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Climate-controlled shifts in sediment provenance inferred from detrital zircon ages, western Peruvian Andes

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ABSTRACT

Provenance analysis of Pleistocene terrace deposits, together with modern sediments from the same streams, from four catchments draining the western margin of the Andes in Peru is used to infer changes in erosion patterns between the past and the present period by matching detrital zircon ages with crystallization ages of source rocks. Age populations suggest major changes in sediment provenance through the past 100 k.y. At present, sediment sources are mainly located along the steep middle reaches of the rivers, whereas during the Pleistocene, sources were additionally located in the low-relief headwaters of these catchments. These shifts in the loci of erosion are interpreted to reflect changes in precipitation patterns, where periods of stronger precipitation on the Altiplano allowed the entrainment of material from the low-relief plateau in the past. In contrast, modern precipitation patterns result in negligible erosion rates on the Altiplano, and the site of material entrainment shifts to the knickzone reaches where steeper slopes and higher stream power promote erosion. In that sense, this work illustrates that terrace aggradation is associated with major shifts in provenance sources.

INTRODUCTION

Measuring U-Pb ages on detrital zircon has become a commonly used method for the determination of provenance and for inferring sedimentary dynamics within erosional basins (e.g., Cawood et al., 2003; Beranek et al., 2006; He et al., 2014). Related age populations allow determination of provenance by matching detrital zircon ages with crystallization ages of potential source rocks exposed in the erosional hinterland. For the Andes Mountains, however, no studies have focused on provenance information recorded by detrital zircon from sediment archives to infer temporal changes in erosional patterns. In this mountain belt, variations in precipitation rates and patterns have led to remarkable lake-level variations on the Altiplano (Fritz et al., 2004) and pulses of erosion on the western Andean margin (Bekaddour et al., 2014; Veit et al., 2016) during the Quaternary. These variations have also resulted in the formation of cut-and-fill terrace systems, particularly in lower valley reaches along the western Peruvian margin (Steffen et al., 2009, 2010; Trauerstein et al., 2014). Although this accumulation of alluvial deposits indicates the occurrence of a sediment pulse (Norton et al., 2016), possibly driven by climate change (Steffen al., 2009, 2010; Bekaddour et al., 2014) and/or by earthquakes (McPhillips et al., 2014), the provenance of this terrace material remains unclear. Here, we present U-Pb ages of detrital zircons to determine the provenance of terrace and modern deposits in four catchments along the western Peruvian margin. The goal is to determine changes in loci of erosion that we will use to infer shifts in precipitation patterns.

SETTING: BEDROCK GEOLOGY, MORPHOLOGY, AND CLIMATE

The western margin of the Peruvian Andes comprises the Western Escarpment, which separates the Altiplano Plateau, situated at ~4000 m a.s.l. (above sea level), from the Pacific Ocean. The boundary of the escarpment is delineated by the Western Cordillera, which comprises a chain of volcanic cones ranging in elevation between 5000 m and 7000 m a.s.l. Relief along the Western Escarpment was formed through incision by numerous rivers (e.g., Schildgen et al., 2007). Quaternary cut-and-fill terrace sequences occur on the floors of these valleys, offering excellent opportunities for reconstructing changes in erosional and sediment-transport dynamics and related shifts in provenance (Steffen et al., 2009; Bekaddour et al., 2014; Norton et al., 2016). The bedrock of the western Andean margin is dominated by Tertiary and Quaternary volcanic rocks (mainly andesitic or dacitic tuffs and ignimbrites) originating from distinct phases of volcanic eruption (Caldas Vidal, 1993). These rocks rest on Mesozoic and lower Tertiary sedimentary units (Fig. 1) intruded by Late Cretaceous to late Eocene plutons that are referred to as the Coastal batholith (Figs. 1 and 2). In Peru, these plutons have various intrusion ages and crops out almost continuously along the entire Western Escarpment (Fig. 1).

