QUATERNARY FAULTING ALONG THE SOUTHERN LEMHI FAULT NEAR THE IDAHO NATIONAL ENGINEERING LABORATORY SOUTHEASTERN IDAHO

Mark A. Hemphill-Haley, Thomas L. Sawyer and Ivan G. Wong
Woodward-Clyde Consultants
500 12th Street, Suite 100
Oakland, CA 94607

Peter L.K. Knuepfer
Department of Geology
State University of New York,
Binghamton, NY 13901

Steven L. Forman
Byrd Polar Research Center
The Ohio State University
Columbus, OH 43210

Richard P. Smith
EG&G Idaho, Inc.
Idaho National Engineering Laboratory
Idaho Falls, ID 83415

ABSTRACT

Four exploratory trenches excavated across the Howe and Fallert Springs segments of the southern Lemhi fault in southeastern Idaho provide data to characterize these potential seismic sources. Evidence for up to three surface faulting events is exposed in each trench. Thermoluminescence (TL) and radiocarbon analyses were performed to provide estimates of the timing of each faulting event. The most recent event (MRE) occurred at: 1) about 15,000 to 19,000 years B.P. at the East Canyon trench (southern Howe segment); 2) approximately 17,000 to 24,000 years B.P. at the Black Canyon site (northern Howe segment); and 3) about 19,000 to 24,000 years B.P. at the Camp Creek trench (southern Fallert Springs segment). A Holocene event is estimated for the Coyote Springs trench (central Fallert Springs segment) based on degree of soil development and correlation of faulted and unfaulted deposits. The oldest Black Canyon event is constrained by a buried soil (Av) horizon with a TL age of 24,700 ± 3,100 years B.P. Possibly three events occurred at this site between about 17,000 and 24,000 years ago followed by quiescence. Stratigraphic and soil relationships, and TL and ^{14}C dates are consistent with the following preliminary interpretations: 1) the MRE's for the southern segments are older than those for the central Lemhi fault; 2) the Black Canyon site may share rupture events with sites to the north and south as a result of a "leaky" segment boundary; 3) temporal clustering of seismic events separated by a long period of quiescence may be evident along the southern Lemhi fault; and 4) Holocene surface rupture is evident along the central part of the Fallert Springs segment but not at its southern end; and 5) the present segmentation model may need to be revised.

INTRODUCTION

The 28 October 1983 moment magnitude M 6.9 (surface-wave magnitude M_S 7.3) Borah Peak earthquake along the Lost River fault in southeastern Idaho focused attention on the seismogenic potential of the normal faults north of the eastern Snake River Plain (ESRP). As part of ongoing seismic hazard studies for the Idaho National Engineering Laboratory (INEL), Woodward-Clyde Consultants (WCC), supported by EG&G Idaho, Inc., has undertaken a paleoseismic investigation in an effort to characterize past earthquakes along the southern Lemhi fault and to specifically estimate their magnitudes, times of occurrence and late-Quaternary recurrence. Specific objectives for this study are to estimate: (1) the displacements of the most recent two or three surface-faulting earthquakes along the southernmost two rupture segments of the fault; (2) the timing of the most recent events; and (3) the time intervals between these events for the purposes of characterizing short-term earthquake recurrence along the two segments. This information will be used to characterize the late-Quaternary rupture behavior of the southern Lemhi fault. Of concern is whether the two southern segments act independently of one another, that is, does each segment have its own "characteristic earthquake" [1] or do the segments sometimes rupture together or partially together in individual earthquakes.

A field investigation was undertaken in the spring and early summers of 1990 and 1991. Four exploratory trenches were excavated along the southern part of the fault. Two of the trenches, at East Canyon and Black Canyon, are located along the Howe segment of the fault (the southernmost segment). The Camp Creek trench is located along the southernmost portion and the Coyote Springs trench is located along the central portion of the adjacent Fallert Springs segment. Evidence for multiple surface-rupture events were exposed in each trench.

GEOLOGIC SETTING

The Lemhi fault is one of three major 140 to 150-km-long, north-northwest-striking range-front normal faults, also including the Lost River and Beaverhead faults, located north of the ESRP in the northeastern Basin and Range structural province (Figure 1).

Quaternary activity on the Lemhi, Lost River, and Beaverhead faults has reportedly been highest along their central sections and lowest at their ends [2]. This would agree with observations reported by Anders *et al.* [3] in the Swan, Grand, and Star Valleys to the south of the ESRP. This pattern of fault activity is suggested [2, 3, 4, 5] to be associated with the northeastward migration of the Yellowstone hotspot. Anders *et al.* [3] suggest that fault activity is migrating away from the Snake River Plain as a result of transient thermal influences of the hotspot that have decreased or increased lithospheric strength.

The range-front of the southern Lemhi Range rises abruptly from the Little Lost River Valley along the Lemhi fault. The front is typically linear suggesting the fault has had sufficient late Pleistocene uplift to overcome erosion. Older fan deposits have been displaced by the fault near the range front as evidenced by a discontinuous fault scarp, eroded and/or locally buried in places by younger alluvial fans. In some places where multiple displacements of the fault have occurred in deposits without subsequent alluvial deposition the preserved late-Quaternary scarp can be as high as 13 to 14 m. Typically, in the younger faulted fan deposits, the scarp is on the order of 3 m high.

