Late Quaternary Stratigraphy,
Idaho National Laboratory,
Eastern Snake River Plain, Idaho

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ABSTRACT

The Snake River Plain in eastern Idaho is a relatively flat terrain formed mostly of Quaternary basalts. Loess has accumulated on and deflated from the surface of these basalts, and shallow basins formed by basalt embayment have accumulated loess and other sediment, particularly during the last major glacial period (^{18}O stages 2-4). The Radioactive Waste Management Complex at the Idaho National Laboratory is located in one of the sediment-accumulating basins and provides the opportunity for detailed study of sedimentation and surface processes that have occurred since the most recent basalt emplacements about 100-200 ka. For each of the sedimentary and pedogenic horizons, we qualitatively and quantitatively analyzed particle-size distribution, elemental content, and pedo-stratigraphic processes. Coupling our data with thermoluminescence and glacial outburst flood information, we identified stratigraphic units of Holocene slopewash and eolian sand, late Wisconsin (^{18}O stage 2) loess and outburst flood deposits, and an early to mid-Wisconsin silty-clayey alluvium over an early Wisconsin loess (^{18}O stage 4). The two periods of loess deposition suggest that alpine glaciation in this part of the Rocky Mountains also occurred in early as well as late Wisconsinan time. The intervening silty-clayey alluvium of early to mid-Wisconsinan age indicates moister (pluvial) conditions with runoff into the basins.

INTRODUCTION

The Idaho National Laboratory (INL) is a 2300 km^2 Department of Energy reserve on the eastern Snake River Plain (ESRP), Idaho. Design for safe, long-term (10^3 to 10^4 yr) storage of low-level radioactive wastes at the Radioactive Waste Management Complex (RWMC) of the INL is partially dependent on the assessment of geomorphic development and associated hydrologic changes, particularly of basin areas. This study focused on identifying geomorphic processes that have been operative in the RWMC basin and associated basins during the late-Pleistocene and Holocene time. The resulting stratigraphic understanding of the area is considered to be the best predictor of surface processes that might occur in the future.

The objectives of this study were to (1) characterize the aggradational and erosional

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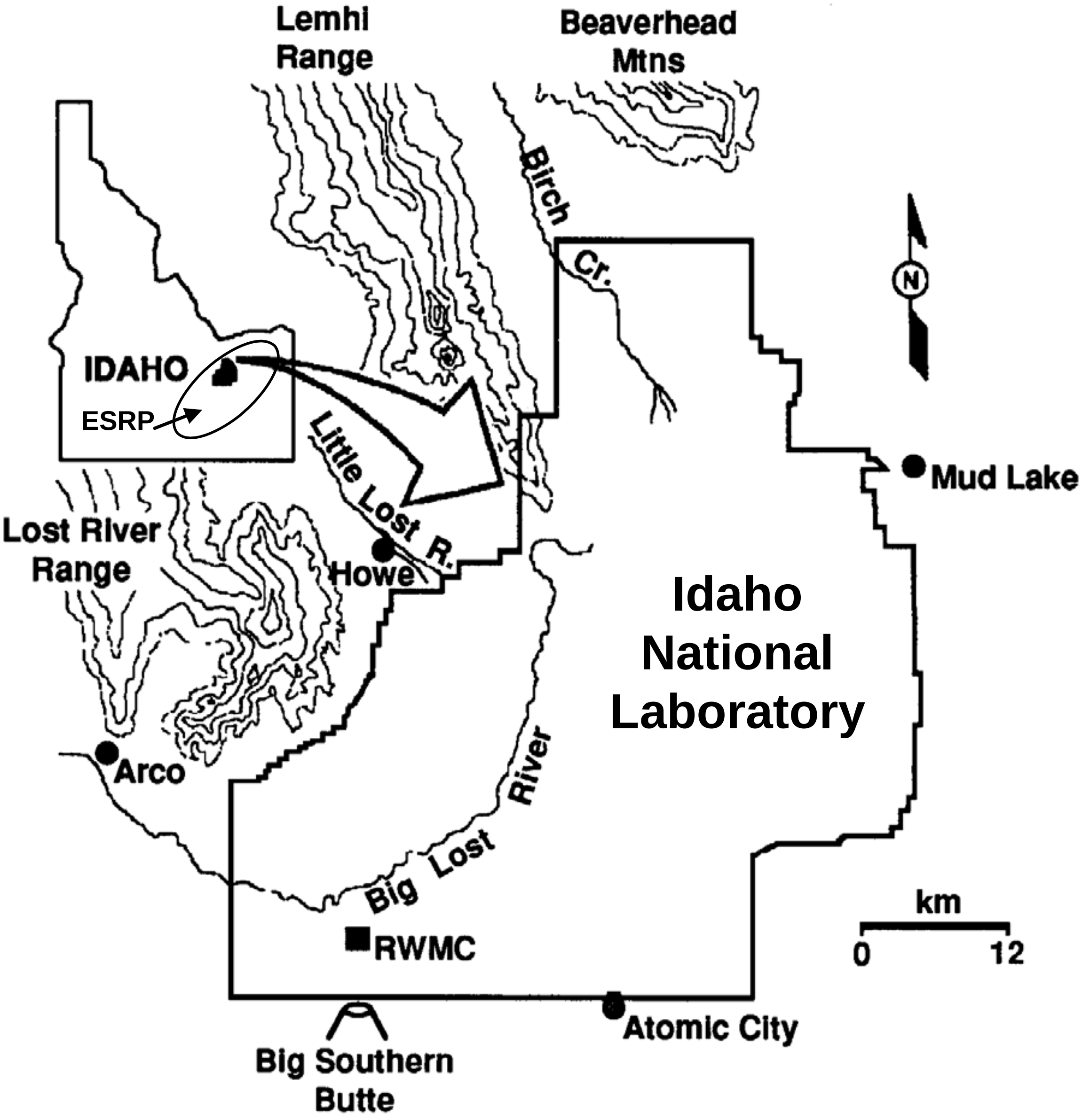

Figure 1. Location map of southeastern Idaho, the eastern Snake River Plain (ESRP) and the Idaho National Laboratory (INL).

history of the sediments and soil materials in and around the RWMC basin and (2) identify and characterize stratigraphic units of the area.

QUATERNARY GEOLOGIC SETTING

The ESRP is a 350-km-long by 90-km-wide linear trench rising from an elevation of 950 m on the southwest to 2000 m on the northeast (Malde, 1991). North and south of the plain are Basin and Range Province mountains with peaks up to 3700 m and relief up to 2000 m (Figure 1). The ESRP floor consists of late Cenozoic basalt flows interbedded with and overlain by loess and alluvium. Surface relief of the ESRP is generally less than 50 m. It tends to have a subtle topographic high along its center axis, which is studded by three prominent buttes. Of these, Big Southern Butte (2308 m), a rhyolitic dome (~300 ka; Armstrong et al., 1975), 10 km south of the RWMC, forms the headwaters of a drainageway that passes through the study area.

