# Glacial anticyclone recorded in Palouse loess of northwestern United States

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## ABSTRACT

**Climate simulations for the Last Glacial Maximum using general circulation models typically show a glacial anticyclone that produced an easterly wind anomaly south of the North American ice sheets. Evidence of this phenomenon has not been found in eolian sedimentary deposits that record surface wind patterns. Luminescence ages of loess and accompanying paleoecologic records from opal phytoliths and paleosol units across the Columbia Plateau, Washington State, United States, document a decrease, up to fivefold, in regional dust production and accumulation from 35 ka to 15 ka. This interval corresponds to simulations indicating that a glacial anticyclone weakened prevailing south-southwesterly winds that have shaped the eolian landscape of the Columbia Plateau since at least 75 ka. At the same time that the glacial anticyclone suppressed dust production and accumulation, enhanced cold and dry conditions resulted in soil formation dominated by intense bioturbation in periglacial steppe accompanied by shallow calcium carbonate precipitation. This is the first evidence from eolian deposits in North America verifying that the glacial anticyclone altered surface wind patterns and affected eolian systems during the Last Glacial Maximum.**

**Keywords:** loess, Last Glacial Maximum, glacial anticyclone, Columbia Plateau.

## INTRODUCTION

Simulations of the Last Glacial Maximum (LGM, 21 ka) in North America using general circulation models (GCMs) suggest that the Laurentide Ice Sheet had major effects on atmospheric circulation patterns (Kutzbach and Wright, 1985; COHMAP Members, 1988; Hostetler and Bartlein, 1999; Bartlein et al., 1998). These simulations show that the ice sheet caused a shift in the jet stream to the south, resulting in moist conditions in the southwestern United States (Bartlein et al., 1998) and a decrease in winter precipitation for the Pacific Northwest (Whitlock et al., 2001). A glacial anticyclone, produced by high atmospheric pressure over the ice sheet, generated an easterly surface wind anomaly just to the south of the ice sheet (Kutzbach and Wright, 1985; COHMAP Members, 1988; Hostetler and Bartlein, 1999; Bartlein et al., 1998) (Fig. 1). Some GCMs show a persistent easterly flow south of the ice sheet (Kutzbach and Wright, 1985; COHMAP Members, 1988), but more recent simulations show easterly flow as less pronounced and more seasonally variable, with westerly flow returning in winter months (Bartlein et al., 1998; Whitlock et al., 2001) (Fig. 1). Although eolian sand dunes and loess should record major changes in wind patterns, evidence of the glacial anticyclone has been lacking from field studies of eolian deposits. For example, in the Great Plains region of the United States, eolian sand dunes and loess reflect northwesterly flow during the LGM (Muhs and Bettis, 2000; Krieg et al., 2001). The conclusion in the Great Plains was that the anticyclone, if it did exist, did not disrupt the normal wind patterns long enough or frequently enough to leave a record in the eolian sediments (Muhs and Bettis, 2000). Stabilized late-glacial dunes in Saskatchewan that formed between 10,000 and 8800 yr B.P. record anticyclonic winds from a shrunken Laurentide Ice Sheet prior to the onset of modern wind patterns (David, 1981), confirming that ice sheets affected local wind regimes during the beginning of the Holocene.

The eolian system on the Columbia Plateau (Fig. 2) is composed of sand dunes and loess derived from deflation of sand- and silt-rich glacial outburst-flood sediment contained in upwind sedimentary basins (Busacca and McDonald, 1994). Catastrophic flooding was the result of ice-dam failure that drained glacial Lake Missoula repeatedly between ca. 18,000 and 15,000 cal. yr B.P. (Waitt, 1985).

