PREFACE

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Long Quaternary Record in Eastern Washington, U.S.A., Interpreted from Multiple Buried Paleosols in Loess

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ABSTRACT

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Loess that is from a few meters to 75 m thick covers an area of more than 20,000 km^2 on the Columbia Plateau in Washington, Idaho and Oregon. The region of deepest loess is in eastern Washington and is called "The Palouse". The Palouse is downwind of the Channeled Scabland, through which massive outburst floods from Glacial Lake Missoula flowed repeatedly during glacial stages of the Pleistocene. The deepest stratigraphic section yet studied is in a remnant of the once continuous loess cover that is surrounded by Scabland channels. A normal over reverse magnetic polarity zonation in this section supports an age of more than 790,000 yr, but 15–35 m of loess may be present beneath this section, so a total of 1.5–2 million yr is possible. Upward fining of texture in some layers in the loess at this site and stratigraphic evidence at nearby sites suggest that at least some pulses of loess deposition were triggered by episodes of cataclysmic floods. Nineteen or more individual paleosols can be recognized in 26 m of section based on field morphology, physical and chemical properties, and micromorphology. The paleosols consist of calcic, petrocalcic and duripan horizons, many of which are associated with cambic horizons. Less strongly developed soils in this and other sections have been obscured by partial overlap of soil development in an episodically rising loess landscape. Paleosols in the loess at other sites reflect a dry-to-moist climatic gradient from west to east across the region during the Pleistocene that was grossly similar to today's. Accumulation of pedogenic carbonates and silica dominates in a western zone where the present-day mean annual precipitation is less than about 450 mm. Translocation of silicate clays and leaching of carbonates dominate in a central steppe zone where precipitation is between 450 and about 700 mm. Fragipans are common in an eastern zone along the steppe-forest transition at present-day precipitation of over 700 mm. Reconnaissance study suggests that these climatic-pedogenic zones have been somewhat stable during many of the episodes of soil development preserved in the loess, although some paleosols have different features from the majority of the paleosols in that zone, e.g., paleosols with fragipans in a sequence of paleosols with argillic horizons, which suggests that some episodes of soil development took place under different climatic conditions.

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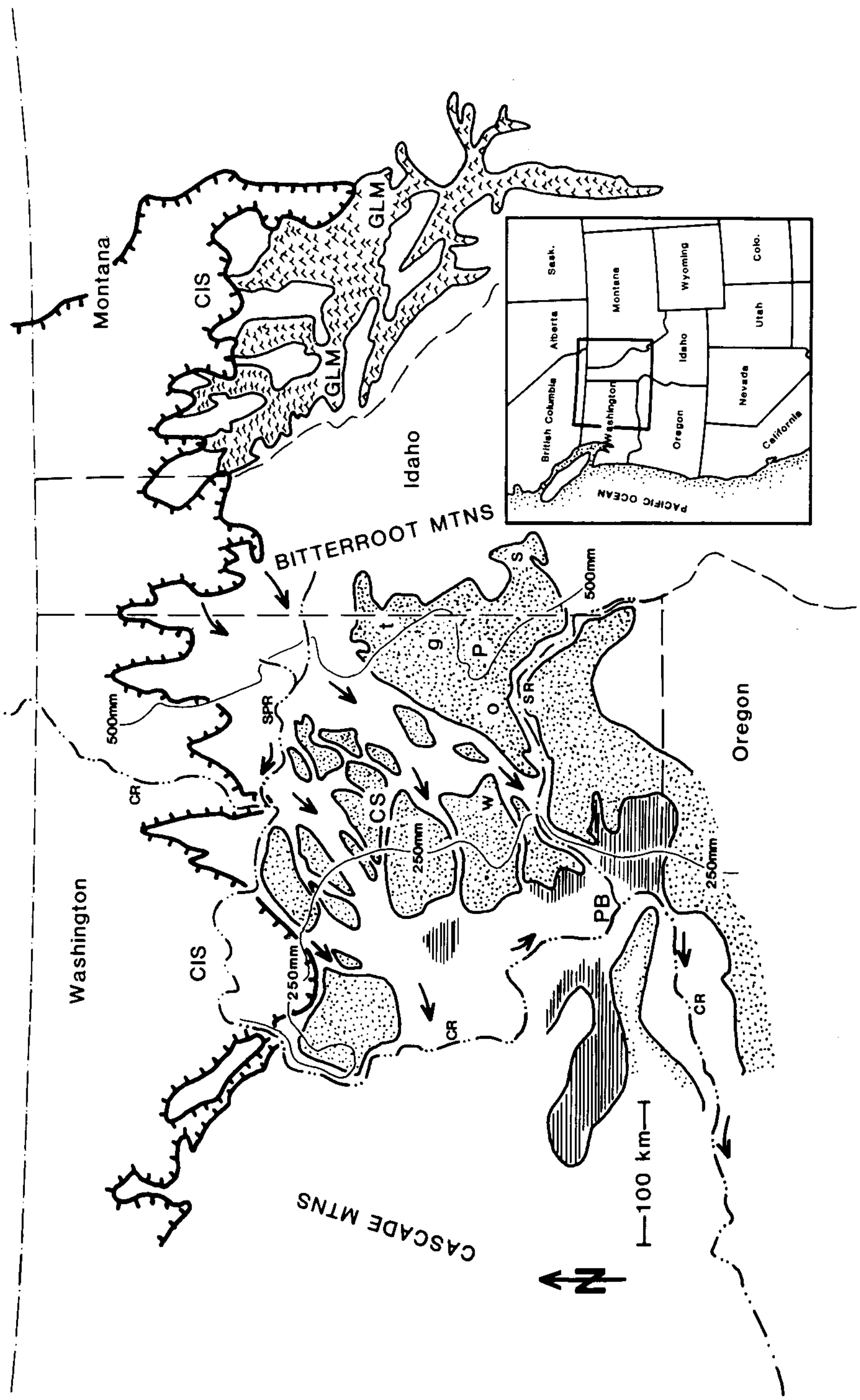

