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Invited review

Proglacial lake sediment records of Holocene climate change in the western Cordillera of Peru

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ABSTRACT

Sediment records from proglacial lakes between 9 and 10°S in the western Cordillera of the Peruvian Andes document the waxing and waning of alpine glaciers since the end of the Lateglacial stage. These records from the southern tropical Andes provide supporting evidence that the early Holocene (between 12 and 8 ka) was relatively warm and dry, and the middle Holocene (between 8 and 4 ka) was marked by a shift to cooler, and possibly wetter conditions in certain regions, leading to glacial advances. Although there were multiple periods of brief ice advances that interrupted the overall trend, glaciers in multiple valleys generally retreated from ~4.0 ka through the Medieval Climate Anomaly (1.0–0.7 ka). This late Holocene pattern of ice retreat occurred during a period when lake level studies, and both lacustrine and speleothem stable isotopic records indicate wetter conditions relative to the middle Holocene, suggesting that higher temperatures contributed to the pattern of ice retreat. Following this period of glacial retreat, multiple proxy records suggest that the start of the Little Ice Age (~0.6–0.1 ka) was a colder and wetter time throughout much of the tropical Andes. There appear to be two primary synoptic-scale climatic controls on temperature and precipitation linked to insolation dynamics that drive changes in ice cover in the southern tropical Andes during the Holocene: 1) the strength of the South America Summer Monsoon, which is linked to Northern Hemisphere temperatures and the mean position of the Intertropical Convergence Zone over the Atlantic, and 2) sea surface temperature distributions in the tropical Pacific Ocean and its influence on atmospheric temperature, precipitation and circulation patterns.

1. Introduction

Discerning the timing and causes of Holocene temperature and precipitation variations in the tropical Andes is important for our general understanding of global climate change (IPCC, 2007). The tropical hydrologic cycle, for example, plays a critical role in low-latitude climate dynamics through ocean and atmospheric circulation (Baker et al., 2001; Münnich and Neelin, 2005; Cruz et al., 2009), and our ability to predict future environmental changes linked to these processes requires a better understanding of how these parameters changed during the Holocene (Seltzer et al., 2000). Recent studies of glacier fluctuations document the timing and pattern of high-altitude environmental changes that are linked to ocean-atmospheric dynamics (Francou et al., 1995; Vuille et al., 2008a; Bradley et al., 2009; Rabatel et al., 2013). However, fundamental questions remain regarding the relative contributions of precipitation and temperature to glacier mass-balance in the tropical Andes, and the synoptic-scale mechanisms that caused the observed changes over longer, pre-instrumental time-scales (Jomelli et al., 2009).

Rodbell et al. (2008) provide a review of clastic sediment records from the tropical Andes, highlighting the potential for using proglacial lake sediment cores to document the history of glaciation, and discuss the potential mechanism for the observed changes. They focused on the timing and magnitude of variations in clastic sediment flux to proglacial lakes during the last local glacial maximum and Lateglacial stage (~30–10 ka). Many of the lake sediment records they used are from drainage basins that have been devoid of glaciers for the entire Holocene. Here, we build on this work by focusing on lakes from catchments in the western Cordillera of central Peru that are presently glacierized, and likely have been for much of the Holocene. A compilation of three lake

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sediment records, with west-facing slopes in the Cordilleras Blanca, Huayhuash and Raura, document changes in clastic sediment flux in their respective valleys since the end of the Lateglacial stage (ca 12 ka). We compare our findings with proxy reconstructions of regional precipitation (Baker et al., 2001; Cruz et al., 2009; Bird et al., 2011a; Strikis et al., 2011), ice core records (e.g. Thompson et al., 2006) and dated positions of paleo-ice margins (Buffen et al., 2009; Licciardi et al., 2009) in order to differentiate between the effects of temperature and precipitation on glacial variability during the Holocene.

2. Study site

2.1. Regional geology

The three proglacial lakes discussed in this study are from west-facing slopes of adjacent mountain ranges in the tropical Peruvian Andes that collectively form the NW-SE-trending, western-most glacierized cordillera of Peru (Fig. 1). From north to south, these ranges are the Cordillera Blanca, the Cordillera Huayhuash and the Cordillera Raura. The Cordillera Blanca is a ~200-km-long mountain range that is actively uplifting due, in part, to the prominent southwest-facing Cordillera Blanca Detachment Fault (McNulty and Farber, 2002). Modern glaciers in the Cordillera Blanca sit almost entirely on Miocene to Pliocene granite and granodiorite. There are also Cretaceous and Jurassic metasedimentary rocks that are mostly hornfels and quartzite (Clapperton, 1993). The Cordillera Huayhuash is located between the Cordillera Blanca and the Junin Plain. Most of the Huayhuash is southeast of the influence of the major normal faulting that is occurring in the Cordillera Blanca, and instead, thrust faulting and folding of Mesozoic sedimentary and metasedimentary rocks are evident along with Tertiary volcanic and intrusive rocks (Coney, 1971). Likewise, the Cordillera Raura exhibits thrust faulting and folding of rocks that are the similar in composition and age as those in the Huayhuash. The bedrock in these regions is mostly Cretaceous sedimentary and metasedimentary rocks, with some Tertiary volcanic and intrusive rocks, and descriptions of these units are found in Coney (1971), Cobbing et al. (1981), and Cobbing and Garayar (1998), with geochemical data in Stansell (2009).

