

# Glacial-interglacial-scale paleoclimatic change without large ice sheets in the Oligocene of central Oregon

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## ABSTRACT

Abundant late Oligocene paleosols in eastern Oregon compose a paleoclimatic archive rivaling the resolution of deep-sea cores, recording 105 Milankovitch-scale cycles over the 5.1 m.y. duration of the middle John Day Formation. Paleoclimatic cycles are apparent from the fossil record of snails, mammals, trace fossils, soil structure, depth to calcic horizon of paleosols, and carbon and oxygen isotopic composition of pedogenic carbonate. Interpreted Oligocene alternation between semiarid sagebrush steppe and subhumid wooded grassland has the same amplitude as that inferred during accumulation of the Quaternary Palouse Loess in Washington and Oregon. This similar amplitude is surprising because large ice caps like those of the Quaternary did not extend across North America or Europe during the Oligocene. Thus ice-albedo amplification of Milankovitch-scale insolation variation cannot explain the similar magnitude of Oligocene paleoclimatic fluctuation. Weak orbital signals were more likely amplified by greenhouse gases such as CO<sub>2</sub> and CH<sub>4</sub> due to changing carbon budgets in the sea and on land.

**Keywords:** paleosols, paleoclimate, Oligocene, Oregon, carbon isotopes, oxygen isotopes.

## INTRODUCTION

Global climate change on time scales of tens to hundreds of thousands of years is more or less in tune with variations in Earth's orbital configuration (Hays et al., 1976), such as precession of the equinoxes (23 k.y.), obliquity of the rotational axis (41 k.y.), and eccentricity and inclination of the orbital ellipse (~100 k.y.). However, insolation differences due to orbital eccentricity are small compared with those due to obliquity and precession, and all are smaller than needed to explain observed high-amplitude glacial-interglacial temperature change (Muller and MacDonald, 2000). If orbital variations are pacemakers of the ice ages (Hays et al., 1976), then what is the heart of this metaphor for global paleoclimatic change?

Milankovitch (1941) not only discovered the link between orbital variations and paleoclimate, but considered the main amplifier of Quaternary orbital signals to be changing volumes of ice sheets, a view that is still popular (Clark et al., 1999). In contrast, Arrhenius (1896) still has supporters (Berger, 2002) in considering variations in atmospheric CO<sub>2</sub> to be at the heart of Quaternary paleoclimatic change. Other plausible amplification mechanisms for orbital pacemakers include fluctuations in cosmic and atmospheric dust (Muller and MacDonald, 2000), but these are difficult to tease apart from ice or greenhouse amplification because sedimentary records are responsive both to glacial advances and to ecosystem-CO<sub>2</sub> fluctuation. These ideas are here reevaluated with new evidence from late Oligocene paleosols of the John Day Forma-

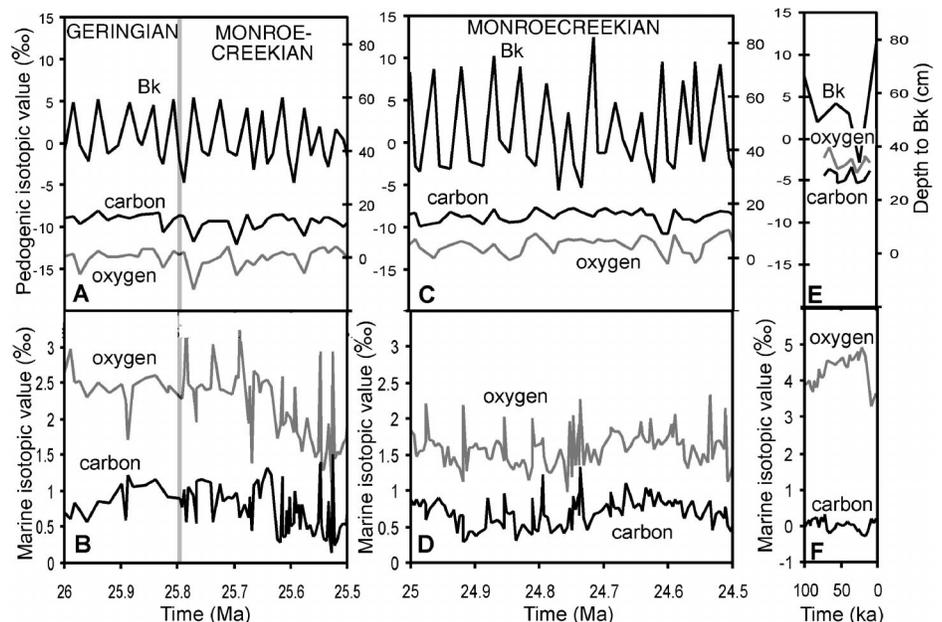
tion of central Oregon that record climatic fluctuations surprisingly similar to those of Quaternary paleosols in the Palouse Loess of eastern Washington (Figs. 1 and 2).

