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A new Andean deep ice core from Nevado Illimani (6350 m), Bolivia

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Abstract

A new ice core record from the Nevado Illimani (16°S), Bolivia, covers approximately the last 18 000 years BP. A comparison with two published ice records, from Sajama (18°S), Bolivia [Thompson et al., Science 282 (1998) 1858–1864] and Huascarán (9°S), Peru [Thompson et al., Science 269 (1996) 46–50], documents a regionally coherent transition from glacial to modern climate conditions in South America north of 20°S. The strong resemblance between the Illimani and Huascarán water isotope records and their differences from the Sajama record, in particular during the period from 9000 years BP to 14 000 years BP, suggest that local water recycling or local circulation changes played a major role for Sajama. We interpret the common Illimani/Huascarán water isotope history in terms of a common change from wetter/cooler conditions during glacial times to drier/warmer conditions in the Early Holocene.

Keywords: glaciology; ice cores; tropical climate during the last glacial; water isotopes in the Andes

1. Introduction

Two existing continuous ice records in the Andes, Sajama and Huascarán, date back to the last glacial stage (LGS) [1,2]. Based principally on the information deduced from the isotopic composition ($\delta^{18}O$ or δD) of the ice of these two deep drillings, Thompson et al. [3] described the deglaciation sequence for the tropics (Huascarán) and subtropics (Sajama) in South America. For the first time, an uninterrupted isotope signal was available covering the last 18 000 years in the case of the Huascarán and the last 24 000 years in the case of Sajama. At the bottom of the Huascarán and Sajama cores, the ice is isotopically depleted by approximately 5‰ relative to modern conditions.

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In high latitudes, the isotopic composition of meteoric water is usually interpreted as a temperature proxy. However, in low latitudes empirical evidence linking temperature and the stable water isotopes in modern precipitation breaks down and instead, precipitation amount dominates the signal [4,5]. Using the slope of the classical isotope–temperature relationship for high latitudes of about 0.7‰/°C Thompson et al. [2] estimated an 8–12°C temperature change at high elevation in the tropics. In a recent publication based on a more complete analysis of available paleodata Thompson et al. [3] refrained from this straightforward explanation for tropical isotope records, but they still interpret the isotopic depletion found in glacial ice from the Andes as ''a reflection of significant cooling''.

Ice core records provide us with additional information on paleo-climate and paleo-environmental conditions. Atmospheric dust loading is principally controlled by atmospheric turbidity, humidity, and vegetation coverage [6]. The extreme rise of the number of dust particles at the bottom of the Huascarán ice core by up to a factor of 200 was interpreted as an indicator of much drier conditions during the LGS in this part of the Andes. This conclusion was further supported by a comparison with reconstructed vegetation coverage in the Amazon Basin indicating a much larger expansion of savannah at the expense of tropical rainforest and even the appearance of sand dunes in the northern part of the basin (see [3] and references therein). In contrast, glacial dust levels in the Sajama ice core remain low throughout the LGS indicating relatively moist conditions in this part of the Andes. In summary Thompson et al. [3] depicted a climatic scenario for the LGS with cold and dry conditions in the tropics and cold and wet conditions in the subtropics based on the comparison of the Sajama and the Huascarán ice cores. Here the term 'subtropics' for the Sajama region is used rather in a climatological sense than in a strict geophysical sense. Situated at 18°S the Sajama is of course still situated in the tropics. However, the extremely dry Bolivian Altiplano is part of the globe which is controlled by the downdraft zones of the Hadley cell typical for the subtropics [7].

Though the general picture of climatic changes during the deglaciation deduced from these two ice cores is similar, in detail the sequence of isotopic events is remarkably different. Both records (Huascarán [2] and Sajama [1]) show rising isotope signals from about 17 000 years BP and reach a first maximum at 14 500 years BP. However, whereas in the Huascarán record this maximum is only about halfway between the low values during the LGS and a well-pronounced Early Holocene, the synchronous maximum clearly sticks out as the isotopically most enriched portion of the Sajama record. A reversal (named the deglaciation cold reversal, DCR [8]) to more depleted values is found in both records, roughly between 14 000 years BP and 12 000 years BP. Again the amplitude in the tropical record was different from the subtropical. The Sajama record jumps abruptly back to near glacial levels (relatively depleted by 6‰) whereas the Huascarán record smoothly becomes isotopically more depleted by just 1‰. In [3] this isotope signal was associated with cooler conditions during the Younger Dryas climate reversal documented in many paleorecords, in particular in the North Atlantic sector. At about 10 000 years BP both records reach Early Holocene isotope levels. Only the Huascarán record however shows a well-defined isotopic optimum during that period. Summarizing one can say that the Huascarán isotope record looks Antarctic-like [9] and the Sajama record Greenland-like [10]. This is the reason why the latter was partly dated by wiggle matching to the GISP2 ice core.

The absolute dating of both ice cores is poor and does not allow any conclusion on exact timing of these events. For example, it is not possible to distinguish if the described DCR took place synchronously with Antarctic records (the Antarctic cold reversal) or with records documenting the Younger Dryas in the Northern Hemisphere or neither. The time lag between the two hemispheric climate reversal signals amounts to at least 500 years [9].

In this study we test a number of these conclusions with results from a third ice core drilled on Nevado Illimani. The questions we investigate in this study are the following. (1) Are the isotope

signals from high Andean glaciers faithful recorders of regional climate conditions? Or are they at least partially artifacts due to ice layer thinning and other post-depositional effects at the bottom of more than 100 m thick ice caps? The Early Holocene and glacial part of these cores amounts to only 5 m in the Huascarán core and to 30 m in the Sajama core. (2) Does a third isotope and dust record confirm the described climate scenario for the LGS of cold/dry tropics versus cold/wet subtropics? (3) Can we add information on the interpretation of low latitude isotope records in terms of temperature or precipitation changes?

