

PLEISTOCENE HISTORY OF VOLCANISM AND THE OWENS RIVER NEAR LITTLE LAKE, CALIFORNIA

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Abstract.—During pluvial periods of the Pleistocene and Holocene, a large river flowed south from Owens Lake to China Lake between the Sierra Nevada and the Coso Range. The most recent channel, dry during historic time, is clearly marked by cliffs and falls. An older, now-abandoned part of the channel beneath Pleistocene lavas east of the present course is inferred from a meander-shaped ridge in Mesozoic basement rocks and a strong positive magnetic anomaly, presumably produced by a wedge of canyon-filling basalt. Three cycles of eruption and stream erosion have occurred along the present course. The first resulted when water impounded by damming of the now-abandoned eastern course found its way along the west margin of a basalt flow at the base of the Sierra Nevada escarpment, eventually carving a canyon at least 150 meters deep. Subsequently, two cycles, each consisting of an intracanyon basalt flow followed by major stream erosion, modified this canyon to its present configuration. A potassium-argon age of about 440 000 years before present for the oldest of the three eroded lavas indicates that the river was not diverted from its easterly course until after that time. The age and character of lacustrine deposits in Searles Lake, a downstream part of the same drainage system, indicate that the greatest discharge of the river, and therefore, erosion of the two younger lavas since 440 000 years B.P., probably occurred between 130 000 and 10 000 years B.P. An estimate of the rate of erosion during this period of time together with loosely constrained potassium-argon ages for the basalt of intermediate age suggests that the youngest lava is probably a few tens of thousands of years old and the intermediate lava somewhat less than 100 000 years old. The youthfulness of the youngest basalt suggests that a fourth cycle of an intracanyon lava flow followed by stream erosion is a likely event for the near geologic future.

During part of Pleistocene time, much of the Western United States was dotted with systems of lakes and interconnecting rivers (Snyder and others, 1964). One such drainage system in eastern California included a river that flowed southward through a slot between the Sierra Nevada and the Coso Range, carrying the overflow from Owens Lake into China Lake intermittently during Pleistocene and Holocene time (fig. 1). Farther down drainage, water flowed from China Lake into Searles Lake, into Panamint Lake, and finally into Manly Lake, the sump of the drainage system in Death

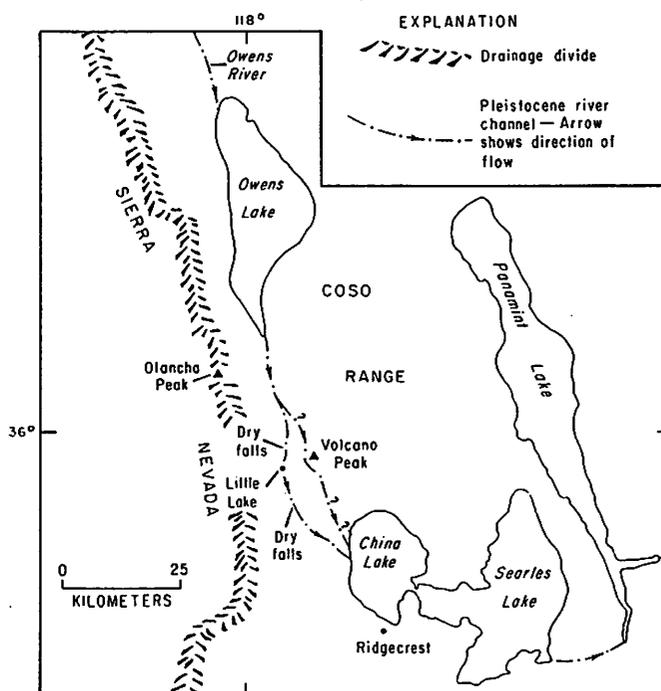


FIGURE 1.—System of Pleistocene lakes and interconnecting rivers in eastern California. Older Pleistocene river channel near Volcano Peak (queried where least certain) probably forced to westerly course near Little Lake by damming from intracanyon lava flow.

Valley. The channel, now dry, is the site of the 11-kilometer-long, manmade Haiwee Reservoir north of the mapped area, a naturally occurring shallow lake (Little Lake) near the village of Little Lake, two dry falls, and several kilometers of river-cut cliffs as high as 160 meters, mute reminders of considerable past flow of water through the area. (To avoid confusion between the village and the nearby body of water, the name Little Lake will refer to the village, except where otherwise noted.)

Discharge of the river, primarily a function of a fluctuating climate, has been deduced indirectly

through the study of lacustrine deposits in Searles Lake (Smith, 1968, 1976a, 1976b). Locally, the path followed by the discharge was repeatedly altered by intracanyon lava flows. Putnam (1955) was the first to note the presence of such lava flows. More recently, Duffield and Bacon (1977) showed that twice during Pleistocene time basaltic lavas entered the channel near Little Lake, presumably damming the river long enough to form ephemeral upstream lakes before overflow reestablished a channel along the margins of and over parts of the lava dams. Our present study suggests that during an earlier part of Pleistocene time, the river channel was about 5 km east of this course near Little Lake. At the site of this early channel, in a manner similar to the well-documented younger events, an intracanyon lava flow apparently dammed the river and forced it to the more westerly course, leaving behind a 3-km-long meander-cut escarpment in basement rocks and a thick prism of intracanyon basalt as evidence of the abandoned channel.

As the course and, to some degree, the discharge of the river have been affected by lava flows during the Pleistocene, a reasonably complete understanding of the history of the drainage system requires careful examination of local geology, especially late Cenozoic lava flows, in the Little Lake area.

Acknowledgments.—Richard J. Blakely helped with interpretation of the measured magnetic profiles and was largely responsible for computer modeling of the profiles.

DESCRIPTION OF THE ROCKS

The Little Lake area lies at the foot of a lofty fault-line escarpment that marks the boundary between the Basin and Range and the Sierra Nevada physiographic provinces. Present relief across the escarpment is about 1200 m, suggesting at least this much normal offset on the Sierra Nevada fault zone.

Basement rocks in the Sierra Nevada and the Coso Range constitute a Mesozoic crystalline complex dominated by plutons that range in composition from gabbroic through intermediate types to granitic. In the Coso Range, this basement complex is unconformably overlain by a patchy veneer of late Cenozoic sedimentary and volcanic rocks, many of which have been dated radiometrically by Lanphere, Dalrymple, and Smith (1975). The general volcanic sequence and its structural setting were summarized by Duffield (1975) and mapped by Duffield and Bacon (1977). Eruptive activity began about 4 million years ago and has occurred as recently as late Pleistocene. Some of the youngest Pleistocene lavas disrupted drainage in the Little Lake area.