## MATERIALS AND METHODS

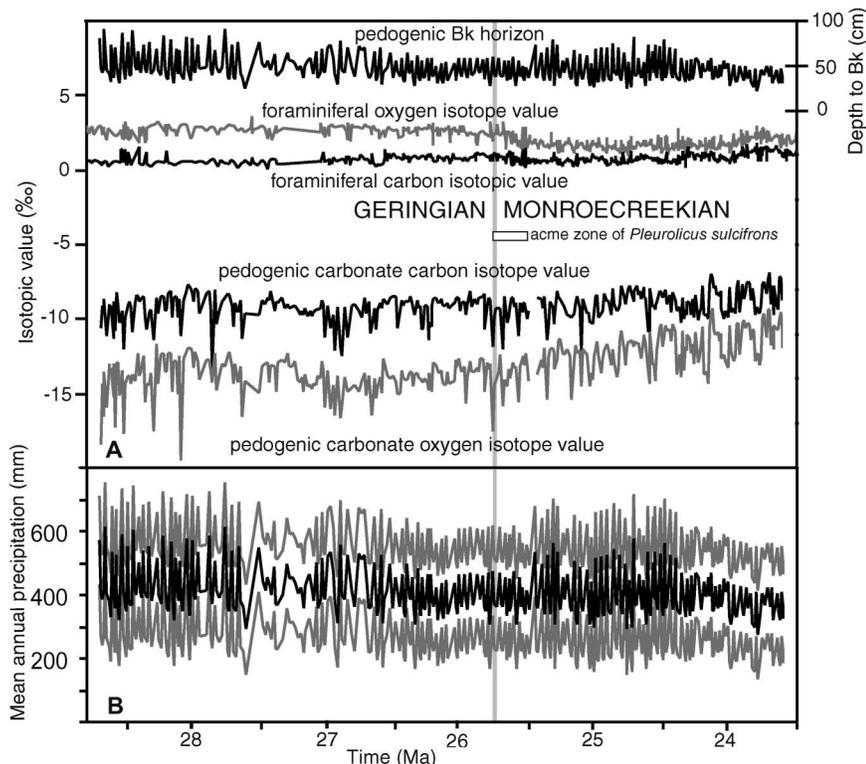
The Oligocene upper John Day Formation (Retallack, 2004) and Quaternary Palouse

Loess (Busacca et al., 1998) are sequences of silt-sized, air-fall and redeposited rhyodacitic volcanic ash. Fresh volcanic ash is volumetrically minor in both sequences, because of redeposition and weathering within abundant calcareous paleosols formed in the rain shadow of the Cascade volcanic arc. Sequences of paleosols were measured near Kahlotus in Washington (Busacca et al., 1998; Blinnikov et al., 2002), and Kimberly in Oregon (Retallack, 2004).

Palouse Loess has been dated by thermoluminescence, tephrostratigraphy, and magnetostratigraphy (Berger and Busacca, 1995). The upper John Day Formation has been dated by four high-precision <sup>39</sup>Ar/<sup>40</sup>Ar radiometric dates (Fremd et al., 1994), supported by magnetostratigraphic dating (Prothero and Rensberger, 1985), and mammalian biostratigraphy (Retallack, 2004; newly collected fossils cataloged on line at <http://www.museum.nps.gov>). We estimated ages for particular paleosols in each section by applying a linear interpolation of age versus meter level of dated



**Figure 1.** Time series for selected intervals of Oligocene (A–D) and Quaternary (E–F) variation in depth to calcic (Bk) horizon, and oxygen and carbon isotope values of pedogenic carbonate, compared with marine foraminiferal carbonate carbon and oxygen isotope values. Paleosols are in Quaternary Palouse Loess near Kahlotus, Washington (Busacca et al., 1998) and in Oligocene John Day Formation on Longview Ranch, near Kimberly, Oregon (Retallack, 2004). Carbon and oxygen isotopic composition of Quaternary foraminifera are from equatorial Pacific Site 849 (Mix et al., 1995) and those for Oligocene foraminifera are composite of 36 Ocean Drilling Program and Deep Sea Drilling Project cores (Zachos et al., 2001).



