Spatial and temporal variability in denudation across the Bolivian Andes from multiple geochronometers

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A B S T R A C T

We quantify spatial and temporal variations in denudation rates across the central Andean fold-thrust belt in Bolivia with particular focus on the Holocene. Measured and predicted 10Be cosmogenic radionuclide (CRN) concentrations in river sediments are used to calculate catchment-averaged denudation rates from 17 basins across two transects at different latitudes, and (2) evaluate the sensitivity of Holocene climate change on the denudation history recorded by the CRN data. Estimated denudation rates vary by two orders of magnitude from 0.04 to 1.93 mm yr⁻¹ with mean values of 0.40 ± 0.29 mm yr⁻¹ in northern Bolivia and 0.51 ± 0.50 mm yr⁻¹ in the south. Results demonstrate no statistically significant correlation between denudation rates and morphological parameters such as relief, slope or drainage basin size. In addition, the CRN-derived denudation rates do not reflect present-day latitudinal variations in precipitation. Comparison to 130 previously published denudation rates calculated over long (thermochronology-derived; >10⁶ yrs), medium (CRN-derived; 10⁴–10⁶ yrs), and short timescales (sediment flux-derived; 10³ yrs) indicate temporal variations in denudation rates that increase between 0 and 200% over the last 5 ka. CRN modeling results suggest that the CRN-derived denudation rates may not be fully adjusted to wetter climate conditions recorded in the central Andes since the mid-Holocene. We conclude that large spatial variability in CRN denudation may be due to local variations in tectonics (e.g. faulting), while large temporal variability in denudation may be due to temporal variations in climate.

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1. Introduction

A close link between tectonics, climate, and denudation in the evolution of mountain belts has been hypothesized in a variety of modeling and observational studies (e.g. Willett, 1999; Leturmy et al., 2000; Beaumont et al., 2001; Hilley and Strecker, 2004). For example, it has been proposed that regional variations in climate may strongly influence spatial variations in denudation, thereby affecting the style and location of deformation and exhumation (e.g. Willett, 1999). The 8000-km long Andes Mountains in South America are thought to exemplify these linkages because correlations between latitudinal variations in tectonic deformation, topography, and precipitation as well as denudation rate estimates suggest that climate-driven denudation exerts a fundamental control on mountain evolution (e.g. Masek et al., 1994; Montgomery et al., 2001). In particular, the central Andean fold-thrust belt (~14–26°S) is characterized by high relief and steep slopes north of 18°S that have been hypothesized to reflect high orographic precipitation and high denudation rates, while the more gentle and wider topography of the drier regions south of 18°S may reflect a tectonic landform less modified by climate and denudation (Masek et al., 1994; Horton, 1999; Barnes and Pelletier, 2006; McQuarrie et al., 2008). Improved quantification of the spatial and temporal variations in magnitude and mechanism of denudation across the central Andes reveals variations in denudation processes that might be related to changes in tectonics, climate, or land use, and is essential to understand the role of denudation in shaping landscapes (Gillis et al., 2006; Barnes and Ehlers, 2009). Terrestrial denudation rates are sensitive to both tectonics and climate, but the importance of each effect is difficult to constrain. Averaged long-term (~10⁶ yrs) denudation rates in the Bolivian Andes that are estimated from low-temperature thermochronology (e.g. apatite fission track [AFT] dating) mainly represent denudation driven by tectonic-related processes and are similar along strike (Benjamin et al., 1987; Barnes et al., 2006; Gillis et al., 2006; Safran et al., 2006; Ege et al., 2007; Barnes et al., 2008; McQuarrie et al., 2008a). Averaged medium-term (10⁴–10⁶ yrs) denudation rates calculated from cosmogenic radionuclides (CRN) in the northern

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Bolivian Andes are within the range of long-term denudation rates in the same area (Safran et al., 2005). No medium-term denudation data exist from the southern part of the Bolivian Andes. Short-term (10⁻¹⁰² yrs) denudation rate estimates from sediment flux data in the Bolivian Andes mirror the present-day latitudinal precipitation gradient and indicate a disparity with ~3 times higher mean denudation rates in northern Bolivia (14–18°S) compared to the south (18–22°S) (Barnes and Pelletier, 2006). Previous studies suggest that the along-strike variability in denudation existed throughout the Holocene with an increase in denudation and north-south contrast since as early as the late Miocene (~10 Ma) (Anders et al., 2002; Safran et al., 2005; Barnes and Pelletier, 2006). Structural and thermal data and basin sedimentation histories were used to infer orographically controlled and/or South American monsoon system-related intensification of precipitation and denudation in Bolivia also in the late Miocene (McQuarrie et al., 2008b; Uba et al., 2009). This intensification could be related to plateau uplift beyond some substantial elevation threshold (Garzione et al., 2006; Ehlers and Poulsen, 2009; Insel et al., 2009; Mulch et al., 2010).

In this study, we integrate 17 new cosmogenic ¹⁰Be analyses with 43 previously published CRN data (Safran et al., 2005) to quantify catchment-averaged denudation rates from the Andean fold-thrust belt in Bolivia (Fig. 1a). New samples were collected across two different transects in the northern (~15°S) humid and southern (~19°S) dry part of the Bolivian Andes (Fig. 1b) with a focus on the Subandes which have been uplifted since the Miocene (e.g. Barnes et al., 2008; Uba et al., 2009). These data are used to quantify (1) spatial variations in denudation by comparing CRN-derived denudation rates from the northern and southern transects, and (2) temporal variations in denudation rates by comparing rates on different time scales. In addition, we (3) compare magnitudes of denudation with modern variations in precipitation and geomorphic indices (e.g. slope and relief). Our results complement previous work in the northern Bolivian Andes (Safran et al., 2005) and add new data from the southern Bolivian Andes to verify the strong disparity in denudation rates over time. The combination of our results with previously estimated sediment flux-derived denudation rates (Alto et al., 2006; Barnes and Pelletier, 2006) reveal Holocene variations in denudation processes and the possible effect of climate change on radionuclide concentrations over the last ~5 ka.