Old gravels

The oldest post-Mesozoic deposits in the Little Lake area are alluvial gravels. These gravels apparently once formed a continuous apron of coalescing alluvial fans at the foot of the Sierra Nevada escarpment but are now represented by three isolated erosional remnants, one that overlies granitic rocks of the Sierra Nevada immediately northwest of Little Lake, another similar remnant about 8 km south of Little Lake, and a third that underlies basalt east of the present river channel south of Little Lake (figs. 2, 3). The beds in the remnants against the Sierra Nevada are graded to points east of the present channel and are being eroded by streams graded to the level of that channel, as much as 100 m below the present surface of the old gravels.

The gravels crop out best in roadcuts west of the present channel. Depositional units range in thickness from about 1 to several meters and consist of poorly sorted, moderately to well-rounded clasts ranging in size from silt to boulders as much as 3 m in diameter. All clasts are from the Mesozoic crystalline basement complex of the adjacent Sierra Nevada, and most are granitic. Some massive units contain abundant coarse fragments that are suspended in sand and silt, suggesting emplacement as mudflows. Other units are better sorted and stratified and appear to represent normal alluvial material.

Ten or more well-developed soil or weathering zones are exposed in the gravels west of the present channel, especially south of Little Lake, indicating an equal number of periods of nondeposition of sufficient duration for such soils to develop. These gravels are extensively weathered throughout; for example, both within and between soil zones, virtually all clasts that are relatively rich in biotite may be easily disaggregated to grus with a hammer or even by hand. Bulldozed roadcuts slice across large boulders of such rocks, exposing equally weathered material throughout. This degree of weathering is similar to that of biotite-rich boulders in Sherwin glacial deposits along the east side of the Sierra Nevada about 200 km north of Little Lake, as described by Blackwelder (1931) and Sharp (1968).

The remnant of old gravels preserved beneath the cap of basalt along the east side of the present river channel is poorly exposed and crops out as loose granitic sand and cobbles admixed with basalt talus from the overlying lava. The gravels of this remnant are interpreted to represent the eastern extension of the alluvial fan derived from the adjacent Sierra Nevada, although they are now separated from the gravels to the west by a 1-km-wide stream channel and two intracanyon lava flows. Former continuity between the

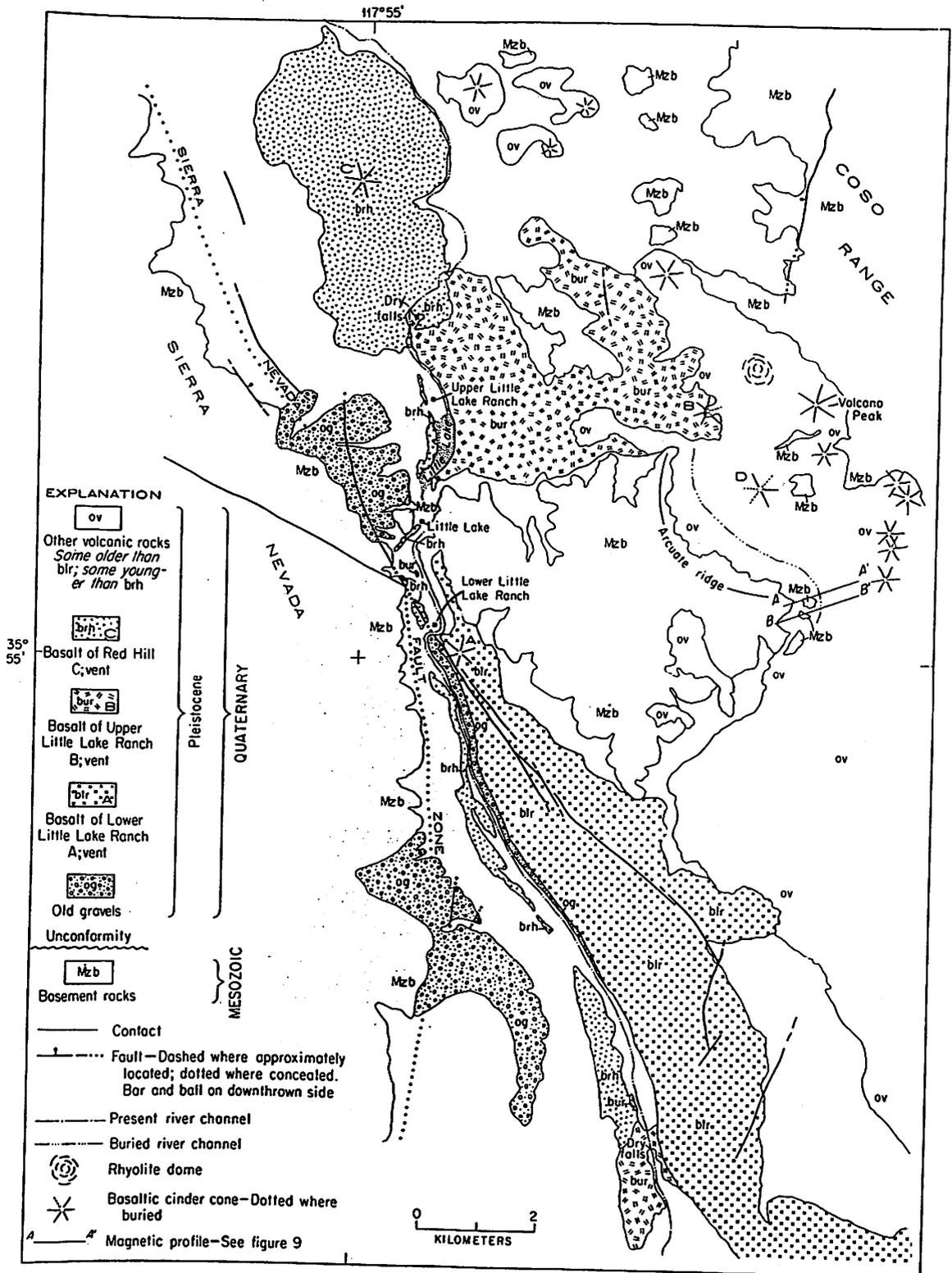


FIGURE 2.—Generalized geologic map of Little Lake area. Mostly buried basaltic cinder cone (D) may have fed an intracanyon flow, diverting river westward to Little Lake. Unlabeled areas include both Pliocene and (or) Pleistocene sedimentary rocks and Holocene deposits.

weathering in the western deposits suggest an age of hundreds of thousands of years, and the eastern gravels are overlain by 440 000-year-old basalt, consistent with such an age. It seems likely that the three remnants of old gravels do indeed represent parts of a single alluvial fan complex that grew eastward from the base of the Sierra Nevada escarpment several hundreds of thousands of years ago.

Contemporaneous gravel, derived from the adjacent Mesozoic terrane of the Coso Range (figs. 2, 3), probably interfingers from the east with the deposits from the Sierra Nevada, but direct evidence of such interfingering is lacking. Considering the relative sizes of the source areas, we suspect that gravel from the Coso Range would have been overwhelmed by the Sierra Nevada contribution to such an alluvial plain.