**Figure 2.** Comparisons of Oligocene marine and nonmarine time series. **A:** Oligocene depths to calcic (Bk) horizon in paleosols and variation in pedogenic carbon and oxygen isotopic values compared with variation in carbon and oxygen isotopic values of marine foraminifera (Zachos et al., 2001). **B:** Oligocene mean annual precipitation in central Oregon based on application of transfer function relating this to depth of Bk horizon (Retallack, 1994, 2000). Error envelope (gray in B) is one standard deviation.

levels. Aperture altitude measured for snails is the height of the opening coplanar with the columella; other snail measures were also as defined by Baker (1934). Hypsodonty of rodents was measured as height of enameled molars above the jaw.

This study uses stable isotopic values for Bk horizons of paleosols in the Palouse Loess, rather than all analyses of Busacca et al. (1998). Stable isotopic composition for oxygen and carbon from carbonate nodules of 354 paleosols in the middle John Day Formation on Longview Ranch were analyzed in the Stable Isotope Laboratory of the Earth Environmental Group at the Australian National University, in Canberra, Australia, using a Finnigan MAT-251 attached to a Kiel-1 automatic carbonate reaction device, and NBS-19 and NBS-18 standards.<sup>1</sup> Results are reported in delta notation with respect to Vienna Pee Dee belemnite. Reproducibility of  $\delta^{13}\text{C}$  determined by replicate analyses is within 0.05‰ per specimen, 0.15‰ within a nodule, and 0.2‰ within a paleosol.

<sup>1</sup>GSA Depository item 2004050, isotopic analyses of Oligocene pedogenic nodules, is available online at [www.geosociety.org/pubs/ft2004.htm](http://www.geosociety.org/pubs/ft2004.htm), or on request from [editing@geosociety.org](mailto:editing@geosociety.org), or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

### PEDOGENIC CARBONATE DEPTH FLUCTUATION

Both Oligocene and Quaternary paleosol sequences show comparable patterns in depth and kind of pedogenic carbonate horizons (Fig. 1). The average amplitude of cyclical variation in depth to calcic horizon within Oligocene paleosols was  $25 \pm 8$  cm (one standard deviation, after burial compaction of ~80%), and the average amplitude within the Quaternary record near Kahlots, Washington, was  $21 \pm 5$  cm (uncompacted). Among 358 Oligocene paleosols observed near Kimberly, Oregon, between the 28.7 Ma John Day Tuff H and the 23.6 Ma uppermost Kimberly Member, there are 105 cycles (Fig. 2A). Most of the Oligocene paleoclimatic cycles represent Milankovitch-obliquity cycles (41 k.y.), but eccentricity cycles (100 k.y.) may also be reflected in some full and bundled cycles (Figs. 1 and 2). Most cycles consist of one paleosol with large nodules in a deep (>50 cm) calcic horizon, overlain by two paleosols with diffuse, small nodules in a shallow (<50 cm) calcic horizon (Retallack, 2004). Each cycle in Palouse Loess is similar, except that deep-calcic paleosols have small (2–3 mm) and sparse nodules.

The common observation that carbonate

nodules are shallower in modern soil profiles of dry regions than in profiles of humid regions has been quantified to provide a transfer function yielding mean annual precipitation from depth to calcic horizon, provided allowances are made for other soil-forming factors (Retallack, 1994, 2001), and depths are corrected for compaction due to burial (Sheldon and Retallack, 2001). Application of this previously published transfer function to the Oligocene paleosols reveals that deep-calcic paleosols represent subhumid paleoclimates (mean annual precipitation [MAP] =  $490 \pm 50$  mm,  $n = 124$ ) and the shallow-calcic paleosols represent semiarid paleoclimates (MAP =  $366 \pm 36$  mm,  $n = 235$ ) (Fig. 2B). Paleoprecipitation estimated in the same way from Quaternary paleosols near Kahlots, Washington, is surprisingly similar (MAP =  $502 \pm 39$ , and  $383 \pm 80$  mm,  $n = 7$  and 3, for deep and shallow calcic paleosols, respectively).

