930, Geologic history of the Yosemite Valley: U. S. Geol. Survey Prof. Paper 160, 137 p.
Meinzer, O. E., 1922, Map of the Pleistocene lakes of the Basin-and-Range province and its significance: Geol. Soc. Am. Bull., v. 38, p. 541-552.
Moore, B. H., 1934, Deposits of possible nuee ardente in the Crater Lake region, Oregon: Jour. Geol., v. 42, p. 358-375.
Morrison, R. B., 1961a, New evidence on the history of Lake Bonneville from an area south of Salt Lake City, Utah: U. S. Geol. Survey Prof. Paper 424D, p. 105-111.
_ _ _ 1961b, Lake Lahontan stratigraphy and history in the Carson Desert (Fallon) area, Nevada: U. S. Geol. Survey Prof. Paper 424D, p. 111-114.
_ _ _ 1961c, Correlation of the deposits of Lakes Lahontan and Bonneville and the glacial sequences of the Sierra Nevada and Wasatch Mountains, California, Nevada, and Utah: U. S. Gol. Survey Prof. Paper 424D, p. 122-124.
_ _ _ 1964, Lake Lahontan: Geology of southern Carson Desert, Nevada: U. S. Geol. Survey Prof. Paper 401, 156 p.
_ _ _ 1965, Quaternary geology of the Great Basin: In The Quaternary of the United States, H. E. Wright, Jr., and D. G. Frey, eds., Princeton, N. J., Princeton Univ. Press, p. 265-285.
_ _ _ 1970, Conflicting pluvial-lake evidence on climatic changes between 14,000 and 9 millenia ago, with particular reference to Lakes Lahontan, Bonneville, and Searles (abs.): In American Quaternary Assn., 1st Mtg., Yellowstone Park, Wyo. and Bozeman, Mont. Bozeman, Montana, Montana State Univ., p. 97-98.
_ _ _ 1975, Predecessors of Great Salt Lake (abs.): Geol. Soc. Am. Abstracts with Programs, v. 7, p. 1206.
Mullineaux, D. R., Waldron, H. H., and Rubin, Meyer, 1965, Stratigraphy and chronology of late interglacial and early Vashon glacial time in the Seattle area, Washington: U. S. Geol. Survey, Bull. 1194-0, 10 p.
Olson, E. A., and Broeker, W. S., 1961, Lamont natural radiocarbon measurements, vii: Radiocarbon, v. 3, p. 141-175.
Pease, R. W., 1969, Normal faulting and lateral shear in northeastern California: Geol. Soc. Am. Bull., v. 80, p. 715-720.
Peck, D. L., 1961, Geologic map of Oregon west of the 121st meridian: U. S. Geol. Survey Misc. Geol. Inv. Map I-325, scale 1:500,000.
Peterson, N. V., and Groh, E. A.. 1963, Maars of south-central Oregon: Oregon Dept. Geol. and Min. Ind., The Ore Bin, v. 25, p. 73-88.
_ _ _ 1964, Crack-in-the-ground, Lake County, Oregon, Oregon: Oregon Dept. Geol. and Min. Ind., The Ore Bin, v. 26, p. 158-166.
Peterson, N. V. and McIntyre, J. R., 1970, The reconnaissance geology and mineral resources of eastern Klamath County and western Lake County, Oregon: Oregon Dept. Geol. and