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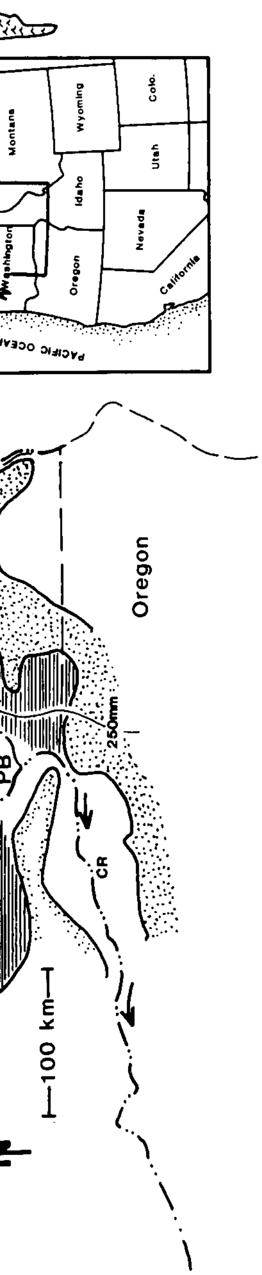

INTRODUCTION

The deepest and most continuous loess deposits in the northwestern U.S.A. are centered on eastern Washington state in a region called "The Palouse". The Palouse loess may help us to better understand the Quaternary history of North America because it is very near the southern margin of the Cordilleran Ice Sheet (Fig. 1) and because some of the cycles of loess deposition were triggered by cataclysmic glacial outburst floods from Glacial Lake Missoula in western Montana (McDonald and Busacca, 1988; Busacca, 1989) that created the Channeled Scabland in central Washington (Baker and Bunker, 1985). Recent research has demonstrated that there were at least six and perhaps more episodes of giant floods during glacial maxima of the Pleistocene Epoch (McDonald and Busacca, 1988). A thick Cordilleran Ice Sheet extending into southern Canada or the northern U.S. is required to block drainages and generate these large-scale floods, so the stratigraphic record in the loess one day may be one of the best terrestrial proxy records of glacial–climatic cycles in North America.

Paleomagnetic measurements prove that the geologic record in the loess spans at least the last one million years (Packer, 1979; Kukla and Opdyke, 1980; Foley, 1982; Busacca, unpublished data). Thin layers of volcanic ash from the Cascade volcanic mountain chain to the west are interstratified in the loess, and some of these have been correlated to known and dated eruptions (Foley, 1982; McDonald and Busacca, 1988; Nelstead, 1988).

Within the Palouse loess are interstratified dozens of buried ancient soils (paleosols). The paleosols are the record of episodes of relative landscape stability and the beds of loess are the record of episodes of rapid eolian sedimentation. Early work on the stratigraphy of the Palouse loess conducted by Roald Fryxell (Fryxell et al., 1965; Richmond et al., 1965) was cut off by his untimely death in 1974. It is known, however, that paleosols in loess sequences can be

Fig. 1. Location map of the Palouse (*P*) and Channeled Scabland area (*CS*) with a schematic representation of Quaternary features discussed in text. Maximum extent of the Cordilleran Ice Sheet (*CIS*) during the late Wisconsin is shown by the heavy hatchured line; maximally developed Glacial Lake Missoula (*GLM*) during the late Wisconsin shown by patterned area in western Montana. Areas of thick loess are shown by the stipple pattern; the Palouse is the roughly triangular area on the Idaho-Washington border. Major pathways of glacial outburst floods illustrated by arrows; significant deposits of quiet-water silt and sand from floods are shown by pattern of closely spaced horizontal lines. Pasco Basin (*PB*), Columbia River (*CR*), Snake River (*SR*), and Spokane River (*SPR*) also shown. *W* denotes the location of the Washtucna site; *O* the Oliphant site; *T* the Thatuna site; *S* the Santa site; *G* the town of Garfield. The Washtucna stratigraphic exposure is 46°46′10″N 118°20′50″W, elevation 500 m; the Oliphant pedon is 46°42′32″N 117°46′45″W, elevation 550 m; the Thatuna pedon is 47°13′31″N 117°6′37″W, elevation 800 m; and the Santa pedon is 46°50′N 116°36′45″W, elevation 915 m. Isohyets of 250 mm and 500 mm of present-day mean annual precipitation plotted for the Palouse and Scabland areas only.

excellent indicators of past climates (see, for example, Liu, 1985), can be used as stratigraphic markers for regional correlations (e.g. Ruhe, 1976), and, in a few cases, paleosol-and-loess sequences have been used to reconstruct glacial–interglacial cyclical patterns (e.g. Kukla, 1975, 1977; Kukla et al., 1988), so further work on the loess of the Palouse is clearly warranted.

A new phase of research on the history and origins of loess and paleosols in the Palouse region has been underway for several years, and a picture is beginning to take shape of the nature of the paleosols in the loess and their climatic and stratigraphic significance. The purpose of this paper is to show some of the results of this recent work and to discuss new ideas and hypotheses.

