STUDIES IN GEOLOGY

Number Eleven

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Geology of Pluvial Lake Chewaucan, Lake County, Oregon

STUDIES IN GEOLOGY NUMBER ELEVEN

By Ira S. Allison

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Abstract

Pluvial Lake Chewaucan was a late Pleistocene lake, as much as 375 feet deep, covering 480 square miles in the northwestern part of the Great Basin in southern Oregon. The lake basin, now occupied by Summer Lake, Upper and Lower Chewaucan Marshes, and Lake Abert, was formed by down-dropped fault blocks bounded by imposing fault scarps, notably Winter Ridge and Abert Rim. Several large landslides occurred along the east side of Winter Ridge.

Lake Chewaucan shore features include wave-cut cliffs and caves, beaches, terraces, bay bars, spits (as at The Narrows), and a huge alluvial fan built by Chewaucan River at Paisley. Later, at lower lake stages, part of the fan deposit of sand and gravel was distributed across four-mile-wide Paisley Flat, which subsequently became a divide between Winter Lake in the Summer Lake basin and ZX Lake (new name) in the Chewaucan Marshes-Lake Abert part of the Lake Chewaucan basin. Overflow from ZX Lake later cut a shallow channel across the divide enroute to Winter Lake.

The bottom sediments of Lake Chewaucan are exposed mainly in the bluffs of Ana River, the main source of Summer Lake water. The stratigraphic section there is about 54 feet thick and composed mainly of silt, with numerous seams of sand, oolites, occasional pebbles, and many layers of volcanic ash, especially near the top.

Fossils found in the area include 1) mammals and birds obtained from man-occupied caves near Paisley, 2) ostracods, diatoms, and small mollusks in the Ana River section, 3) similar tiny snail shells in a gravel pit north of the Ana Springs Reservoir, and 4) additional shells from the 4425-foot level near Ten Mile Butte east of Summer Lake. The snail shells have radiocarbon ages of >25,900, 22,000, and 17,500 years — all within the span of the Tioga-Pinedale glacial stage of the Sierra Nevada and the Rocky Mountains. The top 4520-foot shoreline, the 4485-foot beach and Paisley Caves, and the bulk of the Paisley fan may possibly be Tahoe in age, but the wave erosion of the Paisley fan, development of Paisley Flat, overflow from ZX Lake, and later formation of ZX Red House beach are assigned to Tioga-Pinedale time.

The history of Lake Chewaucan is thought to be analogous to those of Lake Bonneville, Lake Lahontan, and Searles Lake, and correlative with climatic changes recorded in marine deposits.

The post-Lake Chewaucan history of the basin includes Anathermal, Altithermal, and Medithermal climatic changes, as shown by a pollen profile in Upper Chewaucan Marsh. Mount Mazama pumice sand fell in the area about 6,600-6,700 years ago. Desiccation and wind work were strong in Altithermal time. In the Neopluvial (new term), corresponding to Neoglaciation in the mountains (perhaps 4,000-2,000 years ago), new lakes many tens of feet deep developed in the Summer Lake and Chewaucan Marshes-Lake Abert basins. Later, Summer Lake and Lake Abert were reduced to the very shallow, alkaline bodies of water of the present day.

Preface

My study of pluvial Lake Chewaucan began in 1939 at the request of Dr. John C. Merriam, a noted vertebrate paleontologist, who was then president emeritus and research associate of the Carnegie Institution of Washington. Merriam had a wide-ranging interest in the mammalian fossils (horse, camel, elephant, etc.) found at Fossil Lake in the Fort Rock Valley north of the Lake Chewaucan basin, in the ongoing archeological studies of prehistoric man in south-central Oregon by Dr. L. S. Cressman of the University of Oregon, and in the work of Dr. Howel Williams, vulcanologist from the University of California (Berkeley), on the origin of Crater Lake.

Cressman and his students were engaged in archeological digs in several caves in the region including Paisley Caves in the Lake Chewaucan basin and Fort Rock Cave in the Fort Rock Lake basin. These caves are wave-cut features along the shores of former lakes, about which little information was available. Williams had confirmed that pumice found by Cressman in the Paisley Caves was the product of volcanic Mount Mazama, the predecessor of Crater Lake. To aid in determining the age relations of the archeological material in the caves, a detailed study of the pluvial lakes was needed.

Merriam organized a group of consultants, including (besides Cressman, Williams, and me) Earl L. Packard and Chester Stock, paleontologists; Warren D. Smith and John P. Buwalda, geologists; Daniel Axelrod, paleobotanist; and Ernst Antevs, glacial geologist and climatologist, to coordinate the geological, vulcanological, paleontological, climatological, and archeological studies in the area between Crater Lake on the west and Steens Mountain on the east.

After a reconnaissance of the Fort Rock, Summer Lake-Chewaucan, Goose Lake, Warner, Catlow, and Alvord basins in the summer of 1939, my later field work was mainly in the pluvial Fort Rock Lake and Lake Chewaucan basins. Interruptions and other duties have delayed this report until now. The results of this research, as hoped, have proved to be particularly helpful in integrating the geological and archeological findings over the years. And, as with mountain climbing, this investigation of pluvial Lake Chewaucan has been fascinating in its own right, because "it was there."

Acknowledgements

Funds for payment, subsistence, and field expenses of student assistants during this study were supplied by the Carnegie Institution of Washington and by the General Research Council of Oregon State University. I am indebted to Keith F. Oles, William A. Scott, George W. Walker, and Robert S. Yeates, who kindly read the manuscript and offered helpful suggestions. Publication of this monograph was underwritten in part by the Research Office of Oregon State University.

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Introduction

As one approaches Summer Lake from the north on Oregon Highway 31, there is a scenic overlook site at the north end of the Summer Lake basin. Immediately below the overlook and directly ahead is a patch of greenery, and in the distance is 10-mile-long Summer Lake. The green area near the present Summer Lake post office is well watered by perennial Ana Springs, Ana River, and modern wells. Summer Lake, south of the oasis, is a shallow sheet of very alkaline water. On a hot gusty afternoon, clouds of white alkaline dust rise hundreds of feet from the barren plain east and southeast of the lake.

The overlook has an elevation of approximately 4520 feet above sea level, about 370 feet higher than the surface of Summer Lake. To be told that the basin below, reaching to Lake Abert more than 50 miles away (Fig. 1), once held water as much as 370 feet deep may strain one's credulity. Yet part of the evidence is underfoot. The overlook ridge is a former beach, formed of water-rounded gravel that is well exposed in a pit east of the highway. A second, better developed beach stands at the 4485-foot level. Another prominent beach, an even-topped ridge with a lagoonal basin immediately north of it (Figs. 2 and 3), occurs at the 4365-foot level below the overlook. These beaches were shorelines of former pluvial Lake Chewaucan.

Additional evidence of the previous existence of Lake Chewaucan is supplied by the evenly stratified layers of lacustrine sediment exposed in the banks of Ana River below Ana Springs reservoir, which is seen on the flat just beyond the 4365-foot beach.

Definition

Pluvial Lake Chewaucan was a four-lobed body of water which occupied about 480 square miles in the confluent structural basins of modern Summer Lake, Upper Chewaucan Marsh, Lower Chewaucan Marsh, and Lake Abert in south-central Oregon (Fig. 1). The area is easily reached from Bend, Oregon by way of the Fremont Highway (Oregon Highway 31) or from Burns or Lakeview via U.S. Highway 395. The term pluvial refers to the former wetter climate that was broadly equivalent to Pleistocene glacial stages elsewhere.

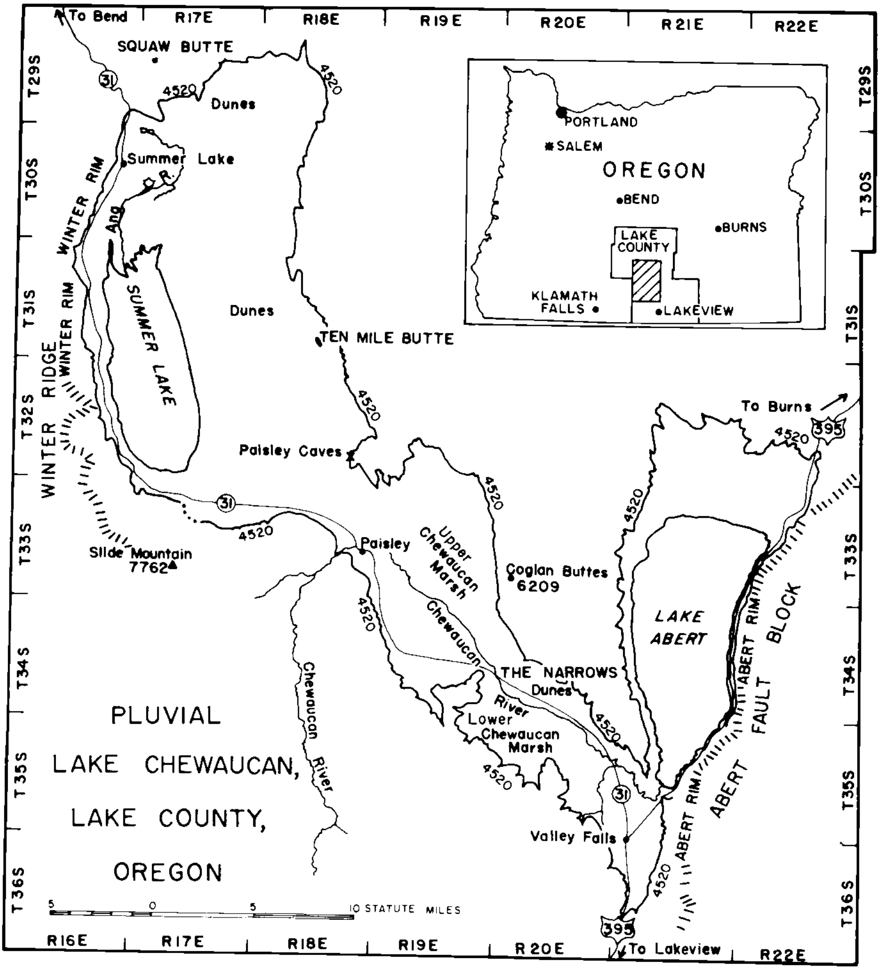

Figure 1: Map of pluvial Lake Chewaucan and its environs. The contour line at 4520 feet traces the approximate shoreline of the lake at its highest level.

The water that accumulated in these basins rose sufficiently in Pleistocene glacial or pluvial time to join these somewhat detached lakes into one large lake. The basins have present elevations of 4,147 feet above sea level on shallow Summer Lake* (on U.S. Geological Survey topographic map), 4,310 to 4,300 in Upper Chewaucan Marsh,

* Its historical variations have ranged from 4,145.5 to 4,154.4 feet (K.E. Phillips, pers. comm., 1961)

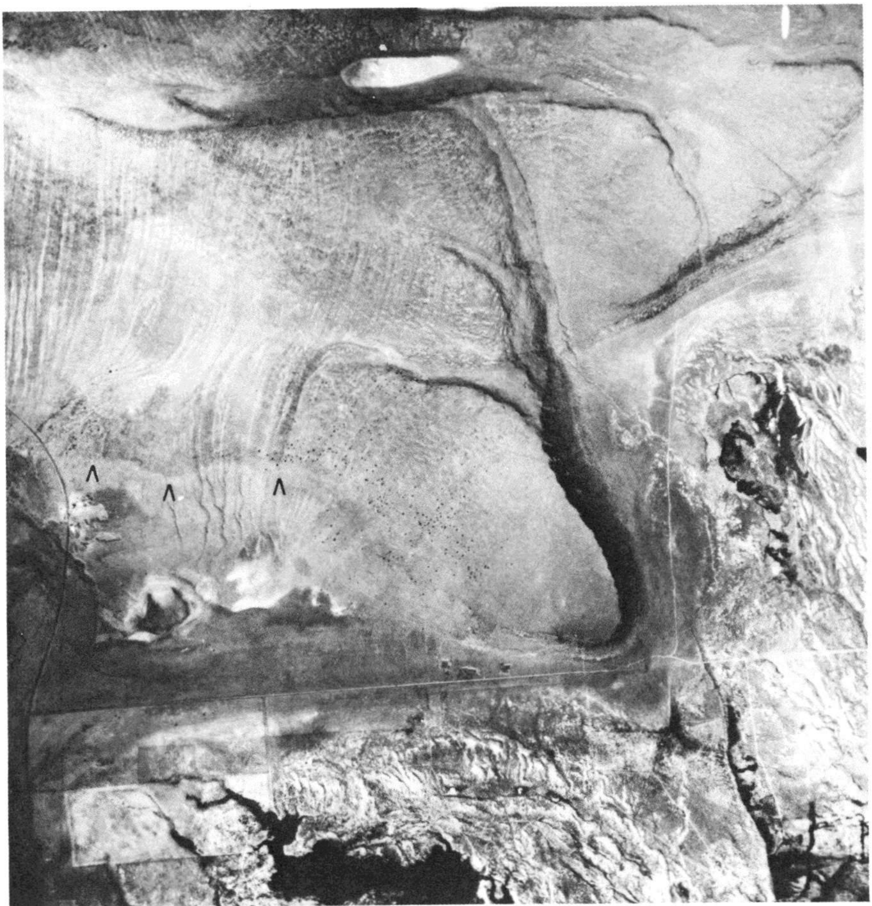

Figure 2: Aerial photograph of fault structure at north end of Summer Lake basin. The block in the center is shown in Fig. 5. The highest pluvial Lake Chewaucan erosional shoreline crosses the block diagonally and then turns westward (Λ marks shoreline). Ana Springs Reservoir is at the bottom. A Lake Chewaucan gravel bay bar (dark gray) at 4365 feet elevation, with a 27-foot depression behind it (see Fig. 3), is just above the east-west road north of the reservoir. The stripes (upper left) are rainwash channels on basalt. The area is about 3 by 3 miles.

4,300 to about 4,290 in Lower Chewaucan Marsh, and 4,255 feet on Lake Abert (1966 map). The Pleistocene water level reached a maximum elevation of 4,520 feet, so the maximum depth of water in Summer Lake basin, the lowest one, was about 375 feet.

Figure 3: Juniper-studded bay bar (across middle, beyond depression) in northwest corner of Lake Chewaucan basin. Note its even crest, as seen from the north. Its location is shown on Fig. 2.

Names

Colonel John C. Fremont named Winter Ridge and Summer Lake in 1843 while on an expedition with troops and horse-drawn cannon to California. Almost marooned in a few feet of early winter snow on the ridge top, the military party managed laboriously to struggle down the steep rim to the pleasantly contrasting verdant lake basin below. He also named Lake Abert for his superior officer.

Pluvial Lake Chewaucan gets its name from Upper and Lower Chewaucan Marshes. The name Chewaucan was derived from Klamath Indian *tchua*, meaning wild potato, and *keni*, a suffix denoting place or locality (McArthur, 1973). The names Lake Chewaucan, Winter Lake (a successor in part of the Lake Chewaucan basin), and Fort Rock Lake (another pluvial lake in Fort Rock Valley to the north), were first applied by Allison (1940). This monograph introduces the name ZX Lake for a later Pleistocene lake that was confined to the Chewaucan Marshes area and the basin of Lake Abert.

Previous Work

Lake Chewaucan was only one of many pluvial lakes of the Great Basin. These lakes, especially Lake Bonneville in Utah and Lake Lahontan in Nevada, have long been subjects of study by many individuals (bibliography by Feth, 1964). I. C. Russell (1884) made a reconnaissance map of the lakes in the Great Basin physiographic province. In specific relation to Lake Chewaucan, he traversed the basins of Summer Lake and the Chewaucan Marshes, identified certain landslides along Winter Rim (west of Summer Lake), recognized Abert Rim and other great fault structures, and obtained an analysis of the alkaline water of Lake Abert. Waring (1908), in a report of the regional water supply, added details regarding the geology of the region — its lithology, structure, and available water. He identified the "gravel-covered terraces at Paisley" as a deposit in a former lake, the "river-wash" in the "low divide between Summer Lake and Chewaucan Marsh," and a stream channel across it. O. E. Meinzer (1922) compiled a map of the several Pleistocene pluvial lakes of the Great Basin. Snyder, Hardman, and Zdenek (1964) and Morrison (1965) prepared updated versions of the map.

The regional bedrock geology has been described by Walker (1969, 1973). The fault structures in the area have been treated by Allison (1949), Raisz (1955), Donath (1958, 1962), Trauger (1958), Walker (1969, 1973), and Lawrence (1976). In general the region is a volcanic terrain underlain by widespread lava flows (mainly of basalt) and local thick sections of tuffaceous rocks broken by numerous faults that trend north-northwest, north-south, or north-northeast. Faulting developed a topographic relief ranging from a few tens of feet to as much as 3,250 feet.

Geography

Climate

The area presently has a semiarid continental climate characterized by large daily, monthly, and annual ranges of temperature, and low, variable precipitation. Winters are cold and summers hot; the mean temperature in January is about 30° F, in July about 66°. Hot days in summer are followed by cool nights because of radiational cooling at these altitudes. Weather records are available from nearby stations at Summer Lake, Paisley, and Valley Falls (Table 1), situated at elevations of 4192, 4371, and 4326 feet, respectively. The minimum temperatures known at these stations are −27°, −25°, and −39°, and the maximums are 102°, 103°, and 105°.

Table 1. Climatic data for Lake Chewaucan vicinity (from NOAA data)

	Summer Lake (20 years)	Paisley (50 years)	Valley Falls (44 years)
Mean annual temperature (°F)	48.1	48.4	46.7
Mean annual precipitation (in.)	11.86	10.25	13.54

Precipitation falls mainly as snow in winter and rain in spring; summers are generally dry. All three stations are in the rain shadow of mountains immediately to the west, where precipitation is estimated to be 20 to 30 inches, and in the still greater rain shadow of the Cascade Range. Total precipitation varies from year to year within a known range of 5.89 to 22.40 inches, but it usually ranges between 7 and 15 inches.

Clearly moisture must have been more abundant in Pleistocene pluvial time in order to sustain pluvial Lake Chewaucan. Climatologists are not sure whether this was due to greater total precipitation, a greater ratio of snowfall as compared to rain, lower summer temperatures than now, or some combination of these factors.

Vegetation

Lowlands of the area are in the Upper Sonoran life zone, but the highlands, such as Winter Ridge, reach into the Canadian life zone. The well-watered high ground along or beyond the western margin of pluvial Lake Chewaucan is forested with merchantable stands of ponderosa pine, but most of the pluvial Lake Chewaucan basin has few trees. Instead, the characteristic vegetation is shrubbery of sagebrush (*Artemisia*), rabbit brush (*Chrysothamnis*), horsebrush (*Tetradymia*), or locally, where there is an intermediate water supply, juniper trees. Short-lived herbaceous plants are few. Upper Chewaucan Marsh originally was a tule swamp with cattails, bulrushes, sedges, and other associated wetland species. Saline areas have halophytes: greasewood (*Sarcobatus*), saltbush (*Atriplex*), and salt grass (*Distichlis*). Highly alkaline areas, such as the southeast border of Summer Lake or the north border of Lake Abert, are virtually devoid of plants.

