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# Orbital control, climate seasonality, and landscape evolution in the Quaternary Rocky Mountains

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ABSTRACT

While climate has long been implicated in the extensive erosion of Eocene through Miocene-aged basin fills in the Rocky Mountains, lack of precise, high temporal-density datasets of landform ages has made it difficult to detail the mechanisms by which climate increased relief. A dense dataset of (U–Th)/He dates from the Powder River Basin, Wyoming and Montana, USA, indicates correspondence between elevated exhumation and peaks in orbital eccentricity. Here we use an atmospheric general circulation model to investigate the potential role of eccentricity in enhancing erosion in the Rocky Mountains. We find that with high orbital eccentricity (0.05767), elevated seasonality (the moving vernal equinox of perihelion [MVELP] = 270°) results in 10–100% more summer precipitation and surface runoff than low seasonality (MVELP = 90°). Under low orbital eccentricity (0.0034), precipitation and runoff changes across a precession cycle are negligible. These results suggest that elevated eccentricity could, indeed, be associated with more intense summer precipitation and runoff, which could then drive higher landscape erosion rates. This finding could explain the occurrence of ~100-kyr cyclicity in Powder River Basin landform ages and provides a clear, non-glacial, link between climate variability and landscape evolution in the Rocky Mountains. In this, and other low-to-mid-latitude sedimentary basins, runoff volume and not glacier dynamics may be the variable that exerts primary control on landscape evolution.


## 1. Introduction

Increased late Cenozoic relief in the Rocky Mountains is associated with extensive stream incision into Laramide basin fills of Eocene through Miocene age (McMillan et al., 2006). The climate's role in this incision has been hypothesized to occur via glaciation, with incision occurring during interglacial periods and lateral erosion and aggradation dominating during glacial times (e.g. Reheis et al., 1991; Hancock and Anderson, 2002). In this view, sediment supply is the variable that most strongly controls erosion rates and, thus, incision; increased sediment supply from glacial activity exceeds available stream competence, armors valley bottoms, and prevents bedrock incision (Ritter, 1967; Baker, 1974; Bull, 1991; Hancock and Anderson, 2002). However, widespread similarities between Quaternary gravel deposits and incision across the Cordillera, including glaciated and unglaciated drainage basins (e.g. Pierce and Scott, 1982; Riihimaki and Reiners, 2012), suggest that, while climate forcing must have played a significant role in driving erosion, the influence of climate on landscape evolution need not have been via glacial processes. Correlation of the cyclicity of eccentricity with a precise, temporally-dense dataset of landscape ages derived from (U–Th)/He dating of zircon grains from clinker outcrops in the Powder River Basin, Wyoming and Montana, USA (Riihimaki et al., 2009; Reiners et al., 2011; Riihimaki and Reiners, 2012) suggests an alternative mechanism for climate influence of regional erosion in the Rocky Mountains.

Clinker is a metamorphic rock that results from the burning of coal in underlying strata; because coal readily ignites through surface ignition sources or through spontaneous combustion only when it has been exhumed to within ~10–30 m of the surface (Heffern and Coates, 2004), the ages of clinker layers can be used as a proxy for erosion and exhumation of coal and, thus, regional landscape evolution (Heffern et al., 2007). The probability density function of Powder River Basin clinker ages shows direct correlation between times of clinker formation and times of high orbital eccentricity (Riihimaki et al., 2009; Reiners et al., 2011; Riihimaki and Reiners, 2012). Additional spectral analysis of the probability density functions shows power at ~100 and 400 kyr cyclicity, similar to orbital eccentricity (Riihimaki and Reiners, 2012). The relationship between the age of clinker formation and known episodes of elevated eccentricity is statistically significant for samples located >50 km from the Bighorn Mountain front, but not for the group of samples closer to the range. This empirical relationship suggests that eccentricity may be involved in pacing landscape evolution in the Powder River Basin through mechanisms that preferentially impact the parts of

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the basin farther from the mountain front. Alternatively, it could indicate that there are processes active closer to the range front that mask the influence of eccentricity, which could be uniform across the region.

Do such mechanisms exist? Processes that modulate sediment supply, such as fluctuations in rates of glacial erosion, would likely have the greatest impact on clinker formation close to the source of the sediment within the Bighorn Mountains. The impact of sediment can be complex (e.g., Sklar and Dietrich, 2001) and might be large enough to mask other, more subtle influences on landscape evolution. Farther from the mountain front where the sediment supply influence is weaker, the strong correlation between periods with high eccentricity and clinker formation may reflect incision rates that are controlled primarily by changes in stream power (e.g., DiBiase and Whipple, 2011) and hillslope erosion rates that are controlled by steepening of the hillsides (e.g. Bilderback et al., 2014) and greater runoff (e.g. Guzzetti et al., 2008), all with little lag in the timing of the forcing and the landscape response. These variations in stream power could be driven by fluctuations in precipitation and runoff that are, in turn, associated with changes in Earth's orbit, thus the strong connection between clinker formation and elevated eccentricity. While eccentricity alone has a limited impact on received insolation and, thence, climate variability (e.g. Imbrie et al., 1993), it modulates the influence of precessional cycles and can, thus, indirectly exert strong influence on the seasonality of climate. Climate simulations incorporating elevated seasonality at various times in earth history have shown that in regions with clear wet and dry seasons (such as the North American continental interior), elevated insolation in the wet season can lead to marked increases in precipitation and continental runoff (Sloan and Huber, 2001; Beckmann et al., 2005; Horton et al., 2012).