2. Geologic, geomorphic, and climate setting

The central Andes (14–26°S) form the widest and highest portion of the Andean Cordillera. The central Andean fold-thrust belt occupies the eastern flank of the Cordillera and is divided into four physiographic units (Fig. 1a; Kley et al., 1996; McQuarrie, 2002): (a) the low relief, internally-drained Altiplano (AP) with an average elevation of >3 km; (b) the structurally bivergent, high elevation Eastern Cordillera (EC); (c) the Interandean zone (IA); and (d) the tectonically active Subandes (SA). The thrust belt is the result of Cenozoic crustal shortening and thickening related to subduction of the Nazca plate below the South American plate (e.g. Isacks, 1988; Sempere et al., 1990; Allmendinger et al., 1997; Jordan et al., 1997; Kley and Monaldi, 1998; Oncken et al., 2006).

The central Andes are characterized by significant along-strike contrasts in the morphology and the style of deformation that have been ascribed to strong latitudinal changes in climate and/or tectonics (Fig. 1) (Isacks, 1988; Masek et al., 1994; Allmendinger et al., 1997; Horton, 1999; Montgomery et al., 2001). The high relief and narrow fold-thrust belt in the northern portion of the Bolivian Andes (~14–18°S) is distinctive from the wide and smooth topography in the south (~18–22°S). Based on cross-section balancing and low-temperature thermochronology, the average vertical exhumation over the last 20 Ma is higher (4–9 km) in the north than in the south (3–6 km) (e.g. Barnes et al., 2006, 2008; McQuarrie et al., 2008b).

Lithologies involved in the deformation and exposed today are similar north to south, ranging from Ordovician to Devonian marine siliciclastic rocks and Carboniferous to Cretaceous non-marine clastics to Cenozoic synorogenic sediments (e.g. Sempere, 1995; Sempere et al., 1997; Horton, 1998; McQuarrie, 2002). As addressed in the discussion section, the mechanical strength of these sedimentary rocks in the study area is also similar along strike (McQuarrie and Davis, 2002) implying no latitudinal variation in erodibility of the different lithologies.

The central Andes are characterized by both latitudinally and orographically enhanced changes in precipitation (e.g. Aceituno, 1988; Garreau and Wallace, 1997; Garreau, 2000). The large-scale atmospheric circulation over South America leads to a strong regional precipitation gradient with up to 4 m yr⁻¹ rainfall north of ~18°S and less than 1 m yr⁻¹ south of 18°S (Fig. 1b). In addition, the central
Table 1

Cosmogenic sample locations, drainage basin statistics and information for CRN-derived, basin-averaged denudation rate estimates from the central Andes in Bolivia.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>River</th>
<th>Sampled latitude (°S)</th>
<th>Sampled longitude (°W)</th>
<th>Sampled altitude (m)</th>
<th>Drainage (km²)</th>
<th>Fm age</th>
<th>Quartz yield (%)</th>
<th>Mean relief (m)</th>
<th>Mean slope (%)</th>
<th>Mean annual precipitation (mm yr⁻¹)</th>
<th>Mean latitude (°S)</th>
<th>Mean altitude (m)</th>
<th>Production rate (atoms (g(qtz) yr⁻¹))</th>
<th>¹⁰Be conc (10⁴ atoms g(qtz)⁻¹)</th>
<th>²⁶Al conc (10⁴ atoms g(qtz)⁻¹)</th>
<th>Denudation rate (mm yr⁻¹)</th>
<th>Apparent age (kyr)</th>
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<tr>
<td>N02</td>
<td>Rio Yucumo</td>
<td>15.16</td>
<td>67.04</td>
<td>263</td>
<td>48</td>
<td>Dv-Te</td>
<td>79</td>
<td>460</td>
<td>24</td>
<td>1669</td>
<td>15.18</td>
<td>618</td>
<td>5.26</td>
<td>0.52 ± 0.06</td>
<td>26.72 ± 1.89</td>
<td>0.83 ± 0.11</td>
<td>0.99</td>
</tr>
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<td>N04</td>
<td>Rio Quiquibey</td>
<td>15.39</td>
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<td>595</td>
<td>332</td>
<td>Cb</td>
<td>66</td>
<td>425</td>
<td>23</td>
<td>1678</td>
<td>15.50</td>
<td>1106</td>
<td>7.58</td>
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<td>17.23 ± 3.70</td>
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<td>15.51</td>
<td>67.17</td>
<td>562</td>
<td>205</td>
<td>Te</td>
<td>34</td>
<td>494</td>
<td>23</td>
<td>1648</td>
<td>15.55</td>
<td>1027</td>
<td>7.19</td>
<td>4.37 ± 0.12</td>
<td>31.68 ± 4.73</td>
<td>0.11 ± 0.01</td>
<td>7.10</td>
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<td>67.43</td>
<td>840</td>
<td>34</td>
<td>Dv</td>
<td>50</td>
<td>645</td>
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<td>1502</td>
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<td>19.79</td>
<td>63.26</td>
<td>871</td>
<td>4</td>
<td>Cb-Me</td>
<td>73</td>
<td>414</td>
<td>41</td>
<td>767</td>
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<tr>
<td>S05 S05g</td>
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<td>64.15</td>
<td>1374</td>
<td>7</td>
<td>Dv</td>
<td>26</td>
<td>820</td>
<td>41</td>
<td>688</td>
<td>19.56</td>
<td>2059</td>
<td>15.49</td>
<td>28.86 ± 0.84</td>
<td>0.04 ± 0.003</td>
<td>18.63</td>
<td>0.04</td>
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<tr>
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<td>19.10</td>
<td>65.30</td>
<td>2499</td>
<td>1318</td>
<td>Me/Ord</td>
<td>62</td>
<td>514</td>
<td>26</td>
<td>581</td>
<td>18.92</td>
<td>3515</td>
<td>36.16</td>
<td>73.47 ± 2.88</td>
<td>0.04 ± 0.003</td>
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<td>832</td>
<td>129</td>
<td>Cb-Te</td>
<td>85</td>
<td>378</td>
<td>19</td>
<td>760</td>
<td>19.52</td>
<td>1082</td>
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<td>Rio Charagua</td>
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<td>152</td>
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<td>86</td>
<td>435</td>
<td>21</td>
<td>765</td>
<td>19.75</td>
<td>1125</td>
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<td>5194</td>
<td>Dv-Te</td>
<td>70</td>
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<td>S11 S11g</td>
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<td>989</td>
<td>20</td>
<td>(Dv-)Te</td>
<td>54</td>
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<td>31</td>
<td>753</td>
<td>19.92</td>
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<td>83</td>
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<td>1115</td>
<td>52</td>
<td>Dv-Te</td>
<td>77</td>
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<td>25</td>
<td>729</td>
<td>19.75</td>
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<td>Rio Nancahuazu</td>
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<td>0.27 ± 0.05</td>
<td>1.93 ± 0.36</td>
<td>0.42</td>
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</tr>
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</table>