The paper is structured as follows. In a first part we present the new drilling site and compare its climatological situation with those of Sajama and Huascarán. Then we describe the different chemical and physical measurements performed on the Illimani core. Subsequently we present in detail the dating methods and, finally, focussing on the established isotope/dust records from the three drilling sites we discuss the questions mentioned above.

2. Presentation of the new drilling site

In June 1999, a French/Swiss/Bolivian team took an ice core on Nevado Illimani (6350 m, 16°37′S, 67°46′W), which reached bedrock at 136.7 m. Though the Illimani ice cap is only 150 km distant from Sajama, local conditions and the positions of the two sites relative to the main moisture flux from the Amazon Basin are quite different [11,12]. Illimani, located in the Cordillera Oriental near La Paz and Lake Titicaca, is more directly exposed to the humid and warm moisture flux coming from the Amazon Basin (see Fig. 1). In contrast, Sajama is located in the semi-arid western part of the Bolivian Altiplano. Consequently, the different local humidity conditions are reflected in different ice accumulation rates on Illimani (580 mm/year [13]) and Sajama (440 mm/year [1]). However, these numbers should be regarded with some caution. They represent preliminary estimates since post-depositional effects and different observational periods may have an important influence on their calculation. In contrast to Sajama (6542 m, 18°06′S, 68°53′W) and Illimani, Huascarán is clearly situated in the tropics (6048 m, 9°06′S,77°36′W,[2]). A much shorter and less pronounced dry season (only ∼3 months) is observed at Huascarán compared to Sajama (∼9 months). The dominant water vapor source of all three sites is the tropical/subtropical Atlantic. The vapor is advected by northeasterly trade winds into the Amazon Basin and, finally, after Amazonian recycling, precipitated on the Andes [14].

3. Methods

On the drilling site ice core sections of 50 cm length were sealed into polyethylene bags and transported in a frozen state to the LGGE (Laboratoire de Glaciologie et Géophysique de l'Environnement) in Grenoble, France. Here the core was further subsampled and chemically analyzed.

First we performed electrical conductivity measurements (ECM) on the Illimani ice core. These measurements were done in a cold room using a two-electrode method as described in [15]. In polar ice cores ECMs are mostly linked to the acidity of the ice, which itself mainly depends on the concentration of H_2SO_4. In the Andes, this acid may originate from various, still not well-quantified sources. There is probably a continuous background amount due to marine biological activity and fumarolic volcanic activity. From time to time, cataclysmic volcanic eruptions bring about significant ECM spikes.

Subsequently, the ice was cut into pieces of 10 cm (from the top to 40 m), 7 cm (from 40 m to 120 m), 3 cm (from 120 m to 133 m) and 1 cm (over the bottom 3 m) and prepared for further chemical and isotopic analysis. Calcium concentration was measured by ionic chromatography. Calcium concentration reflects atmospheric aerosol loading that is incorporated into the ice of Nevado Illimani, mainly during the 6 month dry season.

Another time marker for the dry season is the dust particle concentration. Particle concentrations and grain sizes have been measured with a