Drainages entering the north side of the ESRP are blocked by the central high axis, resulting in a series of sinks along the northern margin. Particular to this study, the Big Lost River flows out of the glaciated Lost River Range and Pioneer Mountains onto the ESRP and passes 2 km north of the RWMC. To the northeast of the RWMC, the river flows into its main "sink" area where it evaporates and percolates into the ESRP as it meanders across the dry floor of pluvial Lake Terreton.

The local topography in the study area is controlled by late Quaternary basalt flows. Most of the topographic lows forming the basins important to this study occur along the boundary between two basalts flows: the basalt of Quaking Aspen Butte (~100 ka) was deposited to the west of and against an older topography formed by Basalt Flow B (~200 ka; Kuntz et al., 1990). The margin between the two flows has partly filled with sediments resulting today in a series of interconnected

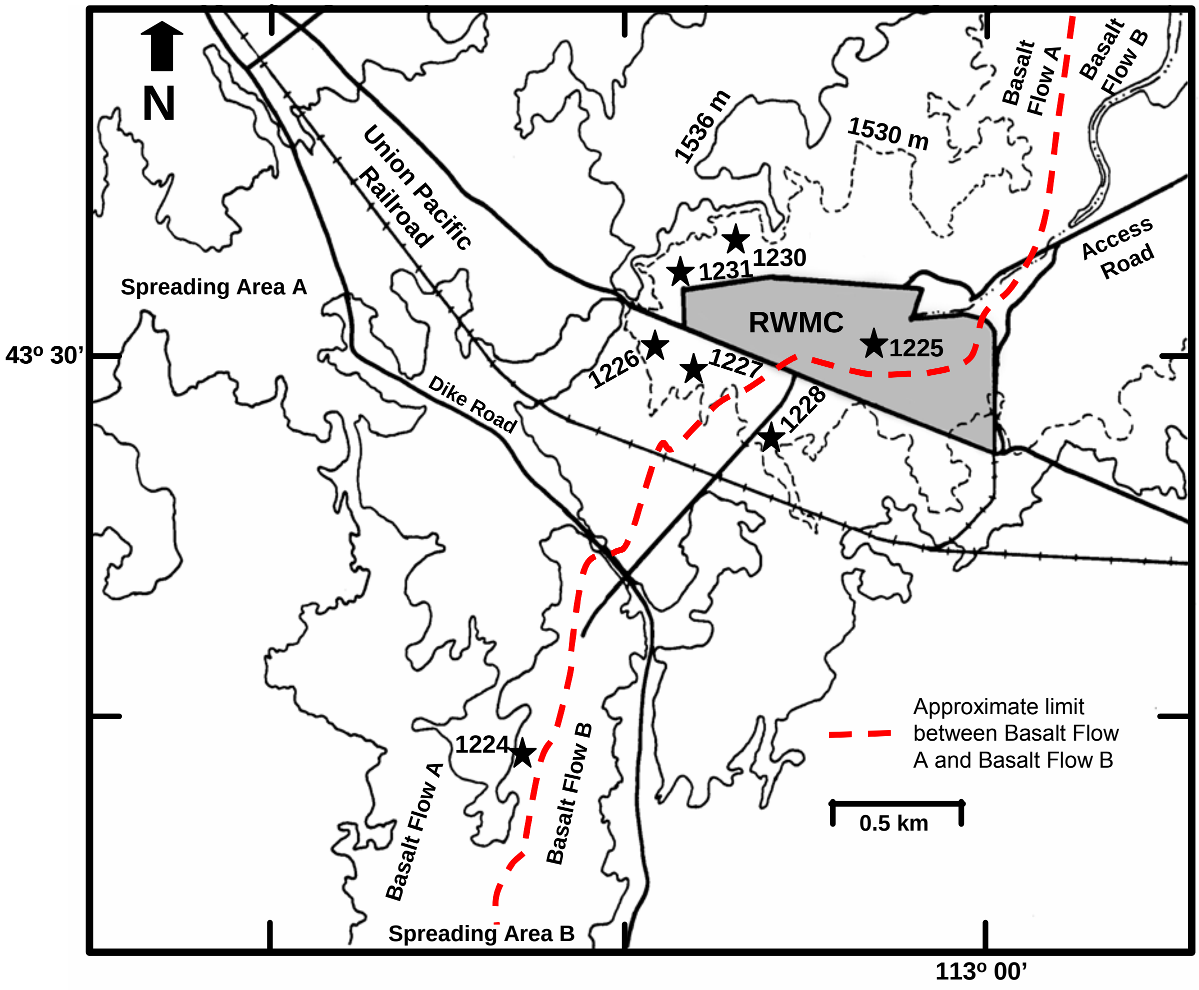

Figure 2. Map of study area, RWMC, and sampling sites.

shallow basins 2 to 3 km wide like beads spaced out along a string. This series of basins provides the only local surface outlet for runoff from Big Southern Butte. Runoff in the area is infrequent under modern climatic conditions, making field recognition of this drainageway difficult. Under modern, arid conditions, the drainageway basins function as playas and sinks as mapped by Scott (1982).

Loess has both accumulated and partially been deflated from the higher areas on the basalt flows. In the basins formed by the basalts, silty Quaternary sediment has accumulated. This study is concerned with Quaternary sediment that has accumulated in these basins, primarily because activities associated with the RWMC are limited to the basin areas, and secondarily, because these basins contain the most complete sedimentological record. The sediments consist of loess, fine-grained playa sediment, slope wash, and alluvium, all of which have been deposited in the last 100 ka.

Loess deposits from 50- to 175-cm-thick blanket most of the ESRP (Lewis et al., 1991; Lewis, 1986; Lewis and Fosberg, 1982) with deposits tens of meters thick occurring close to large sources like the Snake River glacial outwash plains. Most of the surficial loess on the ESRP was deposited during the Pinedale glacial period (10-40 ka). However, work by McDole et al. (1973), Pierce et al. (1982), and Forman et al. (1993) has demonstrated that paleosols in deeper loess deposits are relicts of earlier loess deposits and subsequent soil formation. Loess and loess-like deposits up to 3-m thick occur on the INL, offering the possibility of using such identified paleosols as stratigraphic markers.

Pierce et al. (1982) defined a simple stratigraphy for loess units at stable bench or upland sites along the margins of the ESRP. Loess unit A was defined as resting on a buried soil having better development than any of the surface soils for a given section. Loess unit A was considered to have been deposited in the interval of ~10 ka to ~70 ka (^{18}O stages 2-4). Loess unit B underlies loess unit A and accumulated before development of the buried soil that separates the two loess units. Based on stratigraphic relations to glacial deposits, basalt flows, and tephra whose ages were at least roughly known, soil development in loess unit B was thought to have occurred in the interval between the Bull Lake and Pinedale glaciations (^{18}O stage 5). Out on the ESRP, the loess units would have been deflated or otherwise eroded at all but protected sites because of present-day strong winds and arid conditions and probably even more extreme windiness/dryness at some older times (Pierce et al., 1983; Figures 2 and 3). While the sites of this study are on the ESRP, their basin locations favor better preservation of the loess record. These basin sites also include nonloess deposits of slope wash and finer-textured alluvium.

