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Monte Rosa, a book written in the ice.

History and research perspectives at high altitude.

ICE MEMORY

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History and research perspectives at high altitude.

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Preface

When I first approached ice core science I was a young researcher looking for inspiration on what the research topics of my life would be. In the early 1990s I was blown away when I found myself on Colle del Lys, Monte Rosa, to test an ice core barrel that we would later use in Antarctica. It was an overwhelming experience that came at the right time, since I had to find something that characterised me and indicated my future scientific career in my research group.
Until then, the research group had always dealt with the environmental contamination of polar areas, mainly for what concerned the marine environment.Now, a new horizon was opening up for me.
A few years later I participated in my first expedition at Colle Gnifetti, which was already a key site for the few research groups committed to developing this research field. However, innovative aspects had always fascinated me, so we tried to apply new methods of analysis to these truly valuable samples.
A reflection on how we used to analyse our samples before and how much we have refined analytical techniques in recent decades highlights the technological and scientific progress of which we have been an integral part.
The idea of Ice Memory arose from considerations like this. We cannot predict which tools and which methodologies our doctoral students, our students of today, will have in a few decades. Certainly, they will not have the same quantity and quality of ice to be analysed coming from alpine and mountain glaciers, compared to that potentially available a few decades ago.
For this reason, research centers from various countries have decided to join forces today, for the knowledge of tomorrow.
For this reason, Ice Memory is an act of responsibility and trust towards the researchers who will follow us.
Monte Rosa plays a central role in this challenge. We think it is still safe and relatively untouched by melting, but we cannot lose a single extra metre. The next drilling campaign at Colle Gnifetti, which will entrust to the future generation scientists an invaluable ice core, gives us the opportunity to look at the past. In these pages, two researchers who, with respect and dedication, will climb the glacier, offer us a summary of what is relevant to know about our science, the discoveries made, the history that Colle Gnifetti has already told us and the chapters we want to write in the near future.
As always, if we want to understand the scenarios we face, we cannot take our eyes off the past.

Carlo Barbante
Director of the Institute of Polar Sciences of the National Research Council
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Monte Rosa: stories of scientific explorations

Since the last years of the 19th century, Monte Rosa and Capanna Margherita have attracted the attention of scientists. Among the first to conduct scientific experiments in this area was the Piedmontese physiologist Angelo Mosso, who focused his studies on the adaptation of human beings to high altitudes and on the effects of altitude sickness on the human body.
In recent years, Monte Rosa and Capanna Margherita have been the subject of new scientific campaigns including the extraction of ice cores at Colle Gnifetti and cutting-edge experiments on Internet signal transmission using low-cost devices.

Located at 4560 meters above sea level, Capanna Margherita is the highest refuge in Europe and the first high-altitude scientific laboratory ever built. It was built at the request of the CAI of Turin and inaugurated on August 18, 1893 in the presence of Queen Margherita of Savoy. From the start, the Refuge, thanks to its unique position on the international scene, proved to be a privileged scientific observatory for the study of different disciplines including physiology and medicine, environmental sciences and atmospheric physics. It was in this place that the physiologist Angelo Mosso started his first experiments in high mountain physiology. Mosso also used the scientific observatory of Capanna Margherita for meteorological observations and terrestrial physics. However, he focused on the adaptation of human beings to high altitude environments and on the effects of altitude sickness on human health. His studies were published on the volume *La fisiologia dell'uomo sulle Alpi* in 1897. The studies conducted by Mosso contributed to the official recognition of Capanna Margherita by the International Council of Academies which defined it as an *"institution of scientific utility and worthy of support"* in 1913. During his scientific activity, Mosso inaugurated an observatory at Col d'Olen (2900 m above sea level), which can also be visited today. The results of his research revolutionised the world of physiology and, together with the establishment of the observatory, laid the foundations for setting up a laboratory for the selection of aspiring pilots during the First World War under the direction of a successor of Mosso, Amedeo Herlitzka. The Mosso Institute at Col d'Olen was a reference point for meteorological and glaciological observations until a devastating fire destroyed it in 2000. Thanks to an INTERREG project, the