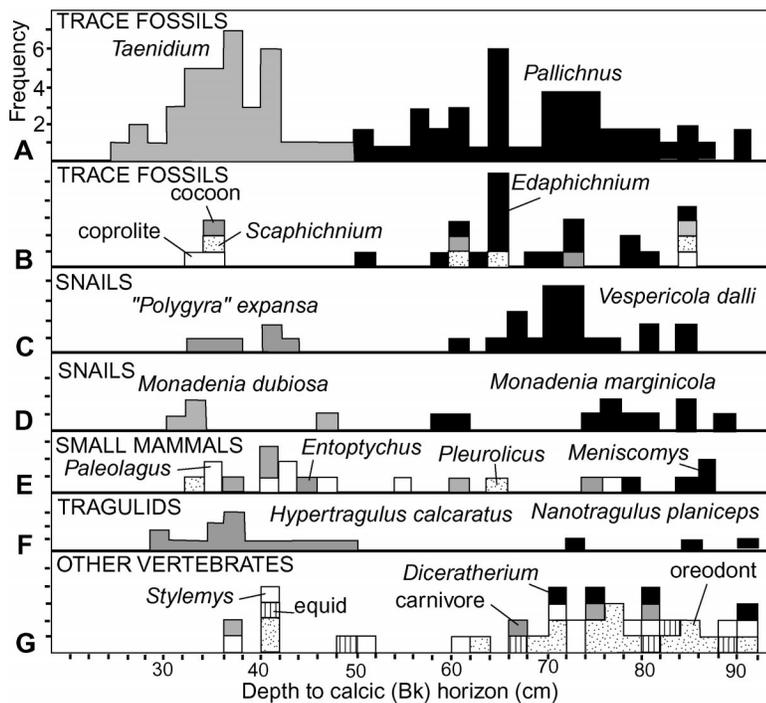
### PEDOGENIC CARBONATE ISOTOPIC FLUCTUATION

Paleoecological and paleoclimatic changes also are revealed by  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  isotopic analyses of carbonate nodules within paleosols of the Palouse Loess and John Day Formation (Figs. 1 and 2), both showing amplitudes of 2‰–4‰. Stable isotopic variations may reflect paleoclimatic fluctuation, with less evaporative loss of  $\text{H}_2^{16}\text{O}$  and less soil respiration of  $^{12}\text{CO}_2$  during cold-dry phases than warm-wet phases, as modeled by Cerling (1984). Isotopic values found in both Quaternary and Oligocene paleosols are consistent with dominantly  $\text{C}_3$  vegetation (Koch et al., 2003). There is no isotopic evidence for  $^{13}\text{C}$ -enriched  $\text{C}_4$  plants in any known Oregon or Washington fossil soils, plants, or mammals (Cerling et al., 1997). A small component of isotopic  $^{13}\text{C}$  enrichment could have come from desert succulents (Cactaceae, Euphorbiaceae) and shrubs (such as saltbush, *Atriplex*), which use CAM (Crassulacean acid metabolism) as a water-conserving mechanism (Quade et al., 1989).

### FOSSIL ASSEMBLAGE FLUCTUATION

Fossils in the paleosols are evidence of local ecosystem change coordinated with paleoclimatic fluctuations. Alternating assemblages of grassland versus sagebrush phytoliths (Blinnikov et al., 2002), fossil burrows of grassland earthworms versus sagebrush cicadas (O'Geen and Busacca, 2001), and fossil teeth of bog lemmings versus sagebrush voles (Rensberger and Barnosky, 1993) are well documented in the Quaternary Palouse Loess of Washington.

