

Timing of Late Quaternary Glaciations in the Western United States Based on the Age of Loess on the Eastern Snake River Plain, Idaho

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The most viable sources for ubiquitous loess deposits on the eastern Snake River Plain, Idaho are aggraded river valleys, active alluvial fans, and fluctuating pluvial lake margins associated with regional late Pleistocene glaciation of the northern Rocky Mountains. Stratigraphic studies on the Idaho National Engineering Laboratory document two distinct loess deposits, separated by a well-developed paleosol, resting on basaltic lava. Baked sediments beneath this lava yielded thermoluminescence (TL) age estimates of $108,000 \pm 13,000$ and $101,000 \pm 7,000$ yr, and baked organic matter gave radiocarbon ages of $>32,000$ yr B.P., consistent with an earlier K/Ar age for the flow of $95,000 \pm 25,000$ yr. The overlying two loess deposits yielded TL age estimates of $74,000 \pm 6,000$ and $28,000 \pm 3,000$ yr. The available geochronology indicates that the latest period of loess deposition commenced ca. 40,000 to 35,000 yr ago and ceased approximately 10,000 yr ago, which is generally coincident with the inferred timing of regional Pinedale glaciation and pluvial lake expansion. We estimate that the penultimate loess depositional episode dates between 80,000 and 60,000 yr ago, which is significantly younger than previous age estimates of 140,000 to 150,000 yr based on stratigraphic position. We speculate that this period of loess deposition may correlate with documented early to middle Wisconsinian glaciation and a high stand of pluvial lakes in the Basin and Range province. ©1993 University of Washington.

INTRODUCTION

Quaternary lava flows dominate the landscape of the Snake River Plain, Idaho. Vast areas of these basaltic flows are covered by eolian sediments, predominately loess. The greatest areal distribution of loess occurs in proximity to the Snake River and its tributaries, a presumed source of eolian silt (Scott, 1982). During the last regional glaciation (ca. 30,000 to 10,000 yr ago) this fluvial system aggraded to a higher base level, with exten-

sive floodplains and numerous active alluvial fans emanating from drainages in the adjacent mountain ranges (Pierce and Scott, 1982). These fluvial and alluvial surfaces were probably optimal sources for eolian particles. An additional source of eolian sediment on the Snake River Plain may have been the fluctuating margins of pluvial lakes Terretton and American Falls (Scott, 1982). These lakes covered large areas (100s of km^2) on the Snake River Plain during the last glaciation and probably earlier stadial intervals (Stearns *et al.*, 1939; Nace *et al.*, 1979; Scott 1982). Although the exact origin of Pleistocene loess on the Snake River Plain remains partially unresolved, the available evidence indicates that the aggraded valleys, alluvial fans, and pluvial lake margins that existed during glaciation were the most viable sources. There is compelling evidence from a well-dated moraine sequence of the Yellowstone Plateau, Wyoming (Richmond, 1986) for at least four glacial episodes in the last 150,000 yr, which like the latest glacial event, may have been associated with regional loess deposition. The stratigraphic record of loess deposition on the Snake River Plain therefore may be an important proxy for deciphering the timing and duration of glaciations in the Rocky Mountains.

Expansion of pluvial lakes in the Basin and Range province is hypothesized to reflect changes in jet stream position forced by the maximum elevation of the Laurentide Ice Sheet (Benson and Thompson, 1987). Climate-model simulations for the last glaciation show the mean position of the jet stream displaced southward over the western United States, resulting in a substantial increase in winter precipitation and annual cooling (Kutzbach and Wright, 1985). This atmospheric circulation pattern is believed to have led to a rise in pluvial lake levels and also would have been conducive for the growth of mountain

glaciers. This paleoclimatic reconstruction implies that the expansion of the Laurentide Ice Sheet, mountain glaciers, and pluvial lakes in the intermountain western United States should be generally synchronous. Detailed geochronologic studies of loess deposition and other proxy climatic sequences in the western United States are needed to test this hypothesis.

Previous stratigraphic studies in southeastern Idaho have documented two loess deposits separated by a well-developed paleosol (Pierce *et al.*, 1982). We identify a similar loess stratigraphy on the eastern Snake River Plain. The uppermost eolian silt, designated loess A, is believed to have been deposited between 70,000 and 10,000 yr B.P. principally based on limiting K/Ar ages of underlying volcanic deposits and the relation of this loess to Bonneville Flood deposits. The second loess, "B", lies below a prominent buried soil, but its age is not well defined and the loess is inferred to correlate with glacial deposits of Bull Lake age having an assumed age of 140,000 to 150,000 yr (Pierce *et al.*, 1982).

