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Late Quaternary deglacial history of the Mérida Andes, Venezuela

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ABSTRACT: Radiocarbon-dated sediment cores from seven lakes and two bogs spanning the Cordillera de Mérida in the Venezuelan Andes were used to identify and date the regional history of late Pleistocene and Holocene glacial activity. Coring sites were selected at different elevations across a pronounced rain shadow from southeast (wet) to northwest (dry). Sediment lithostratigraphy and magnetic susceptibility, in conjunction with AMS radiocarbon dates on macrofossils and charcoal, were used to constrain deglaciation. The local expression of the Last Glacial Maximum occurred between 22 750 and 19 960 cal. yr BP. On the wetter southeastern side of the Cordillera de Mérida, glaciers had significantly retreated by 15 700 cal. yr BP, followed by several minor glacial advances and retreats between 14 850 and 13 830 cal. yr BP. At least one major glacial readvance occurred between 13 830 and 10 000 cal. yr BP in the wetter southeastern sector of the region. The drier northwest side of the Cordillera de Mérida records initial glacial retreat by 14 240 cal. yr BP. Multiple sites on both sides of the Mérida Andes record a further phase of extensive deglaciation approximately 10 000 cal. yr BP. However, the north-northwest facing Mucubají catchment remained partially glaciated until ca. 6000 cal. yr BP. Deglacial ages from the Venezuelan Andes are consistently younger than those reported from the Southern Hemisphere Andes, suggesting an inter-hemispheric deglacial lag in the northern tropics of the order of two thousand years. Copyright © 2005 John Wiley & Sons, Ltd.

KEYWORDS: northern tropical Andes; climate change; lake sediments; glacial flour; magnetic susceptibility.

Introduction

Understanding the pattern of glacial variability in the high Andes during the late Quaternary is of particular interest to palaeoclimatologists because tropical glaciers are sensitive indicators of climate change, their mass balance being controlled by the combined effects of precipitation, temperature, and solar radiation (e.g. Seltzer, 1992, 1994; Kaser and Osmaston, 2002; Mark and Seltzer, 2005). Additionally, comparison of glacial chronologies between the Northern and Southern Hemisphere Andes allows the spatial pattern of tropical climate change to be assessed, including its relationship to higher latitudes (Clapperton, 2000). Currently, our knowledge of the inter-hemispheric synchroneity of glacial activity in the tropical Andes relies on glacial deposits with limited age control (Seltzer, 2001). However, continued research using lake and bog sediments that archive continuous records of environmental change are improving our knowledge of the timing and extent of glaciation (Seltzer, 1990).

The late Quaternary glacial history of the Southern Hemisphere tropical Andes has been described by several workers (e.g. Rodbell and Seltzer, 2000; Seltzer *et al.*, 2002; Smith *et al.*, 2005), but currently there are limited records from Northern Hemisphere counterparts (Schubert, 1970, 1974; Schubert and Clapperton, 1990). Earlier research in Venezuela documented regional climate during the last glacial–interglacial transition (Salgado-Labouriau, 1980, 1984, 1989, 1991; Bradley *et al.*, 1985; Weingarten *et al.*, 1991; Rull, 1996). However the exact timing and pattern of deglaciation since the Last Glacial Maximum (LGM) remains poorly constrained. In the present study, sediments from seven alpine lakes and two bogs are used to reconstruct the history and chronology of the late Pleistocene–Holocene transition in the Cordillera de Mérida. These deposits have the advantage of containing abundant organic matter that can be exploited for precise radiocarbon dating (Seltzer, 1990). These results build upon previously published results from the region, collectively

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refining the understanding of glacial history since the LGM in the northern tropical Andes.

Study area

The Cordillera de Mérida is located in the Venezuelan Andes, between 8.5 ° and 9 ° N (Fig. 1). The climate of the northern tropics is largely modulated by the position and intensity of the Intertropical Convergence Zone (ITCZ), which follows the seasonal cycle of solar declination. Average temperature in the Cordillera de Mérida varies little seasonally, but diurnal temperature fluctuations may be as much as 20 °C (Schubert and Clapperton, 1990). Moisture in the Andes is derived predominantly from evaporation over the tropical Atlantic and evapotranspiration from the Orinoco River Basin, which is advected to the Andes by easterly trade winds. Precipitation in highly seasonal, with a maximum during the boreal summer and minimum during winter. At altitude, precipitation patterns are also affected by orographic controls and local mountain circulation systems (Pulwarty *et al.*, 1998). A prominent rain shadow influences the distribution of precipitation as moisture becomes concentrated along a southeast to northwest axis along the Mérida Andes. Precipitation data for the study area are available from a station near Laguna de Mucubají, where annual precipitation is ca. 970 mm yr^{-1} (Bradley *et al.*, 1991). Here, the wet season occurs from April to November, peaking in June. At Pico Aguila in the Páramo de Piedras Blancas, located across the Santo Domingo Valley to the north of Mucubají, average precipitation decreases to ca. 790 mm yr^{-1} (Monasterio, 1986).

Kaser and Osmaston (2002) provide a thorough overview of the dynamics that drive tropical glaciation. Generally, precipitation is higher in the inner (equatorial) tropics, making temperature variability and cloudiness the most important factors in regulating glaciation at these latitudes. Glaciers in the outer tropics are sensitive to temperature changes during the wet season but switch to become more sensitive to changes in moisture availability during the dry season. The Mérida Andes are situated on the boundary between the inner and outer tropics. In this region, precipitation is abundant yet seasonal, whereas humidity remains high throughout the year (Azocar and Monasterio, 1980). Glacier regimes in Venezuela therefore appear most similar to the inner tropics, in the sense that mass balance is being primarily controlled by temperature.

LGM and modern glaciers

During the LGM, ice covered approximately 200 km^2 of the Cordillera de Mérida (Schubert and Clapperton, 1990). Modern glaciers occupy less than 2 km^2 and are restricted to the highest peaks in the region (i.e. >4800 m). These glaciers are rapidly retreating, a trend that has been consistent for the last 50 years of observation (Schubert, 1998). Melting is most rapid on southeastern facing slopes that receive the greatest solar radiation (Hastenrath, 1985; Schubert, 1992). The modern freezing altitude (0 °C isotherm) is approximately 4700 m (Schubert, 1998). The lowest modern glaciers extend to ca. 4450 m, and are thus clearly out of equilibrium.

Geology and geomorphology

The glacial geomorphology associated with the LGM in the Mérida region has been described and dated by several workers

