LAST GLACIAL MAXIMUM EQUILIBRIUM-LINE ALTITUDE RECONSTRUCTIONS, PALEO-TEMPERATURE ESTIMATES AND DEGLACIAL CHRONOLOGY OF THE MÉRIDA ANDES, VENEZUELA

by

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The magnitude and underlying cause of glacial variability in the Venezuelan Andes during the late Quaternary are investigated in order to better understand tropical climate and its forcing mechanisms. Paleo-glaciers were mapped using field observations, aerial photographs, satellite imagery and high-resolution digital topographic data. Paleo-glacier equilibrium-line altitudes (ELAs) were reconstructed using the accumulation-area ratio (AAR) and the area-altitude balance ratio (AABR) methods. During the local Last Glacial Maximum (LGM) in Venezuela (~20,600 to 17,800 cal yr BP), ELAs were ~870 to 1420 m lower. Paleo-temperature estimates were calculated for the northern Sierra de Santo Domingo region which had a ΔELA of -980 m. Using a combined energy and mass-balance equation (Kuhn, 1989) it appears that temperatures were at least 8.8 ± 2°C cooler than today. This is greater than that estimated by an atmospheric lapse rate calculation, which yields a value of 6.4 ± 1°C cooler. The paleo-ELAs presented here are consistent with other northern tropical sites and the maximum estimates from southern tropical/sub-tropical Andean records. Our paleo-temperature results, based on estimates that take into account the total energy budget across a glacier's surface, are greater than Porter's (2001) overall tropical average of 5.4 ± 0.8°C cooler temperatures during the LGM using an atmospheric lapse rate calculaion. The pattern of the LGM gradient in ELA values of Venezuela is consistent with the modern precipitation and cloud cover patterns suggesting similar moisture sources and circulation patterns at both times.

The regional deglacial history is characterized using lake sediments and bog deposits. Analyses include AMS radiocarbon dating, sedimentology studies and magnetic susceptibility on a series of cores from 7 lakes and 2 bogs in the Venezuelan Andes. Results show that by 15,950 cal yr BP, glaciers began to retreat. This retreat was interrupted by at least one readvance between 14,000 and 10,000 cal yr BP. Glaciers rapidly retreated after 10,000 cal yr BP in arid areas, whereas ice remained in north facing humid areas until after 6,200 cal yr BP. The deglacial history of the Venezuelan Andes cannot be attributed to insolation forcing alone and must be combined with changes in temperature and moisture availability.

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1. THESIS INTRODUCTION

The focus of this work investigates the temperature change in the Venezuelan Andes during the Last Glacial Maximum (LGM) and the following deglacial history. The LGM occurred approximately 21,000 cal yr BP, though the exact timing of maximum glaciation around the globe has been found to lead or lag this date by several thousand years. In Venezuela, the LGM was centered closer to 18,000 cal yr BP. During the CLIMAP (Climate Long-Range Investigation Mapping and Prediction) project during the 1970's and 1980's, scientists attempted to reconstruct LGM climate conditions by means of fossil evidence from terrestrial and marine records. The CLIMAP project had major implications for global circulation models (GCM's) and for researches attempting to reconstruct the pattern and timing of global climate change.

The results of CLIMAP remain controversial. For example, glacial geologists find it difficult to reconcile temperature estimates of ~ 1 to 2°C cooler at high elevations with field observations that suggest glacier equilibrium line altitudes may have been 1000 m or lower during the LGM. Reports, such as Porter's (2001), suggest that temperatures at high elevations may have been closer to 5 to 7°C cooler during the LGM. At the time of Porter's synthesis, ELA data from the northern tropical Andes of Venezuela were based on sparse geological evidence. The work presented here provides a more comprehensive evaluation of the LGM glacio-geological evidence and a more thorough paleo-temperature estimate for this region of the northern Andes.

The field area for this project is the Mérida Andes of Venezuela, located between the latitudes of 8.5 and 9.0°N, at elevations above 2900 m. This study focuses specifically on three geographic sub-regions for paleo-glacier analysis based on slope orientation and distance from moisture source. Average monthly temperatures in Mérida remain relatively constant throughout the year and temperatures vary by only about 2°C monthly. On a diurnal cycle, however temperatures can vary by as much 20°C. Precipitation is strongly seasonal and is governed by the seasonal migration of the intertropical convergence zone (ITCZ). This region experiences a summer wet season whereas humidity remains high throughout the year.

A glacier's ELA is sensitive to changes in precipitation and temperature and is therefore a useful recorder of climate change. The ELA is the dividing line at which a glacier's mass-balance equals zero. In other words, it is the boundary between a glacier's accumulation and ablation zones. The ELA cannot be directly observed however the ELA can be estimated as being approximately equal to the lower limit of snow and ice following the ablation season. The climate change associated with a change in ELA (ΔELA) can be determined when a paleo-ELA is determined.

Paleo-ELAs in this study are determined from paleo-glaciers which were mapped using geomorphic evidence. Mapping techniques in this paper combine field observations with aerial photographs, satellite imagery and Shuttle Radar Topography Mission (SRTM) data. Contours for the surface area for paleo-glaciers are constrained by using a basal shear stress equation which takes into account ice thickness and the ice-bedrock interaction. Modern glaciers have been found to have shear stress values in the range of 50 to 150 kPa (Paterson, 1981). This range of values is used to check the accuracy of contour spacing for paleo-glaciers.

Glacial mapping was aided through the use of high-resolution digital topographic data. Specifically, digital elevation models (DEMs) for Venezuela have been derived from SRTM data. Combined with geographic information system (GIS) software DEMs can be used to determine the surface area of each successive contour range of a paleo-glacier. The surface area values are then entered into a spreadsheet and hypsometric plots are generated.

The ELA can then be estimated from a hypsometric plot by using a variety of methods. The most accurate reconstruction techniques take into consideration the size and shape of the glacier and not just the upper and lower limits of ice. This paper uses the accumulation-area ratio (AAR) and the accumulation-area balance ratio (AABR) methods. The AAR method assumes that the accumulation area of a glacier occupies some fixed proportion of its total surface area above the equilibrium line. The ELA is estimated using an AAR value applied to a hypsometric plot. The AABR method takes into account hypsometry as well a glacier's balance ratio. The balance ratio (BR) is the ratio of the rates of accumulation and ablation at elevation for a given glacier which is determined empirically. The AABR method utilizes a spreadsheet developed by Osmaston (in press).

The proper BR and AAR values for Venezuela are not known because modern glacier mass-balance studies are required in order to determine these values. These studies are not possible in Venezuela because modern glaciers in the Venezuelan Andes are limited to a few high peaks in the region and are melting quickly. These glaciers will most likely be gone within two decades. As a result, AAR and BR values must be estimated theoretically based on observations of existing glaciers in other tropical locations.

In order to determine the causes of mass-balance variability, the individual climate setting of each glacier needs to be determined. Many previous tropical paleo-glacial studies have used glaciers from temperate regions in order to estimate paleo-ELA's. Temperature glaciers behave differently than tropical glaciers and should not be considered as an appropriate comparison.

The tropics themselves are diverse climatologically based on seasonality of precipitation and distance from the equator and should be evaluated carefully. For instance, temperature in Venezuela is relatively constant during the year, precipitation is strongly seasonal and humidity remains high year-round. Understanding the role of these mechanisms in driving glacier variability is critical in order to determine the causes of mass-balance fluctuations and paleo-glaciers need to be interpreted in a regional context.

Paleo-temperatures can be estimated when a ΔELA is known. A ΔELA is determined by comparing the paleo-ELA to the modern ELA. The modern ELA for certain regions of the Venezuelan Andes can be estimated using the existing glaciers on Pico Bolivar which are 4620 to 4680 m a.s.l. The modern ELAs in other regions of the Venezuelan Andes, where glaciers do not currently exist, were estimated using an equation from Greene et al. (2002). This equation estimates an ELA using the modern values for the regional freezing height and precipitation values. This equation is strictly an estimate however as it does not take into consideration local effects such as wind, cloud cover and topography.

The combined results of this study indicated that ELAs were ~ 870 to 1420 m lower in the Venezuelan Andes during the LGM than today. Paleo-temperatures were estimated using the Kuhn (1989) equation which takes into account the energy balance of a glacier's surface area. This is important because many paleo-temperature reconstruction techniques for the tropics have commonly relied on using atmospheric lapse rate calculations. The use of an atmospheric lapse rate calculation assumes that the temperature change associated with a parcel of air rising in the atmosphere is the same as the temperature change that causes a lowering of an ELA. The Kuhn equation takes into consideration such factors as the regional precipitation and humidity gradients and their relationship to the ELA. The temperature change associated with a lower

ELA is greater than what atmospheric lapse rate calculations would estimate when these factors are considered.

The Kuhn equation additionally takes into consideration the temperature change associated with changes in accumulation on the ice surface. Humidity is high and precipitation is abundant in Venezuela. Therefore, glacier mass-balance in this region more sensitive to changes in temperature that precipitation. The results for the Venezuelan Andes during the LGM suggest that changes in precipitation are negligible in order to explain a change in ELA values and changes by up to 50% relative to the modern annual mean only results in less than ± 1°C of the overall required temperature depression.

The interpretation presented here is that glaciation in Venezuela during the LGM was driven mostly by changes in temperature. The results of this study suggest that temperatures may have been by as much as 8.8 ± 2°C lower. This is greater than Porter's (2001) tropical LGM temperature average of ~5.0 to 6.4°C cooler using an atmospheric lapse rate calculation. The estimates presented here are similar to other reports from northern tropical sites and are similar to the upper estimates from the central Andes.

The second half of this work focuses on the timing of deglaciation in the Venezuelan Andes. This is difficult as recurring glacial advances often remove a datable sequence of glacial events. However, certain lakes and bogs are archives of paleo-glacial events and record at least the latest phase of deglaciation. We cored seven lakes and two bogs which span the glacial-interglacial transition and reconstructed a radiocarbon dated time-line of events.

Glacial versus non-glacial sediments were determined by measuring the magnetic susceptibility of the cores. Magnetic susceptibility is governed by the concentration and size of magnetizeable minerals contained in the sediment (Thompson and Oldfield, 1986). The majority of magnetic minerals preserved in lake systems are allogenic (derived from an outside source). Inorganic mineral sediments tend to plot as a high magnetic susceptibility whereas organic materials plot as low values. Sediments can be interpreted as being glacially derived when the majority of the material is inorganic and allogenic. The cores presented here show a sharp transition from glacial to non-glacial sediments and the timing of these events was determined radiometrically.

The timing of deglaciation is important in order to determine the role of various mechanisms in driving climate change in the tropics. For instance, the climate change responsible for warmer conditions in the northern hemisphere following the LGM was likely driven by an increase in insolation values at the top of the atmosphere due to the Earth's orbital configuration. Changes in insolation are gradual and occur over thousands of years. Insolation values in the Venezuelan Andes continued to increase between ~15,900 to the onset of the Holocene at ~10,000 cal yr BP. A glacial readvance occurred during a period of continuously increasing insolation values. This readvance requires another mechanism in addition to insolation in order to explain it, such as a decrease in temperature or an increase in moisture availability. The interplay of these mechanisms in driving glacier variability in the northern tropical Andes is discussed throughout this paper.

2. LAST GLACIAL MAXIMUM EQUILIBRIUM-LINE ALTITUDE AND TEMPERATURE RECONSTRUCTIONS FOR THE CORDILLERA DE MÉRIDA, VENEZUELAN ANDES

2.1. INTRODUCTION

The Last Glacial Maximum (LGM) occurred ~21,000 cal yr BP (CLIMAP 1976, 1981), however the timing of the LGM in specific regions has been found to lead or lag the CLIMAP global average by up to several thousand years (e.g. Mann and Hamilton, 1995; Lowell et al., 1995; Denton et al., 1999; Seltzer et al., 2002). In the Venezuelan Andes, the local LGM occurred between 20,600 to 17,760 cal yr BP (Schubert and Rinaldi, 1987). During this period, glaciers covered ~200 km^2 of surface area and extended down to elevations as low as 2900 m (Schubert and Clapperton, 1990).

The CLIMAP reconstruction of tropical sea surface temperatures (SSTs) led to extensive debate about the true degree of atmospheric cooling that took place in the tropics during the LGM. These data have important implications for global circulation models (GCM's) and for determining the exact role of the tropics in global climate change. CLIMAP proposed that tropical SSTs were 1 to 3°C cooler at sea-level during the LGM. However, glacial-geological evidence suggests that tropical temperatures at higher elevations during the LGM experienced greater cooling than proposed by CLIMAP for sea surface (*e.g.* Porter, 2001). A more refined geographic distribution of paleo-temperature sites is needed in order to reconcile the difference between high and low elevation temperature reconstructions.

Determining the climate change indicated by more extensive glacier coverage in the tropics during the LGM is a challenging paleoclimatological issue. Using the glacier equilibrium-line altitude (ELA, the dividing line between the accumulation and ablation zones) as a measure of glacial extent, it is possible to model the modern glacial response to climate change (Hastenrath, 1984; 1989; Ames and Francou, 1995; Francou et al., 1995; Kaser, 1995; Kaser and Noggler, 1996; Oerlemans, 2001; Kaser and Osmaston, 2002). However, the climate change associated with alpine glaciations during the LGM is difficult to gage because the associated meteorological conditions are more uncertain. Therefore, glacial geologists commonly rely on simple and questionable atmospheric lapse rate calculations to estimate the temperature change responsible for an ELA lowering. These calculations do not accurately represent the energy exchange at the glacier surface, including the partitioning of sensible and latent heat loss and ignore the effects of changes in accumulation (Seltzer, 1992). As an alternative, models that combine energy and mass-balance equations should be used in order to reconstruct the temperature change associated with an ELA lowering (Kuhn, 1989; Seltzer, 1994). These models take into consideration the effects of changes in accumulation on paleo-temperature reconstructions as well as the energy exchange across a glacier's surface.

The mass-balance profiles of glaciers are driven by rates of accumulation and ablation as a function of elevation and vary depending upon the associated climate regime. These regimes are important to characterize in order to interpret changes in a glacier's ELA. For instance, glaciers in the tropics are differentiated from temperate sites because they are affected by the annual migration of the intertropical convergence zone (ITCZ), and they experience a greater diurnal than annual temperature variation (Kaser, 1995; Kaser and Noggler, 1996). The mechanisms that drive glacier mass-balance variability within the tropics are not uniform. Inner-tropical glaciers receive precipitation year-round and are most sensitive to changes in temperature. In contrast, outer tropical glaciers experience nearly year-round constant temperature and precipitation is strongly seasonal. This scenario causes outer tropical glaciers to have an annual mass-balance that is seasonal and sensitive to variations in both precipitation and temperature (Kaser and Georges, 1999).