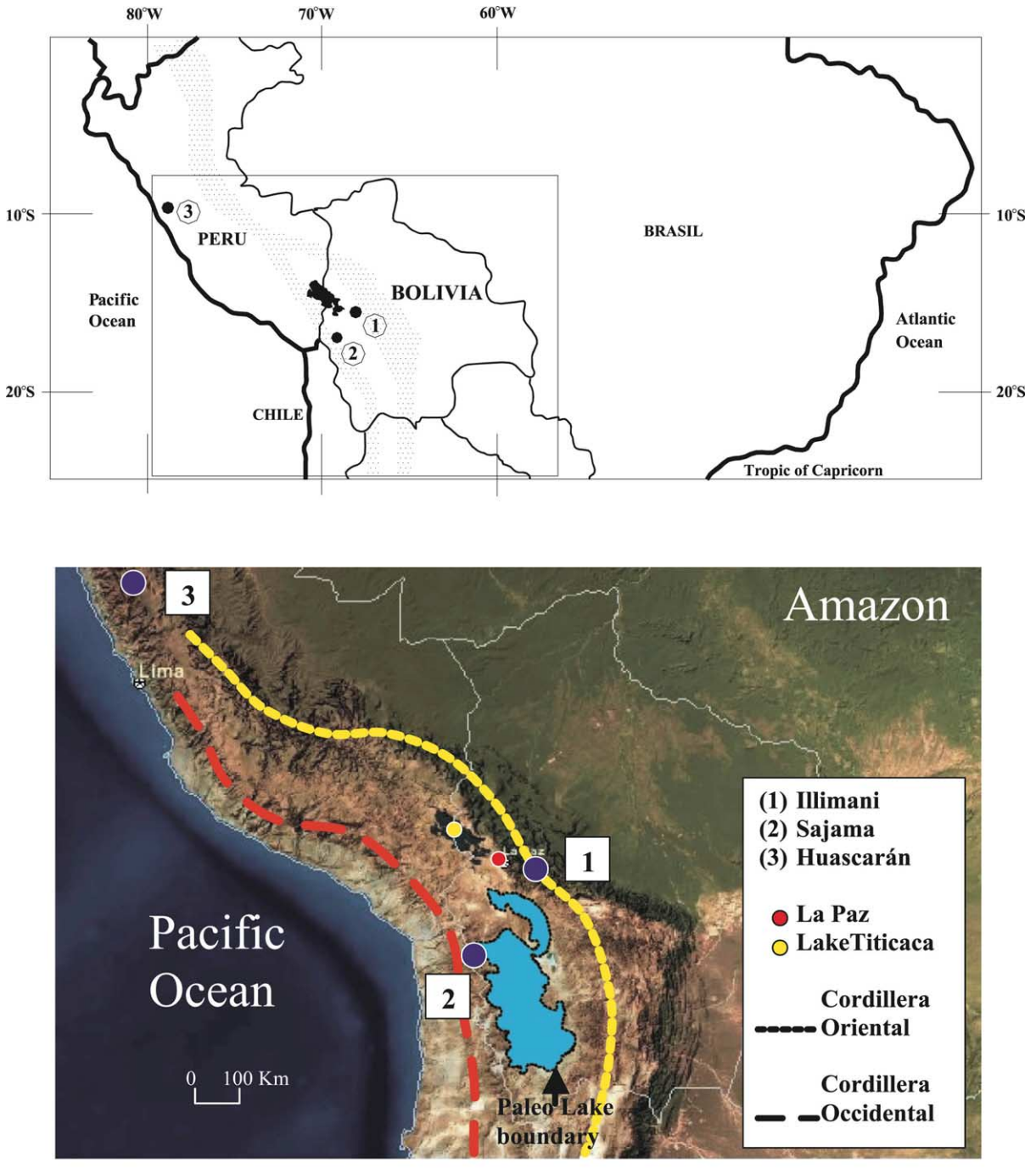


Fig. 1. Map of the Andes including the three drilling sites of high altitude ice cores discussed in this study. The Illimani glacier is situated on the natural frontier between the Amazon Basin and the Central Andes, 50 km east of La Paz, Bolivia, and 180 km east of Lake Titicaca. The Sajama glacier is located in the Andes, 160 km east of the Pacific Ocean and 200 km southwest of the Illimani glacier. The Huascarán, the third deep drilling site, is located in the northern part of the Peruvian Andes. Quelccaya is also situated in Peru and it contains a high resolution record of the last 1500 years which is why it is not included in our discussion on climate changes from the LGS to the Holocene.

Coulter Multisizer permitting the differentiation of 256 size classes from 0.67 μm to 20.89 μm diameter.

To identify elevated bomb-produced tritium concentrations, water samples of 22 cm^3 volume were converted to methane by means of aluminum carbide at 150°C. After purification the counting gas was rested for 3 weeks to allow radon decay that may originate from the aluminum carbide production. After this time the gas was transferred to a proportional counter at 7 bar. Depending on the activity of the individual sample, the counting time was between 48 and 72 h. Very low activities were checked against samples of tritium-free water (one blank sample between every pair of unknowns). The error (1σ) for a sample of 4 TU (tritium units) is in the order of 0.4 TU [16].

A new method has been applied in this study that allows us to fingerprint volcanic eruptions in the ice. We measured the isotopic composition of sulfur in sulfate, SO_4, over the first 100 m of the core. The SO_4 concentration was first measured by ion chromatography, then the isotopic composition of the sulfate, $\delta^{34}S$, was measured using the EA-CF-IRMS technique (elemental analyzer-continuous flow-isotope ratio mass spectrometry) with an analytical precision of ± 0.4 ‰ [17,18].

$\delta^{18}O$ and δD were measured at the Laboratoire des Sciences du Climat et de l'Environnement, LSCE. The isotopic measurements are given here as deviations in permil from the Vienna Standard Mean Ocean Water (V-SMOW) [19]: $\delta_{Sample} = R_{Sample}/R_{V-SMOW} - 1$, where R specifies the mixing ratio of the heavier isotope (i.e. deuterium or ^{18}O) relative to the lighter and more abundant H_2 ^{16}O. The experimental precision of the isotopic analysis is 0.8 ‰ for δD and 0.05 ‰ for $\delta^{18}O$ (1σ).

The analysis of the isotopic composition of atmospheric oxygen, $\delta^{18}O_{Atm}$, enclosed in the ice of the Illimani core was also performed at the LSCE by melting ice samples of about 20 cm^3. The air was extracted into sealed glass vessels and subsequently analyzed. The precision of the $\delta^{18}O_{Atm}$ measurements was ± 0.03 ‰ [20] corresponding to 1σ.