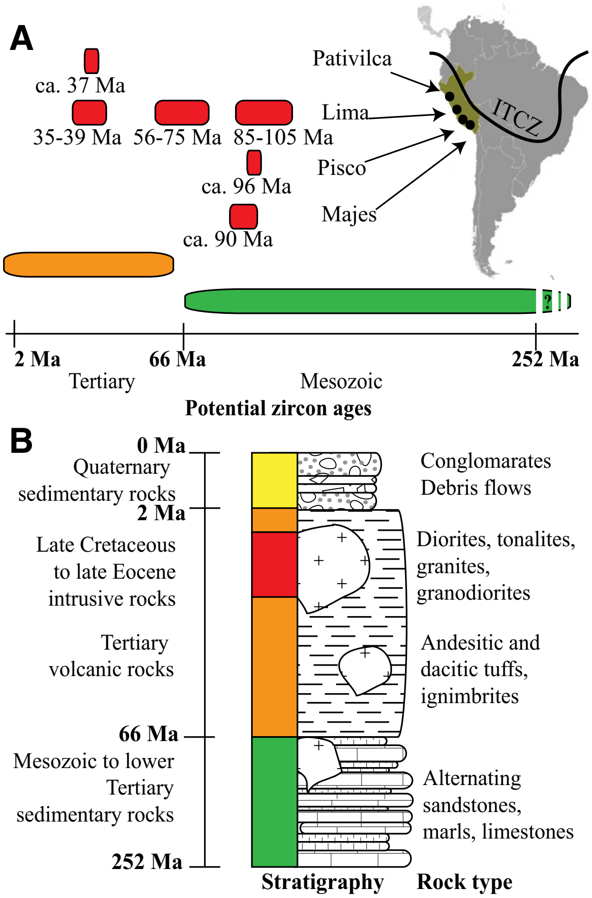

Figure 1. Compilation of ages and simplified stratigraphic log for the western margin of the Peruvian Andes, showing zircon ages potentially encountered in different lithologies of studied catchments. See Data Repository (see footnote 1) for compilation of intrusion ages of batholiths. ITCZ—Intertropical Convergence Zone. Vertical scale is not to scale.

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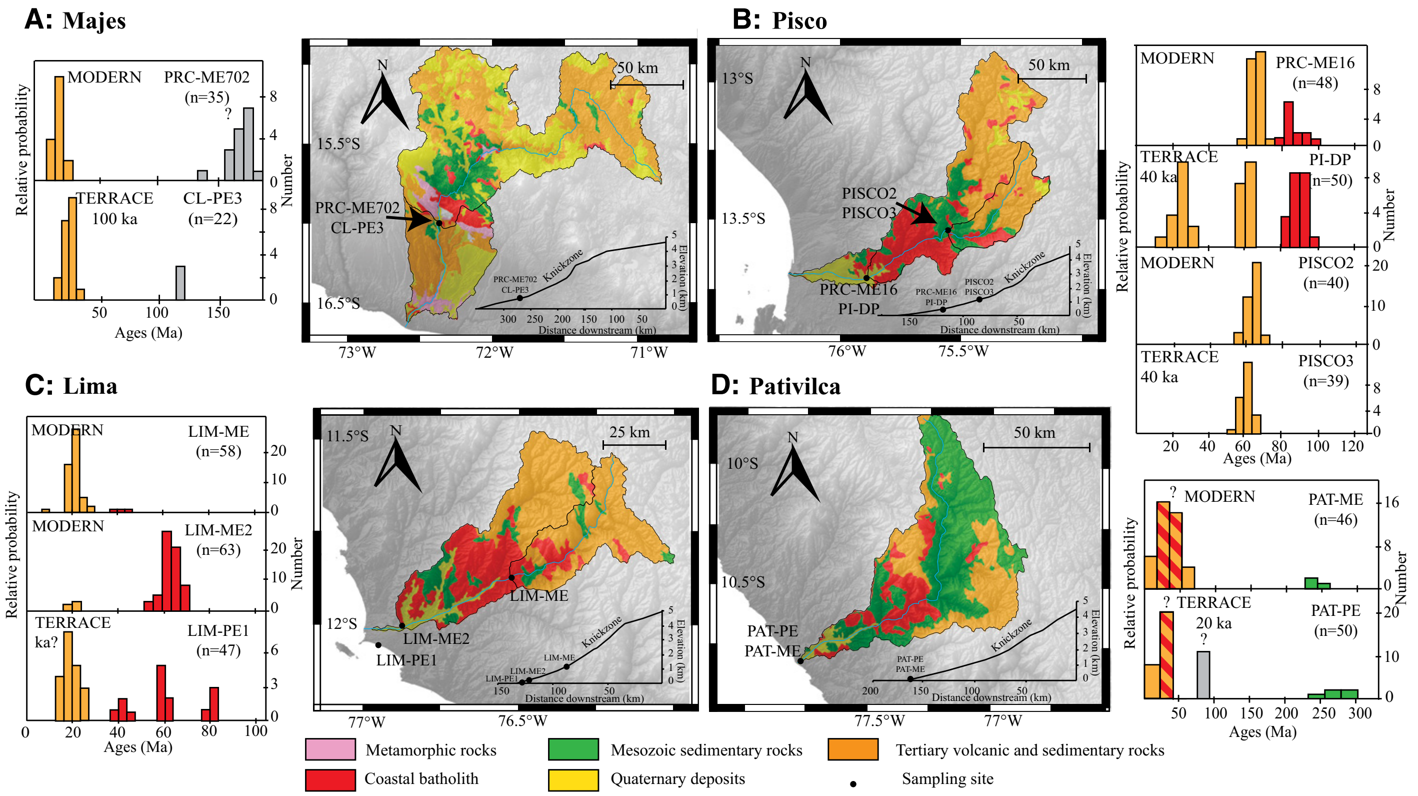