The climate of Venezuelan Andes is intermediate between the inner and the outer tropics because this region experiences strongly seasonal precipitation and high humidity throughout the year (Azocar and Monasterio, 1980). These conditions play an important role in the mass-balance process because humid air inhibits latent heat loss through sublimation and promotes melting. Melting as an ablation process is faster and more efficient than sublimation because it requires less heat energy. High ablation rates reduce the overall glacier surface area below the equilibrium-line that is needed to balance accumulation. As a result, a substantial part of a humid tropical glacier's surface area is maintained in the accumulation zone and the equilibrium-line is situated near the base of the glacier (Kaser and Osmaston, 2002).

Previous investigations in the Venezuelan Andes have shown glaciers were much more extensive during the LGM. Paleo-ELAs have been estimated by several authors. The paleo-ELA in the Paramo de La Culata (north-central Venezuelan Andes) has been previously reported as being ~1200 m lower during the LGM (Schubert and Valastro, 1974). Porter (2001) estimated an ELA lowering for Pico Bolivar in Venezuela of ~900 m using data from Schubert (1974, 1984) and Clapperton (1993). However, Porter's report does not specify the paleo-glaciers used in the study, nor does it take into consideration the regional ELA gradient. Further, the paleo-ELA was referenced to an estimated zero degree isotherm (Porter, 2001) and needs to be re-evaluated.

The work presented here re-evaluates the available paleo-glacial data and examines the underlying causes of a LGM ELA lowering in the Venezuelan Andes. We map the LGM glacier extent and ELAs for three different regions in the Venezuelan Andes. The temperature changes associated with the ELA lowering during the LGM are then calculated using an energy and mass-balance equation (Kuhn, 1989) and are compared to results using a conventional atmospheric lapse rate calculation. The results are then compared to other tropical Andean paleo-temperature and paleo-environmental records from the Venezuelan Andes.

2.2. STUDY AREA

This study focuses on the Cordillera de Mérida of the Venezuelan Andes which is located between the latitudes of 8.5 and 9°N at elevations above 2900 m (Figure 2.1). Three geographic sub-regions which have different aspects and distances from the primary moisture were studied. From southeast to northwest, these regions are: 1) the southern Sierra de Santo Domingo, 2) the northern Sierra de Santo Domingo and 3) the Paramo de Piedras Blancas.

2.2.1. Modern climate

Moisture in northern South America is primarily derived from Atlantic Ocean evaporation. Easterly trade winds then transport this moisture onto the continent and into the Andes. In the Mérida Andes, circulation patterns and a steep topography combine to form a strong southeast to northwest gradient in precipitation and cloud cover. Diurnal patterns of circulation and cloudiness have been shown to contribute to an asymmetry in precipitation and glaciation for other tropical South American and African regions (*e.g.* Hastenrath, 1985; Mölg et al., 2003). This diurnal pattern is observed in the Mérida Andes, where cloud cover is minimal during the morning hours and increases throughout the day. In the Sierra de Santo Domingo, the east facing slopes receive high solar radiation, whereas afternoon cloudiness reduces radiation on west facing slopes. In the Paramo de Piedras Blancas, conditions are drier than in the Santo Domingo region and cloud cover is minimal throughout the majority of the day.

The climate of the Mérida Andes is cold and humid throughout the year (Azocar and Monasterio, 1980). Precipitation is controlled by the position and intensity of the intertropical convergence zone (ITCZ), which is linked to the seasonal cycle of solar declination. Precipitation patterns have a bimodal annual distribution at lower elevations near Mérida (1498 m), with peaks in May-June and September- November and a minimum in July-August (Bradley et al., 1991). A shift to a unimodal precipitation regime occurs at elevations above Mérida where the wet season occurs from April-November, and peaks in June (Pulwarty el al., 1998).

The steepness of the regional precipitation gradient can be determined from the available station data (Table 2.1). The closest station to the southern Sierra de Santo Domingo is Barinitas which has a similar aspect and receives ~2650 mm of precipitation per year. The elevation (550 m) of this station is lower than the study area (3000 m) and is likely an overestimate. Adjusting for elevation using the precipitation gradient from Pulwarty (1998), the precipitation for the southern Sierra de Santo Domingo region is probably ~1600 mm/yr. The Mucubají precipitation data record ~969 mm/yr and represents the northern Sierra de Santo Domingo. Pico Aguila is representative of the Paramo de Piedras Blancas and records an average precipitation ~790 mm/yr. The data were adapted from Monasterio (1986) and must be evaluated carefully because collection times and techniques were not specified. East of Piedras Blancas, station data recorded 1190 mm/yr for the Paramo de La Culata (Schubert and Valastro, 1974), however monthly values are not available.

Temperature in the Cordillera de Mérida is typical of the low latitudes and shows little seasonal variability, but this region experiences a substantial diurnal freeze-thaw cycle. Daily temperature variation can be as much as 20°C (Schubert and Clapperton, 1990), and greatly exceeds the total annual variation. National Center for Environmental Prediction (NCEP) data indicate that the free atmosphere lapse rate is ~0.55°C/100 m for this region of the Andes (Kalnay et al., 1996). Atmospheric lapse rates based on station data from the Mérida Andes range from 0.4 to 0.7°C/100 m with an average of 0.6°C/100 m (Salgado-Labouriau, 1979). Other sources indicate an average of ~0.63°C/100 m (Bradley et al., 1991).

Table 2.1. Precipitation data from the Cordillera de Mérida, Venezuela

Station	Lat (°N)	Lon (°W)	Alt.(m)	Average Monthly Precipitation (mm)												
				Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Barintas[1]	8.80	70.80	550	41	49	83	247	332	347	331	337	310	316	182	73	2647
Mucubají[2,3]	8.80	70.83	3650	19	15	26	104	101	153	149	124	110	95	51	21	969
P. Aguila[3]	8.87	70.80	4118	18	17	29	75	101	105	105	97	95	95	36	17	790
Merida[1]	8.60	71.18	1498	47	48	64	167	243	162	119	142	194	263	201	86	1737
P. Espejo[4]	8.58	71.17	4765	15	17	38	85	97	80	54	75	89	81	56	30	717
Source: (1) Global Historical Climatology Network (2) Bradley *et al.*, 1991 (3) Monasterio and Reyes, 1986 (4) Pulwarty *et al.*, 1998																

2.2.2. Modern and past glaciation of the Venezuelan Andes

Glaciers in the Sierra Nevada de Mérida are currently restricted to Picos Bolivar (5002 m), Humboldt (4942 m) and Bonpland (4839 m). These cirque glaciers cover less than ~ 2 km^2 and extend down to elevations of ~4450 m. Glaciers at these locations have been continuously retreating during historical times (Schubert, 1998).

There is abundant evidence for more extensive glacier coverage in the Cordillera de Mérida during the late Pleistocene and it is estimated that glaciers covered approximately 200 km^2 during the LGM (Schubert and Clapperton, 1990). Based on radiocarbon dating of a 30 m thick glacio-fluvial sequence, Schubert and Rinaldi (1987) concluded that the local LGM for Venezuelan occurred between 20,600 to 17,800 cal yr BP. The associated glaciation produced extensive moraines, cirques, arêtes, horns and U-shaped valleys. In addition, there are glacial striae, roches moutonnees, whale back forms and erratic boulders (Schubert, 1974).

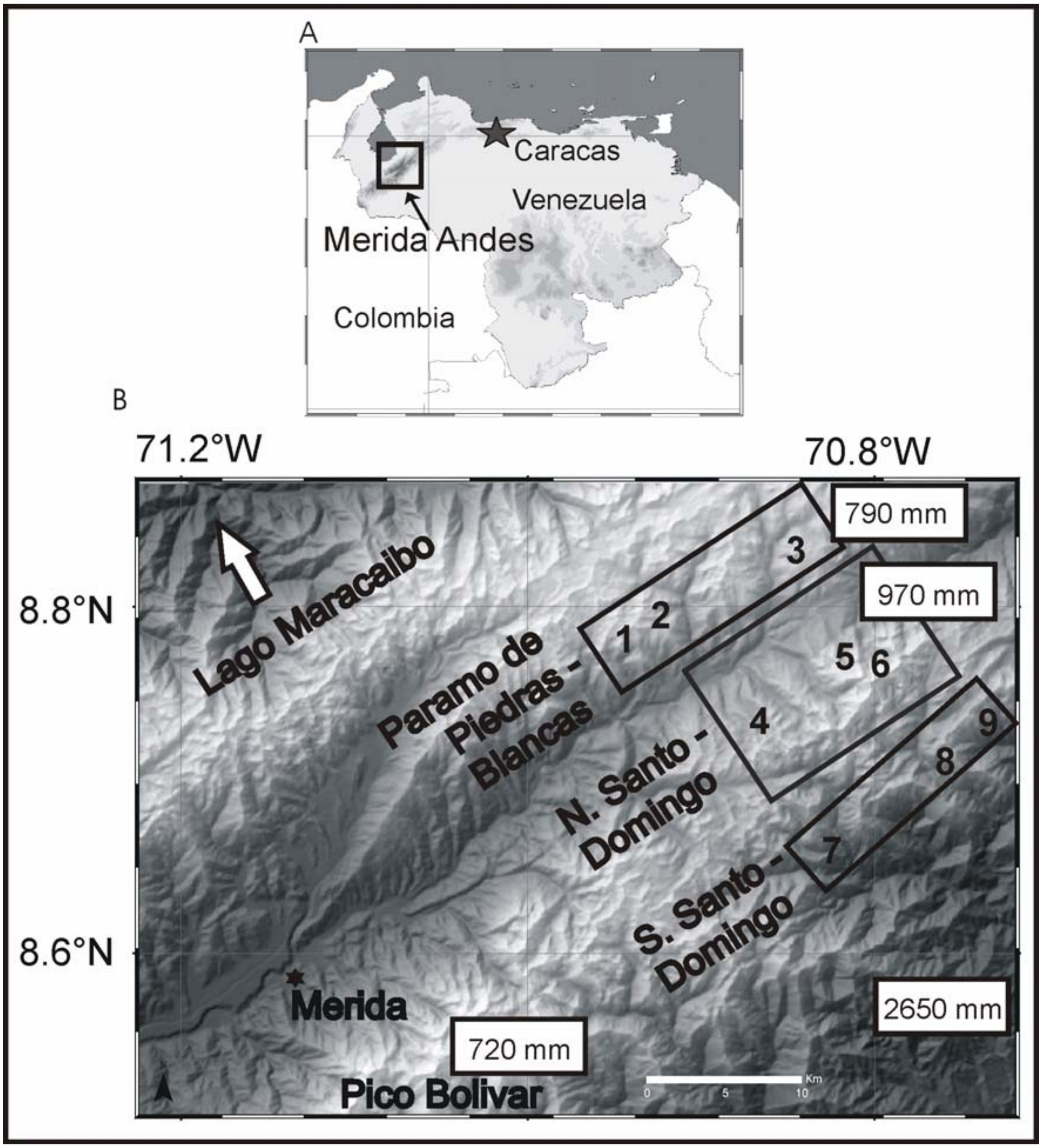

Figure 2.1. A. Location map of the Cordillera de Mérida, Venezuela. B. Average annual precipitation (mm/yr) for select areas, shaded relief image of the Cordillera de Mérida and index map of reconstructed glaciers: 1. Las Viraviras, 2. Cerro Los Pantanos, 3. El Balcon, 4. Michurao, 5. Mucubají, 6. Negra, 7. Llano del Trigo, 8. Filo Los Pantanos, 9. Granates.

Previous research has identified principal moraines at two levels: a lower level between 2600 and 2800 m and an upper level between 2900/3000 to 3500 m (Schubert, 1970; Giegengack and Grauch, 1973; Schubert, 1974; Schubert and Valastro, 1974; Schubert and Rinaldi, 1987; Schubert and Clapperton, 1990; Schubert, 1992). The lower level is characterized by weathered till, covered by abundant vegetation, whereas the upper level is characterized by fresh, well preserved till, forming prominent ridges. The lower levels appear to date to ~81,000 cal yr BP (Mahaney et al., 2000). Schubert (1974) concluded that the upper level represents the last major glacial advance that he named the late Pleistocene Mérida glaciation. In the Páramo de Piedras Blancas, the lower level has not been identified and moraines do not extend below elevations of ~ 3400 to 3700 m (Schubert, 1974).

2.2.3. Geology

The bedrock and surficial geology of the Sierra de Santo Domingo and Piedras Blancas regions consist primarily of Precambrian metamorphic rocks, including banded gneiss, schist and amphibolite cut by granitic and quartz dikes and veins (Schubert, 1970). These units have been uplifted along a series of major active reverse faults. In addition, the axis of the Santo Domingo valley is controlled by a series of right lateral strike-slip faults. Most notable is the Bocono fault, a major NE-SW trending, dextral fault that has offset moraines and other Quaternary deposits by as much as 100 m since the Pleistocene (Schubert and Sifontes, 1970; Audemard et al., 1999).

2.3. METHODS

2.3.1. Mapping of paleo-glaciers

Schubert (1982) mapped and identified glacial features in the Mérida Andes using photographs from the Cartografía Nacional aerial photograph mission of 1952. These maps were digitized on a smaller scale for this project. Because aerial photographs are susceptible to planimetric distortions and are limited in spatial coverage we also used Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data for digital mapping. Each ASTER scene can be used to produce false-color composite images with ~15 m resolution over a broad spatial area.

Spatial information and elevation data used for contouring were derived from Shuttle Radar Topography Mission (SRTM) data which were collected by the space shuttle Endeavour during February of 2000. These data were processed by the SRTM ground data processing system at the Jet Propulsion Laboratory (JPL) and were post-processed by the National Imagery and Mapping Agency (NIMA). Elevation values are presented in meters and referenced to the WGS84 geoid. Digital elevation models (DEMs) with 3 arc-second resolution (~90 m) for South America have been derived from SRTM data and were downloaded from the JPL. These data were acquired and imported into ArcView® 9.0 software for spatial analyses.