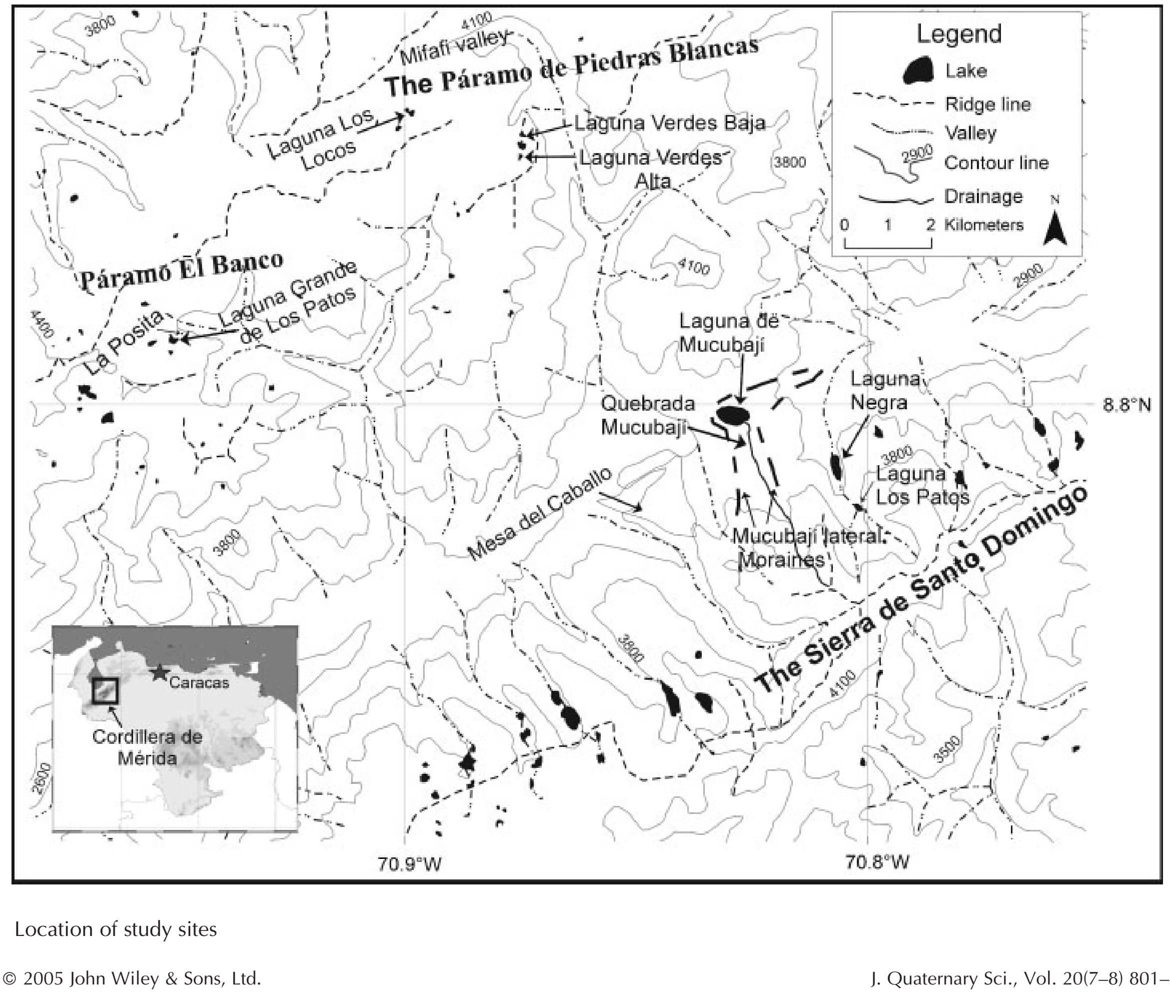

Figure 1 Location of study sites

(Schubert, 1970, 1974, 1992; Giegengack and Grauch, 1973; Schubert and Valastro, 1974; Schubert and Rinaldi, 1987; Schubert and Clapperton, 1990). Two distinct moraine systems have been identified regionally, one restricted to elevations of 2600 to 2800 m, and another between 2900 and 3500 m. The lower glaciation level is demarcated by highly weathered till and continuous vegetation, whereas the upper level is characterised by a less weathered and well-preserved till, and prominent morainic ridges up to a 150 m in local relief (Schubert, 1970, 1974). The fresh appearance of this till led Schubert (1974) to conclude that the upper deposits are attributable to late Pleistocene glaciation. The elevation of these deposits is offset by as much as 500 m between the humid and arid slopes of the moutain range (Schubert, 1975). Additional geomorphic features include cirques, arêtes, horns, glacially sculpted bedrock, erratic boulders and U-shaped valley morphologies (Schubert, 1974). Glacigenic sediments in the region are derived mostly from Precambrian high-grade metamorphic rocks including banded gneiss, schist, and amphibolite, with frequent granitic dikes and quartz veins (Schubert, 1970).

Methods

Site selection and fieldwork

In order to capture a regional deglacial trend, seven lakes and two bogs from a range of elevations were cored and analysed. Lake depocentres were located by sounding with a Garmin® GPS fishfinder. Sediment cores were extracted from the deepest part of each lake using either a modified Livingstone square-rod piston corer (Wright *et al.*, 1984), or a percussion coring system. Sediments were cored with overlapping depth intervals to span breaks between individual drives. The Mucubají recessional moraine bog was cored using a vibra-corer. All core descriptions and lithologies presented here are based on composites of overlapping sections. Cores were transported to the University of Pittsburgh, split, and kept in refrigerated storage at 4 °C.

Sedimentology

Glacial and non-glacial sediments have sharply contrasting sedimentological characteristics. Glaciolacustrine sediment texture is highly variable as it depends on local conditions and the lithology of material supplied (Brodzikowski and van Loon, 1991). Glacial flour is composed of finely comminuted lithic fragments that differ from organic and non-glacial minerogenic lacustrine sediments on the bases of colour, grain-size, and organic content. The primary source material for deposition in glacial lakes is sediment in suspension in glacial meltwater streams (Drewry, 1986), whereas lake sediments in non-glacial environments preserve higher organic contents.

The magnetic susceptibility (MS) of lake sediments is related to the concentration and size of magnetisable minerals contained within a sample (Thompson and Oldfield, 1986). Ferro/ferrimagnetic minerals, such as magnetite, tend to dominate the magnetic properties of lake sediment (Sandgren and Snowball, 2001). Lake sediments may also contain paramagnetic substances which are also moderately magnetisable and include a wide variety of iron-bearing minerals other than magnetite. The bedrock in the study area is largely composed of high-grade metamorphic rocks that weather to sediments that have high concentrations of mica, quartz and clays (Weingarten *et al.*, 1991). Some of these minerals are iron-bearing and are the source for the measured MS signal presented in the core data. Magnetic suceptibility therefore provides a simple first-order proxy for glacially sourced fine-grain sediments (e.g. Seltzer *et al.*, 2002).

Volume magnetic susceptibility (MS) was measured on split cores at 0.2 to 0.5 cm intervals using a Tamiscan automated sediment track and a Bartington high-resolution surface-scanning sensor connected to a Bartington susceptibility meter. After MS measurement, cores were photographed and sampled for measurement dry density, organic content, and biogenic silica (not reported here). Core lithology was determined by smear-slide mineralogy and detailed assessments of Munsell colour, texture, sedimentary structures, and biogenic features. Total and organic carbon were measured either by coulometry, CN elemental analyser, or loss on ignition at 550 °C.

Chronology

Intervals for radiocarbon dating were selected as close as possible to transitions between glacial and non-glacial sediment lithologies. Samples were sieved to isolate charcoal and either terrestrial or aquatic macrofossils for AMS ^{14}C measurements. Radiocarbon ages were converted to calendar ages using CALIB 5.0.1 and the IntCal04 ^{14}C dataset (Stuiver *et al.*, 1998a; 1998b; Reimer *et al.*, 2004). The median calibrated age is reported as well as maximum and minimum ages from the $\pm 1\sigma$ distribution (Table 1). Unless noted, all ages are reported as calendar years BP.

Results

Stratigraphic descriptions and chronological results are presented sequentially for each of three sub-regions that trend from the wet southeast to the drier northeast section of the Cordillera de Mérida. Where appropriate, results of previous investigations are summarised in order to complete the database of available radiocarbon dates pertaining to glacial history.