METHODS

Stratigraphic and soil descriptions

One deep stratigraphic exposure in the drier part of the region and three surface pedons from progressively wetter zones were studied and are discussed below. The large section was selected because it is one of the deepest excavations in the loess. The description was made from a hand-dug, stepped trench in a roadcut 3.3 km northwest of the town of Washtucna, Washington (*W* in Fig. 1). The site is at the crest of a north–south trending hill at an elevation of 490 m. The roadcut exposes the upper 26 m of section. The hill is part of a "loess island", a remnant of the deep loess cover that is surrounded by channels of the Scabland system. The trenching extended 0.5–1.5 m back from the face of the roadcut to expose fresh material. Individual loess strata and paleosol horizons were described using standard methods for soils (Soil Survey Staff, 1981) that were supplemented with additional terms to describe sedimentological features, tephra layers and unusual morphologic features that resulted from bioturbation.

Pedons of the surface soils discussed below were selected to illustrate the great changes in pedogenic character across the Palouse region. They were described from freshly excavated backhoe pits. The soils were described using standard methods for soils (Soil Survey Staff, 1981). The Oliphant, Thatuna and Santa sites are 45 km east, 113 km east-northeast, and 137 km east of the Washtucna site, respectively (Fig. 1). Each of the three sites was on the convex upper part of a loess hill with southwesterly (Oliphant series), northeasterly (Thatuna) and westerly (Santa) aspects and slopes of less than seven degrees. The three sites are all within the main body of the Palouse loess geographically and are therefore not near any Scabland channels.

Sampling and analysis

Bulk samples of each soil and paleosol horizon and loess layer were collected for analysis. Sampling intervals at the Washtucna and other sites ranged from

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RESULTS AND DISCUSSIO

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10 to 100 cm. Oriented undisturbed blocks of paleosols and loess layers were collected from the Washtucna site. These were impregnated with resin and thin sections were made and then examined with a petrographic microscope. Pedogenic calcium and magnesium carbonates were analyzed by treating samples for 30 min with a sodium acetate buffer solution (0.5 *M* NaOAc in 13% HOAc) heated to 90°C; the calcium and magnesium were analyzed by atomic absorption spectroscopy. Samples for the determination of particle-size distribution were pretreated twice using the same procedure as above to remove carbonate cements. The samples were then dispersed by sonicating them for 15 min in a 3% Na_2CO_3 solution in a cup-type ultrasonic vibrator (Busacca et al., 1984). Sands were first separated from silt and clay by wet sieving, then dried and weighed. Clay content was determined by pipette method (Jackson, 1975) and silt by subtracting the weight of sand and clay from the oven-dry weight of the pretreated sample. Organic carbon content of the pedons of surface soils was determined by an acid-dichromate digestion procedure (Soil Survey Staff, 1984, 6A1C); extractable iron was determined for the Oliphant and Thatuna pedons by a dithionite-citrate procedure (Soil Survey Staff, 1984, 6C2).

RESULTS AND DISCUSSION

Washtucna deep stratigraphic exposure

Deep roadcuts in the Palouse expose multiple paleosols interstratified with sheets of loess. One of the deepest and most extensively studied roadcuts is 3.3 km northwest of Washtucna, Washington. Twenty-six meters of stratigraphic section is exposed; the total depth appears to be 40–60 m based on interpretation of topographic maps. The sediments in the lower one-half of the exposed section are reversely magnetized (Fig. 2) (Kukla and Opdyke, 1980; Foley, 1982; Busacca, 1989), implying deposition before the Brunhes Normal Polarity Chron and therefore an age greater than 790,000 yr B.P. (Johnson, 1982).

The paleosols in this section have cambic, calcic, petrocalcic and duripan horizons, as do paleosols in other exposures in the semiarid western Palouse and Channeled Scabland. Present-day mean annual precipitation (MAP) and mean annual air temperature (MAT) at the Washtucna site are 280 mm and 10.5°C, respectively. The native vegetation in the area surrounding the site was sagebrush steppe before settlement (Daubenmire, 1970). Holocene surface soils are Mollisols that are intergrading to Aridisols (Soil Survey Staff, 1975).

Calcium and magnesium carbonates in relatively unaltered loess layers range from 1 to 5% (Fig. 2); grains of detrital limestone or marble are seen in thin section. Pedogenic horizons have 7 to almost 40% carbonates. The carbonates occur as thin filaments, soft masses, cemented insect burrows (earthworm and