Min. Ind., Bull. 66, 70 p.
Powers, H. A., and Wilcox, R. E., 1964, Volcanic ash from Mount Mazama (Crater Lake) and from Glacier Peak: Science, v. 144, p. 1334-1336.
Putnam, W. C., 1950, Moraine and shoreline relationships at Mono Lake, California: Geol. Soc. Am. Bull., v. 61, p. 115-122.
Raisz, Erwin, 1955, Landforms of Oregon (rev. ed.). Portland, Oregon. Oregon Dept. Geol. and Min. Ind. (map).
Randle, K., Goles, G. G., and Kittleman, L. R., 1971, Geochemical and petrological characterization of ash samples from Cascade volcanoes: Quaternary Research, v. 1, p. 261-282.
Richmond, G. M., 1961, New evidence of the age of Lake Bonneville from the moraines in Little Cottonwood Canyon, Utah: U. S. Geol. Survey Prof. Paper 424D, p. 127-128.
_ _ _ 1962, Three pre-Bull Lake tills in the Wind River Mountains, Wyoming: In Geol. Survey Research 1962, U. S. Geol. Survey Prof. Paper 450D, p. 136.
_ _ _ 1965, Glaciation of the Rocky Mountains: In The Quaternary of the United States, H. E. Wright, Jr., and D. G. Frey, eds., Princeton, N. J., Princeton Univ. Press, p. 217-242.
_ _ _ 1970, Comparison of the Quaternary stratigraphy of the Alps and Rocky Mountains: Quaternary Research, v. 1, p. 3-8.
Roosma, A., 1958, A climatic record from Searles Lake, California: Science, v. 128, p. 716.
Rubin, M., and Alexander, C., 1958, U. S. Geological Survey radiocarbon dates, 4: Science, v. 127, p. 1476-1487.
_ _ _ 1960, U. S. Geological Survey radiocarbon dates, 5: Am. Jour. Sci. Radiocarbon Supp., v. 2, p. 129-185.
Russell, I. C., 1883, Sketch of the geological history of Lake Lahontan, a Quaternary lake of northwestern Nevada: U. S. Geol. Survey Ann. Report 3, p. 189-235.
_ _ _ 1884a, A geological reconnaissance in southern Oregon: U. S. Geol. Survey Ann. Report 4, p. 431-464.
_ _ _ 1884b, Lakes of the Great Basin: Science, v. 3, p. 322-323.
_ _ _ 1885, Geological history of Lake Lahontan, a Quaternary lake of northwestern Nevada: U. S. Geol. Survey Monograph 11, 288 p.
_ _ _ 1889, Quaternary history of Mono Valley, California: U. S. Geol. Survey Ann. Report 8, p. 261-394.
_ _ _ 1905, Preliminary report on the geology and water resources of central Oregon: U. S. Geol. Survey Bull. 252, 138 p.
Sharp, R. P., and Birman, J. H., 1963, Additions to the classical sequence of Pleistocene glaciation, Sierra Nevada, California: Geol. Soc. Am. Bull., v. 74, p. 1079-1086.
Shuey, R. T., 1972, Paleomagnetic and paleoclimatic implications of a deep core from Pleistocene Lake Bonneville (abs.): Eos, v. 53, p. 356.
Snyder, C. T., Hardman, G., and Zdenek, F. F., 1964, Pleistocene lakes in the Great Basin: U. S. Geol. Survey, Misc. Geol. Inv. Map I-416, scale 1:1,000,000.
Stanley, G. M., 1949, Elevations of some Lake Lahontan shore lines (abs.): Geol. Soc. Am. Bull., v. 60, p. 1945.
Stewart, J. H., Walker, G. W., and Kleinhampl, F. J., 1975, Oregon-Nevada lineament: Geol. Soc. Am., Geology, v. 3, p. 265-268.
Thayer, T. P., 1939, Geology of the Salem Hills and the North Santiam River basin, Oregon: Oregon Dept. Geol. and Min. Ind. Bull. 15, 40 p.
Thompson, G. A., and Burke, D. B., 1973, Rate and direction of spreading in Dixie Valley, Basin and Range province, Nevada: Geol. Soc. Am. Bull., v. 84, p. 627-632.
Trauger, F. D., 1958, Fault scarps and age of faulting in Lake County, Oregon (abs.): Geol. Soc. Am. Bull., v. 69, p. 1747.
Wahrhaftig, C., and Birman, J. H., 1965, The Quaternary of the Pacific Mountain system in California: In The Quaternary of the United States. H. E. Wright, Jr., and D. G. Frey, eds., Princeton, N. J., Princeton Univ. Press, p. 299-340.
Walker, G. W., 1969, Geology of the High Lava Plains province, in Minerals and water resources of Oregon: Oregon Dept. Geol. and Min. Ind. Bull. 64, p. 77-79.
_ _ _ 1973a, Preliminary geologic and tectonic maps of Oregon east of the 121st meridian: U. S. Geol. Survey Misc. Field Studies, MF 495, 2 sheets, scales 1:500,000 and 1:1,000,000.
_ _ _ 1973b, Tectonism and silicic vulcanism of eastern Oregon: Geol. Soc. Am., Abstracts with Programs, v. 5, no. 1, p. 119.

Walker, G. W., Peterson, N. V., and Greene, R. C., 1967, Reconnaissance geologic map of the east half of the Crescent quadrangle, Lake, Deschutes, and Crook Counties, Oregon: U. S. Geol. Survey Misc. Geol. Inv., Map 493.

Walker, G. W., McLeod, N., and McKee, E. H., 1974, Transgressive age of late Cenozoic silicic rocks across southeastern Oregon; implications for geothermal potential: Geol. Soc. Am., Abstracts with Programs, v. 6, p. 272.

Waring, G. A., 1908, Geology and water resources of a portion of south-central Oregon: U. S. Geol. Survey, Water Supply Paper 220, 87 p.

Wilcox, R. E., 1965, Volcanic-ash chronology, in The Quaternary of the United States, H. E. Wright, Jr., and D. G. Frey, eds.: Princeton, N. J., Princeton Univ. Press, p. 807-816.

Williams, H., 1932, Geology of the Lassen Volcanic National Park, California: Berkeley, Univ. Calif. Dept. Geol. Sci. Bull., v. 21, p. 195-385.

_ _ _ 1942, The geology of Crater Lake National Park, Oregon: Carnegie Inst. Washington Pub. 540, 162 p.

Williams, J. S., 1962, Lake Bonneville group in Cache Valley, Utah (abs.): Geol. Soc. Am., Special Paper 68, p. 110.

Willman, H. B., and Frye, J. C., 1970, Pleistocene stratigraphy of Illinois: Illinois State Geol. Survey Bull. 94, 204 p.