The western piedmont of the southern part of the range is largely comprised of Pleistocene alluvial fans. These fans are ranked according to their relative ages based on geomorphic relations, alluvial fan surface morphology, and the degree of soil development. Numerical ages of the units were estimated, in this study, by TL analysis of loess overlying alluvial fans and from Quaternary stratigraphic studies in the region by Scott [6].

Three broadly different age units, two late Pleistocene and one Holocene, have been recognized regionally and are preserved locally. The older late Pleistocene unit might correlate with the Bull Lake glaciation, which culminated about 130 to 150 ka [7, 8]. Remnants of this unit lie along the range front as uplifted fanheads and within mountain canyons as fluvial terraces. They stand high above surrounding fan surfaces on the upthrown side of the fault, but are buried by younger deposits on the downthrown side. The latest Pleistocene unit may have been deposited during the Pinedale glaciation about 18 to 20 ka [7, 8]. It is the most extensive unit on the piedmont of the southern Lemhi Range.

There has been little Holocene deposition in the region. Associated deposits are limited to active washes, flood plains and mountain canyons and in some places as thin deposits on terraces inset into latest Pleistocene fans.

SEGMENTS OF THE SOUTHERN LEMHI FAULT

It has been suggested that the Lemhi fault can be divided into at least six segments [2, 9, 10, 11, 12, 13, 14, 15] (Figure 1). Criteria used to define distinct segments within the fault include fault scarp and range-front morphology, and structural relief [9].

The approximately 20 km-long Howe segment is the southernmost segment of the Lemhi fault. Holocene sand dunes bury the the southernmost 2 to 3 km of the scarp. The segment, as mapped by Haller [9] extends to the northwest to a location about 2 km north of South Creek; Turko [13] places the boundary farther south near South Creek. The apparent segment boundary is the South Creek block [9, 13], a large, low relief rhombic salient which extends into the valley for a distance of almost 8 km from the range front. Fault scarps within the Howe segment are located in early to middle-Pinedale deposits and are discontinuous and range from 2 to 5 m high. They occur along a single fault strand and in places are associated with a graben. Younger, inset alluvial fan deposits have eroded and, in places, buried the fault scarp. No evidence of Holocene surface rupture is apparent along the segment.

A large trench excavated in 1969 across an approximately 14 m-high scarp near Black Canyon [16] revealed a complex, multiple faulting history containing at least five faulting episodes. Malde [16] suggested that the

