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Reply: Late Quaternary deglacial history of the Mérida Andes, Venezuela: response to comment

We welcome the opportunity to respond to Mahaney *et al.*'s critique of our article on the deglacial history of the Venezuelan Andes (Stansell *et al.*, 2005). The source of our disagreement appears to stem primarily from differences in research strategies and methodology. Our work in the Venezuelan Andes employs lake sediment archives that record continuous sedimentary sequences and can be dated using accelerator mass spectrometry (AMS) radiocarbon dating of identifiable terrestrial macrofossils. Mahaney *et al.* focus on temporally discontinuous deposits (moraines and glacial–fluvial sediments) and radiocarbon dates on refractory organic matter that are most likely to yield anomalously old results. The comment of Mahaney *et al.* is fraught with serious misunderstandings of the data we presented, and is thus misleading to readers who have not examined the original data. In our reply, we specifically address their claims regarding: (1) the local timing of the Last Glacial Maximum; (2) the chronology of the late Pleistocene–Holocene transition; and (3) Holocene environmental variability.

Lakes in previously glaciated catchments are excellent recorders of glacial variability because these systems commonly preserve uninterrupted glacio-lacustrine sequences, and contain *in situ* organic matter that can be isolated for ^{14}C dating. Lake sediment cores can also be analysed at high stratigraphic resolution for an array of sedimentological parameters, which in turn can be used to infer environmental changes over a range of timescales. Lithologic transitions in peat bogs that either formed within or directly adjacent to moraines can also date significant movements of a glacier margin. Combined, these types of records are advantageous for dating glacial activity because they are less susceptible to surface processes such as erosion and weathering, and provide broadened perspectives on the attendant climatic conditions prior to, during, and after a given glacial advance.

Local timing of the Last Glacial Maximum (LGM)

Schubert and Rinaldi (1987) radiocarbon-dated a presumed LGM sedimentary sequence at the southern margin of Mesa del Caballo in the Pedregal fan complex. They interpreted the sequence as part of an outwash plain that extended from the terminal and lateral moraines of the El Caballo and La Mucuchache glaciers. A chemically untreated organic sample from 1.5 m above the base of the section yielded a conventional age of 22 750 cal. yr BP (19 000 ^{14}C yr BP), whereas a peat sample immediately below the top of the section yielded an age of 19 960 cal. yr BP (16 500 ^{14}C yr BP).

We recognise that other workers (e.g. Mahaney *et al.*, 2001, 2004; Dirszowsky *et al.*, 2005) have re-analysed the Pedregal fan complex. For example, the sedimentology was described in detail by Dirszowsky *et al.* (2005). However, the chronology in these papers is questionable and not useful for constraining the LGM. All of the recently published dates are on refractory organic matter isolated using a cellulose extraction technique which concentrates refractory carbon, resulting in ages between 47 000 and 60 000 ^{14}C yr BP. These ages include multiple reversals and are at the very edge of interpretability as finite radiocarbon ages; nonetheless, the authors have interpreted them as valid ages. Similar extraction methods for isolating the most refractory organic matter have been shown to produce ages that are much older than the age of deposition (Abbott and Stafford, 1996). Mahaney *et al.* (2001) described and dated palaeosols in the region; however, these data are not relevant to this discussion because the ages presented are all between 48 000 and $>64\,000$ ^{14}C yr BP and predate the LGM by tens of millennia. Mahaney *et al.* (2004) allude to the LGM without refining the chronology of its local expression, and we neither cited this paper in our analysis from lake sediments, nor have reason to believe that the original dates for the LGM reported by Schubert and Rinaldi (1987) have been refined by their recent analyses.

