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Summit Lake landslide and geomorphic history of Summit Lake basin, northwestern Nevada

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ABSTRACT

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The Summit Lake landslide, northwestern Nevada, composed of Early Miocene pyroclastic debris, Ashdown Tuff, and basalt and rhyolite of the Black Rock Range, blocked the upper Soldier Creek–Snow Creek drainage and impounded Summit Lake sometimes prior to 7840 yr B.P. The slide covers 8.2 km^2 and has geomorphic features characteristic of long run-out landslides, such as lobate form, longitudinal and transverse ridges, low surface gradient (7.1°), and preservation of original stratigraphic position of transported blocks. However, estimated debris volume is the smallest reported (2.5×10^5 m^3) for a landslide of this type.

The outflow channel of the Summit Lake basin was a northward-flowing stream valley entrenched by Mahogany Creek. Subsequent negative tectonic adjustment of the basin by about 35 m, accompanied by concommitant progradation of a prominent alluvial fan deposited by Mahogany Creek, argues for a probable diversion of drainage from the Alvord basin southward into the Lahontan basin. The landslide occurred while the creek flowed southward, transferring about 147 km^2 of watershed from the Lahontan basin back to the Alvord basin. Overflow northward occurred during high stands of Pluvial Lake Parman in the basin; otherwise, under drier climates, the Summit Lake basin has been closed.

Within large depressions on the slide surface, the ca. 6800 yr old Mazama Bed and other sediments have buried a weakly developed soil. Disseminated humus in the soil yields an age of 7840±310 yr B.P. Absence of older tephra (such as St. Helens M) brackets the slide age between 7840 and 19,000 yr B.P. Projectile points found on the highest strandlines of Pluvial Lake Parman suggest a ca 8700 yr B.P. age by correlation with cultural artifacts and radiocarbon ages from nearby Last Supper Cave, Nevada. Organic matter accumulation in landslide soils suggests ages ranging from 9100 to 16,250 yr B.P. Estimation of the age of the slide from morphologic data for the isolated Summit Lake population of Lahontan cutthroat trout does not conflict with the radiometric ages.

Introduction

Study objectives

The Summit Lake landslide, on the northwestern flank of the Black Rock Range in western Humboldt County, Nevada (W 119°10′00″, N41°29′30″; Fig. 1), is one of several large, undescribed landslides of the Black Rock region (Stewart and Carlson, 1976), but is worthy of study because of the unusual slide morphology and tectonic setting, and it is the only mass movement that impounds a permanent lake in this region. Furthermore, most of the slide is within the Summit Lake Paiute Indian Reservation; fisheries resources of the lake are of economic value, and the tribal council concluded that study of the lake and slide was useful for future planning.

Physical setting

The Summit Lake slide traveled about 5.8 km from scarp to toe, displacing about 2.5×10^5

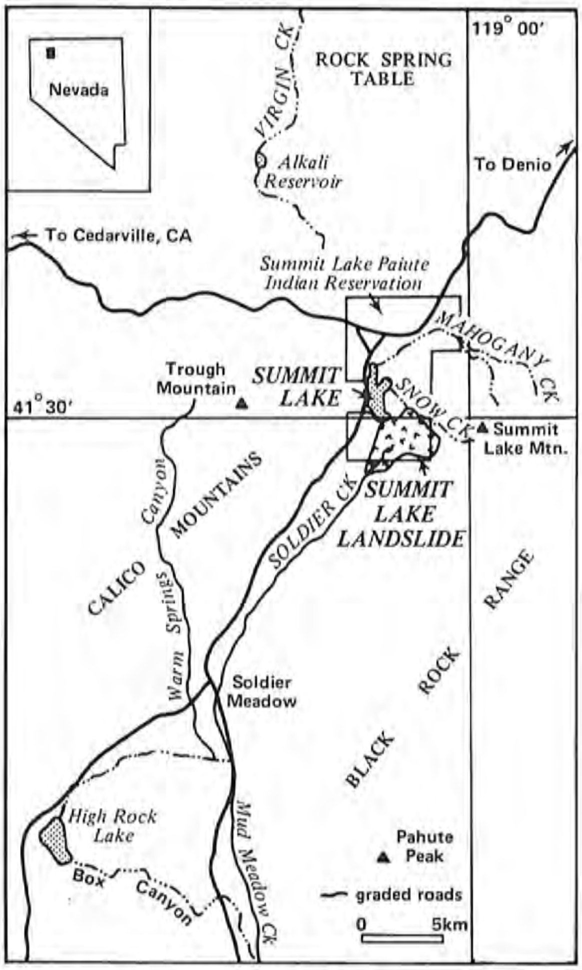

Fig. 1. Location map of Summit Lake area.

m^3 of debris over an area of 8.2 km^2. After breaking away from Summit Lake Mountain, debris partly buried the Soldier Creek and Snow Creek valleys (Fig. 1). Southward drainage to the Lahontan basin from an area of about 147 km^2 north of the slide also was blocked, creating the basin now occupied in part by the slide-dammed Summit Lake. Although the lake elevation now is about 1779 m, and the lake area is only about 2.6 km^2, the lake level during the latest Pleistocene or Holocene rose to at least 1787 m, flooding about 16.8 km^2 (Pluvial Lake Parman; see Layton, 1970). Maximum lake size and volume were controlled by an outlet that discharged northward through a canyon previously cut by Mahogany Creek, eventually reaching Virgin Creek and Pluvial Lake Alvord basin in Oregon.

Sinclair (1963b), Morrison (1964), and Layton (1979), have reported some of the complex history of the Summit Lake basin. Otherwise, there is little published information on Quaternary–Holocene geology and geomorphology of this part of northwestern Nevada. A cursory examination by LaRivers (1962), a fisheries biologist, led to the erroneous conclusion that the lake formed as a result of a lava flow blocking Soldier Creek.

Most recently, Mifflin and Wheat (1979) stated that Summit Lake resulted from damming by a "Snow Creek" landslide. They note that the lake probably had a complex overflow history to the Alvord and Lahontan basins during Lahontan (late Wisconsinan) time, and further suggested that during the Middle- to Late Pleistocene there existed the possibility of "a potential hydrologic mechanism for transfer of indigenous fish between ... two major basins" (Mifflin and Wheat, 1979, p. 27). We independently recognized this possibility during the course of the Summit Lake investigation and attempted, apparently for the first time in the geomorphologic literature, to compare age estimates based on seriological and morphological data from disjunct native fish populations with estimates derived from other methods of dating geologic events, such as archaeology, tephrochronology, organic carbon accumulation in relict and buried soils, and ^{14}C ages. Tephra data and ^{14}C ages of buried soils provided the best estimate of the minimum landslide of the age.

