Rapid Communication

Cross-cutting moraines reveal evidence for North Atlantic influence on glaciers in the tropical Andes

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ABSTRACT: Surface exposure dating of boulders on an exceptionally well-preserved sequence of moraines in the Peruvian Andes reveals the most detailed record of glaciation heretofore recognised in the region. The high degree of moraine preservation resulted from dramatic changes in the flow path of piedmont palaeoglaciers at the southern end of the Cordillera Blanca (10°00' S, 77°16' W), which, in turn, generated a series of cross-cutting moraines. Sixty$^{10}$Be surface exposure ages indicate at least four episodes of palaeoglacier stabilisation (>65, ca. 65, ca. 32 and ca. 18–15 ka) and several minor advances or stillstands on the western side of the Nevado Jeulla Rajo massif. The absence of ages close to the global Last Glacial Maximum (ca. 21 ka) suggests that if an advance culminated at that time any resulting moraines were subsequently overridden. The timing of expanded ice cover in the central Peruvian Andes correlates broadly with the timing of massive iceberg discharge (Heinrich) events in the North Atlantic Ocean, suggesting a possible causal connection between southward migration of the Intertropical Convergence Zone during Heinrich events and a resultant increase in precipitation in the tropical Andes. Copyright © 2010 John Wiley & Sons, Ltd.

Supporting information is presented in the online version of this article.

KEYWORDS: tropical glaciation; Peruvian Andes; cosmogenic dating; Heinrich events; $^{10}$Be surface exposure dating.

Introduction

Palaeoclimatic connections between glaciation in the Tropics and drivers of climatic variations at higher latitudes have been hypothesised (Mercer and Palacios, 1977; Baker et al., 2001; Zech et al., 2007; Blard et al., 2009; Bromley et al., 2009; Licciardi et al., 2009), but not firmly established. Although tropical glaciers clearly respond to changes in climate, identification of the controlling climatic parameters remains elusive. As Earth’s most glaciated tropical region (Kaser and Osmaston, 2002), the Peruvian Andes have a geomorphic record of past glacier fluctuations that offers an excellent opportunity to investigate tropical glacial cycles. Glacial chronologies based on surface exposure dating have greatly improved our understanding of palaeoglacier fluctuations in the tropical Andes. In Peru, studies on the Junin Plain (Smith et al., 2005a,b, 2008; 11°00' S, 76°00' W; Fig. 1) and in the central Cordillera Blanca (Farber et al., 2005; 9°30'S, 77°00' W; Fig. 1) reveal that the local Last Glacial Maximum (LGM; ca. 30–26 ka) was likely earlier than the global LGM (ca. 21 ka; Martinson et al., 1987) and was relatively minor compared to glacial advances predating the last glacial cycle (herein, between Marine Isotope Stage (MIS) 5 and MIS 1). At both sites, the local LGM was followed by late-glacial readvances (ca. 16–15 ka). Bromley et al. (2009) identified two major Late Pleistocene advances in southern Peru (15°33' S, 72°39' W), and Hall et al. (2009) reported extensive late-glacial and early Holocene advances in the Cordillera Huayhuash (10°16' S, 76°54' W; Fig 1) of central Peru. Here we present a detailed glacial chronology from the southern Cordillera Blanca (Fig. 1) that provides new insights into the glacial history of the region.
Altiplano ca. 18–14 ka (Plazcek 2005a,b, 2008); PT, approximate extent of palaeolake Tauca on the C24 level (a.s.l.), the adjacent Conococha Plain (CP; (QRV) – for 10Be surface exposure dating. JV still hosts small (Fig. 2, M1–M9) – Jeullesh Valley (JV) and Quenua Ragra Valley supporting information, Note 1).

Blanca Normal Fault (CBNF; Fig. 2) runs along the western side side of NJR (Fig. 2, M1–M9). The west-dipping Cordillera sets of well-preserved moraines extend onto CP from the west 4100 m a.s.l.) and Laguna Conococha (Figs 1 and 2). Multiple (Fig. 2). M9 appears to be a lateral moraine deposited by ice southeast along the CBNF and joined ice flowing out of cirque X.

