CRONOLOGÍA ACTUALIZADA DE NUCLEIDOS COSMOGÉNICOS EN EL ÁREA DE MUCUBAJÍ, ANDES DE MÉRIDA (VENEZUELA). CONTRIBUCIONES AL CONOCIMIENTO PALEOGLACIOLÓGICO Y NEOTECTÓNICO

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RESUMEN

Durante la última década, parte de la morfología glaciar en los Andes centrales de Mérida ha sido estudiada utilizando la geocronología con el isótopo cosmogénico terrestre ^{10}Be. La cronología está disponible para las morrenas del Desecho, La Victoria, Los Zerpa, Las Tapias y el valle de Mucubají. Sin embargo, los datos han sido obtenidos utilizando diferentes tasas de producción y diferentes parámetros para escalar en el tiempo dicha producción. En esta forma, es difícil compararlos y discutir sobre historias de desglaciación y neotectónica. En este artículo, la cronología fue recalculada usando mismos parámetros de tasa de producción y el mismo modelo de variación de producción del isótopo comsogénico dependiente del tiempo. Las edades de exposición indican que la desglaciación comenzó en el valle de Mucubají durante el Último Máximo Glacial hace unos 22-21 ka, mientras que los paleoglaciares de las morrenas del Desecho, Los Zerpa y Las Tapias comienzan a desaparecer durante un episodio de calentamiento entre los 19-18 ka. También han sido determinadas tasas de desplazamiento de la falla de Boconó. Valores entre 1.90-2.35 mm/año han sido obtenidas para la traza norte, mientras que, para la traza sur, han sido obtenidos valores entre 3.33-6.25 mm/año.

Palabras clave: geocronología con isótopos cosmogénicos terrestres, morfología glaciar, historias de desglaciación, Mérida Andes, Falla de Boconó, neotectónica.

REVISED COSMOGENIC NUCLIDE CHRONOLOGY IN THE MUCUBAJÍ AREA, MÉRIDA ANDES (VENEZUELA). CONTRIBUTIONS FOR GLACIAL AND NEOTECTONIC KNOWLEDGE

ABSTRACT

Glacial chronology based on ^{10}Be-Terrestrial Cosmogenic Nuclide dating during the last decade, have been obtained in the central Mérida Andes. Data is available from El Desecho, La Victoria, Los Zerpa and Las Tapias moraines and the Mucubají valley. However, exposure ages have been obtained considering different cosmogenic production rates and scaling schemes to obtain cosmogenic production in time. Such data as it stands is not comparable in order to establish deglaciation histories and neotectonic rates. So, previously published exposure ages of the Mucubají valley and surroundings were recalculated using the same ^{10}Be production rate and scaling scheme. Exposure ages indicate deglaciation has begun during the Last Glacial Maximum in the Mucubají valley at around 22-21 ka and, a warming episode between 19-18 ka yield paleo or former glaciers retreats from El Desecho, Los Zerpa and Las Tapias moraines, and in the Mucubají valley. Moreover, deglaciation histories and Boconó Fault slip rates were also refined with updated exposure ages. In the northern strand of the Boconó Fault slip rate values were estimated between 1.90-2.35 mm/a, whereas in the southern strand rates range between 3.33-6.25 mm/a.

Keywords: terrestrial cosmogenics nuclides geochronology, glacial landforms, deglaciation histories, Mérida Andes, Boconó Fault, neotectonic.

INTRODUCTION

In the Mérida Andes, glaciers and glacial landforms have been studied since the end of the XIX and beginning of the XX centuries (e.g. Sievers, 1885; Jahn, 1912, 1925). Moraines have been an important glacial landform studied to reconstruct glaciations or deglaciation histories (e.g. Schubert, 1974; Mahaney et al., 2000; Mahaney et al., 2010; Stansell et al., 2005; Carcaillet et al., 2013) and, to understand neotectonics in the region (e.g. Schubert and Sifontes, 1970; Audemard et al., 1999; Wesnousky et al., 2012).

Well preserved moraines are evidenced in the landscape of the central Mérida Andes, some of which have been dated based on different chronological methods, such as radiocarbon (Schubert, 1970; Mahaney et al., 2001; Mahaney et al., 2007), Thermoluminescence (TL; Schubert and Vaz, 1987; Bezada, 1989), Optically Stimulated Luminescence (OSL, Mahaney et al., 2000) and more recently, Terrestrial Cosmogenic Nuclide (TCN) dating (Wesnousky et al., 2012; Carcaillet et al., 2013; Angel, 2016). However, glacial chronology is still limited and this hinders the reconstruction of deglaciation histories and glaciation knowledge in the region (e.g. Carcaillet et al., 2013).

