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6 **Stable Isotope Variations ($\delta^{18}\text{O}$ and δD) in Modern Waters**
7 **Across the Andean Plateau**
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ABSTRACT

29 Environmental parameters that influence the isotopic composition of meteoric water ($\delta^{18}\text{O}$ and δD) are
30 well characterized up the windward side of mountains, where orographic precipitation results in a
31 predictable relationship between the isotopic composition of precipitation and elevation. The topographic
32 and climatic evolution of the Andean Plateau and surrounding regions has been studied extensively by
33 exploiting this relationship through the use of paleowater proxies. However, interpretation on the plateau
34 itself is challenged by a poor understanding of processes that fractionate isotopes during vapor transport
35 and rainout, and by the relative contribution of unique moisture sources. Here, we present an extensive
36 dataset of modern surface water samples for the northern Andean Plateau and surrounding regions to
37 elucidate patterns and causes of isotope fractionation in this continental environment. These data show a
38 progressive increase in $\delta^{18}\text{O}$ of stream water west of the Eastern Cordillera ($\sim 1\text{‰}$ / 70km), almost
39 identical to the rate observed across the Tibetan Plateau, attributed to a larger fraction of recycled water in
40 precipitation and/or increased evaporative enrichment downwind. This may lead to underestimates of
41 paleoelevation, particularly for sites deep into the rainshadow of the Eastern Cordilleran crest. That said,
42 elevation is a primary control on the isotopic composition of surface waters across the entire Andean
43 Plateau and its flanks when considering the most negative $\delta^{18}\text{O}$ values, highlighting the need for
44 sufficiently large datasets to distinguish minimally evaporated samples. There is a general increase in
45 $\delta^{18}\text{O}$ on the plateau from north to south, concomitant with an increase in aridity and decrease in
46 convective moistening (amount effect). Lastly, stable isotope and seasonal precipitation patterns suggest
47 easterlies provide the vast majority of moisture that falls as precipitation across the Andean Plateau and
48 Western Cordillera, from Peru to northern Bolivia (-13° to -20° latitude), with Pacific-derived moisture
49 contributing a minor amount at low elevations near the coast.

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1.0 INTRODUCTION

Modern stable isotope variation in precipitation is fairly well-understood for the windward side of mountains where $\delta^{18}\text{O}$ and δD have been shown to be inversely related to elevation (Garzzone et al., 2000; Gonfiantini et al., 2001; 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; Kar et al., 2016; Kent-Corson et al., 2009; Leier et al., 2013; Mulch, 2016; Mulch et al., 2006; Rowley and Garzzone, 2007; Saylor and Horton, 2014; 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 poignant 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 $\delta^{18}\text{O}$ 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 $\delta^{18}\text{O}$ and elevation for water that has not experienced significant evaporation across the entire Andean Plateau including its flanks; 3) a general increase in $\delta^{18}\text{O}$ 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.

2.0 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 (Figure 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 4000m elevation and is bound by the Western and Eastern cordilleras, which can reach elevations over 6000m (Figure 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) (Figure 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 ($\delta^{18}\text{O}$ 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 Amazon Basin results in a steady depletion of relatively heavy isotopes (the continental effect). This is attenuated by widespread transpiration resulting in a continental gradient in isotopic composition that is less than that observed in

other continental environments (0.75-1.5‰ / 1000 km inland compared to 2‰ / 1000 km for Europe) (Rozanski et al., 1993; Salati et al., 1979). The isotopic composition of precipitation and surface water have been shown to inversely correlate with elevation from the lowlands of Brazil up the eastern (windward) flank of the Eastern Cordillera (Bershaw et al., 2010; Fiorella et al., 2015a; Gonfiantini et al., 2001). This pattern is consistent with the progressive removal of relatively heavy isotopes during orographic ascent and condensation of atmospheric moisture, typical of the windward side of mountain ranges globally (Poage and Chamberlain, 2001). The relationship between the isotopic composition of stream water and elevation breaks down south of -24° latitude along the Eastern Cordillera where convective storms dominate, masking the depletion of heavy isotopes in precipitation as a function of elevation. This observation is based on trends in stream water datasets located at -22° ($R^2 = 0.68$), -24° ($R^2 = 0.43$), and -26° ($R^2 = 0.17$) (Rohrmann et al., 2014).

2.3 Stable Isotopes on the Andean Plateau

Spatial patterns in water isotopes across the northern Andean Plateau, which sits on the leeward side of the Eastern Cordillera, are not well-constrained. However, Fiorella et al. (2015a) observe a significant correlation ($R^2=0.82$) between elevation and $\delta^{18}\text{O}$ of annual mean precipitation throughout the southern Altiplano and Eastern Cordillera (Figure 1). Evaporation in an arid (low relative humidity) environment causes kinetic fractionation that often increases $\delta^{18}\text{O}$ values of residual surface water reservoirs (Gat, 1996; Stewart, 1975). Unlike precipitation, there is evidence that surface waters are highly evaporated across much of the southern Altiplano (Fiorella et al., 2015b). In addition, precipitation samples along transects up the Western Cordillera in northern Chile show a very steep isotopic lapse rate that is almost four times the global average, -10‰ / km and -2.5‰ / km, respectively (Aravena et al., 1999; Poage and Chamberlain, 2001). This has been interpreted by Aravena et al. (1999) to be the result of air mass mixing

where Atlantic-derived moisture dominates precipitation at high elevations in the Western Cordillera and Pacific-derived moisture dominates at low elevations in the hyper-arid Atacama Desert.

To better understand controls on the isotopic composition of meteoric water for the Andean Plateau where evaporation may be significant, we report deuterium excess ($d\ excess = \delta D - 8 * \delta^{18}O$) values (Dansgaard, 1964; Stewart, 1975). A function of both H and O in a water sample, $d\ excess$ may be used to constrain both the source of moisture and evaporative processes during and after transport in meteoric water samples (Froehlich et al., 2001). Relatively low $d\ excess$ of precipitation is often associated with subcloud evaporation of raindrops during their descent through the air. Similarly, $d\ excess$ can be lowered in surface water samples through evaporation, often seen in closed basin lakes with high residence times. Relatively high $d\ excess$ values have been observed in moisture derived from the evaporation of surface water reservoirs (both marine and continental) at low relative humidity (Bershaw et al., 2012; Froehlich et al., 2008; Pang et al., 2011). Relatively high $d\ excess$ values can also be caused by precipitation at very low temperatures, observed in Antarctica and at high elevation in some mountain ranges (Jouzel and Merlivat, 1984; Liotta et al., 2006; Samuels-Crow et al., 2014b).

3.0 METHODS

The strategy was to collect surface water samples, both with high and low residence time across the northern Andean Plateau to observe spatial patterns, including the magnitude of evaporation, across a region where little published data currently exists. We focused on sampling from high elevation (> 3500m) on the plateau, but also collected lower elevation samples when convenient. We targeted rivers of all sizes and some standing water bodies. Because we are interested in using results to better understand long-term records, including those interpreted from paleowater proxies, we targeted rivers which average numerous precipitation events. Finding surface water to sample in the Western Cordillera was especially

challenging considering the very arid climate there. In total, 275 water samples were collected throughout Peru and Bolivia from 2009 through 2014, during the months of May and June, from many sources.

Analyses completed at the University of Rochester were made by laser absorption spectroscopy on a Los Gatos Research Liquid Water Isotope Analyzer (LWIA-24d DLT-100) with a GC-PAL autosampler. Approximately 900 nl of water was injected into a heated, evacuated block. Water vaporized and was drawn into a laser cavity, where absorption analysis took place. Reported results are the average and standard deviation of 5 - 10 adjacent injections and measurements of a water sample from a single vial. Standardization is based on internal standards referenced to Vienna Standard Mean Ocean Water (VSMOW) and Vienna Standard Light Antarctic Precipitation (VSLAP). The 2- σ uncertainties of H and O isotopic results are $\pm 2.4\text{‰}$ and $\pm 0.20\text{‰}$ respectively, unless otherwise indicated.

Analyses completed at the University of Arizona were made using a dual inlet mass spectrometer (Delta-S, Thermo Finnegan, Bremen, Germany) equipped with an automated chromium reduction device (H-Device, Thermo Finnegan) for the generation of H gas using metallic chromium at 750°C. Water $\delta^{18}\text{O}$ was measured on the same mass spectrometer using an automated $\text{CO}_2\text{-H}_2\text{O}$ equilibration unit. Standardization is also based on internal standards referenced to VSMOW and VSLAP. The 1- σ uncertainties of H and O isotopic results from this lab are better than $\pm 1\text{‰}$ and $\pm 0.08\text{‰}$ respectively.

4.0 RESULTS

Results are listed in Tables 1 and 2 with $\delta^{18}\text{O}$ and *d excess* values mapped using natural neighbor interpolation in ArcGIS ArcMap version 10.3 in Figure DR1A and DR1B respectively. Surface water isotopes from streams show significant variability across the Andean Plateau, from a minimum of -19.6‰ to a maximum of 5.6‰ (Table 1). Standing water samples show similar variability with a range from -17.4‰ to 4.2‰ (Table 2). Because of the broad spatial variability in the dataset, we have produced

a number of transects that highlight patterns observed in data subsets for the Eastern Cordillera (Figure 3), across the Andean Plateau itself (Figures 4-7), and in the Western Cordillera (Figure 8). In each of our plots, elevation is measured as the mean basin hypsometry, which is the average elevation of the watershed upstream from the sample site. The centroid of stream catchments is used instead of sample location to better represent the geographic distribution of meteoric water contributing to the sample. Note that the locations shown in Figure 1 are the sample sites, while locations shown in Figures DR1A and DR1B are the centroid of associated watersheds.

5.0 DISCUSSION

5.1 Isotope Trends up the Eastern Cordillera

On the windward flank of the Eastern Cordillera isotopic lapse rates are consistent with Rayleigh distillation of moisture during orographic ascent, as observed in global datasets (-2.8‰ / km) (Poage and Chamberlain, 2001) and as predicted by thermodynamic modeling (Rowley, 2007; Rowley et al., 2001). West of Cusco, Peru, we observe an inverse relationship between $\delta^{18}\text{O}$ and elevation along transect BC up a tributary of the Rio Ene (Figure 3), with an isotopic lapse rate of -2‰ / km elevation gain. Samples included in this transect are noted in Table 1. This is similar to the isotopic lapse rate of -1.9‰ / km previously recorded up the windward (east) side of the Eastern Cordillera along transects GH and KL. (Bershaw et al., 2010; Fiorella et al., 2015a; Gonfiantini et al., 2001). This pattern reflects moisture transported from the Brazilian lowlands up through valleys in the Eastern Cordillera. Because watersheds that contribute to the Rio Ene (transect BC) penetrate deeply into the Andean Plateau from the north, we show that this $\delta^{18}\text{O}$ -elevation relationship is seen over 100 km into the rainshadow of the Eastern Cordilleran crest. This suggests that water on the leeward (plateau) side of mountain ranges may still faithfully record paleoelevation as calibrated to the isotopic lapse rate on a range's windward flank where deep valleys provide pathways for moisture to bypass a mountain range's highest peaks.

