PLEISTOCENE GLACIATIONS IN THE NORTHERN TROPICAL ANDES, SOUTH AMERICA (VENEZUELA, COLOMBIA AND ECUADOR)

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ABSTRACT. This article presents an overview of glaciation studies in the northern tropical Andes (Venezuela, Colombia and Ecuador) mostly based on glacial geochronological data. The oldest dated evidences of glaciations are recorded in the Colombian Andes at the Bogotá Plain between 3000-3500 m a.s.l., dated between 1-3 Ma. Maximum extent of former glaciers in the northern Andes seems to have occurred prior to the global Last Glacial Maximum (gLGM). In the Venezuelan-Mérida Andes, former glaciers mostly reached the lowest recorded elevations during MIS 5-MIS 4, whereas in the Colombian Andes, the maximum extents are recorded prior to 38 ka. In the Ecuadorian Andes the most extensive glacial cover probably occurred during MIS 8. In the northern tropical Andes, studied glacier advances are mainly related to MIS 2 period between the final gLGM to the Oldest Dryas (~18 ka-15 ka). Glacier advances during the Younger Dryas (~12.7 ka-11.7 ka) are not extensively evidenced and mainly restricted to elevations higher than ~3500 m a.s.l.

Glaciaciones pleistocenas en el norte de los Andes Tropicales, Sudamérica (Venezuela, Colombia y Ecuador)

RESUMEN. El presente artículo es una revisión sobre el conocimiento de las glaciaciones en el norte de los Andes tropicales. Los estudios utilizados en el presente artículo son principalmente aquellos que cuentan con un buen apoyo de cronología glacial. Las evidencias más antiguas de la actividad glaciar en los Andes tropicales se han encontrado en los Andes Colombianos, específicamente en la Llanura de Bogotá entre los 3000-3500 m s.n.m., con edades entre 1 y 3 Ma. Con respecto a la máxima extensión de los glaciares en los Andes tropicales, parece haber ocurrido en edades previas al Último Máximo Glaciar (UMG). En los Andes Venezolanos la máxima extensión hasta ahora registrada ocurrió durante el MIS 5 y el MIS 4, mientras que en los Andes Colombianos ocurrió hace más de 38 ka. En los Andes Ecuatorianos la máxima extensión de los glaciares ocurrió probablemente durante el MIS 8. La mayoría de los avances glaciares en los Andes...
Los Andes tropicales están relacionados con el MIS 2, y más concretamente con el periodo comprendido entre el final del UMG y el Oldest Dryas (OtD) (~18 ka-15 ka). En el norte de los Andes tropicales han sido encontradas pocas evidencias de avances glaciares durante el Younger Dryas, y se hallan generalmente restringidas a elevaciones por encima de ~3500 m a.s.l.

**Keywords:** Glaciations of the tropical Andes, TCN, radiocarbon dating, glacial landforms, Colombian Andes, Venezuelan Andes, Ecuadorian Andes, Pleistocene, Late Glacial, Last Glacial Maximum, Younger Dryas.

**Palabras clave:** Glaciaciones de los Andes tropicales, TCN, datación por radiocarbono, formas glaciares, Andes colombianos, Andes venezolanos, Andes ecuatorianos, Pleistoceno, Tardiglacial, Último Máximo Glaciar, Younger Dryas.

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1. **Introduction**

El Cordillera de los Andes es localizada al oeste de Sudamérica. La Cordillera puede ser dividida en regiones norteña (picos más altos <5000 m a.s.l.), central (<7000 m a.s.l.), y meridional (<2000 m a.s.l.) de acuerdo a características estructurales (Clapperton, 1993). Los Andes tropicales se encuentran en el norte y centro de la Cordillera (10° N-23° S). Los Andes de la Cordillera de los Andes tropicales han sido ampliamente estudiados para reconstruir el tamaño y el tiempo de los glaciares (e.g. Coronato y Rabassa, 2007; Smith et al., 2008; Rodbell et al., 2009; Jomelli et al., 2009). Sin embargo, los datos de glaciaciones en los Andes tropicales del norte son limitados. Los Andes tropicales del norte están localizados entre 11°N-4°S incluyendo los Andes venezolanos, colombianos y ecuatorianos. Los glaciogramas de los Andes tropicales del norte pueden mejorar nuestra comprensión de las glaciaciones tropicales y las relaciones entre climas tropicales y glaciares globales.

Los Andes venezolanos consisten de dos orientaciones nordeste-suroeste de cordilleras conocidas como Sierra de Perijá y los Andes de Mérida entre 11°N-7°N (Schubert, 1979; Schubert y Vivas, 1993) (Fig. 1). Los estudios desarrollados en los Andes Mérida han soporteado el conocimiento sobre la glaciación en los Andes venezolanos; evidencias de glaciaciones en la Sierra de Perijá no han sido reportadas. En los Andes Mérida los glaciares y glaciaciones ontogeneticas han sido desarrollados desde el 19º y el inicio del 20º centurias (e.g. Sievers, 1885; Jahn, 1925). El área ocupada por glaciares durante el Last Glacial Maximum (LGM) fue de alrededor de 200 km² (Schubert y Clapperton, 1990) y actualmente el área de glaciares es reducido a 0.017 km² (Braun y Bezada, 2013). Los estudios glaciares en los Andes venezolanos están basados en sedimentos glacialuviales, sedimentos glaciolacustres y análisis de paleosuelos principalmente usando radiocarbono (e.g. Rull, 1998; Mahaney et al., 2014).
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2001; Dirszowsky et al., 2005; Stansell et al., 2005; Mahaney et al., 2007; Carrillo et al., 2008; Kalm and Mahaney, 2011). However, more recently contributions based on Terrestrial Cosmogenic Nuclide dating (TCN), specifically $^{10}$Be of moraine boulders and roches moutonnées are available (Wesnousky et al., 2012; Angel et al., 2013; Carcaillet et al., 2013; Guzmán, 2013; Angel, 2016; Angel et al., 2016).