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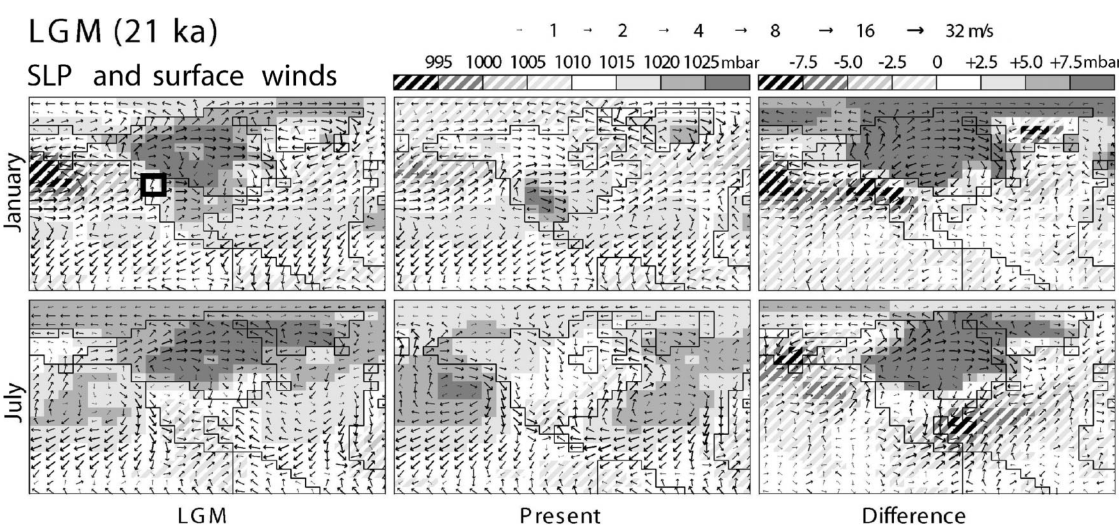


**Figure 1. North America during Last Glacial Maximum (LGM). Maps depict simulated surface winds and sea-level pressure (SLP) generated by glacial anticyclone for winter (January) and summer (July) during LGM, present time, and difference (anomaly). Palouse is represented by square in first panel. Modified from Whitlock et al. (2001).**

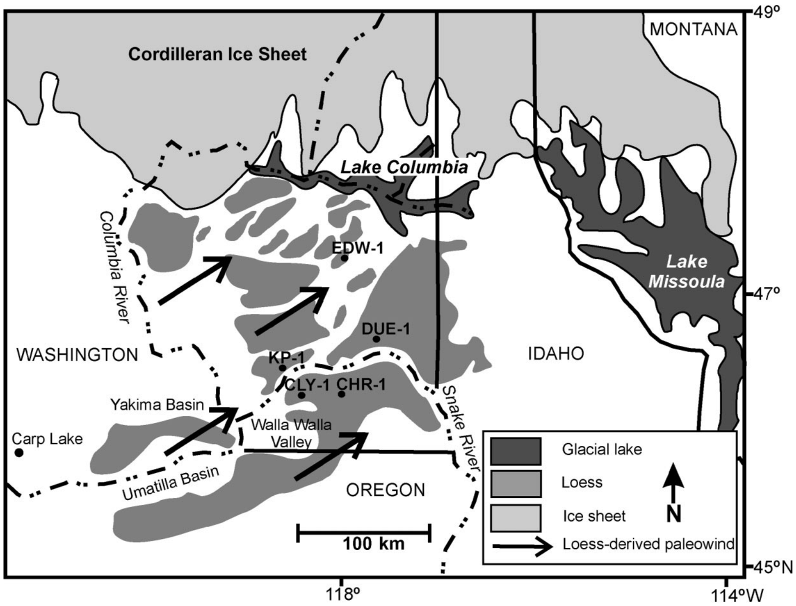


**Figure 2. Palouse loess site locations (black dots) on Columbia Plateau. Loess distribution is shown in relationship to Cordilleran ice sheet, pathways of glacial outburst floods, and prevailing southwesterly winds during Last Glacial Maximum.**

Sand dunes are mostly late Pleistocene to Holocene, and preexisting dunes were likely eroded away by outburst-flooding episodes (Gaylord et al., 2001). The thick loess cover, where not eroded by flooding, may represent episodic accumulation since at least 2 Ma (Busacca, 1991). The two most recent loess units span the late Pleistocene to Holocene and are named L1 (15–0 ka) and L2 (75–15 ka) (Busacca and McDonald, 1994). Loess grain-size and thickness trends from 75 ka to present suggest that dust-transporting winds were consistently from the south and southwest (Busacca and McDonald, 1994). Loess accumulation in the Columbia Plateau is different from that in other regions, including China and the North American Great Plains (Muhs and Bettis, 2003), because most dust production and accumulation on the Columbia Plateau occurred during interglacial and interstadial periods (Busacca and McDonald, 1994). Ice-core records show spikes in worldwide dust fluxes during full-glacial periods (Petit et al., 1999), a time when local dust fluxes of the Columbia Plateau were diminished and soil formation was dominant.