Basalt of Lower Little Lake Ranch

The oldest lava in the Little Lake area is informally called the basalt of Lower Little Lake Ranch (Duffield and Bacon, 1977). This lava was erupted from a vent now marked by a partly eroded cone of cinders and bombs at the rim of a 150-m-high, river-cut cliff about

2 km south-southeast of Little Lake, near the ranch from which its name is taken (figs. 2, 4). Two widespread flows were erupted from this vent, each about 3 to 5 m thick; the absence of an intervening soil or weathered zone indicates that the two were emplaced penecontemporaneously. Parts of the flows spread between 1 and 2 km north of the vent, lapping against Mesozoic basement rocks of the Coso Range and against gravels or basement rocks of the Sierra Nevada immediately south of Little Lake. Most of the lava, however, flowed south-southeastward, apparently spreading over the sloping surface of an alluvial plain composed of the old gravels. A unknown amount of lava may have ponded in the basin of China Lake. The present surface of the upper flow is moderately weathered, but much original rugged topography indicative of an aa-type flow is still preserved.

The rock is moderately porphyritic and contains 10 to 20 percent phenocrysts of plagioclase, olivine, and clinopyroxene, some as large as 3 millimeters. Plagioclase phenocrysts are most abundant, and most of the olivine is altered.

At some time after eruption of this basalt, overflow



FIGURE 4.—Present river channel as seen from Sierra Nevada escarpment near Little Lake. Part of granitic Sierra Nevada escarpment in foreground, erosional remnant of east-dipping old gravels (og) in far right background, cinder cone (A) of basalt of Lower Little Lake Ranch in

left middle distance, and Lower Little Lake Ranch lava flows at top of canyon wall. Approximate base of lava flows shown by dashed line, queried where uncertain. U.S. Highway 395 crosses field of view. View to southeast.

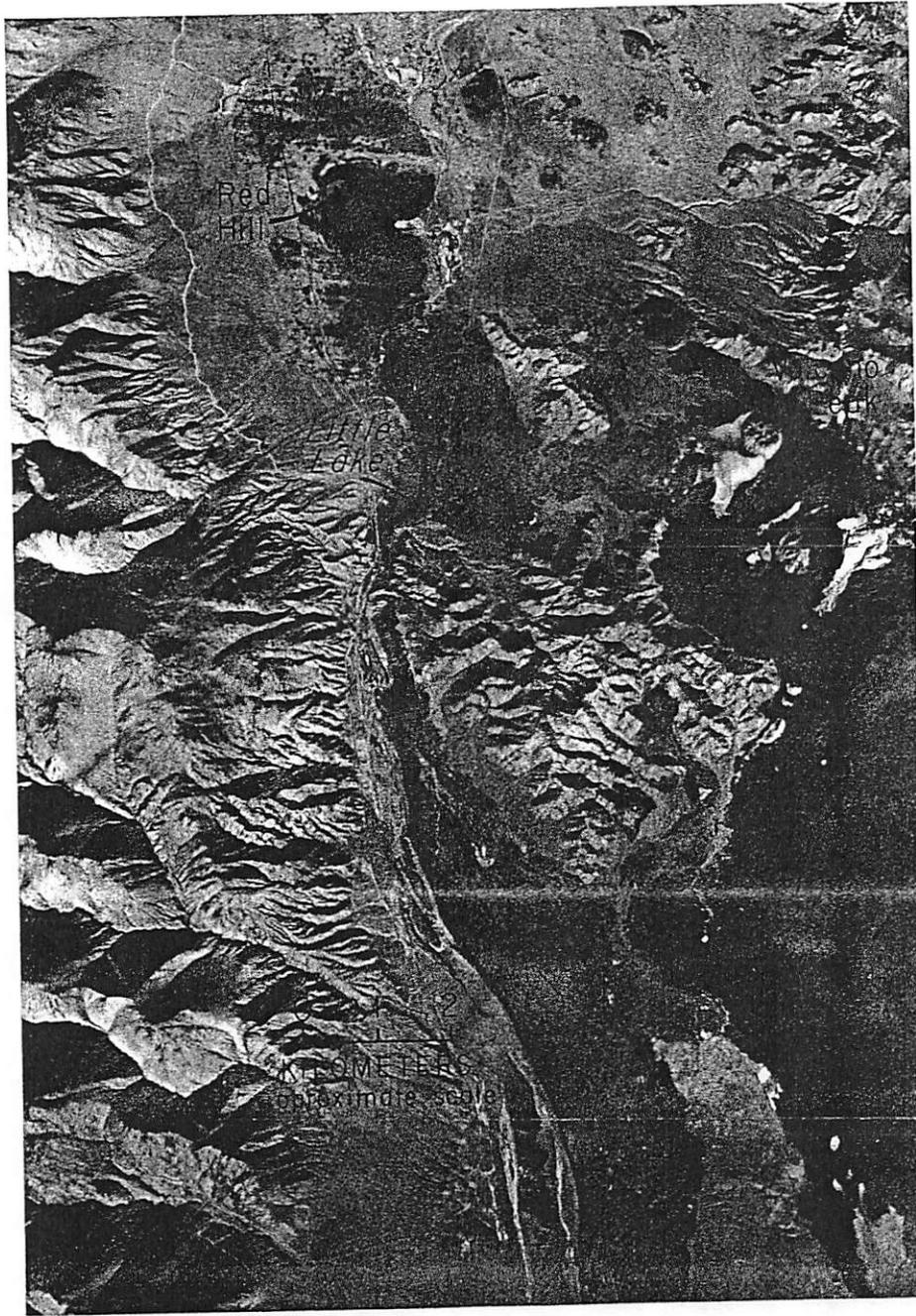


FIGURE 3.—Vertical aerial photograph of Little Lake area. Compare with figure 2. U.S. Geological Survey photograph USAF 744V022 taken by the U.S. Air Force in 1967.

eastern and western gravels is indicated by the facts that: (1) clasts are derived from the Mesozoic basement complex and are mostly granitic, (2) maximum clast size decreases away from the Sierra Nevada, and (3) the present upper surface of the western deposit (virtually parallel to bedding) shows alinement with the top of the eastern deposit when projected along strike across the intervening stream channel. Faulting