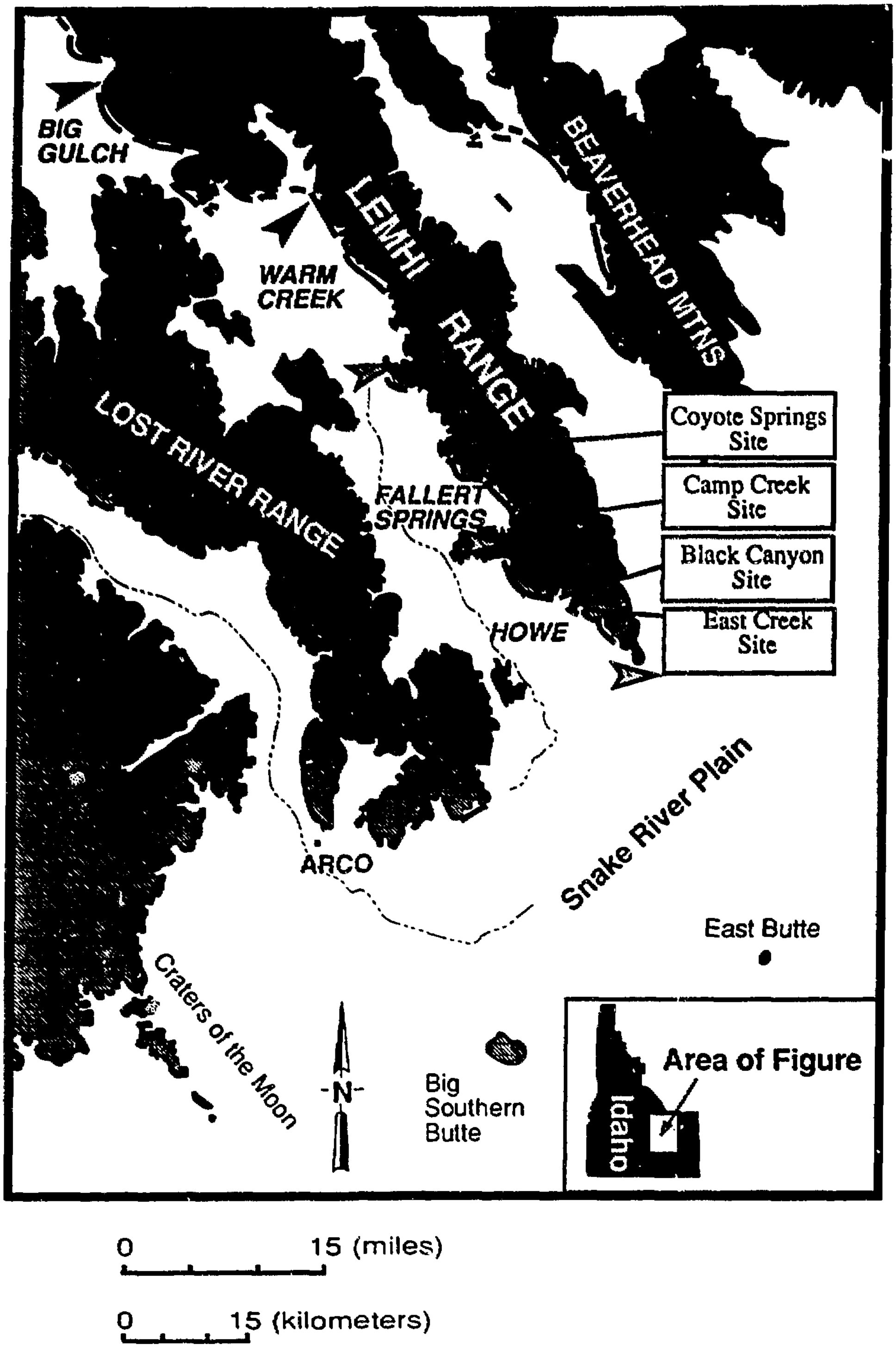

Figure 1. Map of Faults North of the Eastern Snake River Plain. Locations of Four Trenches Excavated During This Study are Also Shown.

youngest event occurred prior to 15,000 years while the oldest exposed event occurred less than 600,000 years ago.

The approximately 29 km-long Fallert Springs segment is mapped from north [9] or south [13] of the South Creek block northward to Horse Creek [9, 10, 11, 13, 14, 15]. Scarps are discontinuous and range from 5.5 to 13 m. The scarp is either buried by or inset by Holocene alluvial deposits. Late Quaternary scarps have been identified only along the southern half of the segment. Haller [9] and Turko [13] suggest that morphologic ages of the Howe and Fallert Springs segments are very similar; however, Crone and Haller [11] conclude that slightly better preserved and steeper scarps along the Fallert Springs segment represent younger faulting than along the Howe segment. Knuepfer *et al.* [14] suggest that the Howe segment has had at least five surface-rupture events in post-Bull Lake time while the Fallert Springs segment has had fewer events suggesting temporal independence between the two segments.

TRENCH DESCRIPTIONS

The following are brief descriptions of deposits and structures exposed along the Lemhi fault at four locations.

East Canyon Site

The site is located along the south-central portion of the Howe segment. The trench was excavated across a single, moderately degraded, 3 m-high fault scarp formed in early middle Pinedale (20 to 30 ka) alluvial fan deposits (age estimation based on morphologic and pedologic similarities to nearby units described by Pierce [17]). The base of the scarp is occupied by a broad (>15 m-wide), barely perceptible graben. The trench is approximately 30 m long and up to 3 m deep (Figure 2).

The northeast end of the trench comprises the footwall of the fault containing debris flow and alluvial deposits. The hanging wall is exposed in the southwest end of the trench. Alluvial gravels are overlain by two tectonic colluvial wedge deposits (see McCalpin [18] and Forman *et al.* [19] for descriptions of colluvial wedge formation). These colluvial units contain gravel, sand, and silt that grade away from the fault scarp and display a depositional fabric that dips away from the scarp. In general, each wedge represents deposition of material eroded from a rejuvenated fault scarp following a surface-rupture event.

The oldest recognizable event is represented by proximal facies colluvium (unit C-1) on the upthrown side of the exposed main shear (Figure 2). The unit truncates the upslope fan stratigraphy and is buried by younger fan deposits. Assuming this wedge formed downslope of the fault-induced scarp, the associated shear or fault zone should be located northeast of the colluvial wedge; however, no such structure was exposed in the trench. We suggest that it lies deeper than the base of the trench. The penultimate colluvial wedge (C-2) can be differentiated into a proximal facies (C-2b) and an overlying, finer-grained, carbonate-cemented (Stage III - IV), slope-wash facies unit (C-2a). The high degree of cementation might be related to a long period of stabilization. The MRE is represented by a small graben and an overlying colluvial wedge deposit (C-3). The graben is filled by a mixture of loess and colluvium (6x) derived from the primary and antithetic scarps. We interpret this graben-fill unit to be contemporaneous with the loess/colluvial unit (2x) in the headwall of the fault. In addition, unit C-3 is interbedded with unit 2x suggesting that the MRE occurred during its deposition.

Based on the presence of the three colluvial wedge sequences, at least three surface rupture events are evident in this trench with a minimum cumulative, vertical displacement of about 6 m. Minimum individual displacements are about 2 m each.

Black Canyon Site

This site is located along the northern portion of the Howe fault segment. The trench was excavated across a 4.5 m-high, multiple event scarp formed in fan deposits tentatively correlated to earliest Pinedale (30 to 40 ka) deposits of Pierce [17].