## PALEOECOLOGY

Opal phytoliths extracted from loess on the Columbia Plateau document a periglacial steppe-vegetation assemblage representing cold and dry conditions during the LGM (Fig. 3). At the KP-1 site (location in Fig. 2), cold and dry conditions persisted from 35 to 15 ka and supported a sagebrush steppe consisting of *Artemisia* and drought-indicating grasses *Stipa* and *Poa* (Blinnikov et al., 2001, 2002). Other sites on the Columbia Plateau such as CHR-1 have assemblages suggesting *Artemisia* steppe at higher elevations and patchy coniferous parkland at middle elevations (Blinnikov et al., 2002). Pollen records from Carp Lake on the western edge of the Columbia Plateau confirm the phytolith record in the loess: 30 to 13 ka was coldest and driest, represented by *Artemisia* steppe (Whitlock and Bartlein, 1997).

The prominent Washtucna paleosol at the top of the L2 loess, formed between ca. 40 and 20 ka (Richardson et al., 1997), is dominated by a cylindrical burrow fabric, formed by nymphs of *Cicadidae* (cicadas), that is indurated with calcium carbonate emplaced during arid soil formation (O'Geen and Busacca, 2001). Cicada nymphs thrive on the root systems of woody shrubs (O'Geen and Busacca,

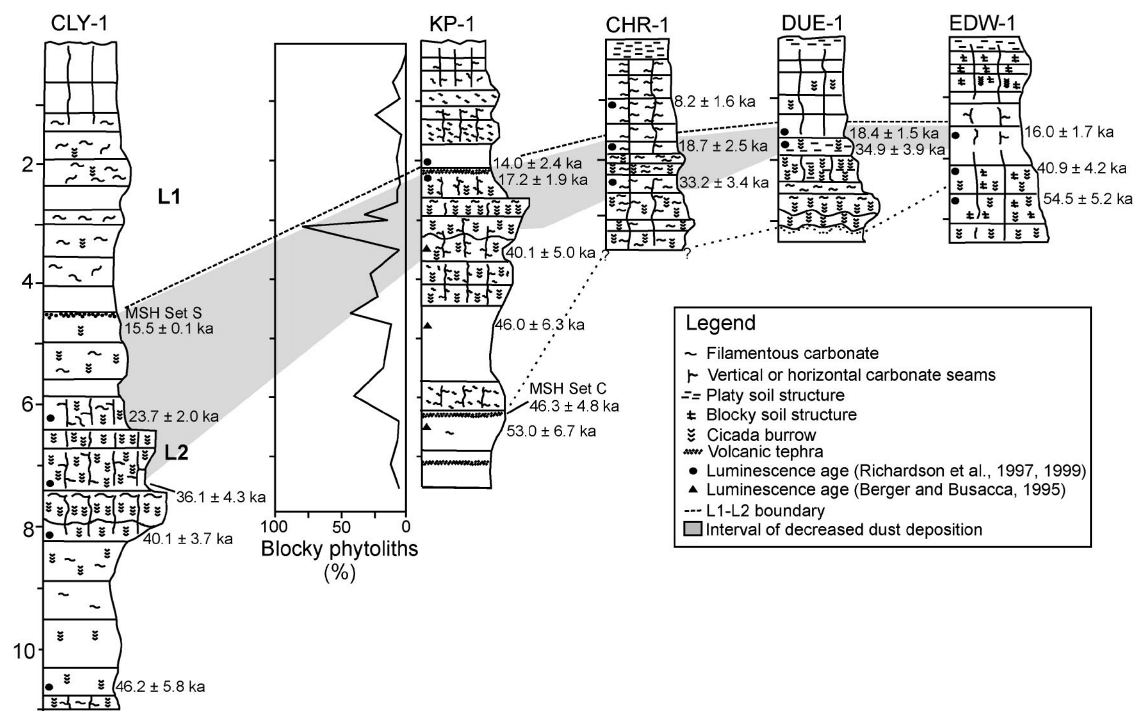


**Figure 3. Loess sections showing paleoecologic and paleosol properties with geochronologic control (age of Mount St. Helens [MSH] Set S tephra based on calibrated $^{14}C$ age of 15.4 ± 0.1 ka [Mullineaux, 1986] recalculated by using CALIB Rev 3 [Stuiver and Reimer, 1993]). Age of Set C tephra is thermoluminescence (TL) age from Berger and Busacca (1995). Ages of loess were determined by TL. Loess sections are in order (left to right) of decreasing distance from dust sources. Blocky phytolith percentages represent shrubs (mostly *Artemisia*) as proxy for low soil moisture at KP-1 (Blinnikov et al., 2001, 2002). For methods of phytolith extraction and analysis, see Blinnikov et al. (2001). Gray zone indicates time of decreased dust accumulation rates. It is important to note that soil features like burrows and carbonates postdate age of loess at same stratigraphic depth.**