Paleo-glacier reconstructions were done in valleys with straightforward geometries and well preserved paleo-glacial landforms to ensure accurate mapping. In each sub-region, three glaciers were reconstructed to increase the signal/noise ratio. By reconstructing multiple glaciers from each sub-region we attempted to minimize the importance of local variables, such as wind speed, precipitation, and cloudiness, and maximize the signal of regional parameters. In addition, reconstructing multiple glaciers allows for characterization of the regional paleo-ELA gradient.

A transect of paleo-glacial valleys was studied, from the humid south-facing slope of the Sierra de Santo Domingo to the arid Paramo de Piedras Blancas.

2.3.2. Paleo-glacier surface area reconstruction

Using a composite of aerial photographs and the ASTER scene, the spatial extents of a total of 9 paleo-glaciers from 3 opposing mountain slopes were mapped (Figure 2.2). The surfaces of these glaciers were contoured at a 50 m interval. The spacing of each contour was constrained by estimating the basal shear stress (τ), which results from the slope of the glacier and bedrock surfaces, using the following formula (Seltzer, 1992).

$$\tau = \rho g t f(\Delta h/\Delta x) \qquad (1)$$

Where ρ is the density of ice (0.93 g/cm^3), g is the acceleration due to gravity (9.80 m/s^2), t is the center line thickness (m), f is a shape factor ($f = A/Pt$, where A is the area and P is the wetted perimeter of a given cross-section of the glacier) and $\Delta h/\Delta x$ is the slope of the ice surface. Calculated shear stress values should approximate those of modern glaciers, which tend to be between 50 and 150 kPa (Paterson, 1981). Horizontal spacing of contours was adjusted if the shear stress value fell outside of this range.

Surface contours were drawn with the convention that glaciers are convex at the base, straight at mid-elevations and concave near the headwall. Using the GIS software, a separate polygon was created for each contour range, delimiting that section of the glacier. A grid surface was created for each polygon, using the spatial data stored in the DEM. The total number of pixels between each pair of successive contours was then determined. A hyposmetric plot was generated using the calculated surface areas for each separate polygon.

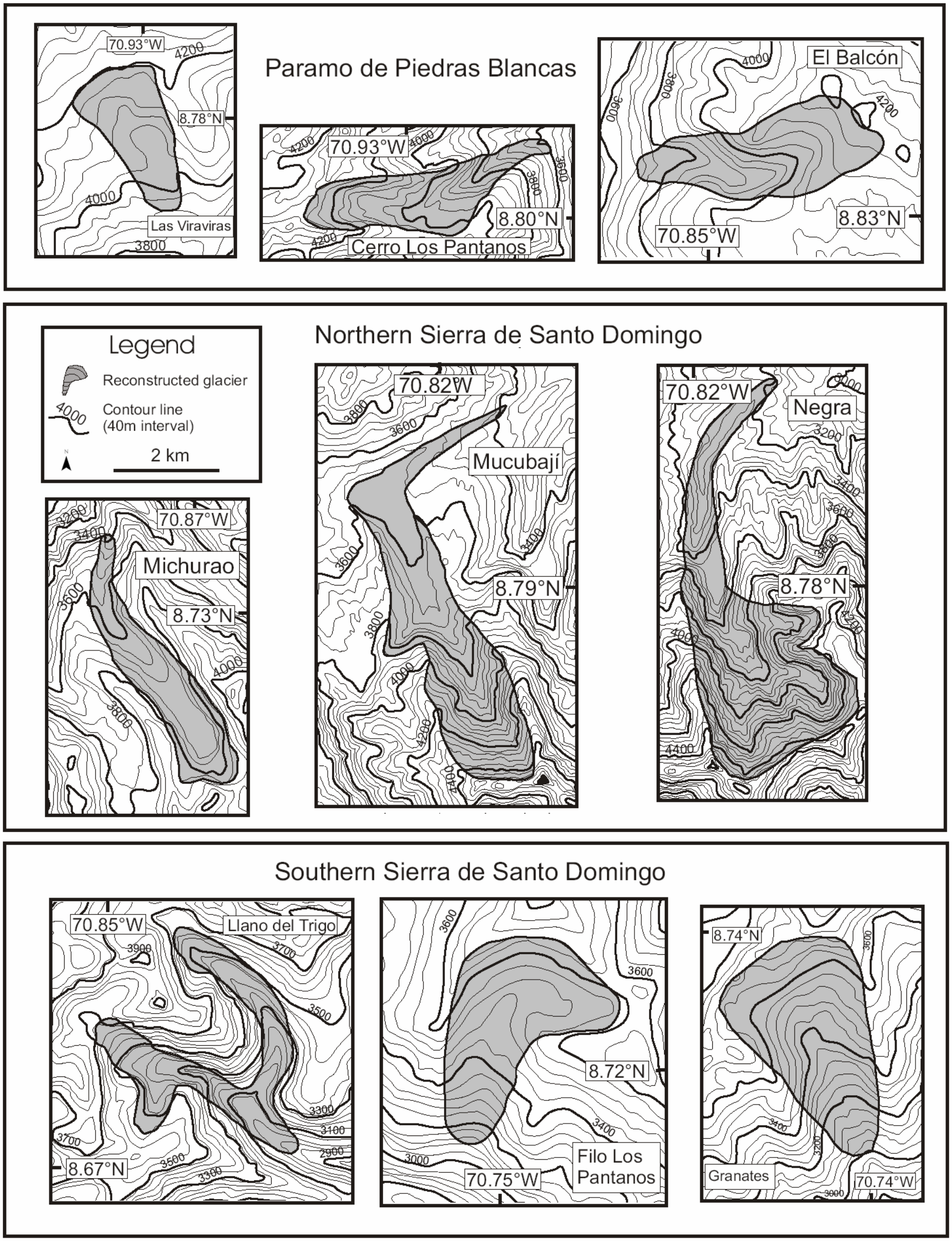

Figure 2.2. Venezuela LGM reconstructed glaciers.

2.3.3. Paleo-ELA reconstructions

The ELA is a statistical concept representing the dividing line between the accumulation and ablation zones. It represents the location at which a glacier's mass-balance equals zero and is sensitive to climate change. Various methods for reconstructing paleo-ELA's have been critically reviewed (Meirding, 1982; Benn and Evans, 1998; Porter, 2001; Kaser and Osmaston, 2002; Osmaston, in press). The more comprehensive reconstruction methods take into consideration the size, shape and distribution of total ice surface area versus elevation. For example, the accumulation area ratio (AAR) method assumes that the accumulation area of a glacier occupies a fixed proportion of a glaciers total surface area. The ELA is then determined by applying an estimated AAR value to a hypsometric plot. AAR values vary geographically and choosing an accurate AAR value requires careful consideration. Temperate glaciers have an average AAR of approximately 0.65 and this value has been commonly applied to tropical glacier hypsometries (*e.g.* Klein, 1999; Porter, 2001). However, the AAR is likely higher in the tropics than the mid-latitudes due to an increased rate of ablation along tropical glaciers surfaces and a more constant thermal seasonality relative to temperate regions (Kaser and Osmaston 2002). In addition, tropical glaciers have a more pronounced ablation process due to warmer temperatures year-round and react faster than mid-latitude glaciers to changes in ablation (Kaser, 1995). Thus, AAR values are higher in tropical regions because melting occurs year-round and the surface area in the ablation zone required to compensate for mass accumulation is less than that of temperate glaciers. It has been observed that AAR values of modern tropical glaciers can be as high as 0.8 (Kaser and Osmaston, 2002; Mölg et al., 2003).

The mass-balance gradient of a glacier is a measure of the rates of accumulation and ablation as a function of elevation. The AAR method assumes that the rates of accumulation and ablation are fixed with altitude and does not consider the vertical mass balance profile of a glacier. As an alternative, the area-altitude-balance-ratio (AABR) method takes into consideration both the hypsometry of the glacier and the shape of the mass-balance curve (Furbish and Andrews, 1984; Benn and Evans, 1998; Osmaston, in press). The balance ratio (BR) is defined as the ratio of the mass balance gradients of the ablation and accumulation zones. As with an AAR value, the BR values are higher in the tropics than in temperate regions due to relatively higher rates of ablation. Tropical glaciers typically have BR values of 2 to 5, but can this value can be as high as 25 (Benn and Evans, 1998). ELAs were estimated with the AABR method with a spreadsheet developed by Osmaston (2005).

In this study we apply both the AAR and AABR methods to determine paleo-ELAs. The proper BR and AAR values are not known for the Venezuelan Andes because the limited existing modern glaciers have not been directly observed. Therefore, we used both methods with a range in AAR and BR values. The AABR method with a BR value of 5 yields an ELA that closely matches the AAR method with a value of 0.73 for the Sierra de Santo Domingo region. Given the theoretical mass-balance scenario for the region, with strongly seasonal precipitation and continuously high humidity, these should be considered minimum estimates. More appropriate AAR values are likely around 0.80, which corresponds to a BR of 10. The results from both methods used to determine maximum and minimum ELA estimates for the LGM are presented in Table 2.2.

As a final note, it is important to consider the effects of lower sea level during the LGM on glacier ELAs. Traditionally, LGM ELAs have been referenced to LGM sea level (120 m lower than present (Fairbanks, 1989) with the idea that the global atmosphere descended by a comparable amount. Broecker (1997) and Porter (2001) argue that such a lowering would make the reconstructed ΔELA values appear to be too high and that these values should be adjusted by the amount of sea level lowering. However, convincing arguments have been made that the transfer of water from the oceans to land displaced enough atmospheric mass to compensate for the lower sea level (Osmaston, in press) and thus both modern and LGM ELAs should be referenced to modern sea level. In this paper we follow this approach and report all elevations above modern sea level.

2.3.4. Determining modern ELAs

The existing glacier on the north-facing slope of Pico Bolivar is used to represent the modern ELA of the northern Sierra de Santo Domingo because both regions have the same aspect and similar patterns of precipitation. During the LGM, glaciers on Pico Bolivar were part of a large ice cap with a complex geometry and are therefore not included in the paleo-glacier reconstruction presented in this paper. The modern glaciers were observed in the field and mapped by Schubert (1972). The modern ELA's were estimated using the AAR method applied to a hypsometric plot generated by Polissar (2005) and the results are presented in Table 2.2.

The Pico Bolivar glaciers provide a minimum estimate of a modern ELA for the northern Santo Domingo because they are out-of-equilibrium with today's climate and are retreating rapidly. Schubert (1992) documented a dramatic rise in the regional snowline from ~4100 m in 1885 AD to above 4700 m during the 1970's using photographic comparison. National Centers for Environmental Prediction (NCEP) reanalysis data show that the modern regional freezing level is ~4860 m (Kalnay et al., 1996). Alternative maximum modern ELA estimates should consider this freezing height and are presented in Table 2.2.

The modern ELA can be estimated in regions where modern glaciers do not exist, if the freezing height is known using the following equation (Greene et al., 2002):

$$\text{ELA} = 537 + 1.01\text{FH} - 0.51\text{P}, \qquad (2)$$

where FH is the estimated annual freezing height (m a.s.l.), and P is the annual precipitation (mm). Modern ELA's for the Paramo de Piedras Blancas and the southern Sierra de Santo Domingo were estimated using eq. 2. Minimum and maximum values were estimated using freezing heights of 4700 and 4860 m. It should be cautioned that this equation represents a statistical average for tropical glaciers and needs to be evaluated carefully when applied to individual glaciers.

2.3.5. Last Glacial Maximum temperature reconstruction

Seltzer (1992) modified Kuhn's (1989) equation to calculate the temperature change (ΔT) responsible for a ΔELA:

$$\Delta T = \frac{L_m}{A_H}\left(\frac{\partial P}{\partial z}\Delta ELA + \Delta P\right) + \frac{1}{A_H}\left[\frac{L_m}{L_s} - 1\right]\left[A_s \frac{\partial p_{va}}{\partial z}\Delta ELA\right] - \frac{\partial T}{\partial z}\Delta ELA \qquad (3)$$

Where L_m is the latent heat of melting, L_s is the latent heat of sublimation, A_H is the transfer coefficient for sensible heat, A_S is the transfer coefficient for latent heat, $\partial P / \partial z$ is the vertical precipitation gradient, $\partial p_{va} / \partial z$ is the vertical gradient in atmospheric absolute humidity, $\partial T_a / \partial z$ is the atmospheric lapse rate, ΔP is the change is precipitation and ΔELA is the change in ELA (refer to Tables 2.3 and 2.4 for the corresponding values). The first component of this equation reflects the contribution from changes in precipitation over time and precipitation change as a function of elevation. The second component reflects how an ELA lowering is affected by a vertical change in atmospheric humidity (Seltzer, 1992). Values for precipitation were derived from modern station data. To model the effects of changes in precipitation during the LGM, values of ± 50% of the modern mean were also used. The precipitation gradient was estimated using the regional maximum and minimum values from Pulwarty (1998). The atmospheric humidity gradient was estimated using the modern annual mean calculated from NCEP data. A range in LGM humidity gradient values was estimated by taking ± 50% of the modern mean. The values for transfer coefficients are from data in Kaser and Osmaston (2001).

Determining an appropriate LGM atmospheric lapse rate requires careful consideration because these values have a large effect on the paleo-temperature calculation. The average modern tropical lapse rate is 0.6°C/100 m (Porter, 2001). There is a range in the published modern lapse rates for Venezuela, from 0.54 to 0.63°C/100 m (Salgado-Labouriau, 1979; Bradley et al., 1991; Kalnay et al., 1996). In addition, atmospheric conditions during the LGM in the Venezuelan Andes may have been more arid than today (Bradbury et al., 1981; Bradley et al., 1985; Weingarten et al., 1991; Yuretich et al., 1991; Salgado-Labouriau et al., 1992) which may have resulted in steeper atmospheric lapse rates. It has been documented that even dry tropical locations tend to approach the maximum of the saturated adiabatic lapse rate (Rind and Peteet, 1985) and therefore these values may not have differed greatly from today. A minimum estimate for an LGM atmospheric lapse rate in the Venezuelan Andes is probably close to the modern minimum of 0.55°C/100 m. The maximum plausible LGM tropical atmospheric lapse rate is 0.75°C/100 m (Kaser and Osmaston, 2002).

