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The Inca child of the Quehwar volcano: Stable isotopes clue to geographic origin and seasonal diet, with putative seaweed consumption

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ABSTRACT

The Incas occupied the west coast of South America between 1438 and 1532 CE. Among the many rites they practised was the *Capacocha*, which involved the offering of children. Here we studied the mummy of a child found on the Quehwar volcano, Salta, Argentina. In order to determine the geographical origin of the child and to understand the living habits prior to its presentation as an offering, we incrementally measured the $\delta^{13}\text{C}$, $\delta^{15}\text{N}$, $\delta^{34}\text{S}$ and $\delta^2\text{H}$ values of keratin from a hair strand and the $\delta^{18}\text{O}$ value of apatite phosphate from a rib bone. Although the origin of the child remains uncertain, the oxygen isotope composition of the drinking water deduced from the rib composition argues for an origin between 2,500 and 3,000 m.a.s.l. bordering the Andes. Furthermore, the sinusoidal $\delta^2\text{H}$ signal measured in hair is compatible with the recording of local seasonal precipitation variations. The results indicate that the child did not move or moved only briefly prior to death. This offering may have occurred at the onset of the wet season (summer), as suggested by the hair $\delta^2\text{H}$ values. By combining $\delta^{13}\text{C}$, $\delta^{15}\text{N}$ and $\delta^{34}\text{S}$ measurements in hair, we also proposed as the most parsimonious hypothesis that seaweed constituted a proportion ($16.2 \pm 12.9\%$) of the diet, with a peak of consumption during the wet season (summer).

1. Introduction

Population displacements are significant indicators of events such as climate change (Li et al., 2017), war, political instabilities (Akeju, 2013), or religious persecutions (Castelli, 2018). To understand the historical context of an archaeological site, it is crucial to determine whether the human remains discovered there belonged to native or non-native individuals. The discovery of non-native individuals on an archaeological site is a frequent occurrence (Clauzel et al., 2023; Płoszaj et al., 2017; Price et al., 2011).

The Inca Empire originated in the Cusco Basin (present-day Peru) during the 12th century (Bellenger, 1982) and expanded to northwest Argentina by 1438 CE. It flourished for almost a century and at its peak, its territory stretched along the Andes chain and the Pacific coast, from

Columbia northwards to Chile and Argentina southwards (Fig. 1). The Inca Empire ended in 1532 CE with the arrival of Spanish conquistadors. Our knowledge of this Empire mainly comes from the accounts of the Spanish chroniclers during their conquest and from archaeological studies, as the Incas did not develop a written language (Zuidema, 1990).

The Incas were known to practice human offerings for the gods, including the offering in sacrifice of children called *Capacocha*. This ritual was performed at crucial moments in the life of the people, such as to prevent or stop a natural disaster (Malville, 2018). The choice of children was paramount as they were selected for their purity and perfection (Cobo and Hamilton, 1990; Kawchuk, 2019). Boys up to the age of 10 and girls up to the age of 15 were selected throughout the Inca Empire by the religious authorities or offered by their parents (Kawchuk,

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Fig. 1. Map of South America with the location of the Quehuar volcano. The green area represents the maximum extension of the Inca territory. Map adapted from <https://www.d-maps.com>.

2019). The young women were often selected among the *acllas*, a word which means ‘chosen’, and were selected for their qualities. The *acllas* were usually destined for roles such as priestesses, concubines to the emperor, and contributors to the production of crafts within the Inca Empire. In some cases, some of them were offered in sacrifice. The process of selecting boys is less well-documented (Faux, 2012). After the children were chosen, they would go on a pilgrimage from Cusco to sacred mountains named *huacas*, accompanied by priests and sometimes members of the religious authority or family (Bray et al., 2005). Upon reaching the top of the mountains, the children, who were already exhausted from the journey, altitude and cold, died and were left behind. Consequently, the cold and dry air at high altitude naturally mummified their remains. The mummies discovered by Johan Reinhard in 1999 at the Lullailaco volcano on the border of Chile and Argentina are among the best-preserved mummies to date (Previgliano et al., 2004).

The archaeological site studied here is the Quehuar volcano (6,130 m above sea level [m.a.s.l.], Fig. 1), located in the extreme North-West of Argentina, in the Salta region. At the summit of the volcano, a child’s mummy was discovered, offered in sacrifice during a *Capacocha*. The objective of this study is to determine the geographic origin and to examine the dietary variations of a child offered in sacrifice, thereby overcoming the limitations of the colonists’ writings that describe this ritual. Isotope geochemistry enables the objective reconstruction of past diets, with a completely neutral eye. The specific contribution of isotopic analyses in archaeology is underscored by their ability to reconstruct past diets and mobility patterns with high precision. We sampled a strand of hair and a rib bone fragment to determine the child’s diet and geographical origin. To achieve this objective, isotopic analyses were conducted on these samples. The hair strand was divided into 16

samples, each approximately 1 cm in length, and labelled from CH1 (closest to the skull) to CH16 (at the tip of the hair). As hair grows incrementally, it records variations in isotope compositions during its growth period. Bones, on the other hand, have remodeled isotope compositions that average over a period of up to a few years (Glimcher, 2006; Stagi et al., 2013; Szulc et al., 2000; Tsutaya and Yoneda, 2013).

The stable isotope compositions of carbon ($\delta^{13}\text{C}$) and nitrogen ($\delta^{15}\text{N}$) in hair keratin enable the reconstruction of diets (Supplementary Material section 1.1). The $\delta^{13}\text{C}$ values indicate whether C_3 or C_4 plants were consumed (DeNiro, 1987), while the $\delta^{15}\text{N}$ values trace the trophic level and diet, including marine products (Ambrose and DeNiro, 1989; Herrscher et al., 2002). The sulfur isotope compositions ($\delta^{34}\text{S}$) indicate whether the diet originates from a marine or terrestrial environment or if individuals lived in geographic area under the influence of sea sprays (Ebert et al., 2021; Katzenberg and Krouse, 1989; Norman et al., 2006; Richards et al., 2001; Vika, 2009; Wakshal and Nielsen, 1982, Supplementary Material section 1.2). These 3 isotopic systems are essential for determining whether the children presented during a *Capacocha* were subjected to a distinctive or ritualized diet in preparation for the sacrifice. Hydrogen and oxygen in the human body primarily derive from drinking water but also from food (Kirsanow and Tuross, 2011, Supplementary Material sections 1.3 and 1.4). Hydrogen and oxygen isotope compositions ($\delta^2\text{H}$ and $\delta^{18}\text{O}$) of environmental waters vary locally depending on climate, altitude, and distance from the coast, providing information on the origin of water consumed (Longinelli, 1984; Luz et al., 1984; Poage and Chamberlain, 2001; Richards and Britton, 2020; Wilson et al., 2007). For the *Capacocha*, these isotopic data are useful to study the mobility of children, showing whether they traveled long distances or remained local prior to their sacrifice.

2. Material and methods

2.1. The Inca site of Quehuar

The Quehuar volcano culminates to an altitude of 6,130 m.a.s.l. in the Andes Mountains, in the Salta region of Argentina. The volcano is situated in the Circumpuna region, which is on the border between Chile, Bolivia, and Argentina (Plaza Calonge et al., 2022), a zone characterized by its extreme aridity (Núñez et al., 2010). This inactive volcano is usually covered with snow and has a glacier in its crater. The ruins were first explored in 1974 by Antonio Beorchia. During an expedition led by Johan Reinard and Constanza Ceruti in 1999, the remains of an Inca child offered during the *Capacocha* ritual were found at the top of the volcano. The tomb had been desecrated and partly destroyed with dynamite by looters. The burial site is located at an altitude of 6,100 m.a.s.l., very close to the summit. It consists of two structures: an oval enclosure with a diameter of 4.5 m and walls up to 2.2 m thick, and an adjacent raised platform, 9.4 m long and 3.4 m wide with walls 1.7 m thick (Reinhard and Ceruti, 2005). A map of the structures on the Quehuar volcano, published by Beorchia, 1975 is available in the Supplementary Material (Supplementary Fig. S1). The site suffered significant damage from the dynamite explosion. However, archaeologists found remnants of Inca potteries, a female statuette, textiles, and a sacrificial camelid bone. The mummy remains were also partially destroyed, including a large portion of the upper bust and head (Reinhard and Ceruti, 2005). DNA analysis revealed that the child was a girl, and X-ray analysis of bones allowed her age to be determined around 12 years at the time of the offering (Ceruti, 2015).