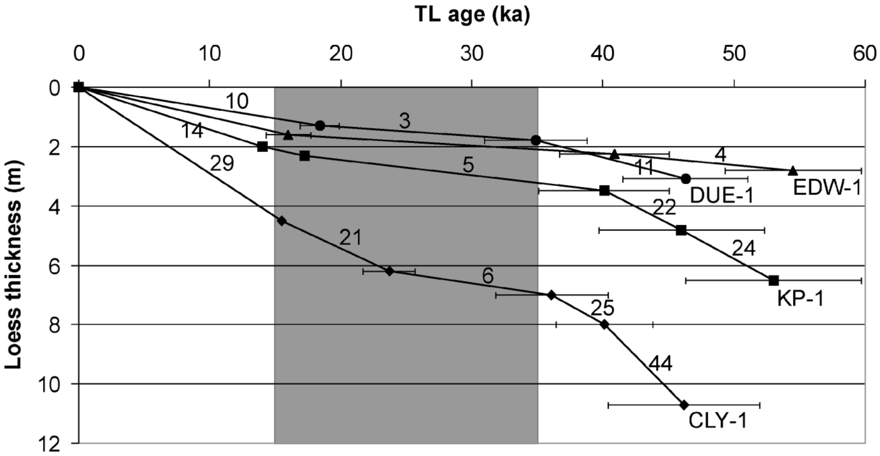


**Figure 4. Loess accumulation rates through time. Basin-wide decrease in Last Glacial Maximum loess accumulation rates (cm/k.y.) are based on thermoluminescence (TL) ages and Mount St. Helens (MSH) Set S tephra. Section tops are modern based on presence of MSH 1980 tephra and intact soil morphology. Selected error bars shown; all errors reported in Figure 3. For detailed methods of TL age determination, see Richardson et al. (1997) and Berger and Busacca (1995). Shaded area represents approximate timing of glacial anticyclone.**

2001), and the phytolith assemblage of this paleosol is dominated by *Artemisia* (Fig. 3; Blinnikov et al., 2001, 2002). The phytoliths and burrows of this paleosol are paleoecologic indicators that further corroborate cold and dry conditions during the LGM. Despite the cold conditions, there is no substantial evidence (such as ice-wedge casts) that the soil was frozen.

## LUMINESCENCE GEOCHRONOLOGY

Loess sequences proximal and distal to dust sources were dated by thermoluminescence (TL) (Berger and Busacca, 1995; Richardson et al., 1997, 1999); ages of the upper part of the L2 loess were determined from five outcrops (Fig. 3). Distribution of ages shows that sites closest to the ice sheet (DUE-1, EDW-1) recorded little to no dust accumulation during the LGM, whereas sites close to source basins (CLY-1, KP-1) recorded continued, though reduced, rates of accumulation compared to interglacials, thus indicating a change to the eolian system (Fig. 4).

The two sites $<$125 km south of the ice sheet (EDW-1, DUE-1) record dust-accumulation rates during the LGM of $<$3 cm/k.y., a marked decrease from pre-LGM and post-LGM rates of 7–11 cm/k.y. (Fig. 4). In contrast, the two sites $>$150 km south of the ice sheet (CLY-1, KP-1) record dust-accumulation rates during the LGM of 6 cm/k.y., compared to rates of $>$20 cm/k.y. prior to 35 ka and after 15 ka (Fig. 4).

## DISCUSSION

The decrease in accumulation rates from 35 to 15 ka in the Palouse has been attributed to an exhaustion of the sediment supply or to an episode of erosion (Richardson et al., 1999). Sediment supply was never exhausted, however, because accumulation rates of 6 to $>$20 cm/k.y. at sites such as CLY-1 show that loess continued to accumulate close to its sources even during the LGM. Erosion of loess that would produce anomalously low deposition rates at distal sites is an unlikely explanation for the changing accumulation patterns because (1) the dry conditions would have decreased the likelihood of water erosion, (2) the loess at these distal sites contains $<$10% sand-sized particles, making wind erosion via saltation bombardment unlikely, and (3) evidence for erosional surfaces in these stratigraphic intervals has not been observed: intact soil morphology suggests little to no erosion. Decrease in sediment availability may also explain the decrease in dust production, but drier conditions during the LGM resulted in a less-dense vegetation cover in the driest parts of the Columbia Plateau, which was the source of dust, increasing sediment availability.