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219 5.2 Isotope Trends on the Andean Plateau

220 5.2.1 Elevation

221 Systematic spatial patterns in the isotopic composition of meteoric water are notoriously challenging to
222 discern on the leeward (rainshadow) side of mountain ranges (Bershaw et al., 2012; Hren et al., 2009;
223 Lechler and Niemi, 2011a). Standing water was collected throughout the plateau with many samples
224 showing extreme evaporation (negative $d\ excess$), typical of arid, closed basin environments (Table 2).
225 Stream water also shows significant variability across the Andean Plateau, from a minimum of -19.6‰ to
226 a maximum of 5.6‰ at elevations $> 3500\text{m}$, suggesting many streams are significantly affected by
227 evaporative enrichment as well (Table 1 and Figure DR1). When the entire stream water dataset is
228 considered, the vast majority of which is from the Andean Plateau itself, we do not observe a significant
229 relationship between $\delta^{18}\text{O}$ and elevation ($R^2 = 0.12$) (Figure 4A). Over half of stream water samples have
230 $d\ excess$ values $< 5\text{‰}$ (Table 1), suggesting that evaporative enrichment is creating considerable scatter in
231 the data. Similar observations have been made in other relatively dry, continental regions including
232 central Asia (Bershaw et al., 2012; Liu et al., 2015; Tian et al., 2007), in the southern Andean Plateau
233 (Fiorella et al., 2015b; Rohrmann et al., 2014), and the southwest United States (Lechler and Niemi,
234 2011b). However, we do observe an inverse relationship between $\delta^{18}\text{O}$ and elevation for the most
235 negative $\delta^{18}\text{O}$ values (Figure 4B). The sample subset used in this regression were chosen based on the
236 most negative $\delta^{18}\text{O}$ value per 200m elevation gain and are noted in Table 1 and Figure DR1 (triangles).
237 The isotopic lapse rate for these most negative values collected across the entire plateau is $-3.5\text{‰} / \text{km}$ (R^2
238 $= 0.72$). This indicates that the isotopic composition of water that has experienced minimal evaporation is
239 controlled by changes in elevation across the entire Andean Plateau. The isotopic lapse rate across the
240 plateau is steeper than that observed up the eastern (windward) side of the Eastern Cordillera ($\sim -2\text{‰} /$
241 km) (Bershaw et al., 2010; Fiorella et al., 2015a; Gonfiantini et al., 2001). This may be due to evaporative

enrichment at relatively low elevations and/or a larger contribution from low $\delta^{18}\text{O}$ snow at the highest elevations. These results are consistent with Fiorella et al. (2015a), who suggest that elevation is the most significant control on the isotopic composition of precipitation for the southern Altiplano ($R^2 = 0.82$). This relationship breaks down in stream water south of -24° latitude on the plateau's eastern flank where convective storms transport moisture vertically as opposed to orographic lifting, resulting in little to no isotopic lapse rate (Rohrmann et al., 2014).

5.2.2 Longitude

While the isotopic composition of surface waters across the Andean Plateau is apparently controlled by elevation, it is often heavily modified by surface water recycling and/or evaporative enrichment. Along transect DEF, which crosses the plateau in southern Peru (Figure 1), we observe a general increase in the most positive $\delta^{18}\text{O}$ values of stream water southwestward while elevation remains relatively constant (Figure 5). The isotopic composition of surface (stream) water also becomes more variable, with a range of $\sim 3\text{‰}$ in the northeast to $\sim 6\text{‰}$ in the southwest part of the plateau (maximum difference between samples 75km and 225km from the Andean foreland respectively). This trend is inconsistent with the continental effect, described from a global long-term precipitation dataset (Rozanski et al., 1993). The approximate rate of increase for the most positive values along this transect ($\sim 1\text{‰} / 70\text{km}$) is conspicuously similar to that observed northward across the Tibetan Plateau ($\sim 1\text{‰} / 72\text{km}$) (Bershaw et al., 2012; Hren et al., 2009; Quade et al., 2011; Tian et al., 2001). The observation that the isotopic composition of meteoric water becomes progressively enriched at a similar rate deep into the rainshadow of both the Andean and Tibetan Plateaux suggests common processes during moisture transport, such as surface water recycling and/or evaporative enrichment, are responsible, as opposed to mixing of unique moisture sources, which would be unique to each region. On the Tibetan Plateau, surface water reservoirs are progressively enriched in ^{18}O through evaporation and partial removal (advection) of relatively low

$\delta^{18}\text{O}$ vapor off the plateau. This trend is observed in *d excess* values which increase in streams but decrease in lakes downwind (north) from the Himalayan rainshadow (Bershaw et al., 2012). As the recycling ratio increases downwind (westward) across the Andean Plateau, the proportion of locally-derived moisture versus that advected from outside the plateau increases (Trenberth, 1999). Standing water, a source of recycled precipitation on the plateau, also shows evidence of evaporative enrichment (high in $\delta^{18}\text{O}$ and low in *d excess*) (Table 2). Continental recycling ratios in South America have been shown to reach a maximum near the Western Cordillera of ~70% (Van der Ent et al., 2010). Similar to the Tibetan Plateau, a larger contribution of recycled surface water to precipitation downwind may contribute to increasing $\delta^{18}\text{O}$ values of streams (Figure 2). However, the relationship between stream water *d excess* and distance from the Andean foreland along transect DEF is weak to non-existent ($R^2 = 0.003$) (Figure DR2).

It is also possible that stream water samples are enriched prior to sampling through surface water evaporation and/or subcloud evaporation of raindrops as they fall through the air (Gat and Airey, 2006). According to this model, we would expect a progressive increase in evaporation downwind to result in an inverse relationship between *d excess* and distance from the Andean foreland. Though this relationship is not clear in our stream water dataset, precipitation samples from Fiorella et al. (2015a) and Aravena et al. (1999) (Tables 3 and 4) on the southern plateau (elevation > 3500m) do show an inverse relationship with distance from the Andean foreland (longitude) ($R^2 = 0.69$), suggesting evaporative enrichment due to subcloud evaporation does play a significant role (Figure 6A). While precipitation *d excess* decreases downwind (westward) across the Andean Plateau, $\delta^{18}\text{O}$ values of precipitation do not exhibit an obvious trend, possibly due to the wide range in latitude and poor sample representation between -67° and -68.5° longitude (Figure 6B). The observation that there is not a clear decrease in precipitation $\delta^{18}\text{O}$ values to the west is consistent with evaporative enrichment mitigating the continental effect.

5.2.3 Latitude

Because this dataset does not include many locations south of -18° , published precipitation datasets from Aravena et al. (1999) and Fiorella et al. (2015a) have been included in a plot of latitudinal variation (Figure 7). When considering these combined datasets, the correlation between isotopic composition and latitude is weak ($R^2 = 0.17$). That said, it appears there is a general shift towards more positive values on the southern Andean Plateau, even in samples with consistently high ($>10\text{‰}$) *d excess* values. A latitudinal gradient in isotopic composition, where $\delta^{18}\text{O}$ values are more positive in the south, would be contrary to global patterns where $\delta^{18}\text{O}$ values of meteoric water are observed to decrease at higher latitudes (e.g. Rozanski et al., 1993). On the Andean Plateau, the south receives less precipitation than the north. Modern rainfall estimates range from >50 cm / yr north of 18°S to <25 cm / yr south of 20°S (Bookhagen and Strecker, 2008; Garreaud and Vuille, 2003; IAEA/WMO, 2016). Higher precipitation amounts in the north are also influenced by Lake Titicaca, a likely source of recycled moisture (García et al., 2007). Higher $\delta^{18}\text{O}$ of surface water in the southern Andean Plateau may be due to this climate gradient leading to higher rates of evaporation (Gat and Airey, 2006) and/or decreased amount effect precipitation and convective moistening on the southern Andean Plateau (Galewsky and Samuels-Crow, 2015). Surface water reservoirs often exhibit high $\delta^{18}\text{O}$ and very low *d excess* (Table 2) suggesting evaporation post-deposition is likely significant. If surface water and/or subcloud evaporation were more intense in the south, one might predict that *d excess* values would be more negative. However, similar to observations made on the Andean Plateau's southeast flank, we do not observe systematic changes in *d excess* with latitude (Rohrman et al., 2014). Relatively dry conditions in the south may also decrease the amount of convective moistening (amount effect) there, resulting in relatively high $\delta^{18}\text{O}$ values of meteoric water.

5.3 Isotope Trends up the Western Cordillera

314 There is a unique relationship between $\delta^{18}\text{O}$ and elevation along transects AB and DE, up the western
315 flank of the Western Cordillera in Peru (Figure 1). These stream water data show a consistently steep
316 isotopic lapse rate of -10‰ / km elevation gain (Figure 8). A remarkably similar pattern was observed in
317 precipitation data farther south along transect IJ by Aravena et al. (1999). An isotopic lapse rate of this
318 magnitude is not consistent with Rayleigh distillation of westerly-derived moisture from the Pacific
319 Ocean (Rowley, 2007). It contrasts with isotopic lapse rates observed up the windward side of the Eastern
320 Cordillera ($\sim -2\text{‰}$ / km) presented here along transect BC (Figure 3) and along transects GH and KL in
321 Figure 1 (Bershaw et al., 2010; Fiorella et al., 2015a; Gonfiantini et al., 2001), consistent with easterly
322 (Atlantic) derived precipitation. These anomalously steep isotopic lapse rates up the flank of the Western
323 Cordillera likely represent mixing between highly evolved Atlantic moisture (low $\delta^{18}\text{O}$ values) and
324 Pacific-derived fog and/or drizzle at low elevations (high $\delta^{18}\text{O}$ values). The Western Cordillera appears to
325 be a transition zone, where the relative influence of easterly (Atlantic) derived moisture increases with
326 elevation. Climate modeling corroborates this interpretation as easterlies contribute more to atmospheric
327 circulation in the Western Cordillera during precipitation events (Aravena et al., 1999; Fiorella et al.,
328 2015a; Garreaud et al., 2009).

