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Stable isotope variations ($\delta^{18}O$ and δD) in modern waters across the Andean Plateau

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Abstract

Environmental parameters that influence the isotopic composition of meteoric water ($\delta^{18}O$ and δD) are well characterized up the windward side of mountains, where orographic precipitation results in a predictable relationship between the isotopic composition of precipitation and elevation. The topographic and climatic evolution of the Andean Plateau and surrounding regions has been studied extensively by exploiting this relationship through the use of paleowater proxies. However, interpretation on the plateau itself is challenged by a poor understanding of processes that fractionate isotopes during vapor transport and rainout, and by the relative contribution of unique moisture sources. Here, we present an extensive dataset of modern surface water samples for the northern Andean Plateau and surrounding regions to elucidate patterns and causes of isotope fractionation in this continental environment. These data show a progressive increase in $\delta^{18}O$ of stream water west of the Eastern Cordillera (~1‰/70 km), almost identical to the rate observed across the Tibetan Plateau, attributed to a larger fraction of recycled water in precipitation and/or increased evaporative enrichment downwind. This may lead to underestimates of paleoelevation, particularly for sites deep into the rainshadow of the Eastern Cordilleran crest. That said, elevation is a primary control on the isotopic composition of surface waters across the entire Andean Plateau and its flanks when considering the most negative $\delta^{18}O$ values, highlighting the need for sufficiently large datasets to distinguish minimally evaporated samples. There is a general increase in $\delta^{18}O$ on the plateau from north to south, concomitant with an increase in aridity and decrease in convective moistening (amount effect). Lastly, stable isotope and seasonal precipitation patterns suggest easterlies provide the vast majority of moisture that falls as precipitation across the Andean Plateau and Western Cordillera, from Peru to northern Bolivia (−13° to −20° latitude), with Pacific-derived moisture contributing a minor amount at low elevations near the coast.

Keywords: Stable isotope geochemistry; Meteoric water; South America; Andes; Altiplano; Climate; Paleoaltimetry

1. INTRODUCTION

Modern stable isotope variation in precipitation is fairly well-understood for the windward side of mountains where $\delta^{18}O$ and δD have been shown to be inversely related to elevation (Garzione et al., 2000; Gonfiantini et al., 2001;

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Poage and Chamberlain, 2001). This relationship has been exploited for paleoaltimetry studies where various proxies for precipitation are used in the rock record to estimate the timing of topographic growth (or decay) for many of the world's mountain ranges and plateaux (Bershaw et al., 2010; Currie et al., 2016; Kar et al., 2016; Kent-Corson et al., 2009; Leier et al., 2013; Mulch, 2016; Mulch et al., 2006; Rowley and Garzione, 2007; Saylor and Horton, 2014; Saylor et al., 2009; Takeuchi and Larson, 2005). Often, modern precipitation or surface water isotope-elevation relationships are used to estimate surface elevation and/or climate changes on the leeward side of mountain ranges where factors other than elevation have a significant impact (Cyr et al., 2005; Fan et al., 2014; Polissar et al., 2009). In many continental environments, evaporation of surface water and raindrops as they fall through the air significantly affects the isotopic composition of both precipitation and surface water, complicating the interpretation of stable isotope variations (Gat and Airey, 2006; Stewart, 1975; Yamada and Uyeda, 2006; Yang et al., 2007). In addition, surface water recycling, where continental surface water is evaporated and integrated into downwind precipitation, may result in isotopic patterns that deviate from simple temperature (elevation) dependent Rayleigh distillation models (Bershaw et al., 2012; Froehlich et al., 2008; Kurita and Yamada, 2008). Elsewhere, moisture source mixing has been inferred to cause both seasonal and spatial variability in the isotopic composition of meteoric water (Sjostrom and Welker, 2009; Tian et al., 2007), along with spatiotemporal variation in air trajectories (Lechler and Galewsky, 2013).