Most moraines have been dated in the region based on radiocarbon dating; however, this chronological method most of time is indirectly related to the deglaciation age of a moraine (e.g. González et al., 1965; Helmens, 1988). This fact renders difficult to reconstruct deglaciation histories. In contrast, a moraine age obtained by Terrestrial Cosmogenic Nuclide (TCN) dating, allows reconstructing a better deglaciation history since the immediate glacier retreat can be dated (e.g. Gosse and Phillips, 2001; Dunai, 2010).

This article compiles glacial chronology based on Terrestrial Cosmogenic Nuclide ^{10}Be dating (^{10}Be-TCN) located in the surroundings of Mucubají valley, Mérida Andes, specifically from El Desecho, La Victoria, Los Zerpa, Las Tapias moraines and the Mucubají valley. In this region, ^{10}Be-TCN ages are available from Wesnousky et al. (2012), Carcaillet et al. (2013) and Angel (2016). Glacial chronology from El Desecho and Las Tapias moraines (Angel, 2016), were obtained thanks to different institutions. French institutions as Université de Grenoble-Alpes and Institute de Recherche pour le Development (IRD), which supplied significant economic resources to dating, and the GIAME project from FUNVISIS which financed field trips.

Glacial chronology from previous published studies (Wesnousky et al., 2012; Carcaillet et al., 2013 and Angel, 2016) are based on different cosmogenic production rates and scaling schemes which hinders any reliable comparison. In the following, exposure ages are recalculated considering same and updated parameters to reconstruct the deglaciation history surrounding the Mucubají valley during the Marine Isotope Stage (MIS) 2. In addition, this article aims at contributing with the regional neotectonic knowledge in the same period using exposure ages of glacial landforms deformed by the Boconó Fault.

REGIONAL SETTING

Geologic, tectonic and geomorphic settings

The Mérida Andes (MA) are located in the southwest of Venezuela, they are ~N45E oriented and extend over 400 km. The MA highest elevation is the Pico Bolivar with 4978 m a.s.l. The MA orogenesis is mainly connected to the geodynamic interaction of the Panamá Arc, Caribbean and South American plates (Taboada et al., 2000; Audemard and Audemard, 2002; Bermudez, 2009; Monod et al., 2010). Quaternary uplift because of these plates interactions ranges between ~0.7 and 5 mm/a (Audemard and Audemard, 2002; Wesnousky et al., 2012; Guzmán et al., 2013).

Present-day deformation in the Mérida Andes is mainly accommodated by the Boconó Fault. It is a NE–SW trending right-lateral strike–slip (RLSS) fault that extends for about 500 km (Audemard and Audemard, 2002; Audemard, 2009, 2014). It extends between the Táchira depression, at the border between Colombia and Venezuela, and the town of Morón located on the Caribbean coast (Audemard and Audemard, 2002). In Morón, the Boconó fault exhibits a 45° clockwise bend, and continues into the east–west striking San Sebastián–El Pilar fault system (Audemard and Audemard, 2002).

Right-lateral offsets of Quaternary features by the Boconó Fault (BF) such as glacial landforms as for example moraines but also drainages, alluvial deposits and shutter ridges, range from 60 to 100 m depending on their age (Audemard, 1998, 2009a; Audemard et al, 1999, 2008; Audemard and Audemard, 2002). Deposits as moraines from the Late Pleistocene glaciation, locally known as Late Mérida Glaciation during Marine Isotope Stages 2 and 1 (MIS 2 and MIS 1) are particularly abundant along the central section of the Boconó Fault (Schubert, 1974; Schubert and Vivas, 1993; Kalm and Mahaney, 2011; Wesnousky et al., 2012; Carcaillet et al., 2013). Quaternary slip rates values for the BF, as individual traces of as a system, are between 3 and 14 mm/a (Audemard et al., 1999; Audemard, 2003). In the central MA, at the Apartaderos pull-apart basin, the BF slip rates for the south and north strands, range between 2.5–10 mm/a based on the shifted moraine of Mucubají, Los Zerpa and La Victoria valleys (Schubert and Sifontes, 1970; Soulas, 1985; Soulas et al., 1986; Audemard et al., 1999; 2008; Wesnousky et al., 2012); and between 2.3–3.0 mm/a for the northern strand based on El Desecho moraine and around 7.5 mm/a for the southern main strand (Audemard et al., 1999, 2008), totaling some 10 mm/a in the Mucubají region.