Climate and vegetation

The closest climatic stations are more than 80 km distant. Interpolating from comparable altitudinal, vegetational, and geographical data given by Houghton et al. (1975) and Sinclair (1963a–c), the Summit Lake basin climate ranges from moist steppe to dry subhumid continental, with an altitudinally dependent 15–65 cm annual precipitation, and a monthly average temperature range of −10 to +25°C.

Vegetation is dominated by sagebrush, especially *Artemisia tridentata*. A native bunchgrass understory apparently has been replaced mainly by introduced annuals as a result of past overgrazing (Layton, 1970). The uplands lack the normally characteristic regional assemblage of *Juniper* sp., but quaking aspen (*Populus tremuloides*) and willow (*Salix* sp.), are present in canyons of the Black Rock Range and historically were scattered around the lake margin.

Stratigraphy

Tertiary

Tertiary stratigraphy of the Summit Lake area has been outlined by Noble et al. (1970, 1973) and is summarized in Table 1. Units exposed in the head scarp, from base to top include a lowermost, unnamed pyroclastic sequence, the Ashdown Tuff, and rhyolite of the Black Rock Range (Fig. 2).

Quaternary landslide deposits

All volcanic units exposed in the head scarp are found incorporated in the landslide debris. Parts of the slide are chaotic mixtures of rock types, but several blockfields on the slide surface are composed only of one or two members of the Ashdown Tuff (Fig. 3).

The slide deposit primarily is a brecciated diamicton derived from the lower pyroclastic sequence and the welded, middle member of the Ashdown Tuff. Identifiable clasts of other stratigraphic units are much less common. Slide diamicton matrix is white, green, pink, or light brown sand or clay. The largest clasts, generally 5 to 8 m in diameter, are composed of agglomerate from the lower pyroclastic sequence. One remarkable boulder is about 75 m across, and has an above-ground vertical exposure of at least 15 m. However, most pyroclastic fragments are broken and weathered to sand-size particles. The most distinctive unit seen on airphotos and in the field is desert-varnished sieve deposits derived from the middle, welded member of the Ashdown Tuff, but locally the slide surface includes coherent, remarkably intact blocks of vertically dipping, fractured tuff as large as 22 m wide and about 105 m long. These linear masses tend to strike parallel to the slide axis, and apparently were rotated during slide movement, meanwhile undergoing lateral transport of at least 1650 m and vertical dislocation of 300 m (Fig. 3). The six partial cooling units (Ross and Smith, 1961) of the welded member, as seen exposed in the scarp, can be distinguished in the translocated masses. Another dislocated, smaller block near the scarp base consists of platy rhyolite of the Black Rock Range. This mass is strongly jointed, but remains a coherent block that was vertically displaced 245 m.

The distribution of large clasts suggests that the core and distal portion of the slide is composed predominantly of fine-grained fragments of the lower pyroclastic sequence, covered in part by coarser-grained brecciated diamicton derived from stratigraphically higher tuff and rhyolite. This breccia thins markedly toward the slide toe.

Post-landslide deposits

Weak to moderately well-developed shoreline strands exist around the margin of Five Mile Flat (see Fig. 7). These deposits are composed of reworked, sand-size tuff particles. The northeastern end of the flat is covered by 2 m high barchan or parabolic dunes of similar composition.

Minor stream channels, either deflected by the slide or formed along the margins at the time of emplacement, are bordered by dissected, lacustrine material at least 2.5 m thick, deposited while local channels were temporarily impounded by the landslide. These terraces

TABLE 1

Local Tertiary stratigraphy, Summit Lake area

Unit	Radiometric age (m.y.)	Thickness (m)	Description
Basalt of Catnip Creek	9.4[a]	3–8	Dixytaxitic, high alumina tholeiitic basalt[b]
Tuff of Trough Mountain	Unknown, but between 15.0–15.5[c]	locally 280	Densely to partly welded peralkaline ash-flow or lapilli tuff
Summit Lake Tuff	15.6[d]	locally 12	Densely welded devitrified peralkaline ash-flow tuff
Basalt of the Black Rock Range	Unknown	locally 60	Dixytaxitic porphyroaphanitic basalt
Rhyolite of the Black Rock Range	24[d]	64.5	Flow-banded, massive vitrophyre; local basalt conglomerate
Ashdown Tuff	24.5[d]	27–85	Upper and lower members: agglomerate, partly to moderately welded peralkaline ash-flow tuff, thin vitrophyre sheets. Middle member: densely-welded, devitrified, 14–34 m thick, thinning southwards along scarp
Lower pyroclastic sequence	Unknown	185	Partly welded lapilli-tuff, minor tuffaceous arkose

[a]McKee and Marvin (1974).
[b]Hart et al. (1984).
[c]Noble et al. (1970).
[d]Noble et al. (1973).

Fig. 2. Rock-stratigraphic units, viewed northwards along landslide scarp. *a*=Upper part of lower pyroclastic sequence, *b*=lower member, Ashdown Tuff, *c*=middle member, *d*=upper member, *e*=basal conglomerate (Curry, 1984), rhyolite of the Black Rock Range, and *f*=rhyolite of the Black Rock Range.

