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The case of a southern European glacier disappearing under recent warming that survived Roman and Medieval warm periods

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Abstract

Mountain glaciers have generally experienced an accelerated retreat over the last three decades as a rapid response to current global warming. However, the response to previous warm periods in the Holocene is not well-described for glaciers of the ~~of~~ southern Europe mountain ranges, such as the Pyrenees. The situation during the Medieval Climate Anomaly (900-1300 CE) is particularly relevant since it is not certain whether the glaciers just experienced significant ice loss or whether they actually disappeared. We present here the first chronological study of a glacier located in the Central Pyrenees (N Spain), the Monte Perdido Glacier (MPG), carried out by different radiochronological techniques and ~~their~~ a comparison with geochemical proxies with neighboring paleoclimate records. The result of the chronological model proves that the glacier endured during the Roman Period and the Medieval Climate Anomaly. The lack of ice from the last 600 years indicates that the ice formed during the Little Ice Age has melted away. The analyses of ~~the content of~~ several metals ~~of~~ with anthropogenic ~~origin~~ source, such as Zn, Se, Cd, Hg, Pb, ~~appear in low amounts~~ reveal low concentrations in MPG ice, which ~~further supports our age model in which the record from~~ provides further evidence that the industrial period is lost. This study confirms the exceptional warming of the last decades in the context of the last two millennia. We demonstrate that we are facing an unprecedented retreat of the Pyrenean glaciers ~~which~~ whose survival is compromised beyond a few decades.

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1. Introduction

Mountain glaciers are ~~often~~ sensitive to climate variations on temporal scales from decades to centuries. It is well known that summer temperature and winter precipitation are the most important climate parameters influencing glacier mass balance (Oerlemans, 2001). Therefore, continuous records of past glacier size fluctuations provide valuable information about the timing and magnitude of Holocene climate shifts (Solomina et al., 2015, 2016), which contributed to explain the characteristics and evolution of plant cover, human movements and land use. Several glacier advances during the Neoglacial (which started around 6000-5000 yr ago) have been identified and associated to sustained cooling periods across the North Atlantic (Wanner et al., 2011). The most recent period of global glacier expansion took place during the Little Ice Age (LIA), beginning in the 13th century and reaching a maximum between the 17th and 19th centuries (Solomina et al., 2016). Afterwards, most glaciers worldwide have retreated rapidly, as indicated by measurements of ice volume and ice-covered area, and this trend seems to have accelerated over the last three decades (Marzeion et al., 2014; Zemp et al., 2015, 2019).

Despite broad agreement on millennial-scale trends in global glacier fluctuations and Holocene climate variability (Davis et al., 2009; Solomina et al., 2015), regional variations are not so well constrained. For instance, for the Pyrenees, a mountain range that currently hosts the majority of the southernmost glaciers in Europe, there is a significant lack of knowledge about Holocene glacier fluctuations, as indicated by scarce evidences of glacier advances during the Neoglacial period (García-Ruiz et al., 2014; Gellatly et al., 1992). Based on Pyrenean tree-ring chronologies, summer temperature during the Medieval Climate Anomaly (MCA, circa 900–1300 CE) were estimated to be as warm as those of the 20th century (Büntgen et al., 2017), but no information has been obtained on the glacier response to MCA warming. Conversely, glacier advance during the LIA is well constrained in the Mediterranean mountains (García-Ruiz et al., 2014; González Trueba et al., 2008; Hughes, 2018; Oliva et al., 2018) and a significant deglaciation is also evident in recent times (López-Moreno et al., 2016; Rico et al., 2017). Thus, Pyrenean glaciers have exhibited during the 20th and 21st centuries multi-decadal variations similar to those of other mountain ranges in the world. In particular,

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the period from the 1980s to present has been the most intense in terms of the number of glaciers that disappeared (from 39 inventoried Pyrenean glaciers in 1984 to 19 at present) (Rico et al., 2017). Given the small size of the Pyrenean glaciers and their current critical situation in the context of global warming, we hypothesize that they could have disappeared completely during the aforementioned warm periods

This study is focused on Monte Perdido Glacier, located in the Spanish Central Pyrenees, which is currently one of the best monitored small glaciers (<0.5 km^2) worldwide. Recent research based on different ground-based and remote sensing techniques has demonstrated a rapid retreat of this glacier, with an average loss of ice thickness of about one meter per year since 1981 (López-Moreno et al., 2019). These results, together with the evidences of long-term retreat since the LIA glacier position indicated by pictures and moraines, suggest that this glacier could disappear over the next few decades (López-Moreno et al., 2016). The present study [illegible]es on a variety of dating techniques and on the analysis of several proxies associated to environmental and anthropogenic changes to construct, for the first time, the chronology of an ice sequence from a Pyrenean glacier. Such analyses will respond to the key question of whether Pyrenean glaciers may have survived previous Holocene warm periods.

2. Study area

The Monte Perdido Glacier (MPG, 42°40′50″N; 0°02′15″E.) is located in the Central Spanish Pyrenees, in the Ordesa and Monte Perdido National Park (OMPNP) (Fig.1). It currently consists of two separate ice bodies, which were connected in the past. Both are north facing and lie on structural flats beneath the main summit of the Monte Perdido Peak (3355 m a.s.l.) and are surrounded by vertical cliffs of 500–800 m in height. At the base of the cliffs, the Cinca River flows directly from the glacier and the surrounding slopes, and has created a longitudinal west–east basin called the Marboré Cirque (5.8 km^2). This is the area within the Pyrenees with the highest variety of recent morainic deposits (García-Ruiz et al., 2014). Additionally, ~~a~~ a 6-m thick sediment core obtained in 2011 from a lake inside the cirque (Marboré Lake) contains valuale information from the last 14,600 years of the depositional evolution of the lake (Oliva-Urcia et al., 2018) and of the regional variations in the vegetation cover (Leunda et al.,

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2017). The Marboré Lake (2595 m a.s.l.) is located in the Marboré or Tucarroya Cirque, in the northern face of the Monte Perdido massif. The distance between the lake and the MPG is approximately 1300 m and, therefore, both have been affected by similar palaeoenvironmental conditions.