329 Additional evidence is found in seasonal patterns of precipitation for sites throughout the region. La Paz,
330 Bolivia receives most of its precipitation during austral summer (Dec, Jan, Feb, and Mar) (Figures 1 and
331 DR3). Precipitation that falls in La Paz is ultimately Atlantic-derived moisture that crosses the Amazon
332 Basin before climbing up valleys that dissect the Eastern Cordillera, recycled many times along the way
333 (Gonfiantini et al., 2001). Though Arequipa, Peru is located much farther downwind, across the plateau in
334 the Western Cordillera, it displays a very similar seasonal pattern of precipitation with the vast majority
335 also falling during austral summer. Closer to the Pacific Ocean, both Tacna, Peru and Iquique, Chile are
336 the opposite, receiving precipitation primarily during austral winter (Jun, Jul, Aug), with dramatically less
337 annual precipitation. These observations suggest that easterlies dominate at high and mid-elevations in the
338 Western Cordillera, but do not contribute significantly to precipitation at low elevations near the Pacific

coast. This may explain an anomalously steep isotopic lapse rate as relatively low $\delta^{18}\text{O}$ (depleted), Atlantic-derived moisture in the Western Cordillera transitions to relatively high $\delta^{18}\text{O}$ (enriched), Pacific-derived fog and/or drizzle at low elevations in Peru and Chile.

Intense evaporation of surface waters at low elevations near the Pacific coast may also contribute to the steep isotopic lapse rate as the total amount of annual precipitation decreases by orders of magnitude down the Western Cordilleran flank (Figure DR3). This is seen in *d excess* values of streams which are relatively negative at low elevations near the Pacific Ocean, consistent with evaporative enrichment. Because precipitation samples from Aravena et al. (1999) do not show relatively low *d excess* values near the coast, it can be inferred that stream samples are primarily experiencing evaporation post-deposition (Figures 8 and DR1B).

5.4 Studies of Paleoclimate and Paleoaltimetry

The isotopic composition of paleowater from the Andean Plateau is often estimated using proxies from the rock record (Garzione et al., 2008b; Leier et al., 2013; Mulch et al., 2010; Saylor and Horton, 2014). Though some may exhibit seasonal bias (Breecker et al., 2009), isotopic proxies have the benefit of time-averaging, reflecting paleoclimate. Across the Andean Plateau, surface water evaporation, evaporation of raindrops as they fall through the air, surface water recycling, and air mass mixing affect the isotopic composition of surface waters to varying degrees. To minimize the effect of post-depositional evaporation, proxies that integrate water with a short residence time at the surface should be targeted. Siliciclastic carbonates, volcanic glass, lipid biomarkers, fossil teeth, and hydrated clays occur in diverse depositional environments and have all been used as proxies for the isotopic composition of paleowater (Bershaw et al., 2010; Canavan et al., 2014; Garzione et al., 2008a; Mulch et al., 2006; Polissar et al., 2009; Saylor and Horton, 2014). The likelihood of evaporative enrichment depends partly on the depositional environment. Lacustrine and/or fluvial proxies may be evaporatively enriched if surface

water is exposed to the atmosphere, particularly if relative humidity is low and residence times are high. For this reason, paleosol proxies may be less susceptible to evaporative enrichment. However, the isotopic composition of soil water may also become enriched in arid environments, particularly if samples are from <50 cm depth (Cerling and Quade, 1993; Quade et al., 2011; Quade et al., 2007).

The likelihood of evaporation in arid environments means that large datasets should be obtained to effectively distinguish between samples that have and have not been evaporatively enriched. Considering the wide range of $\delta^{18}\text{O}$ values observed across the Andean Plateau, individual samples are not a good predictor of elevation (Figure 4A). In some cases, evaporatively enriched samples (e.g. 170511-01) collected at over 3500m elevation predict elevations at sea-level using the isotopic lapse rate from Figure 4B. Proxies that reflect highly evaporated paleowater have similar potential to significantly underestimate paleoelevation, which highlights the need for a sufficiently large dataset to target minimally evaporated samples.

Of 242 stream water samples, we took the most negative $\delta^{18}\text{O}$ value per 200m elevation to establish an isotopic lapse rate ($-3.5\text{‰} / \text{km}$) across the plateau. Stream water samples that plot within 780m of the trend line (standard error) are within statistical uncertainty of the regression. For the plateau (elevations > 3500m), where evaporative enrichment of meteoric water can be pronounced, 26% of stream samples fall within the standard error, suggesting that a quarter of all samples are useful for predicting elevation. At a minimum, individual paleoelevation estimates from proxies on the Andean Plateau should be based on the most negative of at least four samples when using this isotopic lapse rate ($-3.5\text{‰} / \text{km}$). This does not account for additional proxy considerations, each of which have unique uncertainties associated with their recording of paleowater chemistry (Rowley and Garzione, 2007).

Using the modern isotopic lapse rate established up the eastern Cordillera ($-2\text{‰} / \text{km}$) for paleowater proxies in the Eastern Cordillera is warranted. However, using the same isotopic lapse rate for sites in the western Altiplano and Western Cordillera is likely to result in underestimates of paleoelevation and

overestimates of temperature. That said, this data shows that the most negative isotopic values still exhibit a significant relationship with elevation (Figure 4B), suggesting that given a large enough sample population, paleoelevation constraints based on the most negative values and an appropriate isotopic lapse are justified, even deep into the rainshadow of a mountain range.

6.0 CONCLUSIONS

The northern Andean Plateau shows patterns of stable isotope evolution that appear dominated by processes that fractionate during and after vapor transport from the Atlantic via the Amazon Basin, with mixing between easterly and westerly (Pacific) derived moisture limited to the western flank of the Western Cordillera. Considerable recycling and/or evaporative enrichment of meteoric water across the Andean Plateau will likely lead to underestimates of paleoelevation, unless a sufficient number of samples are obtained to distinguish minimally evaporated samples. The most negative $\delta^{18}\text{O}$ values of stream water across the entire Andean Plateau show a significant relationship with elevation ($-3.5\text{‰} / \text{km}$) that is unique to this arid environment, and significantly different from that observed on the relatively wet, windward flank of the Eastern Cordillera ($-2\text{‰} / \text{km}$). Because modeling suggests that lowering the Andes would result in additional aridity across most of the plateau (Insel et al., 2009; Poulsen et al., 2010), we recommend using this steeper isotopic lapse rate for proxies obtained from the Andean Plateau itself, with at least four data points per paleoelevation estimate.

Spatial patterns of isotope variability due to moisture source mixing appear limited to the coastal flank of the Western Cordillera, where we interpret a transition from Atlantic-derived moisture at high elevations to Pacific-derived fog and/or drizzle at lower elevations. This is supported by consistently steep isotopic lapse rates ($-10\text{‰} / \text{km}$) along the Western Cordillera from Peru to Chile (Figure 8), climate modeling (Aravena et al., 1999), and seasonal patterns of precipitation (Figure DR3). We conclude that elevation

exhibits a primary control on the isotopic composition of surface waters across the Andean Plateau and its flanks (-13° to -20° latitude), often modified significantly by surface water recycling and/or evaporation.

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8.0 REFERENCES

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606

607 FIGURE CAPTIONS

608 *Figure 1:* Sample location map of surface water collected across the Andean Plateau and surrounding
609 regions. Dark blue circles are surface stream and river water sample sites (Table 1). Light blue circles are

standing water sample sites (lakes, marshes, etc.) (Table 2). Green squares representing transect IJ are precipitation collection sites with data published by Aravena et al. (1999) (Table 3). Yellow squares are precipitation collection sites on the plateau published by Fiorella et al. (2015a) (Table 4). Transect KL corresponds with precipitation data from the same study, down the eastern (windward) flank of the Eastern Cordillera. Transect GH also corresponds with published surface water data from the windward side of the Eastern Cordillera (Bershaw et al., 2010; Gonfiantini et al., 2001). Red circles show locations of major cities. The basemap was derived from satellite data (SRTM from <http://earthexplorer.usgs.gov/>).

Figure 2: Composite of NCEP/NCAR reanalysis data showing long-term average low-level (850mb) wind vectors (white arrows) and Global Precipitation Climatology Project (GPCP) precipitation amount (colors) for South America during austral summer (DJF) from 1980-2015. Dashed black curve is a smoothed 4000 m elevation contour showing approximate outline of the Andes. Red star indicates region of sampling for this study. Image provided by the NOAA/ESRL Physical Sciences Division, Boulder Colorado from their Web site at <http://www.esrl.noaa.gov/psd> (Kalnay et al., 1996).

Figure 3: A compilation of stream water data along an elevation transect on the plateau corresponding with transect BC in Figure 1. The isotopic lapse rate is approximately -2‰ / km elevation gain, consistent with transects up the windward side of the Eastern Cordillera. Circles are shaded by d excess value with a gradient from 10‰ (black) to -5‰ (white). 95% confidence intervals are shown as grey dashed lines. Elevation is reported as the mean basin hypsometry.

Figure 4: (a) A compilation of $\delta^{18}\text{O}$ values (x-axis) for stream and river water samples collected from the Andean Plateau plotted against elevation (y-axis). A linear regression suggests there is not a significant

relationship when the entire stream dataset is considered ($R^2 = 0.12$). (b) The most negative $\delta^{18}\text{O}$ values per 200m elevation are denoted with triangles (noted in Table 1 and Figure DR1A). The open square shows the annual weighted mean of precipitation at Cuiaba and Manaus, Brazil (IAEA/WMO, 2016) at low elevation (<200 m) in the Andean foreland (NE of the map shown in Figure 1). The black dashed line is a regression through these most negative $\delta^{18}\text{O}$ values (triangles and open square). 95% confidence intervals are shown as grey dashed lines. The standard error on this regression is 780m. Lower elevation (<2.5 km) scatter may be due to low sample density. The isotopic lapse rate is $\sim -3.5\text{‰} / 1 \text{ km}$ elevation gain, suggesting elevation exerts a first-order control on the isotopic composition of relatively non-evaporated surface water across the northern Andean Plateau. Symbols are shaded by $d \text{ excess}$ value with a gradient from 10‰ (black) to -5‰ (white). Elevation is reported as the mean basin hypsometry. Samples with extremely low $d \text{ excess}$ values $< -5\text{‰}$ (18 samples) are not included as they are likely affected significantly by evaporation.