2.4. RESULTS

2.4.1. Last Glacial Maximum ELA values

The combined results of the AABR and AAR methods (Figure 2.3) are used to estimate the LGM ELA values. Minimum ELA lowerings were estimated using AAR and the corresponding BR values that approximate reported tropical averages (e.g. Klein et al., 1999; Porter, 2001). Conversely, maximum ELA depressions were estimated using larger AAR and BR values that are conceptually more plausible for this region based on reports of other tropical glaciers (Benn and Evans, 1998; Kaser and Osmaston, 2002; Molg et al., 2003). Higher BR and AAR values also provided the least variance in the estimated ELA values supporting the contention that they are more appropriate. Results from the Paramo de Piedras Blancas indicate that LGM ELA values are between ~4010 and 3830 m. In the northern Sierra de Santo Domingo, LGM ELA values are between ~3725 and 3560 m. The southern Sierra de Santo Domingo LGM ELA values are between ~3505 and 3210 m (Table 2.2).

The average ELA values indicate that the LGM ELA gradient was ~600 m (Figure 2.4). The LGM ELA lowering (ΔELA) can be estimated by comparing the modern glaciers on Pico Bolivar to the reconstructed LGM glaciers in the northern Sierra de Santo Domingo. The range of modern ELA values for the northernmost glacier on Pico Bolivar was estimated using the same range of AAR values for the northern Sierra de Santo Domingo paleo-glaciers. The average LGM ELA value for the northern Sierra de Santo Domingo is ~3640 m, which yields an average ΔELA of -980 m. ELA's were at least 960 m lower for the Paramo de Piedras Blancas and 1150 m lower for the southern Sierra de Santo Domingo.

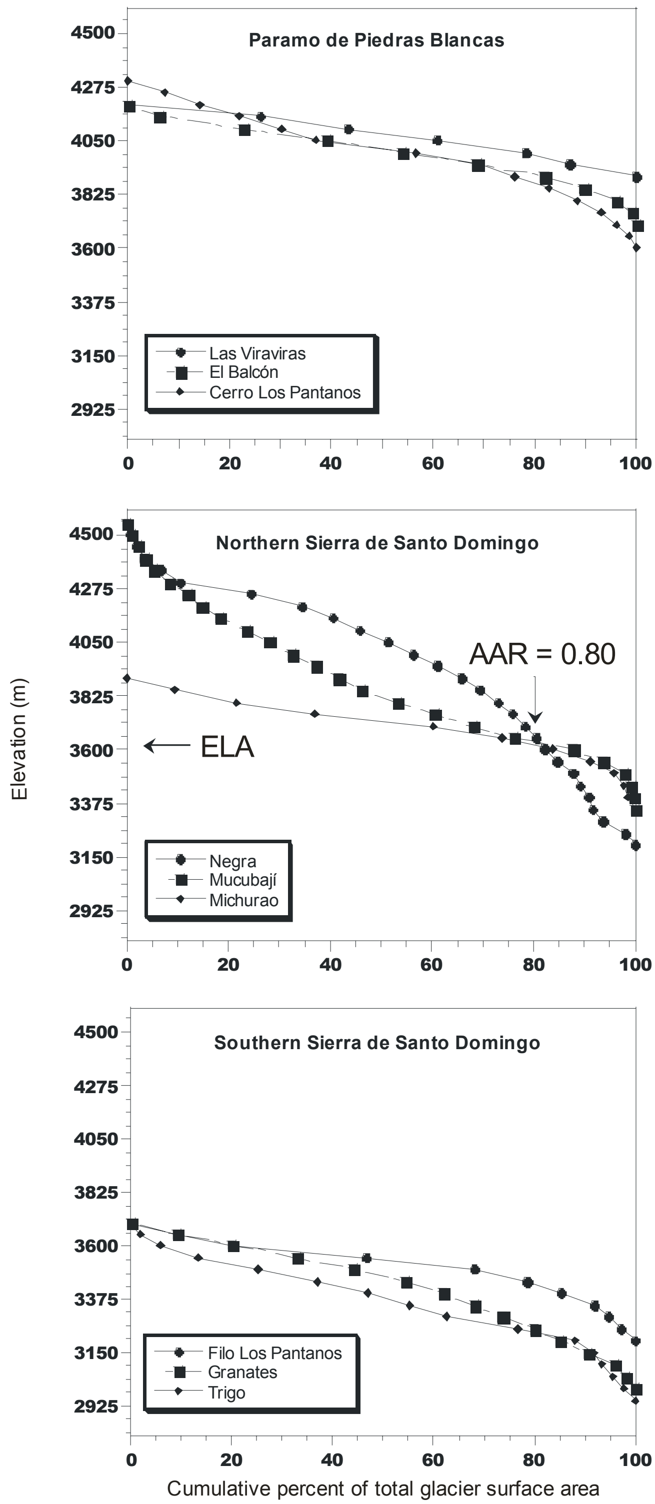

Figure 2.3. Hypsometric plots of the nine Venezuela LGM glaciers used in this study. The paleo-ELA is determined by applying an AAR to the plot and determining the corresponding elevation. The three separate plots represent the geographic sub-regions used in the study.

Table 2.2. Spatial data and LGM ELA values for the Sierra Nevada de Mérida, Venezuela

Paleo-glacier name	Location (DD)	Headwall Contour (m)	Terminus Contour (m)	T: avg. shear stress in kPa	Balance Ratio (BR)	Calculated LGM ELA (m asl)	Accumulation-Area Ratio (AAR)	Modern ELA (minimum estimate)	Modern ELA (maximum estimate[2])	ELA lowering (Δ ELA) min	ELA lowering (Δ ELA) max
					Paramo de Piedras Blancas[1,2]						
Las Viraviras	8.78°N	4200	3900	126	5	4010	0.76	4880	5040	**-870**	**-1030**
	70.93°W				10	3990	0.79	4880	5040	**-890**	**-1050**
					15	3970	0.85	4880	5040	**-910**	**-1070**
Cerro Los Pantanos	8.80°N	4300	3600	103	5	3900	0.76	4880	5040	**-980**	**-1140**
	70.93°W				10	3855	0.83	4880	5040	**-1025**	**-1185**
					15	3830	0.85	4880	5040	**-1050**	**-1210**
El Balcón	8.83°N	4200	3700	92	5	3930	0.74	4880	5040	**-950**	**-1110**
	70.85°W				10	3890	0.83	4880	5040	**-990**	**-1150**
					15	3880	0.84	4880	5040	**-1000**	**-1160**
					Average:	**3920**			**Average:**	**-960**	**-1123**
					Northern Sierra de Santo Domingo [2,3]						
Mucubají	8.79°N	4550	3350	97	5	3720	0.66	4670	4950	**-950**	**-1230**
	70.82°W				10	3670	0.73	4625	4950	**-955**	**-1280**
					15	3650	0.78	4610	4950	**-960**	**-1300**
Negra	8.78°N	4500	3200	83	5	3725	0.77	4620	4950	**-895**	**-1225**
	70.82°W				10	3620	0.81	4625	4950	**-1005**	**-1330**
					15	3560	0.85	4615	4950	**-1055**	**-1390**
Michurao	8.73°N	4150	3250	83	5	3640	0.75	4630	4950	**-990**	**-1310**
	70.87°W				10	3600	0.84	4610	4950	**-1010**	**-1350**
					15	3580	0.86	4590	4950	**-1010**	**-1370**
					Average:	**3640**			**Average:**	**-980**	**-1310**
					Southern Sierra de Santo Domingo[1,2]						
Filo Los Pantanos	8.70°N	3700	3200	123	5	3505	0.68	4470	4630	**-965**	**-1125**
	70.75°W				10	3460	0.76	4470	4630	**-1010**	**-1170**
					15	3435	0.82	4470	4630	**-1035**	**-1195**
Granates	8.73°N	3650	3000	143	5	3300	0.73	4470	4630	**-1170**	**-1330**
	70.73°W				10	3260	0.78	4470	4630	**-1210**	**-1370**
					15	3230	0.82	4470	4630	**-1240**	**-1400**
Llano del Trigo	8.67°N	3650	2950	105	5	3265	0.73	4470	4630	**-1205**	**-1365**
	70.85°W				10	3230	0.81	4470	4630	**-1240**	**-1400**
					15	3210	0.86	4470	4630	**-1260**	**-1420**
					Average:	**3320**			**Average:**	**-1150**	**-1310**

[1] modern ELA minumum values calculated using a freezing height of 4700 m [2] modern ELA maximum values calculated using a freezing height of 4860 m

[3] minimum ELA values for the northern Sierra de Santo Domingo were estimated using the existing glaciers on Pico Bolivar

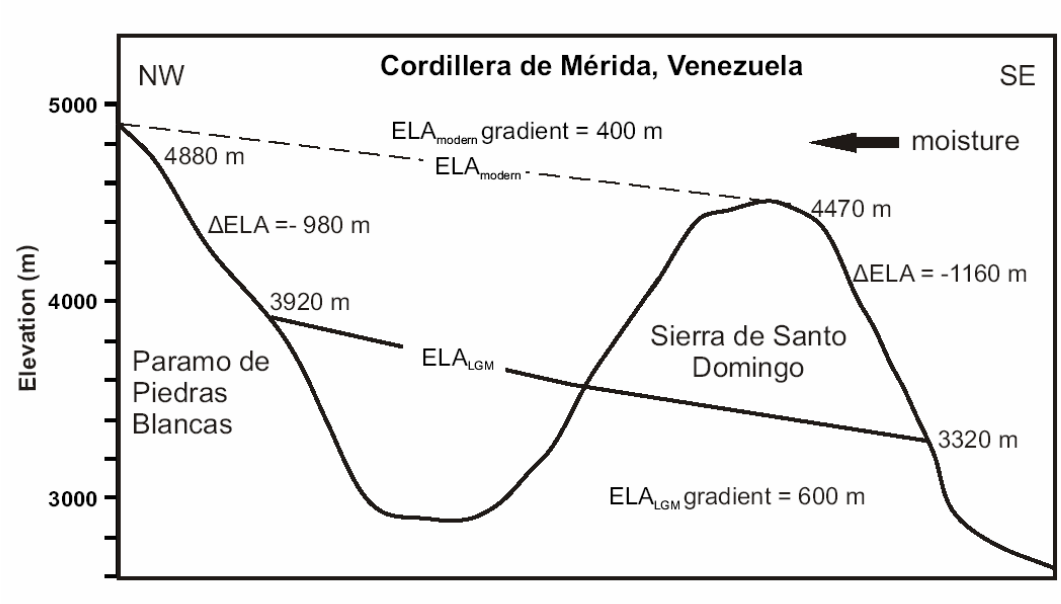

Figure 2.4. Graphical representation of the LGM versus modern ELA values. ΔELA values indicate the difference between modern and LGM ELA values. The distribution of ELAs is strongly controlled by precipitation patterns and moisture is restricted on NW slopes. The data presented here suggest that the gradient of ELA values during the LGM was slightly steeper than today which may have been due to increased aridity.

2.4.2. Last Glacial Maximum temperature reconstruction

The most reliable ΔELA values for paleo-temperature calculations are from the northern Sierra de Santo Domingo region because modern glaciers exist for comparison. The applied temperature equation requires a ~8.8°C cooling to explain a ΔELA of -980 m using modern values for precipitation. Increasing or decreasing precipitation by up to 50% relative to modern values only results in a ± 0.5°C change in the overall temperature calculation.

A sensitivity analysis of the effects of each variable used in eq. 3 was conducted to better understand the uncertainty in the calculated temperature reduction (Table 2.4). For example, the uncertainty in the estimated ELA and the range in atmospheric lapse rate values provide the greatest variability, which is estimated as ± 1.0°C for each. The combined error for the estimated temperature depression, determined from the square root of the sum of squared errors, is ± 2.0°C.

Table 2.3. Venezuela LGM temperature values as a function of changes in the atmospheric lapse rate and precipitation

ΔELA = -980 m		
Lapse Rate °C/100m	ΔP mm/yr	ΔT °C
	+500	-7.47
0.55	0	-7.83
	-500	-8.19
	+500	-8.45
0.65	0	-8.81
	-500	-9.17
	+500	-9.42
0.75	0	-9.79
	-500	-10.15

Table 2.4. Error analysis in the estimation of ΔT for the LGM

Variable	Description	Value used in temperature equation	Min	Max	Units	Error in calculation of ΔT (ΔELA = -980 m)	Reference
*r**	resistance to sensible and latent heat transfer*	56	47	70	s/m	±0.2°C	Kaser and Osmaston (2002)
δP/δz	precipitation gradient	-3.225E-03	-1.360E-03	-5.090E-03	kg m-2 m-1 d-1	±0.5°C	Pulwarty (1998)
ΔP	change in precipitation	0	-500	500	kg m-2	±0.4°C	-
ΔELA	change in ELA	-980	-880	-1080	m	±0.9°C	this study
δt/δz	lapse rate	0.65	0.55	0.75	°C/100m	±1.0°C	-
δpva/δz	atmospheric absolute humidity gradient	-1.223E-06	-1.55E-06	-8.94E-06	kg m-3 m-1	±0.9°C	NCEP
					Combined effect of errors on ΔT:	**±1.8°C**	

*used to calculated transfer coefficients for sensible and latent heat transfer

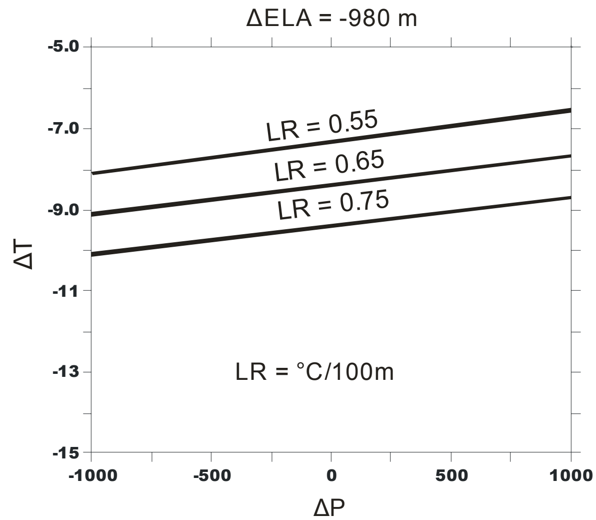

Figure 2.5. Graphical representation of LGM equilibrium-line altitude lowerings in the Venezuelan Andes, and the effects of changes in precipitation and atmospheric lapse rate (LR) values on the estimated temperature depressions.