The modern climate of the ESRP is cold desert with mean annual precipitation ranging between 150 and 250 mm and mean annual temperature ranging from 5ºC in the east at higher elevations to 10ºC around Twin Falls (Water Resources Research Inst., 1968). Vegetation is desert steppe dominated by sagebrushes and bunch grasses. During the Holocene, vegetation has at times been dominated by saltbushes, indicating somewhat warmer and/or drier conditions (Bright and Davis, 1982). Lake Terreton was full as recently and 700 yr BP during the Neoglacial, indicating cooler and/or moister conditions than at present (Bright and Davis, 1982). During full glacial periods, many of the mountains to the immediate north and east of the ESRP were partly covered with glaciers, implying a much colder climate as well on the ESRP (Porter et al., 1983). The presence of patterned ground on the ESRP indicates that permafrost conditions probably existed (Malde, 1964; Fosberg, 1965). Climate models of glacial conditions generally conclude that precipitation probably was not much greater than today, but temperatures were much colder (Morrison, 1991; Kutzbach and Wright, 1985; Pierce and Scott, 1982).

LOCAL SETTING

The overall geomorphic setting of the RWMC basin is a topographic low in a broad, youthful, low-relief basalt and alluvial plain. The RWMC basin is approximately 2 km^2 in area centered in sec. 18, T. 2 N., R. 29 E., Boise Meridian. The RWMC covers much of the basin floor at an elevation of 1527 m (Figure 2). The microrelief shows significant results from the past glacial climate in the form of glacial outburst flood deposits, loess deposits, and periglacially formed patterned ground.

The RWMC basin lies between a ridge of Quaking Aspen Butte basalt on the west and north and the older Basalt Flow B on the east and south (Figure 2). The apparent surface hydrological outlet of the RWMC basin is to the northeast along the current access road to the RWMC, at ~1525 m elevation. The boundary between the two basalt flows south of the RWMC is also the apparent topographic inlet to the RWMC basin. This inlet connects the RWMC with the system of interconnected, sediment-filled basins discussed above which formed between the two basalt flows and served as the drainage for runoff from the north slopes of Big Southern Butte.

To the west of the Quaking Aspen Butte basalt rim of the RWMC is another sediment-filled basin (Spreading Area A, Fig 2) ~2 km in diameter which is similar to those extending from the RWMC to the base of Big Southern Butte. These basins have been named Spreading Areas A, B, C & D (from north to south) and are now engineered to be storage basins for flood water of the Big Lost River. All of these basins except the RWMC basin are nearly filled with sediment to the 1536 m elevational control of the basalt flow top around the RWMC and Spreading Area A basins.

The Big Lost River approaches the north end of Spreading Area A at an elevation of 1536-1538 m, but turns and flows northeastward rather than entering the cul-de-sac of the spreading area basins. To the north of and grading into Spreading Area A, glacial outburst flood gravels of late Pleistocene age (Rathburn, 1991) form a wide plain into which the Big Lost River is shallowly incised. Spreading Area A is mantled by ~0.5 m of Holocene-aged, silt to gravel-sized river overflow deposits from the Big Lost River.

The pressure ridge of Quaking Aspen Butte basalt to the west of the RWMC is of particular interest because it is breached by two "wind gaps" in line with the direction of flow from the Big Lost River as it approaches the RWMC area. Downstream from these wind gaps in the RWMC basin, flood bars with boulders up to 1.5 m in diameter form east-trending trains 75-100 m into the basin on both sides of the west end of the RWMC. These are the result of Pinedale-aged glacial floods (Rathburn, 1991) that probably originated in the Pioneer Mountains (Evenson et al., 1982) and rushed 100 km down the Big Lost River channel. Cerling et al. (1994) determined this flood occurred ~20 ka based on accumulation of cosmogenic ^{3}He and ^{21}Ne in the exposed boulders and basalt scablands.

In the area around the RWMC, Rathburn (1991) identified the upper elevation for the effects of a catastrophic flood as 1540 to 1543

m. In the vicinity of the RWMC, the flooded area as mapped by Rathburn (1991) exhibits a pattern of bare basalt on exposed and convex positions, mostly above 1530 m elevation, and accumulations of loess and silty sediments on concave and lower slope positions.

Within the RWMC basin, a widely scattered, <2-cm-diameter, pebble lag occurs on or just below the surface over most of the area within 200 m of the water gaps. A similar but more dense pebble lag occurs to the west of the water gaps across the Spreading Area A plain. The pebbles are well-rounded and primarily basalt, but quartzose and plutonic rocks from the headwaters of the Big Lost River are common. They are apparently the result of late Pleistocene and/or Holocene-aged Big Lost River floods carrying materials through the wind gaps.

Sand dunes and sand sheets indicating aerial sand movement and emplacement occur immediately to the west of the RWMC basin on the glacial outwash plain and on the Quaking Aspen Butte basalt. These sands are dominantly dark-colored, basaltic materials derived from recent flows and cinder cones to the west of the RWMC. The sand occurs mixed into the surficial loess horizons and as mounds where trapped by vegetation. Within the RWMC basin, the apparent effects of this Holocene wind activity are the mixing of fine sands into the surface loess and an over-thickening of the loess blanket on the east side of the west rim.

METHODOLOGY

Soils and sediments at eleven sections in and around the RWMC (Figure 2) were described and sampled using standard USDA soil terminology and procedures (Soil Survey Division Staff, 1993). Altogether, 120 samples were collected: 90 from sections in and around the RWMC basin and 30 from transects away from the RWMC. The transect data provided a context for understanding the RWMC basin in relation to other basins and uplands of the ESRP. Complete descriptions and data can be found in Dechert et al., 1994.

Samples were air dried, ground with a mortar and pestle, and passed through a 2-mm sieve. Fragments >2 mm were weighed and reported as a percentage of the total sample. The <2 mm fraction was treated with hydrogen peroxide to remove organic matter and ammonium acetate to remove carbonates. The remaining <2 mm fraction was analyzed for particle-size distribution (percent clay, fine silt, medium silt, coarse silt, very fine sand, fine sand, medium sand, coarse sand, and very coarse sand) using a combination of sieving, centrifugation, and sedimentation procedures (Jackson, 1975; Gee and Bauder, 1986). Samples were analyzed for pH and electrical conductivity in a saturated soil-water suspension using a combination glass electrode. Calcium carbonate equivalent was determined by titration (U.S. Salinity Laboratory Staff, 1954).