The footwall (northeast end of the trench) consists of a thick sequence of debris flow and fluvially reworked deposits (Figure 3). The base of the hanging wall exposure is comprised of alluvial fan/debris flow deposits similar to the footwall deposits. The basal strata are rotated toward the fault while overlying units are nearly horizontal. Although this rotation is probably related to a faulting event, no associated colluvial wedge could be identified. The rotated alluvial units are overlain by three colluvial wedges. The oldest colluvial wedge (C-1) contains clasts which display a scarp-parallel fabric. Colluvial wedge C-2, associated with the penultimate event, is small and was faulted during the MRE. Colluvial wedge C-3, associated with the MRE, is the largest of the three colluvial wedges. A poorly developed carbonate soil (Bk) has formed in Unit C-1. An even more poorly developed soil is present in unit C-2 suggesting that a small amount of time transpired between faulting events.

A loess/colluvium deposit (1x) overlies the entire colluvial wedge sequence indicating that the MRE occurred prior to the onset of major loess deposition, unlike the MRE of the East Canyon trench, which occurred during loess deposition.

We interpret the exposures in the Black Canyon trench to possibly represent three scarp-forming events with a cumulative vertical displacement of greater than 4.5 m based on an offset soil in unit 2x. Minimum individual vertical displacements range from about 1.5 to 1.8 m.

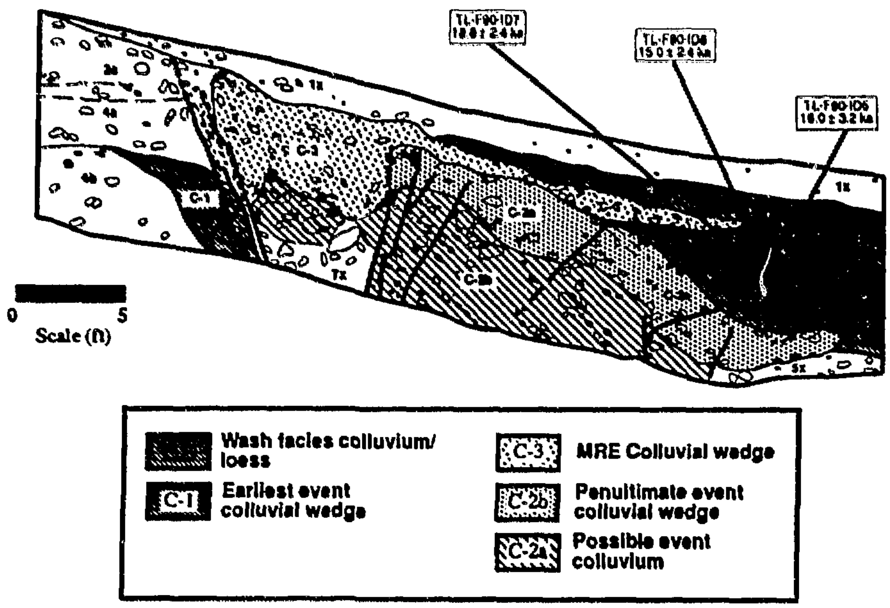

Figure 2. East Creek Trench Log, Howe Segment.

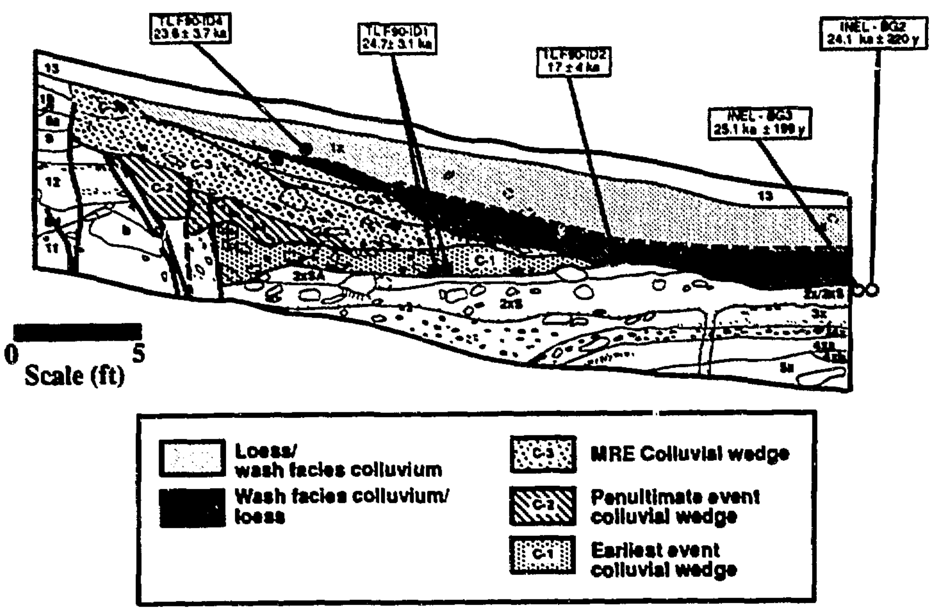

Figure 3. Black Canyon Trench Log, Howe Segment.

Camp Creek Site

This site is located along the southernmost portion of the Fallert Springs segment along a deeply dissected alluvial fan that is possibly early middle Pinedale in age (about 25 ka). The trench is situated across a single, moderately degraded fault scarp; however, it appears that an older, more degraded scarp occurs about 30 m upslope. The trench (Figure 4) is approximately 35 m long and up to 3.7 m deep.