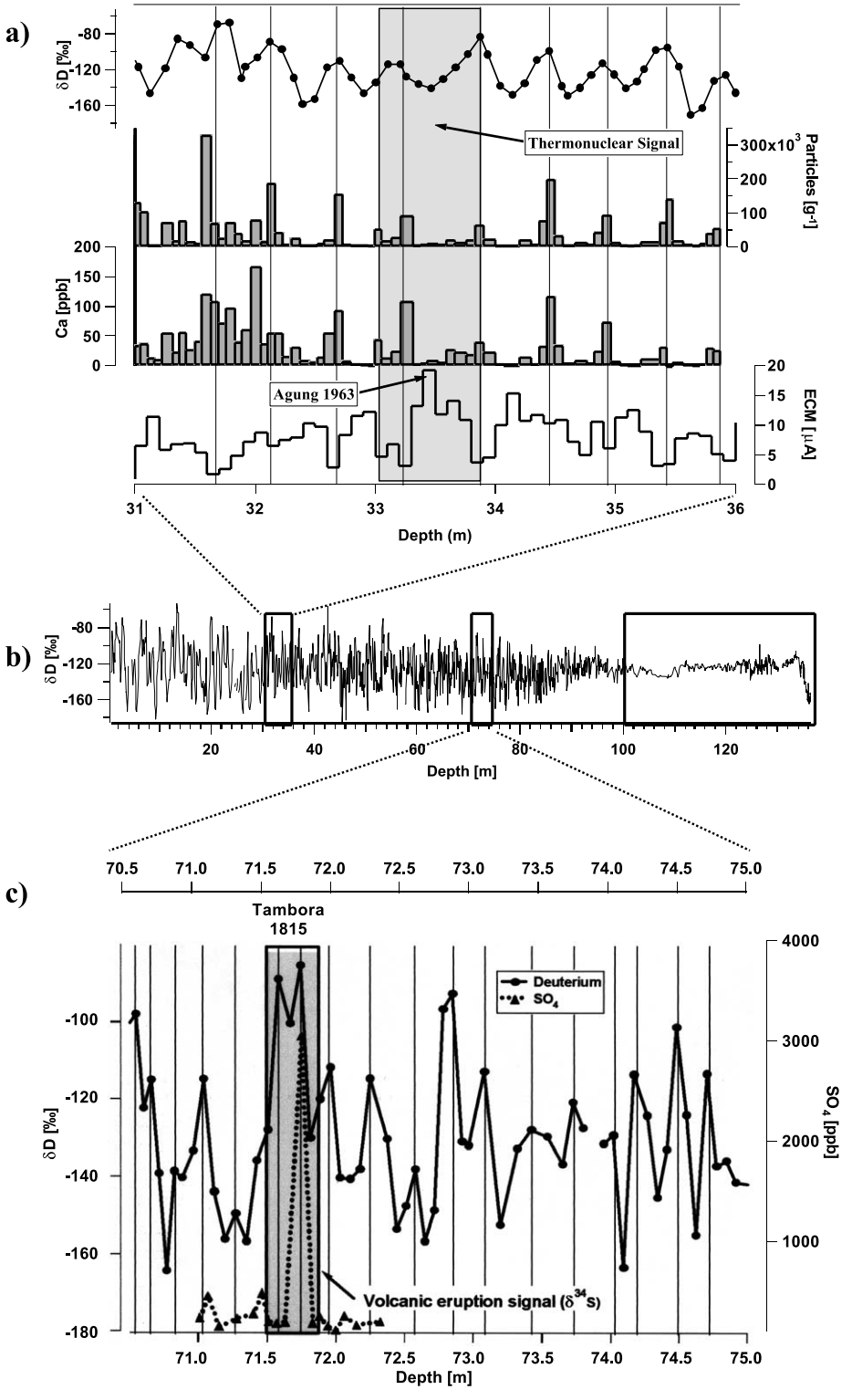
3.1. Dating

Dating techniques, the estimates of dating uncertainties and potential problems were fully explained in [13], a study undertaken on a second parallel core from Illimani. Dating differences between both ice cores were small and never exceeded the estimated depth-dependent uncertainty. Fig. 2 presents the entire Illimani isotope record and illustrates the approach used to establish the time scale. In its upper part, the core was dated by counting annual layers of a number of tracers presented above (see Fig. 2a), such as the ECM, the dust particle number, the Ca^+ concentration and the isotopic composition of the ice. The seasonality of all four of these quantities is well preserved down to a depth of about 40 m corresponding approximately to the year 1947.

Furthermore, a number of tie points have been used: three peaks in the conductivity were associated with well-known volcanic eruptions of the last 40 years (Pinatubo, 1991; El Chichón, 1982; Agung, 1963). A peak in the ^{37}Cs and tritium contents of the ice at a depth of about 33.5 m, associated with the strongest bomb tests (1964) in the northern hemisphere, provided us with an additional time marker.

The Tambora eruption, 1815, was identified in the ice between 71.57 m and 71.88 m by combined measurements of SO_4 and stable sulfur isotopes (see Fig. 2c). The SO_4 concentration peaks to extremely high levels of 3075.1 ppb at 71.75 m depth. Background $\delta^{34}S$ values (excluding major volcanic eruptions and sulfate peaks) at Illimani are about +6.40 ‰. The sample corresponding to the supposed Tambora eruption has the lowest isotopic value measured in the ice core of 1.55 ‰. Volcanic $\delta^{34}S$ is quite variable but generally is between 0 and +5 ‰ [21,22]. Both sulfate concentration and its isotopic value point to a volcanic origin.

The estimated uncertainty (1σ) of the multiproxy approach is ± 2 years down to 40 m. Seasonal layer counting of the δD signal in the Illimani record was possible down to 87 m despite an increasing uncertainty estimated at ± 20 years at 87 m. This gave us an estimated age of 1747 AD corresponding to the depth of 87 m. At greater


a)
δD [‰]
-80
-120
-160
Thermonuclear Signal
300x10^3
200
100
0
Particles [g^-1]
200
150
100
50
0
Ca [ppb]
Agung 1963
20
15
10
5
0
ECM [μA]
31
32
33
34
35
36
Depth (m)
b)
δD [‰]
-80
-120
-160
20
40
60
80
100
120
Depth [m]
c)
70.5
71.0
71.5
72.0
72.5
73.0
73.5
74.0
74.5
75.0
Tambora
1815
Deuterium
SO4
-100
-120
-140
-160
-180
δD [‰]
4000
3000
2000
1000
SO4 [ppb]
Volcanic eruption signal (δ34S)
71.0
71.5
72.0
72.5
73.0
73.5
74.0
74.5
75.0
Depth [m]

depth, solid-state diffusion erases the seasonal isotope signal.

To date older cores, essentially two sources of information were used: the isotopic composition of atmospheric oxygen ($\delta^{18}O_{Atm}$) and the overall similarity between the Huascarán and the Illimani records (see Fig. 3a,b).