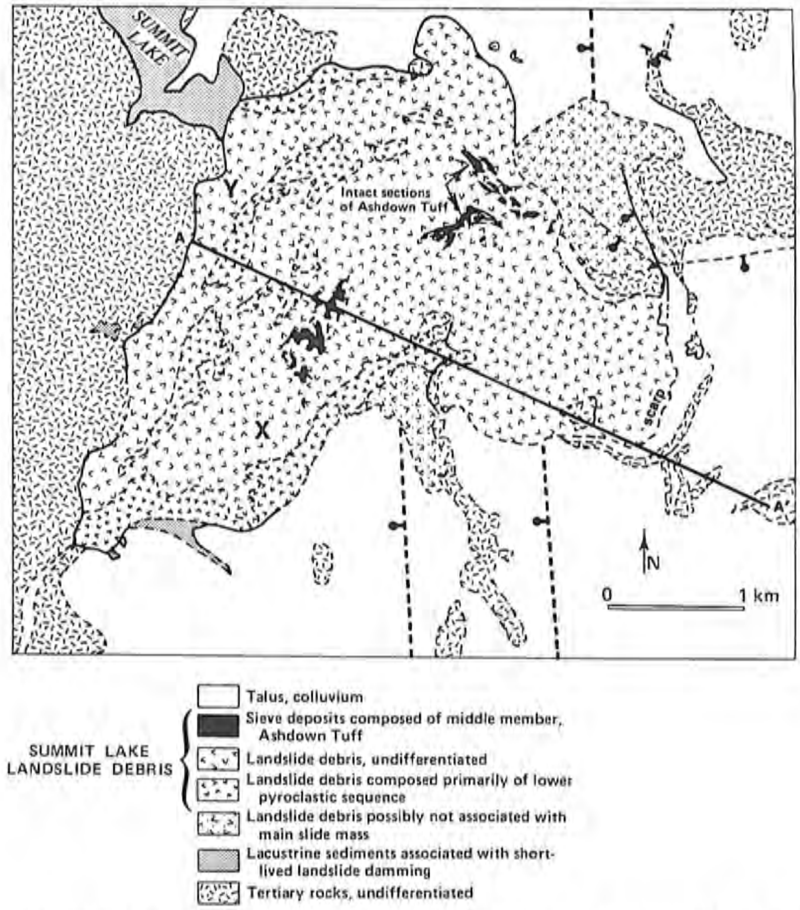

Fig. 3. Geologic map of Summit Lake landslide area. Sites X and Y are soil pit locations referred to in text. Line A–A' is cross-section detailed in Fig. 4.

abut laterally against a preslide stratified, bouldery, poorly sorted debris layer capped by a red, calcic Alfisol; this debris is 1.0 to at least 3.5 m thick where seen beneath distal portions of the landslide.

Tephra and radiocarbon age-dating

In the wall of a 2.6 m deep soil pit dug in a shallow, broad depression (site X, Fig. 3) two conspicuous tephra layers rest on fine-grained colluvium. These layers, 7 cm and about 20 cm thick respectively, are normally graded, indicating primary air-fall origin. Glass composition (Table 2a; Smith and Westgate, 1969), shard morphology (Curry, 1984), and phenocryst mineralogy (Davis, 1978) were used to confirm that these tephra are products of the 6800 yr B.P. Mazama event (Davis, 1985). Data for glass composition of the two layers, as well as other tephra beds in the region (Davis, 1985) are compared by means of similarity coefficients in Table 2b. These primary tephra were buried by about 1.5 m of colluvium derived by reworking of chiefly Mazama Bed deposits from farther upslope.

Several tephra beds ranging in age from about 19,000 yr B.P. (St. Helens M) to 35,000 yr B.P. (St. Helens C) are known regionally from other localities, including Pyramid Lake, Nevada (Davis, 1978) and Summer Lake, Oregon (Davis, 1985). The St. Helens M Bed is

TABLE 2

(a) Chemistry of tephra glass (in wt.%) recalculated water-free. Data for Summit Lake tephra from Curry (1984); other data modified from Davis (1985)

Sample/Tephra bed	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	TiO_2	K_2O
Summit Lake landslide, Site A 149–169 cm depth	73.9	14.7	2.03	0.48	1.61	0.42	2.7
Summit Lake landslide, Site A 169–176 cm depth	73.7	14.6	2.22	0.48	1.61	0.42	2.7
Mount Mazama Tephra Bed	72.5 ±0.2	14.7 0.1	2.22 0.05	0.45 0.02	1.61 0.05	0.43 0.02	2.7 0.1
Mount St. Helens Tephra Set M, Double Hot Springs, Nevada	76.2	13.9	1.21	0.29	1.49	0.17	2.4
Trego Hot Springs Tephra Bed	75.2 ±0.2	13.7 0.2	1.69 0.05	0.21 0.01	1.01 0.03	0.25 0.01	3.3 0.1
Wono Tephra Bed	73.7 ±0.4	14.4 0.2	2.25 0.07	0.30 0.03	1.33 0.05	0.32 0.02	3.2 0.2
Mount St. Helens Tephra Set C	76.3 ±0.2	14.0 0.1	1.03 0.03	0.24 0.02	1.50 0.05	0.11 0.01	2.5 0.1

(b) Similarity coefficient matrix of data in Table 2a

	Mazama	St. Helens M	Trego	Wono	St. Helens C
Summit Lake, 149–169 cm	97	76	75	85	72
Summit Lake, 169–176 cm	98	76	74	86	72

10 to 2 cm thick at these respective localities. The absence of this bed and older tephra, either in this section or elsewhere at Summit Lake, indicate that the slide occurred after 19,000 yr B.P.

A 3.3 m deep auger hole was drilled about 3 m away from the soil pit. The base of the Mazama Bed is at a depth of 1.5 m, and is underlain by about 1.6 m of gleyed, silty clay loam with abundant biotite flakes. The latter has been modified by pedogenesis, as determined by a compacted, granular structure with thick, waxy-appearing, generally continuous opaline coats, and as much as about 1.0% organic carbon. The lowermost 10 cm sample was selected for ^{14}C analysis, and yielded an age of 7840±310 yr B.P. (ISGS #1701; C.L. Liu, pers. commun., 1987). Below the silty clay loam, at a depth of about 3.1 m, is pebbly loam with no evidence of soil structure, possibly in situ landslide debris.

A pit exposure (Site Y, Fig. 3), near the northern margin of the slide, revealed discontinuous humus-rich loam with granular soil structure, as much a 20 cm thick, underlain by primary landslide debris and reworked sediment, the latter as much as 12 cm thick and incorporating glassy shards with Mazama Bed composition; the loam is overlain by colluvium. A sample from the loam yielded a ^{14}C age of 6720 ± 90 yr B.P. (ISGS #1210; C.L. Liu, pers. commun., 1987). The site is on the margin of a wide depression that was submerged during pluvial maxima; thus the radiocarbon date is a minimum age for site emergence.

Structure

The western flank of the northwestern Black Rock Range is a homocline that dips gently northwestward. Two partly concealed normal faults strike parallel to the west-facing mountain front, and cut through or just blow the landslide scarp, with a combined displacement of about 670 m (Fig. 4). The westernmost fault juxtaposes tuff of the Trough Mountain against basalt of the Black Rock Range.

Geomorphology

Summit Lake landslide

The lobate character of the Summit Lake slide is readily seen on aerial photographs. Longitudinal and transverse ridges are pronounced, but the original surface has been deeply dissected by Soldier Creek, which flows almost parallel to the slide axis. Disordered drainage characterizes much of the slide, but is better ordered adjacent to Soldier Creek (Fig. 5).

The Summit Lake landslide covers approximately 8.2 km^2; debris thickness ranges from about 10 m to more than 100 m (Fig. 6). The debris volume is estimated at about 2.5×10^5 m^3. The lip of the scarp is at an elevation of about 2350 m, the toe at 1605 m. After initially breaking away to the northwest, the slide turned southward as it entered a canyon south of the present Summit Lake, and traveled about 6.0 km (Fig. 6). The average gradient (the Fahrböschung of Heim, 1932) is 7.1°.