Quaternary glaciations in the central Mérida Andes

Typical features of high mountains affected by glaciations have been observed in the MA above ~2500 m (Schubert and Vivas, 1993). In the central MA, two moraine complexes are observed between 2600-2800 m and 3000-3500 m; these moraine complexes evidence glacier activity during the Quaternary (Royo and Gómez, 1959; Schubert, 1970; 1972, 1974; Schubert and Valastro, 1974). Schubert (1974), based on these two moraine complexes, established the Mérida Glaciation. The Mérida Glaciation was divided in the Early Mérida (~90-60 ka) and the Late Mérida Glaciation (~24-13 ka) (Schubert, 1970, 1974; Kalm and Mahaney, 2011).

Early Mérida Glaciation moraines (the lowest complex between 2600-2700 m) are covered by abundant vegetation and are characterized by extremely weathered till, deeply eroded, which still shows striated and faceted pebbles (Schubert, 1974). The Early Mérida Glaciation is poorly constrained because few chronologies are available, ages range between ~60 and ~90 ka (Mahaney et al., 2000; Mahaney et al., 2001; Dirszowsky et al., 2005; Mahaney et al., 2010; Kalm and Mahaney 2011), corresponding to the MIS 4, MIS 5. Late Mérida Glaciation (Late Wisconsin) is better constrained, moraines are located between 3000-3500 m and ages range between 25-13 ky (MIS 2) (based on limited radiocarbon ages; Schubert 1974; Schubert and Valastro, 1974; Schubert and Clapperton, 1990).

Study region

The study region is located between El Desecho and Las Tapias moraines (Figure 1). El Desecho moraine is located at the North of the Mucubají valley; this terminal moraine is ~ 1 km long and it is NE-SW oriented (Figure 2a). Evidence of the Boconó Fault across El Desecho moraine can be observed in the field by the fault scarp (Figure 2b). At the east of El Desecho moraine, Las Tapias moraines are located with a NW-SE orientation (Figure 3). Between both moraines, from SW-NE is located the Mucubají valley with different moraines inside the valley (for more details, refer to Audemard, 2009a and Carcaillet et al., 2013). At the NE of this valley, La Victoria and Los Zerpa moraines are located (for more details, refer to Audemard, 2009a and Wesnousky et al., 2012) (Figure 3).

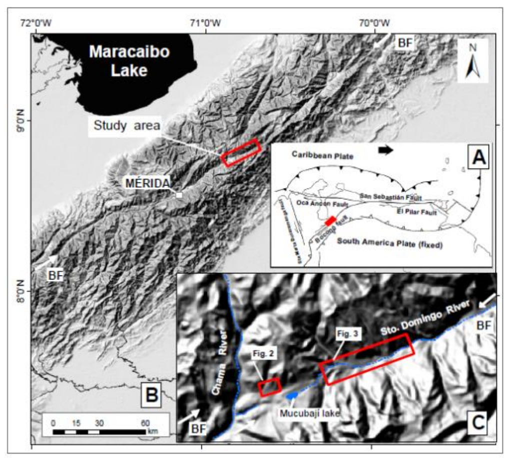

Figure 1. Study region location in the central Mérida Andes (red rectangle). A) A general geodynamic context of northern South America (modified from Audemard et al., 2010). B*) The study region is located close to the Mucubají Lake at elevations higher than 3100 m, with influences of Santo Domingo and Chama River catchments (Digital Elevation Model from Garrity et al., 2004). C) El Desecho moraine is located inside red rectangle with Fig.2 and La Victoria, Los Zerpa and Las Tapias moraines are inside red rectangle with Fig.3. The Mucubají valley is at the southeast of the Mucubají Lake.*

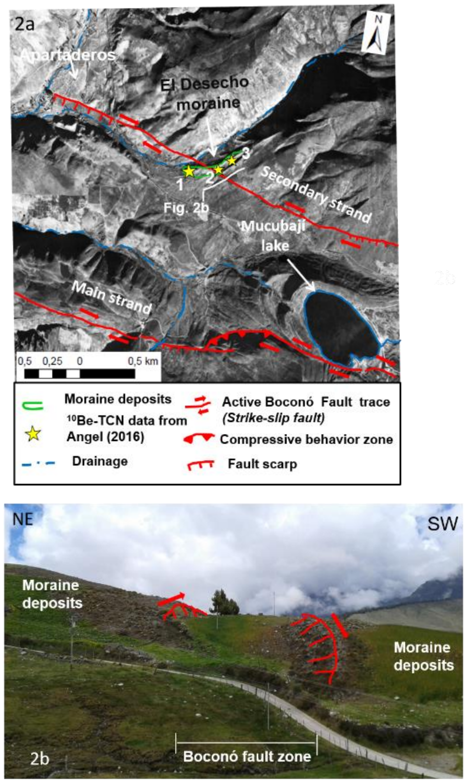

Figure 2. 2a) ^{10}Be-TCN data or exposure ages from the El Desecho moraine from Angel (2016) on aerial photograph from Mission 010455 Cartografía Nacional picture 004. 2b) Boconó Fault scarp on El Desecho moraine (picture from Luz Rodríguez).