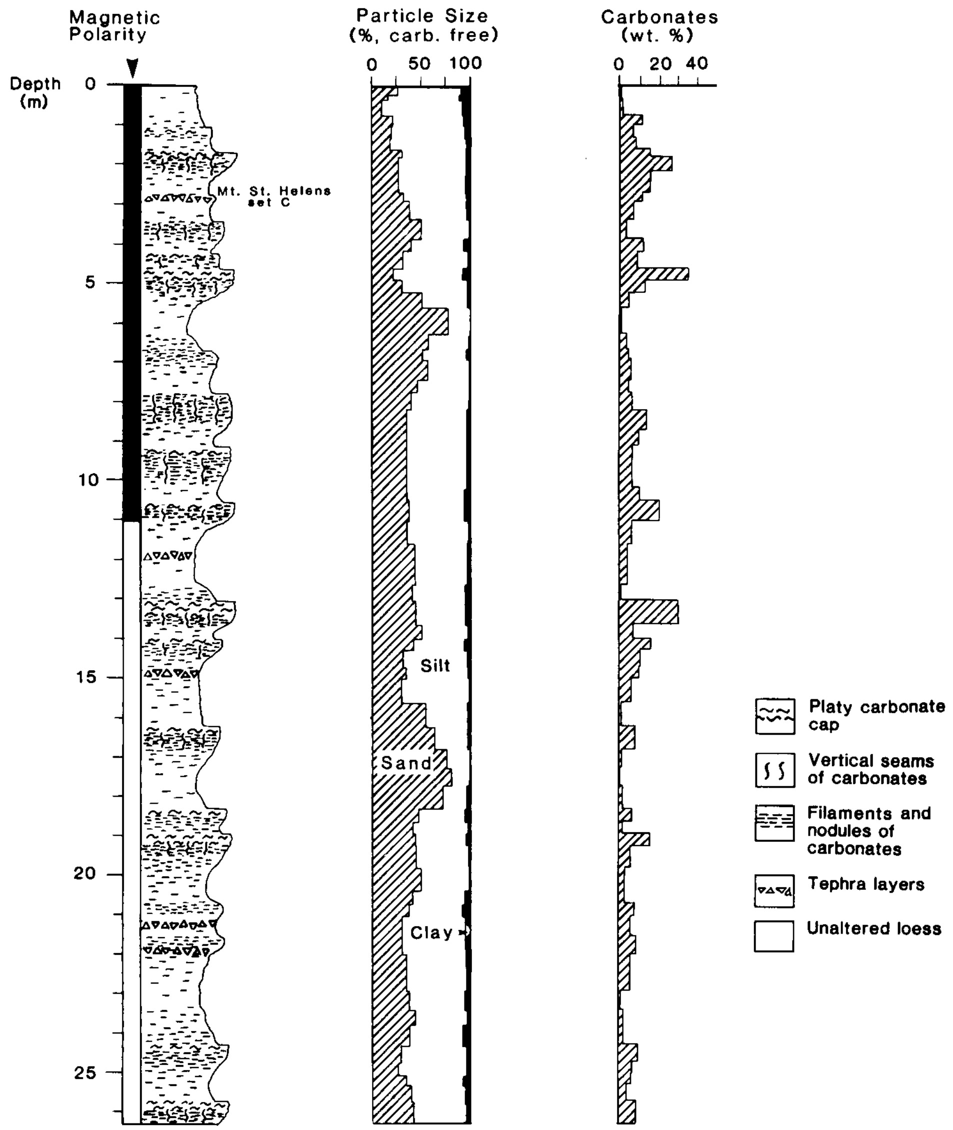

Fig. 2. Stratigraphic-pedologic reconstruction of the deep exposure at Washtucna, Washington. Magnetostratigraphy of the section is shown at left; black is normal magnetic polarity and white is reversed magnetic polarity. Paleosols are shown in schematic form in which closer spacing of symbols and greater distance out from the origin represent greater degree of soil development. Symbols show morphologic features resulting from accumulation of carbonates and silica.

cicada), horizontal laminar caps and vertical seams. Several forms can occur together in individual paleosols.

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paleosols at Washtucna and other sites in the semiarid part of the Palouse even though amounts rarely exceed 1.5% on a carbonate-free basis (S.A. Feldman and A.J. Busacca, unpublished data). Strongly developed paleosols can have dominantly carbonate cements, both carbonates and silica, or in a few cases, dominantly silica. The paleosol at 24 m, for example (Fig. 2), has low carbonate content yet apparently because of silica cementation is one of the most strongly cemented paleosols in the exposure.

Cambic horizons are present above about one-half of the calcic and petrocalcic horizons and duripans. Cambic horizons have higher color chromas than do horizons above and below them; in thin section, they exhibit greater weathering of primary minerals and more secondary iron oxide coatings. Cambic horizons also have slightly higher amounts of dithionite-extractable iron than do non-cambic horizons (about 0.6% versus about 0.3%, on a carbonate-free basis). Even though the amounts are small, the relationship between Fe_d and cambic horizons is consistent enough that it is probably the result of pedogenesis in most cases. Although there are variations in clay content with depth (Fig. 2), field morphology and study of thin sections suggest argillic horizons in this stratigraphic section only for the paleosols at 13 and 24 m. The variations in clay content, therefore, are due principally to depositional processes, perhaps with some contribution by in-place weathering in some horizons.

Zones darkened by humified organic matter or other buried plant remains are not found at this site, and in fact are extremely rare even in the areas of higher precipitation to the east. There is evidence at some sites that A and cambic horizons have been stripped down to duripans and calcic horizons by slope erosion and, in the Channeled Scabland, by flood erosion. More commonly, however, the zones that were the A horizons when soils were actively forming probably are still present in the stratigraphic sequence. They now have the appearance of being part of C horizons, cambic horizons, or calcic horizons of the next overlying paleosols. A horizons may have simply lost their organic matter by oxidation after burial in this dry environment, or, in this landscape that has risen episodically by deposition of new loess, each increment may have been, in turn, the A, then the cambic, then the calcic horizon for successive soil profiles.

Particularly when increments of new loess have been less than about 1 m, the calcic or duripan of the newly forming surface soil has overprinted its features on the former A and cambic horizons of the previous soil. For example, at 5 m in the Washtucna profile, the carbonate enriched horizons from two different episodes of soil development are closely superimposed and the pan of the upper apparently has been formed in the former A horizon of the lower one (Fig. 2). Chemical data, field morphology and micromorphology support this interpretation of partial overlap of soil development for about half of the paleosols at the Washtucna site (Busacca and Feldman, 1985). Several terms such as welded soil (Ruhe and Olson, 1980), compound and composite geosol

(Morrison, 1978) and superimposed soil (Busacca et al., 1985) have been proposed for various forms that overlap can take in specific geologic and pedogenic settings.