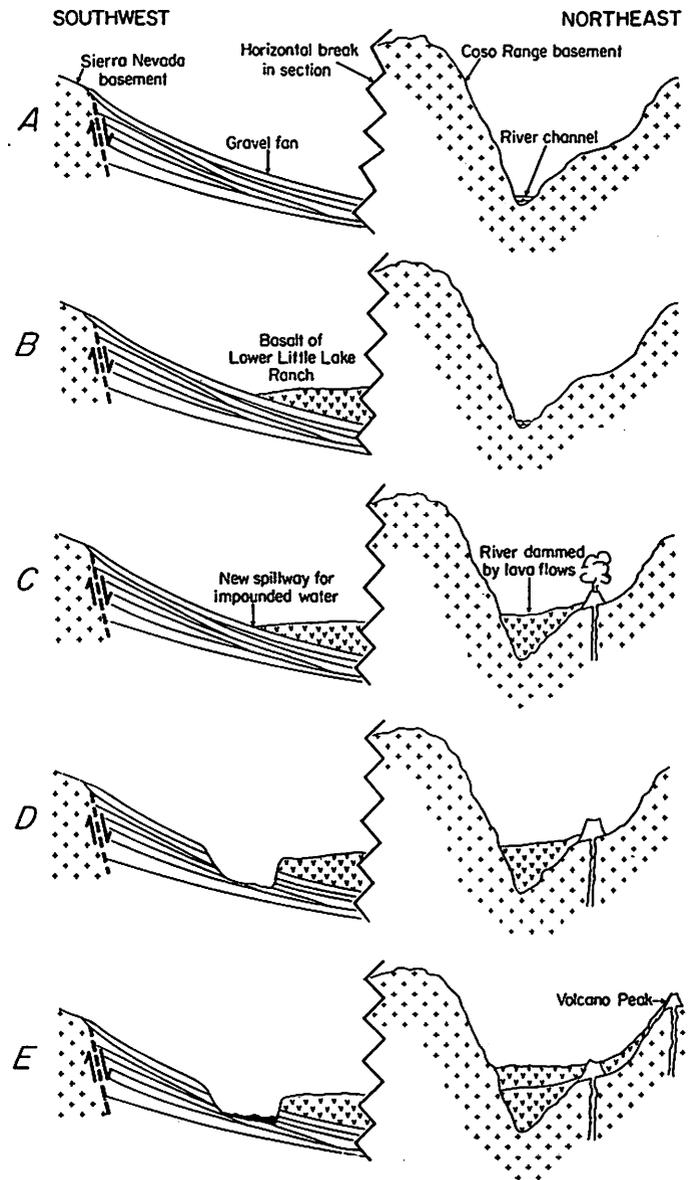
within the Sierra Nevada fault zone that postdates deposition of the alluvial fan gravels must be considered in such a projection; two normal faults with offsets down to the east cut the western gravels (fig. 2), but demonstrable vertical displacement is only about 20 m, an amount that would not significantly alter the original profile of a continuous fan across the area. Moreover, the numerous soils and the pervasive

from Owens Lake fed a major south-flowing stream that eroded a canyon at the foot of the Sierra Nevada escarpment in the Little Lake area. Because no erosional remnants of the basalt occur along the present frontal slope of the Sierra Nevada, we infer that this river first began to flow along the western edge of the lava where it lapped against the escarpment and that it subsequently eroded both vertically and laterally to the east until arriving at about its present position. The lofty river-cut cliff south-southeast of Little Lake (fig. 4) represents a little-altered remnant of the resulting canyon wall, whose present relief indicates a minimum of 160 m of downcutting. This relief probably was formed by washing out of the nearly unconsolidated older gravels while the overlying basalt cap retreated by progressive collapse as the river undercut it laterally, downslope away from the front of the Sierra Nevada (fig. 5).

Basalt of Upper Little Lake Ranch

Once established, the river channel at Little Lake has remained in nearly the same position to the present time and has alternately carried water and lava. The first lava flow to enter the channel, informally called the basalt of Upper Little Lake Ranch (Duffield and Bacon, 1977), was erupted from a vent now marked by a slightly eroded cinder cone partly covered by younger pyroclastic debris, about 5 km northeast of Little Lake (fig. 2). Only a single flow has been recognized from this vent; it spread north and west until it reached the river, then advanced downstream at least 15 km to where the most distant erosional remnant is exposed today. An unknown amount of this lava may have ponded in the basin of China Lake.

Judged by the exposed thickness of 70 m, lava may have completely filled the canyon where it entered the river channel above Little Lake. Downstream from Little Lake, however, the flow stayed well below



EXPLANATION

-  Granitic basement
-  Gravel fan
-  Lava flow
-  Contact
-  Fault — Arrows show relative movement
-  Cinder cone

FIGURE 5.—Schematic cross sections about 8 km south of Little Lake. Elevation datum is constant across break in sections. Vertical exaggeration approximately $\times 7$. *A*, Active river channel 5 km east of Little Lake and alluvial fan at foot of Sierra Nevada before eruption of basalt of Lower Little Lake Ranch. *B*, Basalt of Lower Little Lake Ranch laps onto Sierran fan and against granitic basement of Coso Range. *C*, Unnamed intracanyon lava dams channel, forcing water through new spillway at west margin of basalt of Lower Little Lake Ranch. *D*, Subsequent river erosion forms canyon in alluvial gravels, capped by basalt on east rim. *E*, Present configuration with canyon of *D* partly filled by basalts of Upper Little Lake Ranch and Red Hill and recent alluvium (all shaded).

the canyon rim, as indicated by the position of locally preserved marginal levees that mark the original maximum height of the flow at its edge.

This basalt is sparsely porphyritic, containing 1 to 2 percent phenocryst of olivine and plagioclase, about 1 to 2 mm in size, and is easily distinguished from the basalt of Lower Little Lake Ranch.

After emplacement of this lava, a river channel was reestablished through the area. Below Little Lake, where the prelava canyon had been only partly filled by the lava flow, the position of the new channel changed little, if any. Above Little Lake, however, the river was apparently diverted to the west margin of the new flow, where lava had lapped against the east-sloping wall of the canyon eroded earlier in the alluvial fan now represented by the remnant of old gravels there (fig. 2). Erosion along the contact cut vertically and laterally away from the Sierra Nevada escarpment as it had during the earlier canyon-cutting episode downstream in the basalt of Lower Little Lake Ranch. An impressive 70-m-high cliff was cut,

exposing columnar basalt that now forms the backdrop for Little Lake (the lake) (fig. 6). Erosion of the basalt itself was probably facilitated by undercutting into the unconsolidated old gravels, although the base of the lava is not exposed in the present cliff behind the lake. Our interpretation of these events is shown in figure 7.