An outstanding question is the age of the last two loess sheets deposited on the Snake River Plain during the late Quaternary. Without a secure chronology for the loess and soil stratigraphy in southeastern Idaho it is not possible to understand the relation between eolian deposition, fluctuations of mountain glaciers, and variations in pluvial-lake level during the late Pleistocene. We report five thermoluminescence (TL) and two radiocarbon age estimates from the eastern Snake River Plain, within the boundary of the Idaho National Engineering Laboratory (Fig. 1), that provide new insight on the chronology of loess deposition and additional criteria for evaluating the timing of glacial and interglacial intervals in the western United States.

STRATIGRAPHIC FRAMEWORK

Two excavations on the Idaho National Engineering Laboratory provide superb exposure of the loess stratigraphy of the eastern Snake River Plain (Figs. 2 and 3). These excavations expose a complex sequence of loess, buried soils, and basaltic lavas that is probably widespread on the eastern Snake River Plain. The excavation at site 1 penetrates the loess cover and exposes underlying basaltic lavas (Fig. 2). The lowest unit at this site is a late Quaternary basaltic lava (flow 2). Discontinuously overlying this basalt is reworked loess C, which thickens in a depression on the paleo-surface of lava flow 2. The upper 50 cm of this loess has been extensively baked by the overlying lava flow, evident by a strong reddish-brown color (5YR 4/2.5). The uppermost 25 cm of this baked loess is characterized by a 5- to 10-cm-thick ash zone that grades into a discontinuous dark-gray, carbonized A horizon. Samples for radiocarbon dating were taken from this A horizon and sediment was retrieved

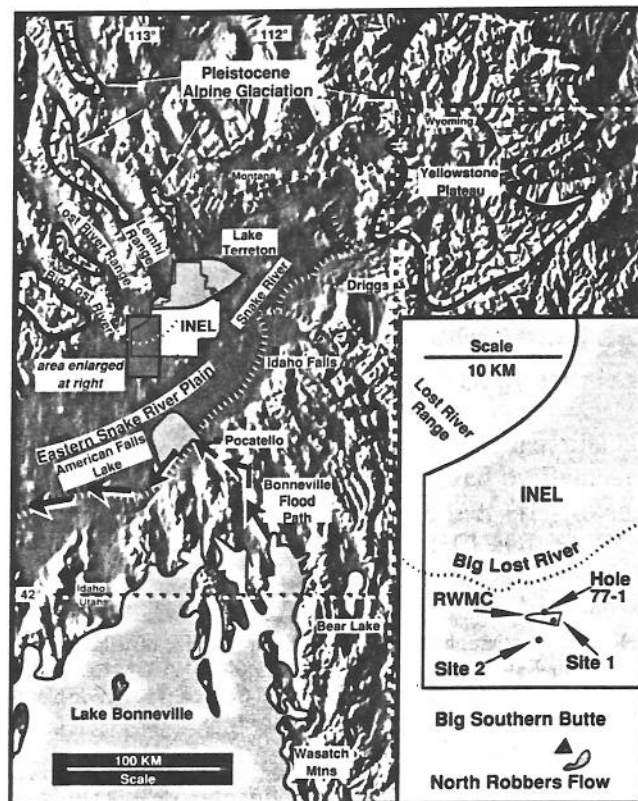


FIG. 1. Map of the Snake River Plain, Idaho, with major rivers and selected geologic features. Study sites 1 and 2 are within the boundary of the Idaho National Engineering Laboratory (INEL).

immediately below the A horizon in the baked loess for TL dating.

Loess B overlies flow 1 and is interpreted as a primary airfall loess with some minor colluvial reworking. This loess sheet buried lava flow 1 and parallels the present topography. Developed in the top 1.5 m of the loess is a prominent buried soil that may have been truncated during excavation. This buried soil is characterized by a Bt horizon with abundant clay cutans exhibiting a maximum clay concentration of 32 to 36% (Fig. 2). The lowermost ca. 50 cm of loess B, below the buried Bt horizon, is pedogenically little altered and was sampled for TL analysis. The upper 1 to 1.5 m at this site is either covered or apparently disturbed by excavation activity, which presumably has removed the record of the last period of loess deposition.