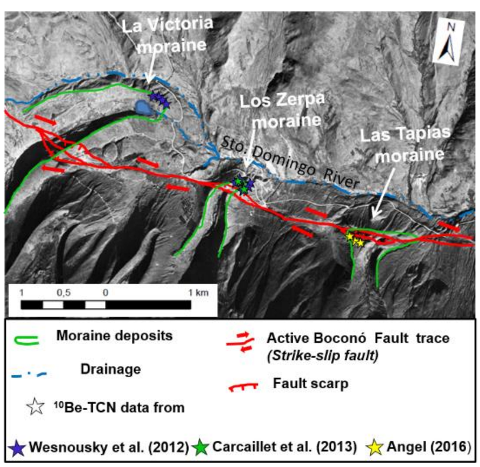

Figure 3. Las Tapias moraines with ^{10}Be-TCN data from Angel (2016) (stars most of the east located in the figure) and, La Victoria and Los Zerpa exposure ages from Wesnousky et al. (2012) and Carcaillet et al. (2013). Moraine deformation caused by the Boconó Fault can be observed (aerial photograph from Mission 010455 picture 004).

METHODS AND MATERIALS

Morphostratigraphic relation of moraines and implications on reconstruction of glaciations or deglaciation histories

Glaciation or deglaciation history reconstructions involve paleo- or former glacier dynamics; this means, the study of paleo- or former glacier advances or retreats in a region. This dynamics of former glaciers occurred in space and time. Timing reconstruction of former glaciers can be deduced from morphostratigraphic analyses of glacial landforms. Spatial distribution of glacial landforms in a landscape provides qualitative chronological information (e.g. Hughes et al., 2005). For example, in a valley, moraines at low elevations were deposited by a glacier before the upper ones. When a glacier retreats, glacial landforms such as moraines or "roches moutonnées" (fr.) lower elevations are first exposed, then, glacial landforms at highest elevation are lately exposed.

Ice-marginal moraines (a lateral, a frontal or a latero-frontal) are created during a period of the glacier equilibrium with climate during deposition followed by a period of positive mass balance (e.g. Benn and Evans, 2010). During a period of positive mass balance, mass accumulation occurs in a glacier, so the glacier grows, it advances and it creates an ice-marginal moraine. Therefore, it denotes a glacier advance. The lowest one limits the maximum glacier advance in a valley. The frontal or a latero-frontal moraine related to the maximum glacier advance is denoted as a terminal moraine.

It is important to note that a moraine, or in general a glacial landform study, represents a partial record of the glaciation history in a region (e.g. Kirkbride and Brazier, 1998). For example, all glacier advances that occurred in a valley could be poorly represented by moraines distribution in a landscape. This is because different processes could remove ancient moraines: a) a more extended and younger glacier advance, b) proglacial erosion, c) denudation and, d) gravitational processes (landslides) (Kirkbride and Brazier, 1998). Therefore, integration with studies from sediment deposits close to glacier margin (proglacial environments), as for example from a proglacial lake or terraces, complements glaciation reconstruction studies.

^{10}Be TCN dating implications on deglaciation histories reconstruction

The interaction between cosmic rays and chemical targets of the Earth environment produces Beryllium-10 (10Be). It is a cosmogenic nuclide isotope (Half-life 1.36 ± 0.07 Ma) (Gosse and Phillips, 2001). This cosmogenic nuclide isotope is named in-situ 10Be when is formed in the first meters of the lithosphere exposed to cosmic rays (Terrestrial Cosmogenic Nuclide, TCN). It thus constitutes a suitable tool for dating exposure age of rock surfaces. Rock surfaces of glacial landforms are exposed to the cosmic rays after deglaciation or ice retreat so; if this rock surface is preserved without erosion, the exposure age or deglaciation chronology denotes time since glacial landform is ice free. In addition, TCN chronologies are assumed as minimum values because of potential post-deglaciation processes could erode glacial landforms surfaces (Nishiizumi et al., 1989; Briner and Swanson, 1998; Siame et al., 2000; Gosse and Phillips, 2001; Dunai, 2010; Balco, 2011). In contrast, when a surface rock was not enough eroded by glaciers (less than 2-3 m) or a moraine boulder was transported in a previous glacial period, inherited or initial in situ 10Be is present in the glacial landform after deglaciation. This inherited in-situ 10Be implies overestimated exposure ages (Gosse et al., 1995; Guido et al., 2007; Balco, 2011).