Oligocene paleosols of the John Day Formation are surprisingly similar because deep-calcic paleosols have trace fossils of dung



**Figure 3.** Distribution of fossils in paleosols of varied depth to calcic horizon in late Oligocene John Day Formation on Longview Ranch, Oregon. Specific ages and levels of fossils are detailed elsewhere (Retallack, 2004).

beetles (*Pallichnus*) and earthworms (*Edaphichnium*) typical of grassland ecosystems (Figs. 3A and 3B), whereas shallow-calcic paleosols have trace fossils of cicadas (*Taenidium*) typical of Quaternary sagebrush ecosystems (O'Geen and Busacca, 2001).

Among fossil snails of the John Day Formation (Roth, 1986), those with deeper and more open body whorls (*Monadenia marginicola*, *Vespericola dalli*) are found in the deep-calcic paleosols, whereas those with less open body whorls (*Monadenia dubiosa*, "*Polygyra*" *expansa*) are found in shallow-calcic paleosols (Figs. 3C and 3D, 4A and 4B). Comparable changes in aperture of related living snails can be seen in geographic clines from Oregon to California (Pilsbry, 1940), and in modern compared with late Pleistocene snails of Illinois (Baker, 1934).

Oligocene rodents and lagomorphs are more hypsodont in shallow-calcic paleosols than in deep-calcic paleosols (Fig. 4D). Deep-calcic paleosols have more large mammals and the tragulid *Nanotragulus*, whereas shallow-calcic paleosols have more small mammals and the tragulid *Hypertragulus* (Fig. 3F).

Oligocene sagebrush and grassland communities presumably formed a nearby ecotone, which moved through this area with each paleoclimatic shift, as envisaged for Quaternary communities of Washington (O'Geen and Busacca, 2001; Blinnikov et al., 2002), and the Great Plains (Baker, 1934).

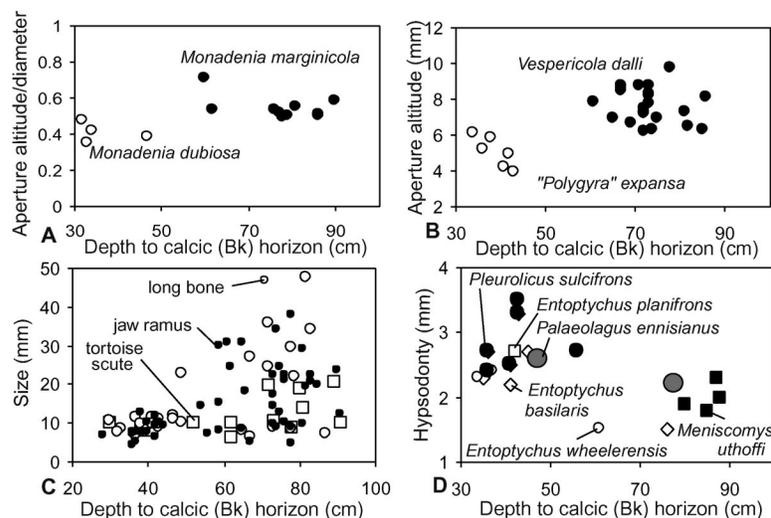
#### COMPARISON WITH GLOBAL MARINE RECORD

On Milankovitch time scales ( $10^4$ – $10^5$  yr), carbon isotope oscillations in marine foraminifera are more muted ( $\pm 2\%$ ) than in our nonmarine records ( $\pm 4\%$ ), but are in phase for the Quaternary (Fig. 1). In contrast, Quaternary oxygen isotopic oscillation in terres-

trial records is out of phase with deep-sea records (Figs. 1 and 2). These differences in amplitude and direction between marine and terrestrial isotopic records have been found in other studies of pedogenic carbonate oxygen and carbon isotopes (Koch et al., 2003).

On longer time scales ( $10^6$ – $10^7$  yr), marine oxygen isotopic values decrease and diverge from the long-term carbon isotopic trend ca. 25.8 Ma. Marine oxygen isotopic values are affected by temperature, as well as salinity variations and ice-cap growth (Zachos et al., 2001). The sense of the oxygen deviation in marine foraminifera suggests interruption of stable ice volume by transitory warming or ice-cap melting at 25.8–25.5 Ma, and then modest long-term ocean cooling or ice-cap growth. In contrast, warming on land at the same time (25.8–25.5 Ma) is reflected by oxygen isotopic values increasing, as they do in Quaternary ice core records during glacial terminations (Muller and MacDonald, 2000). Paleosols, like ice cores, reflect changes in oxygen isotopic composition of water evaporated from the ocean and incorporated in ice or groundwater, whereas oceanic oxygen isotopic composition reflects a residue of these processes.