Landslide mechanics

The Summit Lake landslide has several features characteristic of long run-out landslides, such as (a) preservation of scarp stratigraphy in the debris, (b) lobate form, and (c) low mean gradient (Hsü, 1975). However, the landslide is an order of magnitude less in volume (Table 3) than previously listed for long run-out landslides (2.5×10^5 m^3 compared to 1.0×10^6 m^3 of the Elm Slide, the smallest volume reported by Voight, 1978). Several mechanisms have been proposed for these slides, such as frictionless air-cushion "sliding" (Shreve, 1968), debris flow (Johnson, 1978), basal steam lubrication (Goguel, 1978) and acoustic fluidization (Melosh, 1979, 1983). The latter three mechanisms will promote a greater travel distance for debris with a rela-

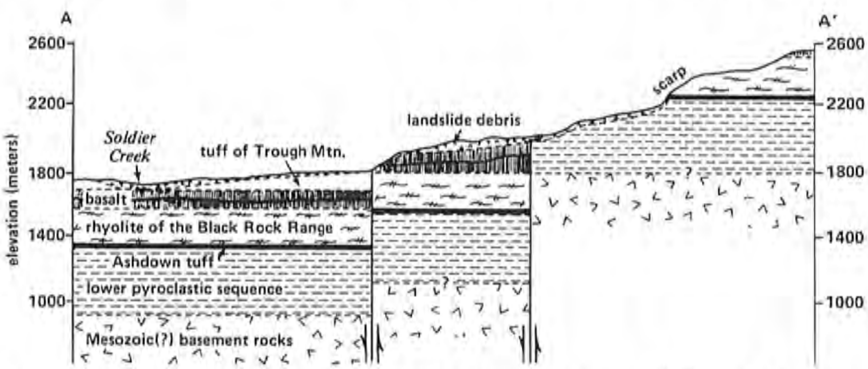

Fig. 4. Generalized stratigraphic cross-section through landslide area along line A–A′ shown in Fig. 3.

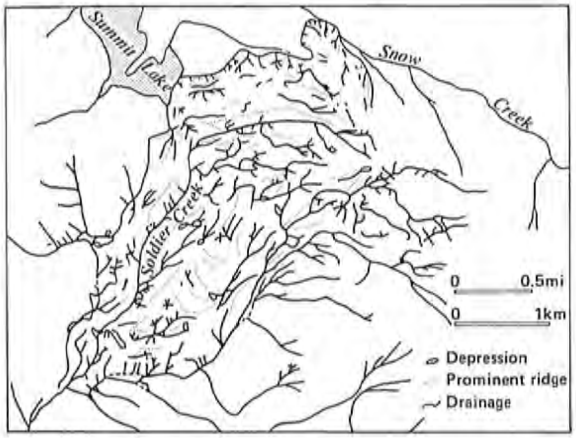

Fig. 5. Drainage map of landslide.

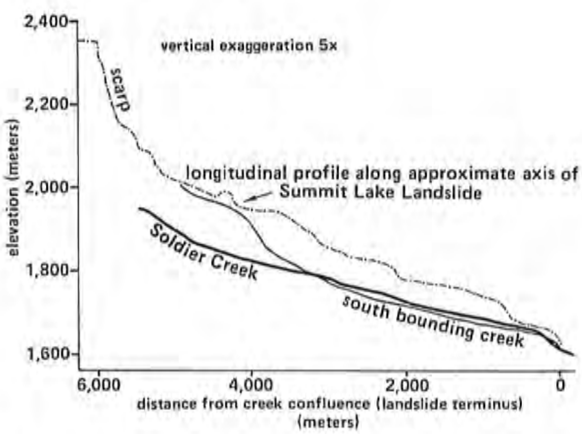

Fig. 6. Longitudinal profiles of landslide axis gradient, and streams bordering or dissecting the landslide. Difference between creek profiles and landslide axis indicates minimum slide thickness.

tive high moisture content, a state that clearly could have been attained at Summit Lake under more moisture-effective, Late Pleistocene pluvial climates. Whatever mechanisms are invoked must account for high debris strength that allowed massive slabs ($20\times100\times10$ m^3) of densely welded tuff (d=2.45–2.55 g/cm^3) to travel "piggyback" at least 1.5 km. Concurrently, debris must have been mobile enough to allow a turn of almost 90° into the valley of Soldier Creek, falling 300 m in a distance of less than 3 km.

End-member rheological models of pseudo-

TABLE 3

Volume and apparent coefficient of friction of "normal" and long run-out landslides. Modified from Voight (1978)

Slide	Volume ($\times10^6$ m^3)	Apparent coefficient of friction
Summit Lake, Nevada, U.S.A.	0.3	0.13
Airolo, Switzerland	0.5	0.64[a]
Montbiel, Switzerland	0.8	0.42[a]
Beaver Flats (north), Canada	4.1	0.49[a]
Beaver Flats (south), Canada	4.8	0.84[a]
Elm, Switzerland	10.0	0.31
Madison Canyon, Montana, U.S.A.	28.0	0.27
Frank, Alberta, Canada	30.0	0.25
Gros Ventre, Wyoming, U.S.A.	38.0	0.17
Blackhawk, California, U.S.A.	280.0	0.13
Sawtooth I, Montana, U.S.A.	370.0	0.24
Flims, Switzerland	12,000.0	0.13

[a]"Normal" large landslides.

viscous flow and basal sliding describe modes of deposition that inadequately account for the morphology of the Summit Lake slide, and indicates that high-energy processes, such as those listed above, must have increased the mobility and strength of the landslide debris. Physical properties of the Summit Lake landslide can be estimated only crudely, however. If we assume that the landslide behaved primarily as a debris flow, then the internal shear strength (k) of a plastic or Bingham material at the distal part of the landslide base when it stopped moving may be calculated by the Johnson (1984) equation:

$$k=T_c d_d \sin\delta \qquad (1)$$

where T_c is the critical thickness, d_d is the debris density, an δ is the slope angle of debris surface.

Assuming that T_c=40 m for the lower part of the slide, $d_d=2.0\times10^3$ kg/m^3 (as estimated from dry clods of debris; original moisture content is, of course, unknown), and δ=4.5°, then $k=6.3\times10^3$ kg/m^2. The internal shear strength of debris flows ranges from about 3×10^1 to 2.5×10^3 kg/m^2 (Johnson, 1984).