The footwall (southeast end of the trench) is comprised of a thick sequence of debris flow and fluvial deposits. The upper 1 m of the trench is comprised of a mixture of colluvium and debris flow deposits (units 2 and 3) which we interpret to possibly represent the distal portion of a colluvial wedge formed from the faint upslope scarp.

The hanging wall of the trench is comprised of debris flows buried by two colluvial wedge deposits which, in turn, are overlain by a thick loess/colluvium unit. The lower colluvial wedge (C-1) represents the penultimate rupture event and grades from coarse, proximal facies gravel to fine-gravelly sand. This unit was backtilted slightly toward the southeast during the MRE. Unit (C-2) also contains a distal and proximal facies. The distal end of the colluvial wedge grades into the loess/colluvium unit (C-2a) suggesting that the MRE either slightly predates or is contemporaneous with deposition of the loess.

We interpret the exposures at this site to represent three surface rupture earthquakes. The oldest event is represented by the colluvial deposits in the upper portion of the footwall exposure. The minimum cumulative vertical displacement for the two events associated with the exposed fault is about 3.7 m. Individual minimum displacements for these two events is about 1.8 m.

Coyote Springs Site

This site is located near the central part of the proposed Fallert Springs segment at an approximately 1 km right double-bend in the fault. The trench is approximately 65 m long and up to 3.5 m deep. The footwall of the trench exposes a thick section of debris flows and fluvially reworked deposits. A zone of shearing and associated fracture fill deposits about 4 m-wide is located about halfway along the length of the trench. The footwall consists of faulted debris flow deposits overlain by proximal and slope wash facies tectonic colluvial deposits related to two surface rupture events. The scarp-derived colluvium is then buried by a silt-rich debris flow deposit. This deposit is, in turn, faulted at its upslope end and is overlain by a relatively thin colluvial wedge.

The oldest colluvial wedge, (C1), is not extensive in the trench exposure mainly because the majority of the unit has been faulted by the two subsequent events within the broad zone of shearing. The penultimate event (C2) is represented by a relatively thick, up to 0.5 m proximal, clast-supported colluvium which is overlain by a slope wash facies colluvium up to 0.5 m thick. The upslope end of this colluvial sequence has been faulted during the MRE. The penultimate event colluvium is overlain by a silt-rich, relatively clast-poor debris flow unit (SUIX) that is compositionally and stratigraphically very similar to the thick loess unit exposed in the prior three trenches. The silty debris flow unit has been faulted at its upslope end and is overlain by a relatively thin (< 0.5 m thick) colluvial wedge.

AGE ESTIMATES OF SURFACE RUPTURE EVENTS

Ten TL and two ^{14}C age estimates constrain the timing of faulting along the Howe and Fallert Springs segments as exposed in the three southern trenches (Tables 1 and 2). Results from the Coyote Springs site are not yet available. The application of TL to dating tectonic events has been tested largely along the Wasatch and East Cache faults in Utah and TL results have been calibrated with radiocarbon age estimates in some locations [19, 20, 21]. We have used TL in the Lemhi fault trenches because of the sparsity of charcoal in the area, its ability to provide dates beyond the radiocarbon method, and because TL allows a more direct date of tectonic events by dating deposits resulting from surface rupture events. The sedimentology of scarp-derived colluvium is described in detail in McCalpin [18], Forman *et al.* [19], Nelson [22], Forman [23].

East Canyon Site

The oldest event exposed in this trench, represented by proximal wedge (unit C-1), could not be dated. The penultimate event is represented by proximal wedge deposits (C-2) including the carbonate Stage III unit (C-2a). The loess/colluvium (unit 2xb) directly overlying this unit provides a minimum date of greater than 16,000 ± 3,200 years B.P. [TL-F90-ID5]. The degree of carbonate development in the soil suggests that this event may have occurred much earlier than this minimum date. The MRE, represented by unit C-3, is interfingered with loess of unit 2xb. This suggests that the MRE occurred during or relatively shortly after the last major influx of loess into the area. TL samples taken from the fine-grained unit directly below and above the C-3 unit provide bracketing ages for that unit between 18,800 ± 2,400 years B.P. [TL-F90-ID7] and 15,000 ± 2,400 years B.P. [TL-F90-ID8]. This range of ages, from about 19,000 to 15,000 years ago, also provides us with an estimate of the timing of the last period of major loess deposition in the ESRP.

