| Cuadernos de Investigación Geográfica<br>*Geographical Research Letters* | 2017 | Nº 43 (2) | pp. 361-376 | ISSN 0211-6820<br>eISSN 1697-9540 |
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DOI: http://doi.org/10.18172/cig.3318

# THE STATE OF KNOWLEDGE ON THE DEGLACIATION OF AMERICA IN 2017

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***ABSTRACT.*** *This work presents a summary of all contributions included in this Special Issue on the deglaciation of America. It analyses the differences and coincidences between the phases of glacial evolution and their chronology in each of the regions studied, and seeks a possible explanation for asynchronies, according to the opinions of the authors of the contributions. Most of the papers show significant diversity within each region due to local factors and different approaches to their study. Often, local differences are even more important than differences with other regions. In North and Central America glacial evolution appears quite uniform, in line with the evolution of the temperature in the North Atlantic. The differences found between some regions may be due to slight variations in the impact of the temperature of the Atlantic in each region, and to differences in approaching their study. The glacial evolution of the Andes presents a greater diversity, probably due to the existence of arid areas along most of the mountain range, which show a greater sensitivity to the reception of humidity than to temperature in their glacial balance. In general, researchers have detected an attenuation of the influence of the temperature of the North Atlantic towards the south, and of the Antarctic Cold Reversal towards the north.*

## *Estado del conocimiento sobre la deglaciación en América en 2017*

***RESUMEN.*** *En este trabajo se realiza un resumen de todas las contribuciones presentadas en el presente número especial sobre la deglaciación de América. Se analizan las diferencias y coincidencias entre las fases de la evolución glaciar y su cronología, en cada una de las regiones estudiadas, y se busca una posible explicación para las asincronías, según las propias opiniones de los autores de las contribuciones. En la mayor parte de las contribuciones se demuestra una importante diversidad dentro de cada región debido a factores locales o a diverso grado de estudio. Muchas veces estas diferencias locales son incluso más importantes que las diferencias con otras regiones. En América del Norte y Central se observa una evolución glaciar bastante uniforme y en consonancia con la evolución de la temperatura en el Atlántico Norte. Las diferencias encontradas entre algunas regiones se pueden deber a ligeras variaciones en el impacto de la temperatura del*

*Atlántico en cada región y a diferencias en su grado de estudio. La evolución glaciar de los Andes presenta una mayor diversidad, seguramente por la existencia de áreas áridas a lo largo de la mayor parte de la cordillera, con una mayor sensibilidad a la recepción de humedad que a la temperatura en sus balances. En general, se percibe una atenuación de la influencia de la temperatura del Atlántico Norte hacia el Sur y de la influencia del Antarctic Cold Reversal hacia el Norte.*

**Key words:** America, Deglaciation, Last Glacial Máximum, Oldest Dryas, Younger Dryas, Antarctic Cold Reversal.

**Palabras clave:** América, Deglaciación, Último Máximo Glaciar, Dryas Antiguo, Dryas Reciente, Inversión Fría Antártica.

Received: 25 April 2017
Accepted: 5 May 2017

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## 1. Introduction

Glaciers accurately reflect the climate of high-latitude and high-altitude regions at a certain point in time. Ice volume and extent increase or decrease depending on the relationship between the prevailing temperature and precipitation at any given moment, and the annual regime of these two parameters. Any climate change may alter the volume and extent of a glacier. The collection of contributions presented in this issue share the common understanding of variations in the extent of glaciers at the end of the Pleistocene. The general trend of deglaciation was frequently interrupted by the alternation of positive phases that left behind moraines, which show glacial advance or ice marginal stagnation. On many occasions, nearby moraine ridges do not indicate small pulsations, but rather important retreats and new readvances during which their glacial fronts reached positions located very close to their previous advance.

This extensive collection of studies, which analyses numerous areas of the American continent, will lead the reader to wonder whether or not the beginning of deglaciation occurred after a contemporary period of maximum extent of the American glaciers, and also whether common phases and timing of deglaciation can be found in all areas. The great extension of the American continent along the meridians, and its latitudinal contrast, may contribute to explain the enigma of the apparently different behaviour displayed by the important pressure centres that configure the General Atmospheric Circulation of the planet, during phases that were much colder than they are today. Moreover, the comprehensive syntheses on the deglaciation of Europe previously published in the present journal (*Cuadernos de Investigación Geográfica* 41 (2), 2015), allow comparisons between the phases of deglaciation of both continents and the extent to which they exhibit synchronous behaviour.

Here I will attempt to summarise the differences and similarities between the different contributions, and search for any common patterns among the evolution of the glaciers in each area. The sole purpose of this analysis is to encourage the reader to study all the regions included in this issue, and not only those that may initially appear to be more interesting. With this goal in mind, I have grouped the contributions that, on the one hand, focus on the subcontinent of North and Central America and, on the other hand, focus on the Andean mountain range that crosses the entire South American subcontinent, in order to analyse the possible similarities and differences between both areas. I have used a time scheme based on the temporal stages established by Greenland ice cores (Rasmussen *et al*., 2014) to explore whether or not the glacier behaviour in either region coincided with North Atlantic cold events.