The Colombian Andes are located between 11ºN-1ºN and are constituted by the Cordilleras Occidental (Western), Central and Oriental (Eastern) (Fig. 1). The area covered by Pleistocene glaciers was approximately 26,000 km$^2$ (Thouret et al., 1996), whereas toward the end of the 20th century it was around 104 km$^2$ (Hoyos-Patiño, 1998). In the Colombian Andes, glaciation studies have been principally developed in the Eastern and Central Cordillera, and these studies are mainly based on radiocarbon dating of paleosols, glaciofluvial and other glacial sediments (e.g. van der Hammen et al., 1973; 1980; 19981; Helmens, 1988; 1996; 1997; 2004; 2011; Clapperton, 2000; Thouret et al., 1996).

The Ecuadorian Andes are located between 1ºN-4ºS and are constituted by the Eastern and Western Cordilleras (Fig. 1). Glaciation studies are mainly based on radiocarbon dating of glaciolacustrine and till sediments (e.g. Seltzer et al., 1995; Clapperton et al., 1997; Rodbell et al., 2002; La Frenierre et al., 2011), as well as tephrochronological work (Heine, 1995).

This article aims at giving an overview of the current knowledge on glaciations in the northern tropical Andes (11ºN-4ºS), using the glacial geochronological literature with values reported from the original publications (Table 1, see supplementary material at http://publicaciones.unirioja.es/revistas/cig2017/Angel_Table01.xls). It is noteworthy that the confidence in radiocarbon dating has improved considerably over the past years. It is also important to note that different scaling schemes and production rates to calculate surface exposure ages were used in the original publications for Terrestrial Cosmogenic Nuclide $^{10}$Be (TCN-$^{10}$Be) (e.g. Wesnousky et al., 2012; Carcaillet et al., 2013; Angel, 2016). Production rates for $^{10}$Be in the tropical Andes have only recently become available (e.g. Kelly et al., 2013). This means that TCN-$^{10}$Be ages can differ based on the exposure age calculation systematics used. The scale of the age differences can lead to changes in paleoclimate interpretations, especially the response of glaciers to shorter climate events such as the Younger Dryas (e.g. Carcaillet et al., 2013; Angel et al., 2016).

A summary of the Quaternary Glaciation of the northern tropical Andes is presented in this article from North to South, covering Venezuela, Colombia and Ecuador, and from ancient to recent time. For more detail about each country, the reader may see further in the original literature.

2. Early and Middle Pleistocene Glaciations

2.1. Venezuela

Evidence of early Quaternary glaciations has not been reported. The lack of early glacial cover has been explained by (i) the assumption that the Mérida Andes reached a
sufficient elevation to generate glaciers very late (Vivas, 1974; Giegengack and Grauch, 1975), or (ii) the assumption that the uplift rate was sufficiently high so each glaciation erased the evidence of the former one (Schubert, 1979; Schubert and Vivas, 1993). This last interpretation is based on the strong uplift and erosion rates between Late Miocene (ca. 10 Ma) to present (Kohn et al., 1984; Pindell et al., 1998). Quaternary uplift ranges between −0.7 and 5 mm/a (Audemard and Audemard, 2002; Wesnousky et al., 2012; Guzmán et al., 2013).

The knowledge on glaciations is limited for the Early and Middle Pleistocene (Mahaney et al., 2010a; Kalm and Mahaney, 2011). Evidences of paleo-glacial cover are observed in the Chama, Mucujún (at 2600 m a.s.l.), Aracay and Santo Domingo river valleys (Tricart, 1966; Schubert, 1984) (Fig. 1, Site 1), with isolated outcrops of diamicton (Schubert, 1984). In addition, evidences of paleo-glacial cover have been observed in the Mesa del Caballo (Fig. 1, Site 2), based on LAG 4 and LAG 5 sections at ~3500 m a.s.l. (Mahaney et al., 2010a). The authors relate these LAG sections to the penultimate glacial, based on the superposition of PED 5 section. This PED 5 is a 40 m section from the Mesa del Caballo composed of till deposits, glaciolacustrine sediments and paleosols (Dirszowsky et al., 2005). The base of the PED 5 section was dated at 60 ka based on radiocarbon dating (Dirszowsky et al., 2005).

Evidence of two glacier advances were found at LAG 4 and LAG 5 sections, based on differences in the weathered state of light and heavy minerals between till layers in LAG 5 (equivalent to the entire LAG 4 section) (Mahaney et al., 2010a). These authors identified an abrupt relation between these two glacier advances, which indicate a hiatus of unknown duration. The weathered state of sands with clay mineral composition in the paleosols of LAG 4 and LAG 5 suggests an older age in the Pleistocene. The authors proposed that the ice source was initially located 2-4 km to the south of Mesa del Caballo. This assumption is based on the Boconó fault movement. The ice source was located at the south of the Mucuchache valley in the Sierra Nevada (Fig. 1, Site 3).

2.2. Colombia

Evidences of the Late Pliocene-Quaternary boundary are recognized in the Eastern Cordillera, specifically at the Bogotá Plain and surrounding mountains (Fig. 1, Site 4). Before this period, the Eastern Cordillera was probably not high enough to support glaciers (Helmens, 2011). In the Bogotá region, major tectonic uplift of approximately 2000 m is recorded between 6 and 3 Ma (Van der Hammen et al., 1973; Kuhry and Helmens, 1990; Wijninga, 1996).