Although playa deposits are mapped in the vicinity (Scott, 1982) excavations at site 2, on an interfluvial, expose two loess units separated by a well-developed paleosol, which represent the last two major intervals of eolian deposition (Fig. 3). The base of lower loess B was determined by hand augering and was not exposed for TL sampling. The lower paleosol in loess B consists of a composite Bt horizon (24% clay and abundant clay cutans) and represents a prolonged period of pedogenesis, possibly exceeding 20,000 yr (cf. Lewis and Fosberg,

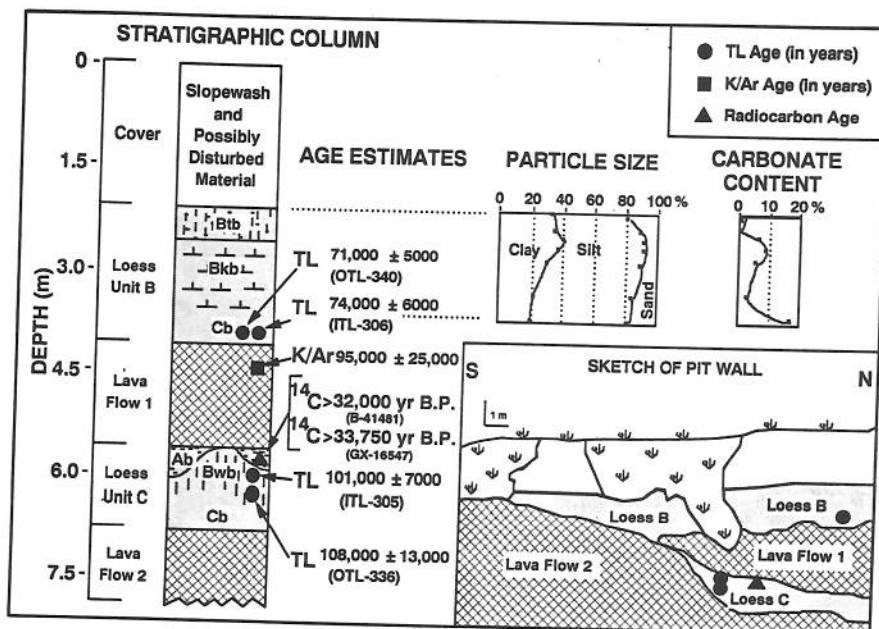


FIG. 2. Stratigraphy, age estimates, particle-size distribution, and carbonate content of loess and basaltic lava flows at site 1, Idaho National Engineering Laboratory, Idaho (43°30'N; 113°02'W: T.2 N.R. 29 E. Sect. 18; Big Southern Butte, 7.5' quadrangle). The uppermost flow is from core 77-1 retrieved from ca. 550 m north of the site 1 (Champion *et al.*, 1981). A K/Ar age (1 σ error) for the limit of the Bw and Bt horizons, respectively.

1982; Pierce *et al.*, 1982). Overlying this paleosol is loess A with an included buried soil. The paleosol in loess A is less well developed than the Holocene surface soil and exhibits a weak Bw horizon (Fig. 3); thus, it probably formed in <10,000 yr (cf. Lewis and Fosberg, 1982). This buried soil represents a slight decrease in the rate of loess deposition and (or) a modest increase in the rate of soil development. During the initial excavation at this site, only the loess above this weak paleosol was adequately exposed for sampling. TL age estimates from this level provide a close, but minimum, estimate on the beginning of the last interval of loess deposition. The lower loess at site 2 is tentatively correlated to loess B at site 1 (Fig. 2) based on stratigraphic position, general similarities in paleosol morphology, and mapped continuity of the underlying lava flows (Qbb flow: Kuntz *et al.*, 1990).

GEOCHRONOLOGY

Ages for the basaltic lavas at site 1 were previously determined by whole rock K/Ar dating of core 77-1 retrieved approximately 550 m north of the studies exposure (Champion *et al.*, 1981). The uppermost flow (flow 1) yielded a single K/Ar age of $95,000 \pm 25,000$ yr (1 σ error) and the two subjacent flows gave ages of <200,000 and <190,000 yr, respectively. Paleomagnetic determinations and K/Ar ages of these and lower basalt flows indicate that the flows were emplaced in the Brunhes Chron and after the Big Lost River Polarity Subchronzone at 0.586 ± 0.014 myr (Champion *et al.*, 1981, 1988). The lack of a noticeable hiatus (i.e., pedogenesis) be-

tween the three upper flows indicates that they were probably deposited in <10,000 yr.