Before starting this analysis, it is important to emphasise that there are still limitations when comparing the results from different areas. On the one hand, according to glacial dynamics, small differences in the phases of advance and retreat of glaciers can make great differences in the number and size of the landforms left behind as evidence. On the other hand, many of the results have been obtained through cosmogenic dating applied directly to glacial forms. These two facts should be considered in light of the following points:

(i) The existence of a single morainic ridge does not indicate that only one advance occurred, since the most recent advance may have obliterated evidence of the previous ones.

(ii) Later advances may or may not have wiped out the traces of previous advances, according to their erosive capacity. For this reason, it is always possible to find inheritance in cosmogenic ages of bedrock polished outcrops or morainic boulders dating from phases previous to the ones that eventually shaped the present relief.

(iii) The cosmogenic isotope dating method and the age calculation models have improved considerably, but broad ranges of uncertainty still remain, especially when using isotopes such as $^{36}$Cl. Therefore, assigning a particular landform to a glacial phase is a difficult task, as is the case for example of attaching a moraine to a specific advance or stagnation of a glacier, since these advances extend over very short periods of time when compared with cosmogenic ranges of uncertainty.

(iv) As knowledge of a region improves, it is possible to describe its glacial evolution, both the general patterns of paleoglacier changes that are similar in different sites throughout the region as well as local anomalies due to differences in orientation, altitude, rain shadow, etc. Perhaps the most likely danger in this context of pioneering research in new regions is interpreting anomalous events as the general rule.

## 2. The deglaciation of North and Central America

North America held the Laurentide Ice Sheet (LIS), the largest that existed at the end of the Pleistocene and the one contributing most to sea level rise during deglaciation.

Stokes (2017) presents a very clear synthesis on its evolution, the first one since Dyke (2004), which will serve as a reference for the analysis of the rest of the regions. The evolution of glaciers in three western mountain ranges of North America is described in this issue with the contributions made by: Briner *et al.* (2017) on Alaska, the first one after (Kaufman *et al.*, 2011); Clague (2017) on western Canada; and Riedel (2017) on the North Cascade Range. Unfortunately, there are no contributions on the Central and South Cascades, the Central Rocky Mountains or the Great Basin, but the important contributions in this issue of Leonard *et al.* (2017) on the Southern Rocky Mountains and Phillips (2017) on the Sierra Nevada allow for an interesting north-south contrast in the results. In addition, the inclusion of glaciers on the great stratovolcanoes of Mexico and in the mountains of Costa Rica and Guatemala by Vázquez-Selem and Lachniet (2017) contributes to improve this contrast.

### *2.1. The maximum ice extent and the beginning of deglaciation*

The first major question arising from the comparative analysis is whether or not the deglaciation began from a maximum ice extent common to all North and Central America, and whether that maximum extent coincided with the Last Glacial Maximum (LGM). The LGM has been defined by the already classic work of Clark *et al.* (2009), as the period in which the ice sheets reached their maximum integrated volume and the sea level reached its lowest point, between 26 ka and 19 ka. Stokes (2017) shows how the LIS acquired its maximum extent and volume, coinciding fully with the LGM, although not all the areas behaved exactly the same way, since some of them began retreating earlier than others and some areas advanced quite late to their local maximum position. The maximum volume would have been reached between 25 ka and 20 ka, more precisely around 21 ka, very similarly to the European Ice Sheets (EIS), as has been pointed out by Toucanne *et al*. (2015). In fact, the maximum glacial volume and extent of EIS might date from around 22 ka (Stroeven *et al*., 2016; Toucanne *et al*., 2015) or 21 ka (Hughes *et al*., 2016). From that moment, the glaciers of the LIS would have begun their retreat. The glacial maximum, i.e. the moment from deglaciation began, would be placed mainly at the end of LGM in Alaska, 21.4 ka in the North Cascades, sometime before 19.5 ka in the Southern Rocky Mountains, between 22 and 21 in the Sierra Nevada and at 20 ka in Costa Rica. All these data show synchrony throughout the continent and a lack of North/South or East/West divergence, which means that glaciers would have begun to recede from their maximum by 21 ka, probably as a reaction to the maximum insolation of the Northern Hemisphere 23 ka ago. However, two regions do not seem to follow this pattern. This is the case of Western Canada, where the glacial maximum would have remained until 16 ka, and the Mexican volcanoes, where the retreat would have been delayed until 15 ka. As we shall see, these may not be truly exceptional cases.