To further differentiate primary loess from water-reworked loess and/or silty loess-like alluvium, we developed a methodology using a 200-ìm aperture on a Coulter Counter Model TAII to divide the 2 to 63 ìm particles into fifteen classes, each of which is approximately 1/3 phi-unit wide. We dry-sieved the sands into eleven classes. These data were combined to produce detailed cumulative particle-size curves of the sands and silts, and the following statistical parameters were calculated for the sand-silt fraction: geometric mean particle diameter, geometric mean standard deviation (Shirazi and Boersma, 1984), skewness, kurtosis, sorting, and maximum slope (Folk, 1980). Clays were not included in the statistical analyses to characterize the sediments since there are no quantitative methods to differentiate between inherited and pedogenically derived clays.

Elemental composition of coarse silt fractions of forty selected horizons was determined by Acme Analytical Laboratories in Vancouver, British Columbia. Samples were fused with $LiBO_2$ and analyzed using inductively coupled plasma spectroscopy. Significant differences between the mean elemental compositions of different stratigraphic units were determined using a standard means difference t-test.

STRATIGRAPHIC UNITS

We identified two major stratigraphic groups, a "surface complex" and a "buried complex," in the area around the RWMC. Figure 3 shows the stratigraphic relations among the sampling sites within the RWMC basin. Stratigraphic units in the surface complex (Table 1) include an upper loess (Lo1), a surface layer of slopewash and/or recent alluvium (Sl), and Holocene-aged, sandy eolian material (Eo). The buried complex includes the boulder train (BT) and an associated rock line below the late Pleistocene loess (RL), silty to clayey-textured alluvium (Ac), and a buried loess (Lo2).

THE SURFACE COMPLEX

We used the upper loess (Lo1) as the most easily identifiable stratigraphic marker in the area. Using thermoluminescence (TL) dating, Forman et al. (1993) dated the base of the surface loess at ~28 ka at site 1224, with other

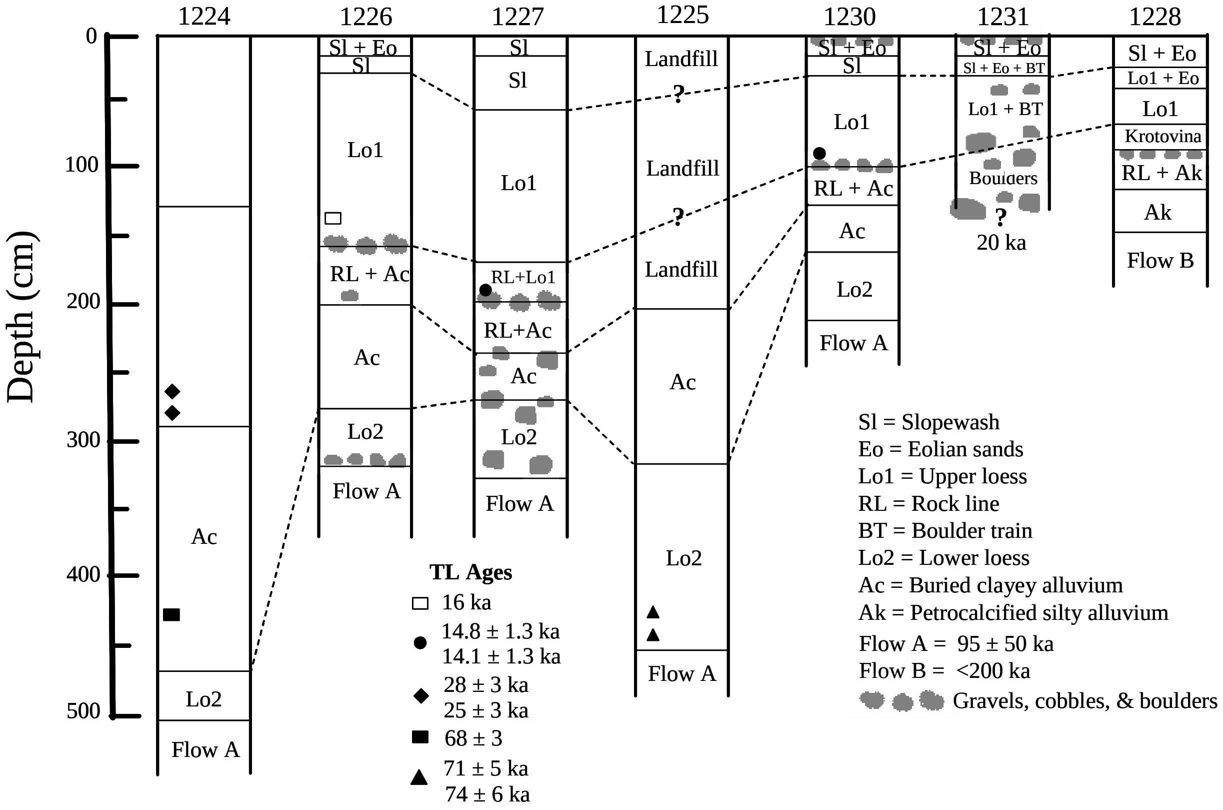

Figure 3. Stratigraphic relationships between sites in the RWMC basin.

dates from samples in this unit being younger. The upper loess, therefore, was most likely deposited during the last major glacial advance/retreat of the Pinedale (^{18}O stage 2, ~10-30 ka).

The shaded data in Table 1 indicate primary loess based on its appearance *in situ* and our data analyses. It is generally >50% very fine sand plus coarse silt (30-100 ìm), with very fine sand in the range of 10-25%, coarse silt >30%, and total clay <25%. Table 2 presents the set of statistics developed to differentiate loess from other silty materials. In general, the 2-200 ìm fraction from loess is characterized as having a sorting value <1.4, positive skewness >0.1, and kurtosis >1.0, as described by Folk (1980). Additionally, the cumulative curve for this fraction has a maximum slope >35%, and the geometric mean particle diameter standard deviation is <2.6 (Shirazi and Boersma, 1984). Our assignment of a given horizon to a stratigraphic unit was based on analyses of the particle size distribution, the set of statistics, and stratigraphic relations.

The upper loess unit deposited around the RWMC was calcareous as evidenced by the pedogenic development of Bk horizons and calcareous nature of the unweathered loess below the Bk horizons. The overlying Holocene deposits are mixtures of slopewash and local alluvium (Sl) and eolian sands (Eo), in many places mixed with the upper loess as the result of freeze/thaw, wind, and biotic activity. These overlying materials exhibit eolian sand enrichment where associated with Quaking Aspen Butte basalt, flood-scoured basalt, or the boulder trains. Concave accumulation sites exhibit relatively higher clay content of the slopewash deposits, as a result of preferential movement of clay in the slopewash process. The pebble lag downstream from the water gaps indicates that flood water from the Big Lost River has entered the RWMC basin sometime during the Holocene, but we were unable to identify any finer textured sediments derived from that event(s?).