The TL method was applied to baked and unbaked loess at the two sites to provide more-detailed chronologic control on loess deposition and on the emplacement of the uppermost lava flow (1). The TL signal of these sediments was reset by two different agents, conductive heating from the emplacement of a lava flow and light exposure during eolian transport. The emplacement temperature at the base of a basaltic lava flow is approximately 1100 to 1200°C, with the 400°C isotherm penetrating (for flows >2 m thick) to at least 1 m depth into the

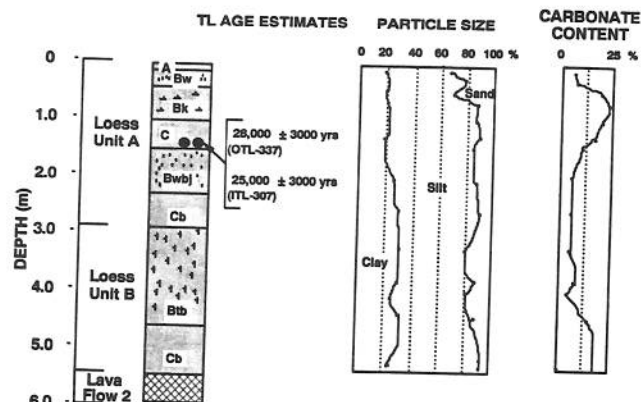


FIG. 3. Stratigraphy, age estimates, particle-size distribution, and carbonate content of loess at site 2, Idaho National Engineering Laboratory, Idaho (43°30'N; 113°02'W: T.2 N.R. 29 E. Sect. 19; Big Southern Butte 7.5' quadrangle). Vertical and crossed lines represent the limit of the Bw and Bt horizons, respectively.

subjacent sediment (G. Valentine, written communication, 1991). Loess C beneath lava flow 1, at site 1, was sampled 20 to 30 cm below the sediment/basalt contact, insuring adequate thermal resetting of the TL signal and uniform dosimetry. Heating to $>400^{\circ}\text{C}$ is exceptionally effective in resetting the TL signal, leaving no remnant signal (Aitken *et al.*, 1968). TL analysis of baked loess C dates the emplacement of the overlying lava flow 1. The other dated sediments, above lava flow 1, are primary airfall loess. The TL signal of these sediments, prior to deposition, was reset by direct exposure to sunlight. TL analysis of these sediments provides an estimate of the time since the deposition of loesses A and B. The solar resetting of the TL signal is less efficient than heating, but almost equally effective, with most of the TL signal eliminated after 8 hr of light exposure (Wintle and Huntley, 1980; Forman, 1991).

Two separate analysis are needed to calculate a TL age estimate. The first determination is the equivalent dose, which is a measure of how much ionizing radiation (in grays) the sediment has been exposed to during the burial period to yield its current TL signal. The second analysis is the dose rate (grays/1000 yr), which is an estimate of the environmental radioactivity during the burial period. The equivalent dose was determined on the polymineral fine-grained (4–11 μm) fraction by the total-bleach method (Table 1) as discussed by Forman (1989, 1991). Specifically, additional doses were applied to the natural TL signal by a series of extended radiations with a cali-

brated $^{90}\text{Sr}/^{90}\text{Y}$ source. The highest radiation added onto the natural TL signal was at least five times the calculated equivalent dose (Fig. 4). Both ultraviolet and blue TL emissions were measured for one of the older samples, OTL340, and yielded TL age estimates that overlap at 1σ (Table 1). This analysis indicates that ultraviolet emissions from these sediments do not yield underestimates as was documented with other sediments (Balescu *et al.*, 1992). The dose rate estimate is derived from the uranium and thorium content, as determined by alpha counting (assuming secular equilibrium), and the ^{40}K level, calculated from the potassium content assayed by atomic absorption spectrophotometry (Table 2).

Portions of one sample of baked organic material collected from beneath flow 2 were analyzed by Beta Analytic Inc. and Geochron Laboratories Inc. Prior to analysis these samples were soaked in HCl and NaOH to remove contaminants. The beta activities for these samples are not statistically above background levels (H.

TABLE 1

Thermoluminescence Data and Age Estimates by the Total Bleach Method for Samples from Sites 1 and 2, Idaho National Engineering Laboratory, Idaho

Sample number	Stratigraphic unit	Temperature ^a ($^{\circ}\text{C}$)	Equivalent dose ^b (grays)	TL age estimate (10^3 yr) ^d
ITL305 ^c	Loess unit C	270–400	468.8 ± 17.6	101 ± 7
ITL306	Loess unit B	280–400	397.6 ± 24.5	74 ± 6
ITL307	Loess unit A	270–400	139.8 ± 12.8	25 ± 3
OTL336 ^c	Loess unit C	270–400	513.2 ± 69.0	108 ± 13
OTL337	Loess unit A	260–360	141.9 ± 15.9	28 ± 3
OTL340	Loess unit B	250–400	352.5 ± 5.98	71 ± 5
OTL340b	Loess unit B	240–390	322.2 ± 4.00	79 ± 6

^a Temperature range used to calculate equivalent dose.