Late Pleistocene–Holocene transition

Our interpretation of Late Pleistocene and Holocene glacial activity in the Mucubají valley is based on multiple sedimentary records, including a recessional moraine bog, a lateral moraine bog, a continuous record from Laguna Mucubají, and palaeoenvironmental evidence from the Mucubají Terrace (Salgado-Labouriau *et al.*, 1977). Our methods utilised multiple proxies, including magnetic susceptibility profiles (Seltzer *et al.*, 2002) and loss-on-ignition (LOI) measured according to standard laboratory protocols (Dean, 1974; Heiri *et al.*, 2001; Boyle, 2004). LOI data were verified against oxidative elemental analysis of organic carbon content. The base of a 10 cm section of lacustrine sediments from the Mucubají recessional moraine bog site dates to 15 730 (15 520 to 15 920) cal. yr BP, and provides a minimum limiting age for ice being restricted far up-valley from its LGM position. The terrace site of Salgado-Labouriau *et al.* (1977) is down-valley of the recessional moraine bog site and contains alternating sequences of interbedded peat, clays and glaciofluvial sediments. The lower ~2.6 m of the 5 m sequence dates between 14 880 and 13 830 cal. yr BP (12 650 and 11 960 ^{14}C yr BP; Salgado-Labouriau *et al.*, 1977), while the sediment lithology implies multiple glacier advances and retreats during this interval. We emphasise that the Mucubají terrace sequence of Salgado-Labouriau *et al.* (1977) shows absolutely no evidence of glacial activity after 13 830 cal. yr BP, in contrast to the bog site reported by Stansell *et al.* (2005). This does not result in a contradiction of findings because the upper 2.6 m of the Mucubají terrace was not dated by Salgado-Labouriau *et al.* (1977) and does not appear to preserve the upper sequence of Holocene age. The ~900 yr earlier age of glacial retreat proposed in the comment by Mahaney *et al.* is based on unpublished data that extrapolates deglaciation ages from dated horizons using average 'early postglacial' sediment accumulation rates. The high clastic input during and following glacial retreat is likely to vary dramatically from site to site, implying that any extrapolation based upon 'average' rates is likely to be, at best, an educated guess. Regardless, a difference in 900 yr for the age of deglaciation does not affect the principal findings in our paper. We also strongly emphasise that only tentative evidence of a Younger Dryas equivalent exists from terrestrial records in the Venezuelan Andes (Salgado-Labouriau, 1989; Weingarten *et al.*, 1991), nor is it conclusive that a widespread cooling event took place in the region during that time (e.g. Rull *et al.*, 2005).

Our interpretation of the timing of deglaciation in the Mucubají valley is corroborated by data obtained elsewhere in the Venezuelan Andes. Radiocarbon-dated deglacial magnetic susceptibility profiles from lake sediments in the Páramo de Piedras Blancas, the Páramo el Banco, and Laguna Negra (adjacent valley to Mucubají) indicate *at least* two phases of widespread glacial recession at the end of the Pleistocene. The first phase occurred immediately prior to 15 010 and 14 250 cal. yr BP, as recorded in Laguna Verde Alta (4215 m) and Laguna Verde Baja (4170 m), respectively. The second phase of deglaciation is recorded in the western Paramo de Piedras Blancas and in the Paramo El Banco, where there is a sharp transition from glaciolacustrine to postglacial organic-rich lake sedimentation in three uninterrupted records. The transition at Laguna Los Locos (4366 m) dates to 9650 cal. yr BP. The transition at Laguna Grande de Los Patos (4185 m) dates to 10 000 cal. yr BP, and the transition at Laguna La Posita (4228 m) dates to 9360 cal. yr BP.

The highest elevations in the southeast-facing Paramo El Banco and Paramo de Piedras Blancas are about 300 m lower than the headwall of the Mucubají valley (4609 m). It is therefore possible that glaciers survived longer in the Mucubají valley relative to the El Banco and Piedras Blancas paramos. In addition, precipitation and cloud cover are much reduced on the slopes of the Paramo El Banco and Piedras Blancas relative to the Mucubají region. Therefore the geographic setting of these slopes probably drove a regional asymmetry in the elevation of glaciers (e.g. Hastenrath, 1985), and may have contributed to a deglacial lag for the higher, northwest-facing regions.