The export of the samples from Argentina to France has received the approval of the Museum of Anthropology of the Province of Salta by internal regulation No. 002/2019. In accordance with the provisions of Articles 4 and 5 of National Law of Argentina No. 257.43 on the ‘Protection of the Archaeological and Paleontological Heritage’ and the provisions of SC Resolution No. 2272 of July 29, 2004 on the export of archaeological goods, the export was carried out (number IF-2021-120593785-APN-INA YPL#MC).

2.2. Analytical techniques

2.2.1. Sample cleaning

After the removal of endogenous lipids, hair can be regarded as pure keratin (O'Connell et al., 2001). The hair from the Quehwar mummy underwent pre-cleaning at the Universidad de Buenos Aires – CONICET in Argentina, following the protocol described by Hurst and Davis and O'Connell et al. The hair was rinsed with deionised water and ultrasonicated, immersed in a mixture of methanol-chloroform (2:1 v/v) and then rinsed with deionised water. Subsequently, it was cut lengthwise, wrapped, and oven dried. Afterward, the hair was cleaned again and rinsed with distilled water in an ultrasonic bath at the Université Claude Bernard Lyon 1 in France.

The bone fragment of the Quehwar mummy was cleaned using a Dremel™ drill and an abrasive tip to remove all surface bone damage. The bone was immersed in distilled water and ultrasonicated to eliminate any remaining residue in the pores. Finally, it was dried in an oven overnight at 40 °C and ground into a fine powder.

2.2.2. Wet chemistry for apatite phosphate

Human bone was processed following the chemistry procedure described by Crowson et al., and modified by Lécuyer et al. (1993). This protocol isolates phosphate ions from bioapatite as silver phosphate (Ag₃PO₄) crystals using acid dissolution and anion-exchange resin. After dissolution of about 10 mg of powdered apatite in 2 M HF at 25 °C for 24 hours, the CaF₂ precipitate was separated from the phosphate-bearing solution by centrifugation. The CaF₂ precipitate was rinsed three times using double deionized water (DDW), then the rinse water was added to the supernate which was neutralized with 2.2 mL of 2 M KOH solution. Cleaned Amberlite™ IRN78 anion-exchange resin (2.5 mL) was added to the neutralized solution in polypropylene tubes, which were placed on a shaker table for 4 hours to promote the ion exchange process. Excess solution was discarded, and the resin was washed five times with DDW to remove the traces of ionic contaminants. To elute the phosphate ions quantitatively from the resin, 27.5 mL of 0.5 M NH₄NO₃ was added to adjust the pH of the solution to 7.5–8.5, then the tubes were gently shaken for 4 hours. Silver phosphate crystals were precipitated from the eluted solution following the method of Firsching, 2002. The solution was placed in a 250 mL Erlenmeyer flask and about 0.5 mL of concentrated NH₄OH was added to raise the pH to 9–10. 15 mL of ammoniacal AgNO₃ solution was added to the flask. Upon heating this solution to 70 °C in a thermostatic bath, mm-size yellowish crystals of Ag₃PO₄ were quantitatively precipitated. The crystals of Ag₃PO₄ were collected on a Millipore filter, washed three times with DDW, and air dried at 50 °C.

2.3. Data quality control

The C:N molar ratio of modern hair is comprised between 3.0 and 3.8 (O'Connell and Hedges, 1999). We consider that measured C:N ratios falling into this range indicate good chemical preservation of hair keratin. As there are currently no preservation criteria for sulfur and hydrogen contents in archaeological human hair, our results should be interpreted with caution. However, based on the C:N ratios and expected sulfur and hydrogen percentages in modern hair (Verma and Singh, 2016), we will be able to conclude on the reliability of our results.

2.4. Stable isotope measurements

NCS isotope analyses were performed using an Isoprime100™ isotope ratio mass spectrometer interfaced in continuous flow to a VarioPYROCube™ system based on purge and trap technology in combustion mode. The system is hosted by the LEHNA (UMR 5023, Villeurbanne, France, member of the RéGEF national network). Three sample aliquots of 1 mg of hair were loaded into tin capsules and their $\delta^{13}\text{C}_{\text{VPDB}}$, $\delta^{15}\text{N}_{\text{AIR}}$ and $\delta^{34}\text{S}_{\text{VCDT}}$, %C, %N, %S values were determined simultaneously following the method described in Fourel et al. (2014).

Carbon, nitrogen and sulfur isotope compositions were calibrated against the following international standards: caffeine IAEA-600 ($\delta^{13}\text{C}_{\text{VPDB}}=-27.77 \pm 0.04 \text{ ‰}$ and $\delta^{15}\text{N}_{\text{AIR}}=1.0 \pm 0.2 \text{ ‰}$, Coplen et al., 2006), sucrose IAEA-CH-6 ($\delta^{13}\text{C}_{\text{VPDB}}=-10.45 \pm 0.03 \text{ ‰}$, Coplen et al., 2006), ammonium sulfate IAEA-N-2 ($\delta^{15}\text{N}_{\text{AIR}}=20.41 \pm 0.12 \text{ ‰}$, Böhlke and Coplen, 1995), silver sulfide IAEA-S-1 ($\delta^{34}\text{S}_{\text{VCDT}}=-0.30 \pm 0.03 \text{ ‰}$, Coplen and Krouse, 1998) and barium sulfate NBS127 ($\delta^{34}\text{S}_{\text{VCDT}}=20.3 \pm 0.4 \text{ ‰}$, Halas and Szaran, 2001). C, N and S concentrations (reported in weight% in Table 1) have been measured by using the traces obtained with the Thermal Conductivity Detector (TCD) of the VarioPYROCube™ Elemental Analyzer. The calibrated materials used for elemental composition analysis were Aspartic acid B2139 (COA 406626) and Protein B2155 (COA 114859), both from Elemental Microanalysis.

Oxygen isotope data were obtained according to a high-temperature pyrolysis continuous flow technique developed by Fourel et al. (2011). Five aliquots of 300 ± 20 µg of silver phosphates were mixed with 300 µg of carbon black in silver foil capsules. Pyrolysis was performed at 1450 °C using an Elementar VarioPYROcube™ elemental analyzer based on a 'purge and trap' technology (Fourel et al., 2011). CO is desorbed at 150 °C and transferred to a GV IsoPrime™ mass spectrometer in continuous flow mode with helium (He) as the carrier gas. To calibrate the analyses, NIST SRM 120c and NBS127 were analyzed along with the samples. The $\delta^{18}\text{O}_{\text{VSMOW}}$ value of NIST SRM 120c was fixed at 21.7 ± 0.2 ‰ (V-SMOW), as confirmed by published studies (Halas et al., 2011; Lécuyer et al., 1993) and NBS127 $\delta^{18}\text{O}_{\text{VSMOW}}$ value was set to 9.3 ± 0.3 ‰ (Stichler, 1995). Silver phosphates prepared from standard NIST SRM120c were processed through both wet chemistry step as well as isotopic analyses along with each batch of silver phosphate samples derived from the studied bioapatite. They are considered as 'internal calibrated material' to assess for any potential bias due to the chemistry process. Other aliquots of NIST SRM120c from different chemistry batches were also analysed ($\delta^{18}\text{O}_{\text{VSMOW}}=21.9 \pm 0.5 \text{ ‰}$, n = 8), considered as external calibrated material to ensure that no isotopic fractionation took place from one wet chemistry process to another.