^b TL measurements were made with a Schott UG-11 (UV) and HA-3 filters in front of the photomultiplier tube, except analysis of OTL340b, which was preformed with Corning 5-58 (blue) and HA-3 filters. Samples were preheated to 150°C for 16 hr prior to analysis and no anomalous fading was detected within an analytical resolution of 10% after heating and storage for at least 28 days.

^c These samples are baked loess beneath lava flow 1 with the residual TL level defined by heating to 450°C . The residual level for the remaining three samples of airfall loess was defined by exposure to sunlight for 16 hr.

^d Errors are at 1σ and weighted for the variance in the equivalent dose values across the designated temperatures.

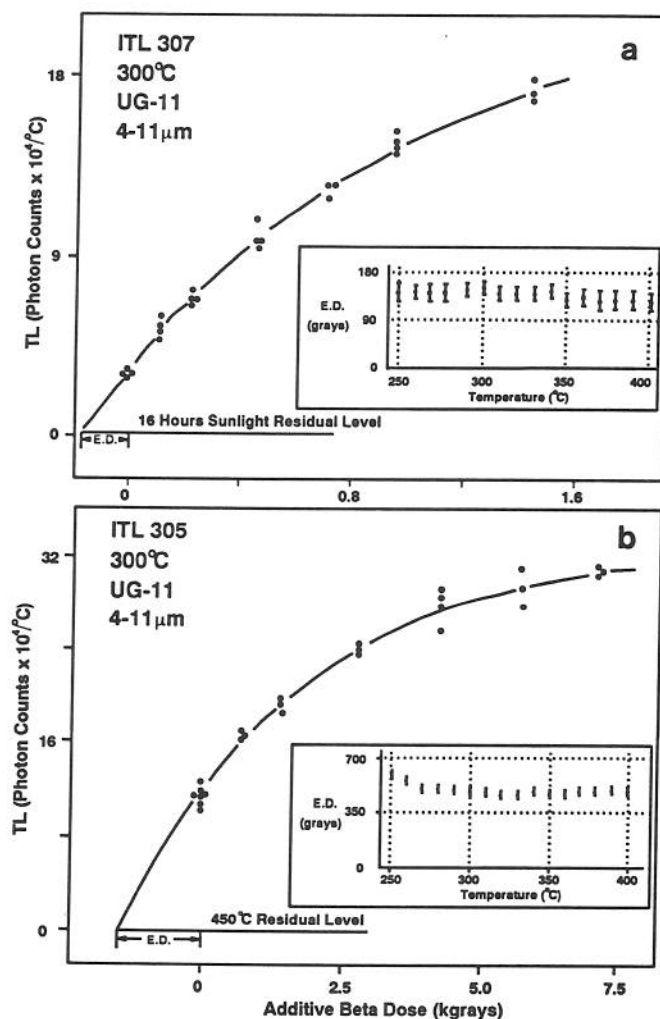


FIG. 4. Additive-dose plots for loess samples ITL307 (a) and ITL305 (b) from southeastern Idaho. Inset figures show equivalent-dose values for a range of temperatures.

TABLE 2

Dose Rate Data for Samples from Sites 1 and 2, Idaho National Engineering Laboratory, Idaho

Lab sample number	Bulk alpha count rate (ks/cm ²)	Unsealed/sealed ^a	%K ^b	A value ^c	Dose rate (gray/10 ³ yr) ^d
ITL305	0.68 ± 0.01	0.99	2.14 ± 0.02	0.10 ± 0.02	4.82 ± 0.35
ITL306	0.72 ± 0.01	0.99	1.91 ± 0.01	0.15 ± 0.01	5.37 ± 0.40
ITL307	0.75 ± 0.02	0.97	1.88 ± 0.02	0.15 ± 0.04	5.59 ± 0.38
OTL336	0.66 ± 0.01	0.96	2.16 ± 0.02	0.10 ± 0.01	4.75 ± 0.38
OTL337	0.72 ± 0.01	1.00	2.01 ± 0.02	0.11 ± 0.01	4.99 ± 0.40
OTL340	0.72 ± 0.01	0.98	1.63 ± 0.02	0.12 ± 0.01	4.45 ± 0.32
OTL340b	0.72 ± 0.01	0.98	1.63 ± 0.02	0.07 ± 0.01	4.08 ± 0.29

^a Ratio of bulk alpha count rate under sealed and unsealed counting conditions. A ratio of >0.95 indicates little or no radon loss.

^b % Potassium determined by atomic absorption spectrophotometry after digestion in HF.

^c The measured alpha efficiency factor as defined by Aitken and Bowman (1975).