2.5. DISCUSSION

A temperature change estimate based on an ELA lowering has often been calculated by multiplying an average atmospheric lapse rate by the ΔELA (e.g. Porter, 2001). This method is useful as a first estimate of paleo-temperature in regions where modern meteorological data are not available. However, this technique is an oversimplification because the thermodynamic processes across a glacier's surface are complex and do not require that the ELA always occur at the same temperature. More comprehensive modeling should be applied by using equations, such as those from Kuhn (1989), that take into account the total energy budget across a glacier's surface. In particular, the rates of latent and sensible heat loss change at elevation because of gradients in humidity and precipitation. If there were no humidity and precipitation gradients, the temperature change associated with an ELA lowering is equal to the atmospheric lapse rate. Using a ΔELA estimate of -980 m, the Kuhn equation requires a temperature reduction of 8.8 ± 2°C for the Mérida Andes during the LGM. The -980 m ΔELA is in reference to a modern ELA estimated from glaciers that are not in equilibrium with the modern climate. Therefore, it is possible that the true ΔELA is closer to -1200 m which requires a temperature reduction of 11.0 ± 2°C. Nevertheless, even the minimum temperature change estimates presented here are greater than what would be estimated using an atmospheric lapse rate calculation (6.4 ± 1.0°C reduction). Seltzer (1992) used the Kuhn equation to calculate a post-LGM temperature depression in the Cordillera Real, Bolivia and similarly found that an atmospheric lapse rate calculation underestimates the cooling associated with an ELA lowering.

Glacier variability in the tropics is driven by changes in temperature, precipitation, solar radiation or a combination thereof. Our results indicated that precipitation can only account for a minor change in the ΔELA for the northern Andes during the LGM. Likewise, changes in potential radiation at the top of the atmosphere were not a major contributor as northern hemisphere insolation values during the LGM were similar to today (Berger, 1978). The results presented here suggest that temperature change was the main driver of glacier surface area changes in the Venezuelan Andes during that time. Decreasing temperatures would lower the freezing height and increase the available accumulation area. Our assumption is that glacier mass-balance processes that operated during the LGM are similar to today and an increased accumulation area would require an increased ablation area to accommodate the volume of ice. Thus, lower temperatures would increase glacial coverage and ELAs would be at lower elevations. This supports Seltzer's (1992) conclusion that in humid regions, temperature plays a larger role than precipitation in driving ELA variability.

Temperature change governs ΔELA values in the Venezuelan Andes, whereas a gradient in ELA values across a region is driven by local meteorological conditions. The ELA estimates from the three regions in the Cordillera de Mérida suggests that there was an ELA gradient of

~600 m in this region during the LGM (Figure 2.4). The lowest ELA values were in the southeast and the highest were in the northwest. A gradient in paleo-ELA's is driven by patterns of moisture availability, cloud cover and aspect. The results from this study are similar to the mapped elevations of cirque floors which Schubert (1982) concluded was a response to contrasting precipitation patterns during the LGM. Using Eq. 2, the modern ELA gradient would be ~400 m if modern glaciers existed. This is a first estimate and needs to be critically evaluated, however it suggests that the LGM gradient was steeper than at present. A steeper ELA gradient in the Andes may have been the result of increased aridity during the LGM (Klein, 1999). Alternatively, the modern gradient is steeper than indicated by Eq. 2, possibly as a result of gradients in cloudiness which are ignored in this equation.

The patterns of the LGM and modern ELA gradients are similar, which suggests that wind direction and the primary moisture source were the same at both times. It is also likely that cloudiness and precipitation patterns were similar. The regional precipitation patterns only explain the ELA gradient between the northern and southern Santo Domingo slopes. Modern precipitation differs by up to 800 mm/yr for these slopes,, whereas this precipitation difference is minimal between the Santo Domingo and the Paramo de Piedras Blancas (~100 mm/yr).

To explain the offset in ELA values between the Santo Domingo and Piedras Blancas slopes requires a meteorological explanation besides precipitation. A contrast in cloud cover between the Santo Domingo region and the Paramo de Piedras Blancas combined with less precipitation may account for the gradient in ELA values. The diurnal pattern of cloudiness and solar azimuth play a substantial role in regional glacial variability in the tropics by decreasing the amount of effective radiation received by the ice surface (e.g. Hastenrath, 1985; Mölg et al., 2003). Cloudiness is especially pronounced during the rainy season in the Santo Domingo region

(Azocar and Monasterio, 1980) where substantial cloud cover is a common feature during the late morning and early afternoon. In contrast, cloud cover in the Piedras Blancas region is greatly reduced, especially during the dry season, as the sky remains clear except for only a few hours in the evening.

Our results are comparable to other reports from the region. Northwest of the Paramo de Piedras Blancas and the Sierra de Santo Domingo is the Paramo de La Culata where Schubert and Valastro (1974) reported that ELAs were ~1200 m lower than today. The change in ELA was estimated based on LGM cirque floors at an elevation of 3500 m relative to a modern 4700 m 0°C isotherm. The reported paleo-ELA values for this region need to be evaluated because the technique used by Schubert and Valastro is only an estimate and does not consider the glacier's hypsometry. Cirque floors were lower in this region relative to adjacent mountain slopes, which may be due to differential precipitation during the LGM. This is a plausible explanation because the modern average rainfall for this region is ~1190 mm/yr, which is ~200 mm/yr greater than the northern Santo Domingo and ~300 mm/yr greater than Piedras Blancas.

Porter (2001) estimated an LGM ELA lowering of ~900 m for one location in the Venezuelan Andes. The results presented here indicate that ELA's were at least 870 to 1160 m lower depending on the sub-region analyzed. If the ΔELA estimates in this paper are referenced to today's freezing height of 4860 m rather than modern glacier ELA's, ELA's may have been lower by as much as 1030 to 1420 m. These values should be viewed cautiously because estimating a ΔELA by comparing a paleo-ELA to a modern 0°C isotherm is a poorer estimate than comparing a paleo-ELA to a modern ELA because the 0°C isotherm is commonly not equal to the ELA (Ohmura, 1992). These results presented here using both methods are similar to the 1075 m lower ELA's identified for Colombia (Hoyos-Patiño, 1998; Porter, 2001), but are less than the ~1500 m reported for Costa Rica (Lachniet and Seltzer, 2002). Other South American sites record ELA lowerings of up to ~1200 m in the Central Andes (Klein et al, 1999), and up to 920 m in Ecuador (Clapperton, 1987; Clapperton, 1993; Porter, 2001). Combined, these reports support data indicating the American Cordillera experienced ~1000 m ELA lowerings during the LGM (Broecker and Denton, 1989).

The temperature estimates based on ELA reconstructions presented herein are supported by independent lines of evidence. Using an atmospheric lapse rate calculation, Rull (1998) estimated a temperature depression of 7 ± 1°C for the LGM in the Venezuelan Andes based on a ~1200 m descent of vegetation zones relative to today. This estimate may be closer to the values presented here if a more comprehensive temperature reconstruction method were to be used. Additional vegetation, lake level and geochemical studies indicate that temperatures at high Andean elevations were ~5 to 6.4°C cooler during the LGM (Farrera et al., 1999). Ice core evidence from the Peruvian Andes indicates high elevation temperatures may have been as much as 8 to 12°C cooler than modern (Thompson et al., 1995) though a reinterpretation of $\delta^{18}O$ of Huascaran ice cores suggests that this may be an over-estimate (Pierrehumbert, 1999).

The large cooling at high elevations inferred from glacial ELAs does not directly correspond with changes in sea level temperature. For example, tropical Atlantic temperatures were only 5 to 6°C cooler during the LGM (Guilderson et al., 1994; Thompson et al. 1995; Stute et al. 1995; Mix et al., 1999). Paleo-temperature estimates from the Cariaco Basin record, off the north coast of Venezuela, indicate conditions were ~3 to 4°C cooler during the LGM (Lin et al., 1997; Lea et al., 2003). The difference between sea level and high-elevation paleo-temperature estimates is an area of active research. One proposition is that a steeper atmospheric lapse rate would lower the freezing height relative to sea level. This is questionable as atmospheric physicists find it difficult to adequately explain a mechanism in order to produce these steeper values (Rind and Peteet, 1985). On the other hand, Betts and Ridgeway (1992) propose that another mechanism is required to lower the freezing height, such as a reduction of mean surface wind speed, or an increase in the net atmospheric transport of tropical heat. Using the model of Betts and Ridgeway (1992), Greene et al., (2002) showed that the observed tropical ELA lowering can be achieved through an average tropical SST cooling of 5°C if wind speeds were 11 m/s higher. These models demand a denser network of paleo-temperature estimates from a suite of elevations and ELAs need to be re-evaluated using methods such as the Kuhn (1989) model.

2.6. CONCLUSIONS

There has been extensive debate since the CLIMAP project about the true degree of LGM cooling in the tropics. The degree of ELA lowering in Venezuela is consistent with other Andean tropical sites. The associated temperatures were lower in the Venezuelan Andes during the LGM by at least 8.8 ± 2.0°C and possibly as much as 11°C. This is ~2°C cooler than what would be estimated by an atmospheric lapse rate calculation. The values presented here are greater than the overall tropical average for LGM temperature presented thus far of 5 to 6.4°C using an atmospheric lapse rate calculation (Porter, 2001). Lapse rate calculations underestimate the cooling associated with lower ELA values because they ignore the sensible and latent heat loss that occurs as a result increasing humidity values at lower elevations. The spatial gradient of LGM ELA values in Venezuela is consistent with the modern cloudiness and precipitation patterns suggesting that similar patterns were operating during the LGM. There is some indication of a steeper ELA gradient during the LGM which may have been the result of increased aridity.

3. LATE QUATERNARY DEGLACIAL CHRONOLOGY OF THE MÉRIDA ANDES, VENEZUELA

3.1. INTRODUCTION

The timing and pattern of climate change within the tropics during the late Quaternary is uncertain. Climate researchers have often studied glaciers to document how they respond to changes in precipitation, temperature and solar radiation. Records of glaciation from the high Andes are necessary in order to compare the timing of tropical climate change versus the higher latitudes (e.g. Seltzer, 2001). These records are difficult to interpret as the mechanisms that drive glacier variability vary across the Andes and need to be carefully evaluated. For instance, the northern Andes are situated on the boundary between the inner and outer tropics where modern precipitation is strongly seasonal, whereas humidity remains high throughout the year. Under these conditions, there is a high rate of ablation by melting and temperature change becomes the main driver in modern glacier variability. This characterizes the modern mass-balance scenario, however, understanding the mechanisms that drove past glacier variability is further complicated as the role of changes in moisture availability and solar radiation are not well known.

Determining the interdependence of the mechanisms which drive glacial variability at high elevations requires the combination of well constrained dates on glacial deposits with other proxy data such as pollen or sediment geochemical records from nearby lowland tropical sites. Reconstructing the glacial sequence at high elevations is equivocal, however, as recurring glacial advances often remove any sedimentary records of glacial variability. Additionally, individual glacial advances are difficult to identify because the poorly consolidated till deposits are easily eroded and usually lack organic material for radiocarbon dating.

Alpine tropical lakes and bogs are archives of paleoclimatological conditions, denoted by abrupt facies changes from inorganic to organic rich sediments, and the sediments commonly record the transition from glacial to nonglacial conditions. Earlier workers studied the glacial-interglacial transition in Venezuela (Salgado-Labouriau, 1984; 1991; Bradley et al., 1985; Weingarten et al., 1991; Rull, 1996) however, the exact timing and pattern of deglaciation for this region remains uncertain. Cores from 7 alpine lakes and 2 bog deposits that span the glacial-interglacial transition were acquired, and radiocarbon dated in order to constrain the timing of deglaciation and glacial readvances (Figure 3.1).

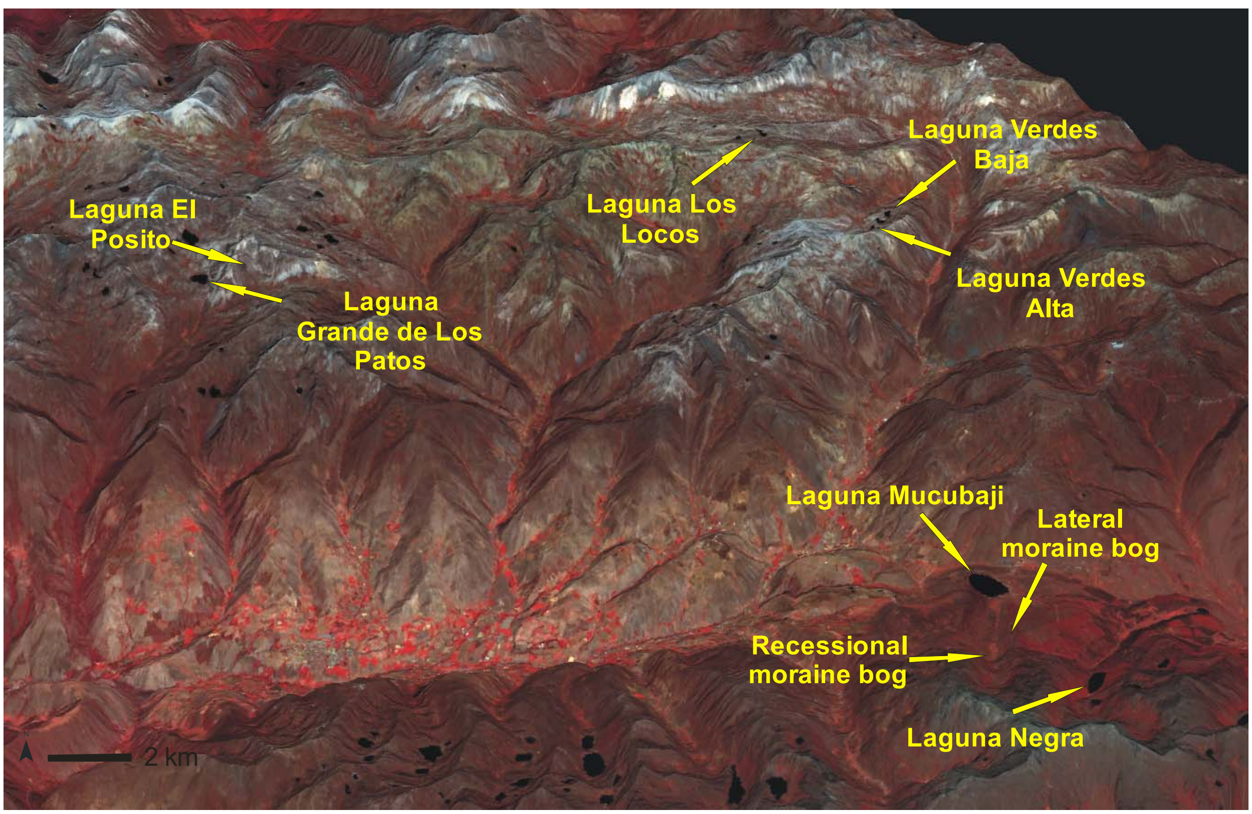

Figure 3.1. Location map of coring sites.