Mucubají and Negra Valleys

The Mucubají and Negra valleys are part of the Pico Mucuñuque massif, located in the southern range of the Cordillera de Mérida (Figs 1 and 2). In both valleys, the maximum headwall elevation is 4609 m, slightly lower than the modern glaciation level. The only four remaining glaciated peaks in Venezuela have elevations of 4979 m (Pico Bolívar), 4922 m (Pico La Concha), 4942 m (Pico Humboldt) and 4883 m (Pico Bonpland). The presence of Little Ice Age moraines in the Mucubají cirque (Polissar *et al.*, 2005) indicates the sensitivity of this catchment to Holocene glaciation. The Mucubají cirque is oriented NNW, while the Negra Valley has two cirques, one facing NNE, the other NNW. Precipitation is locally high (ca. 970 mm yr^{-1}) and the region experiences pervasive cloudiness cover throughout the year, even during the winter dry season.

The morphology of the Mucubají Valley consists of a cirque basin near the headwall with prominent lateral moraines extending down-valley. The lateral moraines curve sharply to the northeast at Laguna de Mucubají, then follow the axis of

Table 1 Radiocarbon ages used to characterise the late Quaternary deglacial history of the Venezuelan Andes

Location	Lat. (° N)	Long. (° W)	Elev. (m)	Sample	Laboratory no.	^{14}C yr BP	±	Median calibrated age (cal. yr BP)	1σ min–max
Mucubají recessional moraine bog	8.784	−70.82	3615	Peat	CAMS-104914	5470	35	6280	6217–6301
Mucubají recessional moraine bog	8.784	−70.82	3615	Aquatic macros	CAMS-104915	13270	80	15 730	15 523–15 925
Mucubají lateral moraine bog	8.785	−70.82	3620	Peat	CURL-4976	8500	50	9500	9483–9532
Laguna de Mucubají	8.797	−70.83	3577	Aquatic moss	AA-35204	635	45	610	559–659
Laguna de Mucubají	8.797	−70.83	3577	Aquatic moss	AA-35205	2640	45	2760	2735–2788
Laguna de Mucubají	8.797	−70.83	3577	Aquatic moss	CAMS-96811	5455	40	6250	6212–6296
Laguna de Mucubají	8.797	−70.83	3577	Aquatic moss	CAMS-96813	7380	100	8200	8054–8328
Laguna Negra	8.783	−70.81	3473	Aquatic macros	CAMS-104916	8910	40	10 040	9934–10171
Laguna Verdes Alta	8.853	−70.87	4215	Terrestrial macros	AA-35203	12 270	150	14 250	13 954–14 570
Laguna Verdes Baja	8.859	−70.87	4170	Terrestrial macros	CAMS-73092	12 740	130	15 010	14 794–15 244
Laguna Los Locos	8.863	−70.9	4366	Charcoal	CAMS-100728	8690	60	9650	9549–9700
Laguna Grande de Los Patos	8.813	−70.95	4185	Aquatic macros	CAMS-99457	8880	60	10 000	9909–10157
Laguna La Posita	8.813	−70.95	4228	Aquatic macros	CAMS-96819	8350	60	9360	9300–9448

the Santo Domingo Valley. Three sites in the Mucubají Valley and one in the Negra Valley were cored and dated. These sites are described sequentially in order of increasing distance from the Mucubají Valley headwall.

Mucubají recessional moraine bog

A series of at least four recessional moraines are dissected by Quebrada Mucubají, and appear to have formed during up-valley retreat in the Mucubají Valley (Schubert, 1970). A series of lacustrine and peat deposits formed behind these moraines during this retreat. A 580 cm long vibra-core was recovered from the centre of the valley behind the uppermost recessional moraine (Fig. 2).

The basal 30 cm of the core contains poorly sorted glacial till with gravel- to silt-sized material. Overlying the till (550 to 380 cm), the sediments fine upward and are characterised by 1 to 5 cm thick bands composed of coarse sand to silt-sized material with low organic matter content (<1%). The sediments between 380 and 230 cm are thinly-bedded (1 to 2 cm) silt and sand that fine upwards and have high magnetic susceptibility (MS). A 10 cm thick interval between 230 and 220 cm contains relatively organic-rich (10% to 15%) and laminated (1 to 2 mm) clays with low MS (Fig. 3). A macrofossil at the base of this unit (229 cm) was AMS radiocarbon dated at 15 730 (15 520–15 920) cal. yr BP. The upper contact of this fine-grained, organic matter-rich unit grades into a more thickly bedded (1 to 2 cm), coarse-silt unit with low organic matter content (<5%) and high MS. At 170 cm there is an erosional truncation from this coarse section into an organic-matter-rich section with low MS. A macrofossil 3 cm above this transition (167 cm) yielded a date of 6280 (6220–6300) cal. yr BP documenting the onset of organic sedimentation and the disappearance of glacier ice from the watershed.

Mucubají terrace

Holocene normal faulting along a minor fault within the Boconó Fault Zone exposed a 5-m terrace of interbedded peat, clays and fluvial glacial deposits (Fig. 2). This terrace is located down-valley from the Mucubají recessional moraine bog core and was sampled and dated by Salgado-Labouriau *et al.* (1977). Conventional radiocarbon ages on the interbedded peats document rapid sediment accumulation between 14 880 (14 630–15 140) and 13 830 (13 730–13 930) cal. yr BP (12 650 ± 130 and 11 960 ± 100 ^{14}C yr BP) and indicate the location was ice-free in this interval.

Mucubají lateral moraine bog

A series of peat bogs formed on the surface of lateral moraines in the Mucubají Valley. The high relief of these moraines suggests that these bogs have been isolated from major erosion or flood events since their inception. A 190-cm core was retrieved from one of these bogs on the easternmost lateral moraine (Fig. 2). At 168 cm depth in the core there is a sharp transition from grey cobbles interbedded with sand to light brown peat (Fig. 4). A macrofossil sample from this transition yielded an AMS radiocarbon date of 9500 (9483–9532) cal. yr BP. The remainder of the core above this transition is pure peat.