Changes in dust-trapping efficiency could also explain the reduced accumulation rates at sites closer to the ice sheet. As the height of vegetation increases, the aerodynamic roughness height also increases, resulting in higher trapping efficiency (Tsoar and Pye, 1987). Sparse herb tundra with low trapping efficiency has been hypothesized to explain the lack of thick LGM loess in Alaska (Muhs et al., 2003), but studies in the Great Plains suggest that thick loess accumulated on ridge tops during the LGM under or in proximity to herb tundra vegetation (Baker et al., 1999; Mason et al., 1994).

The occurrence of cicada burrows in the Washtucna Soil at the DUE-1, EDW-1, and other distal-source loess sites indicates the presence of sagebrush that has a higher trapping efficiency than bunchgrass steppe vegetation, although the density of sagebrush is still a question. At sites proximal to their dust source (CLY-1 and KP-1), as much as 100% of the Washtucna Soil is burrowed by cicadas, indicating widespread sagebrush throughout the LGM when the soil was forming (O'Geen and Busacca, 2001) (Fig. 3). Therefore, trapping efficiency would have been greater than that of today's bunchgrass steppe, ruling out decreased trapping efficiency as a cause for lowered rates of accumulation during the LGM.

The trends in thinning with distance from source (Fig. 3) show the regional thickness patterns of the L1 and L2 loess; however, rates of accumulation drastically decreased at all sites from ca. 35 to 15 ka. We conclude from these data that a change in surface wind regime as simulated by GCMs was responsible for the decrease in dust accumulation on the Columbia Plateau from 35 to 15 ka. Decreased dust accumulation as well as cold and dry conditions occurred on the Columbia Plateau throughout oxygen isotope stage (OIS) 2 (27.6–14 ka; Martinson et al., 1987) and during the later part of OIS 3 (35–27.6 ka), suggesting that the timing of the anticyclone coincided with ice-sheet growth. Loess was aggrading at rates only one-third those of the postglacial period at sites $>$150 km from the ice margin, demonstrating that weakened westerly winds extended as far south as the Washington-Oregon border. Simulated higher sea-level pressures extending from the ice sheet to just south of Washington State (Fig. 1) may be a proxy for the spatial extent of the anticyclone (Hostetler and Bartlein, 1999; Bartlein et al., 1998). The anticyclone would also have deflected moisture-bearing storms from the west, enhancing the dry conditions on the Columbia Plateau (Whitlock and Bartlein, 1997). Furthermore, soil development (e.g., the Washtucna paleosol) during the LGM was a function of decreased dust accumulation rates controlled by the anticyclone. Calcium carbonate development is strong in loess deposited between 40 and 20 ka because the decrease in dust accumulation and enhanced aridity reduced translocation of carbonates to a shallow depth, as shown by the carbonate-cemented A-horizon cicada-burrow fabrics. The presence of the anticyclone and the suppression of dust-transporting winds generated the antiphased relationship in dust accumulation and soil formation in the Palouse compared to places like the Great Plains and Europe where thick loess accumulated during the LGM.

Weakened prevailing winds caused by the anticyclone on the Columbia Plateau apparently did not alter the directional trends of downwind thinning or fining of loess south of the ice sheet, resulting in the lack of geomorphic evidence for the anticyclone. Instead, the anticyclone resulted in more subtle changes in the loess, recorded as decreased accumulation rates. Southwesterly winds still prevailed during the anticyclone, although at a weakened state, and easterly winds off the ice sheet were not likely frequent enough to generate eolian deposits. Consequently, little to no loess was derived from glacial outwash or outburst-flood sediments proximal to the Cordilleran Ice Sheet or from the Columbia River or Snake River floodplains. Fluvial and outwash sediments were confined to deeply incised canyons with minimal floodplains, and the texture of outburst-flood sediments near the ice sheet was too coarse to be transported by wind, further restricting the potential for production of eolian sediment.

## CONCLUSIONS

LGM loess on the Columbia Plateau offers compelling evidence that prevailing southwesterly dust-transporting winds were suppressed owing to effects of the North American ice sheets. From 35 to 15 ka, dust deposition rates decreased to nearly zero within 125 km of the ice sheet, although they continued at greatly reduced rates at sites farther from the ice near dust source basins.

GCMs used to simulate LGM climates utilize few boundary conditions and may have coarse spatial resolution and simplified topographic effects, resulting in a generalized depiction of the real climate system (Kutzbach and Wright, 1985). For these reasons, it may be difficult to accurately simulate wind regimes near ice sheets. The modeled easterly wind anomaly, however, which represents weakened westerly surface winds for the Pacific Northwest, best explains decreased dust accumulation on the Columbia Plateau during the LGM. The response of eolian systems to the glacial anticyclone as demonstrated here may aid climate modelers in understanding effects of dust aerosols on North American climate.

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