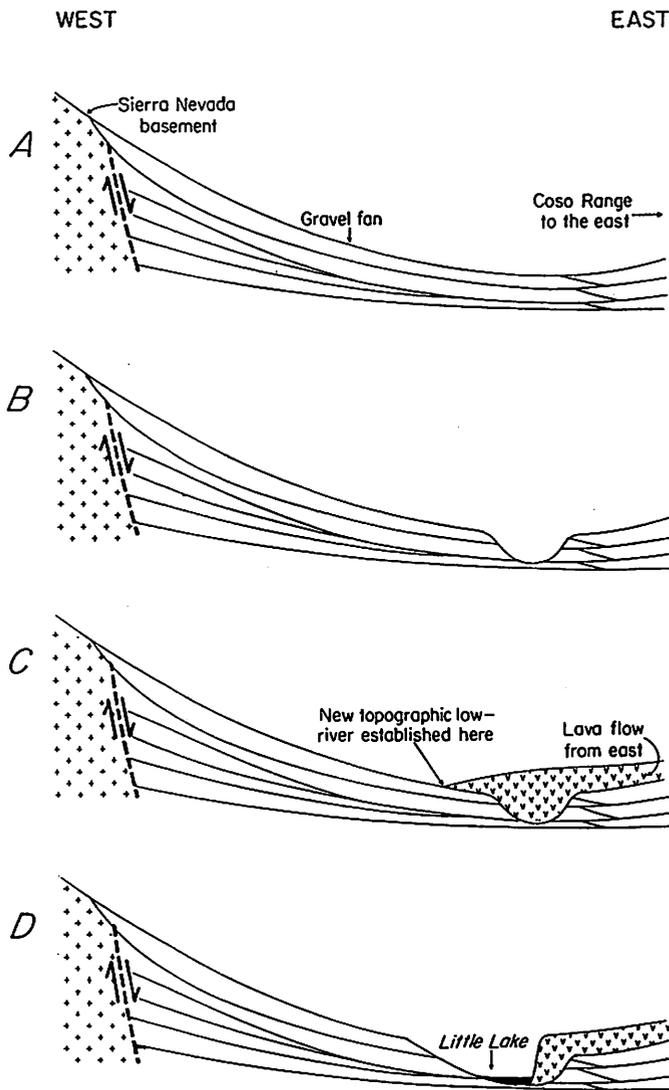
Basalt of Red Hill

After entrenchment of the river channel into the basalt of Upper Little Lake Ranch, an intracanyon lava flow, informally called the basalt of Red Hill (Duffield and Bacon, 1977), was erupted from a vent now marked by a little eroded, though greatly quarried, cinder cone about 5.5 km north-northwest of Little Lake (fig. 2). Lava ponded in an area of at least 2 km radius around the vent and fed a single flow that extended 16 km or more down the river channel. In the vent area, the river canyon was filled to overflowing; some lava lapped over the top of the pre-existing river-cut cliff in the basalt of Upper Little Lake Ranch. At and below Little Lake (the lake), the



FIGURE 6.—Little Lake area as seen from Sierra Nevada escarpment. Note lake (L) in background, lofty erosional cliff cut into basalt of Upper Little Lake Ranch behind lake, exposures of Mezozoic basement rocks (Mzb), erosional remnants of old gravels (og) that

underlie east-dipping surfaces in left middle distance, Red Hill cinder cone (C), and erosional remnants of basalt of Red Hill (brh) along west shore of lake and near railroad track in right middle distance. View to northeast.



EXPLANATION

-  Granitic basement
-  Gravel fan
-  Lava flow
-  Contact
-  Fault — Arrows show relative movement

FIGURE 7.—Schematic cross sections 1.5 km north of Little Lake. Vertical exaggeration approximately $\times 7$. A, Alluvial fan complex between Sierra Nevada and Coso Range before

basalt of Red Hill stayed well below the rim of the preexisting canyon walls. In the downstream areas, the presently exposed rough upper surface on erosional remnants of the flow represent little altered original flow tops and commonly lie tens of meters below nearby canyon walls.

The basalt of Red Hill is moderately porphyritic, containing phenocrysts of plagioclase, olivine, and pyroxene as large as 3 mm. The general appearance is very similar to that of the basalt of Lower Little Lake Ranch, but the two lavas are easily distinguished in the field, as they differ in degree of weathering on flow surfaces and in geomorphic setting, one forming a rim-capping flow, the other, an intracanyon flow.

After emplacement of this basalt, the river connecting Owens and China Lakes again reestablished a channel in the Little Lake area. The course of the river was guided by newly formed topography around the east margin of the lava ponded near the vent, whereas downstream it apparently followed the earlier channel, only partly filled by the new lava flow. Ensuing erosion of the basalt of Red Hill destroyed or buried all but isolated remnants of its intracanyon flow, which can be traced 16 km downstream from the vent, and sculpted a 25-m-high waterfall about 2 km upstream from Little Lake (the lake).

Holocene deposits

The most recent geologic deposits in the area include (1) alluvium of the presently active fans that are encroaching from the west at the base of the Sierra Nevada escarpment and from the east from nearby parts of the Coso Range, (2) sand and gravel that partly fill the present stream channel and cover much of the two intracanyon lava flows, and (3) lacustrine beds that underlie Little Lake (the lake).

The lake appears to result from a natural dam, formed by alluvial fans coalescing from the west and the east near the narrowest part of the river canyon. During recent years, a rise in lake level of only 1 or 2 m would have resulted in overflow and perhaps erosion of a channel to drain the lake. Such an apparently

FIGURE 7.—Continued

erosion of first channel (see fig. 5A). B, Stream erosion cuts channel in fan complex after downstream eruption of basalt of Lower Little Lake Ranch but before eruption of basalt of Upper Little Lake Ranch (see fig. 5D). C, Basalt of Upper Little Lake Ranch fills stream channel and laps upon east-dipping surface of old gravels to west. D, Subsequent erosion cuts into west margin of flow, forming channel later followed by basalt of Red Hill. Channel now partly filled with erosional remnants of basalt of Red Hill, lacustrine deposits of Little Lake (the lake), and recent alluvium (all shaded).

delicate balance between accumulation of the alluvial dam and water level in the lake may have resulted in repeated draining of the lake in the past. Mehringer and Sheppard (1977) cored 11.3 m of the lake beds and obtained a carbon-14 age of about 5000 years B.P. for the deepest material penetrated. Their interpretation of the sedimentary and fossil record of the core suggests alternating grassy meadow and marshy environments between 5000 and 3000 years B.P. and the presence of a shallow lake since 3000 years B.P. Our study suggests the possibility of two older sequences of lacustrine or fluvial deposits, one predating each of the two intracanyon flows. A deeper bore hole is needed to test this suggestion.

LOCATION OF RIVER CHANNEL BEFORE ERUPTION OF BASALT OF LOWER LITTLE LAKE RANCH

Field evidence suggests that there was no throughgoing north-south river channel at Little Lake when the basalt of Lower Little Lake Ranch was erupted. This lava flow spread more than 2 km laterally as it moved down a south-dipping alluvial slope toward China Lake basin; had a river channel existed, the flow probably would have been mostly restricted to that channel, in a manner similar to subsequent intracanyon flows of the basalts of Upper Little Lake Ranch and Red Hill. Moreover, at the time of this eruption, alluvial fan deposits, now represented by the erosional remnant of old gravels, apparently extended unbroken across the narrow slot between the Sierra Nevada and the Coso Range. We suspect that the narrowest part of the present canyon at Little Lake, which now separates steeply rising exposures of Mesozoic bedrock by only about 350 m was the site of a bedrock-cored saddle between north- and south-sloping alluvial plains when the basalt of Lower Little Lake Ranch was erupted. Where was the throughgoing river channel then?