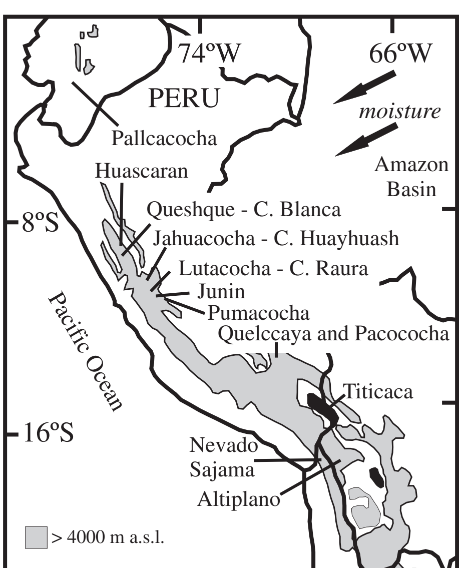

Fig. 1. Location map of sites discussed in the text. Shaded areas represent surface elevation greater than 4000 m asl. Arrows indicate predominant moisture-bearing easterly wind direction that causes higher precipitation on the eastern slopes of the central Peruvian Andes.

2.2. Laguna Queshquecocha – Cordillera Blanca

The Queshque massif is in the southern Cordillera Blanca, Peru (Fig. 2). The headwall of the watershed is ~5600 m asl. Laguna Queshquecocha (9°48′S, 77°18′W, 4260 m asl), with a maximum water depth of ~8.3 m, is dammed by moraines and outwash fans of the last local glacial maximum (Rodbell, 1991). Approximately 600 m up-valley from Laguna Queshquecocha is a smaller lake that is impounded by a Lateglacial moraine, dated by cosmogenic ^{10}Be to ~12.5 ka (Farber et al., 2005); a sediment record from this upper lake was discussed in detail in Rodbell et al. (2008). There are two glacierized drainages that feed sediment to the upper lake, with an outlet feeding lower Laguna Queshquecocha. The bedrock beneath the active glaciers is a combination of granodiorite and metasedimentary rocks, and glaciers advance to override proportionally higher amounts of granodiorite.

2.3. Jahuacocha – Cordillera Huayhuash

Laguna Jahuacocha (Fig. 3) is located on the west side of the Cordillera Huayhuash (10°14′S, 76°56′W, 4076 m asl). The headwall of the watershed is ~6406 m asl. The bedrock beneath the active glacier is dominated by carbonates and granitic intrusions, which contrasts markedly with the siliciclastic rocks that underlie the lake and much of the catchment that is not presently ice-covered (Coney, 1971). The lake is dammed by an end moraine that has been dated by cosmogenic ^{10}Be methods to the early Holocene (10.1 ± 0.9 ka; Hall et al., 2009). The Jahuacocha watershed has the greatest topographic relief and highest headwall elevation of the sites presented in this study. A prominent and very large moraine above Jahuacocha has not been dated, and it is possible that it is a compound moraine that was built during multiple glacial advances during the Holocene. The modern glaciers that provide meltwater and sediment to Laguna Jahuacocha are located mostly on the Santa Formation, which consists largely of carbonates, as well as granitic rocks. Bedrock beyond these active glaciers is dominated by the Carhuaz Formation that consists mostly of siliciclastic rocks.

2.4. Lutacocha – Cordillera Raura

Laguna Lutacocha (10°33′S, 76°43′W, 4320 m asl) is located in the southern Cordillera Raura (Fig. 4). The headwall of the watershed is ~5250 m asl. The lake is dammed by bedrock and has a water depth of ~6.5 m. The lake is the second in a series of three paternoster lakes that extend down-valley from an active glacier. The upper lake acts as a sediment trap, leading to the deposition of relatively fine-grained sediments in Laguna Lutacocha. There are multiple till deposits of varying ages in the Cordillera Raura, and most of these deposits have not been dated. Till in the vicinity of Laguna Lutacocha was initially interpreted as being Neoglacial by Clapperton (1972, 1983), although the deposits themselves have not been dated and could correspond to older events. These presumed Neoglacial till deposits extend down to an elevation as low as 4350 m, which is only ~30 m above the present shoreline of Laguna Lutacocha. This implies that meltwater from glaciers would have been flowing directly into the lake at times of glacial advances, resulting in changes in the composition of sediments being deposited. Topographic maps from A.D. 1965 identify multiple glaciers in the northeast and southwest quadrants of the watershed, but only one glacier in the northeast remains today (McFadden et al., 2011). The modern glacier for Lutacocha is located on the Jumasha limestone that consists of bioclastic and pelletal