If the slide behaved like a Mohr–Coulomb material, the coefficient of friction along the slide base may be estimated if cohesion is assumed to be negligible:

$$\tau=\sigma \tan \phi \quad (2)$$

where τ is the internal shear strength ($=k$, eq. 1), σ is the normal stress ($=T_c d_d$, eq. 1), and ϕ is the angle of internal fraction.

Using the same input values as before, $\phi=0.079$. The angle of internal friction of noncatastrophic debris flows has been calculated at about 2 to 0.5° (Johnson, 1984). Thus, we have approximated slide debris properties assuming two end-member situations; plastic flow in cohesive material (eq. 1), and total basal sliding in material that does not flow (eq. 2). The values clearly indicate the necessity of adjunct high-energy processes acting during landslide emplacement to account for high debris strength concurrent with low friction between debris particles.

Basin evolution and overflow history

A complex drainage history for Summit Lake is suggested by the present basin closure line (1781 m), and closure defined by older landforms. The lake probably has not risen above 1787 m after the landslide was emplaced, as indicated by a lack above that level of shoreline features or any other geomorphic evidence of littoral activity. Adjacent hillslopes are mantled with colluvium, as well as stone circles and stripes of unknown age, which may have eliminated or masked any evidence of higher lake stands or fault traces.

Mahogany Creek (Fig. 7) has built a gently sloping fan-delta into the Summit Lake basin. Color infrared photos reveal several paleochannels on the fan surface that lead to Five Mile Flat, suggesting that Mahogany Creek formerly flowed directly into Five Mile Flat and thence to Virgin Creek.

The course of Snow Creek also was diverted northward because the slide buried part of the older valley. Since diversion, Snow Creek also has built a fan-delta into Summit Lake. Part of the unburied pre-slide valley is adjacent to the lake.

A prominent entrenched meander at the head of the Virgin Creek overflow channel is perhaps the most enigmatic landform of the basin (Fig. 7). It may have formed when an impounded lake breached the margin of the Summit Lake basin and downcut a channel through welded pyroclastics. The lowest possible lake level for this to have occurred is at about 1817 m, a level suggested by the surface elevation of a strath terrace located 35 m downstream from the head of the overflow channel. Thus a rapid downcutting would need to total about 30 m. However, the topography suggests that this lake should have overflowed through lower passes elsewhere. The lowest paleoclosure is a col south of Summit Lake at about 1795 m, but this pass lacks any evidence of overflow. Thus we infer that the overflow channel and the 1817 m strath terrace are part of a pre-existing valley cut by Mahogany Creek, rather than having been formed by some torrential overflow event associated with the Summit Lake slide. The 1787 m shoreline level indicates that outflow from Pluvial Lake Parman further entrenched the overflow valley no more than about 6 to 8 m. Also, besides a lack of geomorphic evidence for a lake stand higher than 1787 m, the overflow channel is cut in resistant, densely-welded tuff, whereas lower cols are developed in poorly resistant, partly-welded tuff.

There is indirect evidence of relatively recent tectonic subsidence on the order of 35 m in the Summit Lake basin. If the previous argument is accepted for the genesis of the overflow channel, subsidence must be invoked to account for the absence of a valley wall extending across Five Mile Flat between the present canyon mouth of Mahogany Creek and the overflow channel. The time of subsidence is totally indeterminate, except that it is younger than the 9.4 m.y. old basalt of Catnip Creek (McKee and Marvin, 1974) which caps Rock Spring Table on the north (see Fig. 1). The re-

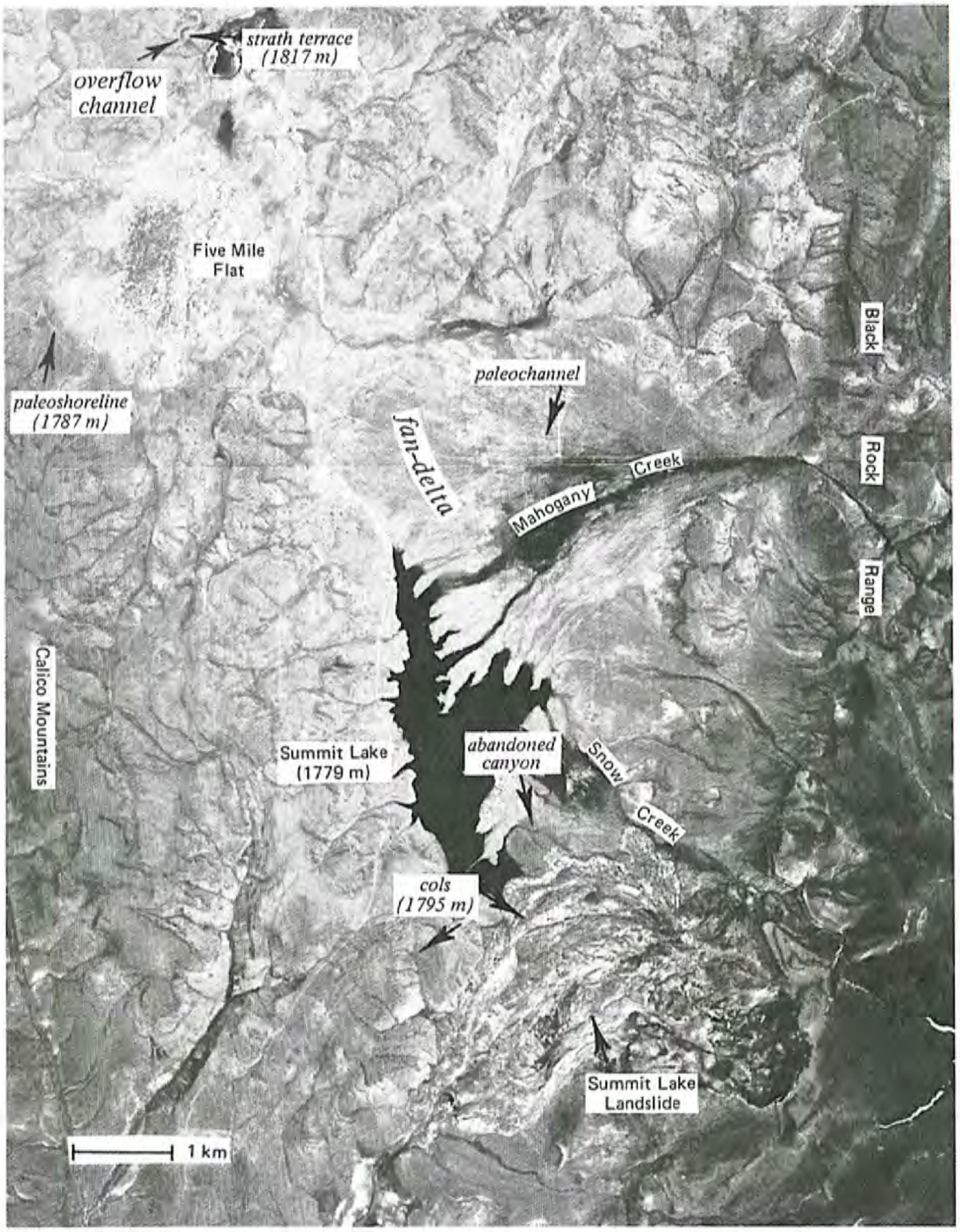

Fig. 7. Geomorphic features of Summit Lake basin. Original scale about 1 : 80,000.