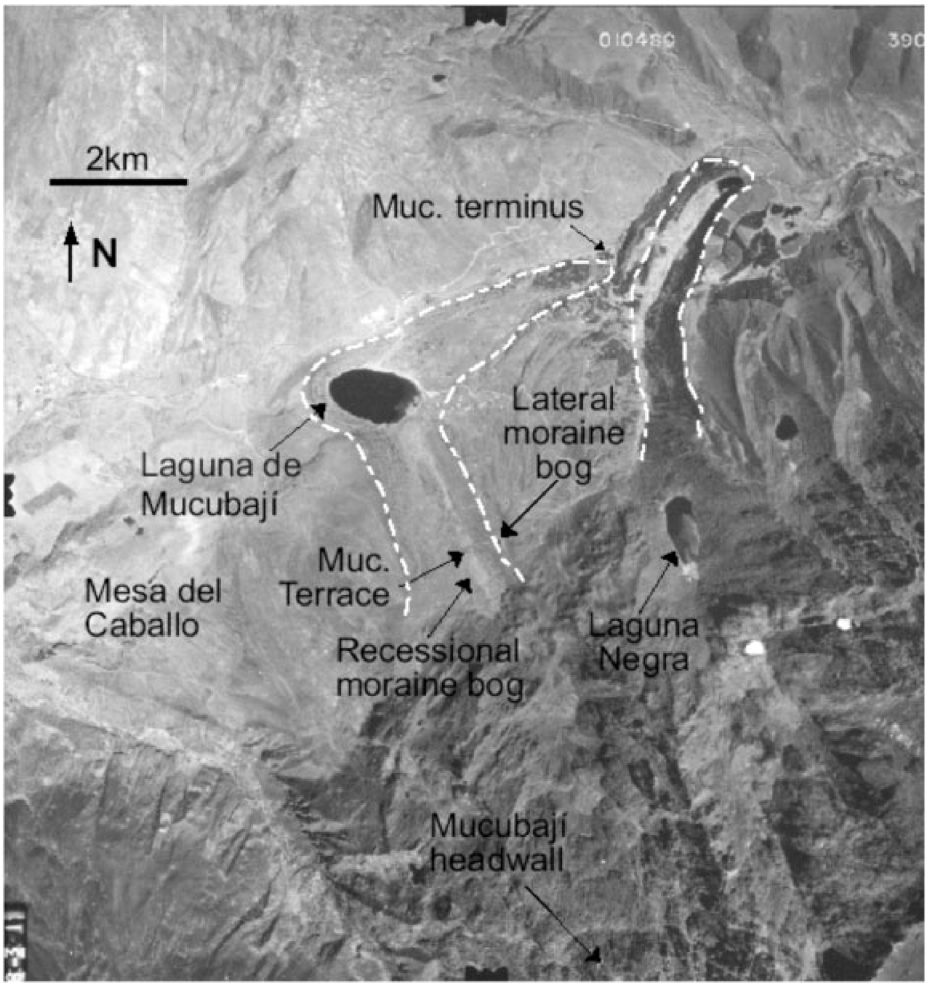

Figure 2 Aerial photograph showing location of study sites in the Mucubají and adjacent valleys. The dashed lines denote lateral and terminal moraine crests that are associated with the most recent (LGM) maximum ice extent

Laguna de Mucubají

Laguna de Mucubají (3577 m) is well situated to record changes in glacial activity in the Mucubají catchment. Dammed by lateral and recessional moraines from the Mucubají Valley, the lake is at a low elevation relative to the headwall, allowing it to remain ice-free when glaciers remain at higher elevations in the catchment. The lake is fed by Quebrada Mucubají, a stream that extends down the valley from the headwall and contributes 80–95% of the lake's inflow (Salgado-Labouriau *et al.*, 1992). There are currently no lakes upstream to trap proglacial sediments, and therefore clastic sediment flux to the lake is an

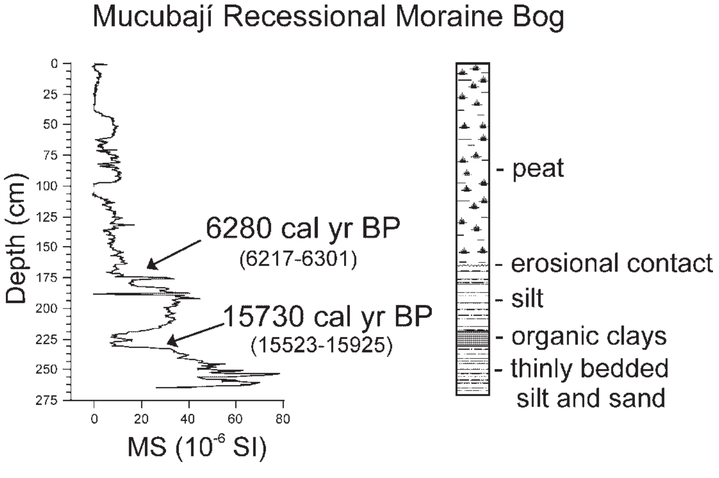

Figure 3 Magnetic susceptibility and stratigraphic profile of the Mucubají recessional moraine bog

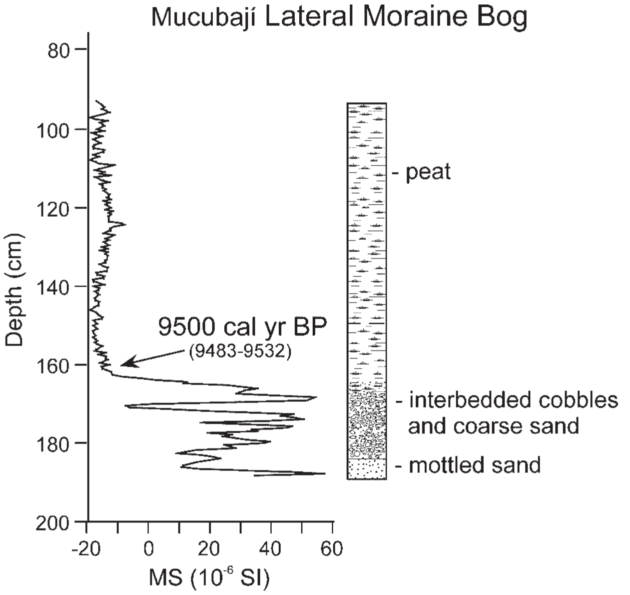

Figure 4 Magnetic susceptibility and stratigraphic profile of the Mucubají lateral moraine bog

unfiltered record of upstream processes. The lake does not have anoxic bottom waters as shown by 3 yr of hydro lab data. It is highly oxygenated with 92% to 98% saturation values.

A 600-cm core was retrieved from the deepest part of the lake. The lower 400 cm of the core comprises fine sand, silt, and clay with relatively high MS and dry density. There is a gradual trend towards finer-grained sediments throughout this section (Fig. 5). The non-biogenic (i.e. clastic) sediment content exceeds 95% between 600 and 400 cm. At ca. 400 cm dry density and clastic sediment content begin to decrease. Unfortunately, there were insufficient macrofossils to date this level. By 240 cm the proportion of clastic sediment decreases to 65%, but thereafter abruptly rises to ca. 90%. An AMS radiocarbon date on aquatic moss at this level yielded a date of 8200 (8050–8330) cal. yr BP (Table 1). The MS, dry density, and clastic content fluctuate for the next 60 cm and then decrease at ca. 180 cm. This decrease occurred closely after 6250 (6210–6270) cal. yr BP. The MS and dry density remain lower until ca. 105 cm when they decrease again, this time to their lowest values in the core. Above 180 cm, the clastic sediment is low but then increases again at ca. 140 cm, then falls above 105 cm to the lowest values in the core. This latter MS drop was AMS radiocarbon dated at 2760 (2735–2788) cal. yr BP. Between 105 and ca. 50 cm the MS, dry density and clastic sediment maintain their low values. At ca. 50 cm all parameters increase and remain high until ca. 10 cm depth where they decrease to low values. The increase at ca. 50 cm is constrained by an AMS radiocarbon date of ca.