3.2. METHODS

Sediment cores from lakes and the lateral moraine bog were extracted using a modified Livingstone square-rod piston corer. The Mucubají recessional moraine bog was cored using a vibra-corer and a 6 m metal tube. Cores were shipped to the University of Pittsburgh where they were opened, split and described based on major sedimentological changes, measured for magnetic susceptibility and sampled for radiometric dating.

3.2.1. Magnetic susceptibility

Glacial versus non-glacial sediment was differentiated based on magnetic properties. The vast majority of magnetic minerals in lake sediments are allogenic (Thompson and Oldfield, 1986). Sediments are interpreted as being glacially derived when the vast majority of a given interval of a core is composed of inorganic, allogenic materials. Eroded sediments in the Mérida Andes tend to be high in metamorphic rock fragments, mica, quartz and clays (Weingarten et al., 1991). Terrigenous mineral matter and glacio-lacustrine sediment has a higher magnetic susceptibility (MS) than organic sediments. The MS profiles of all cores were measured at 0.5 cm intervals using a Bartington Magnetic Susceptibility bridge (Figures 3.3 to 3.7).

3.2.2. Radiometric analyses

Aquatic macro-fossils, peat or charcoal from each core were extracted for accelerator mass spectrometry (AMS) radiocarbon dating. Analyses based upon aquatic macrofossils are potentially problematic as they are subject to lake-reservoir effect (Abbott and Stafford, 1996). However, reservoir ages are negligible in regions where carbonate bedrock is absent and no carbonates have been mapped in the vicinity of the studied lakes. All radiocarbon dates were calibrated using the CALIB program (Stuiver et al., 1998a,b) with one sigma error values.

3.3. SITE DESCRIPTION AND RESULTS

3.3.1. Mucubají Valley

The location and setting of the Mucubají valley (Figure 3.2) and the climatic conditions in the region make it a prime site for glaciation. The aspect of the valley is due north and the headwall elevation is 4609 m, just below the modern freezing height. Precipitation is abundant (~969 mm/yr) and cloud cover is extensive year-round. The watershed contains a cirque basin near the valley headwall. Lateral moraines that are up to 150 m high extend down the valley (Schubert, 1970; 1974). The moraines bend sharply to northeast following the axis of the Santo Domingo valley. A moraine dams Laguna Mucubají (3550m), the regions largest lake. The lake is fed by Quebrada Mucubají, which is a creek that drains the entire watershed and contributes 83 to 95% of its inflow (Salgado-Labouriau et al., 1992).

Situated up-valley of Laguna Mucubají are a series of recessional moraines that formed as ice retreated during the last deglaciation. Schubert (1970) documented the presence of at least 4 moraines that are cut by Quebrada Mucubají. A series of peat bogs have since formed. A vibra-core was extracted from the center of the bog situated behind the uppermost recessional moraine. The lower 2 m of the core contains coarse-grained sand to gravel with no organic material. The core then grades upward from coarse-grained sand to silt to fine clays (Figure 3.4). At 2.25 m, the core contains a 10 cm layer of very fine-grained organic rich, banded clays. The magnetic susceptibility profile shows that this was a period of low clastic input.

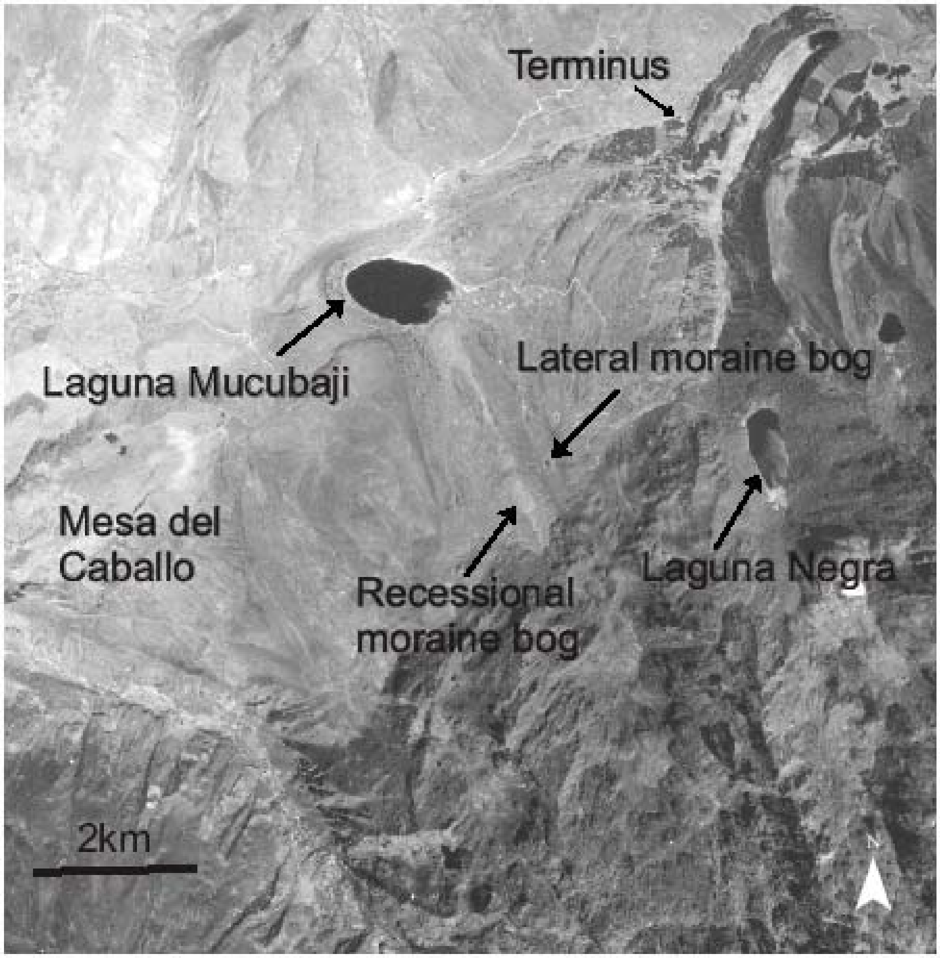

Figure 3.2. Aerial photograph of the Mucubaji valley.

Immediately above the glacial-interglacial sediment transition, aquatic macrofossils were sieved, picked and radiocarbon dated which yielded an age of ~15,950 cal yr BP. Above this sequence is an abrupt transition to inorganic fine-grained silt. A higher abrupt transition occurs at 1.7 m from which point peat dominates the remainder of the core. A sample 3 cm above this transition yielded a radiocarbon age of ~6,220 cal yr BP.

Figure 3.3. Mucubají valley recessional moraine bog coring site.

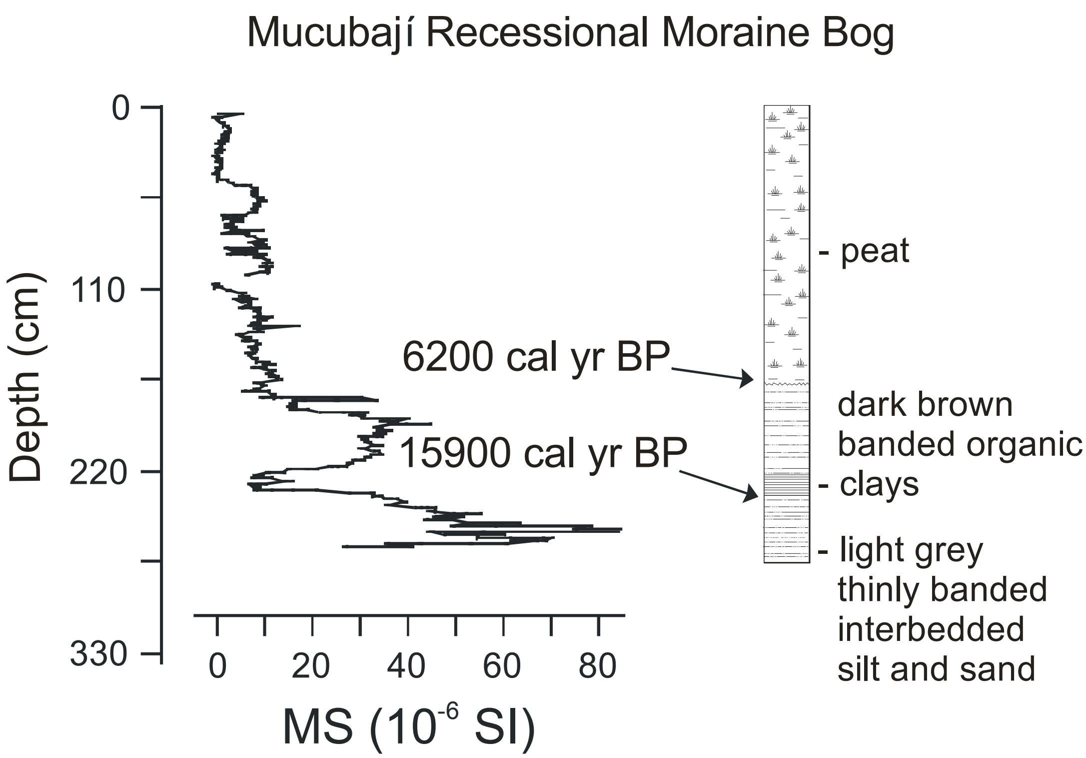

Figure 3.4. Magnetic susceptibility profile and stratigraphic column for the Mucubají recessional moraine bog.

3.3.1.1. Mucubají lateral moraine bog

A series of peat bogs have formed on top of the lateral moraines in the Mucubají valley. These high moraines have kept the bogs isolated from major erosional or flooding events since their time of formation. A 1.9 m long core (Figure 3.6) was retrieved from the surface of the lateral moraine on the eastern flank of the valley. The core grades upward from gray cobbles interbedded with sand to light brown peaty sediments. An organic rich sample from the base of the peat yielded a radiocarbon age of 9,510 cal yr BP.

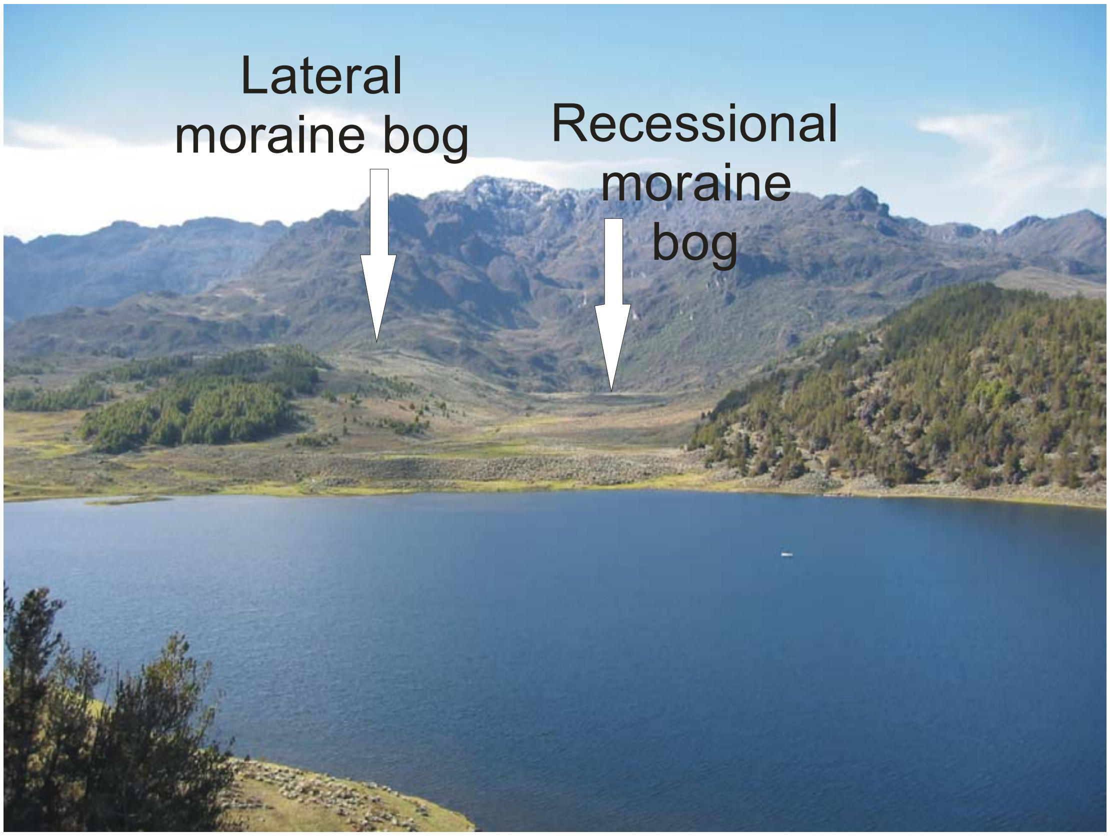

Figure 3.5. South facing photograph of the Mucubají valley. The white arrows indicate the locations of the recessional and lateral moraine bogs.