### *2.2. The pace of deglaciation during its first phases*

The retreat was very slow in the LIS at 21 ka, although it increased around 19 ka, when the ice sheet began to separate from the Cordillera Ice Sheet (CIS) (Stokes, 2017), and accelerated intensely from 16 ka (Stokes, 2017; Riedel, 2017), especially on its southern and eastern margins. Melting was important in Alaska until 18 ka, when it had already lost 40% of its LGM glacial mass. After this moment, deglaciation accelerated, coinciding with the increase of atmospheric $CO_2$. In the North Cascades there was a significant retreat after 21 ka until 18/17 ka. In the Southern Rocky Mountains slightly different behaviour has been detected between areas in the north and east, where rapid deglaciation generally did not occur until after about 17 ka, and farther to the southwest, where deglaciation appears to have accelerated earlier, around 19-18 ka, possibly due to different precipitation conditions. In the Sierra Nevada deglaciation was slow at 18 ka and already substantial at 17 ka. Important deglaciation started also at 18 ka in Costa Rica.

### *2.3. Effects of the Heinrich 1 event*

The Oldest Dryas stadial (GS-2a, 17.5-14.5 ka), commonly referred to in America as Heinrich 1 event (H1), is reflected in the LIS at 17.7/16.8 ka, during which there was a marked advance of the glacial fronts, in at least some areas. Readvances during the H1 have also been detected in some mountains of Alaska around 17 ka, and slightly later in the North Cascades at 16.3 ka, when some of the glacial termini reached their maximum extent. In the mountains of Western Canada the H1 caused the maximum advance at the end of the Pleistocene, but a strong deglaciation began right after 17 ka. This advance has also been detected in the Rocky Mountains at 17 ka, in some areas almost as extensive as the LGM advance, and was immediately followed by a rapid retreat. In the Sierra Nevada glaciers began to re-advance around 16.7 ka until they reached their most advanced positions at 16.2 ka, the exact moment from which the rapid retreat began. In Mexico, the effects of the H1 are considered fundamental for maintaining conditions of maximum late Pleistocene glacier advance until 15-14 ka.

### *2.4. The acceleration of deglaciation and the Bølling-Allerød interstadial*

Many of the areas show a significant retreat even before the Bølling-Allerød interstadial (GI-1, 14.7-12.9 ka). Deglaciation accelerated in LIS after 16.8 ka, particularly between ~15-14.5 ka, when there was already a continuous corridor between the LIS and the CIS, and great lakes formed to the west and south of the LIS. In Alaska the most intense recession had already occurred before the Bølling-Allerød interstadial. In the mountains of Western Canada, the largest retreat had also occurred some time before the Bølling-Allerød interstadial, but most of the mountains were deglaciated between 15 and 12 ka. In the North Cascades, deglaciation had already started by 16 ka, but it was more intense during the Bølling-Allerød interstadial, with rapid disintegration between 14.5-13.7 ka. In any case, some advances in these mountains can be correlated to the Older Dryas period. In the Southern Rocky Mountains, the most significant retreat began between 17 and 16 ka and continued through the Bølling-Allerød, with many glaciers disappearing altogether during this interstadial. In the Sierra Nevada, the most significant glacier retreat occurred at 15.5 ka, around 1 ka before the Bølling-Allerød interstadial, during which many glaciers had already reached their Holocene maximum. In these mountains Older Dryas advance is still not confirmed. In Mexico, deglaciation began around 15 ka and accelerated during the Bølling-Allerød interstadial. Advance phases occurring during the Bølling-Allerød interstadial, which may be linked to the Older Dryas, have been detected only in the LIS, Western Canada and North Cascades, although they may have also occurred in other mountain massifs.

### *2.5. Effects of the Younger Dryas*

Advances and the construction of moraines are characteristic in several areas of the LIS during the Younger Dryas stadial (YD) (GS1, 12.9-11.7 ka), which was followed by intense retreat and the formation of independent glacial domes by 11.5 ka. Conversely, there is no certainty of the existence of advances during the YD in Alaska and, if they existed, they occurred within the limits of the Holocene advances that may have obliterated their traces. YD moraines are indeed evident in the mountains of Western Canada, but they are located very close to those of the Little Ice Age (LIA). The same occurs in the North Cascades, where YD moraines are located no more than 5 km away from the headwalls of cirques, and also very close to the moraines of the LIA. In the Southern Rocky Mountains, only very limited evidence has been identified for a YD glacier readvance. In the Sierra Nevada there seems to be clear moraines from the YD, perhaps from the early phase of the period. The YD is also evident in the glacial valleys of Mexico.