Taking present topography on the Mesozoic basement rocks as a reasonable approximation to basement topography during Pleistocene time, the only other possible gap through which water might have flowed southward in the general area between the Sierra Nevada and the Coso Range is about 5 km nearly due east of Little Lake (Duffield and Bacon, 1977; figs. 2, 3). This gap is now flooded with an unknown thickness of Pleistocene basalt flows and minor rhyolite tuff from as many as 10 nearby vents, burying any river canyon that might be carved in underlying rocks. Geomorphic and geophysical data argue strongly that such a buried canyon does in fact exist. The lava-flooded area is flanked by ridges of Mesozoic basement rocks as high as 300 m. To the east, the basement rocks are mostly covered by Pleistocene volcanic rocks, but ap-

parently they form two en echelon north-northeast-trending ridges capped by cinder deposits (Duffield and Bacon, 1977). To the west, in contrast, the basement rocks form a smoothly arcuate ridge that traces a 90° arc before plunging beneath Pleistocene basalt flows (figs. 3, 8). This shape suggests a river-cut meander, an origin that we favor.

Because contrasting magnetization between basalt and underlying granitic rocks should yield a positive magnetic anomaly over a wedge of canyon-filling basalt, to test our hypothesis of a buried river channel, we measured two parallel magnetic profiles at right angles to the path the river would have followed. Both profiles show a high-amplitude anomaly above the hypothesized canyon (fig. 9).

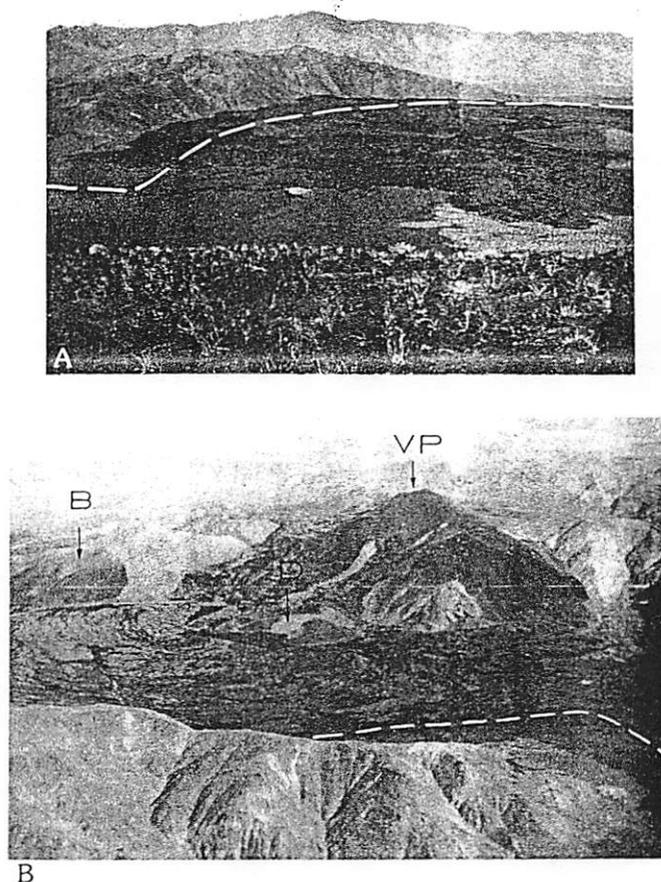


FIGURE 8.—Meander-shaped arcuate ridge in Mesozoic basement rocks and flat-lying Pleistocene lavas that may bury a river channel. *A*, Approximate location of hypothesized channel shown by dashed line. Sierra Nevada in background. View to west. *B*, Approximate location of hypothesized channel shown by dashed line. *B* = cinder cone at vent of basalt of Upper Little Lake Ranch. *D* = basalt cinder cone that may have fed flow that filled channel and diverted river to Little Lake area. *VP* = Volcano Peak, vent area for darkest and youngest flow covering hypothesized river channel. Oblique aerial view to north.