Soil structure formed by burrowing organisms such as earthworms and cicadas is very common in paleosols throughout the semiarid and arid climatic zones of the Palouse and Scabland. The most heavily burrowed horizons, which I describe as having a "cylindrical" soil structure, would seem to delineate the positions of former A and cambic horizons because of the known life habits of these organisms (Hugie and Passey, 1963), but they are almost invariably also part of the most strongly cemented horizons in the paleosols. Root casts of grasses and shrubs that are now strongly cemented by carbonates are also common. These observations are consistent with a complex genesis of the soils in which the A and cambic horizons of a soil are eventually engulfed by carbonate and silica cements as the zone of precipitation of carbonates and silica rises in an episodically accreting loess landscape. As individual loess beds thin to the north and east of source areas in the Pasco Basin and environs (McDonald, 1987; Busacca, 1989), the overlap becomes more severe and the problem of distinguishing individual paleosols becomes more severe. Much remains unknown about the exact sequence and timing of episodes of soil development in the Palouse, yet these observations tell us that the origin of the paleosols has been complex.

Particle-size analysis of strata at the Washtucna roadcut and at other sites within and near the Channeled Scabland show much wider ranges in texture, and in particular higher sand contents, than is typical of loess. The sand content of loess in the Scabland (dominantly very fine sand) ranges from 10 to more than 75% (Fig. 2). In contrast, Frazee et al. (1970) reported sand to be less than 5% for Peoria Loess in Illinois, except within 1 km of the Mississippi and Illinois rivers. Even in these very near-source areas, sand was less than 18%. Loess in the main Palouse is finer in texture, ranging from about 2 to 30% sand and 25 to 5% clay, and is more typical of loess reported elsewhere, presumably because of much greater distances from source areas.

Giant floods in the Channeled Scabland may have been responsible in part for the coarse texture of the loess there by triggering cycles of loess deposition when flood sediments could have been remobilized and winnowed by strong prevailing southwesterly winds: it is known that floods deposited gravel, sand, and silt in and adjacent to channels or "coulees" within the Scabland and deposited silty and clayey quiet-water sediment in the Pasco Basin and surrounding valleys (Fig. 1), where floodwaters ponded before draining to the Pacific Ocean (Baker and Bunker, 1985). It is also known that there have been several episodes of flooding during the Pleistocene (Patton and Baker, 1978; McDonald and Busacca, 1988), each episode consisting of many individual flood bursts from Glacial Lake Missoula and spanning perhaps several thousand years during a glacial maximum (Waitt, 1985; Atwater, 1986). Loess beds

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Large erosional unconformities cut into loess adjacent to flood coulees have been correlated to earlier episodes of floods by stratigraphic position within the loess, by flood sediments that overlie some unconformities and by marker beds of volcanic ash (McDonald and Busacca, 1988). At many sites, loess that overlies these unconformities grades upward in texture from coarse to fine (McDonald and Busacca, 1988). This suggests a shifting balance of sources through time after episodes of flooding: coarse saltated sediment from nearby coulees dominating soon after floods, and finer suspended sediment (true loess) from distant source areas dominating later. The coarse basal parts may be a highly localized form of cover sands or sand sheets reported from a variety of ancient and modern environments (e.g. Ruegg, 1983; Kocurek and Nielson, 1986; Schwan, 1988). Paleosols that cap these beds suggest a return to landscape stability and very low rates of loess deposition some time, probably thousands to perhaps ten thousand years, after each flood episode.

At Washtucna and other such sites in the Scabland that do not have obvious unconformities, some of the loess beds also are very sandy (e.g. at 4, 6, 14, and 16–18 m, Fig. 2). These appear to be correlative to some of the flood-triggered loess beds described above (Busacca, 1989).

Because the Channeled Scabland consists of a system of anastomosing or braided channels that covers thousands of km^2 (Fig. 1), region-wide patterns of particle size and thickness for loess beds within the Scabland that were triggered by floods, such as Holocene loess, are quite complex (E.V. McDonald and A.J. Busacca, unpublished data) and represent a striking contrast to most other loess regions that have line sources such as major rivers.

It is not known how many of the loess–paleosol cycles in sections such as Washtucna could have been triggered by episodes of cataclysmic flooding. There have been a minimum of six episodes of floods during the Pleistocene (McDonald and Busacca, 1988), however, so floods have probably generated at least six loess beds, including the Holocene loess cap that forms the modern surface soil, which was deposited following the last glacial floods. The existence of such a large total number of loess beds and paleosols at sites such as Washtucna (Fig. 2) suggests that climatic cycles or oscillations may have exerted an influence on loess deposition through several other proxies, such as changes in vegetation or in wind direction or intensity, in addition to glacier-dammed lakes.

Paleoclimatic significance of the Palouse loess

Soils developed in the layer of Holocene or "post-Scabland flood" loess in the Channeled Scabland and Palouse reflect the existence of climatic and vegetational gradients across the region during their development, because ochric epipedons, cambic horizons, and calcic horizons have formed in the driest area that is centered on the Pasco Basin and these features are progressively replaced by mollic epipedons, cambic and then weak argillic horizons, albic horizons, and fragipans with increasing distance to the north and east into areas of higher precipitation. Paleosols across the same region show grossly similar trends, suggesting that gradients of climate and vegetation also existed during the Pleistocene Epoch. There is neither sufficient stratigraphic control nor adequate numbers of exposures at present to take full advantage of the possibilities of reconstructing paleoclimates for individual time periods; however, I will present data and interpretations from three pedons that span today's climatic range and discuss the potential for eventual paleoclimatic reconstructions based on a reconnaissance of stratigraphic exposures of paleosols.

The geographic and physiographic setting of the loess is important to understanding the climatic and pedogenic gradients. The Miocene Columbia Plateau Basalt serves as a gently sloping platform on which the loess was deposited; the elevation of the lowest part of the Pasco Basin is about 150 m above sea level and the elevations of the tops of the loess hills increase from about 200 m on the southwest to more than 900 m on the northeast. Present-day mean annual precipitation is as low as 150 mm in Columbia Basin and increases northeastward to more than 1000 mm in the Bitterroot Mountains of north Idaho due to an orographic effect on the cyclonic storms that are carried by westerly winds. Present-day mean annual air and soil temperatures decrease along this transect due to increasing elevation. Native vegetation before arrival of large numbers of American settlers in the late nineteenth century was a sagebrush steppe in the driest southwestern part of the region, a steppe consisting of perennial bunchgrasses in the main body of the Palouse, and conifer forest along the eastern edge of the loess field in northern Idaho (Daubenmire, 1970).