Recent measurements indicate that the total surface area of MP glacier in 2016 was 0.385 km^2 (López-Moreno et al., 2016). During the period 2011–2019, the glacier ice thickness decreased by 7.4 m on average, though such losses exhibit a marked spatial and temporal variability (Fig. S1, Supplementary Material). According to recent measurements of air temperature (July 2014 to October 2017), the 0 °C isotherm lies at 2945 m a.s.l., suggesting that the potential glacier accumulation area is very small, even inexistent during warm years. In an average summer (June to September; temperature measurements were conducted from 2014 to 2017), the temperature at the foot of the glacier is 7.3 °C. No direct observations of precipitation are available at the glacier location, but the maximum accumulation of snow in late April during the three available years was 3.23 m, and average snow density was 454 kg m^{-3} measured in the field, indicating that total water equivalent during the main accumulation period (October to April) could be close to 1500 mm (López-Moreno et al., 2019).

3. Material and methods

3.1. Ice sampling and storage

Ice drilling in MPG was carried out in September 2017 using a Kovacs ice coring device at three sites. These sites were selected based on previously obtained ground-penetrating radar (GPR) results, which, combined with glacier dynamics modelling, suggested that the oldest ice could be located at these locations since the thickness was over 30 m and there was no movement of the ice (López-Moreno et al., 2019) (Fig. 1). Unfortunately, none of the glacio-meteorological and topographical criteria required to obtain a preserved ice-core stratigraphy, such as low temperatures to prevent water percolation, or a large extension and flat surface topography to minimize the influence of glacier flow (Garzonio et al., 2018), are currently met in the glacier. With this technique, only three short ice cores of 4, 3 and 2 m in length could be recovered, which could not provide a complete chrono-stratigraphical ice sequence.

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The cores were preserved intact and later stored at –60 °C at the BC3-IzotzaLab ice core facility (Leioa, Spain) but are not used in this study.

Based on the poor core recovery, we changed our drilling strategy and, in order to collect ice samples from the glacier surface in an ordered chrono-stratigraphical sequence covering from the oldest to the newest ice preserved in the glacier, we took samples in an area with no evidence of major current ice movement, as confirmed by results from interferometric radar and GNSS measurements (López-Moreno et al., 2019) (Fig.S2). This sector has been eroded to form a current steady slope of 20° where it is possible to establish a relation between the sample distances and the ice depth in a formerly much less steep glacier surface. Due to the small size of this glacier, the ice needs to be frozen to bedrock, and hence nearly stagnant, to become of substantial age, i.e., a few hundred years or more, as indicated by previous studies in similar glaciers Gabrielli et al., 2016; Haeberli et al., 2004). Therefore, we measured one-m thickness using the Jacob's staff at every sampling point to measure stratigraphic thicknesses since bedding was unclear (Fig. S2). Once cleaned the most superficial ice to avoid new ice formed recently, we recovered at every sampling position 3–4 small cores (6 cm in diameter and 25 cm in length) using a custom stainless steel crown adaptor on a cordless power drill (see Fig. S2 in Supplementary Material). Following that sampling procedure we recovered a total of 100 samples, every one constituted by 3-4 cylinders, which represent the whole ice sequence in MP glacier. Those ice samples were stored in a freezer room in Zaragoza and further analysed to obtain their chronology (combining ^{210}Pb, ^{137}Cs and ^{14}C techniques) and their geochemical composition (trace element and Hg concentrations) (see below).

3.2. Dating by ^{210}Pb and ^{137}Cs.

The isotope ^{137}Cs usually associated to the fallout from nuclear tests during the 1950s and the 1960s, as well as the Chernobyl (1986) an ushima (2011) accidents was investigated by γ-spectrometry in the uppermost five samples in MPG, but no trace could be detected (Table S1 in ementary Material). This implies that all samples are older than 60–65 years and therefore they were not exposed to the atmosphere after 1950 CE. Another possibility that was discarded once we had ^{14}C dates, is that all

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samples were younger than 1950 CE. Additionally, up to ten samples were selected from the 100 samples that constitute the whole ice sequence to carry out ^{210}Pb analysis as an independent dating method to obtain chronologies for about the last hundred years of glacier ice (Eichler et al., 2000; Herren et al., 2013). Those samples were selected from the top of the sequence (Table S2). Determination of ^{210}Pb activities was accomplished through the measurement of its daughter nuclide, ^{210}Po, by α-spectrometry following the methodology described in (Sanchez-Cabeza et al., 1998) (Table S2 in Supplementary Material). Similarly, ^{210}Pb activity was also undetectable in most cases, except in three samples (MP100, MP73 and MP76) with concentrations above minimum detection activity (MDA; Table S2). Probably, the MP100 sample contained the ^{210}Pb recently deposited because it was the most superficial sample, therefore in contact with the atmosphere. However, this sample, as well as samples MP73 and MP76 contained a large amount of lithogenic particulate material from atmospheric dust or ash deposits. The absence of ^{210}Pb activity in the analysed samples does not allow constructing an age-depth model for the last 100 years indicating that MPG ice samples were very likely older and the ^{210}Pb had completely decayed. We then built up the proposed MPG chronology using AMS ^{14}C dating.

3.3. Dating by ^{14}C method.

Sixteen accelerator mass spectrometry (AMS) ^{14}C dates from MPG ice were obtained by combining bulk organic matter (9 samples), pollen concentrates (3 samples), bulk sediment accumulated in filters (2 filters), and water-insoluble organic carbon (WIOC) particles (2 samples) (Table 1). First, using a binocular microscope [x10], we selected organic particles for dating from the nine selected bulk samples, once the ice sample was melted. However, the small size prevented us from classifying the organic remains. All the amorphous particles were sent to the dating laboratory (Direct AMS, Seattle, USA). Pollen concentrates were prepared from three selected samples (30, 70 and 100 m depth) to complete the previous set of samples following the standard palynological method, including a chemical treatment and mineral separation in heavy liquid (Thoulet: density 2.0; Moore et al., 1991). Additionally, two ice samples previously melted (67 and 81 m depth) were filtered throughout a filtration line connected to a vacuum pump using 47 mm quartz fiber filters (PALL tissuquarzt 2500QAT-UP), parameterized at controlled conditions (temperature: 22–24 °C; relative humidity 25–35%) and weighted twice in different days. Abundant material was obtained, but no control was made on the composition and amount of organic material versus other type of inputs. Concentrated pollen samples and filters were dated at the same laboratory (Direct AMS, Seattle, USA). Since organic fragments (plants, wood, insects) are rarely found in mountain glaciers, a new, complementary dating tool was recently developed based on extracting the microgram-amounts of the water-insoluble organic carbon (WIOC) fraction of carbonaceous aerosols embedded in the ice matrix for subsequent ^{14}C dating (Uglietti et al., 2016). Two samples were dated by the WIOC technique at the Laboratory of Environmental Chemistry, Paul Scherrer Institute, Switzerland, following the usual procedures including removing the outer part of the ice core segment for decontamination purposes (Jenk et al., 2009).