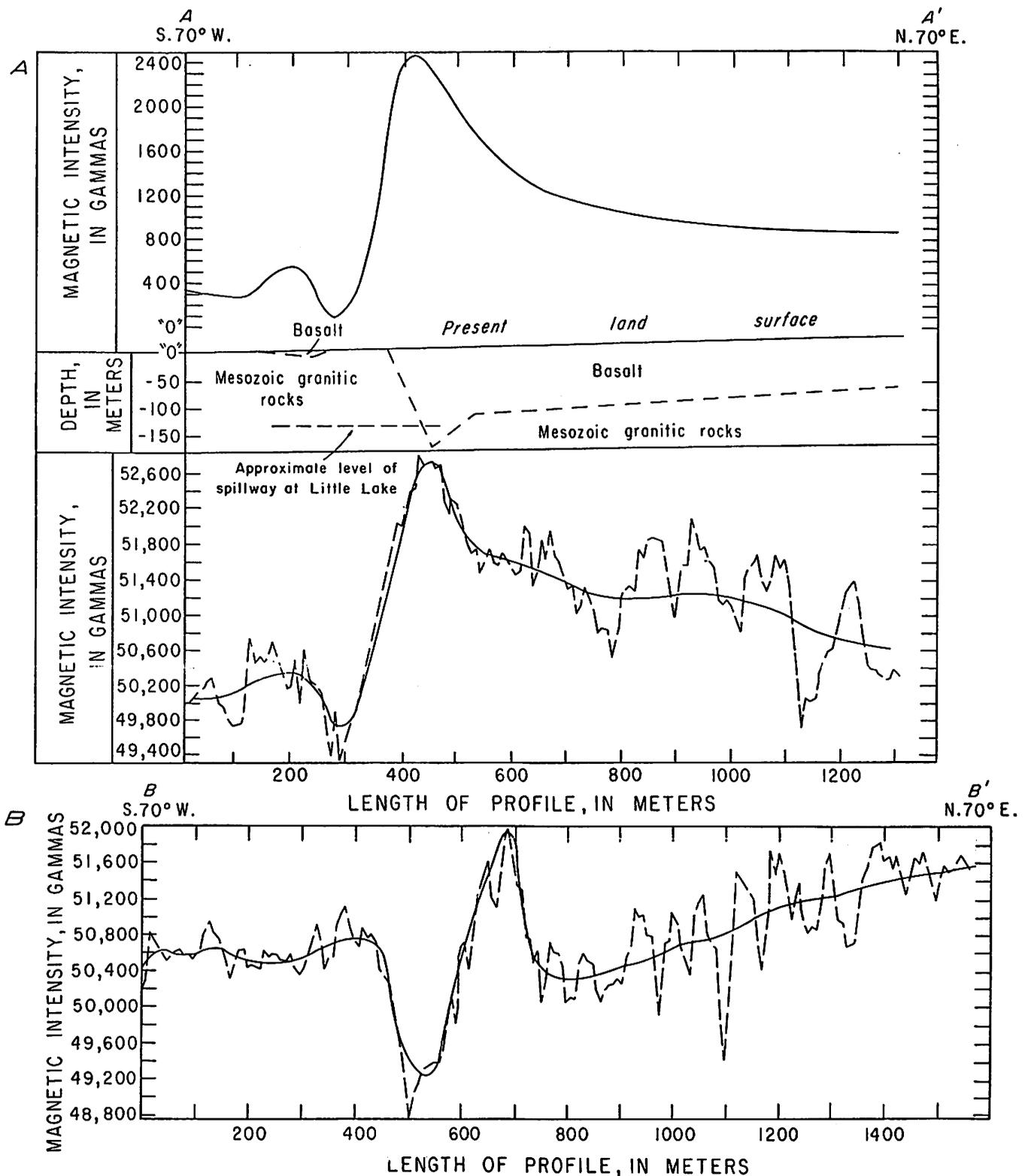


FIGURE 9.—Magnetic profiles across hypothesized river canyon near Volcano Peak (see fig. 2 for locations). *A*, Lower graph shows plot of field data and visually smoothed curve of profile *A-A'*. Note prominent magnetic high, suggestive of a buried river channel near southwest end of section. Upper graph was computed with reference to a geologic cross section, as explained in text. Assumed contrast in magnetizations between canyon-filling basalt and underlying granite

is 0.009, a reasonable figure for such rocks. *B*, Graph of field data and visually smoothed curve along profile *B-B'* about 240 m south of *A-A'*. Shape of curve is similar to *A* except at northeast end, where magnetic intensity increases, consistent with surface geology that indicates deepening granitic basement and thickening basalt there. Magnetic measurements made with Geometrics proton precision magnetometer at 8-m spacing.

Profiles constructed directly from the field data show changes in field strength of several hundred gammas between adjacent stations, 8 m apart, probably reflecting effects such as lightning strikes, irregular surface topography on the traversed basaltic lava flows, and variation in abundance and texture of ferromagnetic minerals. Nonetheless, a major anomaly over the hypothesized canyon is of much greater wavelength and magnitude and is clearly seen through the shorter wavelength noise. A visually smoothed profile (fig. 9), made to average out the short wavelength fluctuations, enhances the major anomaly and provides some control for geophysical modeling.

For the modeling study, a geologic cross section was constructed on the assumption that a river channel in granitic rocks of uniform magnetization is filled with basalt flows of uniform but higher magnetization. The number of flows that fill such a channel is unknown, but they must all be younger than the basalt of Lower Little Lake Ranch, which was erupted about 440 000 years B.P., well within the present period of normal magnetic polarity (Cox, 1969). Accordingly, we assume that remanent magnetism of the canyon-filling flows parallels the present magnetic field; the bulk magnetization, then, consists of the added effects of parallel remanent and induced components and gives rise to the observed anomaly.

Surface geology and an estimate of a reasonable shape for a buried channel provide some control on the configuration of the cross section. The approximate minimum thickness of channel-filling basalt can be computed as the elevation difference between the line of the magnetometer profile and the upper surface of the basalt of Lower Little Lake Ranch near Little Lake, the inferred alternate spillway for impounded water. From the resulting cross section (fig. 9A), a magnetic profile was computed, using a program written by R. J. Blakely (unpub. data, 1977). The computed profile and the visually smoothed version of the measured profile are similar enough to suggest that the constructed geologic cross section is a close approximation of the actual section. Closer agreement between the measured and computed magnetic profiles could be achieved through changes in the assumed configuration of the buried Mesozoic basement rocks and in the magnetic properties of the rocks, but such manipulations would not significantly alter the interpretation. The critical discovery is the existence of the magnetic anomaly where hypothesized on purely geologic evidence. Presumably, anomalies associated with additional magnetometer profiles to the north and south would trace the upstream and downstream path of the river.

CORRELATION OF ERUPTIONS AND EROSION WITH SIERRA NEVADA GLACIAL HISTORY AND SEARLES LAKE LACUSTRINE DEPOSITS

Field determinations with a portable flux-gate magnetometer show that the three Pleistocene eruptions in the Little Lake area occurred during a time of normal magnetic polarity and are, therefore, presumably younger than about 700 000 years B.P. (Cox, 1969). Potassium-argon radiometric dates are consistent with this interpretation and provide enough constraints on timing of eruptive and erosional events to permit tentative correlations with periods of glaciation in the Sierra Nevada, the principal source of water flowing through the Little Lake area, and changing water levels of Searles Lake, a downstream part of the same drainage system.

Two superimposed flows of the basalt of Lower Little Lake Ranch yield potassium-argon ages of $399\ 000 \pm 45\ 000$ and $486\ 000 \pm 108\ 000$ years B.P. (table 1), the upper flow giving the younger age. For our purposes, the two flows can be assumed to have been erupted about 440 000 years ago, the average of the potassium-argon ages. At that time, the river presumably was following its now abandoned and buried course 5 km east of Little Lake. Prior to that time, runoff associated with the Sherwin Glaciation ($>710\ 000$ years B.P.; see Sheridan, 1971), and possibly earlier glaciations in the Sierra Nevada, might account for erosion of the buried channel.

In any event, some time after 440 000 years B.P., the course of the river shifted to the foot of the Sierra Nevada escarpment at Little Lake. Why the eastern channel was abandoned is not well documented, but intracanyon lava or a fault scarp may have diverted the river. At least one basaltic cinder cone that may have fed such a flow barely protrudes through the younger surface lavas in the area of the meander (figs. 2, 8B), and other lavas of appropriate age occur there. The possibility of blockage by a fault scarp is more speculative. There are no scarps cutting the present surface lavas in the area of the meander, but late Cenozoic faulting is common elsewhere in the Coso Range (Duffield and Bacon, 1977). Moreover, the river may have been originally channeled through the area of the present meander-shaped ridge along a west-northwest-trending zone of faults that cut across the south part of the Coso Range and beyond and have been locally active as recently as late Cenozoic time (Duffield and Bacon, 1977) and apparently as early as Mesozoic time (von Huene, 1960). However, the amount of "instantaneous" relief resulting from a fault displacement seems less likely to have provided a sufficiently high dam to cause diversion of the river than

TABLE 1.—Erosion and probable ages of Pleistocene basalt near Little Lake

Channel-cutting episode	Youngest basalt affected	Erosional feature formed	Rock type eroded	Probable age of youngest basalt affected
Youngest	Basalt of Red Hill.	25-m drop at dry falls, 3.3 km north of Little Lake.	Basalt	22,000 years B.P. ¹
Intermediate	Basalt of Upper Little Lake Ranch.	70-m scarp behind Little Lake (the lake).	Basalt and underlying alluvial gravel.	55,000 years B.P. ¹ 140,000±89,000 years B.P. ² >77,000±8,000 years B.P. ³
Oldest	Basalt of Lower Little Lake Ranch.	160-m scarp south-southeast of Little Lake.	Basalt and underlying alluvial gravel.	399,000±45,000 years B.P. ² (Upper flow). 486,000±108,000 years B.P. ² (Lower flow).