Figure 5: A compilation of stream and river water samples along a NE-SW transect shown as DEF in Figure 1. Only samples within 25km of transect DEF are included (noted in Table 1). The gray curve is the average elevation over a 100 km wide swath following this transect. $\delta^{18}\text{O}$ values of stream water decrease significantly up the windward side of the Eastern Cordillera. The most negative values (-19‰) correspond with an elevation of $\sim 4.2 \text{ km}$ based on the isotopic lapse rate in Figure 4B. Westward across the plateau, the most positive values increase at a rate of $\sim 1\text{‰} / 70 \text{ km}$ inland from the Eastern Cordilleran crest, consistent with recycling of evaporatively enriched surface waters. For sample locations, the geographic center of catchments upstream from stream or river sample sites (centroid) is used. Elevation is reported as the mean basin hypsometry. Three samples with very low $d \text{ excess}$ values $< -5\text{‰}$ are not included as they represent extreme evaporative enrichment (170511-01, 030611-01, and 10PE-88w).

657

658 *Figure 6:* (a) A compilation of published precipitation data from Aravena et al. (1999) (Table 3) and
659 Fiorella et al. (2015a) (Table 4). Sample locations are throughout the central and southern Andean Plateau
660 (Figure 1). *d excess* values are plotted against longitude as this part of the Andean Plateau strikes roughly
661 north-south. Though we do not see a meaningful trend in *d excess* from stream water samples (Figure
662 DR2), *d excess* in precipitation decreases with distance from the Andean Foreland, suggesting evaporative
663 enrichment through subcloud evaporation becomes increasingly significant westward (downwind). (b)
664 Interestingly, there is not a meaningful trend in $\delta^{18}\text{O}$ values of precipitation in the same dataset. The
665 observation that there is not a clear decrease in precipitation $\delta^{18}\text{O}$ values to the west may be interpreted as
666 evaporative enrichment mitigating the continental effect downwind.

667

668 *Figure 7:* A compilation of $\delta^{18}\text{O}$ values (x-axis) for stream (circles) and precipitation (triangles) samples
669 from the Andean Plateau plotted against latitude (y-axis). Stream data (circles) is from this study (Table
670 1) while precipitation data (triangles) is from Aravena et al. (1999) (Table 3) and Fiorella et al. (2015a)
671 (Table 4). Published precipitation data was added south of -18° due to a paucity of stream data there.
672 Symbols are shaded by *d excess* value with a gradient from 10‰ (black) to -5‰ (white). 95% confidence
673 intervals are shown as grey dashed lines. The black dashed line is a regression through this combined
674 dataset showing a weak correlation ($R^2 = 0.17$). Though there is considerable scatter, it appears that $\delta^{18}\text{O}$
675 values are generally more positive on the southern Andean plateau, consistent with more arid conditions
676 there. For stream samples, the geographic center of catchments upstream from stream or river sample
677 sites (centroid) is used and elevation is reported as the mean basin hypsometry. Only samples from
678 elevations $> 3500\text{m}$ are included, limiting the dataset to the plateau itself. Samples with extremely low *d*
679 *excess* values $< -5\text{‰}$ (15 samples) are not included as they are likely significantly affected by
680 evaporation.

681

682 *Figure 8:* Compilations of stream water data along three elevation transects on the western flank of the
683 Andean Plateau (Figure 1). The black dashed lines are linear regressions through the datasets. 95%
684 confidence intervals are shown as grey dashed lines. The isotopic lapse rate of all three transects is
685 consistently $\sim -10\text{‰}$ / km elevation gain. This steep isotopic lapse rate is likely due to air mass mixing
686 and/or evaporation at low elevations near the coast. Samples included in each transect are noted in Table
687 1. Unlike Figure 3, samples more than 25 km from transect DE are included as sample density in this area
688 is low. One anomalous low elevation site is excluded from transect DE (sample 20140518-04). The
689 watershed of this sample is likely not defined correctly as its $\delta^{18}\text{O}$ value is consistent with other high
690 elevation sites. Transect IJ shows weighted mean precipitation data from Aravena et al. (1999) (Table 3).
691 Significant scatter (low R^2 values) is consistent with the effects of evaporation in arid environments.
692 Circles are shaded by $d\text{ excess}$ value with a gradient from 10‰ (black) to -5‰ (white). Samples with
693 extremely low $d\text{ excess}$ values $< -5\text{‰}$ are not included as they are likely significantly affected by
694 evaporation. Elevation is reported as the mean basin hypsometry.

695

696 *Figure DRI:* (a) Map of $\delta^{18}\text{O}$ variation across the Andean Plateau using a natural neighbor interpolation
697 of stream water samples (Table 1) and precipitation samples from Aravena et al. (1999) (Table 3) and
698 Fiorella et al. (2015a) (Table 4). Note that the centroid of stream catchments is shown here while actual
699 sample locations are shown in Figure 1. Samples used in the regression shown in Figure 4B are shown as
700 triangles. $\delta^{18}\text{O}$ values range from $\sim 3.5\text{‰}$ to -20.5‰ . Hot colors are associated with relatively positive
701 values and cool colors associated with relatively negative values. (b) $d\text{ excess}$ is plotted using the same
702 dataset as shown in (a). In this case, hot colors are associated with relatively negative values and cool
703 colors associated with relatively positive values. The basemap was derived from satellite data (SRTM
704 from <http://earthexplorer.usgs.gov/>).

705

706 *Figure DR2*: Plot showing variation in *d excess* along transect DEF (Figure 1). This is the same sample
707 population shown in Figure 3. A regression suggests that there is not a systematic pattern in *d excess*
708 longitudinally across the plateau ($R^2 = 0.0025$). Though, one might argue that there is a weak inverse
709 relationship between *d excess* and distance from the Andean foreland. Only samples within 25 km of
710 transect DEF are included (noted in Table 1). For sample locations, the geographic center of catchments
711 upstream from stream or river sample sites (centroid) is used. Elevation is reported as the mean basin
712 hypsometry (average elevation of the watershed flowing into the stream at the sample site). Three samples
713 with very low *d excess* values $< -5\%$ are not included as they represent extreme evaporative enrichment
714 (170511-01, 030611-01, and 10PE-88w).

715

716 *Figure DR3*: Relative monthly precipitation amounts averaged over years where records exist for sites
717 across the Andean Plateau and Western Cordillera (IAEA/WMO, 2016). Note that the seasonality of
718 precipitation changes from easterly dominated moisture at La Paz and Arequipa (austral summer) to
719 westerly at Tacna and Iquique (austral winter). Each graph begins with January (left) and ends with
720 December (right). Mean annual precipitation is annotated below each graph. Satellite image from Google
721 (<http://www.google.com/earth>).