### *2.6. Holocene advances and the culmination of Deglaciation*

After the YD, the LIS still hosted more than 60% of its glacier mass at the LGM, but from 11.5 ka deglaciation greatly increased. However, deglaciation was interrupted by brief periods in which successive morainic ridges were formed between 9.1 to 8.6 ka. Around 9 ka it separated from the Greenland Ice Sheet. A last glacier advance occurred around 8.2-7.8 ka, forming moraines for the last time. The last glacier dome, Labrador, disappeared in 6.7 ± 0.4 ka (Stokes, 2017). The CIS had disappeared by 11 ka (Clague, 2017). Alaskan glaciers did not recover from the late YD to the Holocene Neoglacial period, as happened in Western Canada, the North Cascades, the Rocky Mountains and the Sierra Nevada. Curiously enough, the only place containing mountain moraines that indicate advances or stagnation of the glacial fronts well into the Holocene is central Mexico (Iztaccíhuatl and Nevado de Toluca volcanoes), possibly in relation to the Greenland "8.2 ka cold event" or even slightly later.

### *2.7. Common patterns and causes of asynchronies*

In view of all that has been said, it is not possible to give a regional explanation for the main differences in glacial evolution within North and Central America. At times, the differences and asynchronies arise within each of the regions studied. This happens for example, in the LIS, Alaska, the Cascades, the Rocky Mountains and the Sierra Nevada, and there is no similarity among the Mexican volcanoes or between Mexico and Costa Rica. Often, these internal differences are equal to or greater than the differences between regions. One of the most striking differences emerges at the beginning of deglaciation, but this asynchrony does not establish a geographic pattern, either north-south or east-west, which contradicts many of the common hypotheses about the climate at the end of the Pleistocene, e.g. the different exposure to the evolution of the North Atlantic temperature, or the southward migration of the polar front, pushed by polar anticyclones strengthened by the extent of the LIS.

Without an apparent cause to explain the reasons for these differences, we might have to consider the possibility that the differences are not really such, or at least not so obvious. For example, if we regard the onset of deglaciation in the regions where its beginning has been dated at 21 ka, a strong readvance was also detected during the H1, in which glaciers built moraines in areas close to those of the LGM. In regions where deglaciation began at 16 ka, the H1 may have obliterated the traces of what happened between 21 and 17 ka. In almost all regions, the great momentum of deglaciation is previous to the Bølling-Allerød interstadial, which implies a homogenous behaviour that, as we shall see, occurred in Europe (Hughes *et al*., 2015). The glacial advances and stagnations occurred during or after the Bølling-Allerød interstadial, clearly represented in the LIS, do not show any pattern in the geographic distribution of the mountains studied, which may indicate an uneven progress in the research. Usually, the areas of higher altitude and closer proximity to the headwalls of the cirques are studied later, which means that they are only examined in depth in the more extensively studied massifs. Finally, the wide range of cosmogenic dating uncertainty often exceeds the short periods involved in glacial advances or stagnations, which may increase the sense of anomaly. This is especially important in volcanic mountains, where the $^{36}$Cl cosmogenic isotope used can give uncertainty ranges of up to 2 ka for ages of 14 ka.

### *2.8. Causes that explain the patterns of deglaciation*

In their respective contributions to this issue, Stokes and Phillips study the possible causes of deglaciation. Stokes (2017) agrees with Clark *et al.* (2009) that the beginning of deglaciation after 21 ka was the consequence of increased insolation from orbital forcing, which resulted in increased summer ablation, mainly in the southern marginal areas. From this original cause, several feedback mechanisms would have amplified the initial response, especially $CO_2$ emissions from the ocean to the atmosphere (Shuken *et al*., 2015). However, the surface mass balance remained generally positive in LIS until 11.5 ka, when a rise in temperature up to 7°C in comparison to the LGM resulted in a large expansion of the ablation area and, eventually, the disappearance of the glaciers. It is important to note that, after the LGM, only 40% of the extent of the LIS had disappeared by 9 ka.

Phillips (2017) establishes an interesting contrast between what happens in the Sierra Nevada and the LIS, and reviews the various hypotheses that may explain the behaviour of the Sierra Nevada glaciers, which suffered intense and short variations, while the LIS evolved very slowly. He also demonstrates how the humid periods in southern North America do not correlate with dry periods in the north, thus rejecting the hypothesis that suggests that the Polar Front migrated to the south. Neither does he consider the exceptional arrival of humid tropical air as a possible source of humidity for the Sierra Nevada. For this reason, he defends the existence of teleconnections between the evolution of the North Atlantic and the southwest of North America when explaining the evolution of the glaciers of the Sierra Nevada during deglaciation. Developments occurring in the Sierra Nevada, which can be extrapolated throughout the whole of North America, are closely related to the extent and duration of the sea ice cover in the southern part of the North Atlantic. The evolution of Mexican glaciers also supports this hypothesis (Vázquez-Selem and Lachniet, 2017), but not that of glaciers in Alaska (Briner *et al.*, 2017).