The isotopic composition of atmospheric oxygen ($\delta^{18}O_{Atm}$) was measured between 131 and 136 m. The reproducibility of these measurements (see the pairs of triangles in Fig. 3b) was excellent given the generally poor quality of tropical ice for this kind of high precision gas measurements [23]. The firn closure depth, i.e. the depth where air enclosed in the firn could no longer exchange with the free atmosphere, is at about 50 m on Illimani under present conditions. For this computation we used the Herron and Langway model [24] which was forced with today's observations, i.e. 580 mm/year accumulation rate and −8°C mean annual temperature. The depth for the computed firn/ice transition corresponds to an approximate ice/gas age difference of 80 years. Even under colder, and possibly wetter, climate conditions, this difference increases to a maximum of just 200 years supposing 8°C cooler temperatures and a 30% higher accumulation rate. The $\delta^{18}O_{Atm}$ signal increases from Holocene levels of about −0.2‰ to glacial levels of +0.8‰ (see Fig. 3b) mainly reflect the isotopic composition of seawater [25], though with a delay of more than 1000 years due to the large residence time of atmospheric oxygen. The comparison with the $\delta^{18}O_{Atm}$ record from Vostok, Antarctica [26] points to an age of the bottom of the Illimani ice core of at least 18 000 years BP. However, with only seven $\delta^{18}O_{Atm}$ measurements, and given the large uncertainties due to crystal diffusion at the bottom of the ice core and the variable residence time of atmospheric oxygen (considerably larger in glacial times) it is not possible to establish the time scale for the bottom 5 m of the Illimani exclusively based on the $\delta^{18}O_{Atm}$ measurements.

Sixteen tie points between the Huascarán and the Illimani records have been selected (see Fig. 3a,b). Finally the continuous depth/age relationship was established using four exponential spline functions over four different parts of the core (0–64.5 m, 64.5–121.5 m, 121.5–133.61 m and 133.61 m to the bottom) respecting the estimated dating uncertainties of the fixed points (±2 years at the beginning of the records and ±200 years at the bottom).

About 10 m below the ice surface we measured an ice temperature of −7.2°C. The ice was even colder at 65 m (−8.9°C). At the bottom we measured an ice temperature of −8.4°C which is why melting processes in the ice can be excluded. However, the three bottom isotopic measurements have nearly Holocene levels. For this part of the record we measured both stable water isotopes, δD and $\delta^{18}O$. The deuterium excess $d = \delta D - 8\delta^{18}O$ (i.e. the scaled difference between the $\delta^{18}O$ and the δD) jumps abruptly from relatively stable LGS levels of 15–16‰ to values of nearly 19‰. In the hydrological cycle this second order quantity can change principally due to rapid non-equilibrium processes during evaporation and condensation. However, once buried into the ice only melting and refreezing can change the excess. The shift of 4‰ in d is significantly different from the mean value of about 16‰ ($1\sigma = 2$‰). The elevated deuterium excess, therefore, suggests that melting and partial refreezing processes have occurred at the very bottom of the core, possibly related to mechanic interactions with the bedrock. The presence of small stones and sand, which we

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Fig. 2. Stable water isotope record (δD) from Illimani (b) and different sections of this record (a and c) to illustrate our multi-proxy approach used for dating the upper part of the record. The upper panel (a) shows from the top to the bottom the isotope record (δD_{V-SMOW}), the dust particle and calcium ion concentration, and the ECM measurements. The broad band in the middle indicates high values for different radionuclides (tritium and ^{37}Cs) associated with the nuclear bomb tests in 1963/64. In panel c water isotopic composition and total sulfate concentration are presented together with a band associated with extremely depleted ^{34}S isotopic composition. The peak in both quantities allowed us to identify the Tambora eruption in 1815.