Finally, from the initial 16 dates, we had to discard seven (see the criteria in section 4.1 below) and the age model was developed including nine samples (eight from bulk organic matter and one from the WIOC technique; Table 1). Those nine dates were converted into calendar ages by the CALIB 5.0.2 software, which uses the most updated dataset, INTCAL13 (Reimer et al., 2013) (Table 1). The median of the one-σ probability interval was selected for these dates, resulting in large errors (230 years on average) in the obtained calendar ages. The depth–age model was created using the R package CLAM 2.2 (Blaauw, 2010; Blaauw et al., 2019) (Fig. 2). Given the scattered depths at which dates concentrate, we chose to perform a non-smooth, second order polynomial regression for preventing any model over-fitting and a spurious age–depth relationship. In addition, we run the depth–age model setting a hiatus at 73 m depth where we think an interruption in the ice accumulation was produced. This idea is supported by the observation of several debris layers that increased their frequency towards the top of the glacier. Those layers are interpreted as the result of several phases of melting, dramatically changing the accumulation rates and concentrating samples of similar ages (see section 4.1 below). Full details on how the model was performed and a reproducible workflow with the current chronological dataset are available in the Supplementary Material.

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3.4. Trace elements in soluble and insoluble material.

35 selected ice samples from the altitudinal transect were melted and filtered through a filtration ramp connected to a vacuum pump using 47 mm quartz fiber filters (PALL tissuquarzt 2500QAT-UP). Filters were pre-heated at 250 °C and thereafter prepared in controlled conditions (temperature: 22–24 °C; relative humidity: 25–35 %) before and after filtration. Subsequently, they were weighted in two different days. Mass difference between blank and sampled filters was used to calculate the amount of insoluble material entrapped in ice samples. For every sample, an aliquot and a filter were obtained. From aliquots, anions and cations, as well as major and trace elements were determined. From filters, we determined major and trace elements, as well as organic and elemental carbon, following the method devised by (Pey et al., 2013) (Table 2). Basically, an acidic digestion (HNO_3:HF:$HClO_4$) of half of each filter was conducted, driven to complete dryness, being the remaining material re-dissolved in HNO_3. Inductively coupled plasma mass spectrometry (ICP-MS) and inductively coupled plasma atomic emission spectroscopy (ICP-AES) were used to determine major and trace elements. From the other half of each filter, a 1.5 cm^2 section was used to determine Organic Carbon (OC) and Elemental Carbon (EC) concentrations by using a SUNSET thermo-optical analyzer, following the EUSAAR_2 temperature protocol. Table 1 also contains the Enrichment Factors (EFs) calculated as follows:

$$EF_{iCODD} = \frac{X_{iCODD}/Al_{CODD}}{X_{iUC}/Al_{UC}} \qquad EF_{iMPGID} = \frac{X_{iMPGID}/Al_{MPGID}}{X_{iUC}/Al_{UC}} \qquad EF_{i} = \frac{X_{iCODD}/Al_{CODD}}{X_{iMPGID}/Al_{MPGID}}$$

where EF_{iCODD} is the Al-normalised Enrichment Factor with respect to the Upper Crust (*UC*, (Taylor and McLennan, 1995)) of an *'i'* element in the current Ordesa's deposited dust (*CODD*); EF_{iMPGID} is the Al-normalised Enrichment Factor with respect to the *UC* of an *'i'* element in the current MPG ice dust (*MPGID*); and EF_i is the Al-normalised Enrichment Factor with respect to *CODD* of an *'i'* element in the *MPGID*.

Regarding the Pb/Al ratio, we carried out a normalization with Al in both, ice and lake records, to disentangle the anthropogenic lead variability from possible detrital inputs.

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Aluminum has been selected for normalization since this lithogenic element is immobile and abundant in carbonated watersheds.

3.5. Hg determination.

Total Hg concentration measurements were carried out in 21 selected samples by Atomic Absorption Spectrophotometry using an Advance Mercury Analyzer (AMA 254, LECO Company). This equipment is specifically designed for direct mercury determination in solid and liquid samples without sample chemical pre-treatment. Certified reference materials were used to determine the accuracy and precision of the Hg measurements. These reference materials were ZC73027 (rice, 4.8 ± 0.8 μg kg^{-1}) and CRM051–050 (Clay soil, 4.08 ± 0.09 mg kg^{-1}). The repeatability was Sr ≤ 15 % and the relative uncertainty associated with the method (k = 2; confidence level of about 95%) was ±20 %. All analyses were run at least three times. Total metal concentrations were expressed in μg g^{-1} of dry weight sediment due to the low amount detected.

4. Results and discussion

4.1. Dating of ice from the Monte Perdido Glacier

Dating of ice cores from temperate, non-polar glaciers is challenging and often problematic as annual layer counting is precluded due to periods without net accumulation, and to ice deformation caused by glacier flow (Festi et al., 2016; Thompson et al., 2006). Hence, we have constrained the age of glacier ice within the last 100 years by using ^{210}Pb and ^{137}Cs relative dating methods, and for the oldest sections we used ^{14}C absolute dating from different materials (*Sect. Material and methods* and Tables S1, S2 in Supplementary Material). Additionally, characteristics of the ice stratigraphy, such as the presence of dark debris-rich layers, were integrated into the chronology. Finally, proxy comparison with independently dated sediments of the Marboré Lake located nearby (Corella et al., 2018; Oliva-Urcia et al., 2018) (Fig.1) helped to support the obtained MPG age-depth model .