### *2.9. Contrast between the deglaciation of North and Central America and the deglaciation of Europe*

Stokes (2017) suggests a broadly similar evolution between the LIS and the EIS. The new publications on the EIS also confirm this parallelism (Hughes *et al.,* 2016, Marks, 2015; Stroeven *et al*., 2016; Toucanne *et al.,* 2015), by which both ice sheets seem to behave as parts of the same glacier system that reached its maximum extent 21 ka, began a marked retreat 19 ka, an important readvance during the H1 and an important deglaciation already before the Bølling-Allerød interstadial, although deglaciation is accelerated in this period by the clear interruption of the Older Dryas. Perhaps one of the few differences is the great impact that the YD had on the EIS, but we must bear in mind that these differences are due to an uneven degree of knowledge. As for the LIS, 11.5 ka was key to initiate a rapid retreat of the EIS, until its logically earlier disappearance in Scandinavia at 10 ka. Phillips (2017) makes an interesting and detailed comparison between the Sierra Nevada, a mountainous massif where precipitation comes almost exclusively from the Pacific Ocean, and the Alps, whose source of moisture comes from the North Atlantic. Nevertheless, the parallelism between the two mountain ranges is apparent. If we compare Phillips' findings in the Sierra Nevada with those of Ivy-Ochs (2015) in the Alps, and the same could be applied to other European mountain ranges (Delmas, 2015; Makos, 2015), the degree of coincidence is again apparent, and shows a parallel and synchronous glacial evolution throughout history. Once again, one of the few differences may be the great impact that the YD had in the Alps. The most important glacial advance in both mountain ranges since the beginning of the Holocene had already occurred in the Neoglacial periods and, in many cases, during the LIA.

## 3. The deglaciation of the Andean Mountains and Tierra de Fuego

The Andes extend from equatorial to sub-polar latitudes, where the extensive Patagonian-Tierra de Fuego Ice Sheet developed between 36°S and 54°S during the LGM. From these latitudes to 12°N, glaciers of various sizes extended across the summits of the entire Andean mountain range during this period, and often flooded the valleys and nearby plains. This special issue includes contributions on most of the mountain range. The first two contributions describe the deglaciation of the glaciers situated in the five countries of the Northern and Central Andes. Angel *et al*. (2017) present the state of knowledge in the Northern Andes, i.e. in Venezuela, Colombia and Ecuador. Mark *et al.* (2017) do the same in the Central Andes of Peru and Bolivia. Alcalá-Reygosa (2017) provides an example of the deglaciation of the HualcaHualca volcano, situated in southwest Peru. Jomelli *et al.* (2017) study the possible influence of the Antarctic Cold Reversal (ACR) in the formation of glacial advances during this period in many areas of the tropical Andes (Peru, Bolivia and Colombia). Ward *et al.* (2017) analyse the deglaciation of the Arid Diagonal in northern Chile and southwest Bolivia. Zech *et al.* (2017) study the region immediately south of the previous contribution, that is, the Arid Central Andes of Argentina and Chile (22°S-41°S). Mendelova *et al.* (2017) focus their study on the deglaciation of Central Patagonia, between 49°S and 44°S, but they also include numerous references to other parts of Patagonia. Finally, Hall *et al.* (2017) study the deglaciation of Tierra de Fuego. Therefore, our special issue includes practically the entire glaciated area of the South American continent, except for the western Andean slope in central Chile, which allows us to offer a great North-South and East-West contrast in the Andean deglaciation, updating its last revision as a unit (Rodbell *et al.*, 2009).

In their contribution, Mark *et al.* (2017) indicate that the synchronous or asynchronous nature of the deglaciation of the Tropical Andes is still a matter of debate. In fact, this debate has been going on for over 40 years, and can be extended to the entire Andean region, along with the possibility of the synchrony, or not, of events occurring in the Andes and the evolution of the glaciers in the rest of the northern hemisphere and, in particular, with the evolution of the temperature of the North Atlantic. Apart from the effects derived from global factors, such as the evolution of insolation or the amount of $CO_2$ in the atmosphere, the ongoing scientific debate also includes the possible causes of the greater or lesser extent of glaciers in each region, in relation to their exposure to the different temperatures of the two oceans and to the influence of possible sources of moisture, either from the Atlantic, such as the strength of the South American Summer Monsoon, or from the Pacific, such as the Westerlies and the El Niño Southern Oscillation (ENSO). From this perspective, the analysis and contrast of the current state of knowledge on the phases of deglaciation in most Andean regions may help to clarify the situation and establish common trends and criteria.