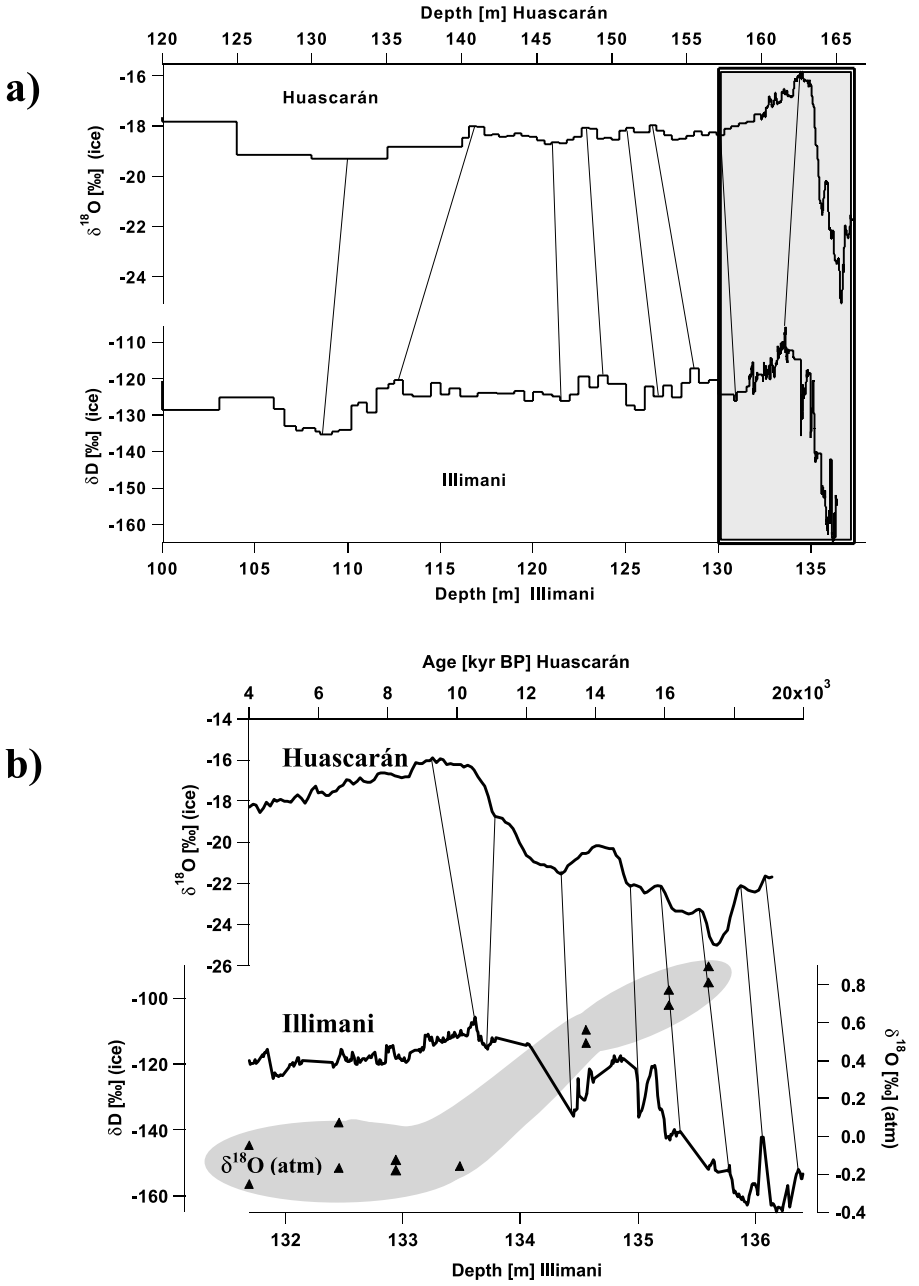

Fig. 3. Dating in the lowest part of the record is based on wiggle matching to the Huascarán record [2] (16 matching points) and on $\delta^{18}O_{Atm}$ measurements of air bubbles enclosed in the ice. The $\delta^{18}O_{Atm}$ data points at one depth (triangles in panel b) indicate duplicate measurements on samples from seven different layers.

found in high concentration in the bottom 15 cm of ice, is a further indicator for such processes. We therefore exclude these three measurements from the further analysis.

4. Results

Fig. 4 shows the three long-term Andean isotope and dust records on a common time scale.

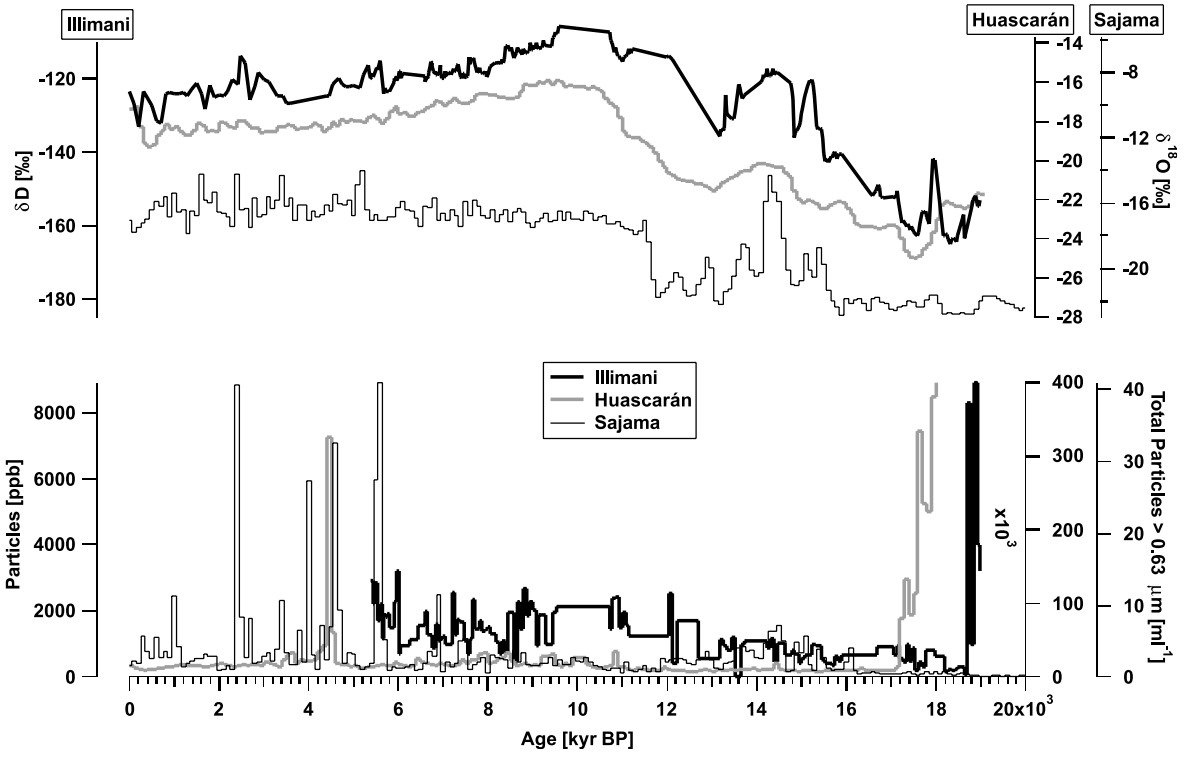

Fig. 4. Comparison of the Andean long-term isotope (top) and dust (bottom) records, Huascàran [2], Sajama [1] and Illimani. The good coherence between the Huascàran and the Illimani records suggests a similar climate history at both sites during deglaciation.

All isotopic records reach full glacial conditions (low isotope values) at about 18 000 years BP. From these minima, both the Huascarán and the Illimani isotopic values rise to a pronounced Early Holocene optimum (HO) then continuously decline to modern values. In the Huascarán $\delta^{18}O$ record [2], this rise from the LGS to HO amounts to $\Delta_{LGS/HO} = 9‰$. The Illimani δD record can be directly compared with the Huascarán $\delta^{18}O$ variations since, at least to first order, the relation between the two stable water isotopes is constant. Thus, the LGS/HO transition in the Illimani record $\Delta_{LGS/HO} = (165‰ - 108‰)/8 \approx 7‰$ is about 2‰ less than in the Huascarán. From the HO, both records decline continuously to a minimum in the 16th/17th century AD in the Huascarán record ($\Delta_{HO/Modern} = 3.5‰$ resulting in a temporal gradient during the Holocene of 0.39‰ per millennium) and about 100–200 years earlier in the Illimani ($\Delta_{HO/Modern} = 3.0‰$ and a gradient of 0.33‰ per millennium).