Soils formed in upper loess and the overlying Holocene materials exhibit an A-Bw-Bk horizon sequence. This is typical of the degree of soil development that has occurred in the last 10,000-15,000 years in this climatic zone of the ESRP (Lewis and Fosberg, 1982). The pHs in these horizon sequences range from 6.5 at the surface to near 8.5 in the Bk horizons. Calcium carbonate equivalents range from ~0 in the A and Bw horizons to 10-25% in the Bk horizons. Electrical conductivity is variable in the surface but is usually <1.0 dS/m, shows a minimum in the Bw and top of the Bk, and increases to a maximum of 2 to 3 dS/m at the bottom of the Bk.

At sites 1224, 1226, and 1227, the base of the upper loess unit is below the modern Bk horizon as evidenced by the decline in $CaCO_3$. These sites are in concave accumulation positions with relatively thicker loess due to downslope movement during the depositional period.

Most upland surfaces in the area of the RWMC exhibit strongly expressed patterned ground (mound/intermound microtopography); however, the mounds are so strongly mixed by late Holocene burrowing animal activity that evidence of pedogenesis and stratigraphic relations are commonly destroyed. These mounds range up to 10 m in diameter and may be up to 0.5 m high. In trenches across mounds and intermounds, relicts of the Bk horizon were identified, with significantly thicker A and Bw horizons in the mounds. For example, at site 1228 which is in an intermound position, adjacent mounds contain an additional 20-40 cm of mixed silty surface material above the Bk horizon. We interpret most of this additional material as being part of the original upper loess deposit.

The presence of the mounds suggests that a significant amount of loess has eroded off the intermounds in upland positions. Similar mounds over extensive areas of the Snake River Plain have been shown to have developed in periglacial climates (Fosberg, 1965; Malde, 1964). Plant pedestalling on upland, intermound positions is evidence that erosion/deflation continues to occur. Deflation of the upland position soils probably occurs by both water and wind. Our data are insufficient to derive a deflation rate or to be able to document any changes in the rate during the Holocene.

THE BURIED COMPLEX

The upper loess unit overlies a buried complex of deposits which we interpret to be glacial outburst flood deposits mixed with older loess and silty alluvial sediments filling the RWMC basin and spreading areas. In general, the buried complex is more poorly sorted than the upper loess because it contains less coarse silt and very fine sand (Tables 1 and 2). Some transition horizons are mixtures of the upper loess with the underlying deposits.

The buried complex includes the boulder train (BT), a rock line below the upper loess (RL), a silty to clayey-textured alluvium (Ac), and a buried loess over the bedrock (Lo2). For the most part, the RWMC basin sites occur on top of the Quaking Aspen Butte basalt flow and, therefore, have an upper age limit of ~100 ka, a fact which is supported by TL dating of these same sediments (Forman et al., 1993).

Within the RWMC basin, the rock line (RL) underlying the upper loess is most likely the lateral extension of debris from the ~20 ka glacial outburst flood that formed the water gaps and boulder trains. The boulder trains themselves are covered by at least 50 cm of the upper loess. Because the boulder trains are buried by some loess, they must have been emplaced prior to the culmination of deposition of the upper loess. The fact that the upper loess lies conformably on top of the rock line and boulder train supports our conclusion that the rock line is a lateral extension of the boulder trains. The rock line does not occur in other basins without the boulder trains. As well, none of the TL dates above the rock line are older than ~16 ka.

The silty to clayey alluvial materials identified as stratigraphic unit Ac dominate the buried complex in the spreading areas and the RWMC basin and were mapped by Scott (1982) as playa deposits. Visually, *in situ*, this unit is remarkably uniform in color and structure with very little evidence of stratification or soil horizon development even in deposits up to 2 m thick. The particle-size distribution of this unit ranges from silty (up to 60% silt) to clayey (up to 50% clay). Most of the sorting, kurtosis and mean particle size standard deviation statistics for this unit are outside of the range for loess.

The siltier parts of the Ac unit occur closer to the edges of the basins, whereas the clayier parts occur in slightly lower positions near the centers of the basins. This distribution pattern of particle sizes is consistent with the results from studies of enclosed basins elsewhere on the ESRP (Passie et al., 1982). We verified this pattern of intra-basinal fining towards the centers by examining a number of other basalt rimmed basins around the INL and agree that it is the result of water reworking and slopewash processes.

In the RWMC basin, the buried alluvium unit has electrical conductivities >4 dS/m, which indicate accumulation of salts and are consistent with the concept of a playa. However, in the spreading areas the salts have apparently been leached down such that electrical conductivities are <1.0 dS/m. In addition to the salts, most of the $CaCO_3$ has been leached out of the Ac unit, resulting in the redder hues and higher chromas observable in the field. Munsell moist chromas in high-$CaCO_3$ horizons are 2 or 3 and are 4 or 5 in the leached Ac unit. These data indicate that sufficient water has leached through the spreading areas to remove the salts and $CaCO_3$. This suggests there has been considerable surface water accumulation and percolation in these areas as compared to the other basins, including the RWMC basin, where salts and $CaCO_3$ content remain high. The presence of Bk horizons in the surface complex overlying the Ac unit indicates that this leaching occurred prior to the deposition of the surface loess (Lo1) and is not the result of diversion of Big Lost River floods over the last 50 years.

When first described in the field, the horizons of the buried alluvium were for the most part identified as buried Bt horizons (Tables 1 and 2) as evidenced by redder hues, higher chromas, and increased clay content. However, on closer examination, there is very little evidence that any of the clay is illuvial in origin since it is dispersed throughout the sediment fabric. Further, if the clay in these strata was pedogenic, the layers would exhibit much greater structural development as a function of accumulation of clay on ped faces and in pores and subsequent shrink/swell activity.

We tested the hypothesis that the alluvial unit in the buried complex is derived from material different from the upper loess unit by conducting a means separation test on elemental analyses of the two materials (Table 3). Elemental analyses were run on the coarse silt fractions of forty samples. Those samples identified as the upper loess unit (Lo1) in the discussion above were placed in one group, and all the horizons underneath them were placed in another group. Differences in Si, Mg, Ca, Na, and Sr content between the upper loess and the buried complex are significant at the 99.9% confidence level; Al is significantly different at the 99% confidence level; and Fe, Ti, Ba, and Zr are significantly different at the 90% confidence level. These results support the conclusion that the upper loess unit is correctly differentiated from the buried complex.

The lowest part of the buried complex is identified as a separate stratigraphic unit which we call the lower loess (Lo2). It is very high in silt (>60%) and in general has the same statistical characteristics as the upper loess. It is difficult to differentiate from the overlying alluvial material *in situ* since it has the same colors and compact nature. It occurs on top of either Quaking Aspen Butte basalt or older paleosols. Using TL, Forman et al. (1993) dated this lowest stratigraphic unit (Lo2) at ~70-75 ka at site 1225. They identified this unit as "Loess B" and concluded that it had been deposited in the 60-80 ka time frame. More recent work by Forman (unpublished data) at site 1224 dates the buried alluvial unit (Ac) at ~65-71 ka.