Drainage

Pluvial Lake Chewaucan occupied an enclosed basin and had no surface outlet. Drainage of the basin is insequent and, except for the upper part of Chewaucan River, it is not integrated into stream systems. Several short streams feed modern Summer Lake, notably Foster, Harvey, Wooley, Kelly, White Hill, Hampton, Withers, and Hadley Creeks, located around its southwestern and southern shores.

Ana Springs. The principal source of water for Summer Lake is Ana Springs in the northwestern corner of the basin (Fig. 4). The original five springs had a reputation for nearly constant flow (Meinzer, 1927), but in fact their yield has varied over the years. According to Phillips and Van Denburgh (1971) and Van Denburgh (1975), flow decreased from 130-150 cubic feet per second prior to 1900 to the present annual average output of about 92 second feet, mainly because of drowning of the orifices to depths of 16 to 46 feet by construction of a dam for an irrigation reservoir in 1922-23 and 1926. The dam and reservoir evidently reduced the hydraulic head of the springs. A flowing well drilled 0.3 mile south of Ana Reservoir, yielding about 4.5

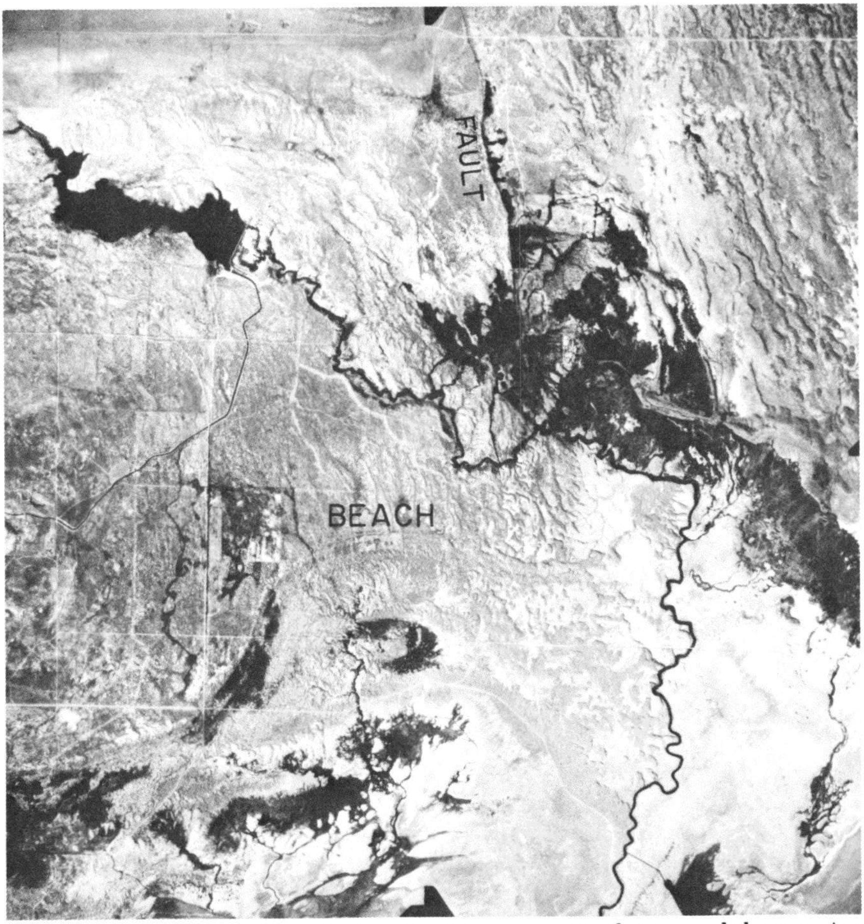

Figure 4: Aerial photo of Ana Springs-Ana River area. North is toward the top. Ana Springs reservoir (upper left) feeds the river. An old pre-lake north-northwest fault line is at the top. The nearly NNW-SSE minor ridges are transverse dunes of sandy Mount Mazama pumice. The curved ridge (near middle) is a later beach of an expanded Summer Lake of Neopluvial age. The area, about 3 miles square, lies just east of the community of Summer Lake located in Fig. 1.

second feet of water and fluctuating sympathetically with the water level in the reservoir, apparently draws upon the same aquifer as Ana Springs. The water-bearing layer is probably a coarse-textured lacustrine sediment.

The source of Ana Springs water has been conjectural for many years — Winter Ridge, Chewaucan River at Paisley, and even Crater

Lake have been suggested — but hydrologists of the Water Resources Division, U. S. Geological Survey, have proposed a more logical source in the Silver Lake-Paulina Marsh-Fort Rock Valley to the north. The bed of Silver Lake (sometimes dry) is approximately 4300 feet above sea level, whereas Ana Reservoir, 6.5 to 12 miles distant, is at 4218 feet (Summer Lake quadrangle map, 1966). Thus an ample hydraulic head is available to supply Ana Springs. Paulina Marsh northwest of Silver Lake is well fed by three small perennial streams. Its overflow, as reduced by irrigation and evaporation losses, goes on to Silver Lake. Much of the flattish floor of Fort Rock Valley is between 4310 and 4320 feet in elevation, and the water table there is shallow. On the basis of these observations, F. D. Trauger (1950) concluded that the Paulina Marsh-Silver Lake-Fort Rock Valley area is the ultimate source of water that is channeled toward the north end of the Summer Lake basin through brecciated zones along faults. Several flowing wells (generally hundreds of feet deep) in the north end of the basin east of Ana Springs presumably are similarly supplied. In support of this source, Newcomb (1953) estimated that more than half of the annual recharge of water in the Fort Rock Valley was available for subsurface discharge from the basin. Hampton (1964) envisioned considerable underground outflow from Fort Rock Valley, either toward the Deschutes River basin to the west or toward the closed basin of Summer Lake to the south. The north-northwesterly trend of the major faults in the area would favor the latter route.

Table 2. Chemical composition of Ana Springs, Ana River, and Chewaucan River (parts per million)

	Ana Springs[a]	Ana River[a] (Feb.)	Ana River[a] (July)	Ana River[b]	Chewaucan River[c]
Silica (SiO_2)	---	37	---	36	29
Calcium (Ca)	12	4.9	10	5	7.6
Magnesium (Mg)	6	4.4	5	2.3	1.9
Sodium (Na)	55 (Na + K)	39 (Na + K)	58 (Na + K)	39	6.8
Potassium (K)				3.6	2.5
Carbonate (CO_3)	0	8.6	14	9	0
Bicarbonate (HCO_3)	116	66	89	91	44
Sulfate (SO_4)	12	8.1	37	5.8	4.5
Chloride (Cl)	39	11	19	12	0.5
Salinity	220	158	214	158	85

[a] Van Winkle, 1914
[b] Phillips and Van Denburgh, 1971
[c] Van Winkle, 1914; 12 months mean at Paisley

The temperature of Ana Springs water is 66°F, only about 15° above the mean annual air temperature of the area, so the depth of travel of the water underground before emergence is moderate in scale — perhaps little more than 1,000 feet. This temperature contrasts with the 123°F temperature of Summer Lake Hot Spring (Waring, 1908) situated in the NE¼ Sec. 12, T. 33 S., R.17 E., where water evidently rises along a fault from a depth of 4,500 feet or more. The water of Ana Springs has a low salinity, largely of sodium bicarbonate (Table 2).

Ana River. The discharge of Ana Springs and the seepage occurring from the river bank is carried to Summer Lake by Ana River, a stream about six miles long in the northwest corner of the Summer Lake basin (Fig. 4). Discharge of the river, according to Waring (1908), was 155 second feet near Ana Springs and 175 second feet near its mouth. Van Denburgh (1975) in his calculations of the solute balance in Summer Lake used 77,000 acre-feet as the river's present average annual contribution to the lake. This is equivalent to about 106 second feet.

Chemical analyses of Ana River water (Table 2) show that like Ana Springs, its major source, the river water has a low mineral content, mostly of sodium bicarbonate. Dilution of Ana River water by surface water occurs during spring thaw.

Chewaucan River. The main source of running water in the pluvial Lake Chewaucan basin is the Chewaucan River, which enters the lowland at Paisley. It then traverses Upper and Lower Chewaucan Marshes and finally carries about two-thirds of its upstream volume into the south end of Lake Abert. Several ephemeral streams occur in physiographically young valleys along the west and south sides of Upper and Lower Chewaucan Marshes, but except for wetting the marshes they contribute little to Chewaucan River. Moss Creek at the south end of Upper Chewaucan Marsh is the main one draining into that marsh. In the Lower Chewaucan Marsh basin, Willow Creek on the southwest side, a few miles northwest of Valley Falls, loses itself in the marsh entirely, but Crooked Creek, at the southeast corner of the marsh basin, continues northward until it reaches Chewaucan River.

The chemical composition of dissolved solids in Chewaucan River water over a one-year period is given in Table 2. Unlike Ana Springs and Ana River, Chewaucan River is low in alkalies and chloride; instead, its water is primarily a weakly mineralized solution of calcium bicarbonate, typical of streams in its type of terrain.

Crooked Creek Valley. Crooked Creek joins Chewaucan River in the lower (southeast) end of Lower Chewaucan Marsh. At its highest stage, Lake Chewaucan may have extended up Crooked Creek basin as far as the northwestern part of upper Crooked Creek Valley by way of a narrow channel now at an elevation just below 4500 feet. Farther south, upper Crooked Creek Valley widens into a nearly flat-floored depression (a fault trough) which evidently was also the site of a pluvial lake. The overflow of such a lake probably cut the narrows mentioned above and established the present course of upper Crooked Creek.

If, as seems likely, the channel through Crooked Creek narrows resulted mainly from overflow of a lake in upper Crooked Creek Valley and subordinately from post-lake erosion, then the southern limit of Lake Chewaucan would have been at the former divide and not into the edge of upper Crooked Creek Valley as present elevations would allow. The addition of the head of Crooked Creek Valley enlarged the basin tributary to Lake Chewaucan.

The divide between upper Crooked Creek Valley draining northward and the Goose Lake drainage basin leading southward is more than 4800 feet above sea level, too high to permit a southerly outlet for either Crooked Creek Valley or Lake Chewaucan.

Lakes

Summer Lake and Lake Abert occupy the lowest areas in the bottom of the pluvial Lake Chewaucan basin. They are shallow bodies of alkaline water (pH 9.6 to 9.8) as noted by many observers (Van Winkle, 1914; Allison and Mason, 1947; Mason, 1969; Phillips and Van Denburgh, 1971; Van Denburgh, 1975). Both lakes fluctuate greatly in area on nearly flat beds according to the seasons, prevailing winds, and long-range differences in rainfall (Table 3).

Table 3. Data regarding Abert and Summer Lakes[a]

	Lake Abert	Summer Lake
Drainage basin area	660 mi^2	390 mi^2
Area at high-water level	65 mi^2	70 mi^2
Elevation of lake bed	4244.4 feet	4144.4 feet
Elevation, 1966 maps	4255 feet	4147 feet
Lowest level	dry	dry
Highest known level	4260.5 feet	4149 feet (in 1905)
Maximum known depth	16 feet	5 feet
Pre-1900 level (calc.)	---	4151.4 feet (7 feet deep)
Average post-1926 level	---	4146 feet

[a]From Phillips and Van Denburgh (1971) and Van Denburgh (1975)

Summer Lake at a high-water stage covers about 70 square miles but less than half as much at ordinary low-water stages, and is sometimes dry. Summer Lake is computed to be about five feet shallower now than it was before part of the water of Ana Springs was diverted for irrigation and for maintenance of a migratory-waterfowl sanctuary (Van Denburgh, 1975).

The sediments of Lake Abert — their sources, grain sizes, mineral and rock composition, and reaction with the saline alkaline lake water — are described by Deike and Jones (1980).

Table 4. Analyses of Summer Lake and Lake Abert[a] (weight percent)

	Summer Lake	Lake Abert
SiO_2	1.5	0.38
Ca	0.04	0.005
Mg	0.004	0.005
Na	39	40
K	1.6	1.3
HCO_3[b]	13	5.8
CO_3	17	16
SO_4	4.8	1.8
Cl	22	35
Dissolved solids[c]	7,200	40,800

[a]Phillips and Van Denburgh, 1971
[b]Calculated as carbonate
[c]Including minor quantities of other elements

Water analyses for Summer Lake and Lake Abert are shown in Table 4. Summer Lake is essentially a carbonate-bicarbonate-chloride solution of sodium. In Lake Abert total salinity is many times greater than in Summer Lake, probably due at least partly to more frequent drying of Summer Lake and ensuing deflation of the precipitated salts. Lake Abert also has a greater percentage of chloride. Both lakes are low in potassium. The main variations in concentration in each lake are caused by seasonal changes in volume from inflow on the one hand and evaporation on the other. The usual range of volume changes is

Table 5. Analyses of soluble salt crusts from lake-border playas, 1944[a] (in weight percent after desiccation)

	At Summer Lake	At Lake Abert
Na_2CO_3 (soda ash)	70.80	78.95
$NaHCO_3$ (baking soda)	9.45	0.60
NaCl (common salt)	12.12	15.55
Na_2SO_4 (sodium sulfate)	7.83	1.11
K_2SO_4 (potassium sulfate)	1.64	1.40
Total	101.84	97.61[b]

[a]Mason (1969); analyses by L. L. Hoagland, Oregon Dept. Geol. and Min. Ind.
[b]Total soluble salts 39 percent.

about two to one. An interpretation of the geochemistry of these lakes is offered by Van Denburgh (1975), who found large quantities of dissolved carbonate-bicarbonate in the underlying lake sediments and adjacent playa sediments. The playa flats upon drying become coated and impregnated with alkaline salts (Table 5).

Geomorphic Setting

The pluvial Lake Chewaucan basin has four interconnected parts, each one a down-faulted trough. Summer Lake basin is the lowest and deepest. A review of the four subsidiary basins, each one holding a lobe of former Lake Chewaucan, follows.

Summer Lake Basin

North Border. The Summer Lake basin has an area of about 390 square miles. It is bounded on the north by a complex of tilted fault blocks (Figs. 2, 5, and 6), which separate it from the Silver Lake-Fort Rock-Christmas Lake basin to the north — the former site of pluvial Fort Rock Lake (Allison, 1966a, 1979), a contemporary of Lake Chewaucan. The main faults, here striking a little west of north, are cut off by others that cross them at high angles. Because of differences in vertical movement on the faults and differential tilting of the fault blocks, the north end of Summer Lake basin is irregular with reentrants and varying elevations of the rim (Fig. 2). An area four miles farther north shows concentric faulting of blocks tilted south toward the Summer Lake basin (Fig. 6).

Figure 5: Tilted fault block at north end of Summer Lake basin, as seen from the south.

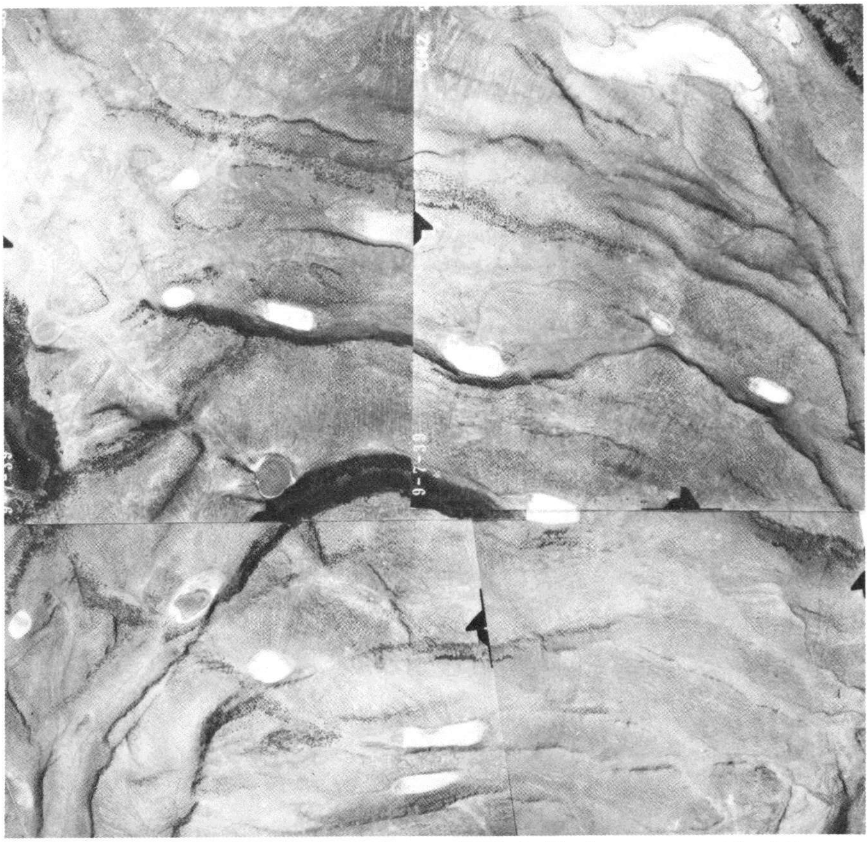

Figure 6: Composite aerial photo of complex fault-block pattern north of Summer Lake basin, as shown by lines of low cliffs on the edges of tilted blocks. Light spots are shallow basins on down-thrown sides of faults. A series of internally broken blocks is tilted south toward the lake basin. The area is about 5 miles square.

West Border. The dominant feature of the west side of the Summer Lake basin is Winter Ridge (Figs. 7, 8, and 9) a large fault block with a steep east scarp and a comparatively gentle west slope. Its highest (eastern) edge stands about 6800 feet above sea level on the north, 7000 to 7200 in the middle, and 7100 to 7400 feet on the south. It rises steeply from the lake flat — 2600 to 3100 feet within a horizontal distance of about one and one-half miles. Hence little drainage enters the basin along this narrow tract.

Large landslides along most of the Winter Ridge fault scarp show the instability of the steep slope. Slides are composed mainly of broken lava flows and intermixed and disrupted beds of volcanic tuff.

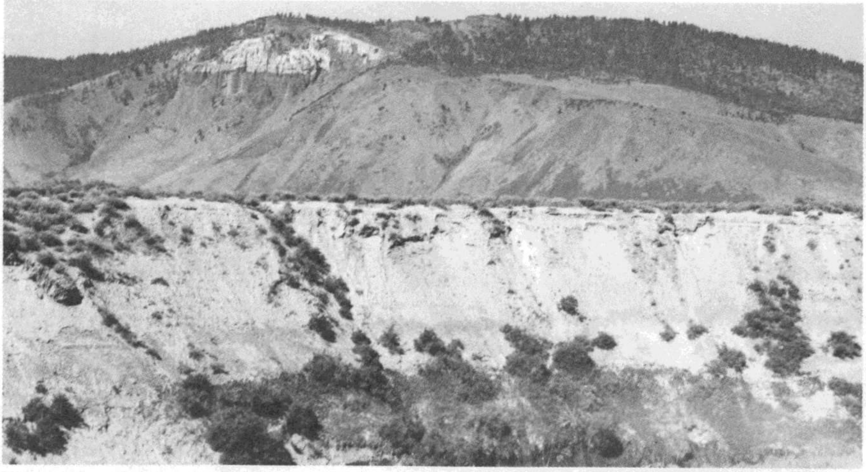

Figure 7: Winter Ridge as seen beyond Ana River bluff. The white patch in Winter Rim is diatomite between Miocene lava flows. The flat surface (middle) is the top of Lake Chewaucan sediments forming the bank of the river.