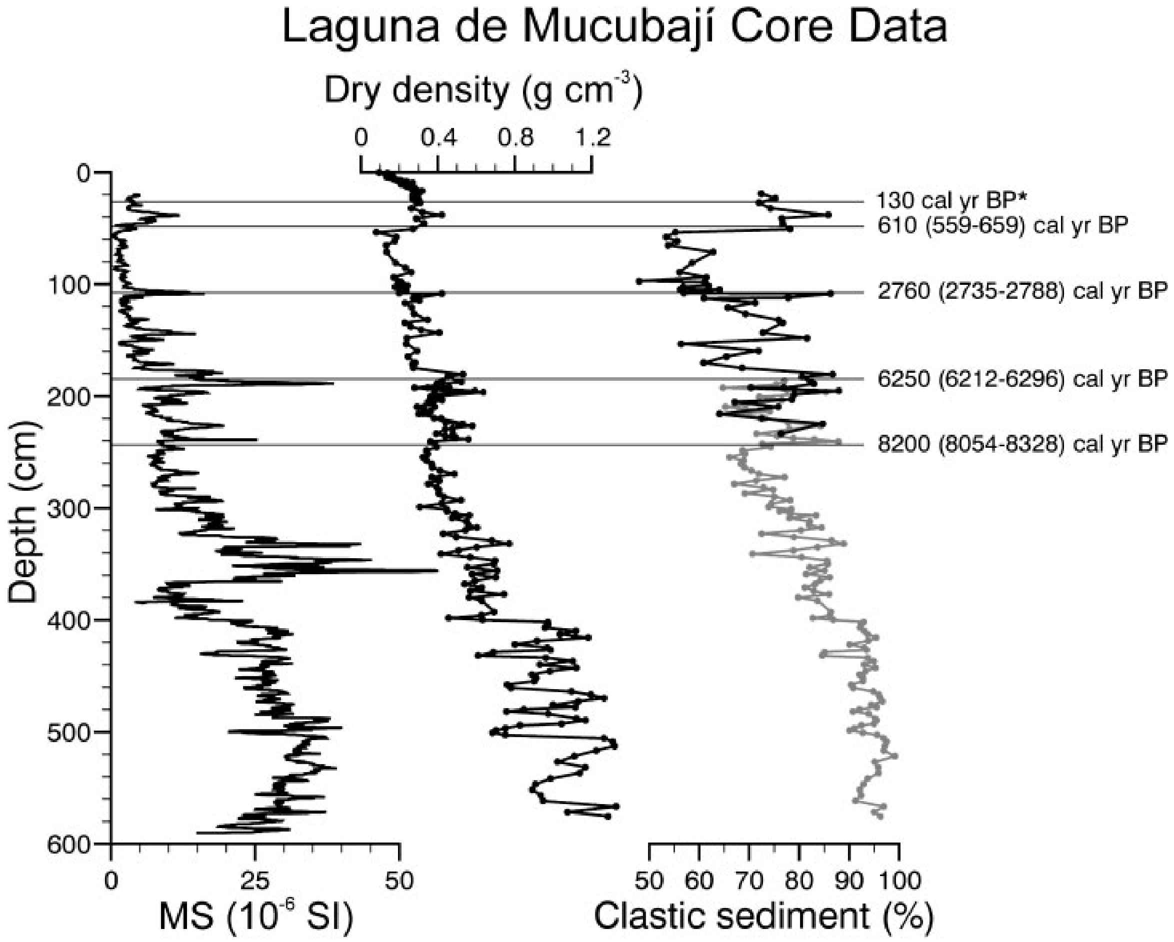

Figure 5 Laguna de Mucubají magnetic susceptibility, sediment dry density, clastic sediment concentration and calibrated radiocarbon ages. The clastic sediment concentration is the total sediment minus the organic matter (OM) and biogenic silica ($bSiO_2$) concentrations. Data in grey is estimated from OM only based upon the relationship between OM and $bSiO_2$ in the upper section of the core ($bSiO_2 = 0.8{*}OM$). The youngest age (*) is interpolated between ^{210}Pb and radiocarbon ages (Polissar *et al.*, 2005)

605 (559–659) cal. yr BP while the age of the decrease at 10 cm is around 130 cal. yr BP based upon interpolation between ^{210}Pb and ^{137}Cs dated near-surface sediments and an AMS radiocarbon age lower in the core (Polissar *et al.*, 2005).

Mesa del Caballo

To the west of Laguna de Mucubají is a small basin situated between the lateral and terminal moraines of the Mucubají Valley and the adjacent valley to the west. The sedimentary sequence in this basin has been dissected approximately 30 m by Quebrada La Cañada, yielding sections that have been described and dated by Schubert and Rinaldi (1987). At the lowest exposed level is a basal till overlain by organic-rich lake sediments. A peat layer within the lake sediments was radiocarbon dated at 22 750 (21 712–23 891) cal. yr BP (19 080 ± 820 ^{14}C yr BP). Above the lake sediments are massive to stratified layers of glacigenic clay, sand, and gravel. A second radiocarbon date on peat capping this sequence indicates cessation of proglacial sedimentation by 19 660 (19 392–19 945) cal. yr BP (16 500 ± 290 ^{14}C yr BP). These sediments are interpreted as belonging to an outwash plain fed by the glaciers in the Mucubají and adjacent valleys. An incised stream valley in the Mucubají lateral moraine near the western edge of Laguna de Mucubají is the presumed source for some of the sediment in the Mesa del Caballo section. This stream valley is currently stranded above the lake and would only be active when the Mucubají glacier filled the lower reaches of the valley and prevented meltwater from reaching the lower elevation stream outlets to the east.

Laguna Negra

The Laguna Negra catchment is situated in the first valley immediately to the east of Mucubají. The valley contains two cirques with northwest and northeast aspects. Below these cirques is a narrow, steep-walled valley where Laguna Negra (3473 m) is situated on a small plateau that overlooks the Santo Domingo Valley. A 520 cm core was retrieved from the deepest part of Laguna Negra. The sediments record an abrupt transition at ca. 380 cm from glacially derived inorganic silt and clay to organic-rich sediments for the remainder of the core (Fig. 6). Macrophytes at this transition yielded an AMS radiocarbon date of 10 040 (9934–10 171) cal. yr BP.

Páramo de Piedras Blancas

The Páramo de Piedras Blancas is located in the northern range of the Cordillera de Mérida, across the Santo Domingo Valley from Laguna de Mucubají (Fig. 1). Schubert (1974) identified a single level of glacial deposits in the Páramo de Piedras Blancas that he attributed to the latest Pleistocene glaciation. In contrast to the Sierra de Santo Domingo, these deposits do not extend below elevations of ca. 3400 to 3700 m. This is probably the consequence of relatively drier conditions and reduced cloud cover on the dry side of the rain shadow. Within the major morainic loops are numerous minor moraines representing minor stillstands or readvances (Schubert, 1974). The limited extent of lateral moraines suggests that LGM glaciation was restricted to alpine ice caps with small outlet valley glaciers. This contrasts the extensive valley glaciation that occurred in the Sierra de Santo Domingo region. Three lakes were cored to determine the glacial history of this region.

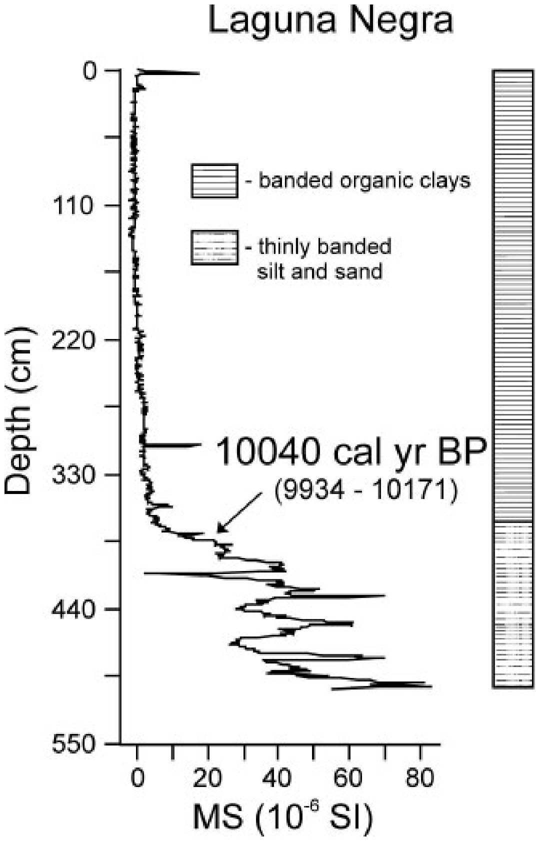

Figure 6 Magnetic susceptibility and radiocarbon ages from Laguna Negra

Laguna Verdes Alta and Baja

Laguna Verdes Alta (4215 m) and Baja (4170 m) are small lateral moraine-dammed lakes located in a tributary to the main valley (Quebrada Mifafi) in the Páramo de Piedras Blancas region (Fig. 1). Sediment cores were retrieved from the deepest part of each lake. Cores from both lakes contain almost entirely organic sediments with coarse-grained glacial silts at their base (Fig. 7). Terrestrial macrofossils directly above the inorganic–organic transition yielded AMS radiocarbon dates of 14 250 (13 950–14 570) and 15 010 (14 790–15 240) cal. yr BP from Lagunas Verdes Alta and Baja, respectively.