Mismatch of terrestrial and marine oxygen isotopic records may explain the puzzling insensitivity of North American mammalian evolution to marine oxygen isotopic records (Alroy et al., 2000). Desertification and subdued Milankovitch paleoclimatic variability (from shallow Bk depths), and cooling or sagebrush expansion (from trace fossil evidence) during an acme zone of moderately



**Figure 4.** Paleosols of the Oligocene John Day Formation on Longview Ranch, Oregon, have deeper calcic horizons, and inferred higher rainfall (Fig. 2B), and have snails with wider apertures, mammals and turtles of larger size, and fewer hypsodont rodents and lagomorphs. A–B: Variation in snail body-whorl size with depth to calcic horizon of paleosols in which they were found. C: Mammal and turtle size vs. depth of calcic horizon in containing paleosol. D: Rodent and lagomorph hypsodontology vs. depth to calcic horizon in paleosols.

fossorial pocket gophers (*Pleurolicus teilzone*) at 25.8–25.5 Ma is followed by the first of the strongly fossorial pocket gophers (*Entoptychus* zones of Rensberger, 1983) at a time of wetter and more highly variable paleoclimate (Fig. 2). The faunal turnover interval (25.8–25.5 Ma) also included first appearances of small tragulids (*Hypertragulus minutus* replacing earlier *H. hesperius*) and the wide-cheeked piglike oreodonts (*Merycochoerus superbus* more common than earlier gracile *Eporeodon occidentalis*; Fremd et al., 1994). Our data thus support prior claims that North American mammal zones correspond to long-term (2.3 m.y.) paleoclimatic wet-dry cycles (Martin, 1994).

## CONCLUSIONS

A surprising observation of our study is the comparable magnitude of paleoclimatic and ecosystem oscillation on 41–100 k.y. time scales during the Quaternary and Oligocene. There was no large Oligocene ice sheet in North America like the Laurentide and Cordilleran ice caps of the Quaternary (Clark et al., 1999), but there were Oligocene ice sheets in Antarctica, and probably alpine glaciers (Zachos et al., 2001). There is thus no clear relationship between global ice volume and magnitude of paleoclimatic or ecosystem change in Oregon and Washington. Ice-albedo effects were less significant paleoclimatic amplifiers of Milankovitch orbital forcing than greenhouse gases such as CO<sub>2</sub> and CH<sub>4</sub>, which would have varied with ecosystem changes.

Oscillations between tundra and boreal forest (Overpeck et al., 2003) and between rain forest and savanna grassland (Dupont et al., 2000) occurred elsewhere at the same time as Quaternary oscillations between grassland and sagebrush in Oregon and Washington (Blinnikov et al., 2002). The end members of such oscillations have very different greenhouse gas emissions, carbon sequestration capacity, and nutrient requirements. The soils produced have a trajectory from young, nutrient-rich loessic soils rich in glacial dust to old, nutrient-depleted carbonate-cemented, clay-plugged or thick peaty soils with diminished productivity and rate of carbon sequestration (Retallack, 2001). Ecosystems do not persist in the face of soil impoverishment, but build slowly and then collapse abruptly in a sawtooth pattern comparable to isotopic time series of glacial terminations. Alternation of stable and unstable soils also explains variations in sediment accumulation rate and concentration of cosmic dust in sediments through glacial-interglacial cycles (Muller and MacDonald, 2000). Globally coordinated cycles of slow soil nutrient depletion and rapid renewal

are plausible paleoclimatic amplifiers of astronomical forcings.

## ACKNOWLEDGMENTS

We thank R.R. Hunt for field assistance and M. Gagan for help with isotopic analyses. C. Whitlock, R.M. Hunt, and N.D. Sheldon offered useful discussion. Funded by National Parks Service contract P9325010503 and National Science Foundation grant EAR-0000953.

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Manuscript received 30 September 2003  
 Revised manuscript received 30 December 2003  
 Manuscript accepted 31 December 2003

Printed in USA