lief between this latter surface and Summit Lake now is 300 m. No fault scarps are seen in the Summit Lake basin, but faults are inferred (Fig. 8), and the basin lies in a region of recurrent Holocene tectonic activity (Wallace, 1984). Additional evidence of regional tectonic adjustment includes the entrenchment of the Virgin Creek canyon downstream from Five Mile Flat and the rejuvenated appearance of other local streams, suggesting relative uplift of the Calico Mountains with respect to the regional base level. Alluvial fans that extend westward into the Summit Lake basin also suggest an uplift along range front faults of the

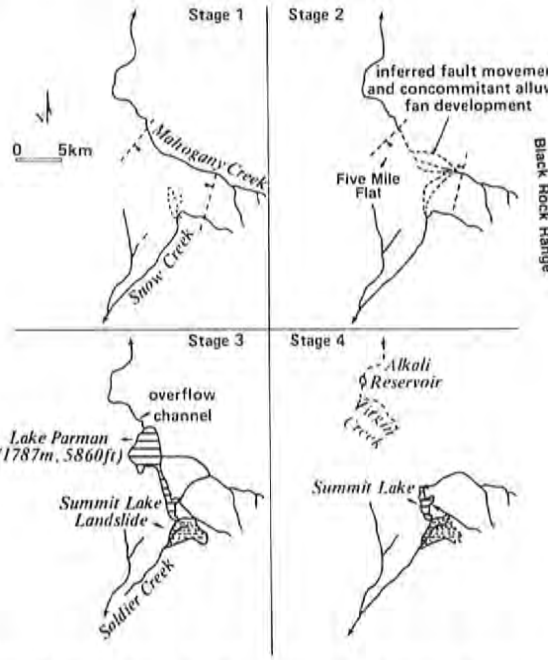

Fig. 8. Four-stage model of drainage history of Summit Lake basin. Stage 1: Pre-Summit Lake drainage. Stage 2: Basin subsidence, severing of Mahogany Creek from Virgin Creek drainage. Stage 3: Mahogany Creek diverted to Lahontan basin, followed by landslide. Stage 4: Present relation of landslide, Summit Lake, and external drainages.

Black Rock Range relative to the basin (see for example, Fig. 4).

Before the Summit Lake landslide occurred, Snow Creek probably flowed south into Soldier Creek. The abandoned canyon in bedrock forms the southern, deepest part (about 15 m) of Summit Lake (Vigg, 1983) and thus extends the canyon trace southward.

From the preceding discussion, a scenario is proposed for the development of the basin (Fig. 8). Stage 1 shows the pre-Summit Lake drainage. Mahogany Creek flowed northwest in a valley that later became the overflow channel. As Five Mile Flat subsided relative to the overflow channel and Black Rock Range, Mahogany Creek responded by building an alluvial fan (Stage 2). As the fan lengthened by progradation, at some point in time the master distributary of Mahogany Creek was severed from Virgin Creek and flowed south, joining Snow Creek, Soldier Creek, and possibly Lake Lahontan. Owing to non-resistance of the tuff of Trough Mountain and the fault juxtaposed lower pyroclastic sequence in the soon-to-landslide area, valleys were deeply excavated and slopes oversteepened, setting the stage (under pluvial conditions?) for initiation of the Summit Lake slide. Pluvial Lake Parman then filled to about 1787 m and overflowed through the abandoned canyon cut earlier by Mahogany Creek (Stage 3). Downstream overflow incision was no more than 8 m. Subsequent desiccation shrank the lake to the present 1779 m level (Stage 4). We emphasize that no specific age or time span is assigned to Stages 1 and 2; the age of the landslide is discussed subsequently, and Stage 4 is the present basin.

The ratio of the maximum pluvial lake area and tributary area of the basin (pluvial hydrologic index of Mifflin and Wheat, 1979) is low (0.13) compared with adjacent enclosed basins, including High Rock Lake basin (0.20), which overflows to the Lahontan basin under favorable conditions (Curry, 1984). This indicator, together with an overall higher basin and tributary elevation than adjacent basins, suggests that Pluvial Lake Parman may have overflowed several times during the late Pleistocene and Holocene. Indeed, during moist conditions between 1980 and 1984, the lake surface expanded 7.7%. Overflow into Five Mile Flat was perennial during this time.

Landslide age estimates

Organic carbon accumulation in relict and buried soils

The minimum age of the landslide may be estimated by determining the rate of organic carbon accumulation in the Mazama Bed (such as at Site X) and then estimating the age of any subjacent buried soils by applying that rate to the carbon accumulated. The age of the slide then is simply the age of the Mazama Bed soil