Here we use an atmospheric general circulation model (AGCM) to test the hypothesis that elevated orbital eccentricity can significantly alter precipitation east of the Rocky Mountains such that stream power and, thence, regional erosion and incision rates would be increased. The use of an AGCM allows us to specifically test this hypothesis by isolating the influence of orbital eccentricity and its relationship to orbital precession. While these results cannot, therefore, provide any specific insight regarding other processes such as sediment supply variation along the range front, they can provide an unambiguous test of the influence of eccentricity on regional surface hydrology.

## 2. Methods

Recognizing the complexities of the climate–landscape evolution system, we design our modeling experiments to minimize uncertainties. For all simulation runs, greenhouse gas concentrations are invariant at 1990 levels ($pCO_2 = 355$ ppm, $pCH_4 = 1709$ ppb, and $pN_2O = 309$ ppb) and surface boundary conditions (sea surface temperatures, topography, geography and vegetation) are prescribed using modern values. Although Pleistocene proxy data exist for all of these quantities, $pCO_2$, sea surface temperatures, ice-sheet extent, and global vegetation varied significantly across the last 1.1 Ma (e.g. Monnin et al., 2001; Loehle, 2007; Dyez and Ravelo, 2014), and the errors associated with proxy reconstructions can be significant (e.g. Loehle, 2007). Furthermore, analyses of clinker formation data indicate significant correlation between clinker formation and warm Pacific sea surface temperatures and low global ice volume (i.e. interglacial conditions; Riihimaki and Reiners, 2012). This suggests that the well-constrained modern interglacial surface conditions may provide the best analogue to surface conditions during past episodes of clinker formation. Finally, by utilizing modern, invariant boundary conditions, we can definitively isolate the influence of orbital eccentricity on the regional climate of the Rocky Mountain foreland.

To test the influence of eccentricity on regional climate, we conduct eight simulations. Orbital parameters vary across the simulations to test all combinations of maximum and minimum orbital eccentricity (0.05767 and 0.0034), obliquity (24.5° and 22.1°), and precession (the moving vernal equinox of perihelion [MVELP] located at either 270° [maximized seasonality] or at 90° [minimized]). A complete list of simulation identifiers and orbital parameters is presented in Table 1. Simulation results in the text are presented as in Table 1 with capital letters indicating maximized conditions and lower-case indicating minimized conditions (e.g. maximized eccentricity, obliquity, and seasonality [precession] would be EOS; minimized orbital conditions would be eos). While not all of our tested combinations occurred during the Pleistocene, many of them did and individual values were all closely approached if not matched (Berger and Loutre, 1991; Table 1). In using end-member values and combinations in our investigation, we efficiently explore the parameter space of orbital interactions, maximize signal to noise and provide a clear test of whether or not elevated orbital eccentricity can have a significant influence on precipitation and runoff east of the Rocky Mountains. Surface runoff is the modeled, climatically controlled variable that would likely have the most direct influence on landscape erosion and stream incision rates.

We conduct our simulations with the National Center for Atmospheric Research (NCAR) Community Atmosphere Model v. 3 (CAM3; Collins et al., 2006) at a spectral resolution of T85 (~1.4° lat. × 1.4° lon.). CAM3 simulates modern climate reasonably well, but does exhibit some biases in cloud properties (particularly at high latitudes) and precipitation (most notably for this study, an underestimate of mid-latitude precipitation; Collins et al., 2006). CAM3 includes the Community Land Model v. 3 (CLM3) to simulate land surface processes. CLM3 contains a 10-layer soil model, and surface runoff is calculated based on soil saturation; all incident moisture runs off from saturated soils, in unsaturated soils the rate of runoff varies with wetness in the top three soil layers (Oleson et al., 2004). CLM3 does a reasonable job of simulating modern climate, but regional biases reflect biases within CAM3 (e.g. excessively wet high latitudes; Dickinson et al., 2006). We integrated all CAM3/CLM3 simulations for 30 years and utilize the final 10 years to produce monthly averages for analyses.

## 3. Results

Although our simulations are global, the results presented here focus on the High Plains and Central Rocky Mountains of the United States in general and on the vicinity of the Powder River Basin (black outline in Figs. 1 and 2) of Wyoming and Montana specifically. While significant changes in snowpack influence spring runoff over much of eastern Canada and parts of the Northern and Canadian Rockies (not shown), snowpack changes in our study area are negligible. The greatest changes in modeled surface runoff in the study area occur during the summer

**Table 1**
Climate simulations, associated orbital parameters and modeled changes in surface runoff*.

| Climate simulation† | Orbital parameters | | | Average summer runoff change[a] | |
|---|---|---|---|---|---|
| | Eccentricity | Precession (MVELP) (°) | Obliquity (°) | (%) | cm |
| EOS | 0.05767 | 270 | 24.5 | 53 | 0.72 |
| EOs | 0.05767 | 90 | 24.5 | | |
| EoS | 0.05767 | 270 | 22.1 | 98 | 0.61 |
| Eos | 0.05767 | 90 | 22.1 | | |
| eOS | 0.0034 | 270 | 24.5 | 15 | −0.19 |
| eOs | 0.0034 | 90 | 24.5 | | |
| eoS | 0.0034 | 270 | 22.1 | 7 | 0.05 |
| eos | 0.0034 | 90 | 22.1 | | |

* Runoff results presented here are for only those grid cells that comprise the Powder River Basin.

† Case abbreviation indicates orbital parameter settings: e = eccentricity, o = obliquity, s = seasonality (precession). Upper case letter = parameter is maximized. Lower case letter = parameter is minimized.

[a] Difference between the upper simulation in the shared row minus the lower simulation; percentage is relative to the simulation with the lower seasonality.