A distinct lithological transition is observed surrounding the Bogotá Plain in the Páramo de Palacio (between 3000-3500 m a.s.l.) (Fig. 1, Site 5) (Helmens, 2011). At higher elevations, moraine deposits are developed towards the glaciofluvial-lacustrine sediment in the basin (integrated by Río Chisaca, Río Siecha, Río Tunjuelito, Subachoque, Guasca Member and San Miguel formations) (Helmens, 2011). In this area, two major outcrops of glaciofluvial sediments (Guasca and Subachoque sections) expose a thickness of 75 m. The Guasca Member underlies the Subachoque Formation. Interbeded tephras were
sampled for fission track dating. The Guasca Member yielded fission-track ages of ca. 3 and 2.9 Ma, whereas the Subachoque Formation yielded fission-track ages of ca. 2.5, 1.7 and 1 Ma (Helmens et al., 1997a).

More extensive glaciations are recorded in the upper part of the Subachoque Formation, based on changes of magnetic susceptibility (MS) recorded by lithology and magnetic geochronology (Helmens et al., 1997a). The upper part of the Subachoque was dated near the Matuyama/Brunhes magnetic Chron boundary at 0.8 Ma (Helmens et al., 1997a).

A shift towards higher magnitude climatic oscillations is also recorded at the Bogotá Plain (the upper part of the Funza pollen sequence at ~3000 m a.s.l.), and has been placed at ca. 0.8 Ma based on fission-track dating and land-sea correlation (Andriessen et al., 1993; Hooghiemstra et al., 1993; Hooghiemstra and Ran, 1994). This switch has been related to a distinct change in the frequency of planetary oscillations from 41 to 100 ka climate cycles (Hooghiemstra et al., 1993).

2.3. Ecuador

The oldest evidences of glaciations in the Ecuadorian Andes have been recorded at the Rucu Pichinca in the Western Cordillera (Fig. 1, Site 6). In this area, six moraine complexes were identified (M1-M6, oldest to youngest) (Heine, 1995; Heine and Heine, 1996). The moraine complex M1 is the oldest one and is located between 3550-3600 m a.s.l. It is oxidized and deeply weathered, and overlies a deeply weathered lava flow dated at >0.9 Ma based on fission track method (Rosi, 1989, reported in Heine and Heine, 1996). Correlative moraine complex were identified in Potrerillos plateau, specifically in the Papallacta valley (Fig. 1, Site 7). In this last area, a lava flow fills the valley and is deformed by moraines M1 (at < 3400 m a.s.l.). This lava flow has been dated at >150-180 ka based on the fission-track method (Heine, 1995).

At 2750 m a.s.l. in the Chimborazo and Carihuairazo Massif (Fig. 1, Site 8), old till deposits with different weathering rates are probably from MIS 8. This assumption is based on weathering and oxidation rates of a separate till constrained by a minimum radiocarbon age of >43 ka (Clapperton, 1990). In addition, to the south of Chimborazo and Carihuairazo Massif, in the Cajas National Park (Fig. 1, Site 9), previous MIS 5 glacier advances were proposed (Clapperton, 1986). These glacier advances were established based on weathered till exposed at 2800 m a.s.l. in the Río Tomebamba valley at the west of Cuenca (Fig. 1, Site 9).

3. Late Pleistocene Glaciations

3.1. MIS 5 to MIS 3

3.1.1. Venezuela

Late Pleistocene glaciations are evidenced in the Mérida Andes by two moraine complexes located between 2600-3400 m a.s.l. (Schubert, 1974). These moraines represent
the main glacier advances in the Venezuelan Andes. The lowest glacier advances arrived at 2600-2800 m a.s.l., and are characterized by extremely weathered till, deeply eroded and covered by abundant vegetation (Schubert, 1974). These glacier advances were assigned to the locally named Early and Late Mérida Glaciation (Schubert, 1974). The Early Mérida Glaciation is poorly constrained and occurred during MIS 5-MIS 4. Few geochronological data are available from the area and ages range between ~90 and ~60 ka (Mahaney et al., 2000; Mahaney et al., 2001; Dirszowsky et al., 2005; Mahaney et al., 2010b). One data point is in the RF3 section of the La Canoa moraine in the Pueblo Llano valley at 2800 m a.s.l., Cordillera de Trujillo (Fig. 1, Site 10). A glaciotectonized diamict at the base of the RF3 section was dated at 81 ka using optically-stimulated luminescence (OSL; Mahaney et al., 2000). A glacier advance was recently proposed in the Pueblo Llano valley at around 2500 m a.s.l. and dated at 72 ka based on TCN-10Be (Angel, 2016). However, this lower Pueblo Llano moraine was proposed based on geomorphological description in aerial photographs and a light field work; a detailed sedimentological description is necessary to verify this proposal. In addition, a glacier advance older than 60 ka BP was identified in the PED 5 section of the Mesa del Caballo at 3600 m a.s.l., based on radiocarbon dating of a peat bog layer (Dirszowsky et al., 2005).

MIS 3 glacier advances have been recently proposed at different locations of the Mérida Andes, based on TCN-10Be dated moraine boulders (Angel, 2016). A glacier advance was dated at ~50 ka in the Pueblo Llano Valley at around 2500 m a.s.l. and at ~50 ka in the El Caballo moraine at 3600 m a.s.l. (Angel, 2016) also proposed glacier advances between 30-36 ka in the Sierra Nevada (Fig. 1, Site 3), specifically in the Mucuchache Valley (at 3400 m a.s.l.) and El Caballo moraine (at 3600 m a.s.l.). Glacial geomorphic landforms in the Mucuchache Valley were also studied by González (1995) and González and Bezada (2001) without providing chronological constraints.

3.1.2. Colombia

Glaciation during MIS 5-MIS 4 is likely related to the moraine complex 1, located at different elevations in the Eastern Cordillera (Fig. 1, Site 4) (Helmens, 1988). The author identified four moraine complexes (1-4) around the high plain of the Bogotá basin. Moraine complex 1 is the lowest in the landscape, and it is located below Páramo de Palacio at around 3000 m a.s.l. This moraine complex shows clear evidence of intense erosion, and denudation occurs in the apical zone of the large fluvioglacial fans.