### *3.1. The maximum ice extent and the beginning of deglaciation*

The knowledge of the characteristics of the maximum ice extent at the end of the Pleistocene reveals a very broad chronological range in the Northern Andes. Practically the only common characteristic is that it precedes the LGM and, although it does not present a great consistence, it could date before 38 ka (Angel *et al.*, 2017). In the Northern Andes, there is still scarce information about the initial and most marked phases of deglaciation. Mark *et al.* (2017) show the average date of the maximum glacial extent would have been 25 ka in Peru and Bolivia, but it would include a broad chronological range of ±7 ka. The deglaciation would have already been significant by 20 ka or even earlier. Ward *et al.* (2017) indicate that the maximum ice extent in the Arid Diagonal was 35-45 ka, and the retreat was already intense during the LGM, 25-20 ka, under dry conditions, although locally moraines have been dated at 25-30 ka and 19-22 ka. Further south, Zech *et al.* (2017) have found an even older age for the maximum ice extent at 40 ka, yet they argue that during the LGM, 26-20 ka, the glaciers advanced, though lower and previous to the intense deglaciation that began 18 ka. Evidence in central Patagonia shows that the glacial maximum advance occurred in synchrony with the LGM; however, in northern and southern Patagonia glaciers reached their maximum earlier. The deglaciation in central Patagonia was underway by 19 ka. Similarly, the knowledge of the glacial maximum extent is very limited in Tierra de Fuego which seems to have occurred after 36 ka, but some of the moraines dated in this area indicate glaciers had already reached those positions during the LGM. In Tierra de Fuego deglaciation was very intense after 18 ka.

### *3.2. The pace of deglaciation during its first phases and the impact of the Heinrich 1 event*

According to Angel *et al.* (2017), the knowledge of the deglaciation history of the Northern Andes is very limited and, therefore, we cannot draw general conclusions from it yet, although most of glacial advances are acknowledged contemporary to the H1. Mark *et al.* (2017) refer to the diverse positive advances that interrupted deglaciation in Peru and Bolivia between 20-18 ka, where a good number of moraines are dated with an average of 18.9 ± 0.5 ka, always coinciding with wet phases. These authors acknowledge a clear impact of the H1 event, as seen from the numerous moraines with an average age of 16.1 ±1.1 ka. Alcalá-Reygosa (2017) indicates that the glaciers of the HualcaHualca volcano reached their maximum extent during H1, in relation to the wet phase of the Tauca paleolake cycle in the Altiplano lasta glacial cycle. Ward *et al.* (2017) also identified glacial advances during H1 in the areas closest to the Altiplano, while deglaciation became more intense in areas located farthest from it after 17 ka. Nevertheless, Zech *et al.* (2017) have glacial advances further south during the H1 event, in line with the Tauca paleolake cycle. No glacier advances coeval with the H1 event have been detected in Patagonia or Tierra de Fuego so far; however, both regions had already been intensely deglaciated by 16 ka.

### *3.3. Deglaciation and the Bølling-Allerød interstadial versus the Antarctic Cold Reversal*

ACR (14.6-12.8 ka), a cooling event identified in Antarctic ice cores, which interrupted an overall warming trend and coincided with the warm Bølling-Allerød interstadial in the North Hemisphere. The implications of this event on climate evolution are stronger at south of 40ºS and decreases towards the north (Pedro *et al*., 2015), but its effects on glacial advance could be found in the tropical Andes. Mark *et al*. (2017) refer to a widespread advance in Peru and Bolivia coinciding with the ACR, resulting in moraines with an average age of 13.7 (± 0.8) ka, followed by a significant recession. Conversely, Alcalá-Reygosa (2017) did not detect with certainty a glacial advance related to the ACR in the HualcaHualca volcano. Jomelli *et al*. (2017) focus their analysis exclusively on the influence of the ACR in the Tropical Andes. From a large number of moraines analysed from Peru, Bolivia and one case from Colombia, and dated by $^{10}$Be and $^{3}$He, they can conclude that 60% of these Late glacial moraines are circumscribed within the ACR or at an immediately previous time. Ward *et al*. (2017) did not find any glacial advances during the ACR in the Arid Diagonal, but rather on the contrary, they have detected a widespread retreat from 14.5 ka. The glacial advances during the ACR are not widespread in central Patagonia, where they are only present in some valleys of its eastern slope, but they are evident in southern Patagonia. In Tierra del Fuego, glacier advances contemporaneous with the ACR were minor, relative to the present day glacier margins in the Cordillera Darwin.

### *3.4. Effects of the Younger Dryas*

The evidence of glacial advances that coincide with the Younger Dryas is very limited in South America. There is evidence of a cold climate in the Northern Andes at that time and some glacial advances have been observed, but not in a generalized way (Angel *et al*., 2017). Mark *et al*. (2017) found that glaciers in Peru and Bolivia retreated significantly during the YD due to arid climates. Alcalá-Reygosa (2017) found an advance or stillstand phase at 12 ka in HualcaHualca volcano. Of the moraines studied by Jomelli *et al*. (2017) in Peru and Bolivia, only 5% were contemporary with this period. Ward *et al*. (2017) have not found evidence of glacial advances in this period in the Arid Diagonal. Conversely, Zech *et al*. (2017) have identified glacial advances further north, which coincide with a wet phase of the Coipasa paleolake cycle (12.8-11.4 ka). Glacial advances restricted to the Cordillera occurred in Patagonia in this period. There is no evidence of advances in Tierra de Fuego in this period.