Table 1

Sample ID	d ¹⁸ O (vsmow)	dD (vsmow)	d excess	Site Elevation (m)	Mean Basin Hypsometry (m)	Latitude	Longitude	Centroid Latitude	Centroid Longitude	Centroid Distance from Andean Foreland (km)	Watershed Area (km ²)	Collection Date	Included in Transect
10PE-01w	-16.1	-121.7	7.3	4034	4212	-13.51	-71.85	-13.51	-71.84	35.12	1.96	5/3/2010	
10PE-02w	-15.9	-118.9	8.4	3447	3900	-13.51	-71.99	-13.48	-72	44.55	15.11	5/3/2010	
10PE-03w	-15.8	-119.3	7	3598	3711	-13.5	-71.98	-13.5	-71.98	44.41	1.5	5/3/2010	
10PE-04w	-15.1	-117	4	3390	3816	-13.54	-71.98	-13.58	-71.98	51	51.23	5/4/2010	
10PE-06w	-16	-121.5	6.5	3776	3912	-13.61	-71.91	-13.6	-71.91	48.06	3.66	5/4/2010	
10PE-07w	-14.9	-114.5	5	3408	3824	-13.67	-71.92	-13.67	-71.9	53.02	3.66	5/4/2010	
10PE-08w	-15.9	-116.7	10.3	3764	4074	-13.69	-71.91	-13.68	-71.89	52.3	3.73	5/4/2010	
10PE-09w	-15.8	-117.9	8.3	3445	3903	-13.72	-71.88	-13.71	-71.87	54.05	3.21	5/4/2010	
10PE-11w	-13.7	-108	1.6	3014	3540	-13.79	-71.84	-13.8	-71.86	61.1	3.79	5/5/2010	
10PE-13w	-14.8	-113.2	5.2	3100	3279	-13.76	-71.84	-13.76	-71.83	56.68	1.5	5/5/2010	
10PE-14w	-13.7	-109.1	0.6	3154	3455	-13.76	-71.83	-13.76	-71.83	56.49	0.26	5/5/2010	
10PE-16w	-15.9	-119.9	7.7	3998	4234	-13.67	-71.85	-13.66	-71.84	47.12	2.03	5/5/2010	
10PE-17w	-14.7	-115.1	2.3	4073	4213	-13.65	-71.85	-13.65	-71.85	46.81	2.22	5/5/2010	
10PE-18w	-15.9	-121	6.5	3562	3847	-13.6	-71.87	-13.6	-71.87	45.5	2.09	5/5/2010	
10PE-19w	-15.6	-119.8	5	3324	3815	-13.58	-71.88	-13.6	-71.86	44.31	25.78	5/5/2010	
10PE-20w	-16	-118.8	8.9	3122	3852	-13.67	-71.68	-13.7	-71.71	44.54	40.83	5/6/2010	
10PE-21w	-15.3	-117.3	5	3202	3955	-13.69	-71.61	-13.68	-71.57	38.94	28.2	5/6/2010	
10PE-22w	-15.2	-115.2	6.4	3234	3893	-13.8	-71.55	-13.79	-71.53	50.67	3.21	5/6/2010	
10PE-24w	-16.2	-121.1	8.4	3457	3989	-14.07	-71.44	-14.06	-71.43	77.27	1.5	5/6/2010	
10PE-25w	-16.6	-124.8	8	3488	3939	-14.13	-71.41	-14.12	-71.4	82.82	3.66	5/6/2010	
10PE-27w	-17.1	-128.5	8.7	3673	4147	-14.35	-71.18	-14.36	-71.22	102.84	36.64	5/6/2010	
10PE-28w	-17.1	-127.9	8.8	3825	4471	-14.41	-71.13	-14.42	-71.15	105.37	6.87	5/6/2010	
10PE-29w	-17.9	-129.5	13.3	3950	4532	-14.43	-71.1	-14.45	-71.12	107.69	9.09	5/6/2010	
10PE-30w	-18.1	-127.8	16.9	4248	4897	-14.48	-71.02	-14.44	-70.99	102.37	18.65	5/6/2010	Triangle in Fig 48
10PE-31w	-17.9	-128.2	14.7	4118	4691	-14.52	-70.91	-14.49	-70.91	103.83	3.99	5/6/2010	DEF (Fig 5)
10PE-32w	-15.9	-117.1	10.2	3994	4415	-14.6	-70.81	-14.56	-70.9	110.27	267.13	5/6/2010	DEF (Fig 5)
10PE-34w	-15.2	-116.1	5.1	3914	3955	-14.81	-70.7	-14.8	-70.69	124.85	3.21	5/6/2010	DEF (Fig 5)
10PE-35w	-12.8	-104.2	-2.1	3912	3980	-14.87	-70.62	-14.86	-70.61	127.77	0.79	5/6/2010	
10PE-36w	-15.4	-119.2	3.6	3885	4075	-15.01	-70.39	-15.06	-70.43	131.56	67.85	5/6/2010	
10PE-37w	-12.7	-105.4	-4.2	3856	4256	-15.17	-70.36	-14.93	-70.71	139.51	4391.02	5/6/2010	
10PE-38w	-15.3	-115.7	6.3	3840	4113	-15.31	-70.23	-15.32	-70.25	140.61	12.04	5/6/2010	
10PE-39w	-14.9	-115.2	4	3992	4096	-15.93	-70.03	-15.92	-70.01	148.05	6.8	5/7/2010	
10PE-40w	-13.9	-108.9	2.2	3973	4173	-16.17	-70.09	-16.16	-70.12	169.41	20.61	5/7/2010	
10PE-41w	-14.8	-113.8	4.9	4007	4266	-16.2	-70.12	-16.21	-70.11	170.74	2.22	5/7/2010	
10PE-42w	-14.3	-111	3.4	4061	4398	-16.24	-70.14	-16.31	-70.14	179.27	73.34	5/7/2010	
10PE-43w	-15.1	-114.9	5.5	4159	4433	-16.28	-70.17	-16.29	-70.18	182.45	29.9	5/7/2010	
10PE-44w	-14.9	-114	5.4	4353	4455	-16.28	-70.2	-16.28	-70.21	183.93	4.19	5/7/2010	
10PE-45w	-13.1	-105.8	-1.2	4417	4582	-16.32	-70.23	-16.26	-70.25	186.79	40.3	5/7/2010	
10PE-46w	-14.9	-115	4.6	4455	4687	-16.37	-70.29	-16.34	-70.32	198.17	28.2	5/7/2010	
10PE-48w	-11.4	-100.5	-8.9	3817	4017	-15.76	-70.05	-15.82	-70.09	152.4	106.05	5/8/2010	
10PE-50w	-17.2	-129.9	7.5	3601	3981	-14.31	-71.24	-14.33	-71.24	99.78	5.1	5/10/2010	
10PE-51w	-16.8	-129.1	5.2	3660	3862	-14.33	-71.27	-14.33	-71.28	100.91	0.85	5/10/2010	
10PE-52w	-16	-122.9	4.8	3794	4182	-14.35	-71.29	-14.38	-71.32	107.93	97.88	5/10/2010	
10PE-53w	-17.6	-133.2	7.9	3947	4252	-14.36	-71.32	-14.35	-71.32	104.95	1.57	5/10/2010	
10PE-54w	-16.2	-123.8	5.5	3999	4036	-14.39	-71.33	-14.39	-71.33	109.33	1.64	5/10/2010	
10PE-56w	-18.2	-137.3	8.6	4222	4381	-14.45	-71.29	-14.45	-71.3	114.94	0.52	5/10/2010	
10PE-57w	-16.5	-127.9	3.8	4250	4349	-14.47	-71.3	-14.46	-71.3	115.89	2.68	5/10/2010	
10PE-58w	-16.6	-129.4	3.7	4018	4173	-14.5	-71.29	-14.51	-71.26	118.94	40.17	5/10/2010	
10PE-59w	-15.7	-122	3.9	3991	4178	-14.52	-71.29	-14.52	-71.28	121.5	3.47	5/10/2010	
10PE-61w	-13	-107.4	-3.8	3983	4145	-14.56	-71.29	-14.58	-71.27	126.95	13.94	5/11/2010	
10PE-62w	-13.9	-112.5	-1.1	4049	4140	-14.59	-71.29	-14.6	-71.26	128.87	10.08	5/11/2010	
10PE-63w	-15	-118.9	1.1	4050	4075	-14.63	-71.28	-14.63	-71.28	132.5	0.92	5/11/2010	
10PE-64w	-14.4	-117.5	-1.9	4000	4019	-14.7	-71.29	-14.7	-71.29	140.19	0.98	5/11/2010	
10PE-65w	-16.3	-127.9	2.4	3917	4015	-14.73	-71.39	-14.72	-71.35	144.41	34.61	5/12/2010	
10PE-66w	-13.3	-111.4	-4.9	3978	4022	-14.73	-71.27	-14.71	-71.26	140.56	10.34	5/12/2010	
10PE-67w	-16.7	-133.1	0.2	3965	4002	-14.88	-71.21	-14.9	-71.19	156.96	13.22	5/12/2010	DEF (Fig 5)
10PE-68w	-14.6	-119.4	-2.7	4086	4158	-15.04	-71.14	-15.04	-71.13	168.39	1.96	5/12/2010	DEF (Fig 5)
10PE-69w	-14.7	-116.7	0.5	4184	4400	-15.11	-71.11	-15.12	-71.13	176.46	4.06	5/12/2010	DEF (Fig 5)
10PE-70w	-14.5	-117.2	-1.2	4230	4365	-15.13	-71.11	-15.13	-71.12	177.61	1.96	5/12/2010	DEF (Fig 5)
10PE-71w	-15.7	-124.2	1	4311	4594	-15.15	-71.14	-15.14	-71.15	180.04	3.6	5/12/2010	DEF (Fig 5)
10PE-72w	-16.7	-128.2	5.4	4459	4551	-15.18	-71.15	-15.18	-71.15	183.7	0.2	5/12/2010	DEF (Fig 5)
10PE-73w	-14.4	-118.1	-3.1	4542	4630	-15.2	-71.15	-15.2	-71.16	185.83	0.79	5/12/2010	DEF (Fig 5)
10PE-74w	-14.4	-114.5	0.6	4645	4763	-15.21	-71.15	-15.22	-71.16	188.16	1.37	5/12/2010	DEF (Fig 5)
10PE-75w	-17.2	-133.4	4.2	4688	4826	-15.23	-71.15	-15.25	-71.17	191.71	24.53	5/12/2010	DEF (Fig 5)
10PE-76w	-16.5	-127.7	4.2	4660	4800	-15.3	-71.15	-15.29	-71.16	195.64	2.75	5/12/2010	DEF (Fig 5)
10PE-77w	-13.6	-112	-3.2	4638	4814	-15.32	-71.18	-15.29	-71.19	197.13	14.46	5/12/2010	DEF (Fig 5)
10PE-78w	-14.4	-115.5	-0.1	4527	4637	-15.37	-71.22	-15.36	-71.22	204.55	3.6	5/12/2010	DEF (Fig 5)
10PE-80w	-14.7	-120	-2.3	4161	4295	-15.4	-71.29	-15.4	-71.3	213.05	1.64	5/13/2010	DEF (Fig 5)
10PE-81w	-14.6	-118.5	-1.8	4441	4577	-15.41	-71.31	-15.41	-71.32	214.7	2.03	5/13/2010	DEF (Fig 5)
10PE-82w	-13.1	-109.1	-4.2	4549	4718	-15.42	-71.32	-15.43	-71.34	217.33	4.65	5/13/2010	DEF (Fig 5)
10PE-83w	-16.9	-129	6.3	4762	4762	-15.44	-71.35	-15.44	-71.35	218.73	0.92	5/13/2010	DEF (Fig 5), DE (Fig 8)
10PE-84w	-19	-138.2	13.9	4699	4757	-15.45	-71.37	-15.45	-71.37	220.36	4.25	5/13/2010	DEF (Fig 5), DE (Fig 8)
10PE-85w	-15	-114.7	5.4	4276	4594	-15.49	-71.38	-15.47	-71.38	223.53	3.99	5/13/2010	DEF (Fig 5), DE (Fig 8)
10PE-86w	-14.8	-114.4	4.3	4099	4529	-15.5	-71.38	-15.47	-71.36	222.94	21.52	5/13/2010	DEF (Fig 5), DE (Fig 8)
10PE-87w	-17.8	-132.6	9.4	3862	3982	-15.5	-71.43	-15.51	-71.43	229.58	2.09	5/13/2010	DEF (Fig 5), DE (Fig 8), Triangle in Fig 48
10PE-88w	-11	-97	-9	3806	4532	-15.51	-71.48	-15.43	-71.24	213.5	3948.61	5/13/2010	