Figure 2. Detrital zircon U-Pb ages, geological maps, and stream long profiles of the four studied catchments with location of sampling sites (western margin of Peruvian Andes). Base maps are hillshades from Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) 90 m topography data (NASA Land Processes Distributed Active Archive Center, 2001). Coastal batholith comprises Late Cretaceous to late Miocene plutonic rocks (see Fig. 1).

The streams dissecting the western Andean margin display longitudinal profiles that are characterized by two segments separated by a distinct knickzone (Fig. 2; Trauerstein et al., 2014). These geomorphic features have formed through headward retreat in response to a late Miocene uplift pulse (e.g., Schildgen et al., 2007). Upstream of these knickzones, the streams are mainly underlain by Tertiary volcaniclastic rocks, while downstream incision has exhumed the Coastal batholith and older metasedimentary units (e.g., Trauerstein et al., 2014).

The modern climate of western Peru is characterized by an east-west–decreasing trend in mean annual precipitation rates from ~800 mm on the Altiplano to ~0 mm at the coast (Huffman et al., 2007). This pattern is related to the position of the Intertropical Convergence Zone (ITCZ; Fig. 1A; Bookhagen and Strecker, 2008). During the Pleistocene, the ITCZ has shifted farther south during times of stronger, possibly orbitally controlled insolation (Strecker et al., 2007). These shifts have resulted in stronger upper-atmosphere easterlies synchronous with higher precipitation on the Altiplano, as recorded by lake-level highstands on the plateau (Ouki [120-98 ka], Minchin [47–36 ka], and Tauca [26–15 ka] pluvial periods; e.g., Fritz et al., 2004) and by the terrace sequences on the valley floors along the western Peruvian margin (Steffen et al., 2009, 2010; Trauerstein et al., 2014).

