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Spatiotemporal distribution of river water stable isotope compositions and variability of lapse rate in the central Rocky Mountains: Controlling factors and implications for paleoelevation reconstruction

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ABSTRACT

Stable isotope-based paleoaltimetry is the most widely used approach for paleoelevation reconstruction. Interpretations of stable isotope data in continental interiors, however, are undermined by surface water isotope compositions that are influenced by multiple factors. Here we present a stable isotope dataset of modern river water samples collected over two summers and one spring from the central Rocky Mountains (Rockies) and the adjacent Great Plains. By examining the spatial and temporal variations of river water $\delta^{18}O$, δD and d-excess values, and their relationships with climatic and geographic parameters, as well as through back trajectory analysis of moisture sources, we elucidate the influences of elevation and climatic parameters on the spatiotemporal variation of river water isotopic values. In the Bighorn River drainage, a typical intermontane drainage in the central Rockies, the isotopic difference between highland and lowland rivers is small, which we attribute to highland precipitation that dominates lowland river discharge. In the North Platte River drainage across the central Rockies and Great Plains, the river water $\delta^{18}O$ values show poor correlation with elevation west of 105°W (central Rockies), but increase as elevation decrease east of 105°W (in the western Great Plains). This eastward increase across the western Great Plains leads to an average oxygen isotope lapse rate of −2.3‰/km, which we interpret as being caused primarily by condensation temperature-controlled isotopic fractionation at various elevations, and secondarily by evaporation in the upper reaches of streams that contribute to the North Platte River plus direct contribution of moisture from the Gulf of Mexico in the Great Plains. In this continental interior setting, multiple moisture sources, including recycled continental moisture, contribute to surface water, and evaporation influences river water isotope values to various degrees depending on the relative humidity within an individual river catchment. These results suggest that paleoclimate and atmospheric circulation pattern must be carefully evaluated when applying stable isotope-based paleoaltimetry in continental interiors. Our findings have implications for paleoelevation reconstruction in the study area, including that 1) within the central Rockies, the isotopic difference of river water and unevaporated basinal precipitation can be used to infer paleorelief of the Laramide ranges with respect to the basin floors; 2) along a regional transect crossing the central Rockies and Great Plains, the modern isotope lapse rate of the North Platte River drainage can be used to constrain the paleorelief between the two regions in semi-arid climate.

1. Introduction

Rayleigh distillation of a predominant moisture source in an open system along the windward side of mountains is a fundamental assumption of stable isotope-based paleoaltimetry (e.g., Rowley et al., 2001; Rowley and Garzione, 2007). By applying an empirical isotopic lapse rate of modern surface water or a theoretical lapse rate based on Rayleigh distillation modeling, histories of surface uplift and collapse of mountains and plateaus have been reconstructed from the stable isotope compositions of many suitable geologic materials. Examples of such geologic materials include, but are not limited to, lacustrine and paleosol carbonate, groundwater carbonate cements, hydrous silicate minerals, fossil mollusks, and plant remains (e.g., Garzione et al., 2000; Mulch and

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Chamberlain, 2007; Fan and Dettman, 2009; Hoke et al., 2009; Hren et al., 2010). In continental interiors, a major challenge for stable isotope-based paleoaltimetry is the characterization of a surface water isotope lapse rate, which can vary from −11.4‰/km (Poage and Chamberlain, 2001) to nearly 0‰/km (Bershaw et al., 2012). This large variation was interpreted to be influenced by multiple controlling factors. Previous studies, mostly conducted in the Tibetan Plateau and Andean Plateau, have suggested that the controlling factors include vapor recycling through surface water evaporation, sub-cloud evaporation, convective storms, and snow sublimation (e.g., Bershaw et al., 2012, 2016; Lechler and Niemi, 2012; Rohrmann et al., 2014; Li and Garzione, 2017), and moisture mixing governed by atmospheric circulation patterns and climate changes (e.g., Froehlich et al., 2008; Liu et al., 2011; Poulsen and Jeffery, 2011; Licht et al., 2017).

The Cenozoic history of surface uplift and collapse of the Rocky Mountains (Rockies), the worlds' longest intracontinental mountain belt, has drawn a great amount of interest in paleoelevation reconstruction (e.g., Wolfe et al., 1998; Cather et al., 2012; Chamberlain et al., 2012; Feng et al., 2013). Many of these studies use stable isotope proxies and have yielded fruitful insights regarding the growth history and geodynamic drivers of the Rockies (e.g., Fricke, 2003; Sjostrom et al., 2006; Fan and Dettman, 2009; Fan et al., 2011, 2014a, 2014b; Fan and Carrapa, 2014; Licht et al., 2017). In these studies, paleoelevation estimates were determined either through the application a theoretical lapse rate based on Rayleigh distillation modeling (Rowley and Garzione, 2007), or by comparing reconstructed surface water isotope compositions from high to low regions with modern surface water in the same regions (Fan et al., 2014a, 2014b) or with GCM simulation-predicted paleoprecipitation isotope compositions for the same regions (Feng et al., 2013). However, like in the interiors of other continents, vapor sources are complex and recycled moisture contributes to precipitation. Furthermore, the relative contributions of moisture sources may change during the geologic past when atmospheric circulation patterns were likely different from today (e.g., Liu et al., 2010). Additionally, the mountain ranges in the Rockies, particularly in the central Rockies, are of various orientations, which may cause orographic precipitation on some mountain flanks, but not others. Therefore, the contribution of each vapor source in the Rockies may be spatially and temporally heterogeneous, and subject to the influence of climate changes.