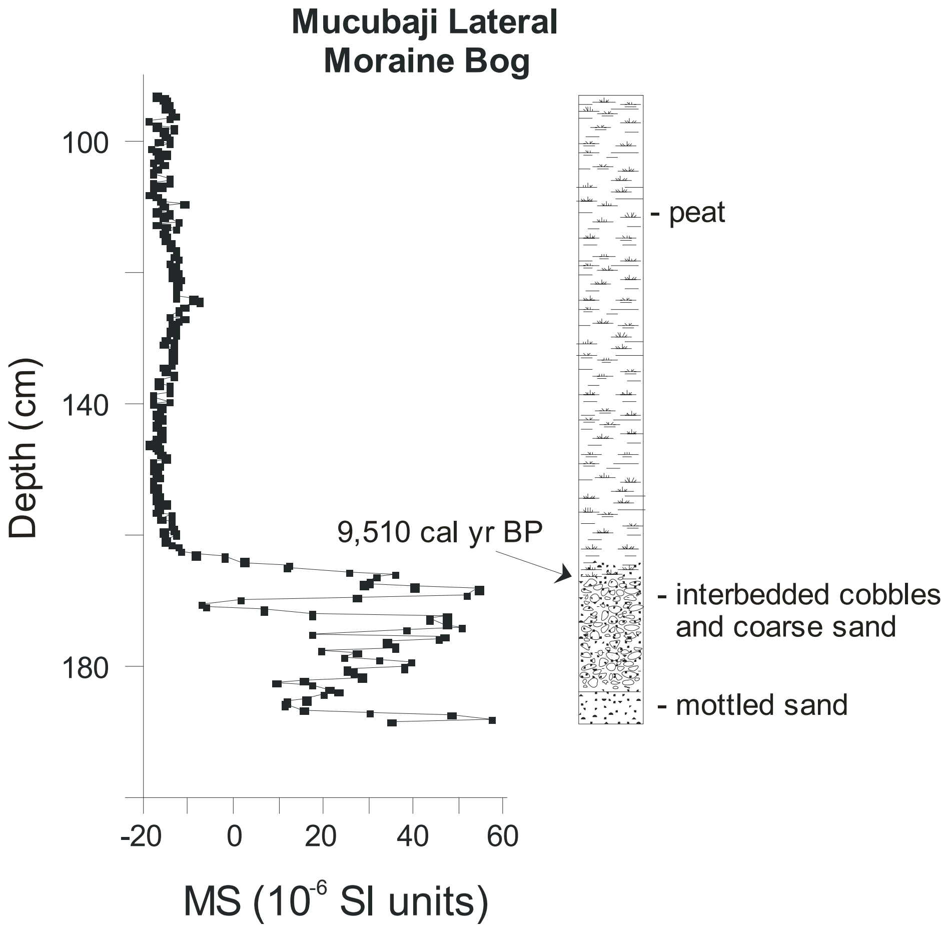

Figure 3.6. Magnetic susceptibility profile and stratigraphic column of the Mucubají lateral moraine bog.

3.3.1.2. Laguna Mucubají

Laguna Mucubají (3540 m) is ideally situated in order to record changes in regional glacial activity. A ~6 m core was retrieved from the deepest part of the lake. The lower ~2 m of the core records a gradually upward decreasing percentage of glacially derived sediment (Figure 3.8). At a depth of ~3.3 m, there is a sharp increase in clastic material. Following this section, clastic sediments decease for the remainder of the core. Polissar (2005) concluded that the watershed was ice free by ~5,400 cal yr BP.

3.3.2. Laguna Negra

The Laguna Negra (Figure 3.7) watershed is adjacent to the Mucubají valley. It is characterized by at least 2 major cirque depressions with northwest and northeast aspects. Laguna Negra (3473m) is situated on a plateau in a narrow, steep walled valley. The northern edge of the lake overhangs the Santo Domingo river valley. A ~5.2 m core was retrieved from the center of the lake (Figure 3.8). At a depth of ~3.8 m, the sediments record an abrupt transition from glacially derived inorganic silt overlain by organic rich, fine-grained clays for the remainder of the core. Aquatic macrofossils immediately above this transition yielded a radiocarbon age of ~10,070 cal yr BP.

Figure 3.7. Photograph of Laguna Negra (3473 m a.s.l.) in the Sierra de Santo Domingo

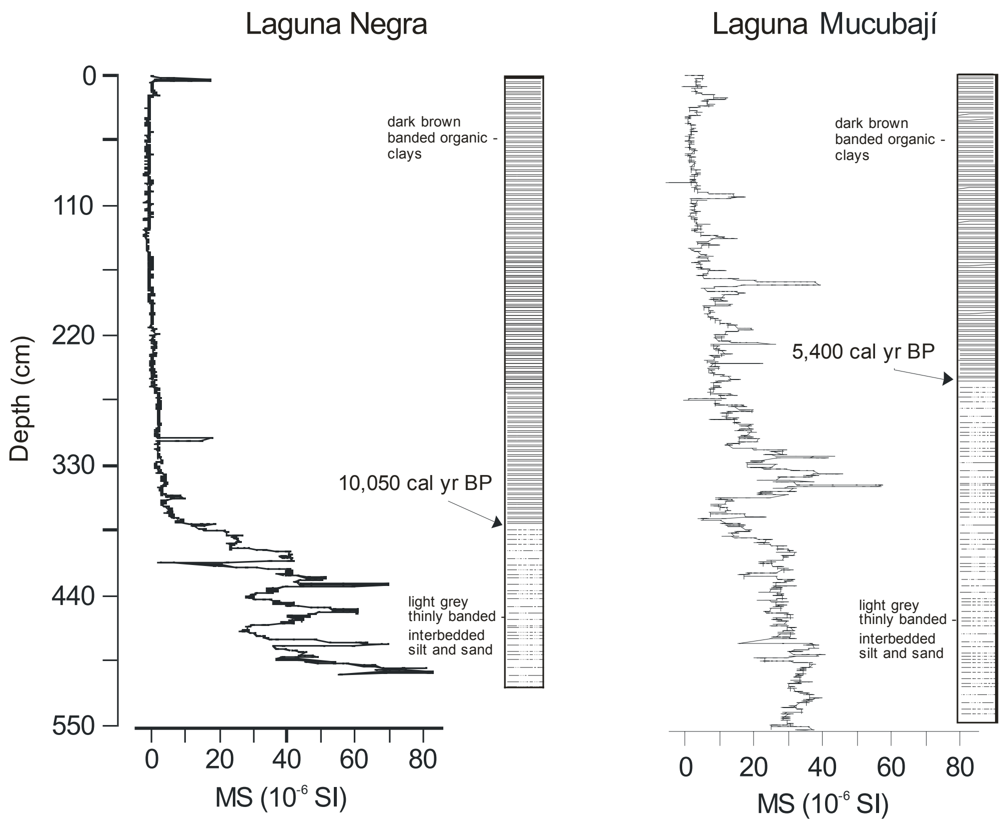

Figure 3.8. Magnetic susceptibility profiles and stratigraphic columns for lake sediment cores from Laguna Mucubají and Laguna Negra

3.3.3. Paramo de Piedras Blancas

The Paramo de Piedras Blancas is situated on a regional topographic divide between the Rio Santo Domingo valley to the southeast and Lago Maracaibo to the northwest. Schubert (1974) identified a single level of major morainic loops in the region that he attributed to the latest Pleistocene glaciation. These deposits do not extend below elevations of ~3400 to 3700 m. Within the major moraine loops are numerous smaller moraines representing minor glacial readvances (Schubert, 1974). Glaciation in this arid region was primarily restricted to large ice caps as opposed to the large valley glaciers that formed in the more humid Santo Domingo region. As the ice caps retreated, they formed a series of small lakes dammed by recessional moraines.

3.3.3.1. Laguna Verdes Alta and Baja

Laguna Verdes Alta (4215 m) and Baja (4170 m) are small lateral-moraine dammed lakes on the SW slope of the Chama river valley (Figure 3.9). Vegetation in the region is sparse, belonging to the desert paramo type (Monasterio, 1980). Water depths are 3 m and 5 m, respectively and sediment cores were retrieved from the deepest part of each lake. The cores from both lakes contain almost entirely coarse-grained glacial silts at the bases overlain by organic clay-rich sediments (Figure 3.10). Plant macrofossils were extracted from these transition intervals, which yielded radiocarbon ages of ~14,240 cal yr BP for Laguna Verdes Alta and 15,400 cal yr BP for Laguna Verdes Baja.

Figure 3.9. Photograph of Laguna Verdes Alta (4215 m a.s.l.).

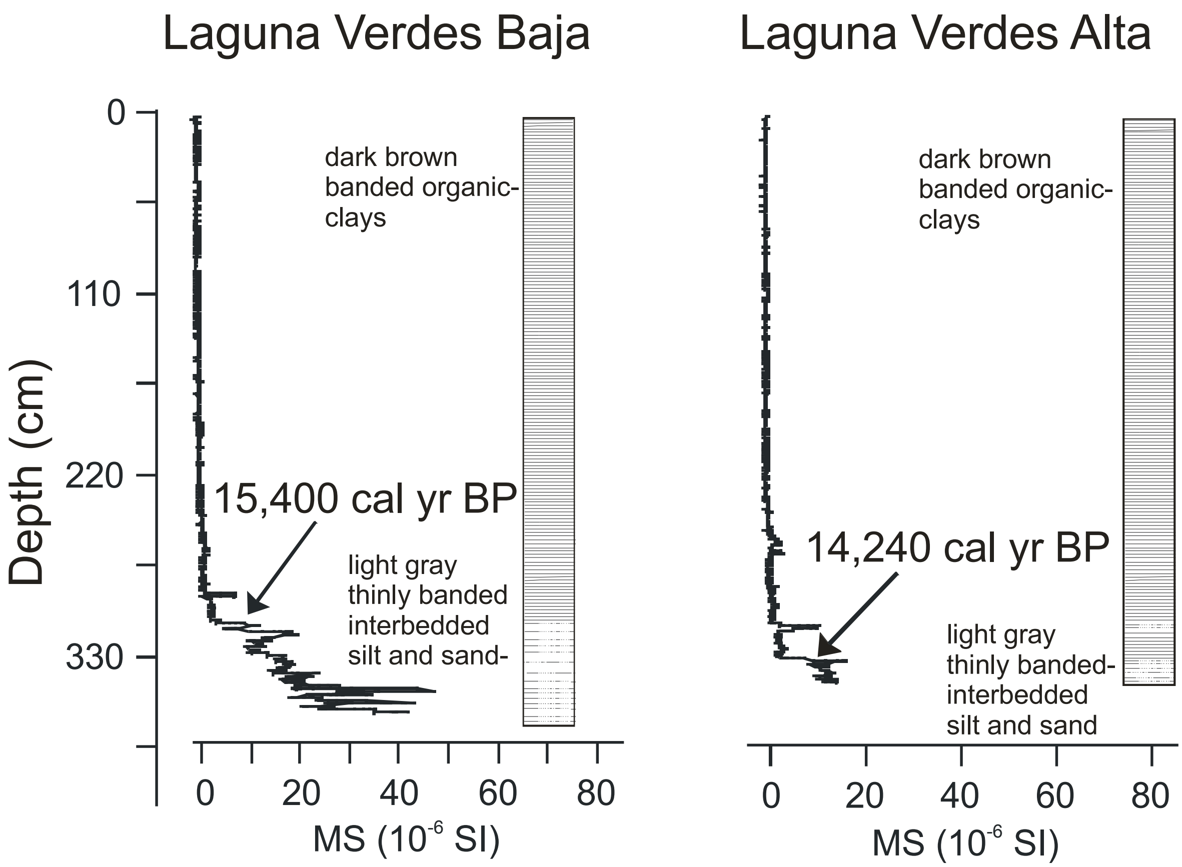

Figure 3.10. Magnetic susceptibility profiles and stratigraphic columns for lake cores from Lagunas Verdes Alta and Baja

3.3.3.2. Laguna Grande de Los Patos

Adjacent to the Paramo El Banco, and west of Mesa Redonda are a series of small closed-basin lakes. Laguna Grande de Los Patos (Figure 3.11) is a ~10 m deep lake situated high on a plateau. The vegetation in the region is restricted to the super-paramo type. The soil is coarse-grained and poorly developed which is likely the result of Pleistocene glaciation and the modern day extreme variability in temperature and precipitation. The surrounding topography is hummocky and the elevation of the lake (4185 m) is approximately equal to that of the headwall of the valley.

Figure 3.11. Laguna Grande de Los Patos (4228 m a.s.l.) in the Paramo de Piedras Blancas.

A 3.8 m sediment core was retrieved from the deepest part of Laguna Grande de Los Patos. The sequence shows a sharp transition from glacial silt at the base of the core overlain by organic fine-grained clays (Figure 3.13). Aquatic macros were sieved and picked which yielded a radiocarbon age of 10,070 ± 80 cal yr BP. Approximately 5 cm above this organic layer is a 3 cm thick interval of inorganic silt. Above this interval non-glacial, organic rich clays dominate for the remainder of the core. These transitions are recorded in the magnetic susceptibility profile, indicating high values during increased silt accumulation and low values for the remainder of the core.

3.3.3.3. El Posito

Approximately 300 m east and 50 m above Laguna Grande de Los Patos is a small isolated lake with a water depth of ~2 m (Figure 3.12). The entire sediment record was collected in a 1.3 m long core. The sediment record shows an abrupt transition from light gray, glacial silt to very fine-grained organic clay rich sediments at the base (Figure 3.13). Aquatic macros were sieved and picked at this transition yielding a radiocarbon age of 9,330 ± 60 cal yr BP.

Figure 3.12. Photograph of Laguna El Posito (4228 m a.s.l.).