^d Dose rate value includes a contribution from cosmic radiation of 0.14 ± 0.01 gray/1000 yr and assuming a moisture content of $10 \pm 3\%$ and secular equilibrium of U and Th. All errors are at 1 σ .

Kreuger, Geochron Laboratories Inc., personal communication, 1991) and yield infinite radiocarbon ages of >32,000 yr B.P. (Beta-41481) and >33,750 yr B.P. (GX-16547).

TIMING OF LATE PLEISTOCENE LOESS DEPOSITION

There are a number of constraints on the timing of the last period of loess deposition on the Snake River Plain. Sediment from the middle part of loess A yielded TL age estimates of $28,000 \pm 3000$ yr (OTL337) and $25,000 \pm 3000$ yr (ITL307). A weak buried soil in loess A, directly below the TL age estimates, is believed to represent <10,000 yr of pedogenesis. Therefore, the age of the base of loess A is estimated at 40,000 to 30,000 yr. Primary airfall loess has been identified beneath the North Robbers lava Flow on the Snake River Plain (S. L. Forman, unpublished data). Previously, organic material from immediately beneath the flow yielded a radiocarbon age of $11,980 \pm 300$ yr B.P. (W-5349; Kuntz *et al.*, 1986), providing a minimum age for the underlying loess. The baked loess beneath the North Robbers Flow exhibits no soil horizonation and <0.5 m of loess was noticed on the flow surface. These observations indicate that the North Robbers Flow may have been emplaced near the end of loess deposition.

Additional age control on the termination of loess deposition is provided by the erosion of loess A by the Bonneville Flood ca. 14,500 yr B.P. (Pierce *et al.*, 1982; Benson *et al.*, 1990). Flood waters scoured the uppermost part of this loess, and <1.5 m of loess accumulated after the flood. These stratigraphic relationships indicate that the Bonneville Flood occurred near the end of loess deposition (cf. Pierce *et al.*, 1982). Organic matter from the upper part of a presumably correlative loess, covered by soliflucted loess and volcanic clasts, just west of Yel-

lowstone National Park yielded ages of $17,460 \pm 500$ yr B.P. (W-2895) and $17,480 \pm 500$ yr B.P. (W-2896), thereby providing another estimate on the latest period of loess deposition (Kelly *et al.*, 1978). The available geochronology indicates that the latest period of loess deposition commenced ca. 40,000 to 30,000 yr ago and ceased prior to 10,000 yr ago.

The new ¹⁴C and TL age estimates are stratigraphically consistent and provide needed data to evaluate the timing of deposition of penultimate loess B. This loess overlies a basaltic lava flow at site 1 which previously yielded a K/Ar age of $95,000 \pm 25,000$ yr. Baked organic matter beneath the flow yielded infinite ¹⁴C ages of >34,000 and >32,000 yr B.P.; baked sediment gave finite TL age estimates of $101,000 \pm 7000$ yr (ITL305) and $108,000 \pm 13,000$ yr (OTL336). The available geochronology suggests that this flow was emplaced $100,000 \pm 15,000$ yr ago, which provides a maximum estimated age for the deposition of loess B. The basal part of overlying loess B at this site yielded the TL age estimate of $74,000 \pm 6000$ yr (ITL306) and $71,000 \pm 5000$ yr (OTL340). We speculate that this period of loess deposition, like the late Wisconsin episode, spanned approximately a 20,000-yr interval, and we tentatively assign the age range of 80,000 to 60,000 yr ago for the deposition of loess B.

We estimate that loess deposition commenced by ca. 80,000 yr ago, which is considerably later than previous estimates of 140,000 to 150,000 yr for a presumably correlative loess (Pierce *et al.*, 1982). This older age estimate for loess B is principally derived from stratigraphic relations with glacial sediments of assumed Bull Lake age. The Bull Lake glaciation is particularly well dated on the nearby Yellowstone Plateau by K/Ar ages of 140,000 to 150,000 yr for rhyolitic lava flows that were emplaced contemporaneously with Bull Lake glacial deposits (Pierce, 1979; Richmond, 1986). A loess in west Yellowstone basin that conformably rests on kame gravels assigned to the Bull Lake glaciation has been correlated with loess B on the eastern Snake River Plain (Pierce *et al.*, 1982). A similar stratigraphic relation was also documented near Driggs, Idaho, where loess B conformably overlies an outwash of presumed Bull Lake age (Pierce *et al.*, 1982). The lack of a noticeable hiatus (soil development) between the loess and underlying glacial deposits strengthens the association of loess B with regional glaciation. However, we believe that this stratigraphic sequence is not uniquely Bull Lake in age, particularly in light of the multiple glacial events during the last 150,000 yr on the Yellowstone Plateau (Richmond, 1986).