We took most of the ice samples for dating in sections where dark debris layers alternated every ca. 5 m with cleaner and clearer ice (Fig. S2 in Supplementary Material). The debris layers were composed of detrital, silty-sandy size deposits, likely

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coming from wind-blown particles (e.g. black carbon-rich particles, dust) and from erosive processes of the limestone catchment, including the fall of gravel-sized particles from the surrounding cliffs. These debris layers contain more organic remains than those formed by clear ice, making them ideal spots to find datable remains. Interestingly, the frequency of debris layers increases towards the top of the glacier, where these layers are most abundant. We consider the accumulation of debris layers to be indicative of reduced ice accumulation and dominance of ablation periods. In such situations, the detrital and organic material concentrates as the ice melts, giving its characteristic dark colour to the ice layers.

The chronology for the last 100 years was not eventually constrained using ^{210}Pb and ^{137}Cs as samples proved to be older than the decay period of both radionuclides (Tables S1 and S2, Supplementary Material). Thus, the lack of ^{210}Pb activity indicated the lack of ice formed during the last 100 years. Regarding the ^{14}C dated samples, some sample limitations precluded the construction of a chronology (Table 1). The sample from 48 m depth (D-AMS 025295) was the only one from the nine bulk organic matter samples to be discarded due to probable contamination, since small plastic debris coming from the painting used in the coring device were identified under the microscope. From the two WIOC-dated samples, one was discarded (MP10m), as it had too small amount of organic carbon (5.3 μg), thus providing too inaccurate results. The other sample (MP59m), with higher organic carbon (28.7 μg), was incorporated into the age model. The other two methods (pollen and filters) used to concentrate organic matter to be dated by ^{14}C were, unfortunately, not successful. The three pollen concentrates provided unreliably old datings. We hypothesize that these old datings are likely associated to melting processes of older ice layers accumulated in the upper ice body of MPG (Neoglacial or Roman times), which later percolated through the ice, as observed in other glaciers (Ewing et al., 2014). Similarly, we discarded the two filter samples from 67 m and 81 m depth (D-AMS 029894 and D-AMS 033972, respectively). The material accumulated in the filters was a mixture of particles containing detrital carbonate eroded from Eocene limestones or supplied by Saharan dust, which was not removed and probably influenced the results incorporating dead carbon to the samples.

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Finally, from the original set of sixteen absolute dates obtained, we selected the nine samples which did not present any problem related to the amount of carbon, possible contamination, material from different sources or percolation within the ice sequence. These nine samples were all chrono-stratigraphically coherent (eight from bulk organic matter and one from WIOC-technique). The age-depth model obtained indicates the presence of ice since 2000 years ago and allows distinguishing three main periods for MPG (Fig. 2). First, an accumulation period from 0 to 700 CE. Second, an ablation-dominated phase from 700 to 1200 CE, which corresponds to the dark-rich layers interval. Third, a new accumulation period from 1200 to 1400 CE. Finally, no ice formed during, at least, the last 600 years has been found today in MPG according to this age model. This indicates that the LIA ice has been melted away, thus demonstrating an intense ablation period since 1850 CE. The MPG chronology is supported by, first, a quantitative comparison with present-day atmospheric particulate matter (Table 2) and, second, by the comparison with the paleoenvironmental sequence of the Marboré Lake for the last 2000 years (Fig. 3) (see text below).

We have used the averaged concentration values of major and trace elements currently obtained at a monitoring station located in Ordesa and Monte Perdido National Park (8 km away from the MPG, at 1190 m a.s.l.), where deposited atmospheric particulate matter is sampled monthly (Table 2). Interestingly, the elements that abound nowadays in the Ordesa station are not so abundant in the ice from MPG. Indicators such as organic carbon, Zn, Se and Cd concentrations, all of which are potential proxies of current anthropogenic emissions, are much higher in the samples from Ordesa, which are representative of today's atmosphere, than in the ice samples from the MPG. The low concentration of these elements in MPG samples could indicate their disappearance from glacier surface layers due to its continuous melting. This supports our suggested age model (Fig. 2), in which the industrial period has not been recorded. Contrariwise, the Al-normalised enrichment factor (EF) of Ti, Mn, Cr, Co, Ni, Cu and Pb, elements linked to the natural fraction (dust deposition, lithogenic elements) and mining activities (Corella et al., 2018), are more abundant in the MPG ice samples than in the present-day Ordesa aerosols (Table 2). From them, Cu

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and Pb were markedly enriched (by a factor >6) in the MPG ice samples compared with the current deposited aerosols in Ordesa station.

Following previous studies on present-day atmospheric particulate matter composition from natural, urban or industrial areas (Querol et al., 2007), the values of some elemental ratios (e.g. Cu/Mn, As/Se, Pb/Zn) help to determine the origin of the particulate matter accumulated today. The Ordesa site can accordingly be mostly defined as remote in terms of atmospheric deposition ("rural background") while the average composition of MPG ice samples could be defined as a site under the influence of Cu mining and smelting activities, due to the high values of the Cu/Mn, As/Se and Pb/Zn ratios. It is noteworthy that Cu, Ag, and Pb mining and smelting have been historically documented in Bielsa valley during pre-industrial times (Callén, 1996). Indeed, MPG is only 7 km east from some of the largest lead and silver ore deposits in the Pyrenees (historical mines of Parzan). The impact of ancient environmental pollution in high alpine environments is archived in the lacustrine sequence of the neighbouring Marboré Lake, providing first evidences of historical metal mining and processing activities during the Roman Period (RP) (Corella et al., 2018, 2020). Therefore, the enrichment of trace elements in MPG ice record most likely corresponds to mining activities during ancient times. Recently, an ice core record from the western Alps has also demonstrated the suitability of glacier ice to record local and regional mining and smelting activities during RP and pre-Roman times (Preunkert et al., 2019).