^{10}Be TCN ages calculation

^{10}Be TCN chronological data from this study was compiled from previous works (Wesnousky et al., 2012; Carcaillet et al., 2013 and Angel, 2016). Exposure ages were re-calculated using same and updated input.

Because ^{10}Be is formed by the interaction between cosmic rays and surface rocks, parameters to calculate exposure ages from moraines are: latitude, longitude, elevation, thickness of the sample, erosion rate values, scaling scheme, topographic shielding and production rates from the point where samples were collected (to see details about sampling refer to Wesnousky et al., 2012; Carcaillet et al., 2013 and Angel, 2016).

Several production rates have been determined at high altitudes in the tropical Andes, which should be considered as the best values for TCN dating for MA. For instance, Kelly et al. (2013) estimated a sea level high latitude (SLHL) in situ ^{10}Be production rate from the Quelccaya Ice Cap (13.95°S, 70.89°W, 4857 m), in the Peruvian Andes, which range between 3.78±0.09 at.($g^{-1}.yr^{-1}$) (atoms/grams.year) to 3.97±0.09 for 0 m/Myr and 4.5 m/Myr erosion respectively. Meanwhile, Blard et al. (2013) computed a (SLHL) production rate of 3.63±0.17 at.g-1.yr-1 from the Bolivian Uturuncu volcano (22° S, 67° W, 3800-4900 m). Also, Martin et al. (2015) computed a SLHL production rate of 3.76 ± 0.15 at.g−1.yr−1 from the Challapata fan-delta in Bolivia (19°S, 3800 m). All these production rates are not significantly different. In this study, we selected the value proposed by Kelly et al. (2013), because it is closest to the MA. The selected scaling scheme is the time dependent model from Lal (1991), modified by Stone (2000). Ages were recalculated using CRONUS online calculator based on Balco et al. (2008) from https://hess.ess.washington.edu/

Glacial landforms and TCN ages of tropical glaciers

A difference between the age of abandonment of glacial landforms (moraine construction, bedrock surface erosion by glacier abrasion) and the effective age of deglaciation assessed by TCN exposure dating. This can be the consequence of significant erosion and/or ancient sediment covering on the glacial landform. The field observation of low erosion of the original surface (glacial striations and polished surfaces are present), suggest insignificant difference, whereas sediment covering lead to an under-estimation of the age of abandonment. Nevertheless, exposure ages are assumed as minimum estimated (Nishiizumi et al., 1989; Briner and Swanson, 1998; Siame et al., 2000; Gosse and Phillips, 2001; Dunai, 2010; Balco, 2011).

When climate conditions lead to accumulate mass in a glacier, glaciers recorded positive mass balances, which means, more mass accumulation occur. When positive mass balance is recorded in a glacier, it advances and builds ice-marginal moraines (Hughes et al, 2005; Bennet and Glasser, 2009; Kirkbride and Winkler, 2012). In contrast, moraine deglaciation occurs during a period with negative glacier mass balances. A time lag could happen between glacier advance and deglaciation. Even if this is difficult to quantify, the time lag is assumed as a minimum, considering the sensitive response of the tropical glaciers to climate changes (Kaser and Osmaston, 2002). The accelerated retreat of the current tropical Andean glaciers occurred at the same time as a major increase in the global temperature curve after 1976 (Rabatel et al., 2013). It indicates that tropical paleo-glacier response to climate changes would rapidly occur in some years.

Boconó Fault slip rates calculation

Landforms deformed by the Boconó Fault in the study region were considered to determine offsets and fault slip rates. For example, at the northern strand, El Desecho moraine was considered to determine a fault offset, and with the weighted average ^{10}Be-TCN or exposure ages from Angel (2016), a slip rate was determined. At the southern strand of the fault, re-calculated ^{10}Be-TCN ages from Wesnousky et al. (2012), Carcaillet et al. (2013) and Angel (2016) from La Victoria, Los Zerpa and Las Tapias moraines were used as chronological reference. Offsets were based on aerial photographs from Mission 010455 Cartografía Nacional picture 004, field trip measurements and previous studies.

RESULTS

^{10}Be-TCN recalculated chronological data

Recalculated exposure ages from Wesnousky et al. (2012), Carcaillet et al. (2013) and Angel (2016) range between 11.02±0.43 to 39.45±3.90 ka, with age uncertainties in generally lower than 10% (Table 1). Compared with the originally published values, ages from this study are 10-14 % older, this is because different ^{10}Be cosmogenic nuclide production rates and scaling schemes were used.

