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Andean-scale highlands in the Late Cretaceous Cordillera of the North American western margin

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ABSTRACT

From the Late Jurassic through the Cretaceous, collision between the North American and Farallon plates drove extensive thin-skinned thrusting and crustal shortening that resulted in substantial relief in the North American Cordillera. The elevation history of this region is tightly linked to the tectonic, climatic and landscape evolution of western North America but is not well constrained. Here we use an atmospheric general circulation model with integrated oxygen isotope tracers (isoCAM3) to predict how isotope ratios of precipitation would change along the North American Cordillera as the mean elevation of orogenic highlands increased from 1200 m to 3975 m. With increases in mean elevation, highland temperatures fall, monsoonal circulation along the eastern front of the Cordillera is enhanced, and wet season (generally spring and summer) precipitation increases. Simulated oxygen isotopic ratios in that precipitation are compared to those obtained from geologic materials (e.g. fossil bivalves, authigenic minerals). Quantification of match between model and data-derived $\delta^{18}O$ values suggests that during the Late Cretaceous, the best approximation of regional paleoelevation in western North America is a large orogen on the scale of the modern Andes Mountains with a mean elevation approaching 4000 m and a north-south extent of at least 15° of latitude.

1. Introduction

Throughout the Cretaceous, subduction of the Farallon plate under North America drove broad regional folding and thrusting in the western craton (DeCelles, 2004). This prolonged deformational event is termed the Sevier orogeny; it was characterized by crustal shortening of up to 75% (DeCelles and Coogan, 2006) and produced north-south trending structures and topography along the western margin of North America from Alaska to Mexico (DeCelles, 2004). By the Campanian (~75 Ma), fluvial transport and deposition of sediments from the growing orogeny had resulted in extensive foreland basin filling and development of a broad, low-relief coastal plain separating the highlands in the west from the Western Interior Seaway to the east (Aschoff and Steel, 2011; DeCelles, 2004; Roberts and Kirschbaum, 1995; Fig. 1).

While the deformation style, regional extent and horizontal translation of crustal material in the Cordilleran (Sevier) fold and thrust belt are relatively well documented (e.g. Burchfiel and Davis, 1972; Currie, 2002; DeCelles and Coogan, 2006; DeCelles, 2004; Elison; 1991; Friedrich and Bartley, 2003; Hudec and Davis, 1989; Weil et al., 2010), the actual elevation of the resulting Campanian-age orogenic highlands (hereafter CAMOH) and the areal extent of the CAMOH are less well-constrained. Nevertheless, it is crucial to obtain such information because of the influence that the elevation of this orogen may have had on the climatic, tectonic, and landscape evolution of the North American Cordillera.

At a global or hemispheric scale, increased elevation can result in changes in the planetary wave pattern or albedo and significant reorganizations of climate (e.g. Broccoli and Manabe, 1992; Ruddiman and Kutzbach, 1989). At local and regional scales, increased elevation results in surface cooling as a result of the adiabatic lapse rate and changes in net moisture balance as a result of disrupted atmospheric circulation and/or the development of rain shadows and enhanced orographic precipitation (e.g. Drummond et al., 1996; Ehlers and Poulsen, 2009; Fricke et al., 2010; Poulsen et al., 2010; Zaleha, 2006) as well as a host of other, resultant feedbacks (e.g. increased albedo of higher, colder, dryer, less-vegetated surfaces). In turn, climatic conditions may influence rates of uplift and rock exhumation (e.g. Reiners et al. 2003; Wobus et al., 2003) and foreland basin subsidence and infilling (e.g. Zaleha, 2006).

A number of different methods have been developed to study the paleoelevation of ancient mountain belts (e.g. rock mechanics: DeCelles and Coogan, 2006; leaf physiognomy: Gregory and Chase, 1992; Wolfe et al., 1998; stable isotope paleoaltimetry: Chamberlain

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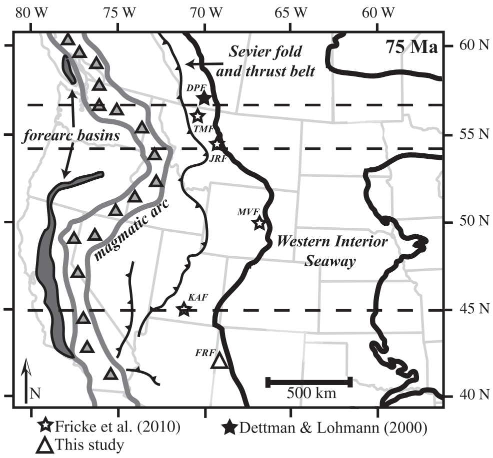

Fig. 1. Campanian paleogeographic map of western North America (after Fricke et al., 2010) showing sample locations (stars and triangles; DPF=Dinosaur Park Formation; TMF=Two Medicine Formation; JRF=Judith River Formation; MVF=Mesa Verde Formation; KAF=Kaiparowits Formation; FRF=Fossil Forest member of the Fruitland Formation), analytical transect locations (horizontal dashed lines), highland locations, and interior seaway extent.