Finally, for the determination of hair $\delta^2\text{H}_{\text{VSMOW}}$, three aliquots of 250–300 µg were weighed into silver capsules. To convert the solid sample into gaseous form, pyrolysis is performed at 1450 °C using a VarioPYROcube™ elemental analyzer based on chromium reduction according to the protocol described by Fourel et al. (2019). The elemental analyzer is connected to an Isoprime™ isotopic ratio mass spectrometer. Hydrogen isotope ratios were calibrated with international standards, namely Polyethylene IAEA-CH-7 ($\delta^2\text{H}_{\text{VSMOW}}=-99.2 \pm 1.2 \text{ ‰}$, Schimmelmann et al., 2016), NBS 22 ($\delta^2\text{H}_{\text{VSMOW}}=-117 \pm 0.6 \text{ ‰}$, Schimmelmann et al., 2016), Polyethersulphone B2203 ($\delta^2\text{H}_{\text{VSMOW}}=-25.3 \pm 5.1 \text{ ‰}$, %H=3.46 ± 0.05, Elemental Microanalysis Certificate BN/132358) and Aromatic polyimide B2205 ($\delta^2\text{H}_{\text{VSMOW}}=-87.8 \pm 2.2 \text{ ‰}$, %H=2.90 ± 0.05, Elemental Microanalysis Certificate BN/132357). The latter two are also used to calibrate the hydrogen concentration in the samples. Thermal Conductivity Detectors are not suitable for hydrogen analyses thus the isotopic traces of the major peak at mass 2 have been used for %H determinations.

2.5. Stable isotope mixing models in R with simmr

To determine the proportion of each food component in the diet of the child of the Quehwar volcano, we used the simmr package (v 0.5.1.214, Govan et al., 2019) in R (v 4.3.1) to solve mixing equations for stable isotope data within a Bayesian framework. We chose maize (a C₄ plant), beans (C₃ plants), camelid meat and algae as the four possible main foods in the diet of the child. The complete script integrating the simmr package is given in the Supplementary Material, along with the selected model values (Supplementary Material, Table S1).

3. Results

The $\delta^{13}\text{C}$, $\delta^{15}\text{N}$, and $\delta^{34}\text{S}$ values of the hair sample CH1 (first cm from

Table 1

$\delta^{15}\text{N}$, $\delta^{13}\text{C}$, $\delta^{34}\text{S}$ and $\delta^2\text{H}$ values, as well as the weight proportions (wt%) of C, N, S and H of the hair strand of the child offered in sacrifice on the Quehuar volcano. The C:N ratio is a preservation indicator of the chemical composition of the studied hair strand.

# Sample	Distance from the skull (cm)	$\delta^{13}\text{C}$ (‰, V-PDB) Mean \pm SD	$\delta^{15}\text{N}$ (‰, AIR) Mean \pm SD	$\delta^{34}\text{S}$ (‰, V-CDT) Mean \pm SD	$\delta^2\text{H}$ (‰, V-SMOW) Mean \pm SD	%C	%N	% S	% H	C: N
CH1	1	-14.2 ± 0.6	13.3 ± 1.6	7.4 ± 1.4	-76 ± 3	45.7	11.2	2.1	6.3	4.7
CH2	2	-13.2 ± 0.2	10.7 ± 0.4	5.8 ± 0.2	-74 ± 4	43.1	14.1	4.2	5.8	3.6
CH3	3	-13.3 ± 0.1	10.3 ± 1.0	5.4 ± 0.2	-73 ± 1	40.8	13.8	4.5	6.2	3.5
CH4	4	-12.9 ± 0.0	9.9 ± 0.5	5.2 ± 0.2	-77 ± 1	43.7	14.8	4.7	6.6	3.4
CH5	5	-13.0 ± 0.2	9.9 ± 0.2	5.4 ± 0.2	-79 ± 0	41.4	13.9	4.3	6.1	3.5
CH6	6	-13.1 ± 0.1	10.2 ± 0.2	5.8 ± 0.4	-90 ± 3	45.0	15.2	4.6	6.8	3.5
CH7	7	-14.0 ± 0.1	10.7 ± 0.9	7.6 ± 0.3	-97 ± 3	44.9	15.1	4.4	5.9	3.5
CH8	8	-14.2 ± 0.1	10.1 ± 0.3	8.4 ± 0.2	-102 ± 2	43.5	14.7	4.5	6.6	3.4
CH9	9	-13.9 ± 0.3	9.3 ± 0.2	9.5 ± 0.0	-97 ± 2	44.0	14.9	4.4	6.3	3.5
CH10	10	-14.1 ± 0.2	9.3 ± 0.4	9.9 ± 0.4	-108 ± 1	43.7	14.8	4.2	6.2	3.5
CH11	11	-14.0 ± 0.1	9.9 ± 0.1	9.5 ± 0.0	-111 ± 2	44.3	15.0	4.2	5.8	3.4
CH12	12	-13.8 ± 0.1	10.9 ± 0.3	9.8 ± 0.3	-106 ± 1	45.9	15.6	4.3	6.6	3.4
CH13	13				-110 ± 4					6.5
CH14	14	-12.6 ± 0.1	9.6 ± 0.2	9.8 ± 0.2	-104 ± 0	45.2	15.3	4.0	6.3	3.4
CH15	15				-100 ± 1					6.0
CH16	16				-98 ± 2					5.8

the skull) are outliers as revealed by the high standard deviations (SD), which are 1.6 ‰, 0.6 ‰, and 1.4 ‰, respectively, for $\delta^{13}\text{C}$, $\delta^{15}\text{N}$, and $\delta^{34}\text{S}$ analyses, thus reflecting an alteration of the sample of unknown origin (Table 1, Supplementary Fig. S2). We have produced box plots of the SDs of the measured values using PAST (v 4.1, Hammer et al., 2001). They are presented in the Supplementary Fig. S1. This sample will not be considered in the further results and interpretations for any isotope system.

The molar ratios C:N of the hair are comprised between 3.4 and 3.6,

except for CH1 which has a value of 4.7, outside the range expected if the sample was well preserved (Table 1). Sulfur and hydrogen percentages measured in hair keratin are also close to those we expect in modern hair. Thus, the hair can be considered well-preserved and unaltered. The $\delta^{15}\text{N}$ values measured along the hair of the Quehuar mummy range from 9.3 ‰ to 10.7 ‰ (Fig. 2A). The average $\delta^{15}\text{N}$ value is 10.0 ± 0.5 ‰ (2σ , $n = 12$) and the average SD value is 0.4. The $\delta^{13}\text{C}$ values presented in Fig. 2B vary from -12.6 to -14.2 ‰ with an average of -13.5 ± 0.6 ‰ (2σ , $n = 12$). The average SD is 0.1. The $\delta^{34}\text{S}$ ranges