institute was rebuilt and, since 2007, it has housed an important museum focused on the dissemination of the scientific research performed on the Monte Rosa massif and on climate and snow education.
Mosso's legacy was collected by the Mountain Medicine Clinic which, since 2007, has been operating within the Umberto Parini hospital in Aosta. The research activities carried out by the clinic and by other bodies associated with the Italian Society of Mountain Medicine, are focused on the study of the reactions of the human organism in hypoxic conditions. The results allow us to understand and prevent the onset of diseases, such as strokes or heart attacks.
Although studies on physiology and medicine have been prevalent at Capanna Margherita, new lines of research have developed. They were oriented towards environmental sciences and climatology. In this regard, Colle Gnifetti, located a few hundred meters lower than Capanna Margherita, is today the most studied alpine site for the reconstruction of the past climate and environmental conditions through the extraction and consequent analysis of ice cores. The research activities, conducted among others by the Paul Scherrer Institut (Switzerland), the Institute of Polar Sciences of the CNR and the Ca' Foscari University of Venice reconstructed the environmental and climatic conditions of the last 10,000 years. More recently, other investigations have focused on the quantification of persistent organic pollutants (POPs) and radioactive contaminants, which, through long-range transport mechanisms, reached the Monte Rosa glaciers. Still in the glaciological field, the University of Turin is involved together with Imageo Srl, the Italian Glaciological Committee, the Politecnico of Milano and other international scientific partners in monitoring activities to determine the thickness of the glacial cover and to evaluate and identify any issue that can compromise the stability of Capanna Margherita.
From an engineering point of view, the Politecnico of Turin used Capanna Margherita to test the applicability of power generation systems with fuel cells. The Polytechnic itself, through the iXemLabs laboratories, has installed Wi-Fi connection at Capanna Margherita that relies on an innovative long-distance transmission system that uses low-cost devices. The installation, which took place in 2007, has important social repercussions, as it will allow the Internet connection to be extended to remote areas, including some regions of Sudan (Darfur) and Latin America.

Figure 1 - Rifugio Capanna Margherita depicted in a vintage postcard (Credits to: cartolinedairifugi.it)

Reading the ice and the glaciers

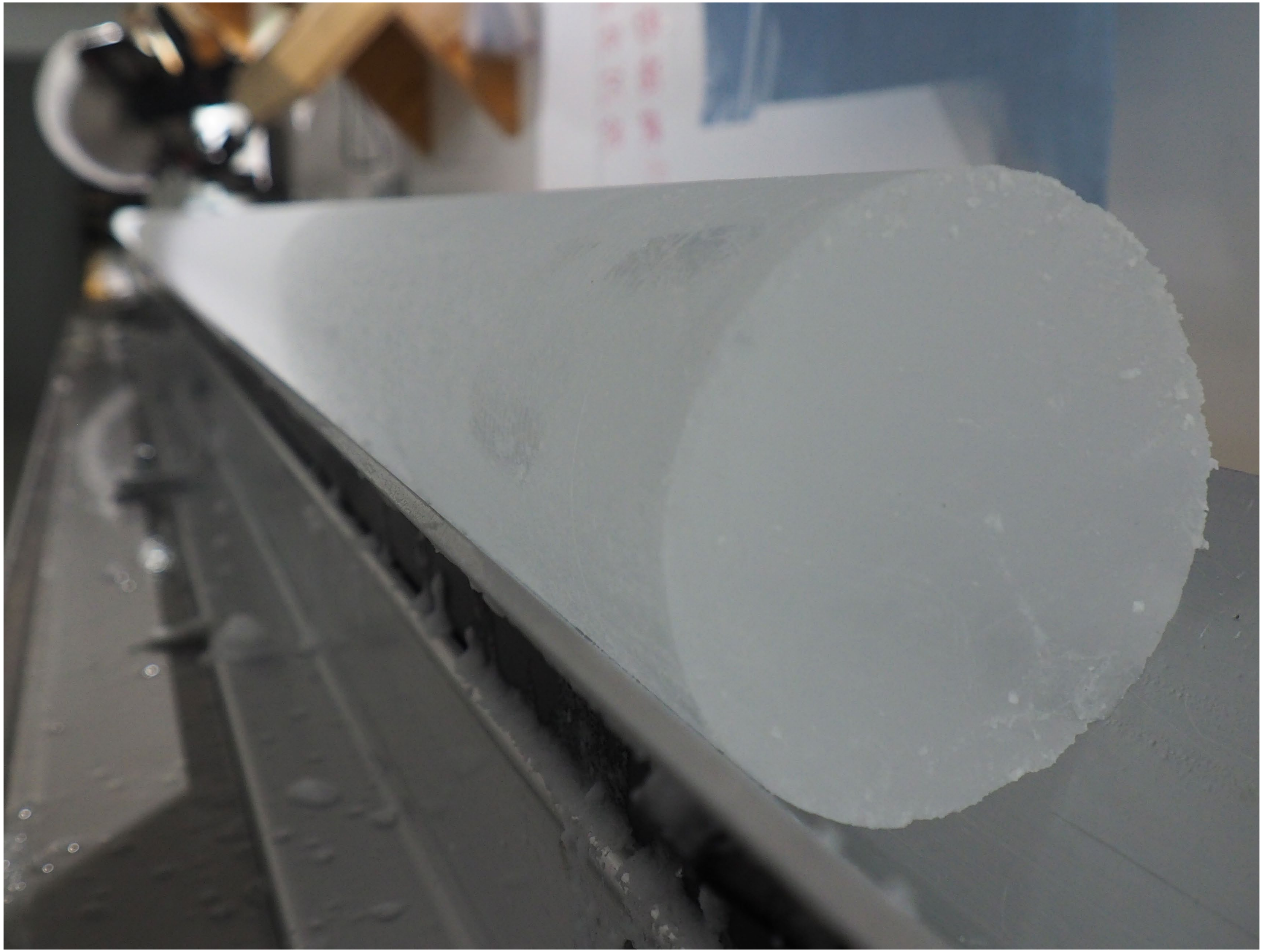
If we think of a glacier as a static body, we are very wrong. Since the first snow falls that contributed to their formation, glacial bodies have been dynamic, lively, constantly moving entities. In addition, they hide valuable chemical information that can tell us about the evolution of climate and the environmental conditions of our planet. The Alps are an ideal place to carry out these studies.