Laguna Los Locos

Laguna Los Locos (4366 m) is situated on a broad upland near the head of Quebrada Mifafi (Fig. 1). During the LGM an ice cap was present on this upland and numerous lakes formed upon its disappearance. The Laguna Los Locos watershed is very small, essentially consisting of the lake basin itself. There are no major inflows into the lake and it is fed primarily by precipitation and surface flow. A 270-cm core was retrieved from the deepest part of the lake and preserves an abrupt transition from high MS, grey inorganic silts to organic lake sediments at 246 cm (Fig. 7). The organic fraction immediately above the silt sequence did not yield enough organic material to isolate for dating purposes. Therefore, a 4-cm core increment 3 cm above the glacial–interglacial transition was sieved and charcoal was concentrated, yielding an AMS ^{14}C date of 9650 (9549–9700) cal. yr BP.

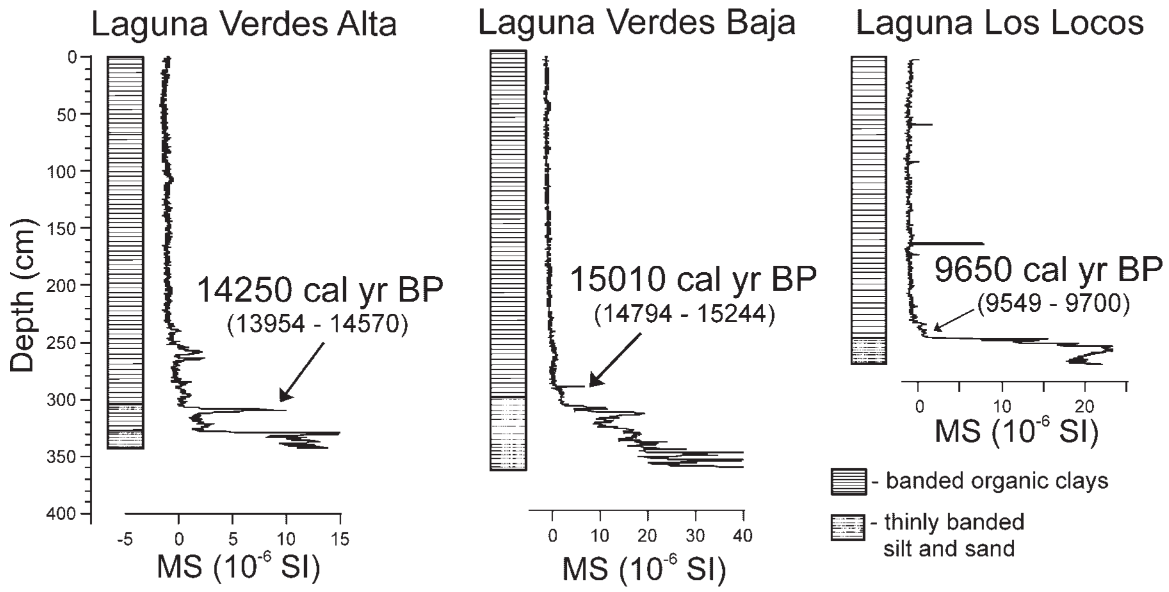

Figure 7 Magnetic susceptibility and radiocarbon ages from Laguna Verdes Alta and Baja and Los Locos

Páramo el Banco

The Páramo el Banco is located immediately west of the Páramo de Piedras Blancas. Glaciation in this region was primarily by ice caps on relatively flat uplands which fed small valley glaciers. Two lakes located on the upland surfaces were cored to determine the glacial history.

Laguna Grande de Los Patos

Laguna Grande de Los Patos (4185 m) is a lake ca. 10 m deep situated high on a plateau. The catchment of the lake consists of the lake itself and the shallow slopes of the basin it occupies. A 380-cm sediment core was retrieved from the deepest part of the lake. This continuous sedimentary sequence contains a sharp transition from glacial silt to organic sediment at ca. 330 cm (Fig. 8). Terrestrial macrophytes from just above this transition were AMS radiocarbon dated at 10 000 (9910–10 160) cal. yr BP. Approximately 5 cm above this organic layer is a 3 cm thick interval of inorganic silt-sized clastic material. This interval is followed by non-glacial sediments for the remainder of the core. Both transitions are recorded in the magnetic susceptibility profile, indicating high values during increased silt accumulation and low values for the remainder of the core which contains organic-matter-rich sediments.

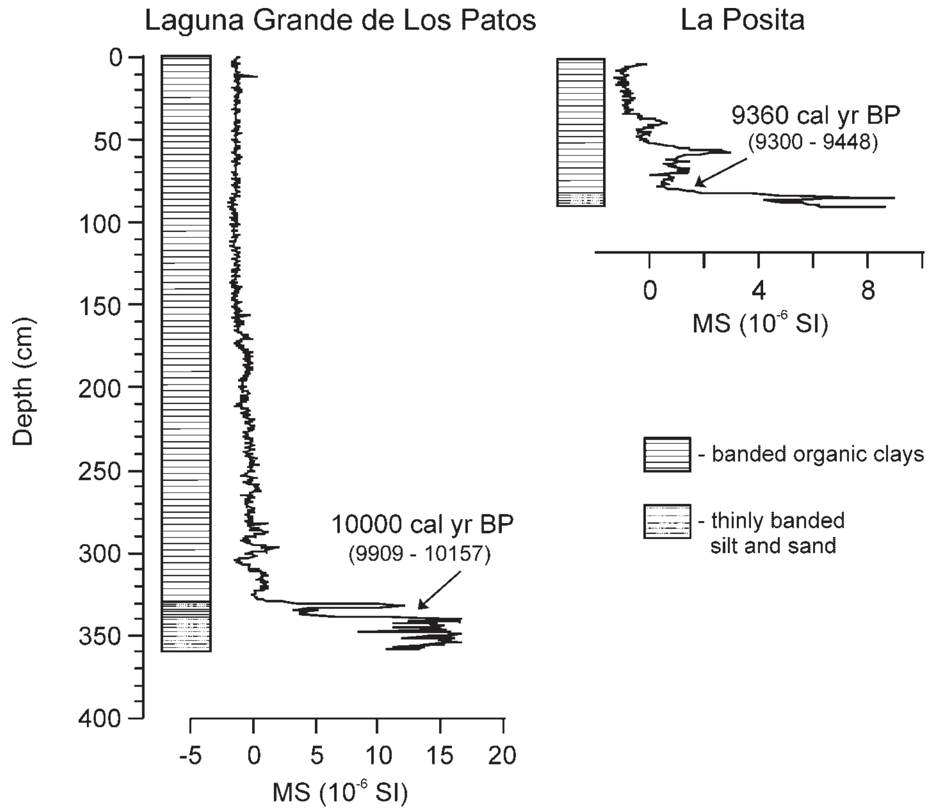

Figure 8 Magnetic susceptibility and radiocarbon ages from Laguna Grande de Los Patos and Laguna La Posita

Laguna La Posita

Laguna La Posita (4228 m) is approximately 300 m east of Laguna Grande de Los Patos. It is a small (ca. 0.1 km^2) lake with a water depth of ca. 2 m. The entire sediment record was collected in a single 130 cm long percussion core. The sediments show an abrupt transition from light grey glacial silt to very fine-grained, organic-rich clay deposits at ca. 80 cm (Fig. 8). A radiocarbon date on a macrofossil just above this transition yielded an age of 9360 (9300–9450) cal. yr BP.