The comparison of Pb/Al ratios from the independently dated records of Marboré Lake and MPG (Fig. 3) shows a reasonable agreement, supporting the obtained age model for MPG ice. Particularly, the high Pb/Al values in both records between the 1st-5th centuries can be explained by increased Pb emissions related to the aforementioned regional mining and smelting activities during the RP. Maximum Pb/Al values have been found in several natural archives in the Central Pyrenees since the onset of Industrialization at 1800 CE as well as in other glacier ice core archives from the Alps (Corella et al., 2017, 2018). Thus, the lack of a Pb/Al peak in the upper sequence of the MPG again confirms the absence of the last two centuries in MP ice record. Similarly, the Hg concentration in the glacier is very stable throughout the ice sequence (Fig.3).

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Hg concentrations in other ice core records preserve an increase during the onset of Industrialization at 1800 CE with maximum values typically 3–10 times higher than preindustrial values (Cooke et al., 2020). In Marboré Lake, the mercury increase occurred over the last 500 years associated to the maximum activity in the Spanish Almaden mines during the Colonial Period (Corella et al., 2020). Again, these results, lacking an expected increase in Hg levels, support the age model from the MPG record where the last six centuries of ice deposition are missing.

4.2. Evolution of the Monte Perdido glacier over the last 2000 years

The analyzed ice from MPG provides remarkable information about the evolution of the glacier in the last two millennia, which deserves be considered in the regional context. Based on published results, the oldest paleoclimatic information in the Marboré Cirque comes from the Marboré Lake, since no glacier deposits corresponding to the Late Pleistocene have been found in the cirque (García-Ruiz et al., 2014). There is sedimentological evidence that the Marboré Lake was already ice-free at least since the onset of the Bølling period (Greenland Interstadial-1, 14,600 yr BP), when clastic sediments were deposited in the lake basin (Leunda et al., 2017; Oliva-Urcia et al., 2018). This is coherent with the nearby La Larri juxta-glacial sequence which showed that the main Pineta glacier had already retreated further up in the headwater by 13,245 ± 120 yr BP (Salazar et al., 2013). In fact, glaciological studies performed in the Central Pyrenees confirm the sudden retreat of glaciers during the Bølling period, when they were reduced to small ice tongues, cirque glaciers or rock glaciers (Palacios et al., 2017).

Like other glaciers all over the world (Davis et al., 2009; Solomina et al., 2015), MPG likely experienced numerous spatial fluctuations during the Holocene, although absolute dates directly obtained from moraines are uncertain. A single boulder was dated from the outermost moraine corresponding to the maximum glacier expansion since the Younger Dryas (recalculated at 6900 ± 800 ^{36}Cl yr BP) (García-Ruiz et al., 2020) in the Marboré Cirque. This is the oldest Holocene date available for glacial deposits in Spain (García-Ruiz et al., 2014), and indicates a glacier advance during the Neoglacial period (Fig. 4A). Other minor advances would have occurred in MPG prior to

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the LIA, as inferred from three polished surfaces dated at 3500 ± 400, 2500 ± 300 and 1100 ± 100 ^{36}Cl yr BP, indicating the occurrence of different deglaciation phases, and therefore glacial re-advances prior to these dates (García-Ruiz et al., 2020). Most likely, the voluminous moraine at the foot of the Monte Perdido Massif, which undoubtedly was deposited during the LIA, incorporates minor moraines and till from prior Neoglacial advances, as has been reported in other Pyrenean cirques (Crest et al., 2017; Palacios et al., 2017).

With the new chronology of the MPG record, we can ascertain that MPG has persisted at least since the RP (circa 2000 yr ago). At that time, which is a well known warm period in the Iberian Peninsula as recorded in both continental (Martín-Puertas et al., 2010; Morellón et al., 2009) and marine sequences (Cisneros et al., 2016; Frigola et al., 2007; Nieto-Moreno et al., 2011), the glacier was still active, but probably smaller than during Neoglacial times (Fig. 4B). This situation probably continued during the following cold period, the Dark Ages (DA, Fig 4C) when the glacier advanced as indicated by the polished surface dated at 1100 ± 100 ^{36}Cl yr BP (García-Ruiz et al., 2020). In glaciers in the Alps, reconstructions based on dating trees found within and at the edge of glacier forefields have revealed a minimum glacier extent during the Iron Age and the RP (Holzhauser et al., 2005), when glaciers were estimated to be smaller than during the 1920s (Ivy-Ochs et al., 2009). Afterwards, in the late RP and the early Middle Ages numerous glaciers in the Alps advanced during the DA, also known as the Göschener II oscillation (Holzhauser et al., 2005).

The MCA (900–1300 CE) is the most recent preindustrial warm era in Europe (Mann et al., 2009). For instance, in the Alps, a general glacier retreat has been observed during this period, mainly associated with a decline in precipitation (Holzhauser et al., 2005). According to the age-depth model, the MPG experienced a spectacular retreat (Fig. 4D), including the complete melting of some minor glaciers in the Marboré Cirque (García-Ruiz et al., 2020). Nevertheless, during the MCA part of MPG was preserved, as we find ice from 0 to 700 CE. No doubt the ice loss was significant, as evidenced by the accumulation of dark strata over a long time interval (600–1200 CE) (Fig.2). On this basis, we propose that the MPG was dominated by ablation processes during the MCA, leading to considerable ice loss as deduced from just six meters of ice remaining from

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this period (Fig. 2). We assume that, by this time, basal ice of Neoglacial age was already removed, but at the end of the MCA the MPG still preserved ice from the RP and the first half of the DA (Fig. 4D).