Combining our results with Forman's, our buried complex consists of the lower loess overlain by mixed alluvial deposits and capped in the RWMC basin with glacial flood outburst deposits. The TL date of the basal loess indicates that it might be a loess pulse associated with an early Wisconsin glacial advance and retreat in the 60-75 ka range--the ^{18}O stage 4 period of worldwide cooling and major ice advances. The overlying alluvial deposits are conceivably the result of both slopewash and channel wash from Big Southern Butte during mid-Pinedale. It seems likely that the strong, ~20 ka glacial outburst flood passing through the RWMC basin stripped any of the loess deposited previous to that time as well as some of the older alluvium and loess.

Sites 1228 and 1234 contain basal paleosols which are indurated by secondary $CaCO_3$ forming a petrocalcic horizon (Soil Survey Staff, 1992). These two horizons overlie Flow B basalt (~200 ka) (Kuntz et al., 1990) and appear to be relicts of older soils. At site 1228, the petrocalcic horizon dips at a considerable angle to the modern surface but parallel to the surface of the underlying basalt. This as an indication that the petrocalcic horizon was part of an older landscape surface graded to a base elevation that was considerably lower than the modern-day RWMC basin floor. This landscape existed before the modern-day basin was filled with sediments and more recent basalts. The age and extent of these much older horizon remnants around the RWMC are unknown. This paleosol is likely older than 100 ka and, as such, is the only sediment in the study area that might be of Bull Lake age.

DISCUSSION AND CONCLUSIONS

TL dates from near the base of the upper loess indicate an age of ~16 ka in areas affected by the glacial outwash flood and ~28 ka in areas above the effects of the flood (Forman et al., 1993; Forman, unpublished data). We concur with other reports from the ESRP that the most recent loess deposition probably ended around 10 ka. Slopewash, sandy eolian deposition, weak river flood events, biological mixing, and soil formation have dominated the Holocene, resulting in loess thinning on convex positions and up to 50 cm of mixed material on top of the loess in concave positions.

TL dating and stratigraphic relations indicate that the buried complex was emplaced during early to mid-Pinedale Glaciation (~75-30 ka), and clearly postdates the Quaking Aspen Butte basalt flow (~100 ka). The loess at the bottom of the complex, immediately on top of the basalt or a buried paleosol, has a TL date of 70-80 ka. This date implies that the loess is the result of an early Pinedale glacial cycle in the area. TL dates for the alluvial unit are in the range of 60-70 ka; however, the stratigraphy indicates that this alluvial activity could have continued up to the beginning of deposition of the upper loess unit, or ~30 ka. Within the RWMC basin, the buried complex is capped by glacial flood outburst deposits dated at ~20 ka (Cerling et al., 1994).

We correlate both the upper and lower loess in the section above the Quaking Aspen Butte basalt with loess unit A of Pierce et al. (1982). We recognize no buried soil of sufficient development to indicate that the buried complex is as old as loess unit B of Pierce et al. (1982). Loess unit A was considered by Pierce et al. (1982) to have been deposited between 10,000 and 70,000 years ago. The TL age of 60 to 75 ka of Forman et al. (1993) for the lower loess, which we correlate with the early part of loess unit A, provides the closest limiting age for the onset of deposition of loess unit A. Pumice in the lower part of loess unit A with an age of 61 ±8 ka provided the previously oldest age for the lower part of loess unit A (Pierce et al., 1982). Pye (1987) identified a similar-aged loess (TL age of 74-77 ka) in Mississippi and concluded that it was deposited during the early part of the last glaciation.

In the RWMC and adjacent basins, a wetter interval interrupted the deposition of loess unit A. The bottomland areas became wet or intermittently wet, accumulated sediments, and were leached of salts and $CaCO_3$.

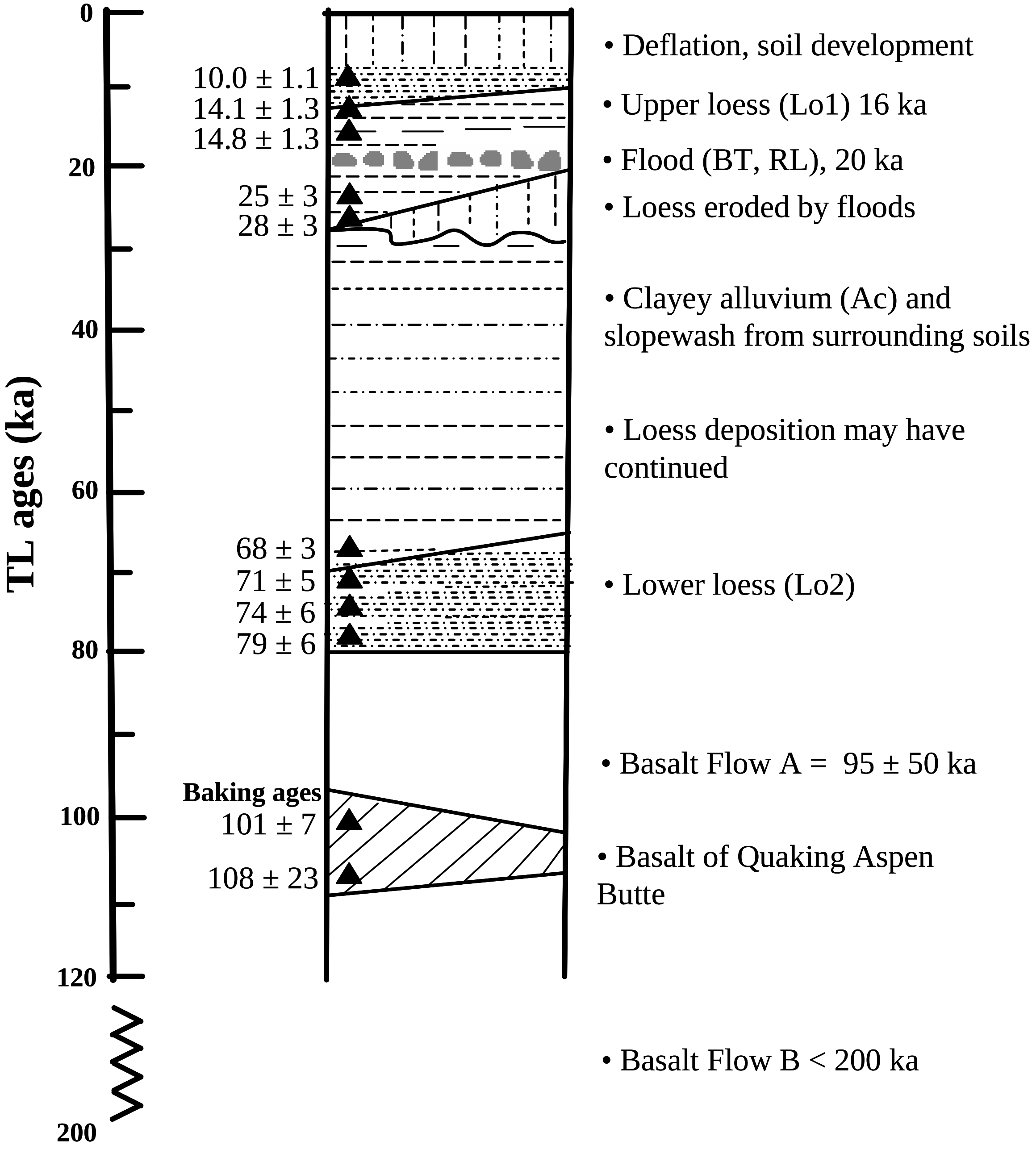

Figure 4. Generalized stratigraphic composite showing TL (ka) ages for the eastern Snake River Plain. BT = boulder train; RL = rock line

Presumably at this time, loess was accumulating on upland areas. The fact that evidence of the glacial flood event from the Big Lost River occurs in the upper part of the alluvial unit (Ac) suggests this unit was accumulating when full glacial conditions prevailed in the headwaters area. We conclude that the alluvial unit accumulated under glacial, pluvial conditions.