The high water level of Lake Chewaucan undoubtedly facilitated extensive landslides off this fault-line scarp. Some of the slides reach the edge of the present lake flat, obliterating whatever shore features may have been developed along this part of the expanded Lake Chewaucan of Pleistocene time. Some lake beds also are involved in the slides, as shown in Figures 10 and 11, and sliding is still in progress.

One landslide, two miles wide, has a typically irregular surface, including The Punchbowl and Hunter Hill (Fig. 9). It has pushed the lake shore to the northeast. Its cirque-like headwall rises more than 1500 feet under the 7054-foot Winter Rim. Another slide scallops Winter Ridge in Secs. 21 and 28, T. 32 S., R. 16 E. (Fig. 9). Its headwall is 2000 to 2200 feet high. The slide supports Big Flat behind a transverse ridge and holds a pond on its surface. Most of Sec. 26 in the same township is also a landslide. Another landslide farther south, more than a mile wide, leaves a headwall 1500 feet high and bears a lowland, Bennett Flat, at midlength. The Harvey Creek basin landslide, more than three miles long and a mile and one-half wide, has a 1300- to 1500-foot headwall. Because of these landslides, shorelines of pluvial Lake Chewaucan are lacking along most of the lower slopes of the Winter Ridge scarp.

South Border. The south end of Summer Lake basin is shown by the Slide Mountain topographic map (Fig. 12) and the northwest part of

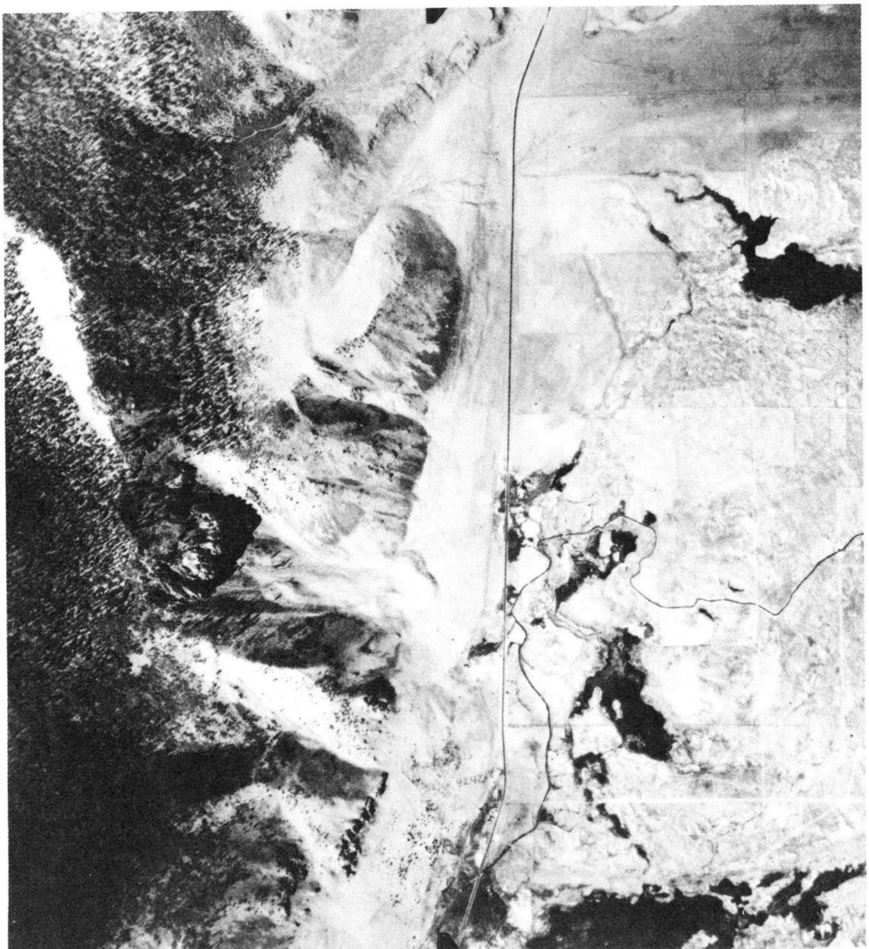

Figure 8: Aerial view of fault-line boundary between Winter Ridge (left) and Chewaucan Lake basin (right). Summer Lake post office is near south edge.

the Paisley map. High ground at the south end of the basin reaches elevations of 7762 feet on Slide Mountain, 7400 to 6793 on other nearby peaks, less than 7000 feet farther east, and only about 5200 to 6500 feet northwest of Paisley. The landslide-scalloped rim of Winter Ridge curves eastward in the Harvey Creek area at the southwest corner of Summer Lake basin, and slides continue eastward for a distance of about four miles along the south rim of the basin. Several

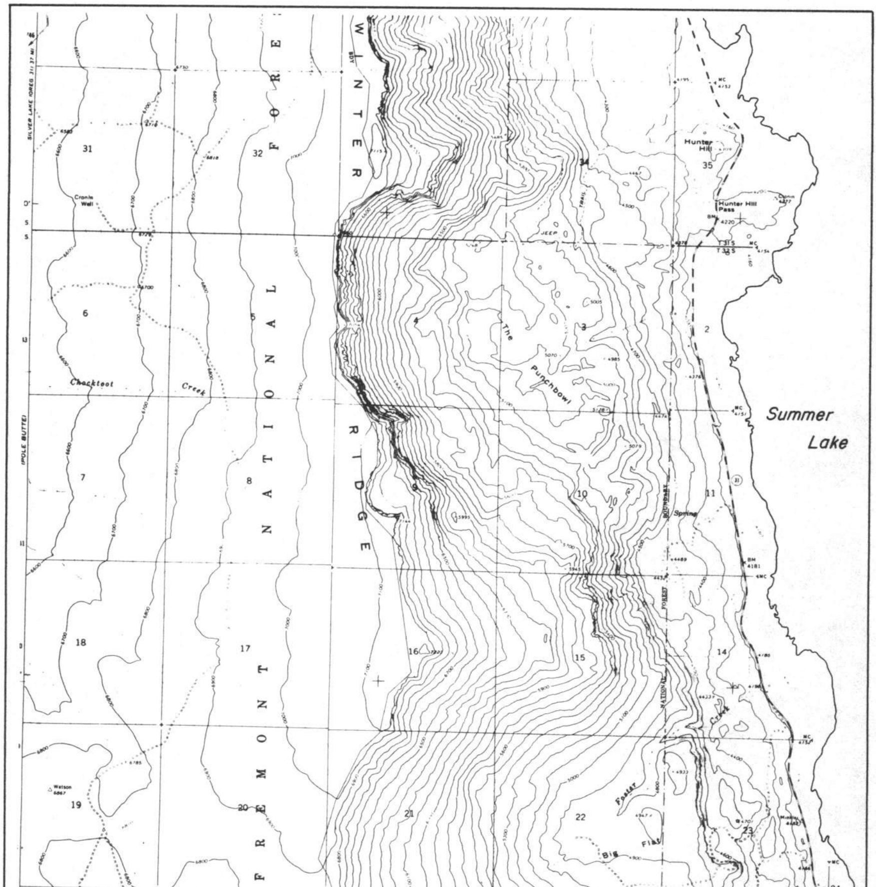

Figure 9: Landslide topography, Fremont Point quadrangle. Note large scallops, steep headwalls, irregular surfaces, and shore protrusions of the slides, and westward-sloping top of Winter Ridge fault block.

Figure 10: Tilted lake beds in toe of a landslide west of Summer Lake. Chewaucan lake sediments and rubble are interbedded. Apparently a major slide has plowed into waterlogged lake sediments (from the right) and upended them.

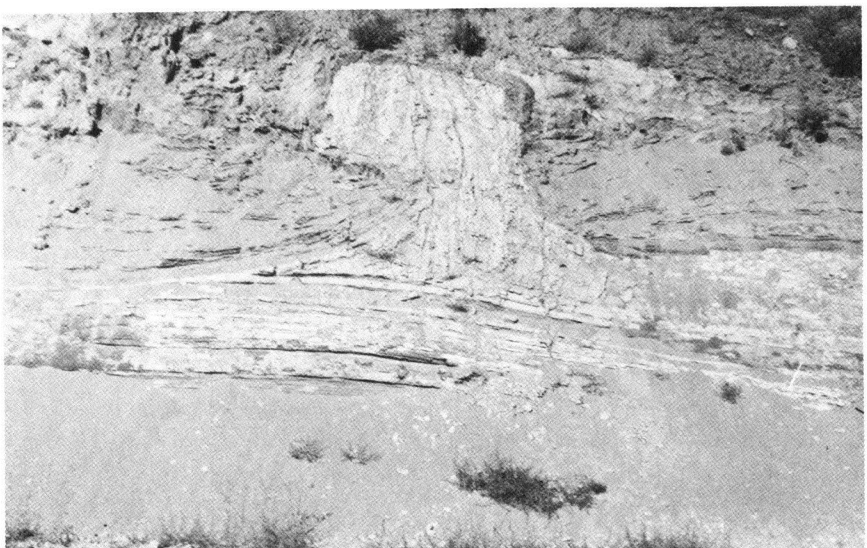

Figure 11: Lake beds deformed by sliding west of Summer Lake. The arrangement suggests that water-soaked bedded lake mud was pushed up through overlying layers by pressure from a landslide.

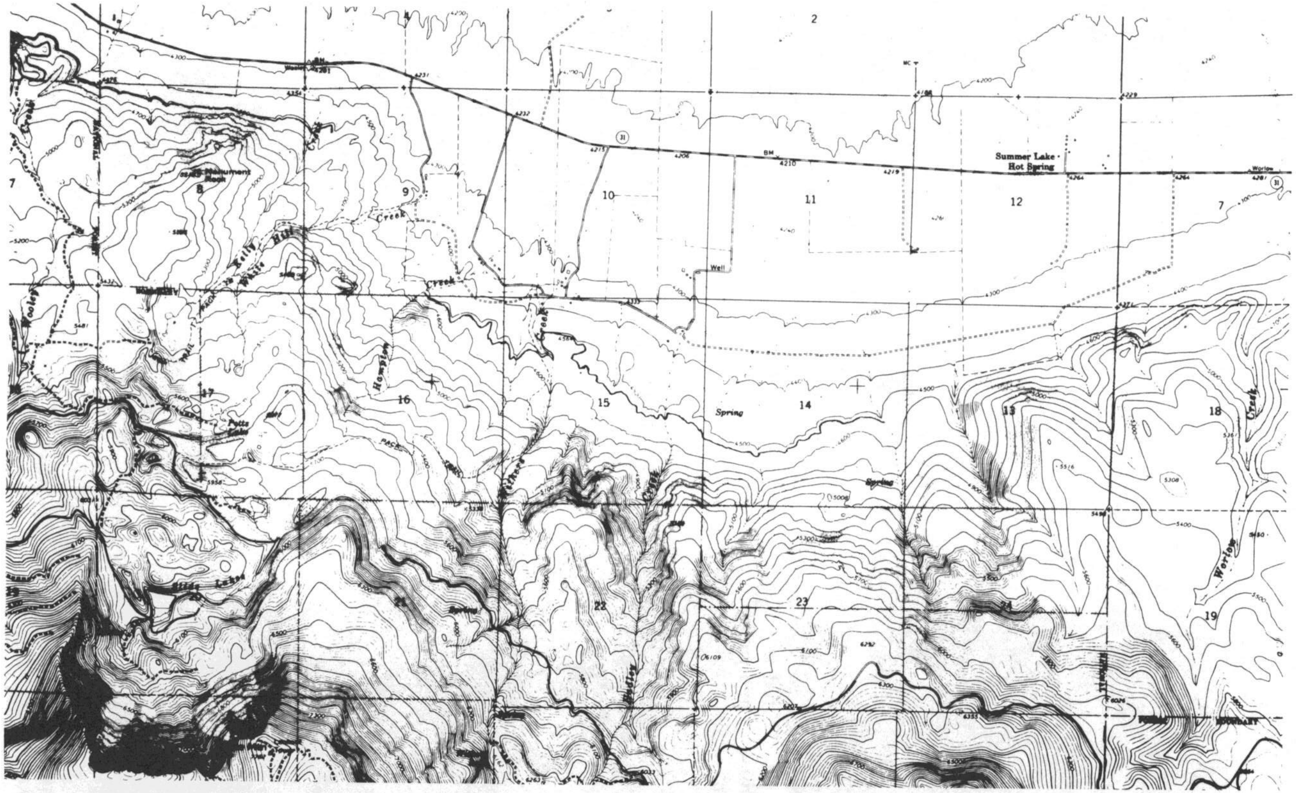

Figure 12. Topographic map of south end of Summer Lake basin, Slide Mountain quadrangle. Slide Mountain landslide is on the left. The Lake Chewaucan shoreline at 4520 feet is smooth against a fault scarp across Secs. 13, 18, and 7 on the right.

Figure 13: A wave-washed fault-line scarp forms the basin boundary, northern part of Slide Mountain quadrangle. The Lake Chewaucan high shoreline crosses near base of the faceted scarp (Λ marks shoreline).

small creeks enter Summer Lake in this section. Farther east, the rim consists of stable basalt flows and lacks landslides (Figs. 12 and 13).

A conspicuous landslide occurs at Slide Mountain, in T. 33 S., R. 17 E. (Fig. 12). It originates in a cirque-like basin a mile wide beginning in the northern part of Sec. 29. Its headwall is more than 1300 feet high, descending from 7600 feet to less than 6300 feet in about three-eighths of a mile. Below the 5000-foot level the slide moved north-northeasterly and pushed out onto the flat adjacent to Summer Lake (Fig. 14). Hence all the Lake Chewaucan shorelines are destroyed across a gap nearly a mile wide. One shoreline as low as 4280 feet in the SW¼SW¼ Sec. 4, T. 33 S., R. 17 E., is interrupted by the landslide. Beds of volcanic tuff, as seen in the White Hills Creek area, no doubt contribute to the local instability.

East of the Slide Mountain landslide, basalt extends down to the base of the exposure, and the rim of the basin is formed by a roughly east-west fault-line scarp, as seen in Fig. 13. The southeast corner of Summer Lake basin is occupied by a deposit of gravel which forms a wide divide, locally called Paisley Flat (Figs. 1 and 15), between the Summer Lake lowland and Upper Chewaucan Marsh, as first noted by Waring (1908, p. 52). I shall discuss Paisley Flat later.

East Border. The eastern border of Summer Lake basin is bounded by a less prominent rim than the scarps on the west and south sides. A gently sloping lowland six to ten miles wide lies between Summer

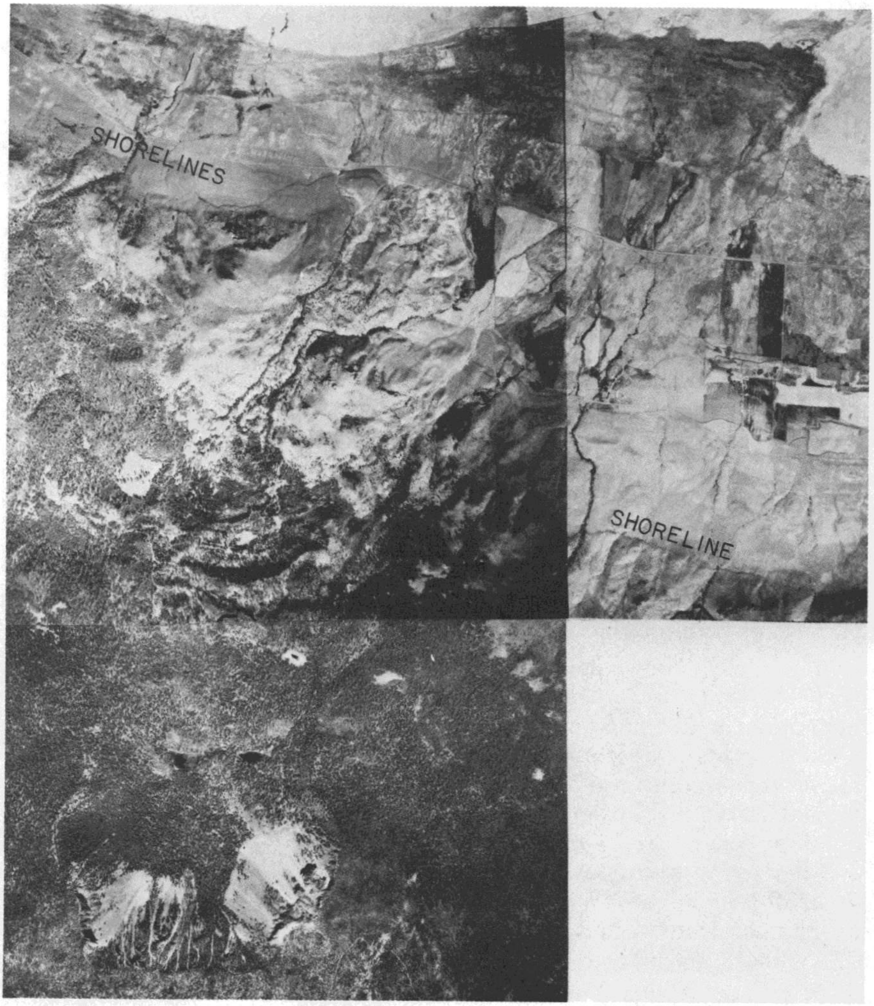

Figure 14: Aerial view of Slide Mountain landslide. The slide breaks the continuity of Lake Chewaucan shorelines between middle right and upper left (north of tuffaceous White Hills).