### *3.5. Holocene advances and the culmination of deglaciation*

The information about the culmination of deglaciation in the Andean world is very limited and divergent. Mark *et al.* (2017) show how glacial advances continued to exist in the transition between the Pleistocene and Holocene in Peru and Bolivia, always associated with wet phases, around 11 ka, coinciding with periods of very marked retreats in the glaciers of the northern hemisphere, until a definitive retreat began after 9.4 ka. Alcalá-Reygosa (2017) distinguishes a definitive retreat in the HualcaHualca volcano and Patapampa Altiplano from 11.5 ka. Ward *et al*. (2017) have found no glacial deposits after 17 ka in the Arid Diagonal. In Patagonia, glacial advances occurred in the eastern area in 11 ka. In Tierra de Fuego, glaciers had practically retreated close to their present limits by 16 ka, except for small advances related to the ACR.

### *3.6. Common patterns and causes of asynchronies*

As in North and Central America, it is not possible to identify a general trend along the Andes, or to differentiate regions with a common behavior during deglaciation, although in this case the lack of unifying elements is even more obvious. Again, the asynchronies in the glacial phases occurring within a given region are very marked, equal to or greater than the differences between several regions, even though these may be in completely different geographical contexts. In any case, some characteristics are more or less common to the entire Andes. The maximum extent of glaciers was occurred prior to the LGM, although the exact timing varied along the Andes and, in some cases, coincident with this period. Deglaciation began to intensify during or immediately after the LGM, the most common dates being between 20 and 18 ka, in line with the global increase in atmospheric $CO_2$ and the events occurring in North America. The effects of the H1 event are the evident cause of the glacial advance in the Tropical Andes, in coincidence with wet phases, but its connection with the temperate and the subpolar regions is not so clear. The behavior of glaciers during the Bølling-Allerød interstadial/ the Antarctic Cold Reversal in the Andes is by no means uniform. While there is clear evidence of advances during this period, we still lack information about many regions and, in fact, evidence is not widespread in the Andes. Lastly, there is only minimal evidence of glacial advances during the Younger Dryas.

### *3.7. Causes that explain the patterns of deglaciation*

All the contributions acknowledge a general trend of glacial retreat driven by global factors, such as $CO_2$ concentration in the atmosphere from 18 ka (Shuken *et al*., 2015). But we should not forget that deglaciation precedes this date in many areas, although it accelerates thereafter in the entire Andes. In explaining the great diversity and lack of regionalisation in the trends followed by the different glacial phases in the Andean world, we must always take into account the problems derived from dating methods and their high degree of uncertainty, as well as the capacity of glacial advances to obliterate the traces of previous advances. Besides, it is important to consider that the Andes comprise a meridional orientation that is perpendicular to the prevalent zonal winds that transport moisture-laden air. This accounts for the existence of arid regions on the leeward aspects along almost the entire mountain range, except in the north, where glacial mass balance is very sensitive to the reception of moisture. Consequently, the alternation of dry and wet periods is very important during deglaciation period in Andes (Placzek *et al*., 2011). This characteristic may increase the variability of the glacial response to climate change (Blard *et al*., 2009). In fact, many of the phases of glacial readvance can be identified from the high water levels of the intra-Andean lakes, especially in the tropics. Thus, Zech *et al*. (2017) explain advances in their study area through the influence of the great lakes formed in Uyuni and Poopo Basin during the LGM (24-20.5 ka). These authors, as well as Mark *et al*., Alcalá-Reygosa, and Ward *et al*. (2017) point out the substantial positive impact of the H1 event on the glaciers, because it coincides with the Tauca Highstand wet phase (17-15 ka). Similarly in Patagonia, the glaciers on the more arid eastern slope are much more sensitive to humidity, and their fronts are prone to advance and retreat more frequently than those on the western slope. Nevertheless, the wetter southernmost regions show a higher sensitivity to changes in temperature. For example, Hall *et al.* (2017) make the case that deglaciation accelerated in Tierra de Fuego due to increases in temperature.

Zech *et al.* (2017) summarise the three main sources of humidity in the Andes: the South American Summer Monsoon (SASM), the Westerlies and the El Niño Southern Oscillation (ENSO). Mark *et al.* and Zech *et al.* (2017) emphasise how the conditions of the North Atlantic can strongly modulate the strength of the SASM and precipitation dynamics in the Tropical Andes. Cold phases in the North Atlantic would have forced the SASM to migrate south to the interior of the South American continent, where a wet phase would follow. For example, this could have caused the maximum extension of Andean glaciers prior to, or coincidental with, the LGM, as well as the wet phase during the H1 event in the Tropical Andes region with its widespread impact on the glaciers. These authors further argue that some of the wet phases in the tropics are related to northward migrations of the Westerlies and La Niña episodes, although it is difficult to correlate these wet periods with arid phases in the temperate areas, according to the corresponding contributions. These authors also describe the significant impact that the El Niño-La Niña alternation had on tropical glaciers, although generalising their respective effects on the Andean glaciers is still very complicated.