a Fm age: formation age; Ord Ordovician; Sil Silurian; Dv Devonian; Cb Carboniferous; Me Mesozoic; Te Tertiary.
b Quartz content derived from the sample material (e.g. amount of quartz in relation to other minerals within the sample).
c Relief is calculated by subtracting the highest and lowest elevations within a circular neighborhood with 2 km in radius.
d Production rate is scaled to lat and lon, and corrected for topographic shielding, first value is for ¹⁰Be, second value for ²⁶Al, no correction necessary for snow coverage or thickness.
e Error on concentrations includes analytical uncertainties.
f Denudation rate based on ¹⁰Be concentration; total error includes analytical uncertainties and calculated uncertainties for production rate that is based on an assumed 10 percent uncertainty in calculated mean altitude and size of the upstream catchment area.
g Grain size: 0.5–1.0 mm, all others are 0.25–0.5 mm.
Andes act as a topographic barrier between the humid Amazon Basin and the more arid Pacific margin to the west. Condensation of Atlantic-derived moisture on the eastern Andean flank leads to focused orographic precipitation in the eastern part of the Andean fold-thrust belt with dry conditions on the western plateau region (Lenters and Cook, 1995; Insel et al., 2009).

3. Methods

3.1. Cosmogenic radionuclide data

Modern river sediments were collected from four catchments along a northern transect and thirteen tributaries and trunk streams in a southern transect (Fig. 1a, Table 1). In the northern transect, our CRN samples are mainly from the SA with elevations between 600 and 1400 m, with previous data focused on the high elevation sites (~1600 to 4500 m) in the EC (Figs. 1a, 2a) (Safran et al., 2005). In the southern transect, CRN data are from basins that span a wide range of basin mean elevations from 840 to 3500 m, but again focused in the SA (Table 1). Drainage areas upstream of sample locations vary in size and range from 4 km² to 5200 km². Samples were collected from within the active channel, focusing on the medium to small sand size fraction.

Samples were washed, dried, and sieved to isolate the grain size fraction between 0.25 and 0.5 mm. In some cases, coarser size fractions between 0.5 and 1.0 mm were used to evaluate the effect of grain size on denudation rate (Table 1). Quartz was separated using standard mineral separation techniques. To eliminate possible contamination by 10Be produced in the atmosphere, quartz was leached with a mixture of hydrofluoric and nitric acid. After dissolution of quartz and...
addition of \(^{30}\)Be spike, Be and Al were separated by extraction and precipitation following von Blanckenburg et al. (1996). Measurements by accelerator mass spectrometry were carried out at PRIME Lab, Purdue University.

Average production rates for each sample site were calculated using the 90 m SRTM DEM taking into account scaling to latitude and altitude and topographic shielding for each pixel in the DEM (Stone, 2000; Balco, 2001). We used a total production rate of 5.1 atoms g\(^{-1}\) yr\(^{-1}\) for \(^{10}\)Be and 31.1 atoms g\(^{-1}\) yr\(^{-1}\) for \(^{26}\)Al at sea level sites and high latitude (Stone, 2000). To account for spallogenic and muonic production, we used spallogenic fractions of 0.978 (\(^{10}\)Be) and 0.974 (\(^{26}\)Al) contributing to the total production rate (Stone, 2000), while the remaining fraction was assigned to slow and fast muons, using a ratio of 0.53 to 0.47 (Heisinger et al., 2002). The original ICN standard (Nishiizumi et al., 2007) was used as reference standard for measurements and values of 4.62 \times 10^{-7} \text{yr}^{-1} (\(^{10}\)Be) and 9.68 \times 10^{-7} (\(^{26}\)Al) were assigned for the decay constants, respectively. Table 1 lists the production rates for each basin, calculated \(^{10}\)Be and \(^{26}\)Al concentrations, catchment-wide denudation rates, and the corresponding errors after Schaller et al. (2001; 2002).

Ratios of \(^{26}\)Al/\(^{10}\)Be in our samples are between 3.6 and 6.2. The range of the ratios is consistent with \(^{40}\)Ar/\(^{39}\)Ar ratios from Safran et al. (2005), although the average of 4.3 is much lower than the assumed production ratio of 6.1. The catchments with lower ratios were mostly basins with Al content close to the detection limit. We interpret that sediment storage is not responsible for production ratios below 6 (see Discussion section) and assume that the lower ratios are a result of incomplete recovery of stable Al during sample processing (e.g. Safran et al., 2005).

3.2. Long-term denudation rates

Long-term denudation rates were estimated from previously published AFT data (Suppl. 1) (Barnes et al., 2006; Gillis et al., 2006; Safran et al., 2006; Barnes et al., 2008; McQuarrie et al., 2008a). We only account for samples along our two transects and AFT analyses with more than 10 grains per sample. To estimate long-term denudation rates from AFT data, we used the most straightforward method of dividing a presumed closure isotherm depth by the cooling age and assuming a linear, temporally invariant geothermal gradient. For the calculation, we assumed (1) an average AFT closure temperature of 110 °C, (2) average surface temperatures of 10 °C for the EC, 15 °C for the IA, and 23 °C for the SA, and (3) previously estimated values of the geothermal gradient based on proximal borehole-measurements (Barnes et al., 2006, 2008).