10PE-89w	-16.4	-121.5	9.3	3888	4686	-15.57	-71.59	-15.52	-71.63	238.35	48.41	5/13/2010	DEF (Fig 5), DE (Fig 8)
10PE-90w	-15.4	-116.9	6.5	3527	3888	-15.66	-71.63	-15.67	-71.63	253.28	3.07	5/14/2010	DEF (Fig 5), DE (Fig 8)
10PE-91w	-17.6	-129.7	10.8	3429	3753	-15.66	-71.71	-15.67	-71.72	256.76	2.03	5/14/2010	DEF (Fig 5), DE (Fig 8), Triangle in Fig 4B
10PE-92w	-16.9	-124.5	10.3	3272	4092	-15.64	-71.75	-15.6	-71.74	250.8	15.18	5/14/2010	DEF (Fig 5), DE (Fig 8)
10PE-93w	-12.9	-101.5	1.4	1949	3395	-16.43	-71.65	-16.29	-71.57	314.28	122.28	5/14/2010	DE (Fig 8)
10PE-96w	-11.8	-93.6	0.8	1145	3180	-16.47	-71.93	-16.16	-71.7	306.79	2295.31	5/14/2010	DE (Fig 8)
10PE-97w	-14.5	-113.6	2.1	1269	3711	-16.34	-72.13	-15.97	-71.93	295.53	1690.33	5/14/2010	DEF (Fig 5), DE (Fig 8)
10PE-99w	-15.9	-121.9	5.7	440	3962	-16.22	-72.46	-15.53	-72.21	253.94	9589.05	5/14/2010	DE (Fig 8)
A	-13.3	-99.6	6.7	3881	4095	-17.31	-67.55	-17.27	-67.55	51.43	133.99	7/19/2007	
C	-10.2	-85.4	-3.6	4004	4084	-17.24	-67.36	-17.24	-67.36	34.13	0.52	7/24/2007	
D	-13	-99.3	5	4034	4162	-17.38	-67.34	-17.4	-67.33	44.41	7.92	7/26/2007	
E	-15	-112.4	7.8	3861	4084	-17.13	-67.96	-17.04	-68.08	66.3	928.12	7/28/2007	
H	-11.3	-87.8	2.4	2546	4202	-17.05	-67.66	-17.26	-67.48	44.69	0.52	7/29/2007	
I	-12.8	-103	-0.3	4003	4095	-17.36	-68.24	-17.34	-68.23	101.97	11.84	7/30/2007	
J	-13.1	-103.3	1.7	3882	4163	-17.25	-68.49	-17.19	-68.39	99.61	214.66	7/30/2007	
K	-14.4	-110.9	4.6	4274	4429	-17.1	-68.3	-17.08	-68.29	83.6	26.69	7/30/2007	
L	-16.3	-119.6	10.9	4309	4513	-17.09	-68.31	-17.08	-68.31	84.89	2.42	7/31/2007	
N	-14.2	-109.7	4.2	4048	4304	-17.2	-68.18	-17.19	-68.24	89.62	113.64	8/1/2007	
T	-12.6	-99.5	1.1	4113	4345	-17.26	-67.32	-17.19	-67.32	27.9	61.11	8/4/2007	
U	-13.5	-99.9	7.9	3171	3695	-16.88	-67.97	-16.84	-68.03	45.81	140.9	8/4/2007	
V	-12	-96	0.3	2562	3846	-16.99	-67.8	-17.1	-67.78	51.08	298.86	8/5/2007	
WV	-14.1	-105.3	7.7	4071	4196	-16.88	-68.04	-16.88	-68.05	49.87	5.36	8/5/2007	
Y	-12.7	-102.1	-0.2	3855	3982	-16.54	-68.4	-16.72	-68.24	53.68	1365.56	8/8/2007	
Z	-10.4	-92.1	-8.9	3853	4082	-16.56	-68.46	-16.84	-68.4	75.76	694.55	8/8/2007	
Z1	-12.3	-100.2	-1.7	3880	3969	-16.59	-68.57	-16.58	-68.55	72.26	3.27	8/8/2007	
Z2	-8.9	-59.5	12	195	667	-14.44	-67.53	-14.89	-67.53	129.7	5553.3	8/9/2007	Triangle in Fig 4B
Z3	-8.8	-59	11.6	205	1759	-14.6	-67.54	-14.48	-68.48	65.25	9643.88	8/10/2007	Triangle in Fig 4B
Z4	-8.1	-53.1	11.8	259	2386	-14.98	-67.69	-16.11	-67.54	46.44	54372.84	8/10/2007	Triangle in Fig 4B
Z5	-12.4	-93.2	5.7	4168	4246	-17.19	-67.1	-17.19	-67.1	10.78	1.18	8/13/2007	
Z6	-13.7	-98.7	11.1	4324	4356	-17.22	-67.09	-17.22	-67.09	11.55	3.14	8/13/2007	
Z7	-11.9	-89.2	5.7	4035	4403	-17.24	-67.09	-17.25	-67.08	13.05	13.94	8/13/2007	
Z8	-12.1	-95.6	1.6	4530	4528	-17.3	-67.15	-17.3	-67.16	22.99	8.18	8/14/2007	
Z9	-11.3	-92.5	-2	4334	4508	-17.48	-67.14	-17.47	-67.14	33.79	4.25	8/16/2007	
CO	-12.3	-95.7	2.8	3910	4047	-17.24	-67.38	-17.26	-67.38	37.36	6.15	5/16/2009	
DO	-13.8	-104.1	6	4075	4215	-17.24	-67.35	-17.22	-67.35	32.25	1.96	5/17/2009	
EO	-13.7	-105.4	4.5	3797	4352	-19.12	-66.76	-19.19	-66.62	99.88	205.04	5/26/2009	
FO	-13	-99.6	4.4	3722	4529	-19.37	-66.86	-19.36	-66.57	106.32	411.98	5/26/2009	
GO	-14.2	-105.4	8	3822	3891	-19.62	-66.8	-19.61	-66.75	134.03	11.71	5/26/2009	
HO	-13	-102.3	2	3788	4085	-20.07	-66.88	-20.01	-66.79	151.84	175.27	5/26/2009	
LO	-9.7	-67.4	10.2	4372	4937	-22.27	-67.82	-22.27	-67.88	301.21	15.51	5/28/2009	
MO	-13.8	-100.6	10.1	4557	4714	-21.88	-67.54	-21.89	-67.54	269.42	3.27	5/28/2009	
NO	-13.9	-102.1	8.8	4025	4293	-21.75	-67.48	-21.64	-67.56	271.44	797.66	5/28/2009	
PO	-12.2	-100.8	-3.5	3711	4257	-18.79	-66.85	-18.84	-66.61	77.22	1415.41	5/31/2009	
030611-01	-9.9	-99.9	-20.7	3916	3994	-14.78	-70.72	-14.75	-70.7	120.27	29.7	6/3/2011	
030611-02	-16.6	-127.9	4.9	3993	4415	-14.6	-70.81	-14.58	-70.8	107.65	5.63	6/3/2011	DEF (Fig 5)
030611-03	-18.7	-133.2	16.3	4246	4648	-14.5	-70.96	-14.5	-70.97	107.17	30.23	6/3/2011	DEF (Fig 5)
030611-06	-19.3	-135.8	18.8	4265	4398	-14.47	-71.07	-14.48	-71.07	108.47	1.5	6/3/2011	Triangle in Fig 4B
030611-08	-15.9	-119.5	7.9	3255	3757	-13.86	-71.52	-13.85	-71.51	55.98	4.06	6/3/2011	
030611-09	-15.2	-117.9	3.5	3275	3903	-13.8	-71.55	-13.78	-71.54	49.75	3.53	6/3/2011	
170511-01	-2.9	-93.9	-70.7	4219	4432	-15.44	-71.26	-15.46	-71.28	218.22	18.19	5/17/2011	
190510-01	-14.9	-114.6	4.4	3992	4088	-16.05	-71.34	-16.05	-71.33	278.01	2.36	5/19/2010	DE (Fig 8)
190510-03	-14.8	-113.9	4.3	3844	4121	-15.31	-70.23	-15.32	-70.25	140.61	1.2	5/19/2010	
190510-04	-6.2	-68.4	-18.9	3852	3983	-14.98	-70.19	-14.93	-70.22	106.5	67.72	5/19/2010	
200510-04	-15.4	-119.8	3.1	4197	4578	-14	-70.48	-14.01	-70.43	34.31	198.89	5/20/2010	DEF (Fig 5)
200510-09	-15	-117.3	2.8	4406	4765	-14.08	-70.51	-14.11	-70.55	49.84	38.86	5/20/2010	DEF (Fig 5)
200510-12	-15.9	-122.3	5.3	4483	4634	-14.07	-70.58	-14.08	-70.58	47.34	0.72	5/20/2010	DEF (Fig 5)
200510-13	-13.7	-110.6	-0.8	4475	4670	-14.08	-70.54	-14.09	-70.55	47.38	5.43	5/20/2010	DEF (Fig 5)
200510-14	-14.6	-116	0.5	4372	4548	-14.08	-70.5	-14.09	-70.5	45.41	1.37	5/20/2010	DEF (Fig 5)
200511-04	-17.8	-142.3	0.1	4487	4601	-15.12	-71.21	-15.11	-71.19	178.35	40.63	5/20/2011	DEF (Fig 5)
200511-05	-19.6	-144.2	12.6	4521	4661	-15.05	-71.26	-15.05	-71.26	175.52	3.14	5/20/2011	DEF (Fig 5), Triangle in Fig 4B
200511-07	-19	-148.5	3.5	3950	4286	-14.87	-71.26	-14.99	-71.1	162.86	1195.91	5/20/2011	
210510-01	-15.1	-118.3	2.8	4597	4775	-14.13	-70.35	-14.15	-70.34	44.44	11.84	5/21/2010	DEF (Fig 5)
210510-02	-16.9	-125.7	9.9	4691	4851	-14.18	-70.31	-14.19	-70.32	46.75	5.69	5/21/2010	DEF (Fig 5)
210510-03	-17.6	-129.5	11.5	4511	4797	-14.19	-70.29	-14.2	-70.3	47.61	4.65	5/21/2010	DEF (Fig 5)
210510-04	-7.5	-75.2	-15.6	4342	4448	-14.42	-69.85	-14.4	-69.84	35.87	5.04	5/21/2010	
210510-10	-9.8	-90.1	-11.7	4506	4575	-14.56	-69.8	-14.56	-69.79	45.12	1.37	5/21/2010	
220510-02	-15.7	-119.6	5.6	4010	4276	-14.84	-70.59	-14.82	-70.59	123.17	7.52	5/22/2010	
220510-05	-16	-121.6	6.5	3994	4404	-14.84	-70.58	-14.82	-70.55	120.92	21.2	5/22/2010	
220510-16	-15.4	-119.5	3.5	3994	4227	-14.72	-70.7	-14.69	-70.67	112.79	49.27	5/22/2010	DEF (Fig 5)
250510-05	-17	-128.6	7.5	4213	4464	-14.77	-70.94	-14.76	-70.96	133.24	6.35	5/25/2010	DEF (Fig 5)
250510-11	-15	-120	0.3	4203	4578	-14.79	-71.05	-14.79	-71.01	138.17	60.65	5/25/2010	DEF (Fig 5)
250511-01	-6.2	-93.4	-43.8	3505	3728	-13.19	-74.31	-13.22	-74.31	67.73	20.67	5/25/2011	
270511-01	-6.8	-95.8	-41.4	3567	4113	-13.67	-73.26	-13.71	-73.25	69	39.39	5/27/2011	
270511-02	-14.7	-114.5	3.1	3772	4000	-13.68	-73.25	-13.69	-73.24	66.1	9.16	5/27/2011	
270511-03	-14.1	-114.3	-1.4	3973	4184	-13.67	-73.22	-13.69	-73.21	65.77	7.59	5/27/2011	
270511-04	-14.9	-116.1	2.7	3922	4185	-13.69	-73.17	-13.69	-73.19	65.74	4.71	5/27/2011	
270511-05	5.6	-68.6	-113.3	3804	4352	-13.72	-73.17	-13.74	-73.19	71.94	30.16	5/27/2011	
270511-07	-15.2	-117.6	4	3738	4132	-13.7	-73.05	-13.71	-73.06	66.83	7.72	5/27/2011	
270511-08	-9.4	-92.5	-17.5	2384	2979	-13.68	-72.96	-13.69	-72.96	64.81	4.58	5/27/2011	