Our interpretation differs from that of Forman et al. (1993), who considered the alluvial unit to be a major buried soil. Consequently, they correlated the lower loess unit with loess unit B of Pierce et al. (1982) and suggested that loess unit B was as young as 60-70 ka based on TL ages. We do not consider this alluvial unit to be either loess or a well-developed buried soil, and therefore find no evidence that the underlying lower loess should be correlated with loess unit B of Pierce et al. (1982). The TL age of the lower loess, its occurrence on top of the 100 ka Quaking Aspen Butte basalt flow, and the generally accepted correlation between ^{18}O stage dates and major glacial advances leads us to conclude that both of the loess units identified at the RWMC correlate to loess unit A of Pierce et al. (1982). The lower loess with its 70-80 ka age is evidence that significant alpine glaciation occurred in this part of the Rocky Mountains during early Wisconsin time (^{18}O stage 4).

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Table 1. Particle size data and stratigraphic units for selected sites in the RWMC basin. Shading identifies particle-size data characteristics of loess.

Horizon	Depth (cm)	V. fine sand %	Total sand %	Coarse silt %	Medium silt %	Total silt %	Total clay %	Text. class	Coarse frag.	EC (dS/m)	CaCO %	Stratigraphic units
					Site 1226							
A	0 - 8	25.2	26.3	27.3	14.7	50.1	23.7	sil	0.6	0.4	0.0	S1 + Eo
Abw	8 - 25	19.2	22.3	24.6	16.8	51.3	26.4	sil	0.3	0.3	0.0	S1
Bw	25 - 48	18.3	22.2	32.6	18.3	59.4	18.4	sil	0.6	0.2	0.0	Lo1
Bk1	48 - 81	16.1	18.2	36.0	18.8	60.7	21.1	sil	1.8	0.3	18.8	Lo1
Bk2	81 - 128	14.7	17.4	35.9	19.0	60.8	21.9	sil	3.0	1.0	17.2	Lo1
BC	128 - 155	14.8	17.5	32.5	18.1	56.5	26.0	sil	1.2	9.8	12.0	Lo1
Btkb1*	155 - 190	8.7	9.5	29.6	19.0	54.1	36.4	sicl	10.1	12.0	10.2	RL + Ac
Btkb2*	190 - 235	10.5	11.1	29.5	18.5	53.7	35.1	sicl	0.5	12.0	10.5	Ac
Bkb1	235 - 270	12.4	15.0	28.6	19.9	53.0	32.0	sicl	0.7	12.0	4.9	Ac
Bkb2	270 - 312	13.0	16.5	23.7	28.8	61.3	22.2	sil	8.8	20.0	13.5	Lo2
R	312+	-	-	-	-	-	-	-	-	-	-	Basalt
					Site 1227							
A	0 - 8	17.7	21.5	29.8	18.4	53.8	24.6	Sil	0.4	1.0	0.0	S1
Abw	8 - 35	11.9	15.8	24.9	19.6	53.2	31.0	sicl	0.3	0.4	0.0	S1
Bk1	35 - 53	10.1	13.5	31.3	21.9	57.9	28.7	sicl	0.0	0.5	11.7	S1
Bk2	53 - 98	13.3	15.2	33.6	23.1	62.6	22.8	sil	0.0	0.4	16.7	Lo1
BC1	98 - 130	16.1	19.5	36.4	20.7	60.9	19.6	sil	0.0	0.7	17.2	Lo1
BC2	130 - 165	5.5	6.2	29.8	30.9	66.1	27.7	sicl	0.0	3.5	10.2	Lo1
Bkb	165 - 196	9.2	9.9	32.7	28.6	66.2	23.9	sil	30.4	8.2	13.2	RL + Lo1
Btkb1*	196 - 232	13.2	16.2	30.3	21.7	55.6	28.2	sicl	23.2	13.0	11.3	RL + Ac
Btkb2*	232 - 266	13.9	15.4	34.6	18.8	58.0	26.6	sil	8.9	21.0	27.9	Ac
B’kb	266 - 320	15.1	16.1	36.7	22.6	63.5	20.5	sil	10.5	20.0	32.6	Lo2
R	320+	-	-	-	-	-	-	-	-	-	-	Basalt
					Site 1230							
A	0 - 8	19.9	38.2	22.8	12.7	39.4	22.4	1	1.4	0.6	0.0	S1 + Eo
Abw	9 - 22	15.7	22.7	32.1	16.1	51.5	25.9	sil	1.5	0.5	3.4	S1
Bk1	22 - 41	15.4	18.0	40.3	20.5	64.2	17.8	sil	2.3	0.5	23.2	Lo1
Bk2	41 - 66	19.4	21.3	39.5	18.0	61.2	17.5	sil	0.9	0.9	17.6	Lo1
Btk	66 - 96	19.3	14.3	32.7	16.3	53.3	22.4	sil	2.4	1.7	11.7	Lo1
Btkb1*	96 - 124	11.3	13.4	20.1	14.8	39.1	47.5	c	15.4	7.8	9.5	RL + Ac
Btkb2*	124 - 158	7.2	8.7	19.7	14.6	38.1	53.3	c	12.7	15.0	67.5	Ac
Bkb	158 - 210	15.3	18.9	43.5	25.1	73.7	7.4	sil	36.9	9.9	14.8	Lo2
R	210+	-	-	-	-	-	-	-	-	-	-	Basalt
					Site 1225							
C	0 - 200	Landfill						-				
Btkb*	200 - 220	11.4	13.6	20.0	21.4	50.1	36.3	sicl	-	1.2	3.4	Ac
Btb1*	220 - 240	10.2	11.3	23.4	20.6	52.3	36.4	sicl	5	1.0	2.3	Ac
Btb2*	240 - 260	5.7	6.0	17.8	20.6	48.0	46.0	sil	5	0.9	8.8	Ac
B’tb1*	260 - 275	5.3	5.8	21.9	23.4	54.3	39.8	sicl	-	2.0	10.1	Ac
B’tb2*	275 - 310	7.8	8.4	27.1	24.3	59.2	32.4	sicl	-	4.0	7.5	Ac
Bwb	310 - 350	11.2	11.9	34.3	22.6	62.5	25.6	sil	-	5.0	5.3	Lo2
Cb	350 - 450	12.5	13.3	30.5	29.2	66.5	20.2	sil	-	1.8	17.9	Lo2
R	450+	-	-	-	-	-	-	-	-	-	-	Basalt
					Site 1231							
A	0 - 9	21.9	61.7	20.0	6.0	28.3	10.0	fsl	7.6	1.0	0.0	S1 + Eo
Abk	9 - 25	19.8	41.2	24.3	10.9	38.4	20.4	1	11.1	0.5	10.6	S1 + Eo + BT
Bk1	25 - 58	18.2	22.9	42.1	15.5	60.5	16.7	sil	14.1	0.3	23.8	Lo1 + Bt
Bk2	58 - 87	24.1	29.7	37.0	15.5	55.8	14.5	sil	21.2	0.9	19.5	Lo1 + Bt
BCk	87 – 130+	23.1	33.1	33.2	15.8	54.8	12.1	sil	44.9	3.7	16.6	Lo1 + Bt