The estimated geothermal gradient for the northern transect is 22 ± 2.2 °C/km for the EC, IA, and SA, while in the southern transect we use a gradient of 27 ± 11 °C/km for the EC and the IA, and 18 ± 5 °C/km for the SA. Where available, we estimated long-term denudation rates based on sample cooling histories quantified with inverse thermal modelling (Barnes et al., 2006; Gillis et al., 2006; Barnes et al., 2008). In these cases, instead of using the cooling age, we used the onset of the most recent rapid cooling from the best-fit thermal model to calculate denudation rates (Suppl. 1). We also re-calculated previously estimated long-term denudation rates from Safran et al. (2006) to make them comparable with the data above. With the smaller geothermal gradient re-calculated denudation rates are mostly the same within error as originally reported, with a few exceptions up to 0.3 mm yr\(^{-1}\) higher (compare Suppl. 1 and Safran et al. (2006)).

Our calculated denudation rates from thermochronometer samples are only an estimate of true denudation rates over this timescale. Temporal variations in the thermal gradient due to transient denudation, magmatism, and/or removal of overlying units with significantly different thermal conductivity could all introduce uncertainty into these estimates (Ehlers et al., 2005). Addressing these complications often requires detailed thermal modelling of sample cooling histories and various thermo-tectonic processes, an endeavour beyond the scope of this study, and poorly constrained with available data. Rather, we report long-term denudation rates with conservative uncertainties (e.g. Fig. 4) related to the large variability in present-day heat flow in each physiographic unit (after Barnes et al., 2006, 2008). This approach provides an empirically-derived estimate for long-term variations in denudation rates based on known variations in the present-day thermal structure of the Andes.

4. Results

4.1. Spatial variations in CRN-derived denudation rates

Denudation rate estimates based on CRN analyses were calculated from 17 basins (Table 1 and Fig. 2). The rates vary by two orders of magnitude from 0.04 to 1.93 mm yr\(^{-1}\) and indicate apparent ages of 0.4 to 20 ka. More than 75% of the basins have an apparent age younger than 5 ka.

In the northern transect, three samples from the northern SA and one from the IA were measured (Figs. 2a, 3a). The denudation rates vary by a factor of 8 and range from 0.11 to 0.83 mm yr\(^{-1}\) over apparent ages of 1.0 to 7.1 ka (Table 1). The highest denudation rate observed (0.83 mm yr\(^{-1}\)) is in a small basin (N02) located along the frontal range of the SA (Figs. 2a, 3a). To the west, denudation rates are smaller with magnitudes ~0.1–0.2 mm yr\(^{-1}\) (Figs. 2a, 3a). Denudation rates are similar for the SA and the IA. Because samples were only available from four basins, general trends in the denudation rates are difficult to define robustly. However, the range of denudation rates is in good agreement with CRN-derived denudation rates for basins in the EC that range between 0.04–1.34 mm yr\(^{-1}\) (Figs. 2a, 3a) (Safran et al., 2005). The mean value for all calculated CRN-derived denudation rates in the northern transect is 0.40 ± 0.29 mm yr\(^{-1}\), including published rates by Safran et al. (2005). Denudation rates for different grain sizes of the same sample do not show noteworthy differences (Table 1).

In the southern transect, 11 samples from the southern SA, 1 from the IA, and 1 from the EC were measured (Figs. 2b, 3b). The denudation rates vary by two orders of magnitude from 0.04 to 1.93 mm yr\(^{-1}\) with apparent ages of 0.4 to 20.3 ka (Figs. 2b, 3b, Table 1). Most sampled basins are located entirely within the SA. One SA basin (S16) indicates an exceptionally high denudation rate of 1.93 mm/yr. Although the sample appears as an outlier relative to the other samples we include it in our analysis because there were no anomalous aspects of the drainage basin (e.g. recent large landslides) or abnormalities in the chemical analysis that would preclude consideration. A denudation rate of 0.1 mm yr\(^{-1}\) is calculated for a basin (S04) situated mainly in the IA. The one EC basin (S06) indicates one of the lowest denudation rates with a magnitude of 0.04 mm yr\(^{-1}\). The mean CRN-derived denudation rate for the south is 0.51 ± 0.50 mm yr\(^{-1}\).

4.2. Temporal variations in denudation rates

Transients in the denudation rates are observable when comparing rates calculated over long- (AFT-derived), medium- (CRN-derived) and short-timescales (sediment flux-derived) (Fig. 4). Results shown compare our CRN-derived rates with long-term rates calculated from published AFT data (see Section 3.2) and short-term rates from sediment gauging stations neighboring our sample locations. Sediment flux determinations include the total suspended and dissolved loads and are thought to be representative of the modern physical denudation rates (Barnes and Pelletier, 2006; see also Aalto et al., 2006).

In the northern transect, short-term denudation rates were calculated from 9 sediment gauging stations that recorded sediment fluxes from drainage basins ranging in size from 270 to 67,200 km\(^2\).
Short-term denudation magnitudes vary between 0.21 and 2.49 mm yr\(^{-1}\), with a mean denudation rate of 1.25± 0.79 mm yr\(^{-1}\) and are therefore two to three times higher than medium-term denudation rates (mean of 0.40±0.29 mm yr\(^{-1}\), Fig. 3). AFT data from the northern transect indicate long-term denudation rates of ∼0.1–1.0 mm yr\(^{-1}\) (mean of ∼0.42±0.19 mm yr\(^{-1}\)) for the EC, 0.05–0.4 mm yr\(^{-1}\) (mean of ∼0.27±0.15 mm yr\(^{-1}\)) for the IA and 0.1–0.2 mm yr\(^{-1}\) (mean of ∼0.18±0.06 mm yr\(^{-1}\)) for the SA (Suppl. 1), suggesting a decrease in long-term denudation from southwest to northeast (Fig. 3a). The mean denudation rate based on the AFT data for the entire transect is 0.38±0.19 mm yr\(^{-1}\) and is within error similar to the CRN-derived denudation rates (Fig. 4).