The similarities between the Illimani and the Huascarán records extend even to the details of the deglaciation history in both records. In the following the amplitude of the full transition from the LGS to the HO, $\Delta_{LGS/HO}$, corresponds to 100%. At the end of the last glaciation in tropical/subtropical South America (about 14.5 kyr BP in Fig. 4) water isotope values start to rise to about 50% of their HO values in the Huascarán record and somewhat more, 70%, in the Illimani record. The climate reversal after this first swing to enriched isotope levels lasts about 1000 years and amounts to 25% of $\Delta_{LGS/HO}$ in both cores.

In contrast to the two other isotope records, the Sajama record shows no pronounced HO followed by a continuous decline to modern values.

The rapid change at the end of the LGS is marked by the isotopically most enriched values in the entire record. The low values in the Sajama record during the climate reversal after this first isotopically enriched phase were interpreted as a reversal to full glacial conditions [3].

The dust records over the last ~10 m of Huascarán and Illimani also show a striking similarity (see Fig. 4). Only in the full glacial state, corresponding to the bottom 0.5–1 m of both ice cores, do the dust levels dramatically increase.

5. Discussion

With this new information we will now address the principal questions of this paper formulated in Section 1.

5.1. Regional representativity of Andean isotope records

In [27] the authors demonstrated the high coherence of isotope records from Andean glaciers situated between 9°S and 18°S in the last century. All available high resolution isotope records for this period (Huascarán, Quelccaya (a fourth ice cap situated in Peru at 13°56′S, 70°50′W [28]), Sajama, Illimani) share the same decadal variability. In the same study it was shown that this variability is produced by shifts of the Hadley–Walker cell over tropical South America controlling the convective activity over the Amazon Basin. These shifts are ultimately linked to decadal variability of Pacific sea surface temperatures in the 20th century.

This result does not prove that such a coherence necessarily holds on all time scales. For example, here we find that Illimani and Huascarán are coherent over the last 18 000 years, but Sajama is significantly different in many aspects. Two possible explanations are at hand for this behavior.

The entire period from the LGS to the Early Holocene is represented by only about 5 m of ice in the Huascarán and the Illimani records whereas this period is covered by about 30 m in the Sajama record. Is it possible that this comparatively low resolution is responsible for the common isotope signals of Huascarán and Illimani? Layer thinning, crystal diffusion, and ice flow in the two glaciers might have produced a common but disturbed signal. Having no further evidence for such processes we feel that this explanation is rather improbable. For tropical glaciers, the $\delta^{18}O_{Atm}$ measurements in the Illimani core were of good quality (see Fig. 4, bottom). Their continuous rise when entering into the glacial part of the Illimani core indicates good preservation of the layering. Moreover, it is hard to see how post-depositional processes at two quite different locations might have produced such similar isotope records. Yearly accumulation, seasonality of the precipitation under modern conditions, and also the total length of the two cores (137 m for Illimani and 166 m for Huascarán) are all significantly different, making it improbable that their common signal was produced by post-depositional effects.

Therefore we prefer an alternative explanation, that the Sajama is different from the other two localities because it was influenced by local climatic conditions. The reappearance of wet conditions and the reformation of large lakes on the Altiplano at about 12 kyr BP [29,30] might have significantly contributed to precipitation on Sajama, but might have been less significant to Illimani located east (that is upstream) of the paleolakes (see Fig. 1 for a schematic reconstruction of the possible extent of this lake during the LGS). Hydrological model studies [31] have demonstrated that small changes in the water budget of the Altiplano can produce such lakes in a few centuries. The abruptness of the isotopic shifts on Sajama during deglaciation is therefore not in contradiction with the lake hypothesis. Situated to the west of the Altiplano and just 160 km from the Pacific Ocean, Sajama might also have come under a stronger influence of Pacific air masses during the LGS. Though the Pacific is not a significant vapor source region for the Bolivian Altiplano under modern conditions the situation may have been different for the LGS when the Southern Hemisphere's westerly zone was displaced far to the North due to the strong cooling around Antarctica.

Both hypotheses influence paleolakes and circulation changes under glacial conditions offering possible explanations for the isotopic differences between Sajama and Illimani are of course speculative. Two approaches will possibly help to test the above hypotheses. Modelling studies with high resolution climate models fitted with water isotope diagnostics can quantify the potential importance of paleolakes on the Altiplano. They can estimate as well small-scale circulation changes under glacial conditions. Furthermore, a comparison of the deuterium excess record from the Illimani and the Sajama will give hints on changing source regions during the LGS. The deuterium excess is usually interpreted as an indicator of climatic conditions prevailing in the vapor source region [32,33]. Intensive recycling and partial reevaporation in continental South America produces an elevated deuterium excess [34] that possibly allows a distinction of the Amazon Basin from the Pacific Ocean as source regions for the Andean ice caps.