et al., 1999; Crowley et al., 2008; Garzione et al., 2000; Mulch et al., 2006; Rowley et al., 2001), and some of the most promising rely on changes in the oxygen isotope ratios of precipitation, which can correlate with changes in elevation. The primary reason for such a correlation is the preferential incorporation of ^{18}O into condensate as water is precipitated and removed from cooling air masses. As more precipitation is removed from an air mass, the oxygen isotope ratio ($\delta^{18}O$) of the remaining vapor becomes progressively lower. Resulting patterns in $\delta^{18}O$ of precipitation ($\delta^{18}O_{pt}$) include a regular decrease in $\delta^{18}O_{pt}$ as air masses cool while rising over mountains (e.g. Dansgaard, 1964; Gat, 1996; Rozanski et al., 1993), thus, changing patterns in $\delta^{18}O_{pt}$ can reflect changes in local elevation. The combination of this relationship with observed isotopic lapse rates and/or Rayleigh distillation models has allowed researchers to estimate the paleoelevation of significant topographic features (e.g. Bissig and Riquelme, 2010; Garzione et al., 2008; Hren et al., 2010; Kent-Corson et al., 2009, 2006; Kohn et al., 2002; Poage and Chamberlain, 2002, 2001; Rowley et al., 2001). However, it should be noted that, while the association with increasing elevation is a robust one, regular decreases in $\delta^{18}O_{pt}$ can also be associated with other climatically or tectonically influenced factors such as changes in original moisture source, increasing distance from moisture source, increased length of meridional transport paths, mixing of air masses with different transport histories, and non-adiabatic cooling (e.g. Dansgaard, 1964; Ehlers and Poulsen, 2009; Gat, 1996; Poulsen et al., 2010; Rozanski et al., 1993), all of which can pose difficulties to accurately estimating paleoelevation from $\delta^{18}O_{pt}$ (e.g. Ehlers and Poulsen, 2009). Due to this potential for complex or confounding interactions and feedbacks between changing tectonics and climate (e.g. Galewsky, 2009; Molnar and England, 1990; Ruddiman and Kutzbach, 1990), many researchers have employed increasingly holistic, nuanced approaches to paleoelevation estimation (e.g. consideration of basin hydrology: Davis et al., 2008, 2009; Hough et al., 2011; quantification/consideration of interactions between tectonics and climate: Ehlers and Poulsen, 2009; Kent-Corson et al., 2009; consideration of climate change: Hren et al., 2010; Molnar, 2010).

Given recent advances in general circulation models (e.g. Mathieu et al., 2002; Noone and Sturm, 2010; Zhou et al., 2008), one of the most straightforward methods for integrating the complex feedbacks between climate, tectonics, and the isotopic signature of precipitation is to simulate past climates with an atmospheric general circulation model (AGCM) enabled with the ability to trace the various species of water isotopes (i.e. ^{16}O, ^{17}O, ^{18}O, ^{1}H, ^{2}H). Variation of the topographic boundary conditions in such simulations (e.g. Poulsen et al., 2010) and comparison between simulated isotopic values in meteoric waters and those derived from oxygen-bearing minerals precipitated or secreted in equilibrium with terrestrial surface waters can offer insight into the development of ancient orogenic features. Here we integrate isotope-tracer-enabled AGCM simulations of Campanian climate and $\delta^{18}O$ data derived from unionid bivalves and soil carbonates to investigate the paleoelevation of the CAMOH of western North America.

2. Modeling methods

We used the National Center for Atmospheric Research (NCAR) Community Atmosphere Model v. 3 (CAM3; Collins et al., 2006) with an integrated isotope tracer code (isoCAM3; Noone, 2003; Noone and Sturm, 2010) to conduct five, fixed lower boundary condition, atmosphere-only simulations of Campanian climate with varying mean elevations for the CAMOH (Table 1). isoCAM3 utilizes a third-generation isotope tracer scheme (Noone and Sturm, 2010) and is coupled to a dynamic land surface model (CLM3: Bonan et al., 2002; Oleson et al., 2004) where the isotopic composition of terrestrial water and evapotranspiration are accounted for by a simple two-bucket scheme (Noone and Simmonds, 2002). Present-day simulations with isoCAM3 have been validated against the Global Network of Isotopes in Precipitation (GNIP; IAEA/WMO, 2006) and show good agreement with observed isotopic patterns at both global and regional scales (Noone, 2003; Speelman et al., 2010).

For all five of our Campanian model simulations, global topography, geography, and vegetation were modified from previously published Cretaceous boundary conditions (Otto-Bliesner et al., 2002; Sewall et al., 2007; see Fricke et al., 2010 for global maps). A monthly varying seasonal cycle of sea surface temperatures (SST) was developed from an equilibrated, fully coupled Campanian simulation of the NCAR Climate System Model (CSM v. 1.4) (Otto-Bliesner et al., 2002). Global land surface conditions and sea surface temperatures are invariant across our five simulations (Table 1). Atmospheric composition was also held constant with pCO_2 specified at 1680 ppm, pCH_4 at 700 ppb, and pN_2O at 275 ppb (Table 1); these are similar to the greenhouse gas concentrations associated with our SST distribution (Otto-Bliesner et al., 2002). Orbital parameters in all cases were

Table 1
Boundary conditions for Campanian climate simulations.

Simulation parameter	Value (s)
Invariant parameters	
pCO_2	1680 ppm
pCH_4	700 ppb
pN_2O	275 ppb
Orbital configuration	Modern
Vegetation distribution	Fricke et al. (2010)
Global topography/geography	Fricke et al. (2010)
Solar constant	1355 W/m^2
Sea surface temperature distribution	Fricke et al. (2010)
$\delta^{18}O$ value of global ocean	−1‰
Variable parameters	
Average elevation of the CAMOH	1200 m
	2000 m
	2800 m
	3500 m
	3975 m