SAMPLING SITES AND METHODS

Four catchments on the western margin of the Peruvian Andes (from south to north: Majes, Pisco, Lima, and Pativilca; Fig. 1A), hosting well-preserved and well-studied cut-and-fill terraces (le Roux et al., 2000; Steffen et al., 2009, 2010; Trauerstein et al., 2014), are explored for possible shifts in sediment provenance (Fig. 2). In each catchment, at least one sand sample from the modern stream (downstream of the knickzone) and one sample from the sandy matrix of the terrace deposits have been collected (Fig. 2; see Table DR1 in the GSA Data Repository[1] for details on sample location and description). Reported optically stimulated luminescence (OSL) ages of the sampled terraces are ca. 20 ka in the Pativilca (Trauerstein et al., 2014), ca. 40 ka in the Pisco (Steffen et al., 2009), and ca. 100 ka in the Majes catchment (Steffen et al., 2010). However, as noted by Trauerstein et al. (2014), these ages have to be considered with care. The ages of the terrace deposits in Lima are unknown.

Samples were crushed and sieved to the 150–400 µm fractions. Zircon grains were extracted using magnetic and conventional heavy-liquid separation techniques. Randomly handpicked single crystals were mounted in epoxy-filled grain mount blocks and polished to expose the interior of the grains suitable for laser-ablation–inductively coupled plasma–mass spectrometry analysis. We measured in situ U-Pb ages for 25–70 individual grains per sample at the University of Bern. See the Data Repository for details on the instrument and the method.

RESULTS

The results are presented for the four studied catchments as U-Pb age probability distribution functions in Figure 2.

In the Majes catchment (southernmost system), the modern sample shows a peak of detrital zircon ages centered on 20 Ma and an older population centered on 185 Ma. The 100 ka sample shows two age populations centered on 25 and 120 Ma.

In the Pisco basin, the modern trunk-stream sediments (sample PRC-ME16) have two zircon-age populations centered on 62 and 90 Ma. Zircons encountered in the 40 ka terrace sediments (PI-DP) yield identical

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[1] GSA Data Repository item 2017015, age compilation of the coastal batholith intrusions, supplementary methods, and U-Pb zircon data, is available online at http://www.geosociety.org/pubs/ft2017.htm or on request from editing@geosociety.org.

age populations, with the addition of a third population centered on 20 Ma. Samples from a modern tributary stream (PISCO2) and a 40 ka terrace (PISCO3) upstream of the Coastal batholith each yield a single main zircon-age population of ca. 62 Ma.

In the Lima basin, zircon ages of modern sediments at the coast (sample LIM-ME2) yield two distinct age populations (20 and 60 Ma). The coastal terrace sample (LIM-PE1) yields a more complex pattern characterized by peak ages centered on 20, 45, 62, and 80 Ma. In addition, while the 20 Ma zircon crystals are mainly present as needles, the older grains have a tetragonal shape (see the Data Repository). A modern sample further upstream (LIM-ME), close to the inland limit of the costal batholith, yields a single main peak zircon-age population centered on ca. 20 Ma.

In the Pativilca catchment, both modern and terrace sediments exhibit zircon age populations that are centered on ca. 35 Ma (majority of zircons) and ca. 250 Ma. Additionally, ca. 80 Ma zircons are encountered in the terrace deposits.

PROVENANCE

In the Majes catchment, zircon ages of both the modern and the terrace material show a major Tertiary peak and a secondary Mesozoic zircon-age population. However, the relative abundance of Mesozoic zircon crystals is larger in the modern sediments than in the ca. 100 ka terrace deposits, implying that nowadays Mesozoic units are representing a more important sediment source.

In the Pisco catchment, zircon ages encountered in both modern and terrace trunk-stream sediments imply that both the Tertiary units and the Coastal batholith have served as sediment sources. Tertiary (62 Ma) zircon ages encountered in both terrace and modern samples of the same tributary indicate that rocks of Tertiary age must have served as sediment sources in this smaller catchment. Likewise, the young zircon ages (20 Ma) encountered only in the terrace deposits in sample PI-DP suggest that the corresponding source rock along the main trunk must have a Tertiary age. Accordingly, we use the detrital zircon ages to constrain 20 Ma and 62 Ma ages for the bedrock exposed in the trunk and tributary basin, respectively (Fig. 3).