In Páramo de Sumapaz, the moraine complex 1 is located along Río Chisaco at 3350 m a.s.l. and along Quebrada Piedra Gorda at 3150 m a.s.l. (Helmens, 1990). Along Río Chisaco, a paleosol directly overlying the moraine complex 1 was radiocarbon dated at 30.93 ± 0.42 ka BP (Helmens, 1990). At Cuchilla Boca Grande, a paleosol was also radiocarbon dated at 31.35 ± 0.5 ka BP (Helmens, 1990). This paleosol was overlying material which seems to be reworked sediments of moraine complex 1 (Helmens, 1990; Helmens and Kuhry, 1995) (Fig. 1, Site 11). In addition, organic rich clay overlying a basal till was radiocarbon dated at 38 ka BP. Therefore, the oldest till studied in Páramo Sumapaz is earlier than 38 ka.
The Páramo Peña Negra is located at around 70 km to the North of Cuchilla Boca Grande (Fig. 1, Site 12). A reworked supraglacial till from moraine complex 1 is found at 2850 m a.s.l. (Helmens, 1988). A palaeosol developed on the till has been radiocarbon dated at $35.8 \pm 1.1/-0.9$ ka BP.

![Figure 1. Location of different studied areas to reconstruct glaciations in the northern tropical Andes on shaded relief map based on SRTM (Shuttle Radar Topographic Mission). Numbers of the studied areas are in accordance with the text order appearance.](image-url)
3.1.3. Ecuador

Glaciations related to MIS 5-MIS 3 have mainly been studied using till deposits in the Chimborazo/Carihuairazo Massif (Clapperton and McEwan, 1985; Clapperton, 1986; Clapperton, 1987; Clapperton, 1990). A till deposit was radiocarbon dated older than 43 ka BP (Clapperton, 1990). The author proposed the till deposit as a glacier advance which occurred during MIS 4 (~70 ka) or even MIS 6 (before 132 ka).

Clapperton and McEwan (1985) identified three groups of moraines in the Río Mocha Valley at the southwest side of the Carihuairazo volcano (Fig. 1, Site 8). General ages as full glacial (Group 3 below 3600 m a.s.l.), Lateglacial (Group 2, located between 3900 and 4050 m a.s.l.), and Neoglacial (Group 1, located between 4300 and 4400 m a.s.l.) based on radiocarbon dating were assigned. Clapperton and McEwan (1985) dated peat from Group 3 moraines. The upper layer of peat was dated at 35.44 ± 0.68/0.63 ka BP; the lower peat layer was beyond the limit of radiocarbon dating (>40 ka BP). Clapperton and McEwan (1985) also radiocarbon dated peat layers within laminated fine sediments underlying till located up valley Group 2 moraines; ages were 10.65 ± 0.06 ka BP and 11.37 ± 0.06 ka BP.

Clapperton (1987) dated peat deposits at altitudes between 3725-3870 m a.s.l. on the north and northeast flanks of the Carihuairazo volcano. Radiocarbon dates from peat lying between the uppermost and the other two till layers (of three) fell between 33 ka BP (uppermost peat) and >40 ka BP (basal peat).

Weathered till deposits probably older than Group 3 have been observed between 2750-2800 m a.s.l. These weathered till deposits are located in the Río Mocha Valley and Río Tomebamba Valley west of Cuenca (Clapperton and McEwan, 1985; Clapperton, 1986). Soil overlying 20 m of the Cuenca Plateau till was beyond the limit of radiocarbon dating (>40 ka BP) (Clapperton, 1986). Clapperton (1986) concluded that around 2800 m a.s.l. marked the absolute limits of Quaternary glaciations in the Ecuadorian Andes.

3.2. MIS 2 to Younger Dryas (YD)

3.2.1. Venezuela

Studied glacial evidences during MIS 2 and MIS 1 mainly consist of moraines and roches moutonnées. These glacial landforms have been studied in the Sierra Nevada (including Sierra de Santo Domingo) (e.g. Mahaney et al., 2008; Stansell et al., 2007; Wesnousky et al., 2012; Carcailet et al., 2013; Angel, 2016), Sierra del Norte (e.g. Wesnousky et al., 2012; Angel, 2016) and Cordillera de Trujillo (e.g Bezada, 1989; Mahaney et al., 2001; Guzmán, 2013; Angel, 2016) (Fig. 1, Sites 3, 13 and 10 respectively). In addition, evidences of glacial cover are also based on palynological studies of glacial lakes sediments (e.g. Rull, 2010; Stansell, 2010).

The global Last Glacial Maximum (gLGM) between 23-14 ka BP with a midpoint at 18 ka BP was originally proposed (CLIMAP Project Members, 1976, 1981; Shackleton et al., 1977). However, Shakun and Carlson (2010) suggested that a global
average age of 22.2 ± 4.0 ka best defines the gLGM, based on 56 terrestrial records. The LGM in the Mérida Andes was established based on palynological analysis of PED5 section between 22.75 and 19.96 ka BP (Fig. 1, Site 2) (Schubert and Rinaldi, 1987). Temperatures were at least 8.8 ± 2°C cooler than currently, based on Equilibrium Line Altitudes (ELA) variations (Stansell et al., 2007).

LGM glacier advances are related to Las Tapias terminal moraines and frontal moraines in the Mucubají Valley, both in the Sierra Nevada (Angel, 2016) (Fig. 1, Site 3). Las Tapias terminal moraine has been dated at 19 ka based on TCN-^{10}Be (Angel, 2016). This terminal moraine is located at 3100 m a.s.l.