What is a glacier? How is it formed? A glacier is a dynamic system composed of snow, firn, glacier and liquid water, the latter being, unfortunately, increasingly present within the system. The formation of what is called glacier ice is a slow process that is very dependent on the climatic conditions of the individual site.

If we want to follow the life of a glacier from its birth to its maturity until its disappearance, we need to start from the first snowfall that triggered the formation of those ice giants that we can still admire in some areas of the Alps. Imagine being in a rock basin in the high mountains and observing the first snowfall of an incipient autumn. The snow accumulates on the rocky layer and, favoured by the low temperatures, is maintained.

Therefore, it is preserved until the next snowfall, which covers it. Now, imagine observing this continuous accumulation of successive layers of snow until the beginning of the following summer. Over the months, we may see meters of snow accumulating until the hot summer temperatures begin to affect it. Therefore, what has been gained during the winter in terms of snow depth begins to get lost. The snow melts, turns into water and is transferred to the streams further downstream. However, since we are at high altitudes, even the hot summer temperatures are unable to melt the entire snow that accumulated during the previous winter. At the end of September, perhaps earlier, the summer season ends, and with it, the temperatures begin to drop again. The remaining snowdrift is covered by the first snowfalls of the new autumn.

Here we are. This is the first step in the formation of a glacier: the snow that has accumulated during winter and is not lost in the form of liquid water during summer is finally covered by fresh autumn snow. We call this snow ‘firn’. Now, imagine following this process for the next ten years. Then, we could count ten different types of firn, the oldest being an age of ten, and the youngest being only one year old. The oldest, and therefore deepest layer, has had a long time to transform into different forms due to both the weight of the new snow that has covered it over time and to freezing and thawing processes that have alternated between the seasons. These transformations have changed the structure of the snow, which is now glacier ice. The firn is therefore an intermediate stage between snow and ice. Now, let us move even further in time to the next 100 years, and let us analyse the different layers. In the deepest part, we have the oldest ice, which is nothing more than the



result of the slow transformation of the first snowfall that happened 100 years earlier. At intermediate depths, we find the youngest ice, then the oldest firn, which is close to transforming into ice. Going further towards the surface, we find younger firn, up to the fresh snow that fell just a few hours ago.