Black Canyon Site

The oldest event, represented by colluvial wedge (C-1), overlies an undeformed debris flow deposit (unit 2x) that has been incised by a small channel containing charcoal providing Accelarator Mass Spectrometry (AMS) age estimates of about 27,000 ± 200 to 28,000 ± 200 years B.P. [INEL-BG2 and 3 (corrected after Stuiver and Reimer

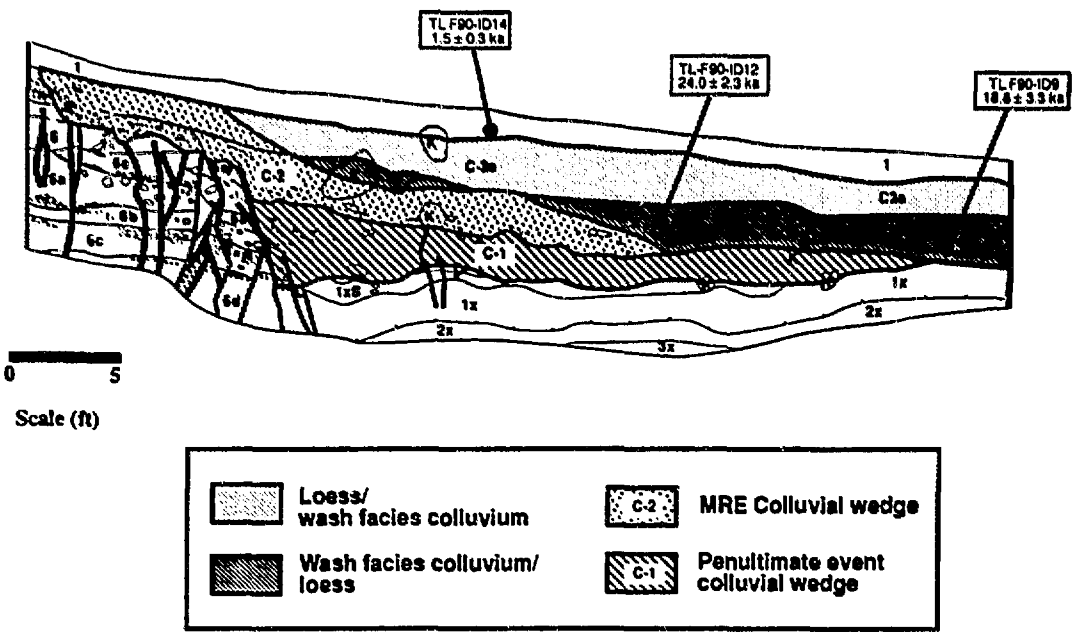

Figure 4. Camp Creek Trench Log, Fallert Springs Segment

Table 1. Thermoluminescence Data and Age Estimates for Samples Collected from Trench Excavations Across the Lemhi fault, Idaho.

Field No.	Lab Sample No	Stratigraphic Unit	Equivalent Dose Method[1]	Light Exposure[2]	Temperature (°C)[3]	Equivalent Dose (grays)	TL age est. (ka)[4]
BLACK CANYON TRENCH, HOWE SEGMENT							
F90-ID1	ITL-296	Buried Av, unit 2xs	Total Bleach	16h sun	270-370	86.20 ± 14.90	24.7 ± 3.1
F90-ID2	ITL-283	Distal coll., unit 1xa	Total Bleach	16h sun	270-400	72.60 ± 26.40	17.4 ± 3.9
F90-ID4	ITL-279	Distal coll., unit 1x	Total Bleach	16h sun	270-400	81.55 ± 19.20	23.6 ± 3.7
EAST CANYON TRENCH, HOWE SEGMENT							
F90-ID5	ITL-284	Distal coll., unit 2xb	Total Bleach	16h sun	270-400	65.80 ± 19.44	16.0 ± 3.2
F90-ID7	ITL-280	Distal coll., unit 2xb	Total Bleach	16h sun	270-380	94.90 ± 15.60	18.8 ± 2.4
F90-ID8	ITL-297	Distal coll., unit 2xa/2x	Total Bleach	16h sun	270-400	57.66 ± 11.55	15.0 ± 2.4
CAMP CREEK TRENCH, FALLERT SPRINGS SEGMENT							
F90-ID9	ITL-285	Distal coll., unit C2a	Total Bleach	16h sun	270-400	79.97 ± 21.08	18.8 ± 3.3
F90-ID12	ITL-281	Distal coll., unit C2a	Total Bleach	16h sun	270-370	100.23 ± 7.26	24.0 ± 2.3
F90-ID13	ITL-298	Buried Av, unit 4SAv	Total Bleach	16h sun	270-400	330.12 ± 27.58	73.6 ± 6.2
F90-ID14	ITL-301	Surface A horizon	Total Bleach	16h sun	270-400	6.16 ± 1.68	1.5 ± 0.3

[1] All TL measurements were made with a Schott UG-11 and HA-3 filters in front of the photomultiplier tube. Samples were preheated to 150°C for 16 hours prior to analysis.
[2] Hours of light exposure to define residual level. "Sun" is natural sunlight in Boulder, Colorado.
[3] Temperature range used to calculate equivalent dose.
[4] All errors are at one sigma and calculated by averaging the errors across the temperature range.

Table 2. Radiocarbon Age Estimates[1] on Charcoal Located in Small Channel Deposit in Black Canyon Trench.

Sample Identification	Description	Weight used (mg)	IsoTrace Lab Number	^{14}C Age (years B.P.)[2]
INEL-BG2	charcoal	1270	TO-2059	24,120 ± 220
INEL-BG3	charcoal	629	TO-2060	25,100 ± 199

[1] Accelerator Mass Spectrometry (AMS) dates provided by IsoTrace Radiocarbon Laboratory, Toronto, Canada
[2] Analysis was conducted for normal precision and have been corrected for natural and sputtering fractionation to a base of $d^{13}C$ = -25‰. Sample ages are uncalibrated conventional dates using Libby ^{14}C meanlife of 8033 years. Errors represent 68.3% confidence limits.