The Laguna Negra site, adjacent to the Mucubají valley, provides supporting evidence for restricted ice in the region at the onset of the Holocene. Laguna Negra (3473 m) is situated at a low elevation relative to the valley headwall (4609 m), and records a lithological deglacial transition at 10 040 cal. yr BP. We agree that the change in sedimentation at Laguna Negra does not necessarily imply that the entire catchment was ice-free, but it strongly suggests that ice was, at best, restricted to the highest elevations of the valley. Likewise, the Mucubají lateral moraine bog indicates that up-valley glacier retreat was almost complete by 10 000 cal. yr BP. A core from this site preserves till capped by peat dating to 9500 cal. yr BP.

We note that these results are directly compatible with the ages for deglaciation obtained in other regions of the northern tropics, including the highlands of Mexico (Vazquez-Selem and Heine, 2004) and Costa Rica (Orvis and Horn, 2000). Thus, they add considerable new data to debates concerning the timing of tropical deglaciation, in relation to the high northern latitudes (Clark, 2002).

Holocene climate and glacial variability

Climate variability in Venezuela during the Late Pleistocene and Holocene has been highly variable as documented by a series of studies (Bradbury *et al.*, 1981; Salgado-Labouriau, 1984; Bradley *et al.*, 1985; Rull, 1998; Curtis *et al.*, 1999; Haug *et al.*, 2001; Rull *et al.*, 2005; Polissar *et al.*, 2006a). However, many of these studies have used pollen stratigraphic analyses at low temporal resolution, making it difficult to compare them directly to the Mucubají sedimentological record. It is noteworthy that inorganic sediment content in Laguna Mucubají is low just prior to 8200 cal. yr BP, after which the values increase until 6250 cal. yr BP. Furthermore there is also an abrupt transition from inorganic silt to peat at 6280 cal. yr BP in the Mucubají recessional moraine bog core. The coincident timing of major transitions at both sites suggests that ice was restricted to the uppermost reaches of the catchment by ca. 6300 cal. yr BP.

The published pollen records from the Venezuelan Andes provide, at best, century-scale integrations of ecosystem development and climate oscillations; short-duration events (e.g. sub-century-scale) cannot be identified. Despite these caveats, 'the known warm period' in the pollen record between ca. 2800 and 2550 cal. yr BP (2690 to 2500 ^{14}C BP; Salgado-Labouriau *et al.*, 1988) indeed corresponds to an overall decrease in clastic sediment content in Laguna Mucubají, punctuated by an abrupt and short-lived increase in sediment around 2760 cal. yr BP. Likewise, the Mucubají record preserves evidence for at least four short-lived glacial advances during the last 400 years, which correspond to the pronounced local expression of the Little Ice Age (Polissar *et al.*, 2006b). It is thus clear that, while broad correspondence between the palynological and sedimentological records exists, only the latter is at present sufficiently resolved to identify the numerous rapid changes that appear to punctuate the Late Holocene glacial and climate history of the Mucubají valley.

The role of seismicity in limnological systems should always be considered; however, the claim that tectonic activity caused the observed sedimentological changes in Laguna Mucubají is not supported by the data. Mahaney *et al.*'s single radiocarbon date bearing on the region's seismic history remains unpublished, so that, without adequate details on the sample's exact stratigraphic context, no meaningful inferences concerning its relevance can be made at this time. Moreover, the available evidence indicates that a strong statistical relationship exists between climate change and the observed Mucubají sedimentological record (Polissar, 2005).

More research using multidisciplinary approaches is still needed in order to refine the timing of cooling and warming events in the northern tropics. Sites with continuous, high-resolution records should be targeted for future fieldwork and improved age control should be emphasised. The evidence gathered to date suggests that the terminal Pleistocene deglaciation of the Northern Hemisphere tropics occurred later than in the Southern Hemisphere, and that multiple cooling events took place in the Venezuelan Andes during the late Holocene, when alpine glaciers developed anew in the highest catchments. Lively discussion is an essential component of any scientific enterprise. We value the different views of Mahaney *et al.* and welcome this opportunity to defend our methods and results. We hope this exchange will both educate readers and further the scientific goal of understanding the timing and causes of environmental change.

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