El Desecho lateral moraine results range between 17.70±0.98 and 21.78±3.09 ka. Exposure ages are not significantly different. El Desecho weighted average exposure age is 19.13±1.88 ka (n=3) (Table 1), whereas ^{10}Be-TCN ages from Las Tapias moraine range between 17.34±1.14 and 19.65±0.96 (Table 1), with a weighted average exposure age from the outermost lateral Las Tapias moraine of 18.88±1.08 ka.

Recalculated exposure ages for La Victoria moraine range between 15.55±0.62 ka and 18.74±3.76 ka (n=4); ages are not significantly different: the weighted average exposure age is 16.78±1.30 ka, whereas recalculated exposure ages for Los Zerpa show a wide range (14.95±1.13 ka to 39.45±3.90 ka, Table 1), suggesting the existence of inheritance in the oldest sample (VEN 24), and post-abandonment movement for the youngest (LZ09-02). Therefore, these extreme values were considered as outliers and the weighted average exposure age for Los Zerpa is 18.34±1.42 ka (n=5).

DISCUSSION

Reconstruction of the deglaciation history during the MIS 2

The paleoclimate during the MIS 2 is characterized by important climatic periods, for example, the Last Glacial Maximum (LGM). The LGM refers to a period when most of the northern ice sheets and many mountain glaciers reached their maximum extent at 22±4 ka (Shakun and Carlson, 2010). In contrast, in the MA, the glacier maximum extension (Early Mérida Glaciation) is located at 2600 m a.s.l., time before the LGM, during the Early Mérida Glaciation between ~90-60 ka (Schubert, 1974; Mahaney et al., 2000; Mahaney et al., 2001; Dirszowsky et al., 2005; Mahaney et al., 2010; Kalm and Mahaney 2011). Evidences in the field of the Late Mérida Glaciation (Late Wisconsin), corresponding to the LGM period, are observed between 3000-3500 m a.s.l. and mainly dated based on radiocarbon chronology between 25-13 ka (Schubert 1974; Schubert and Valastro, 1974; Schubert and Rinaldi, 1987; Schubert and Clapperton, 1990).

In the central MA, cold climate conditions were determined between 22.75 and 19.96 cal ka BP based on palynological analysis of PED5 section from Mesa del Caballo (Schubert and Rinaldi, 1987). Temperatures were at least 8.8±2°C lower than today (Stansell et al., 2007). This cold period yields Mucubají glacier advances around 3500 m a.s.l. because of TCN ages are between 22 and 20 ka (ages modified from Carcaillet et al., 2013) (Table 1). These exposure ages agree with a previous radiocarbon date of 19.08±0.82 ka BP of an outwash fan located down valley at 3400 m in the vicinity of the moraine (Schubert and Rinaldi, 1987). The formation of the outwash fan is compatible with the development of the moraine at elevations higher than 3400 m.

During the LGM, cold climate conditions in the central MA could also provide positive mass balances surroundings the Mucubají valley, specifically in Las Tapias, Los Zerpa and El Desecho moraine catchments until deglaciation began at around 19-18 ka (Table 1). Whereas La Victoria moraine close to Los Zerpa moraines

(Figure 3), the former glacier seems to be the last ice mass which began deglaciation. However, exposure ages are not significantly different of others in the region (Table 1).

After the LGM, different climatic events have been reported in the global paleoclimate named as Oldest

Table 1. Recalculated ^{10}Be-TCN ages from moraines surroundings the Mucubají valley. Ages were recalculated using CRONUS online calculator considering ^{10}Be production rate from the tropical Andes from Kelly et al. (2013).

Moraine/Valley	Sample	Longitude	Latitude	Elevation (m a.s.l.)	Age (ka)	External uncertainty (ka)	Reference
	DESE-1401	-70,8436	8,8008	3556	17.70	0.98	
	DESE-1402	-70,8444	8,8000	3548	17.90	0.73	
Desecho	DESE-1403	-70,8428	8,8022	3548	21.78	3.09	Angel, 2016
	Mu09-01	-70,8279	8,8009	3620	19.89	0.83	
	Mu09-02	-70,8343	8,7954	3589	21.50	1.79	
	Mu09-03	-70,8267	8,7951	3572	18.54	1.28	
	Mu09-04	-70,8233	8,7874	3607	15.82	0.61	
	Mu09-05	-70,8229	8,785	3615	15.87	1.21	
	Mu09-06	-70,8224	8,7852	3620	18.91	1.48	
	Mu09-07	-70,8197	8,7789	3697	16.43	0.82	
	Mu09-08	-70,8189	8,7785	3727	16.83	0.79	
	Mu09-10	-70,8129	8,7667	4067	11.02	0.43	
	Mu09-11	-70,8119	8,7633	4213	12.87	0.50	
	Mu09-12	-70,8121	8,7659	4091	11.46	0.97	
	Mu09-13	-70,8164	8,7689	3982	11.77	0.47	
	Mu09-14	-70,8152	8,7719	3862	12.01	1.02	
Mucubají	Mu09-15	-70,8161	8,7758	3804	15.37	1.39	Carcaillet et al., 2013
	VEN_19	-70,8006	8,8141	3255	18.74	3.76	
	VEN_20	-70,8006	8,8142	3258	17.16	1.03	
	VEN_21	-70,8010	8,8142	3260	15.67	0.73	
La Victoria	VEN_23	-70,7993	8,8139	3243	15.55	0.62	Wesnousky et al., 2012
	VEN_24	-70,7883	8,8117	3128	39.45	3.90	
	VEN_25	-70,7881	8,8121	3115	19.72	1.60	
Los Zerpa	VEN_26	-70,7873	8,8120	3104	16.87	1.76	Wesnousky et al., 2012