* Indicates a stratigraphic unit rich in clay, not a pedogenically clay-enriched horizon.

Table 2. Statistical analyses for loess on selected samples. Shaded horizons have statistics characteristic of loess: generally sorting <1.4, particle size standard deviation <2.6, kurtosis >1.0, slope >35%, and skewness >0.1.

Sample	Horizon	Depth (cm)	**Dg (microns)	Sorting (phi)	***Sg	Kurtosis	Slope (%)	Skewness	Strat. Unit
1224-2	Bw	10 - 30	42.13	1.28	2.67	1.29	45.03	0.28	S1 + Eo
1224-3	Bk1	30 - 45	43.15	1.18	2.53	1.27	52.11	0.24	Eo + Lo1
1224-4	Bk2	45 - 70	31.51	1.19	2.31	1.23	37.80	0.18	Eo + Lo1
1224-6	BC	100 - 125	28.70	1.13	2.24	1.12	43.55	0.23	Lo1
1224-7	Bwb1	125 - 160	27.29	1.24	2.38	1.08	38.48	0.24	Lo1
1224-8	Bwb2	160 - 230	28.96	1.21	2.31	1.12	40.25	0.25	Lo1
1224-9	BCb	230 - 290	27.76	1.21	2.35	1.10	38.57	0.21	Lo1
1224-10	Btb1*	290 - 340	27.11	1.54	2.89	0.87	32.32	0.15	Ac
1224-11	Btb2*	340 - 380	23.84	1.53	2.74	0.89	29.11	0.15	Ac
1224-12	B’tb1*	380 - 400	30.21	1.48	2.80	0.94	34.07	0.23	Ac
1224-13	B’tb2*	400 - 470	28.21	1.46	2.72	0.99	32.83	0.23	Ac
1224-14	Cb	490 - 560	25.88	1.17	2.28	1.08	41.92	0.17	Lo2
1225-1	Btkb*	200 - 220	18.39	1.64	3.18	0.77	21.05	0.01	Ac
1225-2	Btb1*	220 - 240	24.58	1.52	2.88	0.86	41.16	0.36	Ac
1225-3	Btb2*	240 - 260	15.40	1.56	2.71	0.77	26.36	0.05	Ac
1225-4	B’tb1*	260 - 275	15.60	1.52	2.64	0.78	24.80	-0.03	Ac
1225-5	B’tb2*	275 - 310	20.06	1.43	2.56	0.79	29.62	0.15	Ac
1225-6	Bwb	310 - 350	24.90	1.27	2.37	1.10	38.12	0.17	Lo2
1225-7	C	350 - 450	25.60	1.35	2.38	0.89	32.72	0.18	Lo2
1226-2	ABw	8 - 25	25.25	1.42	2.79	1.28	48.54	0.35	S1
1226-3	Bw	25 - 48	34.59	1.37	2.81	1.14	44.22	0.32	Lo1
1226-4	Bk1	48 - 81	26.19	1.30	2.56	0.98	35.31	0.19	Lo1
1226-5	Bk2	81 - 128	30.88	1.28	2.46	1.11	38.21	0.22	Lo1
1226-6	BC	128 - 155	31.51	1.31	2.54	1.12	39.59	0.26	Lo1
1226-7	Btkb1*	155 - 190	23.73	1.33	2.48	1.02	32.76	0.25	RL + Ac
1226-8	Btkb2*	190 - 235	22.48	1.30	2.51	0.84	31.35	0.20	Ac
1227-3	Bk1	35 - 53	21.94	1.52	2.81	0.93	28.21	0.13	S1
1227-4	Bk2	53 - 98	29.46	1.37	2.44	1.18	40.81	0.12	Lo1
1227-5	BC1	98 - 130	30.17	1.30	2.47	1.06	37.03	0.12	Lo1
1227-6	BC2	130 - 165	22.66	1.23	2.322	1.01	35.22	0.23	Lo1
1227-7	Bkb	165 - 196	22.32	1.28	2.39	1.02	34.49	0.13	RL + Lo1
1227-9	Btkb2*	232 - 266	24.11	1.40	2.61	1.06	31.36	0.13	Ac

* Indicates a stratigraphic unit rich in clay, not a pedogenically clay-enriched horizon.

**Dg = geometric mean particle diameter of sands and silts.

***Sg = geometric particle size standard deviation of sands and silts.

Table 3. Statistical comparison of elemental content of the upper loess and the buried complex.

Element	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	Zr
Upper Loess (n = 12)										
Sum	882.25	105.47	29.47	29.27	42.50	18.68	22.55	6.52	1.86	4694
Mean	73.52	8.79	2.46	2.44	3.54	1.56	1.88	0.54	0.15	391
Var.	6.33	0.41	0.21	0.78	1.96	0.02	0.03	0.01	0.0	9188
Buried Alluvium (n = 22)										
Sum	1717.84	205.14	50.10	26.79	47.60	39.76	42.45	13.63	3.54	10351
Mean	78.08	9.32	2.28	1.22	2.16	1.81	1.92	0.62	0.16	470
Var.	3.09	0.17	0.11	0.18	0.60	0.02	0.14	0.01	0.00	32163
Means Separation t-values										
Pool Var.	2.04	0.50	0.38	0.62	1.03	0.15	0.33	0.10	0.06	155.77
Calc. T	***6.20	**2.97	*-1.31	***-5.46	***-3.72	***4.74	0.36	*2.21	0.28	*1.42

*, **, *** Indicate significance at the 0.9, 0.99, and 0.999 levels, respectively.

Tabled t-values: α @ 0.01 = 1.31, α @ 0.01 = 2.457, and α @ 0001 = 3.385.

Positive calculated t-values indicate increases between the upper loess and the buried complex.