Cambic, calcic, petrocalcic and duripan horizons dominate in paleosols that occur to the west and southwest of the 450 mm isohyet (Fig. 1) of present-day mean annual precipitation; albic, cambic, argillic and occasional week calcic horizons occur in paleosols that lie geographically approximately between the 450 and 700 mm isohyets; and albic, argillic and fragipan horizons dominate in a zone about 20 km wide to the east of the 700 mm isohyet.

Because of the complex landscapes, variable thickness of the youngest layer of loess (Holocene and latest Pleistocene in age or about 13,000 yr old; McDonald, 1987; Busacca, 1989), and the ubiquitous presence of paleosol horizons beneath this cover of young loess, about one-half of the upland soil series mapped in the Scabland and Palouse have superimposed profiles (Busacca et al., 1985). Mollic or ochric epipedons, cambic and/or weak calcic horizons have been formed in the young loess layer and these features overlie and merge in development with cambic, calcic, petrocalcic, duripan, albic, argillic, or fragi-

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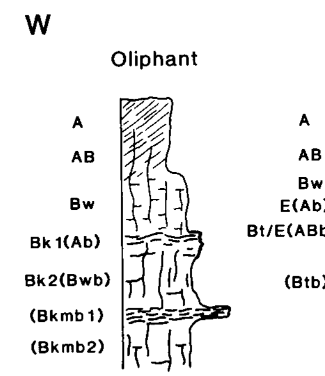

Fig. 3. Schematic diagrams of
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pan horizons of paleosols. Superimposed profiles are a widespread feature of soils in a thin loess cover in which the solum of the surface soil forms throughout the entire thickness of the cover and into the solum of a buried soil formed in an older material. Ruhe and Olson (1980) called this process "soil welding" and such soils "welded soils".

I selected the Oliphant, Thatuna, and Santa series soils (Fig. 3; Table I) to represent welded soil profiles with components of both Holocene and earlier episodes of soil development and to illustrate dominant pedogenic processes in the low-precipitation part of the bunchgrass zone, the high-precipitation part of the bunchgrass zone, and the high-precipitation forest zone, respectively.

The Oliphant series soil has a mollic epipedon and a cambic horizon that have been formed in the layer of youngest loess. A calcic horizon appears to have formed into former A and cambic horizons of the buried paleosol (Fig. 1, Table I). Underlying these horizons is a petrocalcic horizon of the paleosol. Carbonates are in the form of horizontal laminae, vertical seams, soft masses and filaments. No translocation of clay is evident from laboratory data (Table I), although the A and cambic horizons have larger amounts of extractable iron than deeper horizons, presumably due to greater weathering of the near-surface zone.

The Thatuna series soil has a higher organic matter content than does the Oliphant soil (Table I), which is a result of the higher mean annual precipitation and greater biomass production on the Thatuna site. A cambic horizon underlies the mollic epipedon. As with the Oliphant soil, the upper sequence of horizons is thought to have been formed in Holocene and latest Pleistocene loess. Carbonates generally have been fully leached from soils such as those of the Palouse series in this precipitation zone, except that they are not completely removed from thin soils on hill summits that shed water.

Even in this part of the Palouse where present-day MAP is 560 mm, 10–

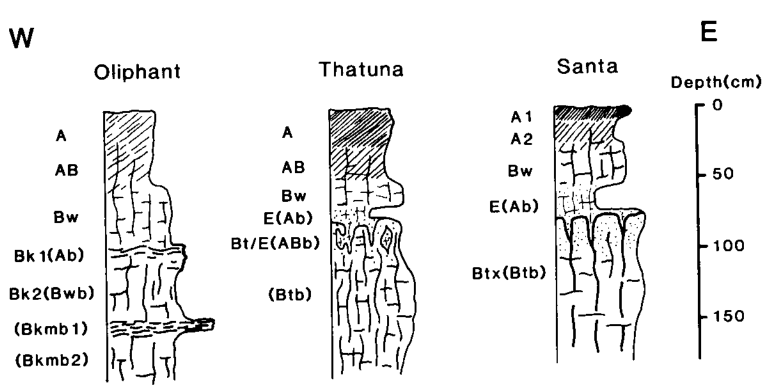

Fig. 3. Schematic diagrams of the Oliphant Thatuna, and Santa pedons. Horizon nomenclature is from Soil Survey Staff, 1981.

TABLE I

Environmental, physical, and chemical data for the Oliphant, Thatuna and Santa series soils

Soil series, great group	Horizon	Basal depth (cm)	MAP*1 (mm)	MAT*1 (°C)	Native vegetation*2	Particle size*3 (%)			Fe_d*4 (%)	Carbonate content (%)	Organic carbon (%)
						sand	silt	clay			
Oliphant, Haploxeroll	A	33	360	10.0	B	16	71	13	1.0	0	1.1
	AB	51				16	71	13	1.0	0	0.8
	Bw	94				15	78	9	0.9	0	0.5
	Bk1(Ab)*5	112				21	70	9	0.5	23	0.5
	Bk2(Bwb)	147				18	76	6	0.7	5	0.5
	(Bkmb1)	152				27	68	5	0.3	30	0.3
	(Bkmb2)	162				19	78	3	0.3	21	0.2
Thatuna, Argialboll	A	38	560	8.9	B,S	6	71	23	1.0	0	2.0
	AB	54				6	70	24	1.0	0	1.0
	Bw	72				7	71	22	1.0	0	0.7
	E(Ab)	83				8	79	13	0.8	0	0.4
	Bt/E(ABb)	117				6	66	28	1.2	0	0.3
	(BtB)	178				3	66	31	1.0	0	0.2
Santa, Fragixeralf	A1	13	720	6.5	C	10	73	17	nd.*6	0	4.0
	A2	23				8	74	18	nd.	0	0.8
	Bw	53				8	74	18	nd.	0	0.5
	E(Ab)	74				8	79	13	nd.	0	0.3
	Btx(Btb)	168				7	65	28	nd.	0	0.2