[24]). A buried soil Av horizon in that unit was buried by the C-1 wedge and provides a TL age of 24,700 ± 3.1 for unit 2x. This is in close agreement with the radiocarbon ages and provides a means for calibration of the TL in the trench. This TL date also provides a maximum age since the deposition of the oldest colluvial wedge. The penultimate event, represented by colluvial wedge (C-2), was not directly dated. The MRE is represented by colluvial wedge C-3 which is buried by loess/colluvium (unit 1xa) representing the wash facies colluvium deposited shortly after the faulting event between 17,000 ± 4000 and 23,600 ± 3,700 years ago [TL-F90-ID2 and TL-F90-ID4, respectively]. Interpretation of the exposures from this trench suggest that the three most recent rupture events occurred within a 7,000 year span of time along this portion of the Lemhi fault.

Camp Creek Site

The oldest event exposed in the trench may be represented by the distal colluvium (units 2 and 3) of a wedge derived from the degraded upslope scarp (Figure 4). A soil Av horizon buried by the distal colluvium provides a maximum age for the oldest event of 73,600 ± 6,200 years B.P. Distal colluvium (C-1) associated with the penultimate event and colluvium (C-2) associated with the MRE is overlain by wash facies colluvium and loess (C-2a) of the latest event that was sampled for TL analysis. These samples provide a minimum estimate for the timing of the MRE of 18,800 ± 3,300 to 24,000 ± 2,300 years B.P. [TL-F90-ID9 and TL-F90-ID12, respectively].

Coyote Springs Site

We have not received results of the TL analyses at this site, however, some preliminary estimates of faulting ages can be made for the penultimate and most recent events based on stratigraphic relationships, soil development, and similarities to sites to the south. The penultimate event colluvial wedge is overlain by a silt-rich debris flow unit that was subsequently faulted by the MRE and overlain by its associated colluvial wedge. We interpret this debris flow unit to be genetically related to the massive loess unit to the south, however, the aeolian silt was not as extensive to the north and only a thin cover was deposited. At some time shortly after the penultimate event, due in part to the oversteepened fault scarp, a debris flow comprised mostly of silt was deposited across the scarp and along the base. Therefore, the age of this unit is approximately 17,000 to 24,000 years, or slightly younger. This provides a minimum age estimate for the penultimate event of greater than about 17,000 to 24,000 years. Soil development on the MRE colluvial deposit is very weak with only thin carbonate films along the base of a few clasts and virtually no carbonate or clay in the matrix. Correlation of the faulted silty debris flow unit to the loess unit to the south provides a maximum age limit for this event at about 17,000 to 24,000 years. The youthful appearance of the deposit suggests that it may be considerably younger and is possibly Holocene in age (<10,000 years).

CONCLUSIONS

The paleoseismic evidence from these trenches suggests that: 1) the MRE at the East Canyon site (southernmost Howe segment) may have been more recent than the MRE at the Black Canyon site further to the north along the same segment; 2) the penultimate event at the Black Canyon site may correlate with the MRE at the Camp Creek site; 3) the current segmentation model for the southern Lemhi fault may be inappropriate; 4) temporal clustering of events, i.e., non-uniform recurrence may be typical for the southern Lemhi fault; and 5) the sizes of associated earthquakes are about M_W 6 3/4 to 7 based on the estimate of single event displacements and comparisons with other Basin and Range faults.

ACKNOWLEDGMENTS

Our appreciation to the U.S. Department of Energy and EG&G Idaho, Inc. for support of these studies. We would like to acknowledge the assistance of Suzette Jackson of EG&G Idaho, Inc. and Susan Buth of WCC. We thank the U.S. Bureau of Land Management, Idaho Falls, Idaho and the U.S. Forest Service, Mackay, Idaho for their cooperation and assistance. This study was performed under DOE Contract DE-AC07-76ID01570.

REFERENCES

[1] D.P. Schwartz, and K.J. Coppersmith, 1984, Fault Behavior and Characteristic Earthquakes: Examples from the Wasatch and San Andreas Fault Zones, Journal of Geophysical Research, Vol. 89, pp. 5681-5698.

[2] W.E. Scott, K.L. Pierce, and J.H. Hait, Jr., 1985, Quaternary Tectonic Setting of the 1983 Borah Peak Earthquake, Central Idaho, BSSA, Vol. 75, pp. 1053-1066.

[3] M.H. Anders, J.W. Geissman, L.A. Piety, and J.T. Sullivan, 1989, Parabolic Distribution of Circumeastern Snake River Plain Seismicity and Latest Quaternary Faulting: Migratory Pattern and Association with the Yellowstone Hotspot, Journal of Geophysical Research, Vol. 94, pp. 1589-1621.

[4] M.H. Anders and J.W. Geissman, 1983, Late Cenozoic Evolution of Swan Valley, Idaho, EOS Transactions, American Geophysical Union, Vol. 64, p. 858.