Lake and the hilly eastern margin of the basin. At some places along the eastern border the ground rises gradually from the lake flat; in others it rises by a succession of steps formed by several tilted fault blocks of different sizes, orientation, and steepness. Parts of three such blocks are shown in the the northeast part of the Paisley topo-

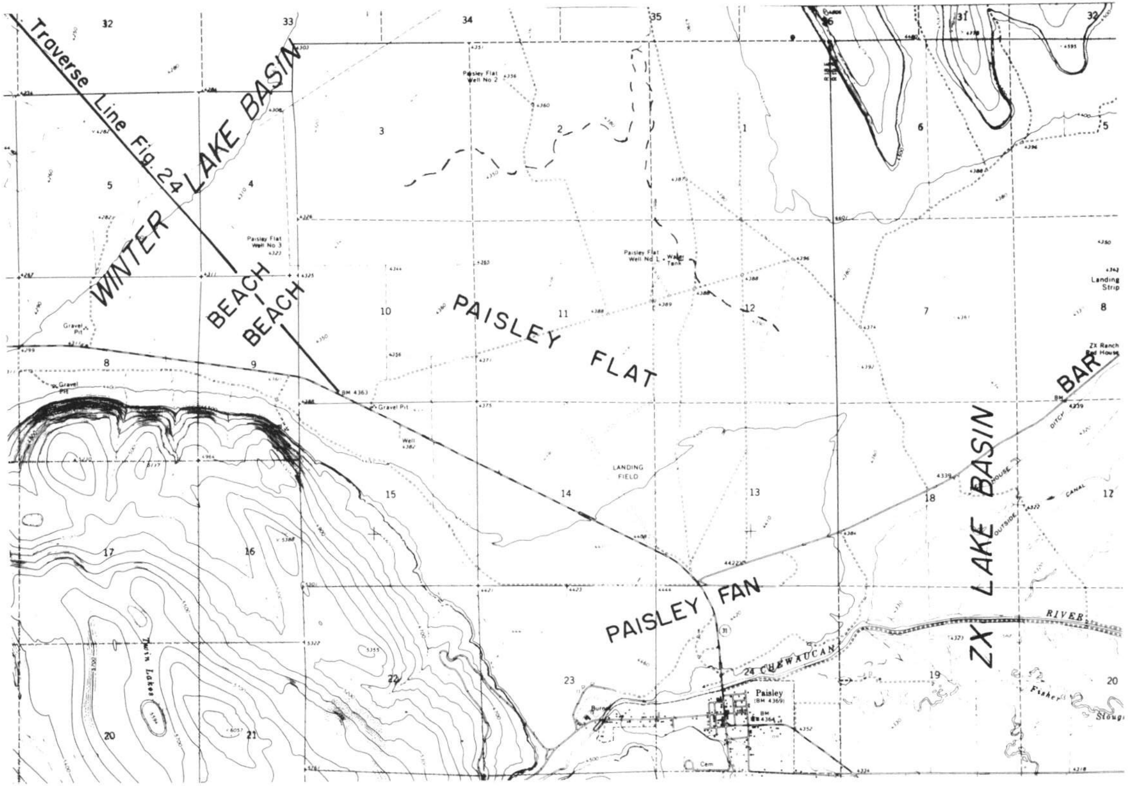

Figure 15. Topographic map of Paisley area, Paisley quadrangle. Note gently sloping Paisley fan (below 4480 feet) north of Chewaucan River, Paisley Flat (below 4410 feet, upper middle) crossed by overflow channel (dashed line added), ZX Lake basin (below 4390 feet, right), and Winter Lake basin (upper left).

graphic map (Fig. 15). Fault blocks near the northeast corner of Summer Lake basin are sharply defined (Fig. 16).

The lowland immediately east of Summer Lake is so nearly flat that strong persistent winds push shallow sheets of lake water long

Figure 16: Fault-block boundary of Lake Chewaucan (Λ marks boundary), northeast of Summer Lake (top is north). The blocks are separated by intersecting faults. Lake flat (left) is covered with dunes of Mount Mazama sandy pumice.

distances over it. A large part of the lowland around the lake is covered with evaporites that dry out and crumble into sand- and silt-size grains. Carried along by the wind, the larger dry particles form dunes; the very fine particles, carried as dust clouds, coat the lowland and the rocky slopes of the basin or blow out of the basin entirely, especially toward the northeast.

Upper Chewaucan Marsh Basin

The Paisley Flat gravel plain (Figs. 1 and 15) on the Summer Lake-Upper Chewaucan Marsh divide north of Paisley is about four miles wide. Immediately southeast of this gravel plain, the basin expands again into another structural depression, now occupied by Upper Chewaucan Marsh. This lowland, as shown on the Paisley, Coglan Buttes, and Tucker Hill topographic maps, is about ten miles long and up to seven miles wide. It is especially important in Lake Chewaucan history because of a fan-delta built at Paisley by Chewaucan River during a high stage of the lake (Fig. 15) and the later redistribution of part of the material across Paisley Flat by waves and shore currents at lower lake stages. Former wave work is also evident at other places around the margin of the Chewaucan Marsh basin.

Upper Chewaucan Marsh, originally a tule-cattail swamp (now drained) has an elevation of about 4310 feet at the northwest end and 4300 feet where Chewaucan River leaves at the southeast corner. The eastern border of the basin is formed by dissected fault scarps along the imposing Coglan Buttes, which have a maximum elevation of 6209 feet. The height of the eastern rim decreases by about 1000 feet northward from Coglan Buttes. The main Coglan Buttes fault block slopes east-northeasterly away from the basin (Fig. 17).

Much of the southeast end of the Upper Chewaucan Marsh basin is confined by a NE-SW ridge of rock of which Tucker Hill (elev. 4964 feet) is part (Fig. 18). This ridge was a peninsula in pluvial Lake Chewaucan and was extensively eroded by waves. West of the Tucker Hill peninsula was a south-southeast extension of the lake into the lower reaches of presumably fault-controlled Moss Creek Valley. At the east end of the peninsula is The Narrows between Upper and Lower Chewaucan Marshes, where abundant shore deposits occur.

Lower Chewaucan Marsh Basin

The Lower Chewaucan Marsh Basin is a lowland ten miles long and two and one-half to five miles wide, shown on the Tucker Hill, Coglan Buttes SE, and Valley Falls topographic maps. Ditched for drainage, the marsh slopes from about 4300 feet on the northwest to 4283 in the middle and 4290 feet near the southeast end. Chewaucan

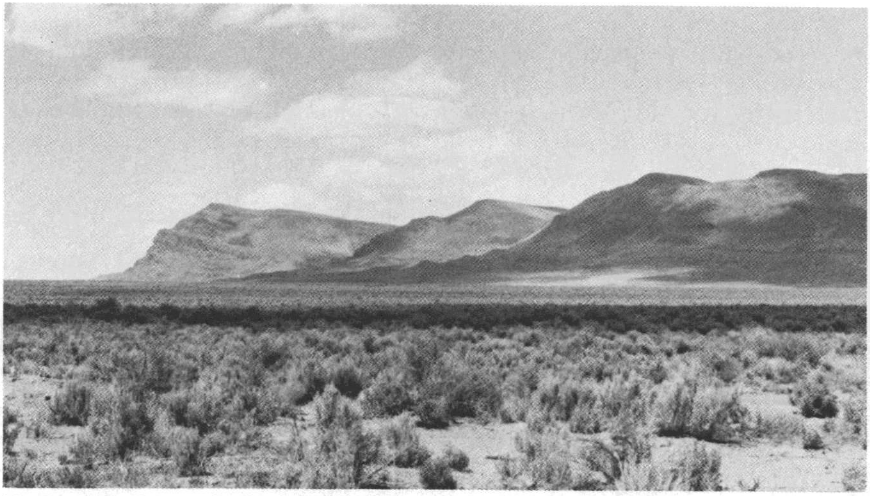

Figure 17: Eastward tilted Coglan Buttes fault block at eastern boundary of Upper Chewaucan Marsh basin.

River flowing through it descends to less than 4280 feet. Near the low end of the basin, Chewaucan River turns sharply north-northeast and flows into Lake Abert.

The northeastern margin of the basin is a persistent fault-line scarp (Fig. 19). Because of irregularities in the fault pattern, the basin has an irregular outline, with indentations and extensions along the edges. One tilted fault block two miles long, near the south margin, shows steep scarps on its south and west sides and a gentle slope to the northeast. A southward continuation of the Coglan Buttes fault block separates Lower Chewaucan Marsh from the Lake Abert basin north of the Chewaucan River exit. This fault block is broken internally by other faults; its upper edge declines in elevation to the southeast, and it slopes gently toward Lake Abert.

The upper end of Lower Chewaucan Marsh basin is drier than Upper Chewaucan Marsh, so the lake flat there has undergone deflation by the wind, leading to the formation of sand dunes in a band about four miles long along the northeast side of the basin.

Lake Abert Basin

The Lake Abert basin is basically a trough between the Coglan Buttes fault block and the prominent fault scarp on the west edge of the Abert Rim fault block. The west side of the basin is the eastward-sloping top of the Coglan Buttes fault block (shown on the Coglan Buttes, Coglan Buttes NE, and Coglan Buttes SE topographic

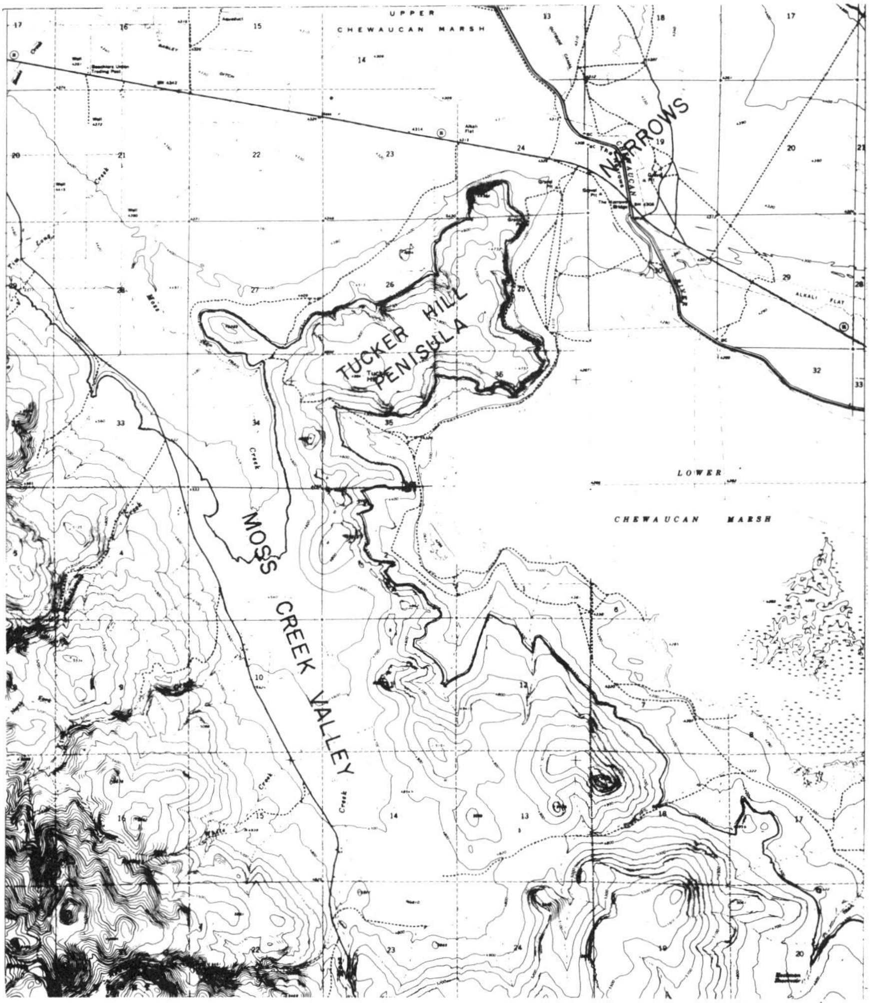

Figure 18: Topographic map of Tucker Hill-Narrows area, Tucker Hill quadrangle. Upper and Lower Chewaucan Marshes are separated at The Narrows (upper right). Tucker Hill ridge (upper middle) formed a peninsula in Lake Chewaucan, opposite a sloping spur (northeast corner), connected by gravel spits and beaches. See Fig. 34 for details at The Narrows.

maps). The north end of the Lake Abert basin rises gradually along minor fault blocks. In contrast, the east side of the basin (shown mainly on the Lake Abert North and Lake Abert South quadrangle maps) is the very impressive Abert Rim. This fault scarp is 2500 feet

Figure 19: Lake Chewaucan shoreline on northeast side of Lower Chewaucan Marsh basin (Λ marks shoreline), formed by faulted basalt flows cut by a dike (left).

high near the north end of the lake and 2700 feet high near the south end. Elevations along the crest of the rim generally range between 6800 and 7000 feet and reach a maximum of 7548 feet. The scarp rises sharply in as little as one-half mile. The top surface of the Abert Rim fault block slopes eastward away from Lake Abert.

Lake Abert basin is open to the southwest where it joins Lower Chewaucan Marsh and Crooked Creek Valley to form a "Y" in which Lower Chewaucan Marsh is the left fork, Lake Abert basin the right fork, and lower Crooked Creek Valley the stem. As the lowest part of the combined Chewaucan-Abert basins, Lake Abert receives the limited discharge of Chewaucan River after its passage through Upper and Lower Chewaucan Marshes. The water is alkaline as a result of evaporation, small inflow, and no surface outlet. The total quantity of salts in Lake Abert fluctuates with the volume of water and the storage and re-solution of salts from adjacent playa muds (A. S. Van Denburgh, pers. comm. 1954; 1975).

Lake Chewaucan Shore Feaures

Many fossil shorelines surround the pluvial Lake Chewaucan basin. Some are erosional in origin and some are depositional. They are described below for each of the four subdivisions of the lake area.

Summer Lake Sector

Because of landslides, the western and southwestern parts of the Summer Lake basin are practically devoid of pluvial Lake Chewaucan shorelines, but these are well developed elsewhere around the perimeter of the basin.

Features at the north end of the basin include 1) the highest known wave-cut cliff within the basin (4520 feet) and associated water-worn gravel at 4517 feet, 2) a beach ridge of gravel at 4485 feet, and 3) a prominent east-west gravel ridge at the 4365-foot level (Figs. 2 and 3). The latter ridge, having a 27-foot deep depression behind it, is thought to be primarily a baymouth bar. The south face of the ridge has a faintly fluted pattern made by stillstands during the declining stages of the lake below 4365 feet.

A series of shoreline levels along the cliffy south end of the Summer Lake basin is indicated by the erosion of pre-lake basaltic talus to form terraces (Fig. 20), which are not smooth enough to provide precise elevations. Intermediate-level Lake Chewaucan shorelines occur at 4398 and 4432 feet, and a high cliff shoreline rising above 4500 feet is obscured by talus except in the lee of projecting rock points.

In the southeastern part of the Summer Lake basin north of Paisley, waves on Lake Chewaucan eroded three caves at or near the 4485-foot level in a basalt cliff at Five Mile Point (Figs. 21, 22, and 23). These caves were occupied by prehistoric people (Cressman,

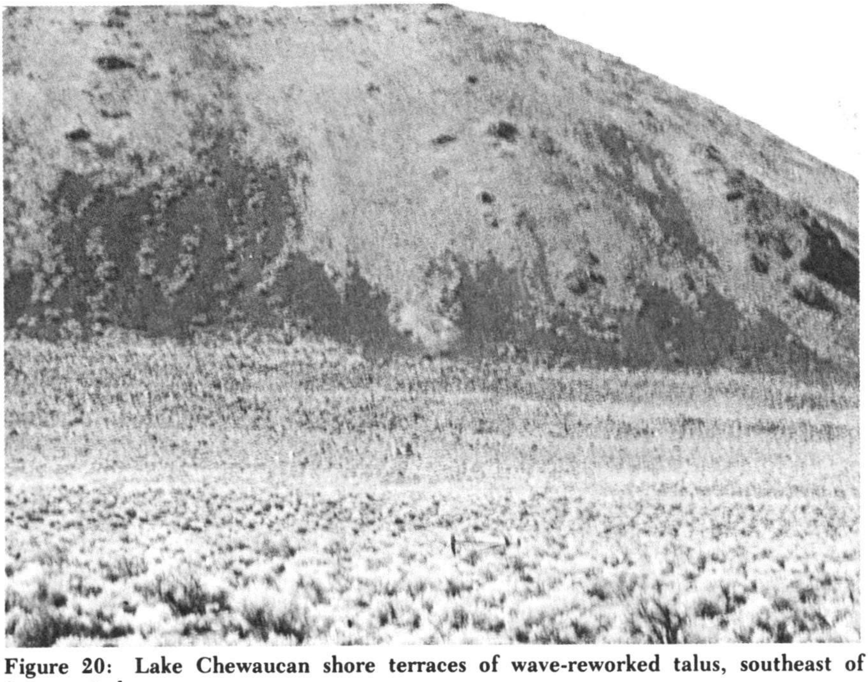

Figure 20: Lake Chewaucan shore terraces of wave-reworked talus, southeast of Summer Lake.

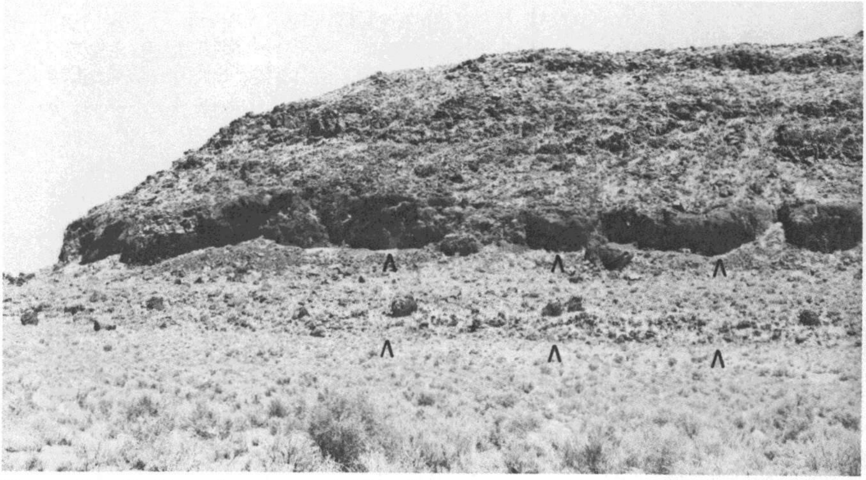

Figure 21: Setting of wave-cut Paisley Caves at Five Mile Point north of Paisley. A lower shoreline also is visible along the front of the bouldery talus (Λ marks both shorelines).

Williams, and Krieger, 1940; Cressman, 1942, 1943), both before and after the deposition of Mount Mazama pumice about 6,600 to 6,700 years ago.

The Chewaucan River fan built into the Lake Chewaucan basin initially may have almost separated Lake Chewaucan into two parts, one part a continuation south and southeastward from Paisley, and the other confined to the Summer Lake basin. In any event, such a separation certainly was completed when gravel from the fan was spread across Paisley Flat by waves and shore currents at a lower lake stage. The part of the lake left in the Summer Lake basin I have previously named Winter Lake (Allison, 1940). The other remnant I now call ZX Lake, named for the ZX Ranches situated in the Upper Chewaucan Marsh basin.

ZX Lake at one stage overflowed the Paisley Flat (Waring, 1908) by a crooked route (Fig. 15) into Winter Lake. The overflow stream eroded a channel 100 or more feet wide and generally 10 to 15 feet deep in sand and tiny pebble gravel. The upper end of the channel is a slot at approximately 4382 feet; the elevation of the rim beside the channel intake suggests that initial overflow began at or near 4390 feet and that the intake was lowered by erosion as much as eight feet. Gravel and sand removed from the overflow channel were deposited as a delta in Winter Lake, mainly just below the 4340-foot level. Distributary channels on the delta are two feet deep. Waves and shore

Figure 22: Mouth of a Paisley Cave, showing its setting in lava flow-breccia.

currents on Winter Lake redistributed part of the deltaic material to form a well-developed beach ridge at 4330 feet, one-half mile farther west (at Paisley Flat Well No. 3, Fig. 15).