In the Mucubají Valley, a frontal moraine at around 3600 m a.s.l. was TCN-^{10}Be dated at 22–20 ka (modified ages of Carcaillet et al., 2013, in Angel, 2016). However, a maximum glacier advance is observed from a damaged terminal undated moraine at elevations lower than 3589 m a.s.l. It is likely that the damaged moraine is not much older than 22 ka, and probably corresponds to the local LGM (Angel, 2016). In addition, TCN-^{10}Be ages of the Mucubají frontal moraines at around 3600 m a.s.l. are in agreement with a previous radiocarbon age. This radiocarbon age was 19.08 ± 0.82 ka BP from an outwash fan located at 3400 m a.s.l. (Schubert and Rinaldi, 1987).

The Oldest Dryas (OtD) was a cold period originally proposed based on biostratigraphic changes in terrestrial records of Denmark (Iversen, 1954). Blunier et al. (1998) proposed the OtD period between 17.50 to 14.60 Cal ka BP. In the Mérida Andes, a cold period named El Caballo Stadial was established at 16.5 ka BP, based on palynological analysis of the Mesa del Caballo (Rull, 1998).

In the Sierra Nevada, specifically in the Mucubají and Gavidia valleys, glacial expansion during the LGM-OtD has been recognized. In the Mucubají Valley, glacier advances related to the LGM-OtD are located around 3500 m a.s.l. (Angel, 2016). In the Gavidia valley (at 3100 to 4200 m a.s.l.), former glacier maximum extent happened at around 21 ka, and complete valley deglaciation occurred at around 16 ka (Angel et al., 2016). This chronological data was mainly based on TCN-^{10}Be exposure dating of roches moutonnées.

In the Sierra Nevada, particularly in Sierra Santo Domingo, LGM-OtD maximum glacier advances are related to the La Victoria terminal moraine. This terminal moraine is located at around 3140 m a.s.l. and dated to a weighted average age of 17.45 ± 0.47 ka (Angel, 2016). Another LGM-OtD glacier advance has been constrained at the Los Zerpa terminal moraine located at ~3100 m a.s.l., and a weighted average exposure age of 18.30 ± 0.46 ka (modified ages of Wesnousky et al., 2012 and Carcaillet et al., 2013 in Angel, 2016). All these moraines (La Victoria, Los Zerpa) chronological data, is based on TCN-^{10}Be of frontal moraine boulders.

In Sierra del Norte, La Culata moraines are located between 3160 m and 3500 m a.s.l. Weighted average TCN-^{10}Be ages of 16.88 ± 0.22 ka and 17.78 ± 0.78 ka and 17.94 ± 0.47 ka of these moraines, are related to LGM-OtD glacier advances (Wesnousky et al., 2012; Angel, 2016). Whereas El Desecho moraine (at ~3500 m a.s.l.), was dated at 17.97 ± 0.58 ka, based on TCN-^{10}Be of terminal moraine boulders (Angel, 2016).
In the Cordillera de Trujillo, the La Canoa terminal moraine is related to a LGM-OtD glacier advance (~2800 m a.s.l., weighted average TCN-\(^{10}\)Be age of 17.89 ± 1.09 ka) (Angel, 2016). The TCN-\(^{10}\)Be ages agree with glaciofluvial sediments dated inside the La Canoa moraine at 18.0 ± 2.1 ka by Thermoluminescence (TL) (Bezada, 1989). Finally, a moraine located between La Capellanía and El Pozo in the Pueblo Llano Valley with a weighted average TCN-\(^{10}\)Be age of 17.32 ± 1.72 ka (~2300 m a.s.l.) (Guzmán, 2013) could also be related. It seems to indicate that in the Mérida Andes, glaciers had their maximum extent during the Late Mérida Glaciation at elevations lower than those originally proposed by Schubert (1974) (< ~3000 m a.s.l.) (Guzmán, 2013). Late Mérida Glaciation is established between 25-13 ka BP (Schubert, 1974).

Features of glaciations during MIS 1 have mainly been recorded based on sedimentological and chronological studies of glacial lake sediments (e.g. Stansell and Rull, 2010). A Younger Dryas (YD) glacier advance was recorded close to Lago Verde (~4000 m a.s.l.) in the Humboldt Massif (Sierra Nevada), at a radiocarbon date of 10.52 ± 2.00 ka BP (12.40 Cal ka BP) (Fig. 1, Site 14) (Mahaney et al., 2008). Moreover, in the Humboldt Massif a YD glacier advance was also suggested from geochemical and sedimentological analyses of Laguna Los Anteojos at 4045 m a.s.l. (Stansell et al., 2010).

In the Mucubají Valley, a small push moraine located at ~3700-3800 m a.s.l. has been linked to the YD (site MUM7B, Mahaney et al., 2008). This assumption is based on peat samples covered by glaciofluvial materials which have been radiocarbon dated at 13.29 ± 0.22, 13.64 ± 0.15 and 13.66 ± 0.44 ka BP. These glaciofluvial materials are located down-dip from the push moraine (Mahaney et al., 2008). However, this push moraine is older than 14 ka; it is not in agreement with a YD glacier advance (Angel, 2016). New TCN-\(^{10}\)Be ages support this assumption. The push moraine is surrounded by glacial landforms dated at 15.4 ± 1.4 ka BP (MU15-09 sample) and 16.8 ± 0.8 ka BP (MU08-09 sample) (modified ages of Carcailllet et al., 2013 in Angel, 2016). A YD glacier advance could rather be related to a moraine located at 3862 m a.s.l at 12.0 ± 1.0 ka based on TCN-\(^{10}\)Be exposure ages (Angel, 2016).