LOESS DEPOSITION, GLACIATION, AND PLUVIAL LAKE LEVELS

We hypothesize that there were distinct episodes of significant loess deposition, separated by periods of

pedogenesis, that may be generally coincident with numerous late Pleistocene glacial episodes documented principally in the Yellowstone Plateau area (Fig. 5). The available data from the eastern Snake River Plain indicate that there were two significant episodes of loess deposition dating between ca. 80,000 and 60,000 yr ago and between 40,000 and 10,000 yr ago, separated by a period of prolonged (>20,000 yr) pedogenesis.

There is also evidence in the mountain ranges adjacent to the Snake River Plain for a number of late Pleistocene glacial events between Bull Lake time (ca. 150,000 yr B.P.) and Pinedale time (30,000 to 10,000 yr B.P.), one of which may correspond to a period of loess deposition 80,000 to 60,000 yr ago. In the Lemhi Range, adjacent to the eastern Snake River Plain, three tills have been differentiated by relative-weathering criteria and are believed to have been deposited during the late Pleistocene at 150,000, 60,000, and 25,000 yr B.P. (Butler *et al.*, 1983). A similar sequence of glacial deposits was described near McCall, Idaho, and was correlated to well-dated sequences in the Yellowstone Plateau area by relative-weathering criteria (Colman and Pierce, 1986). Other relative weathering studies of moraine sequences in the western United States have also led to the inference of a glaciation between Bull Lake and Pinedale events (Colman and Pierce, 1981; Hall, 1989). We speculate that loess deposition 80,000 to 60,000 yr ago may be correlative with the penultimate glaciation.

Perhaps the most securely dated Pleistocene glacial se-

quence in the intermountain western United States is on the Yellowstone Plateau, Wyoming. This sequence may be generally representative of Pleistocene glacier activity in the northern Rocky Mountains. The timing for the expansion of an ice-cap on the Yellowstone Plateau is provided by a series of weighted mean K/Ar ages of $117,000 \pm 8000$ yr, $117,000 \pm 6000$ yr, and $90,000 \pm 2000$ yr for rhyolitic flows that erupted against advancing glaciers (Richmond, 1986). There is also limited evidence for glacier expansion at $70,000 \pm 10,000$ yr based on the stratigraphic position of glacial-lacustrine deposits with respect to a tephra (Richmond, 1986).

The frequency of glacial events in the northern Rocky Mountains during the last 150,000 yr is somewhat mirrored in the Bloody Canyon moraine sequence in the eastern Sierra Nevada Mountains, California (Phillips *et al.*, 1990). Surface-exposure age estimates based on ^{36}Cl concentration in boulders on moraines in this canyon indicate a series of glacial events culminating ca. 120,000, 66,000, and 23,000 yr ago. However, ^{36}Cl age estimates of >66,000 yr exhibit significant scatter, the errors for the above estimates are unknown, and there remains some uncertainty as to whether these estimates represent the true age of the moraines or some time component reflecting episodes of postdepositional weathering. It is prudent to consider many of these age estimates as minima until the stability of boulders on moraines, weathering rates, and concomitant effects on ^{36}Cl concentrations are better understood.

The available data from the Snake River Plain and adjacent areas indicate that the last period of loess deposition occurred between ca. 40,000 and 10,000 yr ago. This period of loess deposition is consistent with other estimates of the duration of the Pinedale glaciation. A variety of chronologic indices indicate that a moraine sequence in the Yellowstone National Park area assigned to the last glaciation was deposited between 35,000 and 12,000 yr ago (Richmond, 1986). Timing of the last glaciation is principally derived from a radiometric calibration of the thickness of rinds on obsidian cobbles from glacial deposits and radiocarbon ages for lake sediments covered by minor readvances during deglaciation (Pierce *et al.*, 1976; Pierce, 1979; Richmond, 1986). A maximum estimate for the beginning of glaciation in the northern Wasatch Mountains, Utah, is provided by a radiocarbon age of $26,080 \pm 1200 - 1100$ yr B.P. (GX-4737) for the <125 μm organic fraction of a soil buried by a till of presumed Pinedale age near the glacial limit (Madsen and Currey, 1979). The presence of Mount St. Helens Jy ash in lake sediments near the continental divide and at lower elevations in northwestern Montana indicates that valley glaciers in this area retreated by 11,200 yr B.P. (Carrara *et al.*, 1986). Begét (1984) also concluded that glacier cover in the North Cascade Range, Washington, was similar to that at present as early as 11,500 yr B.P. Radio-