In the southern transect, short-term denudation rates were estimated from 7 gauging stations for drainage basin sizes between 1600 and 59,800 km\(^2\) (Figs. 2b, 3b) (Guyot et al., 1990; Barnes and Pelletier, 2006). Short-term denudation rates range between 0.05 mm yr\(^{-1}\) and 1.04 mm yr\(^{-1}\), with a mean value of 0.57±0.39 mm yr\(^{-1}\) (Fig. 4). The range and mean of short-term denudation rates in the southern transect are very similar to the medium-term denudation rates (0.51±0.50 mm yr\(^{-1}\), Fig. 4). Long-term denudation rates from AFT data range between ∼0.1–0.3 mm yr\(^{-1}\) (mean of ∼0.20±0.07 mm yr\(^{-1}\)) for the EC, 0.08–0.2 mm yr\(^{-1}\) (mean of ∼0.15±0.06 mm yr\(^{-1}\)) for the IA, and 0.2–0.4 mm yr\(^{-1}\) (mean of ∼0.31±0.11 mm yr\(^{-1}\)) or more for the SA (Figs. 3b, 4). The total long-term mean denudation rate estimated from best-fit denudation rates for the southern transect is 0.22±0.09 mm yr\(^{-1}\), indicating that long-term denudation rates in the south are similar to medium-term denudation rates within error (Fig. 4). However, a direct comparison between medium- and long-term denudation rates along the same structures in the southern SA shows a moderate increase in denudation towards the present at specific locations (e.g. S03/SA2, S11/SA3, Suppl. 2).

Caution should be used when comparing short- and medium-term denudation rates from Bolivia due to the limited amount of data available and the large difference in drainage basin sizes used for short
timescale sediment flux determinations relative to the CRN-derived rates. For example, although the mean denudation rate in the southern transect is very similar for short- and medium-term timescales, a comparison between individual sites (e.g., S04/PZ, S06/NU, S10/SA) reveals a two to three times higher denudation rate from sediment-flux data than for CRN-derived data (Suppl. 2). This discrepancy in denudation rates may indeed be true for all drainage basins in this region (e.g. if the area is in topographic steady state) but a larger data set is needed from future work to verify this. Differences between short- and medium-scale denudation rates are often associated with humans acting as geomorphic agents (e.g. Hooke, 2000; Wilkinson and McElroy, 2007). However, human population in the Bolivian Andes is relatively sparse and smaller villages in most mountain drainages in the Andes have been populated for millennia (Harden, 2006) with small-scale agricultural practices commencing around 3.5–3.0 ka (e.g. Binford et al., 1997; Paduan et al., 2003). Most of the catchments sampled in this study were selected because they have a very low population density, minimal agricultural activity, and limited to no deforestation and therefore suggest anthropogenic effects on CRN-derived and modern denudation rates are low.

4.3. Denudation rates, morphology and climate

Previous studies have suggested that morphologic parameters (e.g. elevation, relief, slope, lithology, drainage size) and climate-related factors (e.g. precipitation, vegetation, runoff) can have a large influence on denudation rates (e.g. Ahnert, 1970; Pinet and Souriau, 1988; Summerfield and Hulton, 1994; Pazzaglia and Brandon, 2001; Reiners et al., 2003). In this section, we explore the relationships between basin size, mean local relief, slope and elevation, mean annual precipitation, and our CRN-derived denudation rates. Comparison between morphologic and climate parameters is also conducted to investigate if the parameters are the source of the large variability detected in CRN-derived denudation rates.

Figure 5 shows the range of short- and medium-term denudation and precipitation rates for the northern and southern transects. The present-day climate pattern is based on an interpolation of a network of rainfall stations (Peterson and Vose, 1997). This approach has the benefit of providing calculated climate normals over a longer times scale (10 to ~90 yr), but has the shortcoming of missing local orographic variations in climate between stations. To address the potential variability in local climate patterns we compared our precipitation rates over each drainage basin to a shorter term (~8 yr) and higher spatial resolution record determined from TRMM satellite data (Bookhagen and Strecke, 2008). In general, we find that the historical climate data capture regional spatial variations in the mean precipitation rate, and have the advantage of providing a climate norm calculated over multiple El Niño cycles (e.g. Fig. 1b).

The impact of modern climate, and in particular precipitation, on denudation rates is still debated (e.g. Riebe et al., 2001; Burbank et al., 2003; Reiners et al., 2003). As described above, latitudinal variations in orogen width, exhumation depth, and rock uplift rate in the central Andes have been attributed to a long-strike differences in climate and associated denudation. Figure 7 shows the range of short- and medium-term denudation and precipitation rates for the northern and southern transects. The present-day climate pattern is based on an interpolation of a network of rainfall stations (Peterson and Vose, 1997). This approach has the benefit of providing calculated climate normals over a longer times scale (10 to ~90 yr), but has the shortcoming of missing local orographic variations in climate between stations. To address the potential variability in local climate patterns we compared our precipitation rates over each drainage basin to a shorter term (~8 yr) and higher spatial resolution record determined from TRMM satellite data (Bookhagen and Strecke, 2008). In general, we find that the historical climate data capture regional spatial variations in the mean precipitation rate, and have the added advantage of providing a climate norm calculated over multiple El Niño cycles (e.g. Fig. 1b).

Short-term sediment flux-derived denudation rates are consistent with the modern precipitation pattern but medium-term CRN-derived rates are not. The northern transect increases in precipitation from ~500 mm yr⁻¹ in the southwest to ~1700 mm yr⁻¹ in the northeast (Figs. 1b, 7a). The southern transect is characterized by low precipitation between 250 mm yr⁻¹ in the east to 700 mm yr⁻¹ in the east (Figs. 1b, 7b). The sediment flux-derived mean denudation rate is 2–3 times higher in the northern transect than in the southern transect, reflecting the precipitation gradient with decreasing rates from the north to the south (Fig. 7). However, CRN-derived mean denudation rates in the north and south are essentially the same within 1σ error (0.40 ± 0.29 mm yr⁻¹ vs. 0.51 ± 0.50 mm yr⁻¹), indicating that denudation rates averaged over several thousand years do not correlate with the present-day latitudinal climate gradient (Fig. 7). Moreover, basins in the northern SA, where precipitation is highest, show the same range in CRN-derived denudation magnitudes as previously estimated rates for
the more arid EC (Fig. 7a) (Safran et al., 2005). In the southern transect, differences in mean annual precipitation between individual sample locations along the profile are too small to determine a correlation between climate and denudation.