[5] L.A. Morgan and K.L. Pierce, 1990, Silicic Volcanism Along the track of the Yellowstone Hot Spot, Geological Society of America, Abstracts with Program, Vol. 22, pp. 39.

[6] W.E. Scott, 1982, Surficial geologic map of the Eastern Snake River Plain and Adjacent Areas, 111° to 115° W., Idaho and Wyoming, U.S. Geological Survey Miscellaneous Investigations Series Map I-1372, 2 sheets, scale 1:250,000.

[7] K.L. Pierce, and W.E. Scott, 1982, Pleistocene Episodes of Alluvial-gravel Deposition, Southeastern Idaho, in B. Bonnichsen, and R.M. Breckenridge, eds., Cenozoic Geology of Idaho, Idaho Bureau of Mines and Geology Bulletin 26, pp. 685-702.

[8] K.L. Pierce, J.D. Obradovich, and I. Friedman, 1976, Obsidian Hydration Dating and Correlation of Bull Lake and Pinedale Glaciations Near West Yellowstone, Montana, Geological Society of America Bulletin, Vol. 87, pp. 703-710.

[9] K.M. Haller, 1988, Segmentation of the Lemhi and Beaverhead Faults, East-central Idaho, and Red Rock Fault, Southwest Montana, During the Late Quaternary, Master's of Science thesis, University of Colorado, 141 p.

[10] A.J. Crone, and K.M. Haller, 1989, Segmentation of Basin-and-Range Normal Faults; Examples from East-central Idaho and Southwestern Montana; in D.P. Schwartz and R.H. Sibson, eds., Proceedings of Conference XLV, Fault Segmentation and Controls of Rupture Initiation and Termination, U.S. Geological Survey Open-File Report 89-315, pp. 110-130.

[11] A.J. Crone, and K.M. Haller, 1991, Segmentation and the Coseismic Behavior of Basin-and-Range Normal Faults: Examples from East-central Idaho and Southwestern Montana, U.S.A., Journal of Structural Geology, Vol. 13, pp. 151-164.

[12] E.M. Baltzer, 1990, Quaternary Surface Displacements and Segmentation of the Northern Lemhi Fault, Idaho, Master's of Science thesis, State University of New York at Binghamton, 88 p.

[13] J.M. Turko, 1988, Quaternary Segmentation History of the Lemhi Fault, Idaho, Master's of Science Thesis, State University of New York at Binghamton, 91 p.

[14] P.L.K. Knuepfer, E.M. Baltzer, and J.M. Turko, 1990, Late Quaternary earthquake recurrence and seismic hazard of the Lemhi fault, Idaho, Geological Society of America, Abstracts with Program, Vol. 22, p. 17.

[15] J.M. Turko, and P.L.K. Knuepfer, 1991, Late Quaternary Fault Segmentation from Analysis of Scarp Morphology, Geology, Vol. 19, pp., 718-721.

[16] H.E. Malde, 1987, Quaternary faulting near Arco and Howe, Idaho, BSSA, Vol. 77, pp. 847-867.

[17] K.L. Pierce, 1985, Quaternary History of Faulting on the Arco Segment of the Lost River Fault, Central Idaho, in R.S. Stein, and R.C. Bucknam, eds., Proceedings of Workshop XXVIII on the Borah Peak, Idaho, Earthquake, U.S. Geological Survey Open File Report 85-290, Vol. A, pp. 195-206.

[18] J. McCalpin, 1987, Geologic criteria for recognition of individual paleoseismic events in extensional environments, in A.J. Crone and E.M. Omdahl, eds., Proceedings of Conference XXXIX, Directions in Paleoseismology, U.S. Geological Survey Open-File Report 87-673, pp. 102-114.

[19] S.L. Forman, A.R. Nelson, and J.P. McCalpin, 1991, Thermoluminescence Dating of Fault-scarp-Derived Colluvium: Deciphering the Timing of Paleoearthquakes on the Weber Segment of the Wasatch Fault Zone, North Central Utah, Journal of Geophysical Research, Vol. 96, pp.595-605.

[20] J. McCalpin, and S.L. Forman, 1991, Late Quaternary faulting and Thermoluminescence Dating of the East Cache Fault Zone, North-central Utah, BSSA, Vol. 81, pp. 139-161.

[21] S.L. Forman, M.N. Machette, M.E. Jackson, and P. Maat, 1989, An evaluation of thermoluminescence dating of paleoearthquakes on the American Fork segment, Wasatch fault zone, Utah, Journal of Geophysical Research, Vol. 94, pp. 1622-1630.

[22] A.R. Nelson, 1987, A Facies Model of Colluvial Sedimentation Adjacent to a Single-event Normal Fault Scarp, Basin and Range Province, Western United States, in A.J. Crone and E.M. Omdahl, eds., Proceedings of Conference XXXIX, Directions in Paleoseismology, U.S. Geological Survey Open-File Report, 87-673, pp.1136-145.

[23] S.L. Forman, 1989, Applications and Limitations of Thermoluminescence to Date Quaternary Sediments, Quaternary International, Vol. 1, pp.47-59.

[24] M. Stuiver, and P.J. Reimer, 1986, A Computer Program for Radiocarbon Age Calibration, Radiocarbon, Vol. 28, pp. 1022-1030.