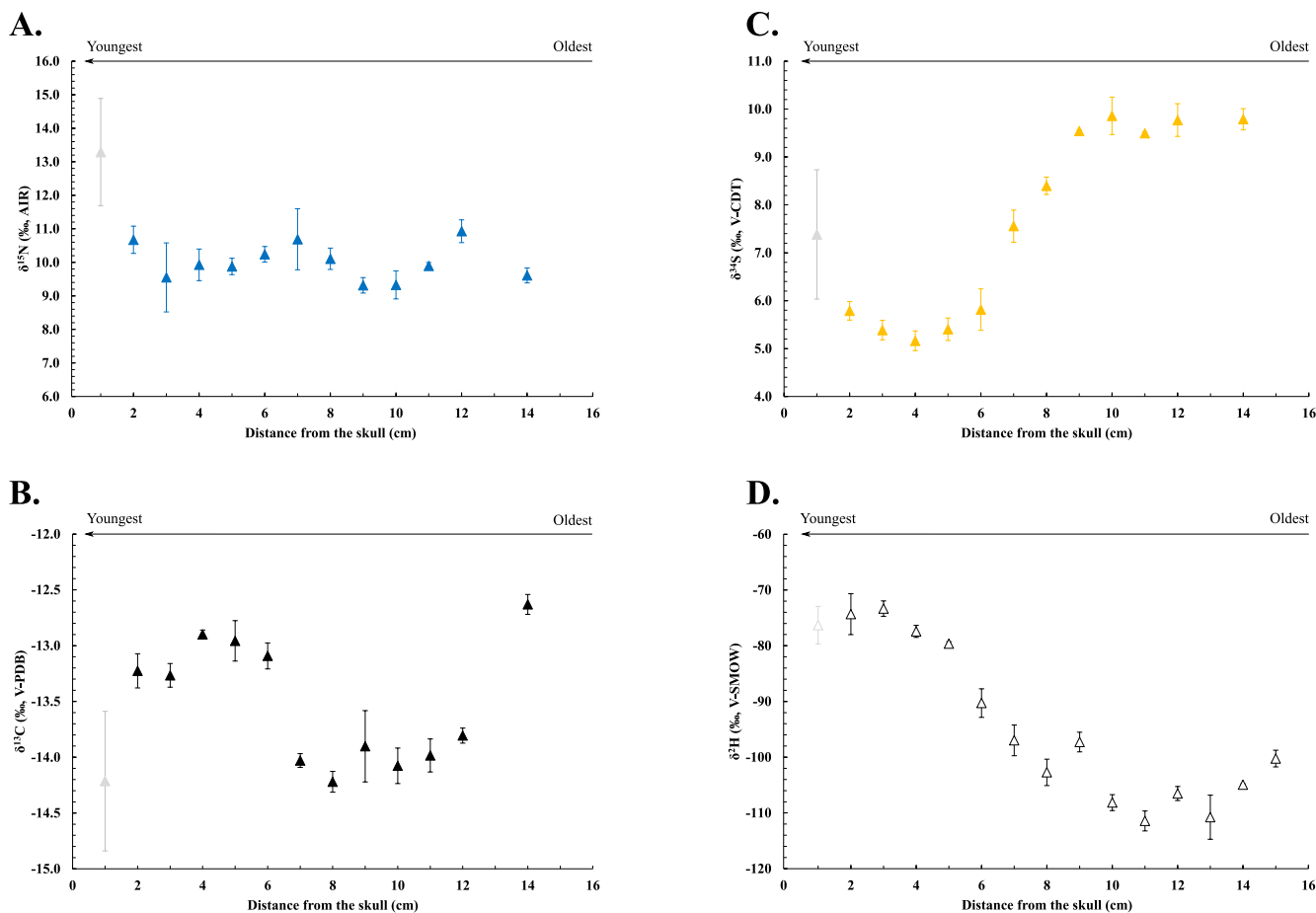


Fig. 2. $\delta^{15}\text{N}_{\text{AIR}}$ (A.), $\delta^{13}\text{C}_{\text{V-PDB}}$ (B.), $\delta^{34}\text{S}_{\text{V-CDT}}$ (C.) and $\delta^2\text{H}_{\text{V-SMOW}}$ (D.) values in the hair from the Quehuar's child as a function of the strand length. The outlier CH1 is represented in grey. Error bars represent the standard error calculated from the mean of multiple measurements per sample.

from 5.2 to 9.9 ‰, with an average at 7.7 ± 2.0 ‰ (2σ , $n = 12$). On average, the SD is 0.2 (Fig. 2C).

Finally, the $\delta^2\text{H}$ values (Fig. 2D) average -95 ± 13 ‰ (2σ , $n = 14$) and range from -73 to -111 ‰. The SD is on average 1.9. The $\delta^2\text{H}$ values measured along the hair of the Quehwar mummy show variations that are best described by a sine wave function ($R^2 = 0.96$; Fig. 3B).

The Quehwar mummy bone has a $\delta^{18}\text{O}$ of apatite phosphate ($\delta^{18}\text{O}_p$) value of 15.8 ‰ with a SD of 0.2 ‰. The $\delta^{18}\text{O}_p$ value of the child rib was here used to estimate the $\delta^{18}\text{O}$ of drinking water ($\delta^{18}\text{O}_w$) that was inferred from the oxygen isotope fractionation equation determined for humans by Daux et al., 2008:

$$\delta^{18}\text{O}_w = 1.54 (\pm 0.09)\delta^{18}\text{O}_p - 33.72 (\pm 1.51)$$

We calculated a $\delta^{18}\text{O}_w$ value of -9.3 ± 0.5 ‰.

Finally, we estimated the proportions of 4 basic foods in the child's diet using the *simmr* package under R (Govan et al., 2019, see section 2.5). Model results indicated that a proportion of marine algae was present in the diet of the child between 7 and 14 months before her death, up to a maximum of 16.2 ± 12.9 ‰ 10 months before her death (Fig. 4, Supplementary Material section 2).

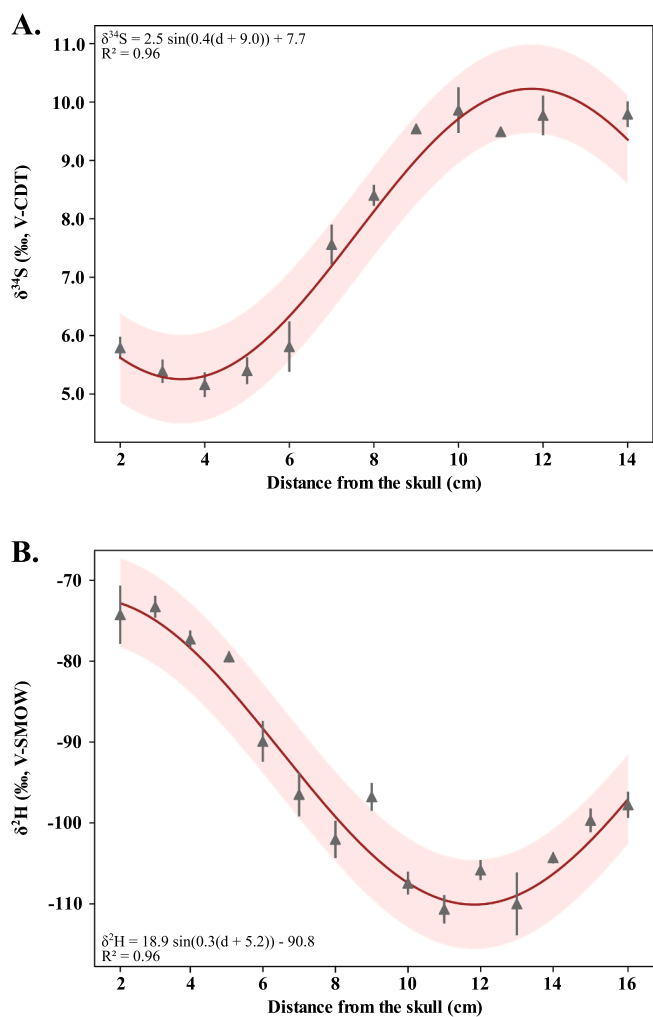


Fig. 3. Sinusoidal model to approximate the $\delta^{34}\text{S}_{\text{V-CDT}}$ (A.) and $\delta^2\text{H}_{\text{V-SMOW}}$ (B.) variations through time. The red line is the best fit to isotopic data, and the light red area represents the envelope error around the best fit. In the equation, d is the distance from the skull in centimetres.