The precipitation in the Bolivian Andes is highly seasonal with ~80% of precipitation falling in austral summer (Garreaud, 2000). Previous studies have suggested that denudation is related to storm activity and extreme precipitation events rather than mean annual precipitation (e.g. Coppus and Imeson, 2002). We have compared denudation rates with maximum summer precipitation, in addition to the mean annual rainfall reported above, and come to the same conclusion; no direct relationship can be found between CRN-derived denudation rates and summer precipitation.

5. Discussion

Previous studies suggest several factors influence spatial and temporal variations in orogen denudation. For example, Montgomery and Brandon (2002) showed a linear relationship between denudation magnitude and mean slope for tectonically inactive regions with a mean slope <25° and either a weak linear or strong non-linear relation between denudation rate and mean slopes >30° in active tectonic settings. A correlation between climate and denudation has been found locally in areas where precipitation varies by an order of magnitude (Reiners et al., 2003). Alternatively, settings where large temporal variations in climate influence hillslope processes and vegetation (Schaller et al., 2002) have led to the interpretation that pronounced climate change might exert a larger control over denudation than the inter-regional climate variability (von Blanckenburg, 2005). Recent work by Stock et al. (2009) in the tectonically active and partially glaciated Wasatch Mountains, Utah, USA has documented large spatial and temporal variations in denudation recorded from similar geo- and thermochronology approaches as used in this study. Results from the Wasatch Mountains and the Bolivian Andes, including those presented here, do not show clear relationships between denudation, tectonics, climate, or landscape morphology thereby making it difficult to determine the factors influencing denudation rates. In the following, we discuss possible reasons for the observed spatial and temporal variations in denudation.

5.1. Lithologic and tectonic controls on denudation rates

The large range in calculated denudation rates (Table 1, Fig. 2) could be the result of local basin characteristics. For example, differences in lithology and the erodibility of different rock types have been suggested as a noticeable effect upon denudation rates in the Bolivian Andes (e.g. Aalto et al., 2006). Previous studies have classified the lithologies in the region into a small number of homogenous groups (igneous, meta-sedimentary, weak-sedimentary rocks) and ascribed an index representing the quartz content or the relative rates of chemical erosion to account for different rock strength (Safran et al., 2005; Aalto et al., 2006). Safran et al. (2005) corrected their CRN-derived denudation for the quartz content in different lithologies by ascribing a higher quartz fraction to areas underlain by plutons, conglomerates, and late Miocene deposits. The

![Fig. 6. Cosmogenic radionuclide (CRN)-derived denudation rates versus geomorphologic indices resolved for basin sizes. Diamonds represent samples from the southern transect, triangles are denudation rates from the northern transect. The northern transect includes 43 denudation rates from Safran et al. (2005).](image-url)
percentages do not re
individual samples spans a wide range between 34% and 83%. These
sample). The quartz yield in the analyzed grain size fraction for
(e.g. the amount of quartz in relation to other minerals within the
sample based on the quartz content derived from the sample material
on denudation rates. However, we estimated the quartz yield for each
the underlying lithology in the study area does not have a direct effect
differences in stratigraphic age (e.g. Barnes and Pelletier, 2006)
for different sample sites. For example, small basins exposing
basins characterized by a >20% difference between corrected and
uncorrected estimated denudation rates the quartz-rich lithologies
(i.e. plutons) occupy high terrain and the correction resulted in an
increase in estimated denudation. Lithologies within our sampled
catchments are composed of metasedimentary rocks and all fall into
the same previously defined groups of erosive indexes, despite their
differences in stratigraphic age (Table 1). Therefore, we assume that
the underlying lithology in the study area does not have a direct effect
on denudation rates. However, we estimated the quartz yield for each
sample based on the quartz content derived from the sample material
(e.g. the amount of quartz in relation to other minerals within the
sample). The quartz yield in the analyzed grain size fraction for
individual samples spans a wide range between 34% and 83%. These
percentages do not reflect the quartz distribution in the source
lithologies, but instead most likely indicate the degree of weathering
for different sample sites. For example, small basins exposing
Devonian aged metasediments have a large variance in quartz
contents of 26, 50, and 82% (Table 1, Fig. 6d). Catchments with the
lowest denudation rates show low quartz content, while catchments
with high denudation rates are characterized by material with high
abundance of quartz (Fig. 6d).

High denudation rates found in some of the smaller basins (e.g.
N02, S03, S11, S13, S16) may reflect active faulting along basin
bounding thrusts, but in general, we find no relationship between
denudation rates and structural activity of different regions. What is
known is the SA are the most tectonically active part of the central
Andean fold-thrust belt and characterized by broad, large wavelength
synclinal basins separated by narrow zones of thrust-faulted antici-
nes (e.g. Baby et al., 1992; Dunn et al., 1995; Lamb, 2000). Evidence for
recent deformation along previously mapped faults is not present. For
example, field mapping and analysis of aerial photos at each sample
location does not show recent faulting or landsliding in the sampled
catchments. In addition, major earthquakes in the region are
typically moderate to deep in depth (~20 to 30 km in the north,
between 50 and 600 km in the south) and associated with deeper
subduction related deformation rather than near surface Holocene to
Quaternary deformation (IRIS, 2009).

We might expect erosion rates to reflect the dominantly eastward
propagation of SA deformation with time. Unfortunately, evidence for
out-of-sequence deformation exists (e.g. Barke and Lamb, 2006; Uba
et al., 2009) but is poorly constrained relative to the temporal scales
over which the CRN-derived denudation rates average. Some basins
(e.g. N02) are located along the frontal range and have high
denudation rates perhaps reflective of active deformation whereas
others (N04, N06) are located within major thrust faults but exhibit
low denudation rates, possibly due to locally reduced deformation. In
the southern transect, small basins with high denudation rates (e.g.
S03, S11, S13, S16: >0.65 mm yr^{-1}) lie in the hanging walls of major
thrust faults in the western part of the SA, while basins located along
the frontal range (e.g. S01, S08, S09) have intermediate denudation
rates of ~0.3 to 0.4 mm/yr. This pattern could be recent out-of-
sequence deformation that would result in the frontal-most structure
not being the most active one (e.g. Barke and Lamb, 2006; Uba
et al., 2009). However, other calculated denudation rates do not correlate
with tectonic structures in the SA. For example, basin S05 has the
lowest denudation rate (0.04 mm/yr) despite the high relief, steep
slopes and a location within the hanging wall of a major thrust fault. In
summary, no obvious relationship exists between CRN-derived
denudation rates and fault activity.