Abrupt colder and drier climate conditions in Sierra Nevada-Mérida Andes occurred between 12.85 ka and 11.75 ka (Stansell et al., 2010). This assumption is derived from geochemical and clastic sediment analyses from Laguna Los Anteojos at 3900 m a.s.l. These authors established that the maximum glacier extension happened at 12.65 ka. ELA values were ~360 to 480 m lower than today, and temperature between 2.2-2.9 ºC colder than today. Rull et al. (2010) using a palynological analysis from Laguna Los Anteojos, also determined cold climate conditions between 12.86 ka and 11.65 ka with temperatures ranging between 2.5-3.8 ºC colder than present. Carrillo et al. (2008) determined cold climate conditions during the YD in Sierra Nevada at ~12.8 ka BP, based on magnetic susceptibility in a sediment core from the Mucubají Lake. Abrupt warming at the onset of the Holocene (~11.6 ka BP) was also recognized by Carrillo et al. (2008).

3.2.2. Colombia

In the Eastern Cordillera at the Bogotá Plain two moraine complexes (2 and 3) have been linked to the LGM and LGM-OtD period. Moraine complex 2 is located at
Páramo de Peña Negra (Fig. 1, Site 12) between 3000-3550 m a.s.l. (Helmens, 1988). Minimum ages for the moraine complex were obtained from organic-rich sediments. Such sediments were overlying glaciofluvial gravel directly behind moraine complex 2 (Helmens, 1988). Radiocarbon ages were 19.19 ± 0.12 ka BP and 18.13 ± 0.17 ka BP. Moraine complex 2 is probably younger than 23 ka BP (Helmens 1988).

Moraine complex 3 at the Bogotá Plain is located between 3100-3750 m a.s.l. (Helmens 1988). Ages for basal lake sediments enclosed by moraine complex 3 were 14.46 ± 1.70 ka BP and 15.51 ± 0.19 ka BP at 3650 m a.s.l., based on radiocarbon dating (Helmens et al., 1997b). Moraine complex 3 was dated between 18.13 ± 0.17 ka BP and 14.66 ± 0.28 ka BP (Helmens, 1988). These glacier advances during the LGM-OtD period were related to the Fúquene Stadial (Helmens, 1988), which was established between 21 to 14 ka BP, according to palynological analysis from the Fúquene Lake sediments 100 km NE from Bogotá (van Geel and van der Hammen, 1973).

YD glacier advances at the Bogotá Plain could be represented by moraine complex 4, located at Páramo de Sumapaz between ~3250-3400 m a.s.l. (Fig. 1, Site 11). Bracketed radiocarbon ages of moraine complex 4 are 12.99 ± 0.19 ka BP and 12.76 ± 0.16 ka BP (Helmens, 1988). Dated samples were light-brown lacustrine clays, which were located directly overlying the rocky subsoil in the area immediately behind the moraines (Helmens, 1988).

In the Eastern Cordillera at the western slopes of the Sierra Nevada del Cocuy, three drifts or till deposits were recognized in altitudes above 2900 m a.s.l. These drifts were numbered 3-6 (old to young) (van der Hammen et al., 1980/1981). Laguna Ciega is located up valley drift 3. The sedimentation in such lake probably began between 24.5-27.0 ka BP, based on radiocarbon dating (van der Hammen et al., 1980/1981 in Helmens et al., 1997). In addition, other drifts have been identified in the Sierra Nevada del Cocuy (Fig. 1, Site 16). These drifts were named 1 and 2 (Helmens et al., 1997). Drift 2 includes isolated moraines located at the eastern slopes, and glacial origin of drift 1 is unknown (Helmens et al., 1997).

In the Sierra Nevada del Cocuy, different moraine complexes have been identified, named Lower Bocatoma, Corralito, Lagunillas, Cóncavo and Río Negro. Lower Bocatoma and Corralito moraines are located below drift 5 (altitudes between 3800-4000 m a.s.l.) (Helmens, 2011). Lagunillas moraines were divided in Upper (~3600 m a.s.l.) and Lower (~3400 m a.s.l.) moraines (Helmens, 2011) as were the Cóncavo moraines, respectively (~3300 m and ~2900 m a.s.l.), whereas Río Negro moraines are located between 2600-2800 m a.s.l. (Helmens, 2011).

A peat layer in the lake sediments located between Upper Lagunillas moraines and Lower Bocatoma moraines was radiocarbon dated at 12.32 ± 0.10 ka BP (Helmens, 2004, in Helmens, 2011). In the inner part of the Lower Bocatoma moraines, a peat deposit was radiocarbon dated at 8.54 ± 0.26 ka BP (Helmens, 2004, in Helmens, 2011). This radiocarbon date was interpreted as the vegetation colonization of moraines, so deglaciation occurred sometime between 12-8 ka.

Deglaciation of the Upper Lagunillas moraines occurred between 12-10 ka (González et al., 1966 in Helmens, 2011). Lake sediments radiocarbon dated up valley Upper Lagunillas moraines indicated that sedimentation began between 11.35 ± 0.14 ka BP and 10.03 ± 0.09 ka BP (González et al., 1966 in Helmens, 2011).
In the Eastern Cordillera, the palynological records indicate a cooling event named El Abra Stadial, which was radiocarbon dated between 10-9.5 ka BP (van Geel and Van der Hammen, 1973; Kuhry et al., 1993). Coldest and driest climate conditions between radiocarbon dates of 11.0-10.5 Cal ka BP have also been interpreted (van’t Veer et al., 2000).

In the Central Cordillera Thouret et al. (1996) provided chronology of moraines in the Ruiz-Tolima volcanic complex (Fig. 1, Site 17). Moraine chronologies were based on radiocarbon dating and inter-site correlation using tephra, paleosols and peat stratigraphy. One of the studied moraines was Río Reció at around 3200 m a.s.l. These moraines were radiocarbon dated at between 28 ka BP and 42 ka BP, suggesting that glaciers were more extensive before the gLGM.