The possible difference in levels of as much as 50 feet between ZX Lake and Winter Lake at the time of the ZX Lake overflow probably means that 1) both lakes had previously declined to lower levels soon after their separation, and 2) ZX Lake later rose to the overflow level while Winter Lake rose less. This difference in levels undoubtedly resulted from a larger water supply (via Chewaucan River) on the ZX side of the divide.

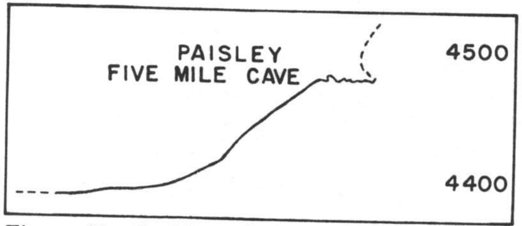

Figure 23: Position of the Paisley Caves in a Lake Chewaucan shore.

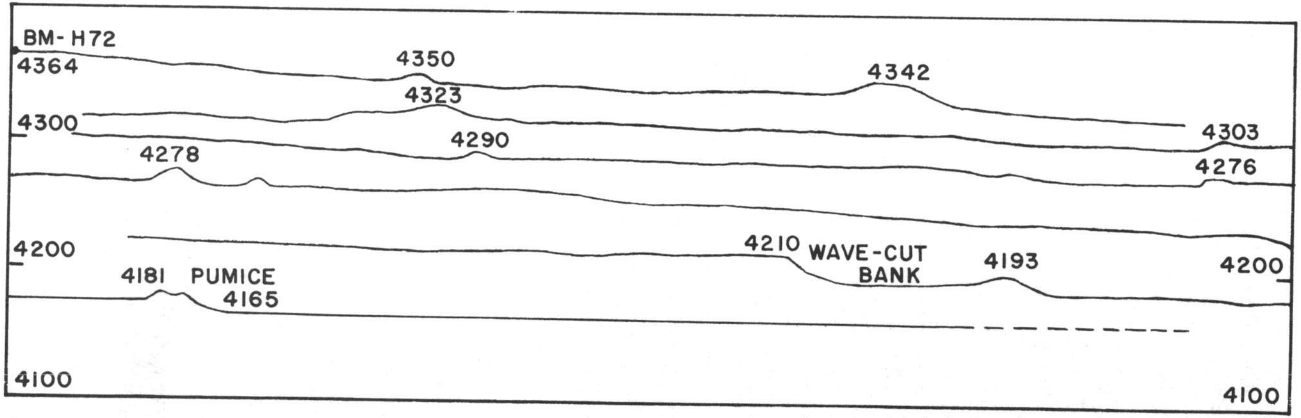

Figure 24. Continuous profile (line by line in sequence downward) from Bench Mark H-72 west-northwesterly across Winter Lake shorelines into the basin of Summer Lake. Beach ridges at 4342 and 4323 feet are especially strong (vertical exaggeration 5x).

Below the Winter Lake delta and associated beach ridges, the profile of the lake bed toward the west shows 1) beach ridges at 4323, 4303, 4290, and 4276 feet; 2) a sandy pumice accumulation at 4275 feet; 3) a steep wave-cut bank between 4189 and 4210 feet; 4) a 10-foot high beach ridge at 4193 feet; 5) a beach between 4165 and 4181 feet; and 6) no other relief feature on the lake flat down to the end of the leveling traverse at 4155 feet (Fig. 24).

The maximum level of Winter Lake conceivably may have been at the 4365-foot gravel ridge at the north end of the Summer Lake basin. If so, the inital overflow of ZX Lake might have been contemporaneous with the construction of this ridge. But if that were true, the level of Winter Lake must have gone down rapidly due to evaporation losses despite the continuing contribution of water by the ZX Lake overflow, because the overflow delta level is near 4340 feet, not 4365 feet. As such a fast drop in Winter Lake level while being fed by ZX Lake overflow is very unlikely, the gravel ridge probably has no connection with the overflow stage. The overflow may have been a single episode or it may have been repeated periodically before a decreased water supply in ZX Lake ended it. The small size of the overflow channel indicates a geologically short total time of overflow.

Upper Chewaucan Marsh Sector

The outstanding feature of the Upper Chewaucan Marsh basin is the high-level alluvial fan at Paisley (Figs. 15 and 25). This deposit

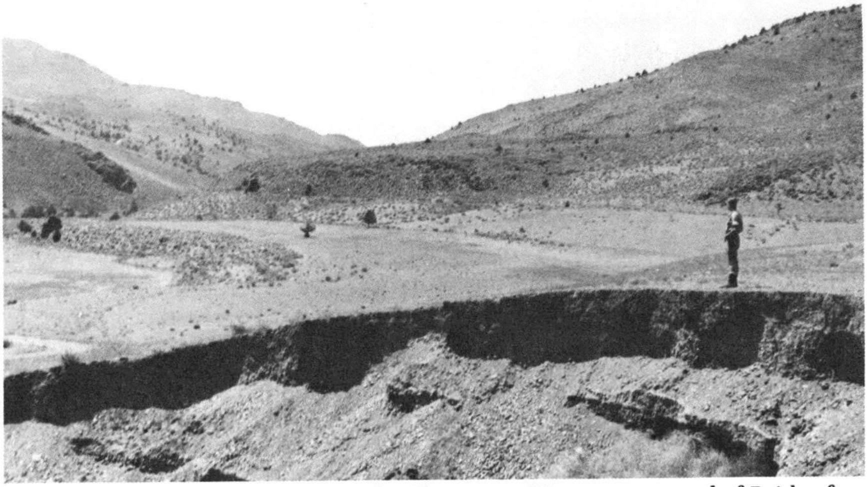

Figure 25: Two stream terraces cut by Chewaucan River at upper end of Paisley fan, as seen from east-southeast. The top surface of the fan is on the right.

was classified by Waring (1908) as a delta of Chewaucan River. It may conceal deltaic components but its present form is that of a fan. Its elevation at the former mouth of the river is approximately 4500 feet, but its apex originally may have been higher. The fan evidently was made at or near the maximum stage of Lake Chewaucan and lost its apex by later river erosion. Its gently sloping surface declines toward the east, northeast, and north until it reaches a later wave-eroded, sharp descent from about 4440 feet to about 4410 feet. Beyond this wave-cut bank on the north side, the fan gives way to the reworked gravel and sand of the Paisley Flat, which includes several minor beaches or bars (Fig. 26). On the east side of the fan, the ground surface exhibits wave-cut slopes at 4433, 4426, and 4367 feet, in addition to the major cut between 4410 and 4422 feet (Fig. 27). A series of north-northeasterly trending spits occurs along the Paisley Flat-ZX Lake margin from 4420 feet down to 4380 feet, evidently a result of shore currents on the ZX Lake side.

Gravel interpreted as an older alluvial fan deposit is exposed along Chewaucan River in Paisley and in a roadcut just north of the river (Fig. 28). The underlying gravel is coarse, poorly sorted, semiconsolidated, and somewhat iron-stained. The roadcut also shows gravel in channel form interstratified with thin-bedded lake deposits, thus seeming to indicate fluctuations of the lake level (Fig. 29) and formation of a combined fan-delta. Distorted bedding (Fig. 30) was probably caused by subaqueous sliding of the material along bedding planes.

Immediately south of the Chewaucan River is a set of lakeshore gravel terraces, one above 4480 feet and another between 4440 and 4460 feet. The river also made cut-terraces as it trenched the Paisley fan deposit (Figs. 25, 28, 29, and 30).

The north end of the Upper Chewaucan Marsh basin east of the Paisley fan was a bay in ZX Lake, enclosed by a broad beach that now forms an arc extending from the eastern eroded foot of the Paisley fan to the eastern shore of the ZX Lake basin. The top of most of this arcuate beach is between 4340 and 4345 feet. For convenience it is called the ZX Red House beach, named for the ZX Red House Ranch upon it. Swales up to ten feet deep lie behind the beach on the north, so the beach may also be aptly called a baymouth bar. The bulk of its material undoubtedly came from wave erosion of the east front of the Paisley fan. The profile at the bottom of the former bay north of the ZX Red House beach shows beach ridges at 4379 and 4386 feet, a rocky north shore with a little waterworn gravel where the slope is gentle, and large basalt boulders on steep slopes at high levels (Fig. 31). At the northeast corner of the Upper Chewaucan Marsh

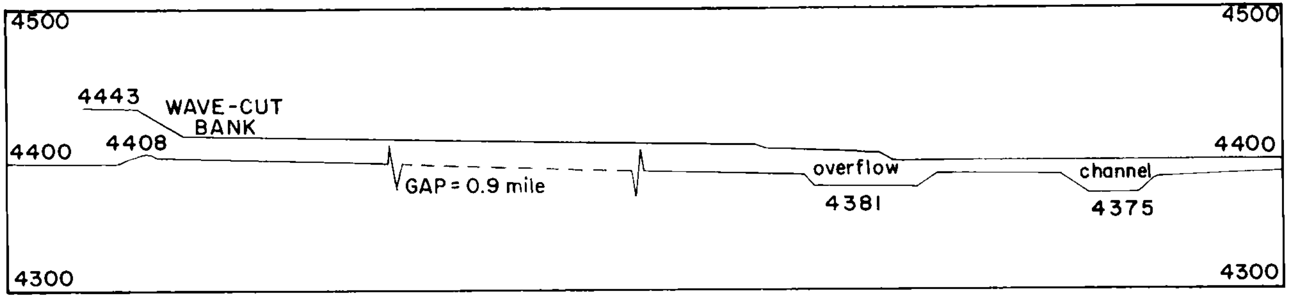

Figure 26: Profile of Paisley Flat from cutbank on north side of Paisley fan to beyond winding overflow channel (vertical exaggeration 5x).

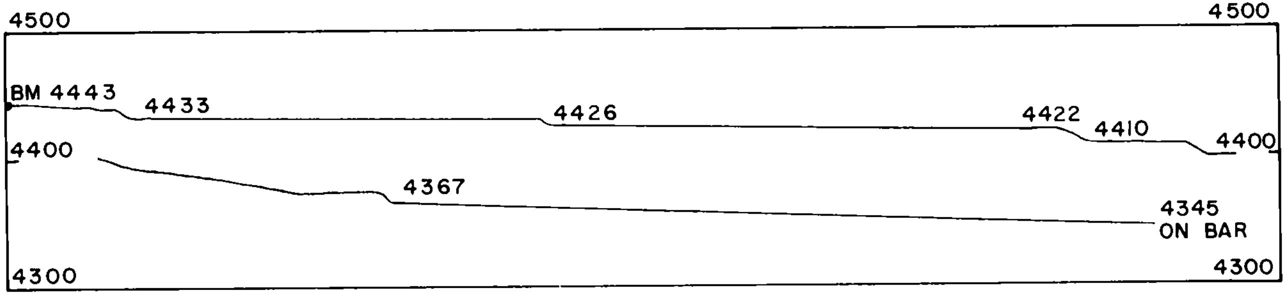

Figure 27: Profile of gravel surface east-northeast from BM 4443 (in N½ NW¼ NW¼ Sec. 24) on the eastern part of Paisley fan down to ZX Red House beach (vertical exaggeration 5x).

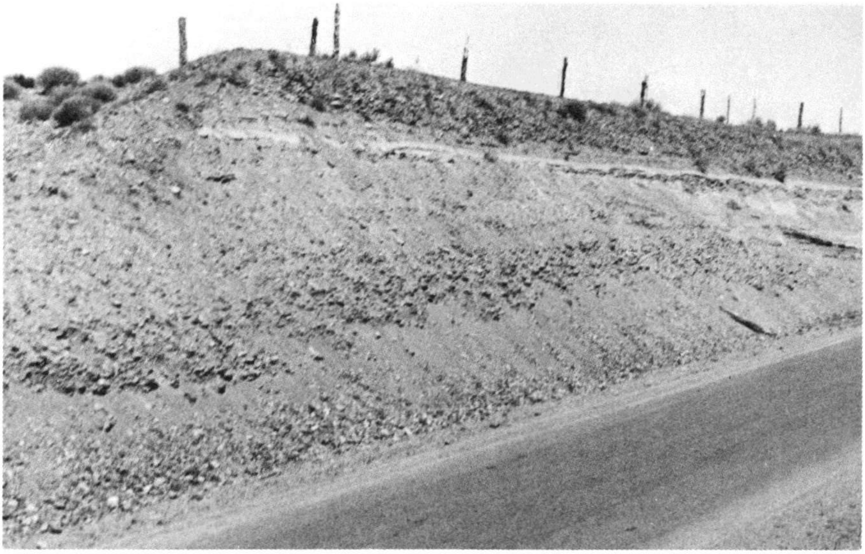

Figure 28: Lower part of roadcut in Paisley fan, showing pre-Lake Chewaucan gravel (on left). Light-colored lake beds are capped by later river terrace gravel.

Figure 29: River gravel on and between lake beds at Paisley roadcut, indicating fluctuations of levels of Lake Chewaucan.

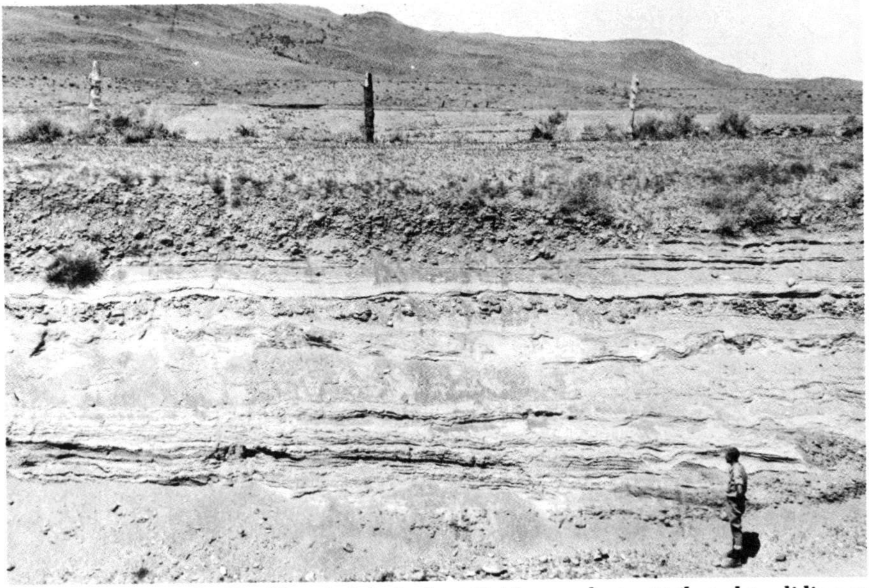

Figure 30: Disturbed bedding in lake beds at Paisley roadcut, attributed to sliding or possibly weight loading of water-soaked sediments.

basin, shore currents and an incoming stream in Sand Hollow built high terraces of gravel in Lake Chewaucan a little above 4500 feet.

The west side of the Upper Chewaucan Marsh basin south of Paisley generally has only faint shoreline markings of former Lake Chewaucan. Gently sloping alluvial fans lie below the mouths of tributary stream courses (Fig. 32).

The south end of the Upper Chewaucan Marsh basin is formed mainly by the Tucker Hill ridge, which formed a peninsula between the Upper and Lower Chewaucan lobes of pluvial Lake Chewaucan (Fig. 18). Wave erosion on the north side of the peninsula made notches at approximately 4370, 4460, and 4520 feet (Figs. 33 and 34). The east end of the peninsula has a high terrace with a covering of rounded gravel at 4484 feet, a wave-eroded bench at 4460 feet, and gravel deposits extending down the slope of the ridge to its foot on the east and northeast. The rhyolitic rock of the Tucker Hill peninsula furnished copious supplies of fragmental rock debris to the lake basin.

The east side of the Upper Chewaucan Marsh basin is formed by the fault-line scarp of the Coglan Buttes fault block (Fig. 17). No outstanding features occur along the seven-mile stretch between the east end of the ZX Red House beach and the vicinity of the The Narrows.

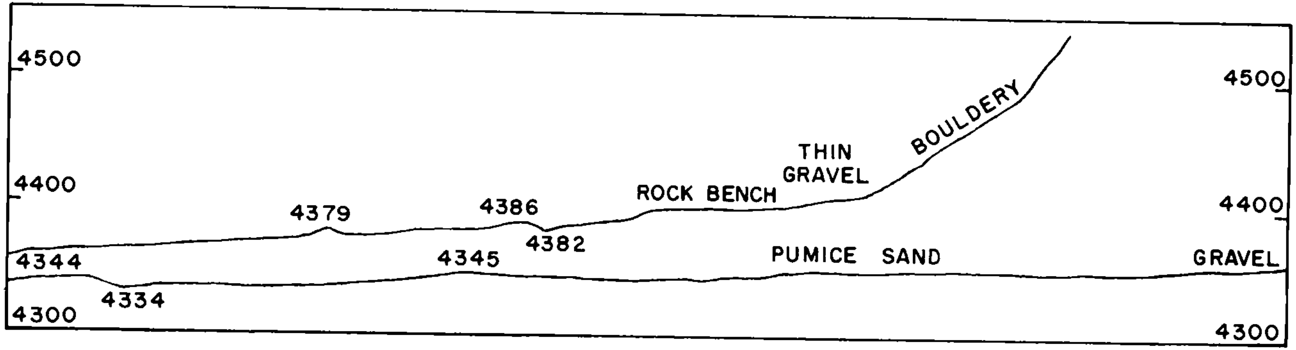

Figure 31: Continuous profile from ZX Red House beach (left on lower line) northward to Lake Chewaucan shore (upper line). Horizontal distance is about 1.6 miles (vertical exaggeration 5x).

Figure 32: West side of Lake Chewaucan basin south of Paisley, little modified by waves. An alluvial fan is on the middle right.

The Narrows Area

The Narrows area records an extended series of shore features (Figs. 35 and 36). The east end of the Tucker Hill peninsula, west of The Narrows, has a gravel pit at the highest shoreline, a gravel terrace above the 4480-foot level, and additional gravel on the intermediate and lower slopes. Spits or gravel terraces are prominent near the 4360-foot level on both sides of The Narrows; they may once have joined not far below this level before being separated by Chewaucan River. The 4340-foot spit and the interrupted beach ridge (in N½ Sec. 19 and S½ Sec. 18, T. 34 S., R. 20 E., Fig. 35) apparently were built by shore currents which obtained their loads from the south and southwest, probably in large part from debris swept alongshore from the Tucker Hill peninsula. As the route of such a current crosses The Narrows, we may surmise that the fill at 4340 feet formed a dam at that level within the gap, if it had not already been blocked at a somewhat higher level sometime earlier. In any event, the overflow from the Upper Chewaucan Marsh basin enabled Chewaucan River to breach the fill to a little below 4300 feet at present. Traces of several distributary stream courses across a belt two miles wide at the head of Lower Chewaucan Marsh apparently indicate the disposal of part of the fill material as an alluvial fan (in N½ Sec. 30, Fig. 35) as the blockade was removed by Chewaucan River.