5.2. Sediment transport and storage

One of the most prominent processes that might influence spatial
and temporal variations in catchment denudation is mass-movements
such as landslides. Landslides are an important source of sediment
supply that might lead to overestimation of denudation rates derived
from CRN data (e.g. Hovius et al., 2000; Gabet et al., 2004). Alternatively,
modeling studies have shown that in some landslide dominated landscapes
derived denudation rates can underesti-
mate the true catchment-averaged denudation rate in small catch-
ments (Niemi et al., 2005; Yanites et al., 2009). However, our sampled
regions are not landslide dominated, and it is unlikely that the small
basin S05 (~7 km²) that is characterized by very low denudation
(0.04 mm yr^{-1}, Fig. 2) but high relief (~820 m) and steep slopes (40%)
can be attributed to an underestimate of denudation due to
landsliding. Nevertheless, landslides are prominent features in the
northern EC (e.g. Bledgett and Isacks, 2007) and we suggest that the
variability in medium- and short-term denudation in these basins
could be in part ascribed to mass-wasting processes.

Temporal storage of sediment within drainage basins could
influence CRN abundance and therefore medium-term denudation
rates (Bierman and Steig, 1996). Sediment storage within a catchment
can increase the measured CRN concentration if sediments are
exposed, or alternatively decrease the concentration if sediments
are shielded by burial and CRN decay. More sediment storage would
be expected in larger basins, but none of the big rivers in the study
area show extensive floodplains within the Andes, and instead

![Fig. 7. Latitudinal variations in denudation and precipitation across two transects in Bolivia. Medium-term (CRN-derived) denudation rates in the north include samples from Safran et al. (2005) (grey triangles, diamonds are from this study). Short-term (sediment flux-derived) denudation rates are from Barnes and Pelletier (2006) (white squares). The gray box highlights the range of medium-term denudation (striped part includes the exceptionally high rate) and precipitation. The thin dashed line represents mean medium-term denudation rates (calculated for all samples in each transect), the thick dashed line represents mean short-term denudation rate. (a) Northern transect. (b) Southern transect.](Image 69x406 to 268x741)
generally cut through the steep, high relief terrain. A relatively short and fast sediment cycle has been observed for large basins (∼10³ and 10⁶ km² drainage area) in the northern Bolivian Andes with a residence time for sediments of only ∼3 ka (Dossetto et al., 2006). In this study, we sampled significantly smaller catchments with lower residence times and CRN-derived denudation rates incorporating several sediment cycles. No additional CRN accumulation is observed during sediment storage so the cosmogenic denudation signal is preserved (Wittman et al., 2009; Wittmann and Blanckenburg, 2009).

The short-term denudation rates derived from sediment-flux data could be potentially biased by modern sediment cycle conditions. Sediment transport and deposition are highly dynamic processes that vary over time and short-term denudation rates from sediment flux data are subject to seasonal-to-decadal-scale fluctuations and the effects of transient sediment storage (e.g. Kirchner et al., 2001). Therefore, short-term denudation rates might reflect only a specific episode within the transport cycle that records a phase of high sediment flux or high sediment storage on decadal timescales. For example, a detailed study of the Pilcomayo River in southern Bolivia revealed interannual variability in river discharge related to El Niño/Southern Oscillation (ENSO) with lower discharge during El Niño Years (Smolders et al., 2002).

5.3. Potential influence of Holocene climate change on denudation

Holocene climate and vegetation change could be an explanation for the observed temporal differences in denudation rates and the discrepancy between medium-term denudation and present-day precipitation. Terrestrial paleoclimate records indicate significant climate variations on millennial and orbital timescales affected the central Andes (Baker et al., 2001a; 2001b; Abbott et al., 2003). Major changes in lake levels, lake sedimentation (Cross et al., 2000; Rowe et al., 2002; Abbott et al., 2003), and vegetation (Graf, 1981; Bush et al., 2005) suggest changes in both precipitation and temperature. Central Andean paleoclimate records show an overall pattern of aridity from the late Pleistocene through the MH in Bolivia (e.g. Cross et al., 2000; Baker et al., 2001b; Rowe et al., 2002; Abbott et al., 2003; Servant and Servant-Vildary, 2003).

Climate changes in the central Andes were linked to modifications in insolation due to changes in orbital parameters, ENSO, and Atlantic sea surface temperatures (e.g. Baker et al., 2001a,b; Moy et al., 2002; Servant and Servant-Vildary, 2003). ENSO is the most likely reason for precipitation changes on HM timescales and is driven by orbital fluctuations. ENSO is an important factor in the modern climate system over the Andean region with a weak tendency towards below average precipitation during El Niño summers over the Bolivian Altiplano (Vuelle, 1999). Model results and observations have shown significant variations in the strength and frequency of ENSO in the past with (1) a more El Niño-like climate stage between 8 and 5 ka (Rollins et al., 1986; Sandweiss et al., 1996), (2) a steady increase in warm ENSO events over the Holocene, with a peak intensity and frequency of these events at ∼1.2 ka (Clement et al., 2000; Moy et al., 2002), and (3) a larger ENSO variability in the last 1.5 ka (Moy et al., 2002; Servant and Servant-Vildary, 2003).