Discussion

Glacial chronology

Mucubají and Negra Valleys

The most complete data pertaining to the glacial chronology of the Cordillera de Mérida come from the Mucubají Valley. The lower radiocarbon date from the Mesa del Caballo indicates that the Mucubají and adjacent valley glaciers reached their recent maximum extent around 22 750 cal. yr BP (Fig. 9). This position was maintained until at least 19 660 cal. yr BP, when deposition of the Mesa del Caballo outwash sediments ceased and the Mucubají glacier retreated up-valley from its maximum position. The glacier had retreated high enough in the valley by 15 730 cal. yr BP to expose the recessional moraine bog coring site, allowing incipient organic sedimentation at this location. A fluctuating up-valley ice position was maintained between 14 850 and 13 830 yr BP, when interbedded peats and outwash sediments were deposited at the Mucubají terrace location. The Mucubají terrace sequence records alternating sections of peat, clay, and fluvio-glacial sediments (Salgado-Labouriau *et al.*, 1977), with no evidence of erosion by subsequent glacial readvances.

The position of the glacier front is not as well constrained between 13 830 and 9500 cal. yr BP. However, the inorganic-peat transition in the Mucubají lateral moraine bog core indicates an ice-proximal position for this location prior to 9500 cal. yr BP. This suggests a re-advance of ice down-valley of the Mucubají terrace some time after 13 830. Supporting

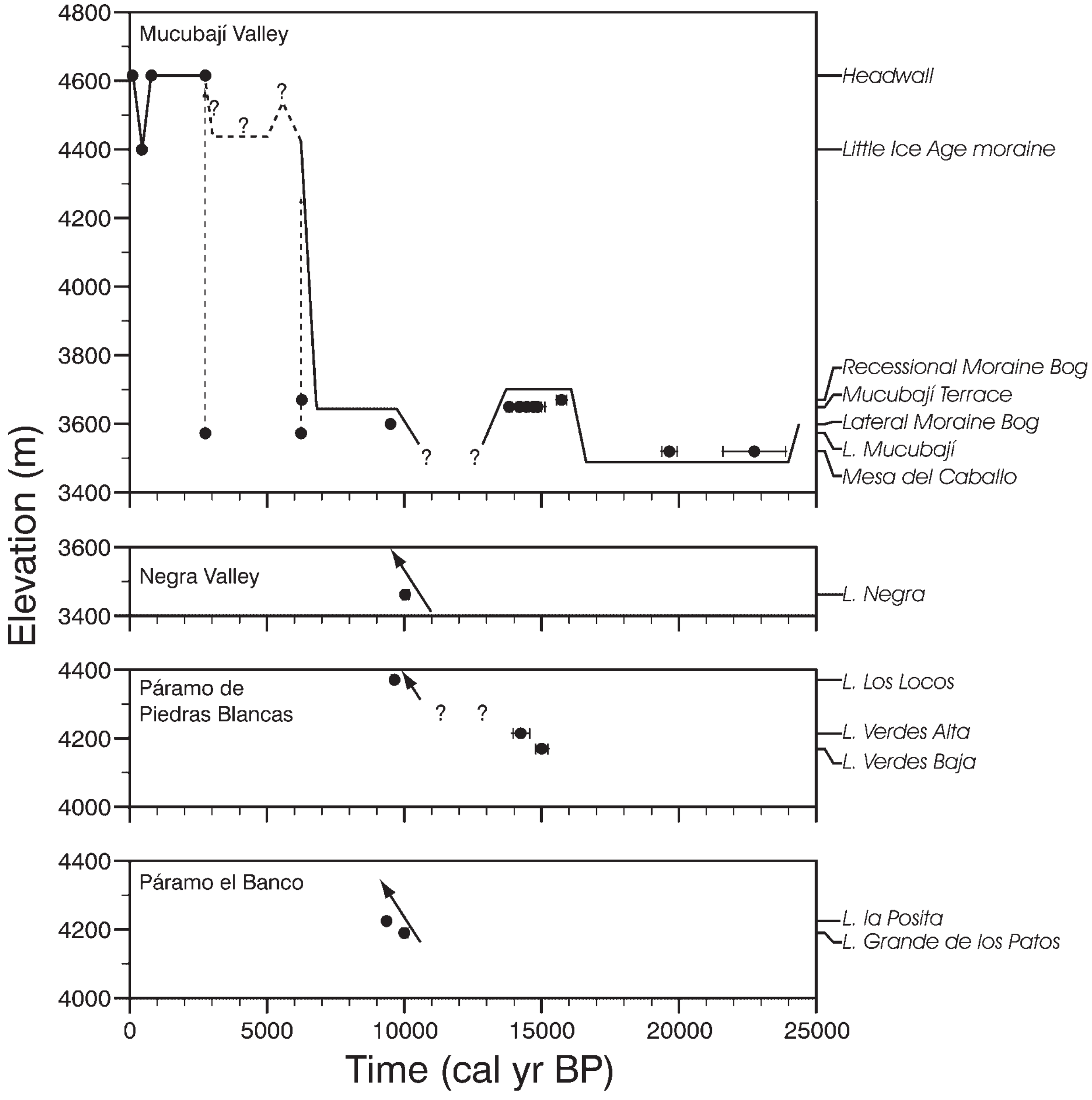

Figure 9 Summary of the late Quaternary glacial chronology in the Venezuelan Andes. Vertical dashed lines in upper panel indicate inferences on approximate glacier position from Laguna Mucubají sediments

evidence for a glacial advance in this region comes from the adjacent Laguna Negra Valley, which indicates ice at a low elevation (ca. 3500 m) at ca. 10 000 cal. yr BP. Combined, these data suggest a readvance of ice down-valley of the Mucubají terrace sometime after 13 830 and before 9500 cal. yr BP. Following this readvance, ice retreated up-valley of the Mucubají lateral moraine bog site around 9500 cal. yr BP. The decrease in clastic sediment in Laguna de Mucubají prior to 8200 cal. yr BP may reflect this retreat. The glacier retreated up-valley of the recessional moraine bog site by 6280 cal. yr BP. This age coincides with decreases in the MS, dry density and clastic content of Laguna de Mucubají sediments after 6250 cal. yr BP.

It is unclear exactly when the Mucubají watershed first became free of glacial ice during the Holocene. The generally lower values of MS, dry density and clastic content in Laguna de Mucubají sediments younger than 6250 cal. yr BP (180 cm) may indicate much reduced glacier cover in the catchment. However, these low, but fluctuating values could also reflect non-glacial processes in a recently deglaciated catchment. If a glacier was still present in the valley, then the increase in clastic sediment between ca. 150 and 105 cm may indicate a minor readvance. Low MS values in Laguna de Mucubají above 105 cm indicates the catchment was most likely ice-free by 2760 cal. yr BP. Thus, the Mucubají glacier was either very small after 6250 cal. yr BP and had disappeared by 2760 cal. yr BP, or the glacier disappeared around 6250 cal. yr BP and catchment erosion led to fluctuating clastic sediment concentrations after this time.

Glacial ice was re-established in the Mucubají watershed around 605 cal. yr BP and remained active for the following 475 years. This period corresponds with the Andean expression of the Little Ice Age (Polissar *et al.*, 2005). The Mucubají watershed became ice-free again approximately 130 years ago, and has remained unglaciated since.