	VEN_27	-70,7875	8,8117	3105	19.72	0.75	
	VEN_28	-70,7873	8,8118	3106	18.97	1.05	
	LZ09-01	-70,7884	8,8117	3127	16.43	1.58	
	LZ09-02	-70,7874	8,8117	3113	14.95	1.13	Carcaillet et al., 2013
	TAPIAS-1401	-70,7736	8,8139	3097	19.63	0.92	
	TAPIAS-1402	-70,7739	8,8139	3096	17.34	1.14	
Las Tapias	TAPIAS-1403	-70,7739	8,8142	3096	19.65	0.96	Angel, 2016

Reference	Offsets (m) /based on	Chronological information	Slip rates (mm/year)
Schubert and Sifontes, 1970	66 m/La Victoria and Los Zerpa moraines	Correlation with Bogotá Plain moraines assumed as 10 ka based on radiocarbon method	6.6
Gingegack and Graunch, 1972	70 m/La Victoria and Los Zerpa moraines	Refute Schubert and Sifontes (1970) premise	Not reported
Audemard et al., 1999	40/El Desecho moraine 60-100/La Victoria and Los Zerpa	15±2 ka based on correlation with a glacio-fluvial deposit radiocarbon dated in the Mucubají valley from Salgado-Laboriou (1977)	2.3-3 5.0-7.7
Wesnousky et al., 2012	100/La Victoria and Los Zerpa	16.7±1.4 ka based on ^{10}Be-TCN	5.5-6.5

Table 2. Previous reported offsets and slip rates from the Boconó Fault

Dryas (OtD), Bølling, Older Dryas, Allerød, and Younger Dryas (YD), the Oldest Dryas stadial occurred between 17.50 and 14.60 ka BP (Blunier et al., 1998). Also cold climate conditions were determined in the central Mérida Andes during the OtD; this period is locally named as El Caballo Stadial, and it was dated at 16.5±0.3 ka BP based on pollen inventory in fluvio-glacial sediments from Mesa del Caballo section (PED5 section; Rull, 1998). The author determined temperatures around 7°C lower than today. This cold period favored former glacier preservation upstream valley at elevations higher than 3550 m (Mu09-04, Mu09-05 and Mu09-06; Table 1) until former glacier began deglaciation at this point around 17-15 ka (ages modified from Carcaillet et al., 2013). This chronology agrees with previous radiocarbon ages of a bog in a recessional moraine from Stansell et al. (2005). In addition, at this age range, complete former glacier deglaciation has occurred around 16 ka in the Gavidia valley, close to Mucuchíes, SW of the Mucubají valley (Angel et al., 2016).

Salgado-Labouriau et al. (1977) define the Mucubají Cold phase at 12.65 ka BP based on paleoecological analysis of the Late Quaternary terrace from the Mucubají valley. This phase had an average temperature of 2.9°C lower than current temperatures. Rull (2005) and Rull et al. (2010) related the Younger Dryas (YD) to the cold period of the Mucubají phase. The YD is a cold period defined in terrestrial record from Denmark which occurred between 12.85 to 11.65 Cal ka BP (Blunier et al., 1998).

Abruptly colder (average temperatures in the region 2.2-3.8°C lower than today) and drier climate conditions occurred between 12.85 ka and 11.6 ka based on sediment analysis from Laguna Los Anteojos and the Mucubají Lake (Carrillo et al., 2008; Rull et al., 2010; Stansell et al., 2010). Whereas Carrillo et al. (2008) determined also an abrupt warming at the onset of the Holocene (~11.6 ka BP) based on magnetic susceptibility from sediments of the Mucubají Lake.