*1 MAP = mean annual precipitation; MAT = mean annual air temperature; climate estimates from Donaldson (1980) and Barker (1981); all sites have xeric moisture regimes.
*2 B, perennial bunchgrass; B,S bunchgrass and mesophytic shrubs; C, conifer forest.
*3 Calculated on a carbonate-free basis.
*4 Fe_d = dithionite extractable iron.
*5 Horizon designations in parentheses are interpretations of paleosol horizon types before Holocene episode of loess deposition and soil development (see text).
*6 nd. = not determined.

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Bw	53	8	74	18	nd.	0	0.3
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15,000 yr apparently is insufficient time to form an argillic horizon in the Holocene loess under a xeric climate, although the cambic horizon shows macro- and micromorphologic evidence in the form of weak argillans and interstitial pore fillings that clay transformation and translocation are taking place in the material.

A strong albic and argillic horizon sequence underlies the young loess in the Thatuna soil. The albic horizon has been formed by lateral water flow over the upper surface of the less permeable argillic horizon (Rieger and Smith, 1955). The argillic horizon has thick or prominent argillans on ped faces and lining tubular pores. Iron-manganese concretions up to several millimeters in diameter are common in the albic and argillic horizons. Translocation of extractable iron as well as clay is evident from a comparison of the albic and paleosol argillic horizons (Table I). The albic and argillic horizons are good examples of the welding process (Ruhe and Olson, 1980) because contemporary processes associated with the modern land surface have extended into what probably was the former A horizon of the paleosol to form the albic (Fig. 3). Degradation of the upper part of the argillic horizon (Fig. 3) and possibly clay translocation appear also to be contemporary processes.

The Santa series soil has an ochric epipedon because it has been formed under a mixed conifer canopy instead of under perennial grasses. It is an Alfisol (Fragixeralf) that is part of a belt of Alfisols and Inceptisols that formed in forest near the forest–steppe boundary in the distal part of the loess field. The ochric epipedon and cambic horizon have been formed in young loess. They overlie a strong albic horizon and an argillic horizon of a paleosol. The albic and fragipan horizons apparently formed during the Holocene as an overprint on the A and argillic horizons, respectively, of the paleosol. The albic and fragipan horizons serve to "weld" the paleosol to the surface soil. They have iron mottles and manganese concretions, indicating alternating conditions of oxidation and reduction in these horizons.

Fragipans are dense, brittle, reversibly cemented subsoil horizons (Grossman and Carlisle, 1969; Soil Survey Staff, 1975). In northern Idaho, as elsewhere, fragipans have a distinct morphology but a poorly understood genesis. Here they occur in a zone only about 20 km wide (Barker, 1981) that is approximately parallel to precipitation isohyets, temperature isotherms, and astride a particular forest habitat type. The steppe–forest transition zone may have been coincident with the zone of fragipans during the driest phases of the Holocene (H.W. Smith, pers. commun., 1984). The parallelism of the fragipan zone and isolines of climate and vegetation suggest a causal relationship but the mechanism(s) are unknown at this time.

It is the zones of transition or "pedogenic tension" between these areas of dominant soil-forming processes (e.g. calcic to argillic, argillic to fragipan) that have the best potential for reconstructing paleoclimates. Have the climates during episodes of soil development in loess been similar for some or all of the paleosol units? That is, for example, have all of the soils in the stratigraphic sequence of the Palouse loess formed under similar climates during interglacial stages or might some of the soils have formed under very different climates during glacial stages? One way to address questions such as these would be to determine whether the geographic position of the key pedogenic transition zones stayed the same or changed between episodes of soil development, as recorded in the properties of paleosols in the stratigraphic sequence of the loess. Two examples from the Palouse will serve to illustrate this point.

A reconnaissance of roadcuts across the zone of fragipans showed as many as seven buried paleosol fragipans in vertical sequence, with more of them likely to be preserved beneath the deepest level of the roadcuts. This observation points to a recurrence across a narrow geographic zone, through at least a part of the Pleistocene, of a rather specific though unknown set of pedogenic or environmental conditions during episodes of soil development. A backhoe trench near the town of Garfield, Washington exposed a paleosol fragipan nearly 20 km west of the zone of fragipans delineated during soil survey (Barker, 1981), which would be the fragipans developed during the Holocene. Given the large gradients of moisture, temperature, and elevation on the eastern edge of the Palouse, this would represent a large shift in the location of the steppe–forest boundary during at least one episode of soil development if my assumption is correct that this ecological boundary is involved in the development of fragipans in northern Idaho. The topographic position of the soil site near Garfield suggested the paleosol fragipan was near the bottom of the loess stratigraphic section and might have represented a period of soil development during the Middle or even Early Pleistocene. One possibility is that this soil and others of great age in the loess formed under a wetter Early Pleistocene climate that might have caused climatic and vegetation zones to have been situated farther to the west than they are today. This could have been caused by a significantly reduced rain shadow effect (and therefore higher precipitation) from an ancestral Cascade Range whose crest had not yet been uplifted to its Late Pleistocene and Holocene elevations, or perhaps by a postulated global secular change from warm and moist to cooler and drier from the Late Pliocene to the present (Dodonov, 1979, 1986).