Understanding the controlling factors of isotopic compositions of modern surface water in the Rockies is fundamental to paleoelevation reconstructions that use stable isotope proxies and assessment of their uncertainties. Despite the fact that several studies have been conducted to characterize surface water isotope compositions in the region (Copeland and Kendall, 2000; Kendall and Coplen, 2001; Dutton et al., 2005; Vachon et al., 2010a, 2010b), none of the studies have high enough resolution to understand the heterogeneity of surface water isotope compositions and their controlling factors. In this study, we present an extensive river water isotopic dataset collected in one spring and two summers of two different years from Wyoming and western Nebraska (Fig. 1A) to understand the spatiotemporal distribution of river water isotopes and variations in isotope lapse rate in the central Rockies and the adjacent Great Plains. By analyzing climatic patterns and vapor trajectories in the major rainy seasons before and during each sampling period, we constrain the controlling factors on river water isotope distribution and lapse rate. This new understanding sheds light on the paleoelevation reconstruction of the Rockies.

2. Background

2.1. Geography and climate

The study area is located in the central Rockies in Wyoming and the adjacent Great Plains in western Nebraska (Fig. 1). Western and central Wyoming (west of 105°W) is mountainous with a mean elevation of ∼2.0 km. Eastern Wyoming and western Nebraska (east of 105°W) are relatively flat, with the mean elevation decreasing eastward gradually from 1.4 km to 0.8 km. The central Rockies of Wyoming are bounded to the west by the Sevier thrust belt. Major mountain ranges in Wyoming and its adjacent regions include the W–E striking Granite, Owl Creek, and Uinta mountains, NW–SE striking Wind River Range and Beartooth Mountains, and N–S striking Bighorn and Laramie mountains (Fig. 1A). The Bighorn River drainage ranges from 1.1 to 4.1 km in elevation, and is the largest river drainage in northwestern Wyoming (Fig. 1A). The Wind River flows northward from the Wind River Range through the Wind River Basin and Owl Creek Mountains, and becomes the Bighorn River in the Bighorn Basin. With major tributaries sourced in the Bighorn Mountain, the Powder River drainage is the largest river drainage in northeastern Wyoming (Fig. 1A). The North Platte River drainage is the largest river drainage in southern Wyoming (Fig. 1A). The river rises in northern Colorado and merges with the Sweetwater River sourced from the Wind River Range in central Wyoming, then flows eastward to the low plains in western Nebraska. The catchment elevation of the North Platte River ranges from 0.8 to 4.1 km, following the relief contrast between the central Rockies and Great Plains. The upper Green River drainage consists of the southward-flowing rivers in southwestern Wyoming.

The climate in Wyoming and western Nebraska is semiarid. The major rainy season in the mountainous area is spring and early summer (March–June), which contributes 50–70% of the annual precipitation amount (Arguez et al., 2010). The major rainy season on the plain area is spring and summer (April–August), which contributes ∼75% of the annual precipitation amount (Arguez et al., 2010). Precipitation amount is generally higher on the plains than in the mountainous area. Within the mountainous area, precipitation amount is higher on the mountain flanks than on the basin floors.

2.2. Moisture sources and transport

Four major moisture sources contribute to precipitation in the study area, including northern cold moisture from the Hudson Bay and regions east of Canadian Rocky Mountains (N), moisture from the north Pacific and the tropical Pacific (P), moisture from the Gulf of Mexico (GM), and continental recycled moisture (C) (Fig. 1B) (Ting and Wang, 2006; Liu et al., 2010). Atmospheric water vapor from N, C, and north Pacific sources contribute to precipitation in the study area throughout the year, while the tropical Pacific and GM sources contribute more to precipitation during summer time than other seasons via the North American Monsoon (Adams et al., 1997). The GM moisture follows two transport paths, which either transports water vapor directly to western Nebraska along the front of the Rockies, or mixes with the tropical Pacific moisture near Arizona before transport northward to Wyoming (e.g., Adams et al., 1997).

3. Methods

3.1. River water samples and isotope analysis

A total of 242 river water samples were collected during three field seasons: one in late July in 2010 during the rainy season of western Nebraska and after the main rainy season of Wyoming,