## 4. Conclusions

After summarising and analysing each of the contributions to this Special Issue, we can now examine some of the most relevant facts. Many of the most important asynchronies occur within each of the regions analysed, and they are often derived from different exposure levels to the sources of moisture, which is especially significant in the Andean region.

The moment at which the maximum ice extent was reached is much more uniform in North and Central America than in the Andes. In most regions of North and Central America this maximum extent coincided with the LGM, in many cases in 21 ka. Conversely, in the Andes the maximum extent of glaciers presents an enormous chronological diversity, and no clear trend has been identified so far along the mountain range, either North/South or East/West. This maximum extent was usually previous to the LGM and, in many cases, coincided with wet phases. In many regions, the LGM coincided with a phase of glacial advance, although not so extensive, and generally coincident with wet phases, whereas in others it coincided with dry periods during which glaciers retreated. Lastly, in some Andean mountains the maximum extent occurred after the LGM, but always in coincidence with wet phases.

While there is no coincidence in the chronology of the maximum extent of glaciers along the continent, it indeed exists when referring to the phase of maximum deglaciation, which occurred in most of America between 19 and 18 ka. The impact of the H1 event throughout the American continent was also very widespread. This impact can be inferred from the glacial advances that occurred mainly in North and Central America, but also in the Andes, mainly in the Central Andes, where it coincided with a significant wet phase, while the impact is unclear in Patagonia and Tierra de Fuego.

Deglaciation accelerated again after the H1 event throughout America, in most cases preceding the Bølling-Allerød interstadial. However, in many but not all the regions of South America, the deglaciation was interrupted by phases of glacial advance associated with the Antarctic Cold Reversal or immediately prior to this period, but its influence was neither very intense nor widespread in the Southern Andes.

Unlike the H1 event, the influence of the Younger Dryas was more attenuated and less widespread in America. The YD is not perceived even in important mountain ranges of North and Central America. Moreover, it does not follow any latitudinal criteria, since it is missing in Alaska, for example, but present in Mexico. In South America the YD has been detected in few Andean areas, as in most cases it coincides with wet phases in otherwise arid regions.

The date of the beginning of the final deglaciation is very unanimous in the mountains of North America. The definitive and very rapid retreat of the glaciers from areas in which they had not yet disappeared has been dated in 11.5 ka, which is fully in line with events occurring in the LIS. Since then, as in Europe, the glaciers of these mountains would not recover again until the Holocene neoglacial period and, in many cases, until the LIA. Although this date is also important to point out the intense deglaciation of many regions in the Andes, advances continued in many other areas until 9 ka. This occurred, in any case, during wet phases in otherwise arid or semi-arid regions.

In short, establishing general rules for the deglaciation of America is a very complex task. On the one hand, there are important asynchronies within each region studied, probably related to local factors and different approaches to their study. On the other hand, asynchronies between regions do not follow any clear regional pattern, either North/South, East/West, within North and Central America, within South America or between the two subcontinents. Accordingly, it is still very difficult to understand the features of the General Atmospheric Circulation during phases that were much colder than today, and the role played by both oceans, Pacific and Atlantic, in the change from one phase to another. Researchers have only detected a widespread reaction of the glaciers to the changes of temperature in the North Atlantic, which was very steep in the northern hemisphere and reached the tropical Andes, but gradually attenuated towards the south, whereas the influence of Antarctic climate phases may have extended from the southernmost regions to the tropical Andes. The great diversity observed in the Andean glacial evolution is due to the special sensitivity of the glaciers that cross most of the Andes to humidity rather than to temperature in their glacial balance, since they are usually situated in arid or semi-arid regions.

There can be no doubt that progress in the knowledge of the deglaciation of the America in the last decades has been enormous, but there is still much to be done. The degree of uncertainty of dating methods, the complexity of the glacial dynamics and erosion on which such methods are based, the very rapid alternation of glacial advances and retreats, and the intensity of these increasingly evident changes, make it difficult to understand when, where and why these changes began, and what the climatic thresholds were.

## Acknowledgements

To all authors of this Special Issue, for their great effort to make it a reality. Most of them have reviewed and provided interesting suggestions in this paper. To Dr. Lorenzo Vázquez-Selem and to the associate editors of the Journal *Cuadernos de Investigación Geográfica* Prof. Jose M. García-Ruiz and Dr. Amelia Gómez-Villar, for the great personal effort made in the preparation of this issue and their help in the coordination. This study has been prepared into the context of the project MOUNTAIN WARMING (CGL2015-65813-R) (Spanish Ministry of Economy and Competitiveness).

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