All of this has happened in a single point of our high-altitude basin. If we extend the entire process to our entire rocky area, we can imagine having infinite columns of snow, firn and ice contiguous to each other, joined to form a single body: the glacier. However, there will be differences among these different columns. Those that are located in the highest part of the glacier (i.e., where it is colder), will keep the snow even during the summer, while those that at lower altitudes (i.e., where it is warmer), will not be able to preserve the winter snow, which will therefore be completely melted during the summer.
Therefore, there is an imbalance between the different areas of a glacier. The high-altitude area is the accumulation zone with a continuous accumulation of layers, while in the ablation zone, located at lower altitudes, a continuous loss occurs.
However, the glacier, as a homogeneous system, compensates for this local imbalance by transferring the excess mass from the accumulation area to the ablation area. If the mass transfer from upstream to downstream is greater than the losses, the entire glacier will expand, thereby increasing its surface and its volume.
Vice versa, if the mass losses in the lower part are greater than the accumulations upstream, the glacier will retreat, decreasing its extension and therefore its volume.
Unfortunately, the latter is the situation of almost all Alpine glaciers and constitutes the decline and death of a glacier.
In other words, all the columns that have accumulated over the years are disappearing.
The study of ice cores is nothing more than the analysis of one of those columns, collected from a precise site on the glacier. The chemical and morphological analyses of the single ice core layers provide scientists with information on the past, on the history of that glacier and on the climate (whether local or regional) that influenced the composition of the snowflake that has turned to ice and has not been lost.

The Gorner Glacier

The Gorner Glacier is the second largest glacier in the Alps. With an area of about 40 km^2, it extends from 2190 m up to 4600 m a.s.l. Given its extension, a volume of approximately 4.9 km^3 was calculated in 2017. Thanks to the particularly high average altitude, the location on the northern slopes and the volumes involved, the Gorner glacier is a less negative example of a reduction in glacial mass. In fact, since the end of the Little Ice Age (PEG), which occurred in the mid-19th century, Alpine glaciers have lost an average of 65% of their area. Compared to the same period, the Gorner recorded a decrease of about 40% of its area, following a retreat of its front of about 3.3 km. The main cause of this is to be attributed to the increase in temperatures. Reconstructions of historical temperature series at 4200 m altitude in a glacial area adjacent to the Gorner from 1860 to present day have shown a 0.7 ° C increase in average summer temperatures from 1900 to 1984 and a some 2.0 ° C increase from 1985 to 2020 compared to the average of the second half of the 19th century.