4. Discussion

Given that hair grows at a rate of about 1 cm per month (Sachs, 1995), it is possible to estimate the timing of the isotopic signals measured in the hair, the first centimeters from the skull recording the last months of life. As the study includes several isotopic proxies providing information on the child's diet, geographical origin, and movement, the variation of these proxies was entered individually and collectively into a decision support matrix. The matrix, which summarizes all relevant hypotheses that could explain the data, can be found in the Supplementary Material (Table S2).

Firstly, it is important to note that seasonal variations in air temperature or precipitation follow a sinusoidal function. For instance, the $\delta^2\text{H}$ values measured by the IAEA station in Salta, close to the Quehwar volcano (Supplementary Fig. S3), indicate a sinusoidal signal obtained from an isotopic proxy recording a seasonal climatic variation, which may ultimately be reflected in a seasonal variation in human diet. The hydrogen isotope signal measured in hair is best described by a sinusoidal function with a peak between 2 and 3 cm from the scalp ($R^2 = 0.96$, Fig. 3B). The most straightforward and simplest explanation for this signal is the recording of climatic variations.

However, previous studies on other Inca children offered in sacrifice have proposed alternative hypotheses to explain the variation of $\delta^2\text{H}$ values in hair. Some of these studies have shown similar ranges of variation, around 40 ‰ over 12 months (Table 1, Fig. 2D), particularly in the cases of Lullaillaco Maiden and the Sarita girl (Wilson et al., 2007). The variation is even greater in the hair of the mount Chuscha girl (Killian Galván et al., 2020), but it occurred over a shorter period of time (3 to 6 months). The authors (Killian Galván et al., 2020; Wilson et al., 2007) proposed a change in the diet with an increased consumption of *chicha*, the Inca corn beverage, or a geographical mobility of the children to explain such variations. The consumption of this beverage and the mobility of the children were anticipated as part of this offering (Wilson et al., 2013). Therefore, we investigated the possibility of these two factors impacting the $\delta^2\text{H}$ signal.

Regarding the *chicha* consumption hypothesis, $\delta^{18}\text{O}$ values of this beverage can increase by up to 9 ‰ when it is made (Gagnon et al., 2015). To our knowledge, no study to date has measured $\delta^2\text{H}$ on *chicha*. Since $\delta^{18}\text{O}$ values and $\delta^2\text{H}$ values vary linearly following the Global Meteoric Water Line (GMWL, Supplementary Material section 1.3), the increase of about 40 ‰ in $\delta^2\text{H}$ values measured in the Quehwar young woman's hair could indicate increased consumption of this alcohol prior to the offering. If $\delta^{18}\text{O}$ values increase by 9 ‰, $\delta^2\text{H}$ values are expected to increase by about 80 ‰ in this drink, based on the GMWL. However, the magnitude of this isotopic enrichment can be significantly reduced as the water temperature during evaporation increases, reaching only 40 ‰ at a temperature close to 50 °C (Rigaudier et al., 2011). In our case, however, this hypothesis is not reasonable as it does not explain the sine wave function fit of the $\delta^2\text{H}$ signal. The increase of $\delta^2\text{H}$ values before death is not due to a significant increase in *chicha* consumption in relation to the ritual.

Similar to oxygen, the hydrogen isotope compositions of human tissues are very sensitive to the isotopic composition of precipitation (Podlesak et al., 2008), which is the ultimate source of drinking water, itself controlled by the seasonal variations in air temperature (Rozanski et al., 1993). The idea that $\delta^2\text{H}$ is the primary indicator of a dietary shift is not supported, as nitrogen isotope compositions remain relatively constant throughout the hair sample (Fig. 2A). If the Quehwar volcano child underwent vertical mobility, $\delta^2\text{H}$ values would decrease rapidly (Lécuyer, 2013). With horizontal mobility, $\delta^2\text{H}$ values would vary with the seasons and the local climate, which in turn varies with latitude (Lécuyer, 2013). Therefore, we can assume that the child did not move before being offered in sacrifice, which is rather unusual, or that the resolution of our analyses is not fine enough to allow us to detect a movement in the last few weeks of the child's life. The $\delta^2\text{H}$ values increasing towards the hairline most likely record the beginning of the

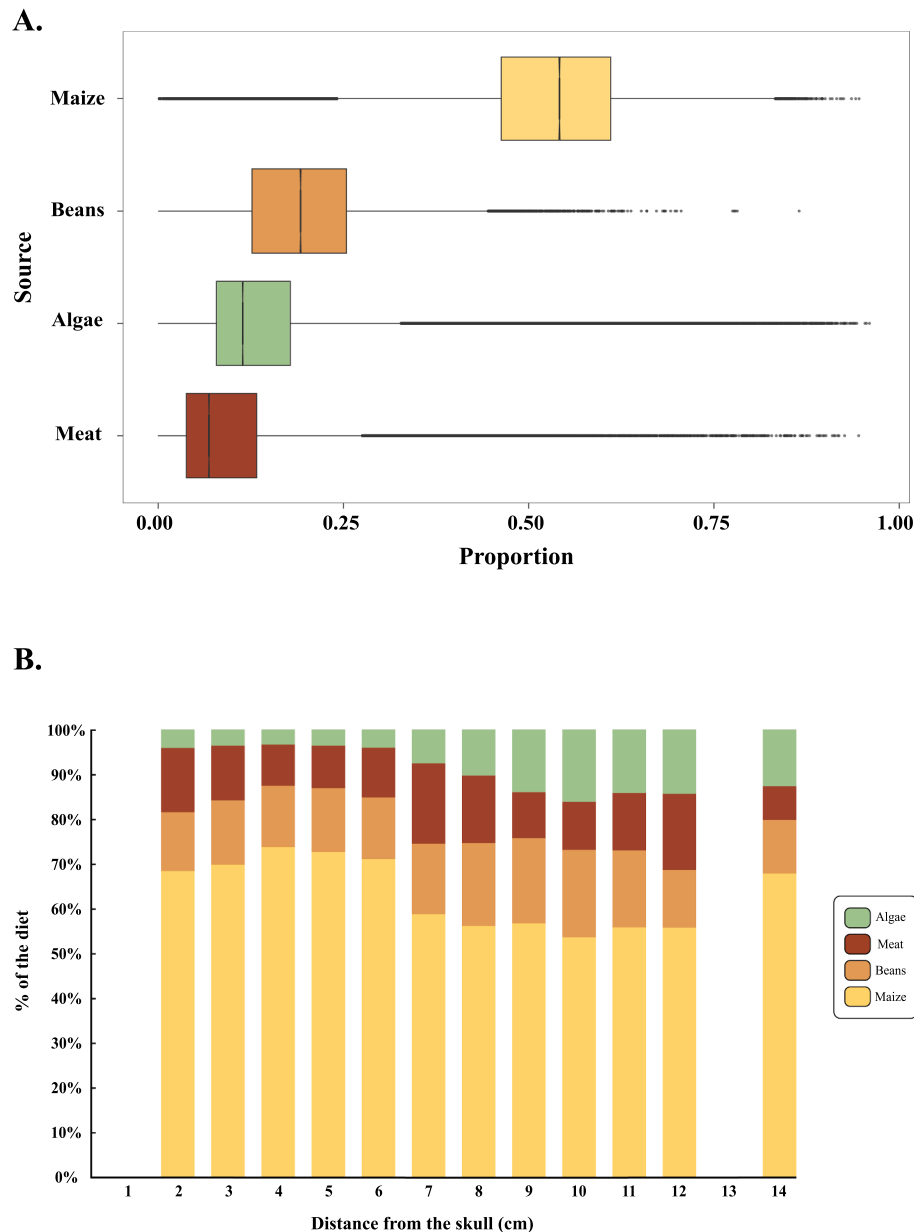


Fig. 4. Box plot (A.) and stacked histogram (B.) displaying the proportion of different foods in the child's diet when considering four probable main foods; maize, meat, algae and beans. For the box plot, we used the CH10 isotopic compositions of the hair. The median value calculated is represented with the line in the box, which includes data from the first to the third quartile. The whiskers extend to a length of 1.5 times the interquartile range. The figure was created with *simmr* package (v 0.5.1.214) under R (v 4.3.1). The main source of food is maize, accounting for $53.6 \pm 12.9\%$ of the diet, followed by beans ($19.6 \pm 9.1\%$), algae ($16.2 \pm 12.9\%$) and camelid meat ($10.7 \pm 10.5\%$). For the stacked histogram, proportions of food were calculated for each month in the child's life, i.e. for each hair sample, except for the outlier samples CH1 and CH13, for which data are not reliable (Table 1). This histogram is based on mean values calculated without considering standard deviations. Algae was gradually incorporated into the diet between months 7 and 14 before the girl's death, with a greater proportion of the diet being devoted to this food during this period.