The effects of ENSO variability are different in the northern and southern regions of Bolivia. In the northern Bolivian Andes, the MH dry phase (∼6 ka) was followed by large magnitude climatic change including a sharp increase in stormy type precipitation between 4.5 and 3.2 ka and an intensification of erosion in the Lake Titicaca watershed on the Altiplano between 4.5 and 2.7 ka (e.g. Abbott et al., 1997; Servant and Servant-Vildary, 2003). After 2.7 ka, coinciding with an increased frequency in El Niño, Lake Titicaca decreased and erosion weakened in the north of the Bolivian Andes, while precipitation was more uniformly distributed (Servant and Servant-Vildary, 2003). These conditions persisted until 0.5 ka, coinciding with the highest El Niño variability of the Holocene. However, convective rainfall did not reach the southern Bolivian Andes and dry conditions remain as evident from aeolian sand dunes, dated 3.5 to 2 ka, extending along the Andes (at 18° and 23°S Servant et al., 1981). The onset of modern conditions in the southern part of the Bolivian Andes was much later than in the north and took place at ∼2.3 ka (e.g. Abbott et al., 2003).

Significant differences between present-day precipitation patterns and climate conditions during the past could have an intrinsic effect on denudation in the central Andes. Denudation rates averaged over thousands of years would not reflect the distinct climate characteristics of today, but would (at least partially) possess an inherited signal from the previous climate. We quantify the potential effect of climate change on CRN-derived denudation rates (Fig. 8). A numerical model was used to evaluate the sensitivity of CRN-derived denudation rates to temporal variations in climate and denudation (for model details see Schaller et al., 2002; Schaller and Ehlers, 2006). The model uses a climate-driven input denudation history to calculate a cosmogenic ¹⁰Be-derived denudation history (Schaller et al., 2001). Temporal variations in the surface and subsurface CRN concentrations for each time step are calculated by numerical integration of a depth-dependent production based on the input denudation rate from the previous step. In our simulations for the Bolivian Andes, we assume low denudation (0.05–0.2 mm yr⁻¹) rates during the MH due to the recorded aridity in Bolivia for our initial conditions. Next, we invoke an increase in denudation rates to modern values (0.30–1.5 mm yr⁻¹) in different time-step scenarios reflecting an onset of wetter conditions (Cross et al., 2000; Abbott et al., 2003). The magnitude of increase in denudation rates associated with wetter conditions in the Andes is unknown. Given this, a plausible range of increases in denudation is explored by evaluating four different scenarios for the magnitude of denudation rate changes between 0–4.5 ka.

The model settings reflect continuous increase in denudation since 4.5 ka and 2.25 ka respectively, imitating the onset of wetter conditions in the northern and southern part of the Altiplano (Fig. 8, (1) and (3)). A stepwise increase in denudation since 4.5 ka, with higher denudation between 4.5 and 2.7 ka, a constant denudation until 0.5 ka, and modern increase in denudation reflects the observed precipitation and
denudation pattern in the northern Andes (Fig. 8, (2)). A uniform increase in denudation for the last 1.5 ka is related to the high ENSO variability during that time interval (Fig. 8, (4)). Calculated modern CRN-derived denudation rates at the end of each simulation vary between 0.07 and 0.7 mm yr\(^{-1}\) and are in good agreement with our observations. The simulations indicate that changes in precipitation lead to a slow adjustment of the CRN concentration, but that it can take thousands of years before the CRNs are in complete equilibrium with the new climate (or denudation) conditions as previously noted (Schaller et al., 2001; Niemi et al., 2005; Schaller and Ehlers, 2006). This conclusion is consistent with a recent study that ascribed fluctuations between high and low denudation periods to changes in climate over medium-term timescales (Dosseto et al., 2006).

In summary, the 3-fold discrepancy between short- and medium-term denudation rates in northern Bolivia can be reconciled if the following conditions are met: (a) aridity in the MH causing very low (<0.1 mm yr\(^{-1}\)) denudation rates, (b) an onset of wetter conditions between 4.5 and 1.5 ka was accompanied by increasing denudation rates, and (c) overall changes in denudation rates are large over medium-term timescales.

6. Implications and conclusions

Our results exhibit large spatial and temporal variations in denudation rates across the central Andes in Bolivia. Cosmogenic \(^{10}\)Be concentrations from modern river sediments indicate catchment-averaged denudation rates of 0.04–1.93 mm yr\(^{-1}\) with apparent ages of 0.4 to 20 ka. No statistically significant correlation exists between CRN-derived denudation rates and morphological indices such as relief, slope or basin size. However, smaller basins reflect a much higher variability in denudation rates, probably due to local basin parameters (e.g. proximity to active faults). Latitudinal variations in precipitation are not reflected in the CRN-derived denudation rates.

Denudation rates averaged over long- (>10\(^3\) yrs) and medium-term (10\(^{-4}\)–10\(^2\) yrs) timescales are similar and within error of each other. Consistency between CRN-derived denudation rates and the much longer-term fission-track exhumation rates implies that on average denudation rates over the last several millions years in the central Andes might have been similar. However, a comparison between best-fit denudation rates estimated from AFT data and CRN-derived data from similar locations along the southern transect suggest at the 1σ-level a moderate increase in denudation rates over time. The along-strike contrast in denudation might have existed since the Miocene, but the total magnitude is difficult to constrain due to large errors associated with the long-term denudation magnitudes.

A significant increase in denudation rates over the last several thousand years is observed with sediment flux-derived denudation rates ~3 times higher than CRN-derived denudation rates in the northern transect. Our data, which cover a previously sparsely sampled medium-term timescale, indicate that the increase in short-term (10\(^{3}\) yrs) denudation rates is relatively recent and that it might be associated with an increase in precipitation since ~4.5 ka. Climate model simulations of the study area indicate that the Bolivian Andes likely experienced a general increase in precipitation since the mid-Holocene. Climate shifts towards more humid conditions and/or towards more variable conditions in the Bolivian Andes may have had a substantial influence on denudation rates.

In summary, our results suggest that the effect of an increase in Holocene precipitation rates over the last ~4.5 ka on denudation rates is prevalent in the CRN data. Thus, CRN data from the central Andes may not reflect the modern climate. Other factors that might have contributed to the recent increase in denudation rates are an increase in sediment yield and/or the sensitivity of sediment flux data to episodic changes in denudation or storage that may influence such data over short time scales.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.geomorph.2010.05.014.

References