In the study region between El Desecho and Las Tapias glacier advances, three moraines could be formed during the YD period due to cold local climate conditions. These moraines are located in the Mucubají valley at elevations higher than 3800 m a.s.l. These glacier advances were less significant than those from the LGM and OtD-El Caballo Stadial. Exposure ages indicate deglaciation of these glacial landforms began at around 12 ka.

Former glaciers probably covered the Mucubají valley surroundings since the LGM. From the Mucubají valley towards the west to El Desecho moraine, ice mass reached down to 3500 m whereas to the NE, towards Las Tapias moraine, ice mass reached down to 3100 m. These altitude differences could be due to different river catchments humidity because cold climate conditions were determined in the region until around 19 ka.

The Mucubají valley and El Desecho moraine have influences of the Chama River catchment whereas at the NE of the Mucubají valley, La Victoria, Los Zerpa and Las Tapias moraines are influenced by the Santo Domingo River catchment. Assuming that during the MIS 2 similar current topography prevailed due the Andes uplift values represent an altitude difference between 14-100 m (based on Audemard and Audemard, 2002; Wesnousky et al., 2012; Guzmán et al., 2013), the region around the Mucubají valley was probably dry as present. In this valley, arid plant cover is observed, in addition, the annual precipitation was 968 mm (Mucubají station) (Monasterio and Reyes 1980; Instituto Nacional de Meteorología e Hidrología de Venezuela INAMEH http://www.inameh.gob.ve.). In contrast, the Santo Domingo River catchment is wetter because more abundant plant cover is observed. In addition, based on the Santo Domingo meteorological station, the annual rainfall was 1359 mm at the same period studied in the Mucubají station (Monasterio and Reyes 1980; Instituto Nacional de Meteorología e Hidrología de Venezuela INAMEH http://www.inameh.gob.ve.).

Contribution to the central Mérida Andes neotectonic development

At the northern strand of the Boconó Fault, offsets around 45 m from the lateral El Desecho moraine (Figure 2a, 2b) were determined based on lateral moraine displacement on an aerial photograph (this study). In addition, El Desecho offset was also determined in the field, and the offset value is around 34 m. Offsets values from this study agree with those obtained for the same moraine from Audemard et al. (1999) (Table 2).

El Desecho moraine age used to calculate Boconó Fault slip rates in Audemard et al. (1999) was 15±2 ka, this age is based on radiocarbon data from a glacio-fluvial terrace in the Mucubají valley from Salgado-Laboriau et al. (1977). However, the exposure age of El Desecho moraine is 19.13±1.88

ka (Table 1). A ^{10}Be-TCN age of a moraine is the closest real age of a moraine compared with a radiocarbon age (see Methods and Materials, and Introduction). Therefore, in this article, we use 19.13±1.88 ka as El Desecho moraine age. Therefore, slip rates of the northern strand of the Boconó Fault based on ^{10}Be-TCN age are between 1.78-2.35 mm/a, whereas previous works reported values between 2.3-3.0 mm/year (Audemard et al., 1999) (Table 2).

At the southern strand of the Boconó Fault in the study region, this fault deforms La Victoria, Los Zerpa and Las Tapias moraines (Figure 3). A detailed topographical survey of La Victoria and Los Zerpa moraines was presented by Schubert and Sifontes (1970) and, Gingengack and Grauch (1972). These studies indicate that these moraines offsets are between 62-69 m. In addition, the aerial photograph study close to Las Tapias moraines (this study) indicates that drainage deformation provides even higher offsets, around 80 m, in the same range proposed by Audemard et al. (1999; 2008) and Audemard (2009a) between 60-100 m. Therefore, this offsets range was considered to calculate slip rates along this strand. Thus, slip rates between 3.33-6.25 mm/a were obtained based on recalculated exposure ages (from ^{10}Be-TCN) of these moraines between 16-18 ka.

CONCLUSIONS

Deglaciation began in the Mucubají valley at around 22 ka, however, cold climate conditions returned in this valley to create moraines dated at around 19 ka. At similar ages, deglaciation also began at the north of the valley in El Desecho moraine and towards the northeast in Las Tapias moraines. La Victoria moraines began deglaciation more recently at around 17-16 ka, although exposure ages are not significantly different from Los Zerpa and Las Tapias.

Slip rates of 1.78-2.35 mm/a were determined for the northern strand of the Boconó Fault, whereas values for the southern strand are between 3.33-6.25 mm/a based on recalculated exposure ages. Higher values for the southern strand compared with the northern strand is a tendency which agrees with previous studies developed in the region. However, slower slip rates ranges were obtained in this study because a different chronological method was applied (^{10}Be-TCN).

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