Over such a diminished MCA glacier, ice started to accumulate again at a rapid rate during the LIA (1300–1850 CE). In most cases, the LIA was the period when mountain glaciers recorded their maximum Holocene extent (Solomina et al., 2016), with remarkable advances in the alpine glaciers (Ivy-Ochs et al., 2009). From a large variety of proxies, several warm and cold periods have been identified in the Iberian Peninsula during the LIA (Oliva et al., 2018). In the Marboré Cirque two generations of LIA moraines have been mapped (García-Ruiz et al., 2014), whose emplacement coincided with the coldest LIA phases, i.e. 1620-1715 CE, when the Pyrenean glaciers recorded their maximum extent, and 1820-1840 CE, when a rapid advance of the ice mass moved over the large moraine leaving parallel furrows, or flutes, as signs of erosion (García-Ruiz et al., 2020; Serrano and Martín-Moreno, 2018). These two cold phases are very well identified in the Marboré Cirque and were confirmed by the study of the altitudinal fluctuations of the timberline in the neighboring Escuaín Valley (Camarero et al., 2015). In fact, according to the map of Schrader from 1874 CE and other historical sources, the MPG made direct contact with the large moraine in the second half of the 19th century (García-Ruiz et al., 2014). Despite the fact that the MPG would have covered an area of 5.56 km^2 at the end of the LIA (in 1894, (González Trueba et al., 2008), Fig. 4E), there is no record today of ice accumulated during the LIA, except for a few meters at the top of the sequence corresponding to about 1400 CE. This means that more than 600 years of ice accumulation have been lost associated to the warming after ca. 1850 CE. This situation is not so common in the Alps, where ice from the LIA, and even from the last two centuries, is still preserved in many studied glaciers (Eichler et al., 2000; Gabrielli et al., 2016; Gäggeler et al., 1983; Preunkert et al., 2019).

Today the MPG is divided in two small ice bodies that together cover just 0.38 km^2 (López-Moreno et al., 2016, Fig. 4F). Comparing the MPG extent at the end of the LIA (ca. 1850 CE), thanks to the moraine location, and today, more than 5 km^2 of MPG would have disappeared, thus indicating that the last 150 years have likely been the period with the largest glacier melting in the last 2000 years.

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5. Conclusions

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This study presents for the first time the chronology of a glacier in the Pyrenees, reconstructed from a set of ^{14}C dates on different organic remains and supported by measurements on current atmospheric deposition and comparison with a nearby lake sequence (Marboré Lake). The ice sequence from MPG covers the last 2000 years allowing defining cold periods of ice advance and warm periods of retreat. We demonstrate that the glacier was active during the RP, a well known warm period in Iberia Peninsula. During the MCA, the MPG experienced a spectacular retreat marked by the presence of dark debris layers indicative of successive years when ablation processes predominated. The LIA was a period of glacier advance but not recorded today in the ice from MPG since more than 600 years of ice accumulation have been lost associated to the warming after ca. 1850 CE. This evidence from the age-depth model is supported by the lack of anthropogenic indicators usually associated to the Industrial Era abundant today in current atmospheric deposition in a nearby site. Additionally, both Hg concentration and Pb/Al ratio appear much higher in the Marboré Lake sediments whereas they don't reflect the anthropogenic increase in the MPG record.

Comparing the present-day glacier situation with that of previous warm intervals, such as the RP or the MCA, we conclude that the MPG is nowadays greatly reduced in area and volume. Additionally, the recent ice mass loss rate is definitely more rapid than during the four centuries spanned by the MCA, thus suggesting that present day warming in the Pyrenees is faster and more intense than in any previous warm phase occurred during the last 2000 years. Under such climatic conditions, it is reasonable to expect the disappearance of this glacier, as well as other glaciers in the Pyrenees and in Southern Europe, over the next few decades.

6. Data availability

The input data file for CLAM, as well as the output results are stored in this journal for reviewing process and will be permanently deposited in the journal upon the acceptance of this manuscript. The other data are included in the tables and in the Supplementary.

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7. Author contributions

The paper was conceived by A.M., M.B., C.S. and J.I.L.M. and F.N., J.O.G., J.L., P.G.S., C.C., J. L.M., B.O., S.H.F and J.G.R. contributed to design this research project. J.G.O. carried out the ^{210}Pb and ^{137}Cs analyses; J.P., X.Q. and A.A. provided the geochemical data from Ordesa site and MPG; P.C., M.J.S. and R.M. provided the Hg data from Marboré Lake and MPG, C.P., M.L., E.A. helped during field work and G.G.R. run the R package CLAM 2.2 to build the age model. All authors contributed to the writing of the paper.

8. Competing interest

The authors declare that they have no conflict of interest.

9. Acknowledgements

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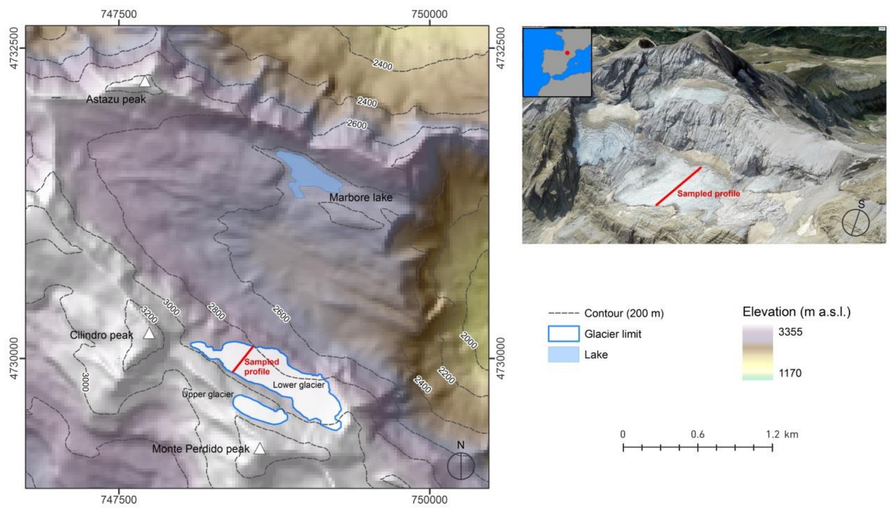

Figure 1. (left) Location of Monte Perdido Glacier (MPG) within a digital elevation map of Marboré Cirque. (right) Picture (©Google Earth) of MPG where the location of the samples is indicated. Note the different orientation of both figures.