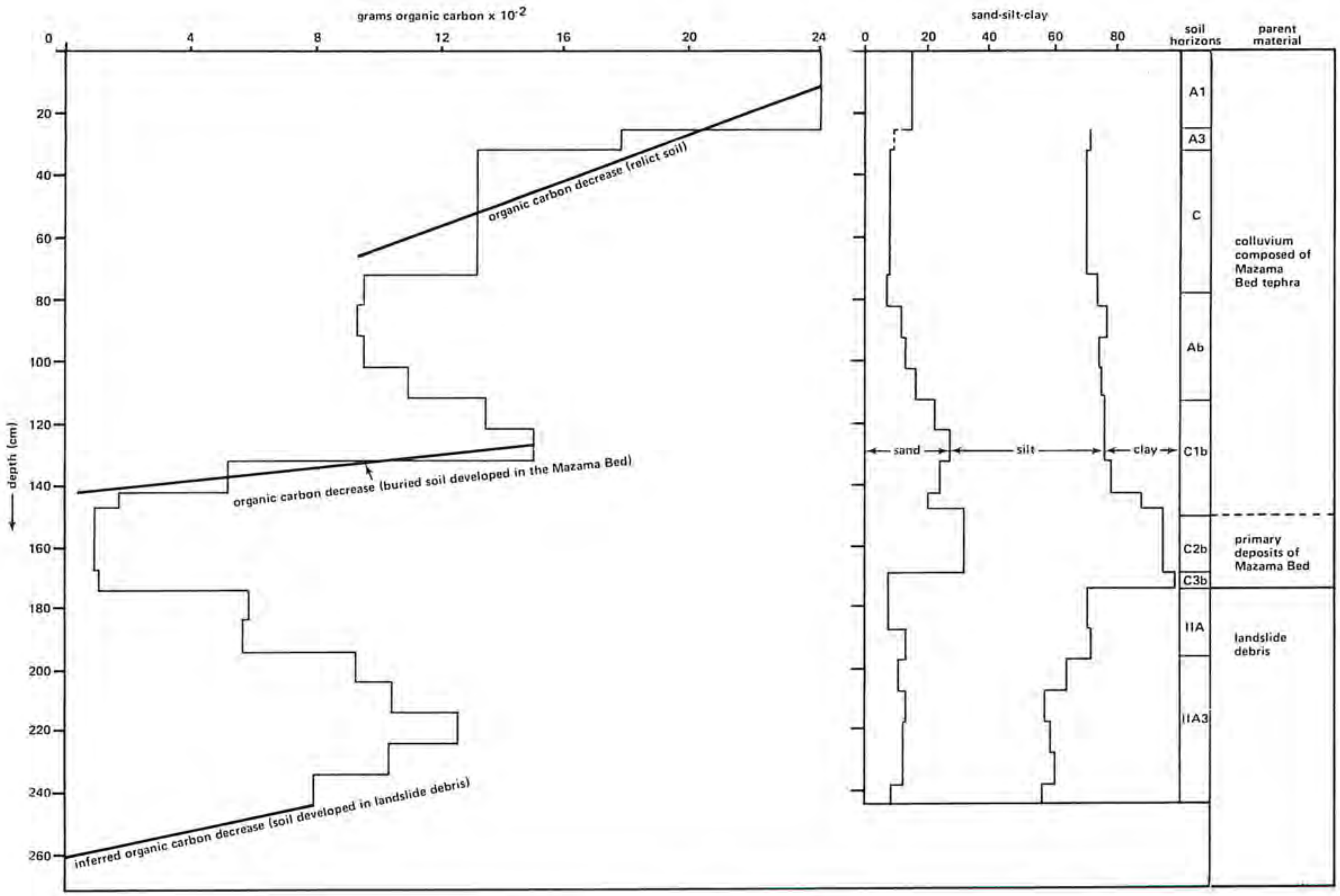

Fig. 9. Organic carbon accumulation in a 1 cm wide column for each horizon (left), particle size data (center), and soil horizons parent material (right) for soil pit at Site X.

TABLE 4

Calculation of soil and minimum landslide age using organic carbon accumulation

Total organic carbon weight in 1 cm wide column extending through profile developed in primary and colluvial Mazama Bed tephra is 2.054 g, and buried soil developed in fine-grained colluvium is 0.696 g (Curry, 1984).

Minimum landslide age is:

6800	Mazama Bed age
+2300	age of buried soil if accumulation rate is 0.302 g/100 yr[a]
9100	yr B.P.

If organic carbon from Alb–C2b horizon is used to determine accumulation rate, organic carbon weight is 0.503 g. Thus:

Minimum landslide age is:

6800	
+ 9450	age of buried soil if accumulation rate is 0.0739 g/1000 yr[b]
16,250	yr B.P.

[a]Rate of accumulation in Mazama Bed is 2.054 g/6800 yr B.P.
[b]Rate of accumulation in Mazama Bed is 0.503 g/6800 yr B.P.

plus the calculated age of any buried soils, assuming equal accumulation rates for both. The accumulation of carbon in soils, however, is not additive, owing to oxidation of carbon by organisms and other factors. Changes in soil carbon accumulation owing to changing vegetation do not appear probable, because the regional vegetation, dominated at this elevation by *Artemisia* and Graminaea, has not changed markedly for the past 10 ka (Mehringer, 1985). The amount of carbon in the depression soils may be chiefly a function of sediment input (rate of burial), assuming constant rates of organic carbon production and oxidation; the greater the rate, the more organic carbon may be preserved as it is buried below the uppermost, most biologically active part of the soil.

An aberrant flux of added carbon also is possible as a result of range fires or activity of organisms, especially introduced mammals. For these reasons, values derived from the organic method will indicate a minimum landslide age only.

Figure 9 shows changes in organic carbon accumulation for soils at Site X in a 1 cm wide column for each horizon with depth. Two zones of maximum organic carbon content occur above the Mazama Bed. Particle size analysis suggests that the lower maximum is a buried A horizon that is overlain by 1.2 m of colluvium. Petrographic and microprobe studies show that this latter material is reworked Mazama ash. Because the slope was probably already contained organic matter, establishing a valid rate of organic carbon accumulation is problematical for this site, but if the assumptions made in Table 4 about minimum and maximum accumulation rates are used, the landslide age is calculated to range from 9100 to 16,250 yr B.P.

Archaeology

Layton (1970) describes crude projectile points found on the highest, abandoned shorelines of Pluvial Lake Parman in Five Mile Flat. This collection establishes a "type Parman" typology. This point type also was recovered from a cultural stratum in Last Supper Cave, a rock shelter along Hell Creek, a major tributary to Virgin Creek, 19 km northwest of the study area. Four radiocarbon dates on charcoal and shell encased in the stratum establish a ca. 8700 yr B.P. age for Parman typology (Sheppard and Chatters, 1976; Valestro et al., 1978). This suggests a near equivalent age for the highest stand of Pluvial Lake Parman and establishes a minimum age for the landslide.

Trout evolution

Especially interesting as adjunct lines of investigation are biochemical and morphological comparisons of isolated populations of *Salmo clarki henshawi* (Lahontan cutthroat trout). These trout are the only native species in Summit Lake (Loudenslager and Gall, 1980); apparently they became isolated from Lake Lahontan basin in Mahogany Creek upstream of the landslide, and later became established in Summit Lake. The present race in Summit Lake morphologically more resembles trout living in sub-basins and tributaries of former Lake Lahontan than the subspecies *S.c. alvordensis* and *S.c. smithi* which inhabit tributaries of Alvord basin (Behnke, 1986), although all three subspecies appear related genetically (Tol and French, 1988).