¹Calculated on the basis of a constant rate of canyon downcutting between 10,000 years B.P. and 130,000 years B.P. See text for discussion.

²Potassium-argon age (Duffield and Bacon, 1977).

³Potassium-argon age (Lanphere and others, 1975). Pyroclastic debris associated with their sample no. 1 overlies basalt of Upper Little Lake Ranch.

ponding of lava. Accordingly, we believe that blockage by lava tipped the balance in favor of the present location of the channel at Little Lake.

The ages of the basalts of Upper Little Lake Ranch and Red Hill are difficult to establish. The basalt of Upper Little Lake Ranch has yielded a potassium-argon age of 140 000 years, but so little radiogenic argon was recovered from the rock that the uncertainty is nearly ±64 percent of this age (table 1). Lanphere, Dalrymple, and Smith (1975) reported a potassium-argon age of 77 000 ±8000 years for a rhyolite dome whose pyroclastic debris partly blankets the cinder cone at the vent of the basalt of Upper Little Lake Ranch; this provides a reasonably well established minimum age for that basalt unit. Repeated attempts to date basalt of Red Hill have proved futile because no radiogenic argon has been recovered (G. Brent Dalrymple, oral commun., 1976). The glacial events in the Sierra Nevada and related lacustrine deposits in Searles Lake provide some constraints on possible ages of the basalts.

Smith's studies (1962; 1968, fig. 4; 1976b) of lacustrine deposits in Searles Lake indicate that the most recent large-scale flow of water that might account for erosion of the lavas and gravels near Little Lake ended

about 10 000 years ago. Some water probably passed through the channel in the Little Lake area en route to Searles Lake during parts of Holocene time, the youngest flow ceasing about 2000 years ago (Smith, 1976a), but the volumes apparently were not large. The Searles lacustrine deposits indicate that the first significant flow of water into Searles Lake through the Little Lake area in post-Sherwin time, that is, since about 710 000 years ago, began about 130 000 years ago. Between 10 000 and 130 000 years ago, the water in Searles Lake generally remained high, at times overflowing into Panamint, the next lake in the chain (Smith, 1962; 1968, fig. 4; 1976b). Accordingly, the eruption and subsequent erosion of the basalts of Upper Little Lake Ranch and Red Hill most likely occurred between 130 000 and 10 000 years ago. With this time constraint, estimated ages of the eruptions may be calculated by assuming a constant rate of erosion. We recognize that erosion probably was episodic, but the record of sedimentation in Searles Lake suggests considerable flow past Little Lake during much of the 120 000-year interval, with few extended, possibly dry periods.

The amount of vertical channel erosion during the 120 000-year period of interest may be estimated from

resent topography. This procedure somewhat underestimates actual erosion, because a basal, though probably small, part of the erosional scarps is buried by younger deposits. Nonetheless, as a first approximation, we have reconstructed three sequential episodes of incision downcutting (table 1) with reference to the cycles of eruption and erosion as explained in preceding sections. The two older episodes were apparently characterized by removal of nearly unconsolidated fluvial gravel and thereby represent directly comparable modes of erosion. The youngest episode was apparently characterized by streambed plucking and abrasion within basalt, a contrasting mode of erosion that almost certainly proceeded more slowly than earlier canyon downcutting. The effect of this slower mode of erosion on our assumption of a constant rate would be to make our calculated ages too young; this effect may be at least partly offset by deepening of the channel since 10 000 years ago.

Total downcutting for the three episodes of erosion, that is, for the entire 120 000-year period, is 255 m, yielding an average rate of 2.125 millimeter per year between 10 000 and 130 000 years ago. At this rate, the scarp in the basalt of Lower Little Lake Ranch and underlying rocks could have formed in about 75 000 years, that in the basalt of Upper Little Lake Ranch about 33 000 years, implying ages of 55 000 and 2 000 years B.P. for the basalts of Upper Little Ranch and Red Hill, respectively (table 1). An age of 55 000 years B.P. for basalt of Upper Little Lake Ranch is consistent with the potassium-argon age of 77 000 ± 8000 years for overlying rhyolite (Lanphere and others, 1975). The independently determined potassium-argon age of 140 000 ± 89 000 years is consistent with both estimates, but only because it is not closely constrained.

In summary, the age of the basalt of Lower Little Lake Ranch seems reasonably well fixed by potassium-argon dates alone. The ages of the younger two basalts are problematic because the possible errors associated with the methods used to date them may be about as great as the true ages of the rocks. Nonetheless, considering all lines of evidence, we suggest that the basalt of Red Hill is probably no more than a few tens of thousands of years old, the basalt of Upper Little Lake Ranch probably somewhat less than 100 000 years old, and the basalt of Lower Little Lake Ranch about 40 000 years old. These ages are generally consistent with available evidence and provide guidelines for possible future dating by more accurate techniques.

CLOSING REMARKS

The Pleistocene history of the Little Lake area primarily reflects a struggle between the fairly steady

force of stream erosion and the less frequent, but more powerful, eruptions of intracanyon lava flows. The decipherable parts of the story indicate that each has prevailed at different times, with an apparent lull in the struggle at the present time. The abundance of nearby volcanic rocks that are only a few tens of thousands of years or less in age suggests the likelihood of future eruption to set the stage for yet another cycle of eruption and erosion.

An understanding of the Quaternary geologic record at Little Lake is critical to an understanding of other parts of the drainage system that passes through that area. For example, we have little idea of how long each intracanyon lava dammed outflow from Owens Lake, but blockage may have lasted long enough to affect the nature of deposits in downstream basins such as China and Searles Lakes, where evaporation to form a salt layer could have occurred in less than a century. During blockage, one or more new lakes must have formed in Rose Valley, immediately upstream of Little Lake; presumably, buried evidence of their former existence still remains. Moreover, the older buried channel east of Little Lake may now provide a major conduit for groundwater to help recharge the heavily pumped subsurface waters of China Lake basin. Continuing studies will better establish the sequence of late Quaternary events in the Little Lake area.

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