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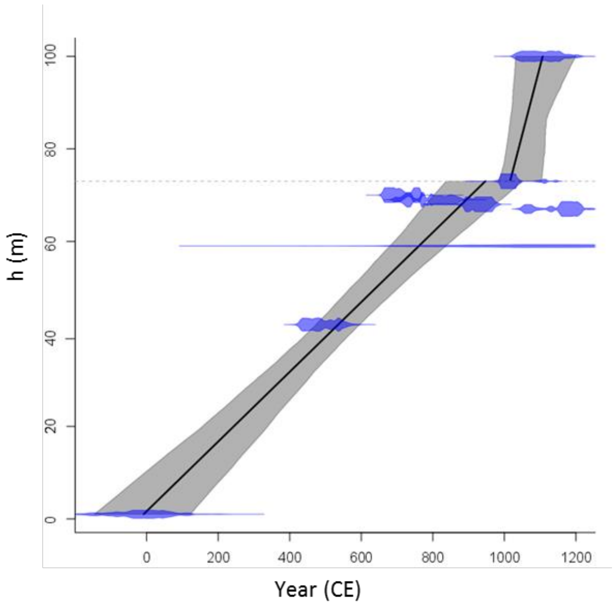

Figure 2. Composite depth-age model for the Monte Perdido ice sequence based on linear interpolation of ^{14}C data (Table 1), obtained using the Clam software (Blaauw, 2010; Blaauw et al., 2019). The dates appear as the calendar-age probability distributions in blue, while the black line is the resulting depth-age model and the gray envelope shows the 95% confidence interval. Note the hiatus located at 73m indicated by a dashed line.

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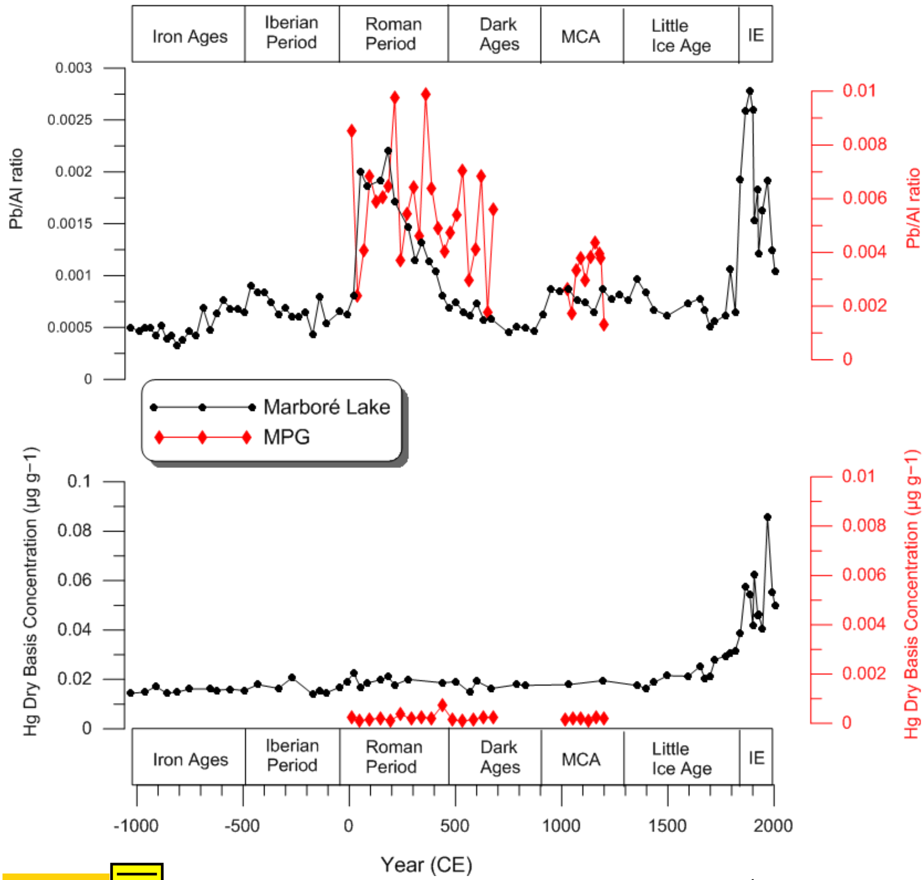

Figure 3. Comparison of Pb/Al ratio and Hg concentration (µg g^{-1} of dry weight sediment) in MPG samples with data obtained from Marboré Lake sediments (Corella et al., 2020). Note the differences in the vertical axis.

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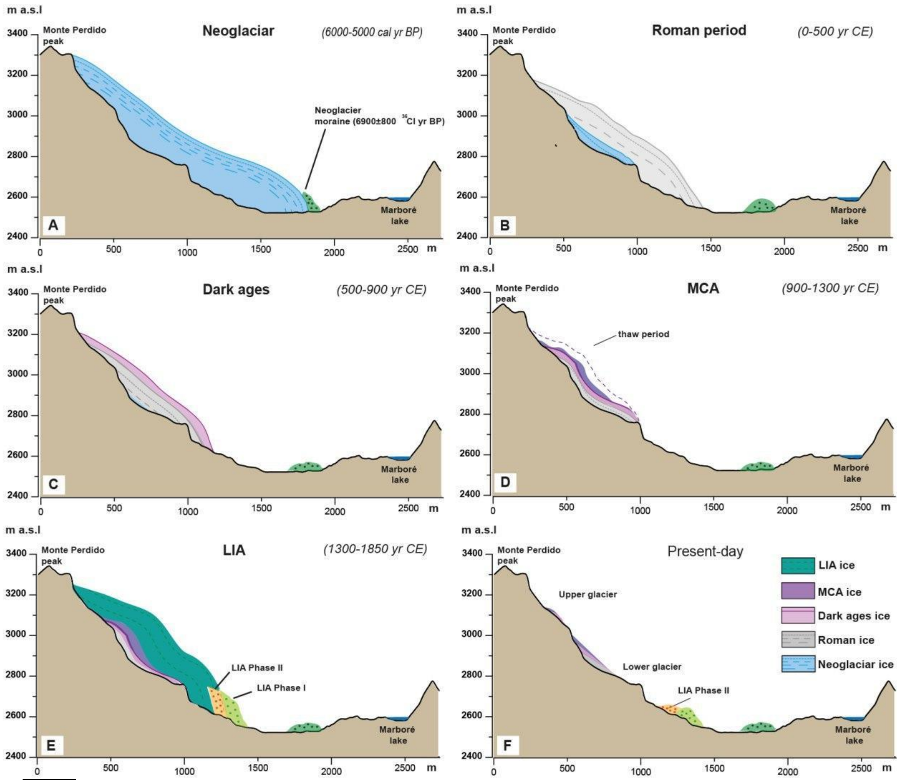