wet season (summer) as the season of child's offering (Fig. 2D, Supplementary Fig. S3). It is highly unlikely that the $\delta^2\text{H}$ variations can be interpreted as a mobility signal, as is the case with *chicha*.

Considering the possible mobility of the child and the increasing consumption of *chicha* as intended by the ritual, it is highly unlikely that such a sinusoidal signal, as we measured, would be observed. Our variation is explained differently from what was suggested in previous studies. Along the hair strand, our pattern of $\delta^2\text{H}$ variations indicates a climate-related seasonality record, which is the most parsimonious explanation for our results.

Assuming that the child did not move before her offering or moved rapidly before her offering, we determined her geographical origin. The

calculated $\delta^{18}\text{O}_w$ value of -9.3 ± 0.5 reflects the environmental water, most likely local meteoric waters ($\delta^{18}\text{O}_{mw}$), consumed by the child over several years prior to death and mummification.

The $\delta^{18}\text{O}_{mw}$ isoscape map illustrated in Fig. 5 displays the average annual $\delta^{18}\text{O}_{mw}$ of precipitation in South America (West et al., 2009). The climate of South America is marked by pronounced contrasts, with arid zones such as the Circumpuna and northern Chile, and areas that are more subject to rainfall, such as the eastern Andes and Bolivia (Espinoza et al., 2020). Based on the calculated $\delta^{18}\text{O}_w$ value, we identified the probable geographic origin of the child to be around the Andes, excluding the southernmost part of Chile and Argentina. It is less likely that the child came from regions that were not part of the Inca Empire.

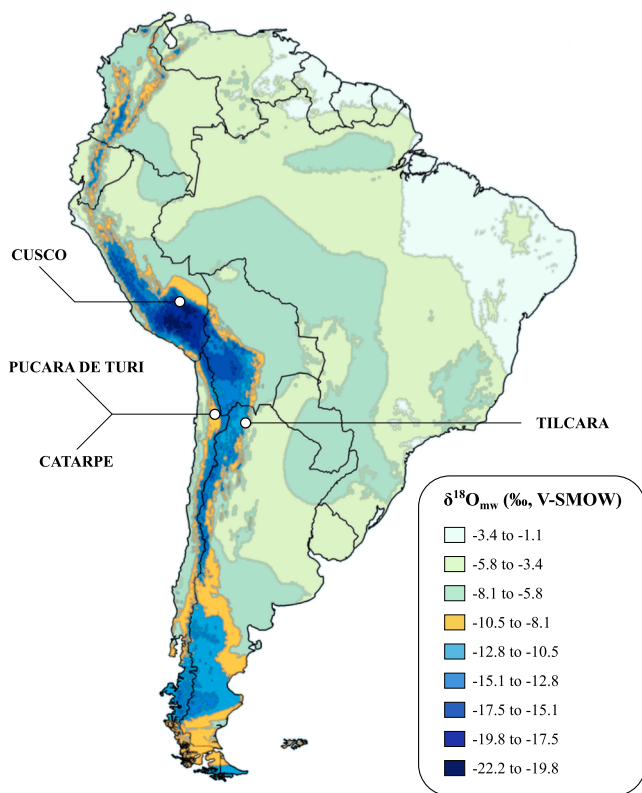


Fig. 5. Isoscape map of meteoric waters ($\delta^{18}\text{O}_{\text{mw}}$) in South America. The orange area indicates the probable origin of the child of the Quehuar volcano based on the calculated $\delta^{18}\text{O}_{\text{w}}$ value. Map adapted from <https://wateriso.utah.edu/waterisotopes/>.

However, when considering the ancient main cities of the Inca Empire, some locations are of a peculiar interest. One is situated between the Loa and San Pedro de Atacama basins, at the northern border between Chile and Argentina (Fig. 5). The discovery of human remains in the Loa Basin region, particularly at Pucara de Turi (22°S, 68°W, 3,100 m.a.s.l.), has been reported (Aldunate, 1993; Gallardo et al., 1995). This renders the region of peculiar interest from an archaeological perspective. The annual rainfall in Pucara de Turi exhibits $\delta^{18}\text{O}_{\text{mw}}$ value of -10.3 ‰, V-SMOW (Bowen and Revenaugh, 2003), which is in close proximity to the calculated values of the water consumed by the child. This region, therefore, appears to be a credible candidate for estimating the child's origin. It is also worth noting that the settlement of Catarpe (22°S, 63°W, 2,520 m.a.s.l.), located in the arid region of Chile of the San Pedro de Atacama basin, has an annual $\delta^{18}\text{O}_{\text{mw}}$ close to -9.0 ‰, V-SMOW (Bowen and Revenaugh, 2003), a value comparable to that of the water drunk by the child. For the city of Tilarca itself, capital of the Empire, mean $\delta^{18}\text{O}_{\text{mw}}$ values are much lower, around -17 ‰, V-SMOW (Bowen and Revenaugh, 2003). A comparison of the isotopic composition of the child's bone with those of other places in the vicinity of the Quehuar volcano region reveals that other regions, like the Quebrada de Huamahuaca (Jujuy province, Argentina), present isotopic compositions that could potentially match those observed in the child's bones. For example, the city of Tilarca (23°S, 65°W, 2,465 m.a.s.l.) exhibits $\delta^{18}\text{O}_{\text{mw}}$ values of -8.9 ‰, V-SMOW (Fig. 5, Bowen and Revenaugh, 2003). Therefore, more generally, we propose that the child came from an area bordering the Andes at an elevation close to 2,500 to 3,000 m.a.s.l. The annual $\delta^{18}\text{O}$ values of precipitation in the Loa and San Pedro de Atacama basins in Chile as well as the Quebrada de Huamahuaca in Argentina suggest they could be suitable locations for the child's origin.

Previous studies have attempted to identify the geographic origin of children offered in sacrifice during a *Capacocha*. Wilson et al. used DNA

analysis to determine that the Llullaillaco Maiden likely originated from the southern region of the Inca Empire, possibly from Chile or Argentina. The other two children discovered on the summit of Mount Llullaillaco were probably from the Cusco region. The origins of both the Aconcagua child and the Mount Ampato child, known as Juanita, have yet to be established, despite the consideration of an allochthonous child case (Faux, 2012; Killian Galván et al., 2020). It is not uncommon for individuals to move within the Inca Empire, even outside of ritual contexts such as the *Capacocha*. A recent study of genetics of the inhabitants of Machu Picchu indicates that they originated from a diverse range of geographical areas, including locations across the Empire and even the Amazon region (Salazar et al., 2023). It can be reasonably said that mobility within the Inca Empire was a common occurrence, perhaps even more so than previously assumed. Our data support a geographic origin within the Inca Empire, specifically in the vicinity of the archaeological site. The fact that the child did not originate from Cusco and exhibited limited mobility, likely constrained by climatic seasonality, suggests a localized selection process for sacrificial offerings. This could point to the involvement of local groups and elites in providing children for the *Capacocha* ritual. Rather than a centrally organized selection from Cusco, these findings imply that regional elites may have been responsible for contributing individuals from their own communities. This practice would not only reinforce the political integration of outlying regions into the Inca state but also reflect the reciprocal relationship between local leaders and the Inca central authority, where the offering of children served as a symbolic demonstration of loyalty and participation in state religious practices.