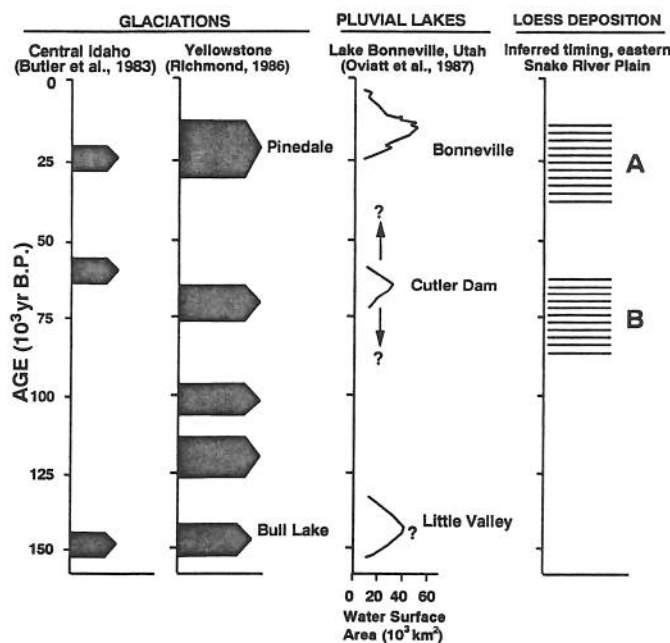


FIG. 5. Comparison of the timing of glaciations in central Idaho and Yellowstone National Park, Lake Bonneville expansion, and the provisional chronology of loess deposition on the eastern Snake River Plain, Idaho. The record of glaciations does not reflect magnitude, but rather the presence or absence of glaciers during the late Pleistocene.

carbon ages from Lake Devlin, formed by the expansion of a valley glacier on the eastern slope of the Colorado Rocky Mountains, provides one of the best estimates on timing of the Pinedale glaciation (Madole, 1986). Stratigraphically consistent radiocarbon ages for organic matter from lake sediments indicate that valley glaciers were at or near their maximum limit between 30,000 and 23,000 yr B.P. and had retreated upvalley by 15,000 to 12,000 yr B.P.

The history of pluvial lake fluctuations provides additional criteria to evaluate the timing of glacial events during the last 150,000 yr (Fig. 5). The last pluvial lake expansion in the Bonneville Basin is associated with regional Pinedale glaciation ca. 32,000 to 10,000 yr B.P. (Currey and Oviatt, 1985; Benson *et al.*, 1990). However, the high stand of this lake occurred ca. 14,500 yr B.P. during deglaciation under favorable hydrologic conditions (Benson and Thompson, 1987; Benson *et al.*, 1990). There is compelling evidence in the Bonneville Basin of northern Utah for a modest pluvial lake cycle, the Cutler Dam Event (Oviatt *et al.*, 1987), chronologically between the Little Valley (ca. 140,000 yr B.P.) and Bonneville Lake cycles (ca. 32,000 to 10,000 yr B.P.). The age of the Cutler Dam Lake cycle is not fully resolved, but a variety of chronologic indices indicate that the most probable age is between 80,000 and 40,000 yr (Oviatt *et al.*, 1987). Similar evidence exists in the Lake Lahontan basin for a large pluvial lake during this same interval. One U-Th age for tufa from the Lake Lahontan paleo-shoreline suggests that this high stand occurred $49,000 \pm 5000$ yr ago (Lao and Benson, 1988). However, this U-Th age may date a high stand late in the penultimate lake cycle, similar to the high shoreline of the last pluvial lake cycle in the western United States (Benson *et al.*, 1990).

CONCLUSIONS

There is evident for at least two distinct periods of loess deposition during the last 100,000 yr on the Snake River Plain, Idaho (Fig. 5). The latest episode of loess deposition, which commenced ca. 40,000 to 30,000 yr ago and ceased ca. 10,000 yr ago, appears to span an entire glacial/deglacial cycle and is generally coincident with the latest pluvial lake and glacial cycle in the region. The rate of loess deposition substantially decreased, and the rate of pedogenesis increased, between ca. 70,000 and 40,000 yr ago to yield a well-developed paleosol with a Bt horizon (clay cutans and >24% clay). Evidence for glacier activity on the Yellowstone Plateau during this interval is lacking (Richmond, 1986), consistent with this analysis. We estimate that the penultimate loess was deposited 80,000 to 60,000 yr ago, which is significantly younger than a previous age estimate of 140,000 to 150,000 yr based on stratigraphic position (Pierce *et al.*, 1982). We speculate that this period of loess deposition may be

broadly correlative with a documented early Wisconsinan glaciation and a high stand of pluvial lakes in the Basin and Range province (Fig. 5).

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