Much less information is available from the adjacent Negra Valley. However, the transition from glacial to organic-matter-rich sediments indicates the glacier was absent from the lower portion of the catchment by 10 040 cal. yr BP. This date coincides with a period of up-valley retreat by the Mucubají glacier and suggests a regionally expressed interval retreat of glacier termini. Input of glacial sediments into Laguna Negra ceased around 10 040 cal. yr BP, nearly 4000 yr earlier than Laguna de Mucubají. It is possible that glaciers remained in the Negra Valley during the early Holocene, but were greatly reduced and hence restricted to higher elevations. In addition, there is a small tarn situated above Laguna Negra that may have trapped sediment upstream of Laguna Negra.

Páramo de Piedras Blancas and Páramo El Banco

The radiocarbon ages from the Páramo de Piedras Blancas and Páramo El Banco suggest at least two major phases of glacier recession, similar to the Mucubají Valley. The first period occurred just prior to ca. 15 010 and 14 250 cal. yr BP and is documented in Laguna Verdes Alta and Baja. In these lakes, the transition from glacigenic to organic lake sedimentation indicates recession of the ice cap which fed the adjacent valley. The second period of recession is constrained by ages on the transition from glacial to organic lake sediments in Laguna Los Locos, Laguna Grande de Los Patos, and Laguna La Posita. These lakes are all located on upland plateaus which were covered by ice caps. Given that these lakes are near the maximum elevations on their respective plateaus, the glacial to non-glacial sediment transition in these lakes indicates complete melting of ice caps between 10 000 and 9360 cal. yr BP.

Regional and global comparisons

Schubert and Rinaldi (1987) dated a series of LGM moraine complexes in the Venezuelan Andes and determined that they formed between 22 750 and 19 960 cal. yr BP. By 15 900 cal. yr BP glaciers had retreated substantially, as recorded by the Mucubají recessional moraine bog. Lagunas Verdes Alta and Baja, across the valley on the drier aspect of the Cordillera de Mérida, record glacial retreat from a maximum position by 14 240 cal. yr BP. This coincides with an oscillating ice front in the Mucubají Valley between 14 340 and 13 970 cal. yr BP (Salgado-Labouriau *et al.*, 1977).

While glacial activity between 14 000 and 10 000 cal. yr BP in the Venezuelan Andes remains somewhat unclear, existing palaeoenvironmental records may provide some insights regarding palaeoclimate. Increased organic matter sedimentation in Lagunas Verdes Alta and Baja suggests that between 13 900 and 12 700 cal. yr BP climate was relatively warm and dry (Polissar, 2005). This coincides with the Mucubají warm phase (Salgado-Labouriau, 1989; Rull, 1999) and with warmer and drier conditions recorded at lower elevation sites, such as Laguna Valencia (Bradbury *et al.*, 1981; Weingarten *et al.*, 1991; Curtis *et al.*, 1999).

As mentioned earlier, temperature is likely to be the dominant control over modern glacier mass balance in the Venezuelan Andes, given abundant precipitation. This model is likely to remain applicable to past glacial events. For instance, favourable conditions for glacial advances occurred between 12 500 and 10 200 cal. yr BP, implying a return to colder conditions. This is recorded at Laguna Los Lirios (Weingarten *et al.*, 1991) and Laguna de Mucubají, where temperatures are estimated as having been 2 to 3 °C cooler, based on pollen assemblages (Salgado-Labouriau, 1989). The northern tropics experienced relatively warm and wet conditions from 11 500 to 5400 cal. yr BP (Haug *et al.*, 2001). During this interval, most catchments in the Venezuelan Andes became ice-free. This suggests that changes in temperature drove glacier variability in the region, rather than moisture availability.

Regional deglaciation records from other northern tropical locations are limited, but in general express similar trends to the Venezuelan Andes. Deglacial records from Cerro Chirripo in Costa Rica have a cluster of radiocarbon dates centred on ca. 9700 cal. yr BP, indicating a minimum age for ice retreat (Orvis and Horn, 2000). In Colombia, moraine complexes in the eastern Cordillera date between 15 300 and 14 300 cal. yr BP (Helmens, 1988), whereas dated glacial advances elsewhere in Colombia occurred at 11 400 and 8300 cal. yr BP (Thouret *et al.*, 1996). Ecuadorian deglaciation occurred between 14 000 and 9000 cal. yr BP (Heine and Heine, 1996). A series of recessional moraines on volcanoes in Mexico suggest that local deglaciation was underway between 11 000 and 10 000 cal. yr BP (Vazquez-Selem, 2000).

On the other hand, the Southern Hemisphere tropics appear to have a different chronology of glacial events than the northern tropics during the Late Pleistocene–Holocene transition. A series of minor glacial advances occurred between ca. 16 000 and 13 000 cal. yr BP in Peru and Bolivia (Mercer and Palacios, 1977; Clayton and Clapperton; 1997; Rodbell and Seltzer, 2000; Goodman *et al.*, 2001; Seltzer *et al.*, 2002). The last of these culminated at ca. 12 800 cal. yr BP (Rodbell and Seltzer, 2000; Seltzer *et al.*, 2002). Smith *et al.* (2005) show evidence of rapid deglaciation in central Peru shortly after 15 000 cal. yr BP.

The dates presented here from the Cordillera de Mérida are primarily minimum limiting ages for deglaciation in the Venezuelan Andes. It should be noted, however, that with the exception of the Mucubají recessional moraine bog core, the sequences presented here record very rapid transitions from glacial to non-glacial environments, which suggests that actual deglaciation closely pre-dates the radiocarbon-dated intervals. Precipitation was unlikely to be a limiting factor to glacier growth because the northern tropics experienced relatively wet conditions after 12 000 cal. yr BP (Salgado-Labouriau *et al.*, 1977; Salgado-Labouriau, 1984; Thouret *et al.*, 1996; Lachniet and Seltzer, 2002), and remained so until the mid-Holocene (Haug *et al.*, 2001). More work is clearly needed and is currently in progress to refine the deglacial chronology of the Venezuelan Andes for a more detailed comparison with the Southern Hemisphere. However, from the available data presented here it appears that glaciers persisted longer in the Northern Hemisphere Andes relative to southern counterparts, and that the last major phase of regional deglaciation lagged that of the Southern Hemisphere Andes by at least two thousand years.

Summary and conclusions

The LGM in the Venezuelan Andes occurred between 22 750 and 19 660 cal. yr BP. After 19 660 cal. yr BP, glaciers began to recede from their maximum positions and had retreated substantially by ca. 15 730 cal. yr BP. There is evidence of a late Glacial readvance in the Mucubají Valley between 13 800 and 10 000 cal. yr BP. Records from both wet and dry sides of the Venezuelan Andes indicate regionally ice-free conditions in most catchments by 10 000 cal. yr BP. The major phase of regional deglaciation is centred at 10 000 cal. yr BP. This corresponds to the warmest and wettest interval of the Holocene for the northern tropics, most likely driven, ultimately, by higher-than-present insolation. These results emphasise the key role of temperature in regulating glacier extent in the Northern Hemisphere tropics. Exceptionally, the NNW-facing Mucubaji catchment retained ice considerably longer, becoming ice-free either by 6250 or 2760 cal. yr BP. A small glacier re-formed in this catchment during the northern Andean expression of the Little Ice Age (650 to 125 cal. yr BP). Radiocarbon ages from the Venezuelan Andes that record the transition to ice-free conditions are consistently younger than those reported from the Southern Hemisphere Andes, suggesting an inter-hemispheric deglacial lag in the northern tropics of the order of two thousand years.

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