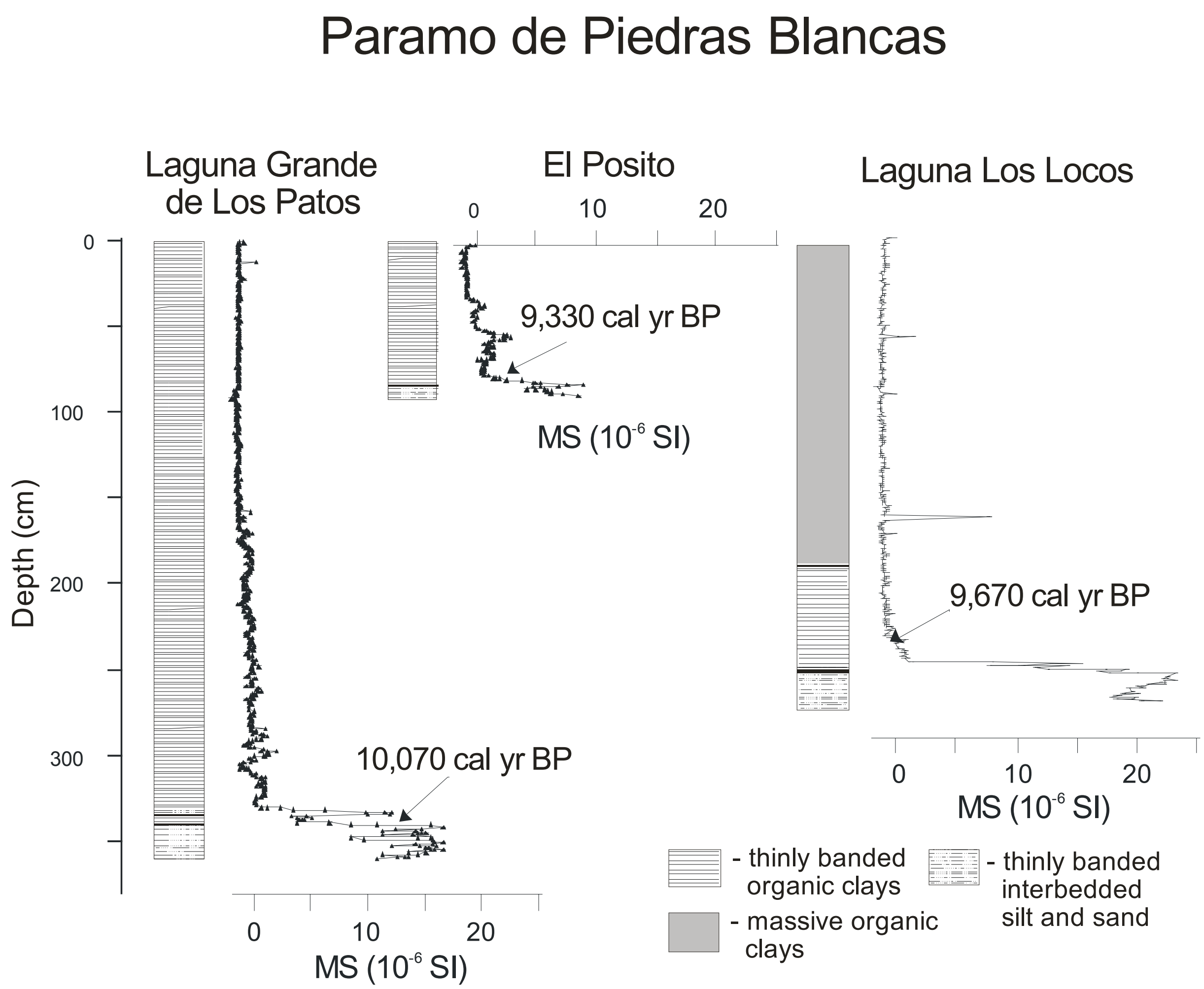

Figure 3.13. Magnetic susceptibility profiles and stratigraphic columns for lake cores from the Paramo de Piedras Blancas

3.3.3.4. Laguna Los Locos

Laguna Los Locos is situated where a large paleo-ice cap accumulated during the last major glaciation. The perimeter of the lake is approximately equal to the highest elevation (4366 m a.s.l.) of the watershed. Vegetation is sparse and soil development is typical of the superparamo. There are no major inflows and the lake is fed primarily by precipitation. A ~2.4 m core retrieved from the deepest part of the lake. This core has an abrupt transition from gray inorganic silt to fine-grained, organic rich sediments near the base of the core. This abrupt transition is shown by the magnetic susceptibility profile (figure 3.13). Charcoal from a 4 cm section immediately above the glacial to interglacial transition was isolated which yielded a radiocarbon age of 9,670 ± 130 cal yr BP.

Figure 3.14. Photograph of Laguna Los Locos (4366 m a.s.l.).

Table 3.1. Radiocarbon dates used to characterize the Late-Quaternary deglacial history of the Venezuelan Andes

Sample location	Lat (°N)	Lon (°W)	Elevation (m)	Sample material	^{14}C yr BP	±	1σ calibrated age (cal yr BP)	1σ error ±	Description
Laguna Grande de Los Patos	8.813	-70.949	4185	aquatic macros	8880	60	10070	80	glacial/organic sediment transition
El Posito	8.813	-70.951	4228	aquatic macros	8350	60	9330	30	glacial/organic sediment transition
Laguna Los Locos	8.863	-70.897	4366	charcoal	8690	60	9670	130	glacial/organic sediment transition
Laguna Mucubaji	8.797	-70.829	3577	aquatic moss	7380	100	8180	30	glacial/organic sediment transition
Laguna Negra	8.783	-70.805	3473	aquatic macros	8910	40	10050	25	glacial/organic sediment transition
Mucubaji lateral moraine bog	8.785	-70.818	3620	peat	8500	50	9510	20	glacial till/peat transition
Mucubaji recessional moraine bog	8.784	-70.823	3615	peat	13270	80	15950	280	glacial/organic sediment transition
Mucubaji recessional moraine bog	8.784	-70.823	3615	aquatic macros	5470	35	6220	15	onset of peat deposition
Laguna Verdes Alta	8.853	-70.874	4215	bulk	12270	150	14238	166	glacial/organic sediment transition
Laguna Verdes Baja	8.859	-70.874	4170	leaf macros	12740	130	15397	246	glacial/organic sediment transition

3.4. DISCUSSION

Schubert and Rinaldi (1987) reported that the Last Glacial Maximum (LGM) occurred in the Venezuelan Andes between ~20,600 to 17,760 cal yr BP. Three major phases of deglaciation followed the LGM, which were interrupted by at least one readvance. The first deglacial phase occurred at ~15,950 cal yr BP as recorded in the Mucubaji recessional moraine bog. The following period is characterized by an oscillating ice front in the Mucubají valley. This is inferred from an alternating peat/fluvio-gravel sediment sequence in the Mesa del Caballo (Figure 3.2) during ~14,340 to 13,970 cal yr BP (Salgado et al., 1977). The Laguna Verdes Alta and Baja cores record ice free conditions by 15,400 to 14,240 cal yr BP.

The period following the initial deglacial phase from 15,900 cal yr BP until the onset of ice free conditions is not well preserved in the sediment records presented in this paper. At least one readvance occurred after ~14,000 cal yr BP at locations above 4200 m where ice remained until ~10,000 cal yr BP. Other records from the region can be used to infer relative changes in temperature and humidity during this period. For instance, the period from 15,500 to 14,000 cal yr BP was relatively warm and arid (Bradbury et al., 1981; Weingarten et al., 1991; Curtis et al., 1999; Rull et al., 2005). An increase in organic material in the LVA and LVB cores suggests that the period between ~14,000 and 12,600 cal yr BP was relatively warm and arid with an increase in upslope orographic winds (Rull et al., in review). This period coincides with the previously reported Mucubají warm phase (Salgado-Labouriau, 1989; Rull et al., 1999).

The Younger Dryas (~10,500 - 13,000 cal yr BP) was a period of colder conditions in the north Atlantic region and the Cariaco Basin off the north coast of Venezuela (Hughen, 2000). However, the Younger Dryas (YD) has not been documented in the tropical Andes. Likewise, the true global effects of this event are not currently resolved. Results from previous work in

Venezuela suggest that the time from ~12,600 to 11,000 cal yr BP corresponds to colder conditions (Rull et al., 2005). This is recorded at Laguna Los Lirios (Weingarten et al., 1991) and Mucubají where temperatures were 2 to 3°C cooler (Salgado-Labouriau, 1989). This is consistent with the Colombian El Abra cold stadial (Van der Hammen and Hooghiemstra, 1995) and a return to colder conditions in the Cariaco Basin off the northern coast of Venezuela (Hughen et al., 2004). Wetter conditions during this period were recorded in Lake Valencia, in lowland northern Venezuela (Salgado-Labouriau, 1980; Leyden, 1985).

Marine records during the YD are also unclear. SST's in the Cariaco Basin, off the northern coast of Venezuela, were reduced by 3 to 4°C followed by an abrupt increase at ~11,490 cal yr BP (Lea et al., 2003). This is in contrast to tropical Atlantic records which indicate warmer SST's of ~3 to 4°C followed by a decrease in SST's from 11,000 to 10,000 cal yr BP (Ruhlemann et al., 1999). Coral records from Barbados indicate Tropical SSTs were similar to today at ~13,000 followed by a ~2°C cooling which lasted until 9,500 cal yr BP (Guilderson et al., 1994).

The titanium record from the Cariaco Basin has been interpreted as being a measure of terrigenous weathering and shows that the Preboreal period (11,500 to 10,400 cal yr BP) was a period of increasingly wet conditions (Haug et al., 2001) and the northern tropics likely experienced stronger monsoons due to increased summer insolation. A trend towards drier conditions started at the peak of the northern hemisphere Holocene thermal maximum (Haug et al., 2001). The Mucubaji valley lateral moraine bog records a major glacial retreat at ~9,510 cal yr BP. This glacial retreat is confirmed in the adjacent Laguna Negra valley which was completely ice free by 10,050 cal yr BP. The Paramo de Piedras Blancas region was completely ice free by 9,330 cal yr BP.

The Mucubají valley was completely ice free by 6,200 cal yr BP based on the peat record from the Mucubají recessional moraine bog core. The Mucubají watershed has a high headwall (4609 m) elevation and a northern aspect, which allowed it to hold ice longer than most watersheds in the region. This period corresponds closely to the end of the Holocene thermal maximum and the onset of drier conditions in the Cariaco Basin sediments (Haug et al., 2001).

Regional deglaciation records for the northern tropics are limited and future work is needed. Glacial records from Cerro Chirripo in Costa Rica show a cluster of radiocarbon dates centered on ~9,700 cal yr BP (Orvis and Horn, 2000) which indicates a minimum date for deglaciation. Colombian deglacial dates are bracketed by radiocarbon ages between 13,810 to 8,040 cal yr BP (Thouret et al., 1997).

Records from the southern hemisphere Andes are not clear. Clapperton et al. (1997) document ice free conditions in Ecuador by ~ 13,800 cal yr BP followed by a readvance between ~12,000 to 11,000 cal yr BP. Deglaciation likely culminated by ~10,200 cal yr B.P. (Heine and Heine, 1996; Orvis and Horn, 2000). A series of glacial advances occurred between ~16,000 and 13,000 cal yr BP in the southern tropical Andes (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 the onset of the Younger Dryas 12,800 cal yr BP (Rodbell and Seltzer, 2000; Seltzer et al., 2002). Abbott et al. (1997) have a series of younger dates from the eastern Cordillera Real, Bolivia that range from 10,240 to 9,540 cal yr BP and on the western slope from 9,680 to 9,440 cal yr BP. Dates from Paco Cocha, Peru indicated ice free conditions at ~10,000 cal yr BP (Mark et al., 1999; Abbott et al., 2003).

Insolation drives gradual, long-term climate variability and therefore cannot be used to completely explain the chronology of glacial events during the Pleistocene-Holocene transition in the northern Andes. Glaciation was likely driven by a combination of moisture availability, temperature fluctuations and gradually increasing northern hemisphere summer insolation values. By ~15,000 cal yr BP insolation values increased by ~40 Langleys/day (e.g. Berger, 1978; Seltzer, 1994), which may explain the initial phase of deglaciation. At a time when northern hemisphere insolation values continued to increase, a major glacial readvance occurred at ~14,000 cal yr BP. This ended by ~10,000 cal yr BP in most humid and arid regions. North facing, high elevation watersheds held ice until ~ 6,200 cal yr BP. Temperature and precipitation must have played a major role though the changes in precipitation would have to have been major. Therefore, it is more likely that temperature was the major driving factor of glaciation in this region of the Andes.

3.5. CONCLUSIONS

Deglaciation in the Venezuelan Andes was underway by ~15,900 cal yr BP in response to increased northern hemisphere summer insolation. Watersheds were ice free by ~12,600 cal yr BP in arid regions below ~4200 m as shown by the records from Lagunas Verdes Alta and Baja. Records from the Paramo de Piedras Blancas and the Sierra de Santo Domingo indicate that at least one major readvance occurred after 14,000 cal yr BP and ice remained until ~10,000 cal yr BP in humid regions above ~4200 m. The record spanning the Younger Dryas in the Venezuelan Andes remains uncertain because a record is not well preserved. However, the paleo-environmental records produced by other workers combined with the results presented here suggest that the Younger Dryas was a period characterized by colder and drier conditions. Ice remained in north facing, high elevation watersheds until 6,200 cal yr BP. Glaciers expanded and remained at a time of increasing northern hemisphere summer insolation. Therfore, glacial variability in the northern tropical Andes following the LGM cannot be attributed to forcing alone and additionally requires changes in moisture availability, temperature, or both.

4. CONCLUDING REMARKS AND FUTURE WORK

There are many field based questions that need to be answered in the tropical Andes. The most obvious are the absolute ages for the LGM and the associated timing of deglaciation. The LGM is difficult to date as organic deposits bracketing the event are difficult to acquire. There are possibilities of using techniques such as cosmogenic dating of the surfaces of moraines. However, these methods are very preliminary and have been used mostly in more arid regions because humid regions tend to have higher analytical errors due to higher weathering rates. Nevertheless, these types of studies will improve the presently available chronology and these ages are essential in order to compare the role of climate change in tropics versus the higher latitudes.

Refining the deglacial chronology requires more AMS radiocarbon dates on lake sediments and bog deposits. Particularly, lakes should be targeted from a series of elevations along transects through the Andes. These records will record multiple glacial advances/retreats from regions with varying aspects and sensitivities to changes in moisture availability. In addition, bog deposits should be utilized more in paleo-environmental research because they have the potential to record multiple glacial events.

There are a number of analytical questions that need to be answered in order to better characterize the climate during the LGM. The best estimate of a LGM atmospheric lapse rate proposed by atmospheric physicists ranges from 0.55 to 0.75°C/100m. Further investigations are needed in order to refine these values. This requires an increased understanding of atmospheric dynamics and an improved model of the thermal structure of the lower troposphere during periods of glaciation. Precipitation values during the LGM also introduce large uncertainties and estimates require other proxy information such as pollen, lake level studies and ice core data. As research in these areas continues and data becomes available, the temperature estimates proposed in this paper may be refined.

Reconstructing climate change is hindered by a lack of modern meteorological data in climate sensitive regions. This problem is compounded as these conditions likely varied on glacial-interglacial time-scales. The spatial and temporal patterns of such conditions as precipitation, air temperature, wind speed, incoming short wave and long wave radiation are important for glacier dynamics. When these data become available, more accurate climate modeling may be achieved.

Future research is needed in order to address climate variability within the Andes. Specifically, there is a need to investigate the mechanisms that have controlled past changes in moisture availability and the concurrent glacial response. The fields of glaciology and paleo-environmental research are segregated, however, the micro-climates of many high-altitude sites during the late Quaternary were impacted by glaciation. Therefore, Andean paleo-environmental analysis requires an understanding of glacier-climate interaction and will benefit by using glaciers as recorders of climate change. Future records of lake response to glacial activity and landform evolution should be coupled with GIS, remote sensing, GPS methods and mathematical modeling in an effort to reconstruct paleo-environmental conditions. Field and analytical techniques of modern glaciology should be incorporated into paleo-environmental research methods to increase the understanding of glacio-lacustrine processes and climate modeling.

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