Figure 4. Geomorphic transects (south to north) taken from the Marboré Cirque, showing the schematic reconstruction of MPG during the six main stages discussed in the text. A) Neoglacial Period (ca 5000 – 6000 cal yr BP) where the Neoglacial moraine is indicated (García-Ruiz et al., 2014); (B) Roman Period (0-500 CE) when the glacier is shown considerably retreated; (C) Dark Ages (500-900 CE); (D) Medieval Climate Anomaly (900-1300 CE), a period when the glacier retreated and ablation made condensing debris and organic remains form dark layers in the glacier ice (discontinuous line aims to highlight the importance of melting processes); (E) Little Ice Age (1300-1850 CE), with the MPG reaching the LIA moraines position and (F) present-day situation characterized by the MPG divided into two ice bodies, no ice remaining from the LIA, and very steep slopes.

Table 1. Radiocarbon dating of MPG samples indicating their origin, the radiocarbon age (^{14}C age BP) and the calibrated date using INTCAL13 curve and presented in calendar years Common Era (CE). Samples in red and *italics* were not included in the age model (see text for explanation).

Laboratory ID	Sample depth (m from base)	Sample description	^{14}C age BP	Cal age (CE)
D-AMS 025291	1	Bulk organic matter	2000±64	8±66
MP10m	10	WIOC	812±755	*854±721*
D-AMS 031464	30	pollen concentration	3906±42	*-2384±1332*
D-AMS 025294	42	bulk organic matter	1554±27	462±32
D-AMS 025295	48	bulk organic matter	73±33	*1897±20*
MP59m	59	WIOC	926±268	1046±242
D-AMS 025296	67	bulk organic matter	876±29	1185±31
D-AMS 029894	67	bulk material (filter)	485±40	*1429±15*
D-AMS 026592	68	bulk organic matter	1128±22	942±24
D-AMS 026593	69	bulk organic matter	1230±23	730±14
D-AMS 025297	70	bulk organic matter	1308±28	680±16
D-AMS 031465	70	pollen concentration	1787±37	*237±255*
D-AMS 025298	73	bulk organic matter	1011±25	1012±16
D-AMS 033972	81	bulk material (filter)	1758±25	*287±68*
D-AMS 025299	100	bulk organic matter	923±39	1074±31
D-AMS 031466	100	pollen concentration	1854±30	*158±807*

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Table 2. Elemental concentration (ppm) of major and trace metals in both Ordesa's current deposited dust and MPG ice deposits (averaged values for the 35 analyzed samples); Upper Crust elemental contents (Taylor and McLennan, 1995); and Al-normalised Enrichment Factors (EF) for dust components and elements for: Ef_i, the MPG ice dust versus the current Ordesa's deposited dust (CODD); EF_{iCODD}, the CODD versus the Upper Crust (UC); and EF_{iMPGID}, the MPG ice dust versus the UC.

Ordesa 2016-2017 (2 years atmospheric deposition)				Monte Perdido (ice dust: 35 filter samples)				U. Crust	Enrichment Factors			
ppm	Max	Min	Average	1mg dust	Max	Min	Average		EF_i	EF_{iCODD}	EF_{iMPGID}	
OC	443270	49659	206814	**OC**	436343	14793	126381		0,4			OC
EC	114519	12506	39995	**EC**	112769	14668	40605		0,6			EC
Al	122401	7883	60410	**Al**	506467	19611	98808	80400	1,0	1,0	1,0	Al
Ca	22578	3182	9663	**Ca**	119648	256,7	11984	30000	0,8	0,4	0,3	Ca
Fe	63218	2901	32665	**Fe**	183957	12504	59477	35000	1,1	1,2	1,4	Fe
K	27478	3907	14839	**K**	57038	4001	18505	28000	0,8	0,7	0,5	K
Mg	27286	2105	12265	**Mg**	72210	3513	16645	13300	0,8	1,2	1,0	Mg
Na	5380	1,2	1413	**Na**	25750	593	5126	28900	2,2	0,1	0,1	Na
Ti	5035	257	2334	**Ti**	52192	3243	13662	3000	**3,6**	1,0	**3,7**	Ti
Mn	1656	128	582	**Mn**	3835	174	979	600	1,0	1,3	1,3	Mn
Sr	170	19	78	**Sr**	200	20	80	350	0,6	0,3	0,2	Sr
Be	7	0	2,1	**Be**	2,3	0	0,4	3	0,1	0,9	0,1	Be
V	208	10	76	**V**	257	28	107	60	0,9	1,7	1,5	V
Cr	720	5	118	**Cr**	2915	12	441	35	**2,3**	**4,5**	**10,3**	Cr
Co	32	0	7,6	**Co**	49	5,4	20	10	1,6	1,0	1,6	Co
Ni	414	7	55	**Ni**	1046	4,3	228	20	**2,5**	**3,6**	**9,3**	Ni
Cu	683	33	127	**Cu**	26451	92	3786	25	**18,3**	**6,7**	**123,2**	Cu
Zn	9391	164	1316	**Zn**	3826	171	988	71	0,5	**24,7**	**11,3**	Zn
As	26	2	10	**As**	51	5,3	18	1,5	1,0	**9,1**	**9,6**	As
Se	90	0	22	**Se**	30	0	5,2	50	0,1	0,6	0,1	Se
Cd	100	0	14	**Cd**	1,5	0	0,3	0,98	0,0	**18,8**	0,2	Cd
Sb	26	0	4,5	**Sb**	59	2	11	0,2	1,5	**29,7**	**43,3**	Sb
Ba	1010	15	287	**Ba**	870	67	317	550	0,7	0,7	0,5	Ba
Tl	1	0	0,1	**Tl**	1,1	0	0,2	0,75	1,7	0,1	0,2	Tl
Pb	175	8	53	**Pb**	2989	86	495	17	**5,7**	**4,2**	**23,7**	Pb
Th	37	1	12	**Th**	26	1,6	9,7	10,7	0,5	1,5	0,7	Th
U	8	0	2,5	**U**	15	0	3,7	2,8	0,9	1,2	1,1	U