As shown in our decision support matrix (Supplementary Table S2), variations in $\delta^{34}\text{S}$ of hair could be attributed to mobility on a substrate with variable $\delta^{34}\text{S}$ values or to the influence of sea sprays. A sea spray effect seems improbable at such a distance as Cusco is at more than 500 km from the ocean, the Catarpe area is already over 200 km away and sea sprays rarely extends more than 50 km inland (Richards et al., 2001). Moisture from the Pacific Ocean is blocked by the Hadley Cell current above 1,200 m.a.s.l., so sea spray has little effect beyond this altitude (Klipsch et al., 2023). We estimated the origin of the child to be above 2,500 m.a.s.l., ruling out the sea spray hypothesis. Klipsch et al. measured $\delta^{34}\text{S}$ values of soils in the Antofagasta region, which is not far from the San Pedro de Atacama region, where the child may have originated. The $\delta^{34}\text{S}$ values measured in soils are close to those observed in hair, between about 4 and 9 ‰ (Table 1). However, the sinusoidal pattern observed in the values of the hair (Fig. 3A) suggests that the geological substrate cannot explain the measured values. If the geological substrates were responsible for the values in the hair, we would expect to see relatively constant values or variations with no particular pattern. This observation rules out the hypothesis that ^{34}S -rich geological substrates isotopically enrich the entire food chain.

The carbon isotope compositions indicate that the child's diet was mainly based on C_4 plants (Fig. 4). This was to be expected, as maize was a significant part of the Inca diet, including in the form of a beer-like drink we mentioned earlier, *chicha*. Amaranth or sugarcane, other C_4 plants, were major in the diet of the Incas (Gagnon et al., 2015; Gheggi and Williams, 2013; Killian Galván et al., 2020). C_3 plants were also part of the diet of the Quehuar volcano girl, but to a lesser extent (Fig. 4). The Incas are known to have eaten some of them, beans were an important part of their diet as well as potatoes for example (Leterme and Muñoz, 2002). However, isotopic values vary along the hair stand, especially in the case of carbon and sulfur isotope ratios, indicating seasonal variations in the composition of the food bowl of Incas (Fig. 2). After ruling out sea spray or geological substrate as explanations for the variation in $\delta^{34}\text{S}$, we can assume that its variation is due to a change in diet. It is noteworthy that $\delta^{34}\text{S}$ values are high when $\delta^{13}\text{C}$ values are low, while the nitrogen isotope composition remains steady. This isotope pattern observed in this case can be attributed to the consumption of marine products at the base of the trophic chain ($\delta^{13}\text{C} \approx -21$ to -13 ‰, Blanz et al., 2020; Kahma et al., 2020; Szpak et al., 2013; $\delta^{15}\text{N} \approx 5$ ‰, Kahma

et al., 2020; Szpak et al., 2013; $\delta^{34}\text{S} \approx 16\text{--}20\text{‰}$, Kejžar et al., 2021; Szpak et al., 2013).

Seaweed is the most plausible explanation for the triple isotope signature recorded in the Inca child's hair strand. Indeed, algae are at the base of the marine trophic chain and therefore have relatively low nitrogen isotopic compositions, usually around 5‰ (Kahma et al., 2020; Szpak et al., 2013). Herbivorous marine organisms, such as cockles, are one trophic level above, and have higher nitrogen isotopic compositions, around 8‰ (Kang et al., 1999). The consumption of seaweed was likely seasonal, as suggested by the robust fit of $\delta^{34}\text{S}$ values to a sine wave function ($R^2 = 0.96$, Fig. 3A). The highest consumption of marine algae took place during the wet season (summer), as revealed by the synchronous record of the lowest $\delta^2\text{H}$ values, reflecting the heavy rainfall that occurs in summer (Fig. 2D, Supplementary Fig. S3), perhaps to compensate for a shortage of certain foodstuffs during this period. Several studies suggest that seaweed consumption was prevalent among the Incas (Aaronson, 1986; Alconini and Covey, 2018; Arakaki et al., 2023; Pérez-Lloréns, 2019), and this resource is still widely consumed in South America today (Avila-Peltroche and Padilla-Vallejos, 2020). Seaweed could be dried and transported in pellet form from the sea to Cusco, the capital of the Inca Empire (≈ 500 km in a straight line, O'Connor, 2017). The transport of goods was ensured by a road network that the Inca Empire developed, named *Qhapaq Ñan* (Alconini and Covey, 2018; Matos and Barreiro, 2015). Consequently, the entire Empire could have benefited from these protein- and vitamin-rich marine products (Ramírez, 1996). It is crucial to acknowledge that the Inca Empire in South America demonstrated an advanced capacity for long-distance interactions, which they referred to as the vertical archipelago (Nielsen, 2009; Tessone et al., 2024). It is hypothesized that these interactions between disparate ecozones have facilitated the exchange of diverse foodstuffs between coastal and terrestrial populations, and vice versa. The *ayllu* (lineage) kinship system, is thought to have been a crucial factor in facilitating long-distance exchanges across a range of ecozones (Alconini and Covey, 2018; Covey, 2006; Hayashida et al., 2022; Murra, 1956). The reciprocal obligations inherent to the *ayllu* kinship system, such as *ayni* (mutual aid) and *mink'a* (communal labour), necessitated the fulfilment of social and economic responsibilities, frequently through the movement of goods between family networks dispersed across diverse ecological zones (Webster, 1981; Sammells, 2018). This interdependence would have made long-distance exchanges not just an economic necessity but a social one, thereby further explaining the presence of marine resources, such as seaweed, in highland diets (Murra, 1972; Santana-Sagredo et al., 2016). The integration of these kinship and economic networks serves to reinforce the idea that ritual offerings, including the *Capacocha*, were supported by intricate systems of exchange that transcended ecological boundaries. Camelid caravans were utilized for the transportation of substantial quantities of marine resources from the coast to the land (Beresford-Jones et al., 2023). Beyond the culinary aspect, seaweed is also recognised for its medicinal qualities. For example, it has been used to prevent iodine deficiency in the Andes (World Health Organization, 2007) and to treat goitre (Bowman et al., 2003). It is therefore possible that the Incas consumed seaweed not only as a food supplement but also for its medicinal properties. The hypothesis that seaweed was a dietary staple of the Inca Empire is supported by the discovery of seaweed at archaeological sites in South America, at diverse periods (Dillehay et al., 2008; Patterson and Moseley, 1968).

Another suggestion for the variation pattern of $\delta^{34}\text{S}$ values could have been the use of marine products (seabird guano, algae) to fertilize the soils. This could have increased the $\delta^{34}\text{S}$ values of the products consumed, but this hypothesis has been disproven because the $\delta^{15}\text{N}$ values of foods would also have increased, which is not visible in the hair (Blanz et al., 2019; Santana-Sagredo et al., 2015).

Finally, we could imagine that the goods were transported inland from coastal areas affected by sea sprays. If food was imported from the coasts, these products would have higher sulfur isotope compositions

than those found in the Andes. Consuming of these products could lead to values similar to those observed in the hair. However, it is unlikely that pre-Columbian populations, including the Incas, who mastered high-altitude farming (Chepstow-Lusty et al., 2009; Londoño, 2008; National Research Council, 1989; Staller, 2016) would have transported foodstuffs from the coasts to the Andes for locally available resources. Therefore, we favour the seaweed hypothesis.