Reconnaissance of sites across the "pedocal–pedalfer" (calcic–argillic) boundary in the central part of the Palouse produced sequences of paleosols that are transitional in character, i.e. buried profiles that have both argillic horizons and calcic horizons. Here also, examination of exposures on both sides of the transition zone produces some paleosols that appear to be anomalous in development compared to other soils in the exposures, suggesting times when critical soil–climatic boundaries had shifted significantly during development of several paleosols within a stratigraphic sequence. At present, the detailed stratigraphic and chronologic controls are lacking and fresh roadcut exposures are generally too infrequent to be able to postulate a chronology of climatic swings in the Palouse; however, research is in progress to establish these controls (McDonald, 1987; Nelstead, 1988; Busacca, 1989; McDonald and Busacca, 1989), at first for Late Quaternary loess.

Paleosols in exposures in the driest zones of the Palouse and Scabland, such as at Washtucna, are somewhat similar in their key pedogenic features. By this I mean that the commonly observed pattern is a cambic horizon over a calcic horizon, a petrocalcic, or a duripan. Large differences do exist in the degree of development of these features (Fig. 2), but these differences may be due to differing lengths of time of soil development as well as differences in climate. Paleosols in the lower part of this stratigraphic section and deep in other sections that appear to be Middle or Early Pleistocene generally have smaller accumulations of carbonates (Fig. 2), larger accumulations of silica, and redder color hues than paleosols higher in the section, and some have cambic horizons that border on argillic character; a few are argillic. It could be speculated, without conclusive evidence at this time, that these soils also reflect a generally higher rainfall during their development as part of a secular change from wetter to drier climate during the Quaternary. The lack of well developed argillic horizons in any paleosols in the exposure at Washtucna, which today has an MAP of 300 mm, suggests that this site has not experienced any significant periods of soil development when effective precipitation was as much as twice what it is today because argillic horizons would be expected to have formed.

CONCLUSIONS AND IMPLICATIONS

About nineteen paleosols can be recognized in the 26-m section at Washtucna based on physical, chemical, morphological (Fig. 2) and microscopic data; some of the less strongly developed soils have been obscured by overlap of soil development in this episodically rising loess landscape (Busacca and Feldman, 1985). Attempts to date tephra layers in the middle and lower part of the Washtucna section (Fig. 2) and other deep exposures by the fission-track method have been unsuccessful (Foley, 1982; A.J. Busacca, unpublished data); nevertheless, the exposed part of the section at Washtucna must span more than one million years based on magnetostratigraphy and based on the fact that as many as 15–35 m of loess may underlie this exposure.

The very great number of paleosols in the loess and the complex erosional and depositional histories of individual hills within the loess so far have thwarted attempts to establish correlations among deep exposures. For example, a deep exposure was studied about 40 km to the northeast of Washtucna because it was thought that the section might be correlative in age and sequence to that at Washtucna. Although the 23-m section has about 25 buried paleosols of grossly similar character to those at Washtucna, the entire 23-m section is normally magnetized (Busacca, 1989), whereas the Washtucna section is reversely magnetized below 12 m (Fig. 2). I tentatively interpret this entire normally magnetized section as having been deposited during the Brunhes Normal Polarity Chron. At best, the section is only partially correlative with that at Washtucna. Because of the great thickness of normally magnetized loess at this second section compared to that at Washtucna, a further implication is that the normally magnetized part of the Washtucna section may have subtle disconformities and that an unknown portion of the geologic record may be missing from this interval. This points further to the need for caution in trying to establish correlations among sites.

Greater success has been obtained in younger loess because there are more exposures and the geologic record is not as fragmented as it is in older loess: loess and paleosols that span about the last 100,000 yr have been correlated among sites within a radius of about 70 km around Washtucna (McDonald, 1987; McDonald and Busacca, 1987; McDonald and Busacca, 1989), based on recognizable pedostratigraphic units and correlated tephras.

Clearly, based on a potential age of 1–2,000,000 yr and on its extraordinary pedostratigraphic record, the Palouse loess must be ranked among the most significant deposits for understanding the Quaternary of North America, but much work remains to bring this record to light.

The somewhat consistent distributions of climatically controlled pedogenic features within loess-stratigraphic sections (based on reconnaissance observations) at sites across the region suggests to me not that the Palouse escaped severe changes in climate during the Pleistocene, but rather that many of the episodes of soil development may have taken place during a consistent part of each glacial–interglacial climatic cycle. If this is true, one of the key questions becomes: *which part* of each cycle experienced stable landscapes, low rates of loess deposition, and soil development.

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Micromorpholog
Luochuan Loess
and Environmen

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ABSTRACT

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loess section, China: pedost
143.

The loess-paleosol sequence
Pleistocene back to 2.5 Ma in
North America. To deduce a r
genesis of the paleosols is impo
have disappeared in the case o
tance because it enables the r
ment, especially in pedocomple
The upper part of the loess-p
in the SPECMAP curve of the
even more detailed record of co
the paleoclimate of the intergla
S1-pedocomplex, the upper pa
natural Holocene soil, indicati
steppe soil also, whereas the fi
cating more moist and partly
quence of the Matuyama epoch
cores known so far. The Lishi l
two more soils (S11 and S13)
similar to the present one and
S10) indicating again more mo
in the Wusheng loess are prob
addition of loess. The "Red Cla
paleosols; the parent material

INTRODUCTION

Sections in the centra
to loess profiles in Europ

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