Lower Chewaucan Marsh and Lake Abert Sectors

Erosional shore features are found here and there around the periphery of the Lower Chewaucan Marsh basin, especially on the

Figure 33. Wave-formed lake-shore terraces on north side of rhyolite hill in Tucker Hill peninsula. Gravel-choked The Narrows is beyond left edge.

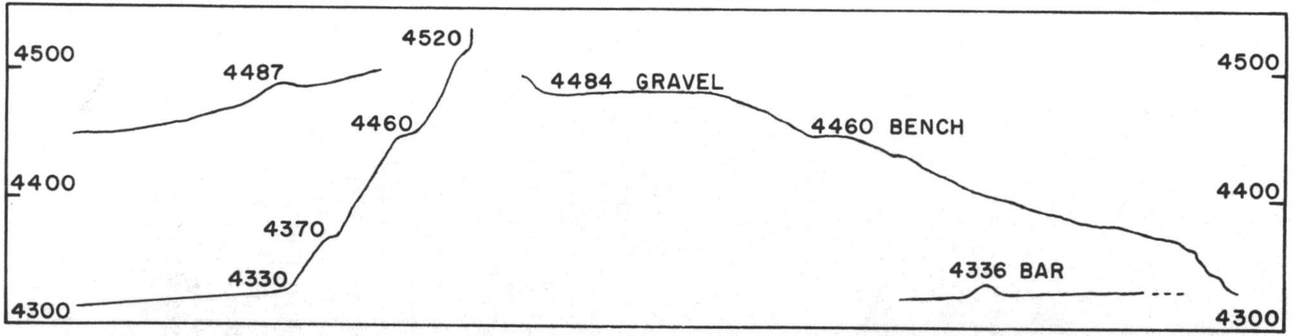

Figure 34. Shore profiles showing benches and gravel ridge on north side (left) and east side (right) of Tucker Hill peninsula in Fig. 33 (vertical exaggeration 5x).

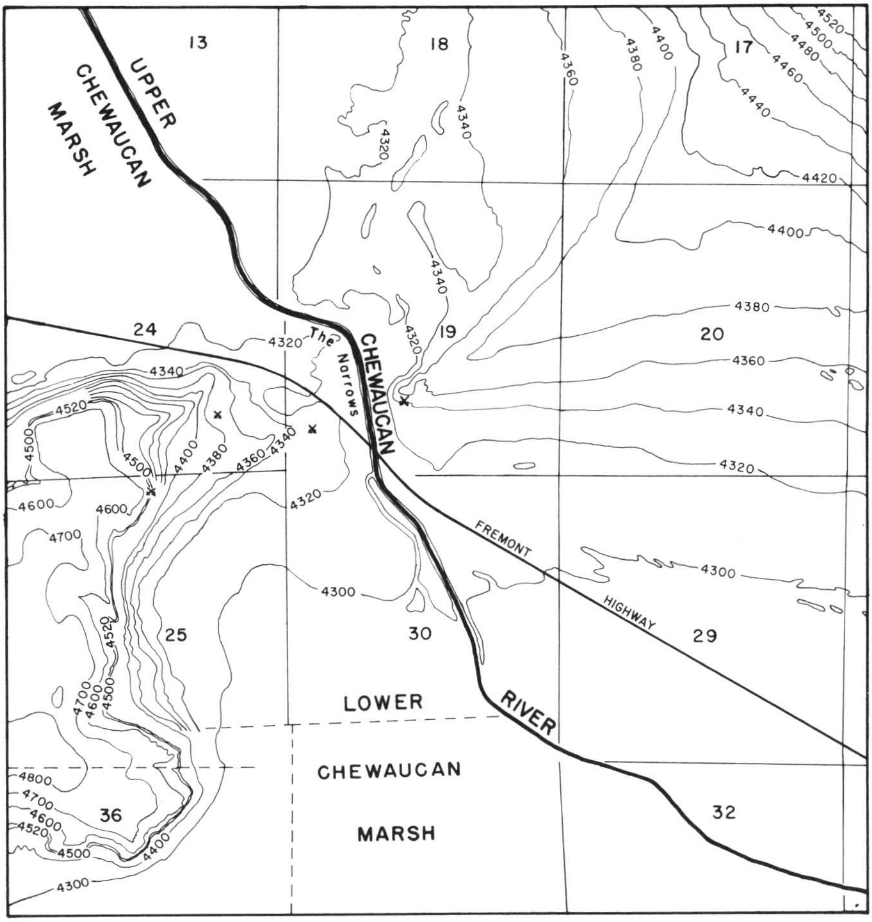

Figure 35: Topographic map of The Narrows area, Tucker Hill quadrangle. Fill made by waves and shore currents once reached at least 4340 feet. Note four gravel pits (marked by x), the largest one east of the river. Removal of part of the fill by Chewaucan River in breaching the barrier made a fan in Sec. 30.

east and south sides. Only in the lower Crooked Creek Valley were any measurements made, and then only by aneroid barometer. Two wave-eroded hills in this valley stood for a time as islands in Lake Chewaucan. The southernmost one was joined to the western side of the valley by construction of a tie-bar (tombolo) at or near the 4485-foot level.

The former level of pluvial Lake Chewaucan in the Lake Abert portion of the basin is easily seen near the base of Abert Rim (Fig. 37).

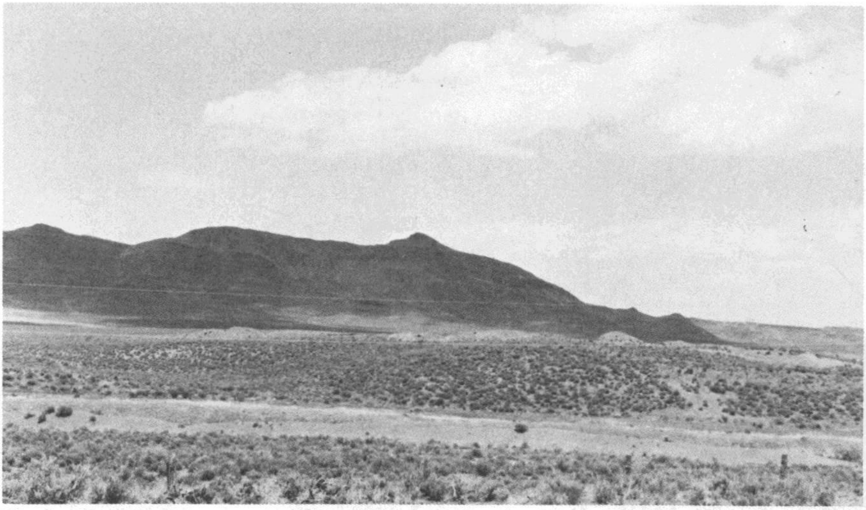

Figure 36: Southwest end of broad gravel ridge (middle of photo) shown in Fig. 34, as cut off by Chewaucan River in The Narrows.

Figure 37: Lake Chewaucan shoreline on lower slopes of Abert Rim, reaching about 265 feet above Lake Abert (Λ marks shoreline). Chewaucan River near its mouth is in the foreground.

Summary of Lake Chewaucan Basin Levels

Elevations of the most significant shore features in four areas within pluvial Lake Chewaucan are listed in Table 6.

Lake Bottom Sediments

Summer Lake Basin

The principal exposure of pluvial Lake Chewaucan bottom sediments in the Summer Lake basin occurs in the banks of Ana River (Figs. 7 and 38) below spring-fed Ana Reservoir, where the accessible stratigraphic section is 54 feet thick (Conrad, 1953). The section includes many layers of pumice or volcanic ash (Fig. 39). Certain of these layers near the top of the section have been described by Allison (1945, 1966a), Randle, Goles, and Kittleman (1971), Kittleman (1973), and Enlows (1979). One of these layers is rich in distinctive biotite flakes. Ostracods from a thin seam five inches below the biotitic layer yielded a radiocarbon age of 30,700 (+2,500 or −1,900) years (Teledyne Isotopes I-1640;1965) (Allison, 1966a).

Two of these ash layers, including the biotitic one, are also exposed in the area southeast of Summer Lake. These two thin layers crop out at 4206- and 4208-foot levels in a bank eroded by Winter Lake (Fig. 24). The upper layer is rich in biotite like that in the Ana River section. The lower one is gray and rich in crystals of feldspar and hypersthene, like a correspondingly situated layer at the Ana River locality. Another layer of volcanic ash crops out at Worlow Creek near Oregon Highway 31 in Sec. 7, T. 33 S., R. 18 E., at 4278 feet.

Conrad (1953) divided the Ana River stratigraphic section into 66 units which he described in detail. The bulk of material is silt with thin layers of sand, fine sand, calcareous oolites, and pebbles. In 29 samples he examined, 71 to 93 percent of the grains were of silt size. The other main constitutent is pumice or volcanic ash, estimated at 15 percent by Conrad. Volcanic material occurs throughout the section, but it is especially abundant near the top.

Occasional granules or small pebbles of basalt are scattered in many stratigraphic units, but other rounded, subrounded, or irregular pebbles up to 1-inch size are concentrated in thin seams (along with sand, oolites, and ostracods) at several depths in the section. According to Conrad, basalt pebbles occur at depths of 3.4, 5.0 to 6.5, 8.3 to 9.3, 11.2, 14.3 to 15.3, 18.8, and 20.9 (a layer 1.6 inches thick), 23.3 to 25.4, 26.4 to 26.7, 29.1, 36.2, 44.3, 47.1, and 49.8 to 49.9 feet. While most or even all of the pebbles may have been transported

Table 6. Elevation of significant shore features

Summer Lake basin	Near Paisley	ZX Red House region	Tucker Hill/The Narrows
4520 base of cliff	4500 Paisley fan	4500 gravel terraces	4520 wave-cut notch
		4500 rock bench	
4485 beach ridge	4485 caves	4485 bay bar	4485 spit
			4484 gravel bench
			4460 wave-cut notch
	4443 north edge of fan	4443 edge of fan	
4432 wave-cut notch		4433 cut in fan	
	4420 cut in fan	4426 cut in fan	
	4410 to 4340 Paisley Flat and minor features on it	4410 cut in fan	
		4400 cut in fan	
		4382 overflow channel intake	
4365 bay bar (north end)		4368 cut in fan	4370 wave-cut notch
4360 notch (south end)			
4350 beach ridge			
4342 bulky beach ridge		4345 large bay bar	4340 spit and beach ridges
4340 overflow channel ends			
4323 beach ridges		4325 beach ridge	
4312 wave-cut bank		4310-4300 Upper Marsh	4312 Neopluvial beach
4303 beach ridge			4300-4290 Lower Marsh
4290 beach ridge			
4276 beach ridge			4255 Lake Abert level
4210-4189 wave-cut bank			
(4208 biotitic volcanic ash)			
4193 Neopluvial beach ridge			
4181 beach of pumice sand			
4165 base of wave-cut bank			
4147 Summer Lake level			

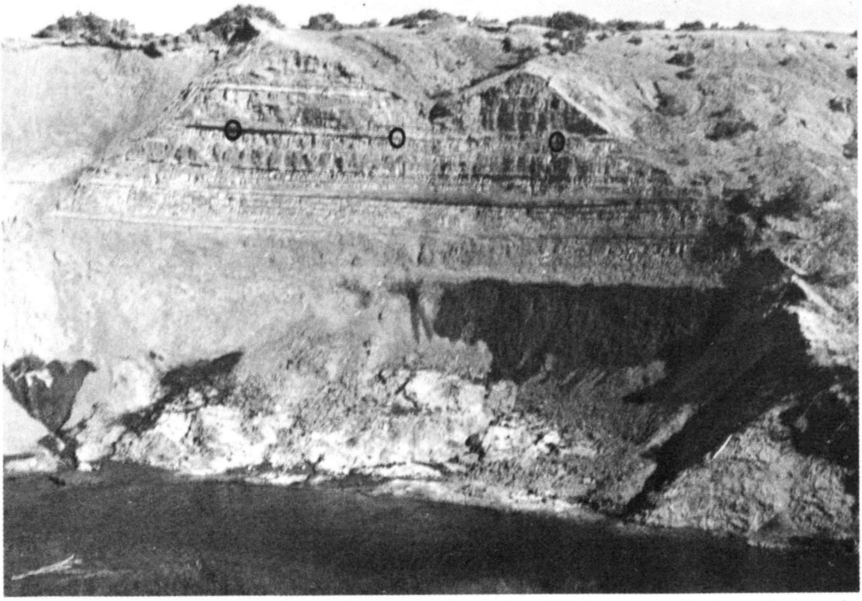

Figure 38: Fossiliferous lake beds in Ana River bluff below Ana Springs Reservoir. The fossil-bearing layer, about a foot thick, (0 marks layer) is approximately one-fourth the distance down from the top. It is the lower and fainter of two light-colored bands that cross the gable-like cliffs in the upper part of the picture. Snail shells from this layer were found to be more than 25,900 radiocarbon years old. The uppermost beds of volcanic ash (see Fig. 39) are lacking here but present a few hundred feet downstream (left).

from shore in ice during spring breakup of lake ice, their concentration in certain layers suggest wave and current activity under shoaling conditions. Their stratigraphic occurrences may be assigned to three groups within the section exposed: an upper one at 3 to 11 feet, a middle one between 14 and 30 feet, and a low one between 44 and 50 feet.

Oolites are especially abundant at depths of 2.8, 2.9, 5.0 to 6.5, 13.4 to 15.6, 17.3 to 17.7, 35.1 to 35.4 (a 3-inch layer), 36.5 and 41.1 feet. Since oolites form only in a high-energy environment of wave action, we may infer that the oolite-bearing layers represent low-water stages in a shallow lake in which 1) wave bottoms reached the water-sediment interface, 2) solutions of calcium bicarbonate had been concentrated by evaporation, and 3) fine-grained sediment particles were more or less winnowed out by the waves.

Figure 39: Beds of volcanic ash and pumice sand near top of the Ana River exposure. The distinctive biotite-bearing layer is just below the upper end of shovel handle.

Conrad noted diatom shells (frustules) especially at depths of 7.0, 7.8, 18.8, 19.0, 31.7, 40.7, 43.9, and 49.8 feet in the section, in the usual association with or following beds of volcanic ash.

Calcareous crusts occur along the outcrop at depths of 4.0, 6.5, 11.2, 15.4, 17.4, 23.3, 25.3, 26.4, 29.2, 39.3, and 49.8 feet, usually in association with oolites, octracods, sand, and basalt pebbles, which together probably provided appropriate permeability for the formation of evaporite crusts at the surface outcrop. Ostracods and oolites from the 5.4-foot level yielded the radiocarbon date of 30,700 years mentioned above.

Undulating contacts between the beds at depths of 19.3 and 21.9 feet may possibly indicate disconformities or time breaks in the stratigraphic section, presumably between pluvial stages or during nonpluvial (nonglacial) intervals.

The total thickness of lake sediments in the Summer Lake basin is not known, but according to Mr. Carl Williams, a driller from Lakeview, Oregon, (pers. comm., 1939) a number of drilled wells have penetrated relatively soft material to depths of hundreds of feet. One hole on the west side of the basin is said to have been 960 feet deep. On the Williams Ranch, now part of the wildlife refuge at the north end of Summer Lake, drilling for water stopped at 1286 feet when the pipe became stuck. According to this report, lake sediments there may be nearly 1300 feet thick. However, part of the "soft" material possibly may have been older beds of lake mud, volcanic tuff, or diatomite instead of late Pleistocene lake deposits.

Sediments in the Upper Chewaucan Marsh Basin

As previously noted, the base of the fan-delta deposit at Paisley is exposed in a cliff undercut by Chewaucan River, where lake beds overlie part of an alluvial fan of an earlier Chewaucan River. Other steep banks, roadcuts (Figs. 28, 29, and 30), and gravel pits expose other parts of the fan-delta. Individual exposures range up to about 40 feet vertically, but the total thickness exposed above the river is about 80 feet. How much more is concealed beneath Upper Chewaucan Marsh is not known. Pluvial Lake Chewaucan at its maximum height stood about 210 feet above the present level of the southern part of Upper Chewaucan Marsh.

In a regional palynological study, Hansen (1947, pp. 32, 102) found a layer of pumice that he attributed to Mount Mazama at a depth of 1.2 meters (47 inches) in a 2.4-meter (95-inch) section of peat deposits he examined in the southern part of Upper Chewaucan Marsh.

A pit dug beside a drainage ditch one-half mile east and one-quarter mile south of the ZX Ranch house (Sec. 5, T. 34 S., R. 19 E.) had an uneven layer of pumice sand at a depth of 54 inches, with peat above and below it. Another pit struck similar pumice at 65 inches depth. Several layers in the upper part of the stratigraphic section in Upper Chewaucan Marsh contain abundant diatoms. The interbedding of peat and diatomite suggests alternate shoaling and deepening of ZX Lake during late Pleistocene and Holocene time. Deepening of this pit revealed a 1½- to 3-inch layer of gray crystal-rich pumice sand at a depth of 9 feet 1 inch. Petrographically it resembles the layer of pumice next below the biotitic ash layer in the Ana River section in the Summer Lake basin. No separate layer of biotite-bearing volcanic ash was found in these pits, although scattered flakes of biotite occur in the upper part of the section. Equivalents of the uppermost ash layers in the Ana River and Fort Rock Lake sections also seem to be missing here. Another excavation in a ditch bank one-half mile farther south showed underlying layers of limnic peat and diatomite (Fig. 40) extending down to a depth of 8 feet 8 inches, the limit dug.

Pre-Lake Chewaucan Sediments

Waring (1908) reported the occurrence of a fossiliferous basalt-pebble conglomerate "along the hills east of Summer Lake, and fully 150 feet above its present level." F. D. Trauger (1950) found the locality in the NE¼ Sec. 34, T. 31 S., R. 18 E. near Ten Mile Butte in the eastern part of the Summer Lake basin. According to the Klamath Falls topographic map, the elevation there is near 4400 feet. Trauger (1950) described the beds as "primarily marly tuffaceous sandstone more or less indurated and light gray to buff in color. The upper 22 feet of a coarse- to medium-grained sandstone yielded abundant and well-preserved shells of various types. Other thin beds contain shells and fragments of shells that make up approximately 90 percent of the rock. The sedimentary beds dip gently westward and are covered by wind-drifted sand and beach deposits of later age." The fossil shells were identified by Teng-Chien Yen of the U. S. Geological Survey as freshwater mollusks of probable late Pliocene age (see Fossils, p. 59), although Trauger (1950) thought the beds might be early Pleistocene in age.

It seems likely that much of the soft sediments found in deep wells in the Summer Lake basin (such as the 960- and 1286-foot holes previously mentioned) was deposited in pluvial lakes preceding pluvial Lake Chewaucan, but no proof of age is yet available. However, a 20-foot bed of compacted mollusk shells, said by Trauger (1950) to have been encountered at a depth of 730 feet in a well drilled about a mile south of Summer Lake post office, suggests a long Pleistocene history of lacustrine conditions in the Summer Lake basin.