It is not clear when and by what route salmonids became established in Great Basin lakes from ancestral stock in the Snake River system (Hubbs and Miller, 1948; Loudenslager and Gall, 1980). Recent investigations by David Lindberg (pers. commun., 1989) indicate a pluvial hydrologic connection between Virgin Creek (Alvord Lake–Lake Coyote basin) and Crooked Creek (Owyhee River–Snake River basin; Fig. 10). Thus, pre-landslide drainage (Stages 1 and 2, Fig. 8) and pluvial conditions would have allowed fish migration from the Lake Alvord to Lake Lahontan basins via shifting distributaries of the Mahogany Creek fan.

Estimates of time required for divergence of allopatric populations of fish have not, as far as we are aware, previously been considered by geomorphologists as a possible means of attempting to date the timing of catastrophic events. Fisheries biologists have tried to use electrophoretic identity scores of proteins to estimate such time divergence (Shaklee et al., 1982). Using the electrophoretic data of Loudenslager and Gall (1980), as determined from the protein identity relationship of Nei (1971), we estimate reasonable isolation ages of disjunct populations of *S.c. henshawi* that range from 3.2 ka to 17.2 ka.

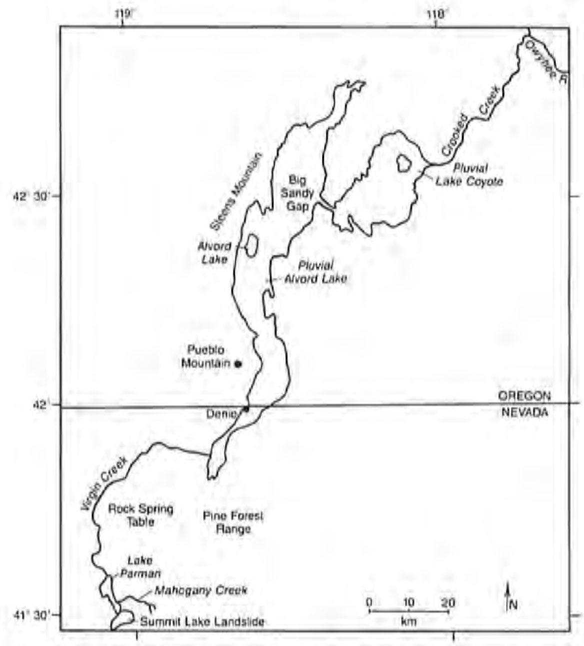

Fig. 10. Pluvial connection between Lake Parman, Virgin Creek, Alvord Lake, and Lake Coyote (Alvord basin) with Crooked Creek and Owyhee River (Snake River basin). Shoreline data for the Oregon lakes provided by David Lindberg.

Comparison of morphological traits also may be used. Behnke (pers. commun., 1988) reports that Summit Lake trout morphologically resemble other *S.c. henshawi*, but average an additional gill raker (25 versus 24); additional gill rakers are an adaptive trait in lacustrine environments. Behnke, from data derived by comparing cutthroat trout populations in Yellowstone Lake, Wyoming and Trappers Lake, Colorado with related river populations, believes that this adaptation may require about 6 to 8 ka of lacustrine trout evolution, a length of time consistent with other evidence presented here.

The historical scenario described in this paper therefore is consonant with an ancient trout

TABLE 5

Summary of minimum age determination methods, Summit Lake landslide

Method	Materials studied	Results
Radiocarbon analysis	Organic carbon in colluvial soils	7840±310 (ISGS – 1701) and 6720±90 yr B.P. (ISGS – 1210)
Tephrochronology	Tephra deposited in depression	Tephra correlated landslide with Mount Mazama Tephra Bed (6800 yr B.P.)
Artifact typology	Projectile points scattered on high-level Lake Parman strand, Five Mile Flat	Correlated with artifacts associated with charcoal and shell (^{14}C age ca. 8700 yr B.P.) in Last Supper Cave
Organic carbon accumulation in relict and buried soils	Relict soil (developed in buried soil (developed in subjacent colluvium)	Between 9100 and 16,250 yr B.P.

spawn migration from Alvord basin up Virgin Creek and Mahogany Creek. This connection was later broken, allowing trait divergence of *S.c. henshawi* in the Lahontan basin and *S.c. alvordensis* in the Alvord basin. As the Summit Lake basin subsided, shifting distributary channels of Mahogany Creek gave access connection to Lahontan basin. Migrating spawn later were severed from the Lahontan basin by the Summit Lake landslide, and became restricted to Mahogany Creek and Summit Lake. Tol and French (1988) suggest a different scenario; namely, that Alvord trout evolved in Virgin Creek and Alvord basin from overflow of Summit Lake. We concur with this possibility, but believe our hypothesis better explains regional dispersal in terms of the probable geologic events.

Conclusions

Mahogany Creek flowed northwestward to Virgin Creek, in an entrenched canyon typical of regional streams, during early development of the Summit Lake basin. As the present Five Mile Flat and Summit Lake basin tectonically subsided relative to the Black Rock Range, the outflow to Virgin Creek was severed. The now-shortened creek terminated at the newly enclosed basin and begun to build a prograding alluvial fan adjusted to the new base level. At some time during fan progradation, the master distributary shifted southward to join the flow of Snow Creek and Soldier Creek, and thus discharged ultimately into the Lahontan basin. This diversion and the resultant increased flow across easily eroded pyroclastic rocks increased downward incision, accompanied by slope instability which, in response to changing climates, may have caused the Summit Lake landslide sometimes between 7840 and 19,000 yr B.P., possibly during the 12,500 yr B.P. pluvial maximum of Lake Lahontan (Thompson et al., 1986). Afterwards, Pluvial Lake Parman filled to a level of about 1787 m, and at times overflowed into the canyon earlier cut by Mahogany Creek. Later desiccation shrank Lake Parman into the closed basin of Summit Lake.

Table 5 summarizes various estimates of the minimum age of the Summit Lake landslide. Tephrochronology and two radiocarbon dates establish that the slide was deposited between 7840 and 19,000 yr B.P.; correlation of artifact typology between Five Mile Flat and Last Supper Cave suggests a minimum age of ca. 8700 yr B.P. Age estimates from soil data are less conclusive, but fall within the range indicated by tephrochronology. Divergence time determined by seriological and morphological characteristics of trout populations (3.8 to 17.2 ka) also is in reasonable agreement with the other estimates.

A delicate hydrologic balance still exists. During abnormally wet years, the present Summit Lake spills at times into normally desiccated Five Mile Flat during the late spring and early summer, indicating that a relative short duration but high magnitude increase in local discharge could temporarily restore outflow of Summit Lake into Virgin Creek.

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