270511-09	-7.9	-91.4	-28.5	2138	3310	-13.65	-72.91	-13.61	-72.9	56.63	26.96	5/27/2011	
270511-10	-6.7	-83.6	-30	2718	3614	-13.61	-72.86	-13.58	-72.86	53.9	27.67	5/27/2011	
270511-11	-12.8	-108.1	-5.4	3442	3782	-13.6	-72.84	-13.59	-72.82	56.45	11.84	5/27/2011	
270511-12	-15.6	-112.2	12.2	3560	3699	-13.58	-73.84	-13.6	-73.86	70.81	17.86	5/27/2011	
270511-13	-14.9	-112	7	3032	3621	-13.56	-72.76	-13.56	-72.79	53.42	32.97	5/27/2011	
270511-14	-11.1	-100	-11.4	2495	3401	-13.55	-72.67	-13.58	-72.72	56.43	154.93	5/27/2011	
270511-15	-11.9	-103.6	-8.1	2120	4161	-13.57	-72.6	-14.4	-72.01	128.54	22753.27	5/27/2011	
270511-17	-14.8	-110.4	8	2587	3802	-13.49	-72.45	-13.42	-72.41	44.57	151.66	5/27/2011	
270511-18	-14.8	-110	8	2968	3612	-13.46	-72.41	-13.46	-72.39	50.32	11.45	5/27/2011	
280511-01	-17.8	-133.8	8.7	3992	4297	-14.77	-70.93	-14.76	-70.94	132.11	4.12	5/28/2011	DEF (Fig 5)
280511-02	-19.3	-139.6	15.1	4600	4616	-14.77	-70.97	-14.76	-70.97	133.62	1.64	5/28/2011	DEF (Fig 5)
NPWS001	-16.3	-128	2.4	3949	4339	-15.02	-70.58	-15.1	-70.6	147.25	191.76	5/20/2011	
NPWS002	-17.2	-128.6	9.4	4087	4187	-14.75	-70.61	-14.74	-70.61	115.38	8.37	5/21/2011	DEF (Fig 5)
NPWS003	-17.7	-131.4	10.2	4272	4353	-14.71	-70.6	-14.71	-70.6	111.92	1.9	5/21/2011	DEF (Fig 5)
NPWS004	-17.9	-130.6	12.6	4337	4420	-14.66	-70.63	-14.67	-70.62	109.03	1.24	5/22/2011	DEF (Fig 5), Triangle in Fig 4B
NPWS006	-16.7	-129.4	4.2	4065	4634	-14.42	-70.57	-14.27	-70.65	69.52	340.87	5/22/2011	DEF (Fig 5)
NPWS007	-16.6	-132	0.5	4154	4641	-14.37	-70.55	-14.26	-70.54	64.37	280.22	5/22/2011	DEF (Fig 5)
NPWS008	-18.1	-140.3	4.5	4633	4788	-14.2	-70.48	-14.21	-70.48	56.44	7.79	5/22/2011	DEF (Fig 5)
NPWS009	-17.7	-126	15.6	2776	4674	-13.81	-70.48	-13.92	-70.66	34.63	1369.15	5/23/2011	DEF (Fig 5)
20140516-01	-14.8	-118.8	-0.4	4376	4410	-15.83	-70.69	-15.83	-70.69	213.67	1.24	5/16/2014	
20140517-01	-16	-126	2.2	4109	4257	-15.9	-70.58	-15.9	-70.57	204.05	6.87	5/17/2014	
20140517-02	-16.7	-128.3	5	4290	4363	-15.85	-70.62	-15.86	-70.63	209.09	1.31	5/17/2014	
20140517-03	-13.4	-109.8	-2.4	4060	4590	-15.69	-70.62	-15.54	-70.78	196.55	1827.92	5/17/2014	
20140517-04	-15.1	-118.4	2.1	4273	4468	-15.64	-70.72	-15.65	-70.73	202.59	15.7	5/17/2014	
20140518-01	-13	-103	1	1959	4145	-16.43	-71.67	-16.14	-71.25	279.94	6077.16	5/18/2014	DE (Fig 8)
20140518-02	-12.5	-98.8	0.9	1149	3884	-16.47	-71.93	-16.15	-71.39	290.34	8730.25	5/18/2014	DE (Fig 8)
20140518-03	-14.3	-113.7	0.6	1275	4472	-16.34	-71.13	-16.3	-71.05	266.73	223.89	5/18/2014	DE (Fig 8)
20140518-04	-16.4	-124.2	6.6	34	1149	-16.59	-72.33	-16.5	-72.3	361.07	127.32	5/18/2014	Triangle in Fig 4B
20140518-05	-16.4	-122.6	8.8	27	3740	-16.42	-73.12	-15.25	-73.08	237.16	16063.86	5/18/2014	DE (Fig 8)
20140519-01	-11.3	-89.3	1.5	3944	4050	-14.67	-74.42	-14.65	-74.38	199.25	42.07	5/19/2014	AB (Fig 8)
20140519-02	-11.6	-89.7	3.5	3751	3995	-14.64	-74.28	-14.66	-74.28	196.34	22.44	5/19/2014	AB (Fig 8)
20140519-03	-13.4	-108.3	-1.4	3083	4019	-14.61	-74.27	-14.47	-74.3	177.36	810.55	5/19/2014	AB (Fig 8)
20140519-04	-11.5	-90.2	1.6	3274	3999	-14.62	-74.22	-14.59	-74.19	184.62	32.91	5/19/2014	AB (Fig 8)
20140519-05	-13.6	-100.7	8.1	3420	3922	-14.63	-74.21	-14.61	-74.19	187.43	7.59	5/19/2014	AB (Fig 8)
20140519-08	-11.5	-87.8	4.1	3708	3749	-14.69	-74.08	-14.69	-74.07	190.75	2.81	5/19/2014	AB (Fig 8)
20140519-11	-16.1	-122.3	6.4	4462	4590	-14.64	-73.71	-14.66	-73.72	180.23	13.35	5/19/2014	AB (Fig 8)
20140519-12	-14.7	-114	3.2	4451	4545	-14.6	-73.64	-14.58	-73.62	169.47	21.46	5/19/2014	AB (Fig 8)
20140519-13	-13.4	-107.8	-0.5	4425	4528	-14.55	-73.66	-14.55	-73.63	166.27	15.37	5/19/2014	AB (Fig 8)
20140519-14	-14	-113.6	-1.8	4377	4502	-14.5	-73.67	-14.5	-73.6	160.75	66.34	5/19/2014	AB (Fig 8)
20140519-15	-14.8	-117.3	1	4237	4468	-14.45	-73.64	-14.46	-73.6	155.61	41.35	5/19/2014	AB (Fig 8)
20140519-16	-15.4	-120.1	3.5	4436	4511	-14.41	-73.6	-14.41	-73.59	150.6	0.85	5/19/2014	AB (Fig 8)
20140521-01	-15.9	-123.4	4.2	3381	4134	-14.22	-73.53	-14.36	-73.44	143.22	695.8	5/21/2014	
20140521-05	-17.1	-128.6	7.9	4257	4449	-14.39	-73.57	-14.4	-73.58	148.93	15.05	5/21/2014	AB (Fig 8)
20140521-06	-14.8	-115.9	2.7	4417	4451	-14.4	-73.6	-14.41	-73.59	150.09	0.52	5/21/2014	AB (Fig 8)
20140521-07	-12.7	-100.3	1.4	3586	4170	-14.64	-74.08	-14.58	-74.04	179	90.94	5/21/2014	AB (Fig 8)
20140521-08	-12	-102.6	-6.4	3998	4097	-14.57	-74.07	-14.58	-74.07	179.33	0.98	5/21/2014	
20140521-09	-13.1	-104.3	0.8	4269	4348	-14.54	-74.04	-14.53	-74.03	173.2	8.31	5/21/2014	AB (Fig 8)
20140522-07	-14	-110.1	2.1	3542	4246	-14.41	-73.96	-14.43	-74.1	164.42	386.99	5/22/2014	AB (Fig 8)
20140522-08	-15.5	-118	5.7	3793	4277	-14.43	-73.95	-14.5	-73.95	166.63	176.45	5/22/2014	AB (Fig 8)
20140522-11	-16.5	-123.6	8	4155	4490	-14.46	-73.92	-14.47	-73.89	162.19	20.28	5/22/2014	AB (Fig 8)
20140522-12	-15.6	-118.6	6.3	4258	4454	-14.54	-73.92	-14.54	-73.91	170.68	24.21	5/22/2014	AB (Fig 8)
20140522-13	-13.9	-112.2	-0.8	4342	4566	-14.58	-73.59	-14.57	-73.59	168.63	4.12	5/22/2014	AB (Fig 8)
20140525-02	-15	-118	2	4198	4503	-14.56	-73.56	-14.54	-73.55	164.46	42	5/25/2014	AB (Fig 8)
20140525-03	-16.5	-126.7	5.5	4138	4429	-14.56	-73.39	-14.58	-73.44	166.83	84.33	5/25/2014	AB (Fig 8)
20140525-04	-16.7	-128.3	5	3428	4390	-14.47	-73.24	-14.58	-73.26	164.35	940.49	5/25/2014	BC (Fig 3)
20140525-06	-17.5	-131.8	8.4	3265	4270	-14.42	-73.21	-14.41	-73.25	145.96	21.07	5/25/2014	BC (Fig 3)
20140525-07	-17.6	-133.3	7.3	3130	4120	-14.37	-73.17	-14.44	-73.18	148.21	188.75	5/25/2014	BC (Fig 3), Triangle in Fig 4B
20140525-08	-17.8	-133.4	8.6	3003	4343	-14.32	-73.2	-14.45	-73.07	148.24	356.24	5/25/2014	BC (Fig 3)
20140525-09	-16.7	-127.3	6.1	2805	3607	-14.25	-73.3	-14.24	-73.28	127.75	5.5	5/25/2014	BC (Fig 3)
20140525-10	-16.2	-123.4	6.5	2748	3507	-14.21	-73.32	-14.22	-73.3	125.62	6.02	5/25/2014	BC (Fig 3), Triangle in Fig 4B
20140525-11	-16.6	-125.9	6.7	2600	3820	-14.13	-73.3	-14.25	-73.28	128.75	522.62	5/25/2014	BC (Fig 3)
20140525-12	-16	-120.2	7.8	2349	3611	-14.03	-73.22	-13.99	-73.26	100.15	33.04	5/25/2014	BC (Fig 3)
20140525-13	-14.8	-113.8	4.7	2172	2912	-13.95	-73.11	-13.97	-73.12	95.26	6.41	5/25/2014	BC (Fig 3), Triangle in Fig 4B
20140525-14	-15.8	-118.5	8.2	1970	3150	-13.81	-72.96	-13.82	-72.93	79.03	13.61	5/25/2014	BC (Fig 3), Triangle in Fig 4B
20140525-15	-15.3	-114.2	8.5	1783	3973	-13.67	-72.92	-14.15	-72.96	115.31	5120.05	5/25/2014	
20140525-16	-15.7	-114.7	10.6	3052	3317	-13.66	-72.91	-13.61	-72.9	56.95	27	5/25/2014	Triangle in Fig 4B
20140525-17	-15.7	-117.6	7.7	2789	4662	-13.56	-72.91	-13.55	-72.91	49.86	0.92	5/25/2014	
20140525-18	-14.1	-107.2	5.3	2001	2632	-13.57	-72.6	-13.57	-72.6	58.25	1.44	5/25/2014	Triangle in Fig 4B
20140525-19	-13.9	-104.3	7.3	2152	3020	-13.53	-72.51	-13.53	-72.48	55.86	9.49	5/25/2014	
20140603-03	-15.8	-121.2	5.1	3105	3825	-13.76	-71.84	-13.72	-71.81	51.76	22.38	6/3/2014	
20140613-01	-15.8	-121.6	4.7	3143	4016	-13.68	-71.62	-13.96	-71.5	67.78	1417.31	6/13/2014	
20140613-02	-16.7	-128.5	5.4	3445	4655	-14.03	-71.46	-13.92	-71.25	57.47	686.31	6/13/2014	
20140613-03	-16.5	-127	4.8	3472	4714	-14.1	-71.44	-14.06	-71.05	64.42	2331.43	6/13/2014	
20140613-04	-17.5	-131.3	8.9	4164	4799	-14.5	-70.93	-14.45	-70.93	100.72	55.28	6/13/2014	
20140613-05	-15.3	-124.2	-1.9	4017	4194	-14.6	-70.75	-14.61	-70.74	108.24	3.6	6/13/2014	
20140613-06	-15.9	-124.5	2.8	3976	4215	-14.52	-70.63	-14.49	-70.69	94.12	101.47	6/13/2014	
20140613-07	-16.4	-127.8	3.6	4037	4667	-14.48	-70.63	-14.3	-70.79	79.56	908.1	6/13/2014	
20140613-08	-15.8	-123.9	2.6	4177	4536	-14.37	-70.55	-14.39	-70.51	75.48	39.91	6/13/2014	
20140613-09	-16.4	-127.1	4.1	4629	4791	-14.19	-70.48	-14.2	-70.47	54.51	2.75	6/13/2014	