In the Lima catchment, we use the occurrence of a single Tertiary age population (ca. 20 Ma) in the modern stream sediments sampled close to the upstream limit of the Coastal batholith to constrain the age of the source rock. Near the coast, however, modern stream samples disclose a Tertiary (20 Ma) and a Coastal batholith zircon age population (62 Ma), suggesting that both units are present-day sediment sources. For the terrace deposits, the zircon age populations of 40, 62, and 80 Ma correspond to at least three intrusive episodes of the Coastal batholith in the Lima segment (Fig. 1), while a major age population centered on 20 Ma in the same terrace material implies that Tertiary units have also served as sediment sources. However, the relative abundance of Tertiary zircons is significantly larger in the terrace material than in the modern deposits, suggesting that the Tertiary units were a more important sediment source during the past.

In the Pativilca catchment, Tertiary plus numerous Mesozoic zircon ages reveal that both the Coastal batholith, including the Mesozoic metasedimentary rocks, and the Tertiary units have served as source rocks for the modern and the terrace sediments. These bedrock units crop out mainly along the middle reaches of the catchment, indicating that this area was a source for both the terrace and the modern deposits. In addition, the ca. 20 ka deposits also contain a Mesozoic-age (80 Ma) zircon population. The results are not accurate enough to further detail the provenance of the material, as Mesozoic rocks are widely exposed in this basin.

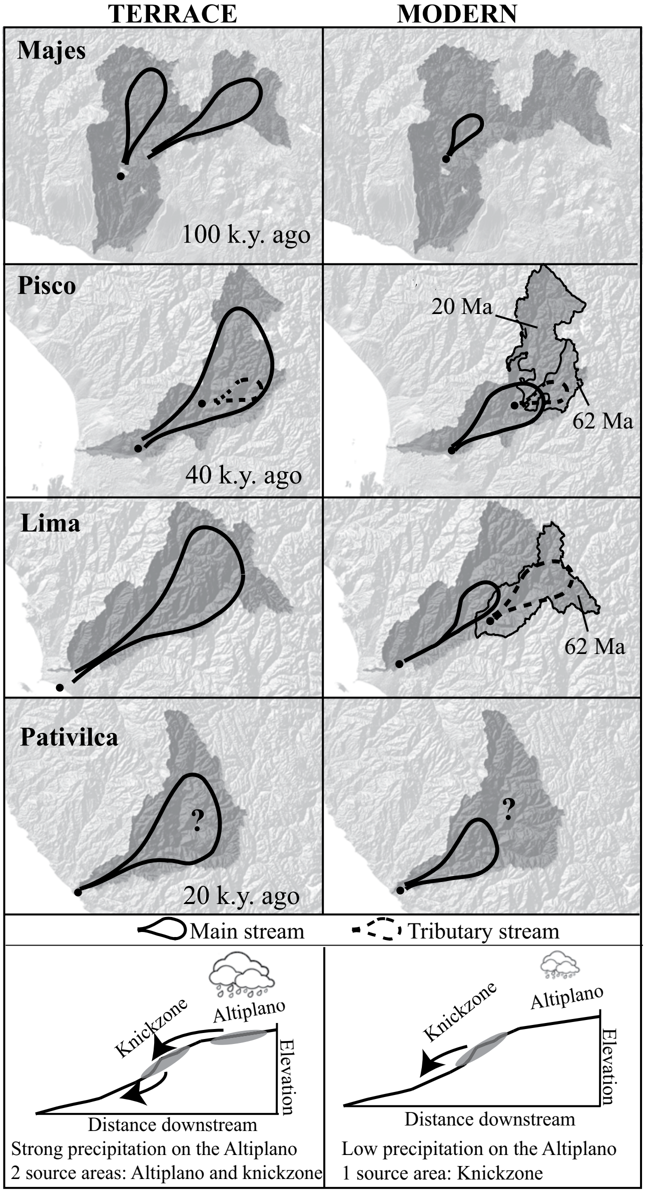

Figure 3. Provenance of sediment today and during accumulation of terrace material (western margin of Peruvian Andes). Base maps and location of catchments (gray shading) and samples (black dots) are same as in Figure 2. Zircon ages in Tertiary units are inferred here from zircon age populations in trunk and tributary streams.