Isotopes of modern meteoric water have been used to constrain the spatial extent, magnitude, and temporal variability of the South American monsoon (Vuille et al., 2012; Vuille and Werner, 2005). Though variation in monsoon strength has been related to the height and/or extent of the Andes (Insel et al., 2009; Poulsen et al., 2010), the modeled effects of changing topography on precipitation patterns vary across the orogen (Garreaud et al., 2010; Jeffery et al., 2012). A better understanding of the forcing mechanisms behind modern changes in water chemistry across the Andean Plateau will enable us to better interpret proxy records of South American paleoelevation, paleoclimate, and by extension, predict future climate change. This is especially important considering an entire Andean civilization perished during an abrupt period of climate change to more arid conditions as recent as ~1100 AD (Binford et al., 1997), with implications for modern farmers on the Andean Plateau, who depend on monsoon rains for their livelihood (García et al., 2007).

Here, we present an extensive surface water dataset from the northern Andean Plateau, providing much needed constraints on modern water isotope evolution across the plateau and a context for the interpretation of elevation and climate proxies from the rock record in this continental environment. This dataset also adds fidelity to our understanding of precipitation source on the relatively arid western Andean Plateau and Western Cordillera. Stable isotope data from surface waters across the Andean Plateau presented here show: (1) a progressive increase in $\delta^{18}O$ west of the Eastern Cordillera that we attribute to a larger fraction of recycled water in precipitation and/or increase in evaporation downwind due to aridity; (2) an inverse relationship between $\delta^{18}O$ and elevation for water that has not experienced significant evaporation across the entire Andean Plateau including its flanks; (3) a general increase in $\delta^{18}O$ on the plateau from north to south due to an increase in evaporation and/or decrease in the amount effect due to aridity; and, (4) stable isotope and seasonal precipitation patterns that suggest easterlies transport the vast majority of moisture that falls as precipitation across the Andean Plateau and Western Cordillera from Peru to northern Bolivia (−13° to −20° latitude), with the Pacific contributing a minor amount near the coast.

2. BACKGROUND

2.1. Climate on the Andean Plateau

The Andean Plateau extends from approximately 15°S to 23°S, occupying the South American countries of Peru, Bolivia, Chile, and NW Argentina (Fig. 1). The climate across the northern Andean Plateau, including the Altiplano basin, Western and Eastern cordilleras, is characterized by large-scale (synoptic) atmospheric circulation modified by surface topography. The plateau itself averages about 4000 m elevation and is bound by the Western and Eastern cordilleras, which can reach elevations over 6000 m (Fig. 1).

Precipitation falls primarily during the austral summer, brought in by equatorial easterlies that originate in the Atlantic and traverse the Amazon Basin (Garreaud and Vuille, 2003; Lenters and Cook, 1997). Easterly circulation is driven by trade winds that converge on the inter-tropical convergence zone (ITCZ) across northern South America. As a whole, this topographic barrier receives intense precipitation on the eastern flank of the Eastern Cordillera, with increasingly dry conditions westward (Bookhagen and Strecker, 2008) and southward (Fiorella et al., 2015a; Garreaud and Vuille, 2003) (Fig. 2). Precipitation on the Andean Plateau is primarily convective and typically occurs during afternoon thunderstorms (Garreaud and Vuille, 2003; Houston and Hartley, 2003; Samuels-Crow et al., 2014a; Vuille and Keimig, 2004). West of the plateau, the Atacama Desert receives negligible precipitation (Miller, 1976). Relatively dry westerlies have been shown to contribute significantly to atmospheric circulation on the Western Cordillera and Andean Plateau, particularly during austral winter. However, westerlies apparently contribute very little to annual precipitation budgets (Aravena et al., 1999; Fiorella et al., 2015a).

2.2. Stable isotopes across the Amazon Basin and Eastern Cordillera

The isotopic composition ($\delta^{18}O$ and δD) of meteoric water across the Eastern Cordillera can be traced back to the equatorial Atlantic Ocean (Bershaw et al., 2010; Fiorella et al., 2015a; Gonfiantini et al., 2001). Progressive rain-out of atmospheric moisture westward across the