20140613-10	-16.3	-126.6	4.2	4461	4687	-14.12	-70.45	-14.15	-70.49	50.94	115.21	6/13/2014
20140615-02	-15.8	-124.6	1.9	4425	4735	-14.08	-70.52	-14.08	-70.59	48.12	55.42	6/15/2014
20140615-03	-16.7	-128.1	5.8	4591	4817	-14.07	-70.6	-14.06	-70.62	47.18	6.67	6/15/2014
20140615-04	-16.7	-127.6	5.7	4578	4884	-14.1	-70.63	-14.13	-70.61	54.35	28.66	6/15/2014
20140615-05	-16.4	-126.5	4.7	4657	4941	-14.1	-70.63	-14.1	-70.67	53.9	30.42	6/15/2014
20140615-08	-14.8	-119.7	-1.4	4307	4651	-14.06	-70.44	-14.08	-70.36	38.06	300.76	6/15/2014
20140616-01	-16	-123.9	4.4	4380	4700	-14.21	-70.16	-14.16	-70.13	36.48	61.3	6/16/2014
20140616-03	-12.5	-103.1	-3.2	4377	4545	-14.52	-69.69	-14.48	-69.66	29.75	18.19	6/16/2014

Table 2

Catchment size, locality information, and stable isotope results for standing water (lakes, marshes, etc.) across the study area

Sample ID	$\delta^{18}\text{O}_{\text{VSMOW}}$	$\delta^2\text{H}_{\text{VSMOW}}$	<i>d excess</i>	Sample Site Elevation (m)	Mean Watershed Elevation (m)	Latitude	Longitude	Latitude (Centroid)*	Longitude (Centroid)*	Catchment size (km ²)	Collection Date
10PE-26w	-14.4	-111.0	4.4	3,495	4,197	-14.196	-71.325	-14.324	-71.188	767	5/6/2010
10PE-33w	1.7	-23.1	-36.6	3,927	4,334	-14.765	-70.732	-14.581	-70.821	932	5/6/2010
10PE-47w	-2.0	-43.5	-27.8	3,824	4,170	-15.835	-70.014	-16.086	-69.545	83,038	5/8/2010
10PE-55w	-10.6	-97.1	-12.4	3,966	4,334	-14.437	-71.285	-14.523	-71.133	467	5/13/2010
10PE-79w	-14.9	-116.7	2.1	4,219	4,612	-15.403	-71.288	-15.523	-71.097	2,049	5/14/2010
B	-8.3	-66.6	-0.5	3,838	3,920	-17.154	-67.625	-17.183	-67.613	14	7/19/2007
Q	4.2	-12.7	-46.6	3,856	3,981	-17.578	-67.332	-17.552	-67.362	45	8/3/2007
R	-8.3	-52.7	13.5	4,666	4,671	-17.104	-67.324	-17.105	-67.323	1	8/4/2007
S	-6.5	-65.8	-14.0	4,645	4,730	-17.079	-67.301	-17.080	-67.299	0	8/4/2007
X	0.1	-30.0	-30.7	4,225	4,251	-16.898	-68.099	-16.895	-68.105	1	8/5/2007
IO	-4.9	-68.0	-28.8	3,694	3,876	-20.900	-67.764	-20.915	-67.725	393	5/27/2009
JO	-12.7	-96.2	5.0	4,138	4,623	-21.502	-68.008	-21.679	-67.999	858	5/28/2009
KO	-12.0	-92.4	3.5	4,122	4,674	-21.573	-68.039	-21.721	-67.974	626	5/28/2009
OO	-11.0	-109.8	-22.2	3,864	4,155	-19.754	-66.821	-19.858	-66.693	623	5/30/2009
Z10	3.6	-19.8	-48.5	4,411	4,463	-17.438	-67.129	-17.439	-67.129	3	8/16/2007
NPWS005	-9.9	-109.6	-30.4	4,027	4,145	-14.468	-70.576	-14.462	-70.584	15	5/22/2011
200511-03	-7.4	-111.5	-52.3	4,789	4,870	-15.258	-71.163	-15.257	-71.184	1	5/20/2011
280511-03	-17.4	-137.1	2.5	4,530	4,628	-14.767	-70.967	-14.764	-70.972	3	5/28/2011

*The centroid is defined as the geographic center of a catchment upstream from a sample site.

Table 3

Locality information and stable isotope results for precipitation samples published by Aravena et al. (2009)

Sample Location	$\delta^{18}\text{O}_{\text{VSMOW}}^*$	$\delta^2\text{H}_{\text{VSMOW}}^*$	<i>d excess</i>	Sample Site Elevation (m)	Latitude	Longitude	Precipitation Amount (mm)
POROMA	-4.5	-21.4	14.3	2,880	-19.867	-69.183	41
HUATACONDO	-11.4	-79.9	11.5	2,460	-20.917	-69.050	15
PUCHULDIZA	-14.4	-104.0	11.2	4,200	-19.400	-68.950	100
COLCHANE	-14.9	-106.3	13.3	4,100	-19.700	-68.883	208
HUAYTANE	-14.1	-100.9	11.9	3,790	-19.543	-68.604	161
CANCOSA	-14.0	-96.4	15.6	3,850	-19.850	-68.600	143
PAMPA LIRIMA	-9.8	-67.8	10.9	4,100	-19.820	-68.900	79
PARCA	-6.6	-40.9	12.2	2,700	-20.017	-68.850	20
COLLACAGUA	-10.2	-68.6	12.8	3,960	-20.033	-68.850	147
COLLAGUASI	-22.1	-165.9	11.1	4,550	-20.983	-68.700	43
UJINA	-10.0	-68.4	11.6	4,200	-20.983	-68.600	123

*Stable isotope averages are weighted by precipitation amount for each site.

Table 4

Locality information and stable isotope results for precipitation samples published by Fiorella et al. (2015a)

Sample Location	$\delta^{18}\text{O}_{\text{VSMOW}}$	$\delta^2\text{H}_{\text{VSMOW}}$	<i>d excess</i>	Sample Site Elevation (m)	Latitude	Longitude	Precipitation* Amount (mm)
SAN JUAN	-14.3	-99.8	14.6	3,663	-20.90	-67.76	162
SALINAS	-17.5	-122.6	17.4	3,719	-19.65	-67.64	255
NOEL MARIACA	-14.1	-97.8	15.0	3,780	-20.68	-66.64	169
GRAN CHOCAYA	-14.0	-92.0	20.0	4,340	-20.97	-66.33	227
ORURO	-15.5	-107.1	16.9	3,718	-17.98	-67.11	401
EL CHORO	-15.6	-109.2	15.6	3,706	-18.36	-67.11	547
QUILLACAS	-15.5	-108.1	15.9	3,780	-19.23	-66.94	360

*Average per year for 3-5 years

Figure 1

Figure 2

Figure 3

Figure 4A

Figure 4B

Figure 5

Figure 6A

Figure 6B

Figure 7

Figure 8

Transect AB

Transect DE

Transect IJ