Another moraine complex in the Central Cordillera is named Murillo moraines, which represent two phases of glacier advances. Murillo moraines are located between 3300-3400 m a.s.l. and were radiocarbon dated between 28-16 ka BP (Thouret et al., 1996). These two glacier advances were related by the authors to Early (21-19.5 ka BP) and Late (17-14 ka BP) Fúquene Stadial. The Early Murillo moraines are the biggest moraines in the Ruiz-Tolima area (Helmens, 2011).

3.2.3. Ecuador

In the Chimborazo/Carihuairazo Massif, two moraine complexes (G2 at 3900-4050 m a.s.l. and G1 at 4300-4400 m a.s.l.) are related to MIS 2-MIS 1 glacier advances, based on radiocarbon ages of 10.7 ± 0.1 and 11.4 ± 0.1 ka BP (G2 moraines between 12.7 and 13.4 Cal. ka BP) (Clapperton and McEwan, 1985). Samples were collected on the upper and lower peat layers within laminated fine-grained sediments underlying the till. Peat layers were located in a drained glacial lake up valley of the G2 moraines. Based on morphostratigraphical analysis, G1 moraines are younger than G2 moraines. G1 ages were not presented.

In the Rucu Pichincha (Fig. 1, Site 6), MIS 2 and MIS 1 glacier advances have been attributed to moraines M4 (at ~3700 m a.s.l.), M5 (between 4100-4200 m a.s.l.) and M6 (between 4200-4400 m a.s.l.) (Heine and Heine, 1996). Peat from a paleolake/bog enclosed by M5 moraines gave a minimum-limiting radiocarbon ages of 11.2 ± 0.1 ka BP (13.0 Cal. ka BP) and 13.0 ± 0.1 ka BP (15.5 Cal. ka BP). Heine (1995) proposed that the M4 moraines were deposited during the gLGM. Bracketed ages for M6 moraines were between 11.2 ± 0.1 ka BP (underlying peat was 13.0 Cal. ka BP) and 8.2-9.0 ka (overlying HL-4 tephra from Rosi, 1989, in Heine and Heine 1996). M6 could be related to a YD glacier advance.

In the Cajas National Park, Hansen et al. (2003) recognized MIS 2 and MIS 1 glacier advances located between 3700-3080 m a.s.l. (moraine complex GZ). Glacial chronological data were based on radiocarbon ages from lacustrine sediments. Three moraines are part of this group, Z1 (at 3760 m a.s.l.), Z2 (at 3360 m a.s.l.) and Z3 (3080 m a.s.l.). Between Z1 and Z2, Laguna Chorreras is located at 3700 m a.s.l., whereas Laguna Pallcacocha is located up valley Z1 at ~4060 m a.s.l. Hansen et al. (2003) reported a radiocarbon age of 13.2 ± 0.1 ka BP from the organic material collected in the Laguna Chorreras. Sedimentation onset was estimated at 17.0 Cal. ka BP. The oldest radiocarbon age in the
Pallcacocha lacustrine sediments core was 11.8 ± 0.1 ka BP, and the sedimentation onset was estimated at 14.5 Cal. ka BP (Hansen et al., 2003). Therefore, Z1 ages are between 14.5-17.0 Cal. ka BP and Z2 and Z3 older than 17.0 Cal. ka BP.

In the Papallacta valley, MIS 2 and MIS 1 glacier advances are evidenced in the M4 or Sucus moraines (at ~3850 m a.s.l.), M5 or Potrerillos moraines (at ~3900 m a.s.l.) and M6 moraine (at ~4055 m a.s.l.) (Heine, 1995; Heine and Heine, 1996; Clapperton et al., 1997). Heine (1995) and Heine and Heine (1996) related the M4 moraines to the gLGM. Authors proposed that M5 moraines were created between the radiocarbon date of 12.3 ± 1.3 ka BP and the gLGM. Meanwhile, the M6 moraine has been related to the Late glacial (bracketed by radiocarbon ages of 10.5 ± 0.8 ka BP below and 7.9 ± 0.9 ka BP above). Clapperton et al. (1997) disagreed with the interpretation of Heine (1995) about M4 moraines timing, which were divided into the Sucus (at 3850 m a.s.l.) and Potrerillos moraines (at 3950 m a.s.l.). Clapperton et al. (1997) reported that the Sucus advance occurred before 13.1 ka BP (average age n=7 and 15.6 Cal. ka BP). This radiocarbon date was based on plant material and peaty organic matter overlying till located between two Sucus lateral moraines. The Sucus advance occurred between 30 ka and 13 ka. This assumption was supported by a radiocarbon date of organic material located at 3500 m a.s.l. (Clapperton et al., 1997). This organic material was beneath two till layers separate by a lava flow (Clapperton et al., 1997).

The Potrerillos moraines were bracketed between radiocarbon ages of 10.9 ka BP (average age (n=11) 12.8 Cal. ka BP) and 10.0 ka BP (average age (n=5) 11.3 Cal. ka BP). Clapperton et al. (1997) interpreted the Potrerillos advance as contemporaneous with the YD climate reversal.

4. Discussions and conclusions

4.1. Oldest glaciation evidences

The oldest dated glaciation evidences are observed at different elevations in the northern tropical Andes. The oldest glaciation evidences are recorded in the Colombian Andes at the Páramo de Palacio, Bogotá Plain-Eastern Cordillera (between 3000-3500 m a.s.l.) (Fig. 1, Site 5). Here major outcrops of glaciofluvial-lacustrine sediments (Guasca and Subachoque sections) have been dated by fission track between 1 and 3 Ma. In the Ecuadorian Andes, the oldest dated evidences (moraine complexes M1-M7) are located at Rucu Pichincha and Papallacta valleys, between 3400-3600 m a.s.l.; their ages range between ~900 ka-150 ka (Fig. 1, Sites 6 and 7).