Fossils

Known fossils from the pluvial Lake Chewaucan area include a limited number of vertebrate animals and numerous invertebrates. Hay (1927, pp. 70, 78, 101, 124, 125, 245) recorded bison teeth found near Summer Lake and at Paisley, a cannon bone of a bison, and a few fossil bones of camels (*Camelops* and *Camelus*), horse (*Equus*), peccary

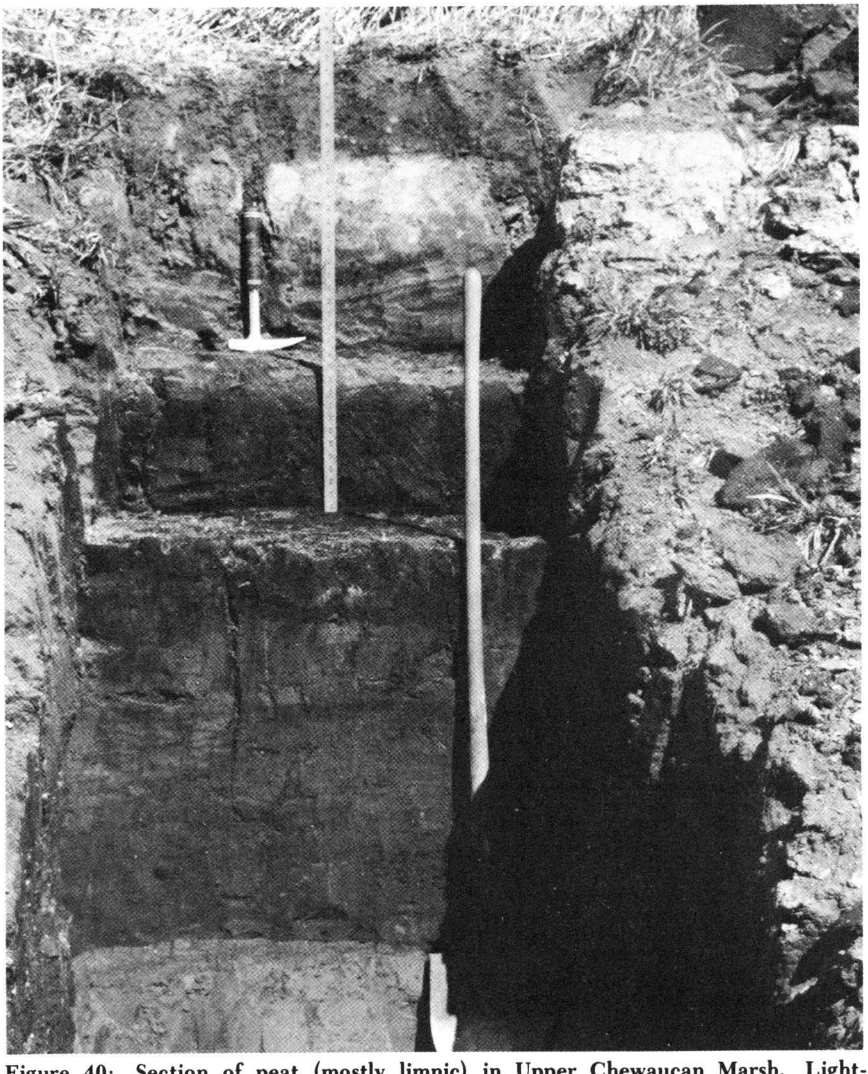

Figure 40: Section of peat (mostly limnic) in Upper Chewaucan Marsh. Light-colored diatomaceous limnic material at the bottom (more than 5 feet dug but only 1 foot shown) is overlain by 1.5 to 3 inches of sandy pumice (at top of shovel blade), 22 inches of light brown peat (silty near its base), 16 inches of dark brown peat, a 1- to 2-inch seam of volcanic ash (below hammer), 7 inches of brown peat, 11 inches of impure diatomite, and 10 to 12 inches of fibrous peat with plant roots. The record indicates a succession of deep-shallow-deep-shallow water stages of unequal length. The thin layers at depths of about 28 and 60 inches record volcanic eruptions in the region.

(*Platygonus*) and a piece of breast bone of a swan (*Olor*) from the Summer Lake area. Unfortunately the stratigraphic positions of these fossils are not known. The group merely indicates the presence of deposits of late Pleistocene age.

Cressman (1942) found bones of bison, horse (*Equus*), camel (possibly *Camelops*), mountain sheep, wolf, fox, and probably bear in the Five Mile Caves north of Paisley, in association with signs of occupation by early aborigines. The bones were identified by vertebrate paleontologist Chester Stock. The collection also included bones of teal, pintail, duck, hawk, and sagehen. The horse and camel imply a late Pleistocene or early Holocene age.

Conrad (1953) reported his recovery of fossils from Lake Chewaucan sediments at Ana River as follows:

Unidentifiable fish bone fragments

Gastropods
- *Parapholyx packardi* Hanna
- *P.* n. s. (?) cf. *packardi* Hanna

Pelecypods
- *Pisidium variabile* Prime

Ostracods (identified by Donald L. Minar)
- *Limnicythere* cf. *reticulata* Sharp
- *Condona* cf. *bolatonica* Dudley
- *C.* cf. *candida* (O. F. Miller)
- *C.* cf. *candata* Kaufman, var. *occidentalas* n. var. Dobbins
- *C.* cf. *decora* n. sp. *tortosa*

Unidentified diatoms

Conrad obtained his tiny snail and clam shells from a layer of silt about a foot thick situated approximately 18 feet below the top of a composite stratigraphic section, most of which is exposed in a steep Ana River bank (Fig. 37) a short distance below the Ana Springs reservoir (Conrad, 1953). This particular layer overlies a few inches of sandy-to-silty, crystal-rich pumice. It also contains a half-inch seam of volcanic ash two inches above the base. The fossiliferous bed also contains a few ostracod shells, diatoms, and occasional angular basalt pebbles. The beds immediately above it are thin layers of lake silt, volcanic ash, sand, and oolites.

A collection of shells taken by me from this fossiliferous silt layer in 1979 yielded a radiocarbon age of at least 25,900 years (Teledyne Isotopes I-11,311; 1980).

This figure is somewhat less than the 30,700-year age previously found for ostracods and oolites in a layer several feet higher in the stratigraphic section (Teledyne Isotopes I-1640; 1945). However, this 30,700-year figure may be too high because of inclusion of old carbonate, or too young because of incorporation of young carbon. Because the 1979 sample was cleaned and had the outermost shell material removed by successive acid washes before dating, it is considered fairly reliable, but it still is only a minimum age. The 1979 sample may actually be older than the previously dated 30,700-years old material higher up in the section.

Waring (1908, p. 24) reported the occurrence of freshwater mollusk shells in a basalt-pebble conglomerate "along the hills east of Summer Lake, and fully 150 feet above its present level..." A collection of shells of freshwater pelecypods and gastropods was obtained by F. D. Trauger (pers. comm., 1950) from a sandy phase of tuffaceous pebble conglomerate in the "NW¼ Sec. 34, T. 31 S., R. 18 E., near Ten Mile Butte" in the eastern part of the Summer Lake basin. The shells were identified by Ten-Chien Yen of the paleontological section of the U. S. Geological Survey as follows:

Valvata oregonensis Hanna
Valvata sp. undet.
Valvata sp. undet.
Amnicola cf. *Amnicola micrococcus* Pilsbury
Lanx sp. undet.
Gyraulis cf. *G. scabriosis* (Hanna)
Paraplanorbis condoni Hanna
Parapholyx cf. P. packardi Hanna
Parapholyx sp. undet.
Pompholopsis sp. undet.
Vorticifex cf. V. tryoni (Meek)
Planiorbifex sp. undet.
Physa sp. undet.
Pisidium sp. undet.

According to Ten-Chien Yen, the composition of this molluscan fauna seemed to indicate a Pliocene age (Trauger, 1950).

Shells collected by me in 1979 from a sandy layer at this same locality, at an elevation of approximately 4425 feet (by Paulin aneroid measurement from a benchmark three miles distant), were found to have a radiocarbon age of 17,500 ± 300 years (Teledyne Isoptopes I-11,177; 1980). The shell-bearing layer tested therefore is clearly a near-shore sediment in pluvial Lake Chewaucan of Late Pleistocene age. Its reported age is within the range of the Tioga-Pinedale glacial stage.

The fossiliferous conglomerate 15 to 25 feet lower was not given a radiocarbon assay. It may be part of a different stratigraphic section.

Its induration, in contrast with the comparative looseness of the dated sample, suggests that it may well be Pliocene (or perhaps Early Pleistocene) in age and that two deposits of disparate ages are juxtaposed.

Age of Pluvial Lake Chewaucan

The problem of dating Lake Chewaucan is to fit its stages into the Pleistocene record of other pluvial lakes of the Great Basin and into the glacial stages of the western mountains. Geologists have long agreed that pluvial and glacial stages were broadly contemporaneous.

Pleistocene Glacial Stages

The standard Pleistocene time scale in North America includes four stages of glaciation: Nebraskan, Kansan, Illinoian, and Wisconsinan (Frye and Willman, 1960, 1963; Frye and others, 1968; Willman and Frye, 1970; Frye and Willman, 1973). The time-stratigraphic substages of the Wisconsinan Glacial Stage and their approximate radiocarbon ages in the Illinois-Wisconsin type region are Altonian (28,000 years ago to est. 75,000), Farmdalian (22,000 to 28,000), Woodfordian (12,500 to 22,000), Twocreekan (11,000 to 12,500), and Valderan (7,000 to 11,000) (Frye and others, 1968). Corresponding time divisions in the western United States are summarized in Table 7.

Table 7. Wisconsinan Glaciations in the West (ages in years before present)

Rocky Mountains (Richmond, 1965)		Sierra Nevada (Sharp, 1972)	Oregon (Scott, 1977)		Puget Sound (Porter, 1976)	
----6,500----		----8,000----		Canyon Creek		----10,000----
Pinedale	Late	Hilyard	Cabinet Creek	(short interval)		Sumas
	Middle	----9,800----		Suttle Lake		----11,000----
	Early	Tioga	(long interval)		Fraser	----13,500----
----25,000----		Tenaya	Jack Creek[b]			Vashon
Interglaciation						----18,500----
----32,000----						
Bull Lake[a]	Late	Tahoe				
	--75,000					
	Early					
---- ? ----						

[a] Later studies suggest that part of Bull Lake may be pre-Wisconsin (Pierce and others, 1976)
[b] Possibly pre-Wisconsin

Two main stages of Wisconsinan Glaciation, Tahoe and Tioga, are generally recognized in the Sierra Nevada (Blackwelder, 1931, 1934), but other divisions have been proposed (Sharp and Birman, 1963; Birman, 1964; Wahrhaftig and Birman, 1965). A weak glaciation, the

Tenaya, was thought to have occurred between Tahoe and Tioga, and another, the Hilyard, reportedly followed typical Tioga in very late Wisconsinan or early Holocene time. On the basis of a study of moraine morphology, weathering effects, and soil development on glacial deposits under comparable environmental conditions, Burke and Birkelend (1976, 1979) consider Tahoe and Tioga sufficient names for the Wisconsinan deposits in the Sierra Nevada.

The Tioga Glaciation in California apparently corresponds to the Pinedale Glaciation in Wyoming (Richmond, 1965; Morrison and Frye, 1965). The Pinedale is estimated to have occurred between 25,000 and 6,500 years ago (Richmond, 1965, p. 268). Because the Tioga Glaciation left a three-fold grouping of moraines in canyons on the east side of the Sierra Nevada (Putnam, 1950), we may infer that, like the Pinedale glaciers, the Tioga glaciers also had periodic pulses of ice advance. However, there is no evidence to show that they melted away completely between pulses.

Three glacial stages are known in the North Santiam River valley of Oregon, the last two correlated with Tahoe and Tioga (Thayer, 1939). Scott (1977) distinguished three glacial stages in the Metolius River area on the east side of the Cascade Range in Oregon.

The Pleistocene glacial record in the Puget Sound and northern Cascade Range areas (Armstrong and others, 1965; Easterbrook, 1966; Porter, 1971; Hansen and Easterbrook, 1974; Porter, 1976; Easterbrook and Rutter, 1981) includes six episodes of glaciation, the last one (Fraser) clearly of Wisconsinan age. The Fraser Glaciation consists of Vashon Stade (18,500 to 13,500 years ago), Everson Interstade (2,500 years long), and Sumas Stade (11,000 to 10,000 years ago). The Fraser Glaciation is considered equivalent to Pinedale in the Rocky Mountains.

Thus the glacial record in Wyoming, the Sierra Nevada, and the Pacific Northwest is one of stages and substages that one may expect to be represented in the pluvial lake history of Oregon. The names Tioga and Pinedale, or Tioga-Pinedale as used in this paper, are assumed to be correlative and approximately contemporaneous.

Marine Climatic Evidence

Cores of marine sediments taken at sea also indicate climatic changes that can be correlated with the glacial chronology in the eastern Great Lakes region (Emiliani, 1972a; Bé and others, 1976), so the climatic changes in late Pleistocene time were global and not merely local (Fig. 41). Warm stages at sea are indicated by an abundance of foraminifera (calcareous), whereas cool stages show less calcium carbonate and more terrigenous detritus. There also were

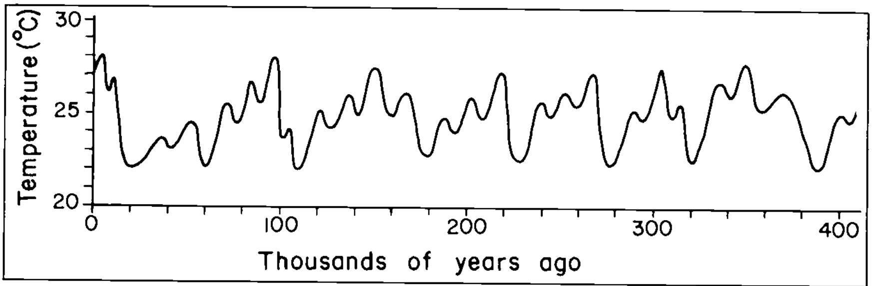

Figure 41: Surface temperatures of the Caribbean Sea in part of Pleistocene time. (After Emiliani, 1972b.)

changes in the composition of the faunas, in oxygen-isotope ratios, rate of sedimentation, and in the estimated water temperatures (Emiliani, 1972b).

Lake Bonneville and Lake Lahontan

These two lakes were the largest, deepest, and most studied of all the pluvial lakes of the Great Basin. Lake Bonneville in Utah (Gilbert, 1890), once about 1,150 feet deep, and Lake Lahontan in Nevada (Russell, 1885), about 700 feet deep, are known to have had long Pleistocene histories (Morrison, 1964, 1965, 1970, 1975; Eardley and Gvosdetsky, 1960; Morrison and Frye, 1965; Eardley and others, 1973; Shuey, 1972; Currey, 1980; Scott and others, 1980).

According to Morrison, Lake Bonneville had three expansions in Pinedale time, five in Bull Lake time — now considered pre-Wisconsinan in age by Scott (pers. comm., 1980) — and twenty or more deep-lake stages during the Illinoian and Kansan glaciations. However, the three Pinedale expansions have been disputed by Scott and his coworkers (1980).

The named Lake Bonneville shorelines — Bonneville, Provo, and Stansbury — occur at elevations of 5,085 feet (at the Red Rock Pass outlet), from 4,790 to 4,825 feet, and near 4,530 feet respectively. These elevations differ considerably from place to place because of differential isostatic rebound of the earth's crust that resulted from removal of the weight of deep water as the lake shrank (Crittenden, 1963). Erosion of loose material in the Red Rock Pass outlet lowered the threshold to bedrock at the 4,740-foot level and released a huge flood (the Bonneville Flood) into the Snake River drainage basin and thence to the Pacific Ocean. The time of one or more such overflows through Red Rock Pass has been controversial. Estimates range from as late as 9,500 years ago (Broekner and Kaufman, 1965), to about 14,000 years ago (Currey, 1980), to between 15,000 and 12,000 years ago (Morrison, 1965), to about 30,000 years ago (Malde, 1965).

According to Scott and others (1980), Lake Bonneville left transgressive deposits at the 1,485-meter level (4,870 feet) 17,580 ± 170 years ago, as dated from charcoal. It later rose to the Bonneville shoreline (approximately 5,085 feet) and developed that shoreline, overflowed Red Rock Pass to form the Bonneville Flood, shrank to the Provo shoreline (approximately 4,800 feet) and developed it – all within a time span of 3,500-5,500 years after the 17,580-year date. Hence the lowering of the lake level to and below the Provo shoreline was rapid (Currey, 1980). These events fall within the time range of the Tioga-Pinedale Glaciation.

The average age of about 10,000 years for wood and dung (dated by radiocarbon) obtained from Danger Cave near Wendover, Utah (Jennings, 1957) limits any Bonneville Lake level during the last 10,000 years to less than the elevation of the cave (4,310 feet). Scott and his associates (1980) state that lake fluctuations after 11,000 years ago were restricted to within about 15 meters (about 50 feet) of the present level of Great Salt Lake.

Lake Lahontan sediments include two main stratigraphic formations separated by eolian and alluvial deposits and a strongly developed soil zone. The older formation records six to eight expansions of Lake Lahontan, the younger one at least six (Morrison, 1965). Morrison correlates these lake sediments with the Tahoe and Tioga stages of the glacial chronology. Below the Lake Lahontan sediments are deposits he considered to be of Illinoian and Kansan ages.

Searles Lake, California

Pleistocene and Holocene fluctuations of climate are also well recorded in Searles Lake deposits (noted for the commercial production of borax, potash, and other salts from the lake brines), in southeastern California. The Searles lake stratigraphic sequence is shown in Table 8.

Table 8. Searles Lake stratigraphy (Smith, 1979)

Typical thickness (meters)		^{14}C ages (years ago)		
Overburden Mud	7	0	to	3,500
Upper Salt	15	3,500	to	10,500
Parting Mud	4	10,500	to	24,500
Lower Salt	12	24,000	to	32,500
Bottom Mud	30	32,500	to	130,000
Mixed Layer	200			>130,000

In general, the Bottom Mud and Parting Mud are correlated with glacial episodes in the Sierra Nevada, and the Lower Salt and Upper

Salt are correlated with warm dry interpluvial stages (Flint and Gale, 1958; Smith, 1962, 1979, 1980). Smith's correlations of Searles Lake deposits with other lacustrine and glacial chronologies are shown in Fig. 42, where certain apparent discrepancies are yet to be resolved.

Application of the Time Scale to Pluvial Lake Chewaucan

Field evidence supports a sequence of at least six distinct stages in the history of Lake Chewaucan and its successors, Winter Lake and ZX Lake. These are: 1) a high level shown by shore features at the 4517- to 4520-foot elevations and by the Paisley fan, 2) a sustained 4485-foot level marked by pronounced beach development, 3) an erosional stage that produced the Paisley Flat, beginning when the lake stood near a 4410- to 4420-foot level, 4) 4365- to 4370-foot stage represented by a baymouth bar north of the Ana Springs reservoir, 5) an overflow stage when water southeast of Paisley Flat (ZX Lake) reached an elevation of about 4390 feet and cut a channel across Paisley Flat, while Winter Lake on the Summer Lake side of the divide was near 4340 feet, and 6) later independent stages in Winter Lake and ZX Lake, especially one in which the ZX Red House beach was built at approximately 4345 feet. Other minor terraces and beaches imply additional intermediate substages but their durations are uncertain. The six stages mentioned are not to be interpreted as separate cycles, because there is no evidence of multiple lake cycles with low-water levels between them, except as noted later.