The 10Be ages from JV, QRV and CP (Figs 3 and 4) indicate at least four palaeoglacier culminations: > 65 ka (till beneath CP), ca. 65 ka (older ages on M1), ca. 32 ka (M2) and ca. 18–15 ka (M3, M6, M8, M9). The cobbles on CP provide a minimum age (ca. 50 ka) for the underlying till; we also assume that the till predates deposition of M1 and is thus > 65 ka. The bimodal distribution of ages on M1 suggests an additional advance ca. 39 ka, prior to avulsion of the valley and subsequent deposition of M2. We interpret M2 as the right-lateral moraine that marks the maximum extent of ice (local LGM) following the major advance that deposited the till beneath CP. M2 was

Results

Sixty 10Be ages indicate that major late-glacial advances deposited the largest lateral moraines in JV and QRV (M3 and M6), and that earlier advances in JV deposited M1 and M2 (Figs 3 and 4; supporting information, Note 2).

In JV, the oldest dated moraines (M1) have a bimodal distribution of ages (ca. 65 ka and ca. 39 ka). The older M1 ages lie within MIS 4, making M1 unique among the numerically dated moraines in the region (e.g. Smith et al., 2005a,b, 2008; Farber et al., 2005; Hall et al., 2009). Ages on M2 are ca. 32–27 ka, with two older outliers (ca. 47 and 42 ka). M3 has a relatively tight span of ages, with an oldest age of ca. 15 ka; the three boulders at the upper end of the left-lateral have ages of 11.8–10.9 ka. M4 has the widest range of ages among the dated moraines, with older outliers of ca. 102 and 30 ka, and five ages ca. 17.7–11.9 ka. Ages on M5 are clustered between 14.3 and 11.1 ka. Our ages on M3, M4 and M5 are consistent with nine 10Be ages from these moraines obtained by Glasser et al. (2009).

In QRV, ages on composite M6 are oldest on the outer left-lateral ridge (ca. 18 ka) and youngest on the inner left-lateral ridge (14.5–8.0 ka); the right-lateral ridges are more tightly clustered between ca. 15.9 and 13.7 ka. M7 has two ages (13.2 and 11.5 ka), while M8 has five, including an older outlier (ca. 53 ka) and four that range between 18.5 and 9.5 ka. The three ages on M9 are 17.9, 13.8 and 12.8 ka. Ages of the three cobbles on CP are ca. 50–41 ka.

Discussion

The 10Be ages from JV, QRV and CP (Figs 3 and 4) indicate at least four palaeoglacier culminations: >65 ka (till beneath CP), ca. 65 ka (older ages on M1), ca. 32 ka (M2) and ca. 18–15 ka (M3, M6, M8, M9). The cobbles on CP provide a minimum age (ca. 50 ka) for the underlying till; we also assume that the till predates deposition of M1 and is thus >65 ka. The bimodal distribution of ages on M1 suggests an additional advance ca. 39 ka, prior to avulsion of the valley and subsequent deposition of M2. We interpret M2 as the right-lateral moraine that marks the maximum extent of ice (local LGM) following the major advance that deposited the till beneath CP. M2 was
partly overridden during emplacement of M3, which culminated ca. 15 ka (or perhaps ca. 18 ka). M4 and M5 probably mark stillstands during relatively rapid retreat from position M3 and are likely correlative with the inner ridges of M6, whereas the outer ridges of M6 are likely correlative with M3. M8 and M9 may also be correlative with M3 and M6, and M7 with M4 or M5. Our data do not indicate a major Younger Dryas advance, in contrast to the interpretation of Glasser et al. (2009).

The absence of ages close to the global LGM (ca. 21 ka) suggests that if an advance culminated at that time any resulting moraines were subsequently overridden during more extensive late-glacial advances. Relative probability plots of \(^{10}\)Be ages on M1–M9 and CP (Fig. 4; supporting information, Note 2) highlight the prevalence of late-glacial ages (ca. 18–15 ka). Schaefer et al. (2006) interpreted moraine ages of ca. 17–18 ka from mid-latitude valley glaciers as marking the initiation of deglaciation from the LGM; under that interpretation, the outer ridges of M6, for example, would be included in that group. We interpret moraines M3, M6, M8 and M9 as marking a late-glacial readvance, but cannot rule out the possibility that they mark the end of an LGM advance.

The identification of moraines dating from ca. 32 ka (M2) and ca. 18–15 ka (M3, M6, M8 and M9) is consistent with results from previous studies in the Peruvian Andes (Smith et al., 2005a,b, 2008; Farber et al., 2005; Hall et al., 2009) that indicate an early local LGM and a late-glacial readvance or stillstand (Supporting information, Fig. 2). The pattern, though not the precise interpretation, is similar to that seen by Bromley et al. (2009) in southern Peru. Although NJR lacks the large, morphologically distinct, pre-MIS 5 moraines identified elsewhere in the region (Smith et al., 2005a,b, 2008; Farber et al., 2005), the presence of till on CP indicates that at least one older glacial advance was far more extensive than those of the last glacial cycle.