Interestingly, all results share the same trends where the loci of erosion have differed between the time spans of terrace formation and today, consistent with ^{10}Be-based sediment budgets for modern and terrace deposits in the Pisco valley (Bekaddour et al., 2014). Additionally, where accurate enough, the results show that the source areas of the modern sediments are mainly situated along the middle reaches of the catchments surrounding the knickzones. Contrariwise, the provenance of the terrace sediments includes the entire drainage basins between the Altiplano and the middle reaches (Fig. 3).

IMPLICATIONS FOR CHANGES IN PRECIPITATION PATTERNS

While McPhillips et al. (2014) proposed that sediment transfer recorded by terrace and modern deposits could be related to earthquakes, we tentatively favor the interpretation by Steffen et al. (2009, 2010) and Norton et al. (2016) who emphasized a climate control on sediment accumulation. In particular, the transfer of material from the hillslopes to the trunk stream by debris flows (Steffen et al., 2009) requires sufficient water (Coe and Cannon, 2008; McArdell et al., 2007), which is not available under the current climate. Following Bekaddour et al. (2014), we thus consider that accumulation of sediment and the formation of terrace sequences requires larger amounts of rainfall on both the Altiplano Plateau and its western edge. As a consequence, the inferred shifts in sediment provenance most likely reflect modifications in erosional and precipitation regimes driven by shifts in the strength of the Andean jet stream (Strecker et al., 2007). In this context, it has been proposed that these shifts are related to an orbital cyclicity of 20 k.y., 40 k.y., and 100 k.y. Related inferences are mainly based on dated highstand lake levels on the plateau (e.g., Fritz et al., 2004) but also on similar OSL ages (e.g., Trauerstein et al., 2014) for the terrace sediments in the Majes and Pisco valleys (Steffen et al., 2009, 2010). We note, however that the 100 ka OSL age for the terrace deposits at Majes was independently constrained through ^{10}Be-based exposure ages of a landslide that interfingers with the terrace sequences (Margirier et al., 2015). Ages for the terrace deposits at Pativilca are less clear, but Trauerstein et al. (2014) presented OSL data that might also point towards these orbital cycles in sediment accumulation. In summary, although very incomplete, available age information do point towards orbital conditions as the driving force for shifts in erosional pattern, leading to sediment accumulation and terrace construction along the western margin of the Peruvian Andes. During wet periods, when accumulation of the terrace material presumably occurred, higher precipitation rates on the Altiplano most likely allowed erosion and material entrainment in the uppermost flat reaches of the catchments (Abbühl et al., 2011), supplying zircons with an Altiplano provenance signal. During these pluvial periods, a mixture of zircons from the knickzone reaches suggests that erosion in this lower segment has occurred due to a combination of high rainfall rates and steeper topographic conditions. In contrast, during periods of lower precipitation including the present day, stream runoff is apparently not sufficient to entrain a significant amount of material on the low-relief Altiplano. In particular, modern detrital zircon-age populations suggest that sediments are mainly entrained in the middle reaches of the catchments surrounding the knickzones, consistent with the pattern of ^{10}Be-based modern catchment-averaged denudation rates (Abbühl et al., 2011; Bekaddour et al., 2014). In these segments, steeper channel gradients yield higher stream power also during relatively dry periods such as today, thereby facilitating the entrainment of bedrock material. Apparently, the detrital-zircon age populations record similar forces at work in all catchments, which in our case appear to be related to shifts in precipitation rates and patterns. These mechanisms are likely to have conditioned erosional patterns along the western Andean margin during multiple phases of terrace aggradation and during different time periods (Fig. 3).

In conclusion, the population of detrital zircon ages established here for modern and terrace material of streams along the western Peruvian margin suggests that the loci of erosion have shifted through time, and that these shifts are linked with the construction of terrace sequences along the valleys. This work has major implications for reconstructions of paleo-erosional and erosional pattern in the Andes and presents one of the first studies showing that terrace aggradation is associated with major shifts in provenance sources.

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