As the covariation of $\delta^{34}\text{S}$, $\delta^{13}\text{C}$, and $\delta^{15}\text{N}$ is most likely explained by algae consumption, we attempted to quantify the proportion of algae in the diet. To achieve this goal, we used R's *simmr* package to solve mixing equations for stable isotopes (Govan et al., 2019, see section 2.5). Six months before being offered, the child most likely did not consume or consumed very little marine algae and had a terrestrial diet as suggested by the hair record with increasing $\delta^{13}\text{C}$ values while $\delta^{34}\text{S}$ values decreased (Fig. 2B, 2C). The *simmr* model confirms this (Fig. 4B). The shift in the diet, which took place between 7 and 14 months, can be explained by the presence of marine algae to the diet in a proportion of $16.2 \pm 12.9\%$ (3.2–29.0%, Fig. 4A, Supplementary Material section 2). The interpretation of the triple isotope signature of the child's hair implies a seaweed consumption that culminated during the wet season (summer, Supplementary Fig. S3).

While the presence of marine algae in the girl's diet may be of significance, it must be considered in the context of broader dietary changes preceding her death. The introduction of seaweed into the diet between 14 and 7 months prior to death may be indicative of a specialized diet that was intended to prepare the individual for the offering, either spiritually or physically. Given that seaweed is and was used for medicinal purposes, it is plausible that it was used to heal the child before she was sacrificed. During the final six months of the child's life, there was a notable increase in maize consumption, a food item that was primarily reserved for the elite (Alconini and Covey, 2018). These dietary shifts suggest the possibility of a preparatory practice that may have held symbolic or ritual significance, partly in alignment with Inca religious traditions, but not as accurately as described by the Spanish conquistadors.

To our knowledge, only one study has suggested a change in diet from marine to terrestrial products for a child offered in a *Capacocha*. Fernández et al., 1999 proposed this interpretation for the Aconcagua young man based on the hair $\delta^{13}\text{C}$ values. However, they acknowledged that it was an unlikely explanation because the two $\delta^{34}\text{S}$ values they measured in hair were far from the expected values of a 100% marine product-based diet. A recent study re-examined the data and concluded that the observed carbon isotope signal was seasonal rather than a marker of marine feeding (Wilson et al., 2007). The observed seasonal pattern has not been observed in other children offered in sacrifice, although there are variations in $\delta^{34}\text{S}$ values of their hair. The hair of the three children from the Lulluillaco volcano showed a maximum variation of around 3‰ over their lifetime, with no discernible pattern of variations (Wilson et al., 2007). The values measured in their hair are even identical 6 months before their death, suggesting that the 3 children were in the same location before starting their pilgrimage. Sulfur may therefore be a marker of geographical location. The sulfur isotope ratios measured in the hair of the Chuscha girl decrease steadily in the hair strand from 8.1‰ to 6.1‰ (Killian Galván et al., 2020). The isotope compositions measured for the Sarita girl are higher, decreasing between 15 and 10‰ (Wilson et al., 2007). The range of variation for the latter is similar to that measured in the hair of the Quehuar volcano girl. It cannot be assumed that the other offered children consumed marine products. However, our study combination of $\delta^{13}\text{C}$, $\delta^{34}\text{S}$, $\delta^{15}\text{N}$ but also $\delta^2\text{H}$ values allows us to formulate this hypothesis.

Finally, the nitrogen isotope ratios vary by a maximum of 1.6‰ (Fig. 2A). The $\delta^{15}\text{N}$ values are not markedly elevated, suggesting that the original environment of the individual's diet was not arid, as the Atacama Desert can be (Knudson et al., 2012; Santana-Sagredo et al., 2015). The child's diet included a proportion of meat, which may have been more prevalent during certain periods of the life, notably 12 and 7

months before death, or just before. There is no significant change in protein diet during the child's last 14 months of life. These almost steady isotopic compositions are not observed in hair of all other known children (Killian Galván et al., 2023; Wilson et al., 2007) offered during *Capacocha*. However, two of the mummies have $\delta^{15}\text{N}$ values close to the one we studied: the Llullaillaco Lightning Girl (Wilson et al., 2007) for which hair $\delta^{15}\text{N}$ values are comprised between 9.3 and 11.7 ‰, and the mummy from Mount Chuscha (Killian Galván et al., 2020) having hair $\delta^{15}\text{N}$ values that vary between 8.4 and 11.0 ‰. The other Andean mummies show distinct isotope variations, as seen in the Llullaillaco Maiden, whose diet shifted from vegetarian to omnivorous in less than a year before her death (Wilson et al., 2013). Factors such as the geographical origin of the child, local habits including diet, and the reason of the offering could have impacted the way *Capacocha* was practiced.

5. Conclusions

Multi-isotope analysis of hair increments from the Inca mummy from the Quehwar volcano, Argentina, firstly revealed that the child probably did not move over long distances as suggested by the $\delta^2\text{H}$ values that recorded a sinusoidal signal resulting from seasonally-controlled air temperature variations. These values enable us to determine the season of the child's death, which was probably at the beginning of the wet season (summer). The oxygen isotope composition of the bone apatite phosphate helped us to determine the origin of the child to be in the Andean plateaus or valleys of the Inca Empire, at an altitude of over 2,500 m.a.s.l., probably in the Loa or San Pedro de Atacama basins in Chile, or the Quebrada Huamahuaca in Argentina. Beyond the girl's geographic origin and limited mobility, these results suggest that local elites may have been responsible for providing children for the *Capacocha* ritual. This points to a more decentralized process, where regional groups played a significant role in state religious practices, reinforcing their ties to the Inca central authority.

Secondly, the $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ values indicate a diet consisting mainly of C_4 plants and a smaller proportion of C_3 plants, with meat also being consumed. Additionally, the combination of $\delta^{13}\text{C}$, $\delta^{15}\text{N}$ and $\delta^{34}\text{S}$ suggests that seaweed consumption may have been a part of the diet (16.2 ± 12.9 %) prior to the offering, particularly during the wet season (summer). The study suggests that the sacrificial child may have consumed algae about a year before death, before switching back to a terrestrial-based diet for the last six months of life. This indicates that the consumption of seaweed may be seasonal.

Our findings offer new insights into the dietary practices of children offered during the ritual of *Capacocha*, which challenge previous assumptions based on historical accounts. The discovery of potential marine resources in the diet of the sacrificial child, here seaweed, might reflect a broader integration of coastal and highland ecological zones, which is a known feature of the Inca *ayllu* system but has rarely been linked directly to ritual offerings. This research makes a significant contribution to Andean and Inca archaeology by providing empirical evidence that enriches our understanding of Inca religious and cultural practices, particularly the *Capacocha* ritual. This allows archaeologists to uncover detailed aspects of ancient lifeways that are not accessible through traditional archaeological methods alone. By examining the seasonal consumption patterns and potential long-distance resource exchange, this study goes beyond general assumptions to provide concrete data on how local groups and communities may have participated in and adapted state rituals.

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CRedit authorship contribution statement

Eve Poulallion: Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Violeta A. Killian Galván:** Writing – review & editing, Investigation, Funding acquisition, Conceptualization. **Verónica Seldes:** Writing – review & editing, Conceptualization. **María Fernanda Zigarán:** Writing – review & editing. **Gabriela Recagno Browning:** Writing – review & editing. **François Fourel:** Writing – review & editing, Data curation. **Thibault Clauzel:** Writing – review & editing. **Jean-Pierre Flandrois:** Writing – review & editing, Conceptualization. **Nicolas Séon:** Writing – review & editing, Resources. **Laurent Simon:** Resources. **Romain Amiot:** Writing – review & editing. **Christophe Lécuyer:** Writing – review & editing, Writing – original draft, Supervision, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All research data/code is available in the main text or [supplementary information](#).

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Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jasrep.2024.104784>.

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