In theory, glacier expansion in the tropical Andes is favoured by high summer insolation, which enhances convection in the lowlands and precipitation in the mountains, thus increasing glacier mass balances (Garreaud et al., 2003). A potential correlation between glacier expansion and increased monsoonal activity during high insolation periods has been identified in the Himalayas (Owen et al., 2006). A similar relationship is expected in the Andes, but we find instead (Supporting information, Fig. 1) that NJR glaciers began to

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**Figure 2** Shaded topographic map of NJR study area showing dated moraine crests (M1–M9) and sample locations. Grey arrows indicate likely ice flow directions during glacial advances. Band (lower left) shows observed exposures of diamicton in stream channel; diamicton is interpreted as lodgement till. X and Y indicate cirque X and valley Y discussed in the text. Base map from Google Maps. Inset: photograph of the NJR massif, with Jeullesh Valley at centre; view to east. M1, M2, and M3 lie directly above the corresponding numbers. Older M1 moraines are cross-cut by younger M2 and M3 right-laterals. M3 rises ~150 m from the valley floor. (Photo by Bryan G. Mark). This figure is available in colour online at www.interscience.wiley.com/journal/qrs
retreat from maximum positions during periods of low (ca. 32 ka) and intermediate (18–15 ka) summer insolation (Berger and Loutre, 1991).

The ages of moraines dated in this study are broadly synchronous with Heinrich events (Rashid et al., 2003; Fig. 4; YD and H1–H6), suggesting a possible link. Correlations between Heinrich events, southward movement of the Intertropical Convergence Zone (ITCZ) in the Atlantic Ocean and climatic changes in tropical South America have been noted previously in studies of the Amazon basin and the tropical Andes (e.g. Baker et al., 2001; Jennerjahn et al., 2004; Wang et al., 2004; Zech et al., 2007; Blard et al., 2009; Licciardi et al., 2009). Much of the precipitation in Peru is advected from the Atlantic Ocean and Amazon Basin by easterly winds during the summer (Vuille and Keimig, 2004). Increases in precipitation in the tropical Andes as a result of Heinrich-related southward shifts of the ITCZ may have played a fundamental role in driving glacial advances. The late-glacial advances that produced the largest moraines (M3 and M6; Figs 2 and 3) culminated after H2 and close to H1, and were contemporaneous with major palaeolakes on the Bolivian Altiplano (Plazcek et al., 2006). Formation of palaeolake Tauca (16.4–14.1 ka; Fig. 1) has been linked (Plazcek et al., 2006) both to southward displacement of the ITZC and to enhanced La Niña-like conditions (wet) on the Altiplano related to strong upwelling in the eastern equatorial Pacific (Palmer and Pearson, 2003). While La Niña conditions in central Peru are generally dry, they also tend to be colder than normal, with enhanced trade winds (Rickaby and Halloran, 2005). In combination with increased precipitation associated with H1, the La Niña temperature decrease may have been sufficient to trigger the major moraine-building ice advance that culminated ca. 18–15 ka (Figs 3 and 4). The local LGM advance that culminated ca. 32 ka occurred at a time of low summer insolation (Berger and Loutre, 1991; Supporting information, Fig. 1) and probably lower temperatures. With increased precipitation during H3, the decreased temperatures may have been sufficient to sustain the substantial advance marked by M2 (Fig. 3). The NJR glacial record suggests that the smaller glacial advances prior to the local LGM (Figs 2 and 3) might also have been triggered by Heinrich-related increases in precipitation during colder intervals.

Conclusions

The NJR chronology provides an exceptionally detailed record of glacial fluctuations over the past ca. 65 ka, including the first clear evidence in the region for an ice advance during MIS 4 and confirmation that the last glacial cycle included two major periods of glacier stabilisation and moraine deposition. Our dating indicates that glaciations culminated ca. 65, 32 and 18–15 ka, and that a larger advance occurred prior to 65 ka. The broad correlation between Heinrich events and moraines in the study area suggests a possible causal relationship. Assuming that Heinrich events in the North Atlantic resulted in southward shifts of the ITCZ and associated rainfall bands, the dominant driving force for glacier expansion in the tropical Andes may have been increased precipitation rather than decreased temperature. If future climatic change results in freshwater discharges to the North Atlantic that again shift the ITCZ southward, the tropical Andes might see an increase in precipitation that could produce glacial advances, as long as air temperatures have not warmed beyond levels that can sustain glaciers.
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