5.2. *Cold/dry tropics versus cold/wet subtropics during the LGS*

The Illimani and Huascarán dust records have a similar shape. We know from many different and independent archives that the Bolivian Altiplano was wetter during the LGS than today [29,30]. Therefore, we conclude that the bottom of the Illimani dust record does not reflect dry atmospheric conditions on a larger regional scale. More probably interactions with the bedrock or exceptional dust deposition during the first phase of the formation of the ice cap are responsible for the high dust levels in the last meter of the Illimani ice core. As discussed previously anomalous deuterium excess values for the bottom three samples of the Illimani core supply a hint about possible melting/refreezing conditions near the bedrock, another potential bias of the dust concentration. If we exclude the bottom-most five dust measurements of the Illimani core, assuming they are biased by processes close to the bedrock, then ice from the glacial and the transitional parts of the core (between depths 134 m and 136 m corresponding to 12 000 to 18 000 years BP) is characterized by very low dust levels. For example, comparing this part of the record with the Early Holocene part (between depths 132 m and 134 m corresponding to 6000 to 12 000 years BP) we find 2.5 times lower dust levels during glacial times indicating wetter conditions than in the Early Holocene. If this conclusion is true then, of course, it also casts doubt on the interpretation of the Huascarán dust record. Based on the observation that both Huascarán and Illimani show similar dust signals at the very bottom of the ice, and that one (Illimani) definitely does not indicate drier regional conditions, we prefer instead to reinterpret the existing isotope/dust records from Andean glaciers.

In Section 5.3 we will argue for a major role of increased precipitation amount in bringing about the more depleted isotope levels of both tropical and subtropical Andean glaciers during the LGS. In our interpretation low isotope ratios of glacial age ice are indications for conditions at least as wet, most probably wetter than present day. Both tropical and subtropical zones of South America would have been in a wet and cold mode during the LGS. However, the previous interpretation of the Huascarán record as an indicator of cold and dry conditions during the glacial [3] was also supported by palynological and other evidence indicating that the Amazon Basin may have become an important dust source during the LGS. According to these studies [35,36] the Amazonian rainforest became fragmented and changed to an open vegetation. Parts of the basin were even covered with large sand dunes, presumably clear indicators of drier conditions in the area controlling Huascarán's potential dust sources.

In [37] these conclusions were largely rejected. On the contrary, the authors state that there is no evidence for increased savannah in the Amazon Basin throughout the entire last glacial cycle. In particular the authors point out the possible erroneous conclusions based on palynological records. They furthermore criticize the interpretation of biogeographical (the 'refuge hypothesis' trying to explain modern genetic faunal and floral diversity in the Amazon Basin) and geomorphological data. The latter, hinting at the existence of paleosand dunes, are, according to [37], either

wrongly interpreted or not sufficiently dated. In this paper, we cannot contribute to this ongoing discussion. However, we feel that there is no generally accepted view of glacial tropical South America being under the influence of strong aridity and becoming a potential dust source.

Another recent study [38] on sediment records from tropical Peru helps to confirm our interpretation of Andean isotope records. Diatom stratigraphy of Lake Junin situated at 11°S on the Peruvian Altiplano indicates clearly wet conditions from 30 000 years BP to about 15 000 years BP. However, the beginning of deglaciation was ^{14}C-dated to about 20 000 years BP and associated with the beginning of significant warming. In summary, these results confirm our view of prevailing wet and cold glacial conditions in the tropical Andes and a change to drier conditions several thousand years after considerable warming had already taken place. Assuming that the dating of Andean ice cores is approximately correct then significant changes from glacial isotope levels to more enriched values happened at about 17 000–15 000 years BP in phase with the change to drier conditions as documented in lake sediments and not in phase with the change to warmer conditions approximately 4000 years earlier. Here, our conclusions are limited by the poor absolute dating of the oldest part of Andean ice cores which is based to a large extent on tie points with independently dated records (for example, the Huascarán was dated between 12 000 years BP and 19 000 years BP by using tie points with a marine record off Portugal [3]).

5.3. *Interpretation of the Andean isotope records in terms of temperature and precipitation changes*

A tentative quantitative interpretation of the observed isotopic shift of about −5‰ from modern (last 500 years) to glacial conditions, common to the Huascarán and the Illimani records, can be attempted based on the analysis of the modern part of the Andean records [27]. In the 20th century, the average of four Andean isotope records compares well with the leading pattern of global precipitation variability associated with El Niño-Southern Oscillation [39]. A similar result has been obtained by analyzing the modern parts (1979–1998) of the Sajama, Quelccaya and Huascarán and comparing them with the results of general circulation models [40,41].

Applying a modern analogue method to long time scales and to presumably significantly different mean climate conditions always carries some risk. Possible uncertainties concern, for instance, circulation patterns that might have been considerably different during the LGS. Nevertheless, a tentative interpretation of the glacial to modern isotope shift can be made using modern climate relationships. Here it is assumed that the Andean isotope signal is entirely controlled by the rainout intensity over the Amazon and the Altiplano. A linear regression between the Andean isotope index and the leading pattern of annual precipitation results in an estimated relation of 0.2 (amplitude of the principal component)×4 (mean amplitude of normalized EOF1 over the Amazon)×80 mm/year (precipitation variance over the Amazon) yielding about 60 mm/‰ change for the isotopes in the Andes. If this relationship, established on an interannual time scale, holds for glacial–Holocene time scales, then a shift of −5‰ translates into 300 mm/year moister conditions. Thus, we calculate that the Amazon and the Altiplano may have been 20% wetter during the last glacial than today (assuming an approximate modern average of about 1500 mm/year [42]).

This modern analogue approach is an extreme estimate supposing the entire isotopic shift to be due to precipitation anomalies. It is not thought to be a best estimate but rather to demonstrate the consequences when interpreting the record as a 'pure' proxy for precipitation amount. However, we point out that the resulting isotope/precipitation gradient of 0.0167‰/mm is perfectly in agreement with our current understanding of the isotopic amount effect in the tropics and subtropics [4,5].

The discussion is not finished what the real isotope signal during the transition from the last glacial to the Early Holocene was, nor how exactly we have to interpret this signal. We here make a point for an Antarctic-like shape of the

transition and a major part for the precipitation amount controlling the isotope signal. The results of future drilling projects in the Andes and high resolution isotope modeling [43,44] certainly will help decide these questions. ***[BARD]***

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