Let us consider the lake stages in reverse order of ages. Because the ZX Red House beach was the last such beach constructed by ZX Lake before the Chewaucan Marshes began, it may reasonably be assigned a late Pluvial or late Wisconsinan age (Allison, 1952) — hence a late Tioga-Pinedale stage. This beach is approximately 90 feet above Lake Abert, the sump of this part of the Lake Chewaucan basin. A late Tioga-Pinedale age is also applicable to the gravel at the same level found at The Narrows between Upper and Lower Chewaucan Marshes.

Working backward in time from the assigned age of the ZX Red House beach, one may reason that the preceding ZX Lake overflow stage (about 45 feet higher) may also have been in Tioga-Pinedale time, perhaps a middle substage. The difference in level between the 4390-foot overflow from ZX Lake and the 4340-foot level of Winter Lake on the receiving end suggests previous low water stages and subsequent rises in which ZX Lake gained on Winter Lake because of inflow from Chewaucan River on the ZX side of the divide.

The occurrence of 17,500-year old fossil shells at the 4,425-foot level near Ten Mile Butte shows that a Tioga-Pinedale lake stage

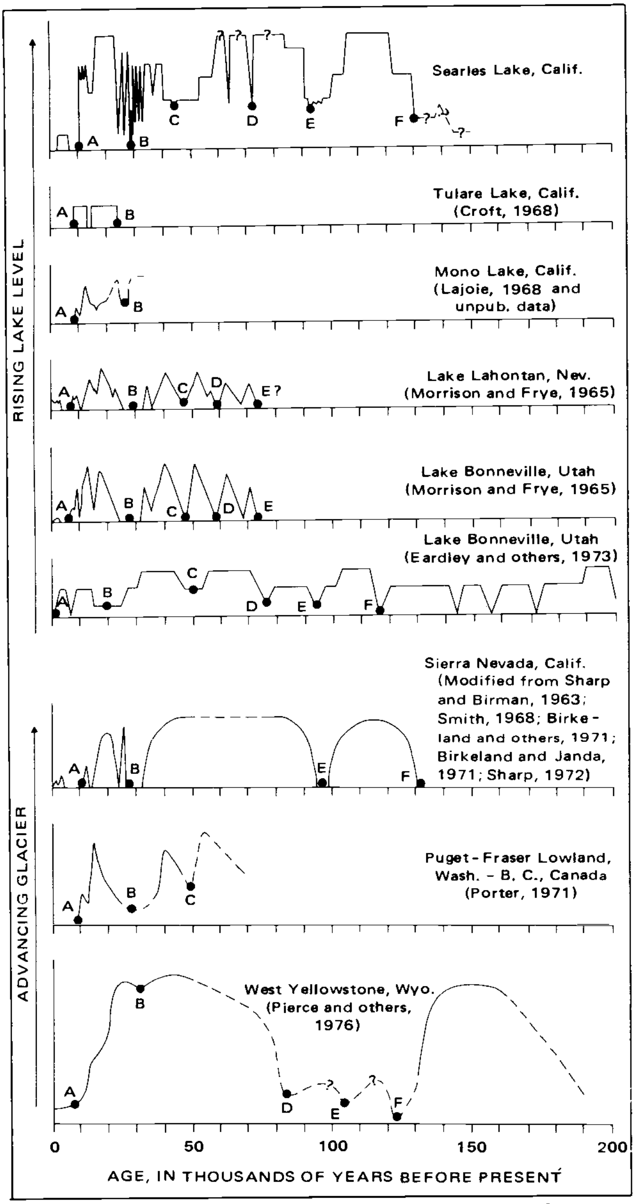

Figure 42: Correlation of Searles Lake deposits with glacial and lacustrine records (from Smith, 1979; Dead Sea omitted).

reached at least that high, but leaves the upper limit uncertain. It does suggest, however, that the partial truncation of the Paisley fan at the 4,410-foot and lower levels and the spread of the gravel to form Paisley Flat probably were Tioga-Pinedale events. The minor shorelines on Paisley Flat represent fluctuating but generally subsiding lake levels in Tioga-Pinedale time.

But when was the Paisley fan built? Is it also Tioga-Pinedale (or possibly Tahoe) in age, or still older? If the Tahoe stage was more pronounced than Tioga-Pinedale (a questionable matter), then a Tahoe age for the fan would seem possible. In that case the 4520-foot shoreline and the 4485-foot beach would likely be Tahoe in age also, and only geologic changes below about 4440 would date from Tioga-Pinedale time. On the other hand, the high-level features as well as the lower ones may all be of Tioga age.

In view of the long histories of Lake Bonneville and Lake Lahontan, a possible pre-Wisconsin age for some Lake Chewaucan sediments is conceivable, but this is not supported by any evidence. Pre-Wisconsin sediments may well be concealed beneath the visible deposits.

In the Winter Lake basin, the delta that resulted from the overflow of ZX Lake across Paisley Flat, the beach ridges associated with this delta, and a few lower shorelines above the Neopluvial (see discussion, p. 70) beach at 4190 feet are also considered Tioga-Pinedale in age.

A small gravel pit, located within the south edge of SW¼ Sec. 36, T. 29 S., R. 16 E. at an elevation just above 4305 feet, exposes about 20 feet of interbedded gravel, sand, and silt, now dipping northward (because of slump) into the south slope of the 4365- to 4370-foot baymouth bar (Figs. 2 and 3). One bed in the north wall of the pit contains numerous tiny snail shells which have a radiocarbon age of 22,080 ± 660 years (Teledyne Isotopes I-11, 136; 1979).* The fossil shells and the baymouth bar as a whole thus belong to Tioga-Pinedale time.

If the beach ridge shown at 4193 feet in Fig. 23 is assigned a Neopluvial age to agree with the 4190-foot beach ridge east of Summer Lake post office, then the next higher wave-cut bank at 4190 to 4210 feet (Fig. 24) should be the late Tioga-Pinedale equivalent of the ZX Red House beach in the ZX Lake basin. As the bank is 20 feet high, the water level may have been at about 4192 feet, or only about 45 feet above the present Summer Lake. The corresponding ZX Red House beach is about 90 feet above Lake Abert. The 45-foot

* Using Libby half-life, uncorrected for variation in atmospheric ^{14}C.

difference presumably arose because the ZX side of the Paisley Flat divide, fed by Chewaucan River, had more water available. To equate the next higher shoreline (at the 4278-foot level) in the Winter Lake basin with the ZX Red House beach would introduce a disparity of about 40 feet in past lake levels above the modern lakes in favor of Winter Lake — a very improbable situation. The later rise of Summer Lake in Neopluvial time to approximately the very late Tioga-Pinedale level of Winter Lake is considered merely a coincidence.

No direct evidence is known for pre-Lake Chewaucan stages to match the pre-Wisconsinan lakes in the Bonneville and Lahontan basins (except perhaps in the vicinity of Ten Mile Butte), but such evidence may well exist beneath Summer Lake.

Bearing of Radiocarbon Dates

The four previously mentioned radiocarbon dates available have limited significance. The 17,500-year-old shells from an elevation of 4425 feet near Ten Mile Butte indicate that a pluvial lake stage reached at least that high. The radiocarbon date suggests that this lake stage was in fairly early Tioga-Pinedale time. The 22,000-year-old shells from a gravel pit at 4305-to-4325 feet low on the south slope of the baymouth bar north of Ana Springs reservoir also have an apparent early Tioga-Pinedale age.

The layer containing the 25,500-year-old (minimum age) shells in the Ana River bluff about 0.1 mile east-southeast from the Ana Springs reservoir dam is approximately 18 feet below the nearby lake flat. A disconformity in the stratigraphic section 1 foot below the shell-bearing bed marks a break in sedimentation, which may have occurred between high-water stages. This radiocarbon date, based on total carbonate, may seem too old for early Tioga-Pinedale time, but not if old carbonate is involved. The date is much too young for any late Tahoe time, unless it is contaminated with young carbon. By comparison, the 30,700-year-old date based on ostracods and oolites from a stratigraphic level several feet higher than the >25,500-year-old layer may seem excessive. One must remember that some radiocarbon dates may be too old because of old carbon in the sample, or too young because of contamination by relatively young carbon.

Note that of the four radiocarbon dates the shells highest in elevation are the youngest, while the lowest elevation beds are the oldest. Possibly the older fossils date from the beginning of the last transgressive cycle, whereas the younger ones date lake stages between a maximum middle phase and regression to the end of the cycle.

Postpluvial History

Time Divisions

The postglacial or postpluvial history of the western United States was divided by Antevs (1925, 1948, 1955) into three parts: Anathermal (increasing warmth, decreasing precipitation), Altithermal (warmer and drier than now), and Medithermal (moderately warm, transitional to the present). The Altithermal in the west was 7,500-4,000 years ago (Antevs, 1955, p. 329), or 6,500-4,000 years ago (Richmond, 1965, p. 227). The stratigraphic term Hypsithermal (Deevey and Flint, 1957) is preferred over Altithermal by some students of the Quaternary.

Antevs thought that the time span since the Valders glacial maximum included about 18,000 years, but numerous radiocarbon dates (unacceptable to Antevs, 1962) obtained from localities widely distributed across the United States and Canada have reduced the postglacial time span to less than 10,000 years (Armstrong and others, 1965). The Fraser River Valley in British Columbia, for example, became free of the Fraser Glacier only a little more than 9,000 years ago. The Valderan Substage of the Lake Michigan ice lobe, which succeeded the Twocreekan Substage (well dated at 11,850 years ago), may have lasted until less than 8,275 years ago at Cochrane, Ontario (Hughes, 1965). The Pinedale Substage in Wyoming ended about 6,500 years ago (Richmond, 1965). Wisconsinan Glaciation in the Sierra Nevada ended 8,000 to 10,000 years ago (Sharp, 1972). So presumably the pluvial lakes in the Great Basin, including Lake Chewaucan, dried up to shallow lakes or playa flats about 10,000 years ago also.

The shrinkage of Lake Bonneville was very abrupt (Currey, 1980). By about 11,000 years ago, Lake Bonneville had receded well below Danger Cave, and not later than 10,500-10,000 years ago (Currey, 1980, p. 60) it reached the Gilbert shoreline of Eardley and others (1957) at an elevation of 4,240 feet (about 40 feet above the level of Great Salt Lake in 1950). Contrary to Morrison (1965, p. 281), Currey (1980) gives the Gilbert shoreline an age of not less than 10,000-10,500 years, hence a Pinedale (not postglacial) age.

Eruption of Mount Mazama

The most striking physical event in this general area during postpluvial time was the climactic eruption of Mount Mazama on the present site of Crater Lake, about 6,600 to 6,700 years ago (average of several published radiocarbon dates). This explosive outburst propelled 17 or more cubic miles of pumice and volcanic ash into the air

(Williams, 1942), where the wind carried some of it many hundreds of miles to the east and northeast (Powers and Wilcox, 1964; Fryxell, 1965; Wilcox, 1965; Lemke and others, 1975).

The northern part of the Lake Chewaucan basin, 65 miles distant from Crater Lake, received enough sandy pumice (probably several inches of it) to make an extensive dune field in the northeastern part of the Summer Lake basin. Wind-blown pumice sand also occurs in the northeastern part of the Lower Chewaucan Marsh basin. A little such pumice is found on the surface nearly everywhere in this part of Lake County.

Altithermal

The Altithermal, warmer and drier than the present, was a time of increased wind activity (Allison, 1966a, 1979). Large deflation basins tens of feet deep were excavated in Fort Rock Valley immediately north of the site of Winter Lake in the Lake Chewaucan basin. The formation of transverse dunes in the northern part of the Summer Lake basin and the removal of salts from the dried-up lakes probably occurred largely in Altithermal time. Lake Abert and Summer Lake presumably became completely dry, as in modern time, because their present salinity is such that all of it can have accumulated at present rates in only a few thousand years. Both lakes are known to have fluctuated in level substantially in recent decades and occasionally they have become dry.

The site of Great Salt Lake in Utah became a large playa characterized by "giant desiccation polygons" (Currey, 1980, p. 60), which now are submerged by 6 to 9 meters (20 to 30 feet) of water.

Neoglaciation

A modification of Antevs's climatic history has been the recognition of a "little ice age" in the Sierra Nevada (Matthes, 1939, 1942), or the presently preferred term Neoglaciation in the western mountains (Moss, 1951; Hack, 1943; Sharp, 1960; Richmond, 1965; Porter and Denton, 1967; Miller, 1973). As Matthes stated, "...many of the lesser glaciers in the Cordilleran ranges of North America are not remnants of Pleistocene glaciers, but 'modern' glaciers that came into existence during the cooler period that followed the 'climatic optimum' of Post-Pleistocene time," less than 4,000 years ago. Crandell (1965) wrote: "Two glacial episodes in post-Altithermal time are recorded on Mount Rainier, Washington. The older episode occurred between 3,500 and 2,000 years ago, and the younger within the last 1,000 years." Crandell and Miller (1974) added more details. The Neoglaciation of Richmond (1965) has two depositional units, 3,100 to 1,800 and 1,800 to

1,000 years ago. Thus the dates in the Rocky Mountains approximate those on Mount Rainier. Miller (1973) interpreted Neoglaciation to include three episodes of glacial advance or rock glacier development: one more than 4,000 years ago to an unknown date, another about 1,800 to 1,000 years ago, and a third one a few centuries long, culminating about A.D. 1850.

Neopluvial

The Neopluvial (new term) in the Great Basin was a time of more effective precipitation than the previous Altithermal. It is equivalent to Neoglaciation in western mountains. In the Neopluvial history of Fort Rock Valley (Allison, 1979, pp. 54-61), lakes formed in deflation basins on the floor of the previous pluvial Fort Rock Lake. The water level rose to form a single shallow lake about 10 ±5 feet higher than the maximum historical level of Silver Lake. Ponds still occupied Altithermal deflation basins after the main lake level receded. Waves on the lake and its successors constructed beaches of Mount Mazama pumice sand, so these lakes clearly postdate the eruption of Mount Mazama.

Similar lakes occurred in the history of other lake basins in the Great Basin. Morrison (1965, pp. 280-281) described alluvium, colluvium, eolian sand, scanty glacial deposits, and shallow-lake sediments of Holocene age in pluvial lake areas in the Great Basin. He identified five post-Altithermal shallow-lake cycles in the Lake Lahontan basin, but only one in the Lake Bonneville basin. Near Great Salt Lake in the Lake Bonneville basin, Van Horn (1979) recognized a lake stage and an associated stratigraphic formation that he correlated in time with Neoglaciation, probably between 4,500-4,000 and 2,500 years ago. The lake at that stage rose about 40 feet higher than the present Great Salt Lake, thus reaching the earlier Gilbert shoreline.

This period of expansion of shallow lakes throughout the Great Basin in the 4,000- to 2,000-year time range I shall call the Neopluvial (analagous to Neoglaciation) for convenience of reference.

The Neopluvial – wetter and perhaps cooler than the present – caused expansion of Summer Lake and Lake Abert and flooded Upper and Lower Chewaucan Marshes to the 4212-foot level (about 60 feet above the present Lake Abert). A wave-cut bank at that elevation truncates colluvium near the south edge of Sec. 5, T. 33 S., R. 17 E. In the Summer Lake basin, the now-dry beach at 4,190 feet just north of Summer Lake (Fig. 4) is assigned a Neopluvial age, because it cuts across Mount Mazama pumice sand dunes. It is a little more than 40 feet above the presently variable level of Summer Lake. The beach ridge at 4,193 feet in Fig. 24 is also considered Neopluvial in age. Another beach ridge just above 4,165 feet in that profile (Fig. 24), the last relief feature in the series and only 18 feet above Summer Lake, is perhaps late Neopluvial in age, since the highest known level of Summer Lake in historical time is 4,149 feet (Van Denburgh, 1975).

Pollen Record

The postpluvial climatic record is substantiated by the succession of pollen grains in peat bogs. The pollen record in the southern part of Upper Chewaucan Marsh, as described by Hansen (1947), includes an early phase denoting a cool and moist but changing climate, a middle phase of maximum warmth and dryness, and a late phase of cooler and wetter conditions (Fig. 43). Mount Mazama pumice is enclosed in 2.4 meters (94 inches) of peat at a depth of 1.2 meters (47 inches). Only the top 0.3 meter (12 inches) of peat is fibrous; the remainder is limnic and presumably slower to accumulate. The basal 0.4 meter (16 inches) in this particular stratigraphic section is silty and lies on gravel. Accordng to Hansen (1947), the climatic history (as shown by the pollen and the dated pumice in the middle of the peat section) show that the record includes essentially all postglacial or postpluvial time — possibly about 10,000 years.

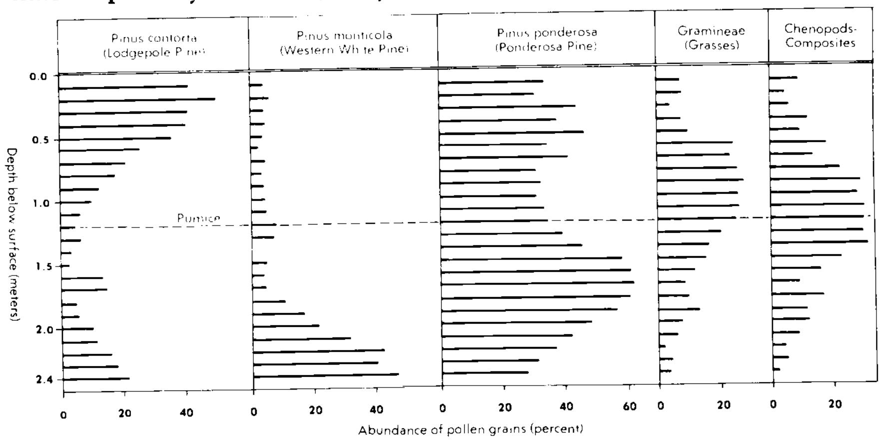

Figure 43: Pollen record in southern Upper Chewaucan Marsh (after Hansen, 1947). The pollen sequence shows a change from a cool moist climate at the base through a warm dry interval in the middle to modern conditions at the top. (Reproduced by permission of American Philosophical Society.)

Archeological Evidence

Changes in climate and corresponding changes in flora, fauna, and human occupation of caves in northern Lake County, Oregon since

13,500 radiocarbon years ago are described by Bedwell (1973, pp. 43-68). These changes confirm the postpluvial climatic changes of 1) increasing warmth and dryness, 2) the dry Altithermal, and 3) a slight return to a moister and cooler climate, which must also have affected the nearby pluvial Lake Chewaucan area.

Addendum

J. O. Davis (1982) counted 46 layers of tephra in Lake Chewaucan sediments exposed in banks of Ana River, suggested correlation of four layers with similar Lake Lahontan layers, and estimated that the Ana River record may cover 150,000 years. His 1978 publication describes the layers correlated.

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