In the Venezuelan Andes, maximum dated glacial extent occurred during MIS 5 (~90-80 ka). These glacial geomorphic deposits are located at 2800 m a.s.l. in the Pueblo Llano Valley, Cordillera de Trujillo (Fig. 1, Site 10). Though possible glaciation evidences related to the Early and Middle Pleistocene have been proposed in the Mérida Andes. These glaciation evidences have been proposed at the Chama, Mucujún (2600 m a.s.l.), Aracay, Santo Domingo river valleys and in the Mesa del Caballo (at 3500 m a.s.l.) (Fig. 1, Sites 1 and 2), geochronological constraints are not available.
4.2. Timing of glaciation maximum extent

Maximum extent of former glaciers in the northern tropical Andes seems to have occurred before the gLGM. In the Venezuelan-Mérida Andes the former glaciers reached the lowest recorded elevations (2600-2800 m a.s.l) during MIS 5-MIS 4. Meanwhile, during the gLGM, they reached elevations between ~3500 m a.s.l. and 3100 m a.s.l. Also in the Colombian Andes, the maximum extent of former glaciers was probably reached at ages older than the gLGM, before 38 ka, with elevations around 2800 m a.s.l. Also, for the Ecuadorian Andes, former glacier maxima likely occurred prior to the gLGM, probably during MIS 8, reaching elevations between 2700 m a.s.l. and 2800 m a.s.l. However, there is no accurate geochronological data to confirm this interpretation.

4.3. Relationship between former glacier dynamics and cold paleoclimate events

4.3.1. During the LGM- OtD

The LGM glacier advances in the northern tropical Andes are not commonly observed, and are located between ~3000-3500 m a.s.l. In the Venezuelan-Mérida Andes, these glacier advances are present in Sierra Nevada at around 3100-3500 m a.s.l., and dated at between 22-19 ka (Mucubají, Las Tapias moraines). In the Colombian Andes, LGM glacier advances seem to be present in the Eastern Cordillera (Bogotá Plain-morainic complex 2) (Fig. 1, Site 12) and in the Central Cordillera (lower Murillo moraines). These glacier advances are located between 3000 and 3500 m a.s.l. In the Ecuadorian Andes, LGM glacier advances seem to be related to a moraine complex located in the Cajas National Park between 3000-3300 m a.s.l. (Fig. 1, Site 9).

In the tropical Andes, most of the studied glacier advances are related to a period that stretches from the final LGM to the OtD (~18-15 ka). These glacier advances are observed between 2500-3800 m a.s.l. In the Venezuelan-Mérida Andes, they are located between 2500-3600 m a.s.l. Most of these advances could be related to the local cold event El Caballo stadial (at 16.5 ka BP). Whilst most of the glaciers grew in this area, in the Gavidia valley (Sierra Nevada) former glacier extinction occurred at around 16 ka at ~4200 m a.s.l.

In the Colombian Andes, glacier advances related to the final LGM-OtD period are located at the Bogotá Plain between 3100-3750 m a.s.l. (moraine complex 3), and dated between 18-15 ka: They are related to the Late Fúquene Stadial (17-14 ka). In the Central Cordillera, the Murillo moraines, located between 3300-3400 m a.s.l., may also be associated to the Late Fúquene Stadial.

Glacier advances related to the final LGM-OtD period in the Ecuadorian Andes, seem to be related to moraine complexes located in the Cajas National Park between 3360-3760 m a.s.l. (Z), as is the case for the Sucus moraine in the Papallacta Valley at 3850 m a.s.l. (Fig. 1, Site 7).
4.3.2. During the YD

Abrupt colder and drier climate conditions in the Sierra Nevada Cordillera of the Venezuelan-Mérida Andes occurred between 12.85 ka and 11.75 ka. Temperatures were 2.5-3.8 °C colder than present. However, evidence of glacier advances during this period is limited so far. Only two YD glaciers advances have been recorded in the Sierra Nevada at elevations higher than 3860 m a.s.l. (3862 m a.s.l. in the Mucubají valley and 4000 m a.s.l. in the Humboldt Massif). Concerning the Colombian Andes, limited evidences of glacier advances during the YD are available. One of these evidences is constrained to the Eastern Cordillera, Sierra Nevada del Cocuy (Fig. 1, Site 16), e.g. the Lower Bocatoma moraines (at between 3800 and 4000 m a.s.l.) and the Upper Lagunillas moraines, at around 3600 m a.s.l. In addition, the moraine complex 4 (between 3250-3700 m a.s.l.) at Páramo de Sumapaz, Bogotá Plain (Fig. 1, Site 11), are examples of the YD glacier advances. Finally, in the Ecuadorian Andes, glacier advances during the YD are not extensively observed. They could be connected to the G2 moraines in the Chimborazo/Carihuairazo Massif at elevations between 3900-4050 m a.s.l. (Fig. 1, Site 8). In addition, glacier advances during this period could also be associated to the M6 moraines in the Rucu Pichincha, between 4200 and 4400 m a.s.l. (Fig. 1, Site 7). Evidence of glacier advances during the YD can be identified in the Papallacta valley, namely the Potrerillos moraines, at around 3900 m a.s.l.

Limited evidences of YD glacier advances are available in the northern tropical Andes. These glacier advances, in general, are mainly located at the highest elevations (> ~3500 m a.s.l.).

4.4. Recent improvements on glacial knowledge and recommendation for future studies

In the last decade, significant improvement in our knowledge of glaciation in the northern tropical Andes has been obtained in the Venezuelan-Mérida Andes, due to TCN-10Be dating.

For a better reconstruction of glaciations in the northern tropical Andes, it is necessary to improve the knowledge of glacier dynamics during the YD and prior to MIS 5. To understand the glaciers cover during the YD, new research should be performed at elevations higher than ~3600-3800 m a.s.l. Nevertheless, to understand glaciers dynamics prior to MIS 5, glacial geomorphological and geochronological work at elevations lower than ~2600-2800 m a.s.l. needs to be conducted.

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