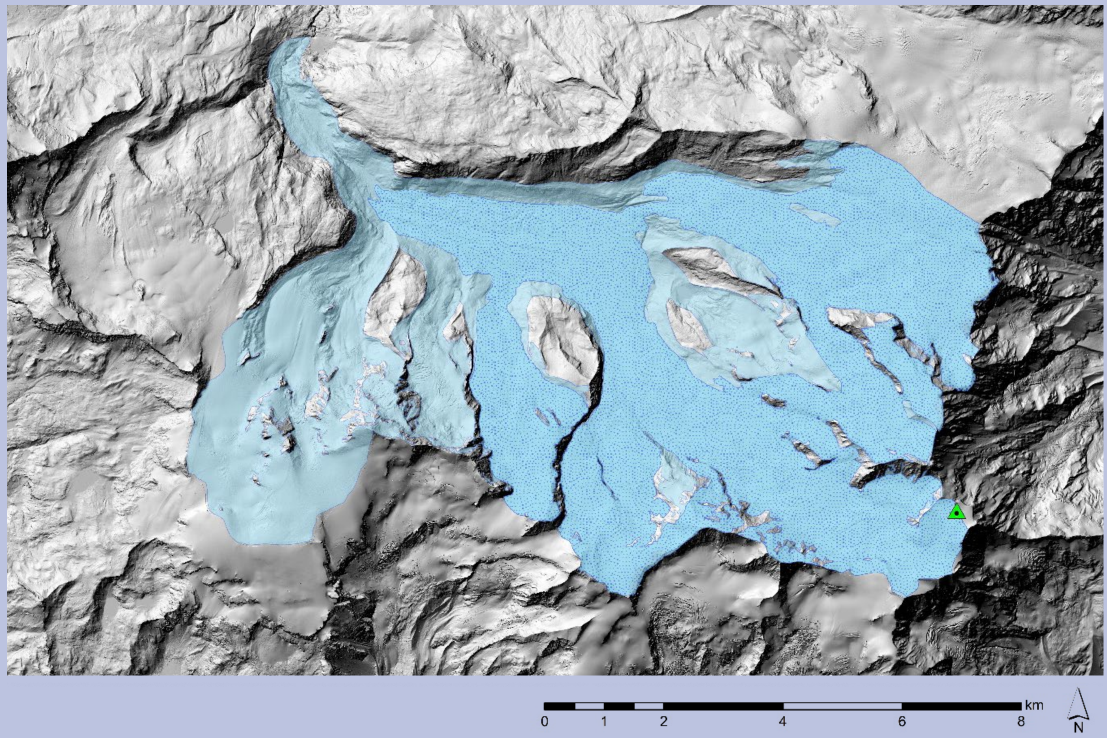
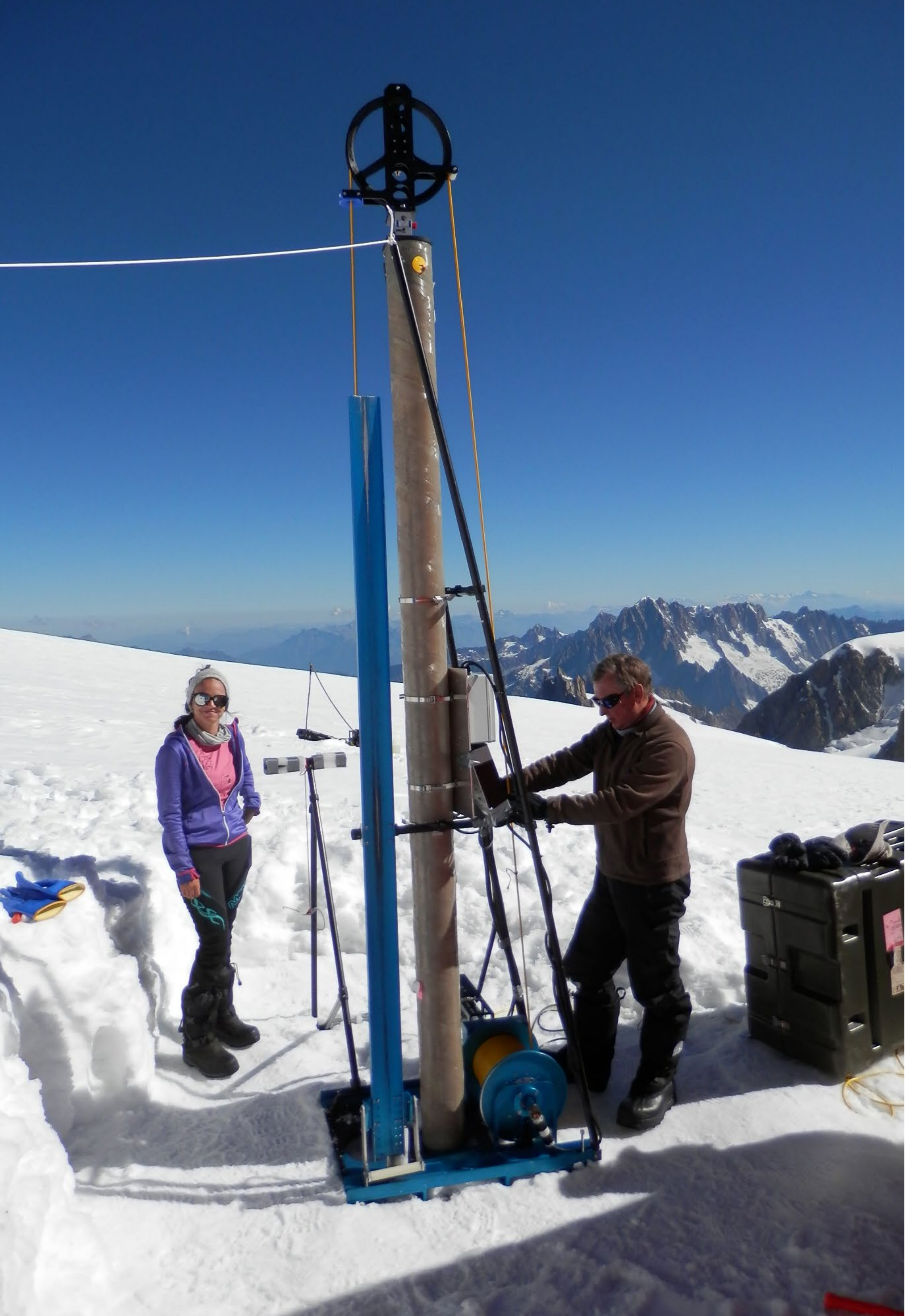


Figure 2: Extensions of the Gorner Glacier: in light blue the boundaries of the glacier in 1850 (65.4 km^2), the extension in 2015 (40.1 km^2) in darker blue. The green triangle represents the Colle Gnifetti, the ice core drilling site at 4500 m a.s.l.(Graphics by F. De Blasi)



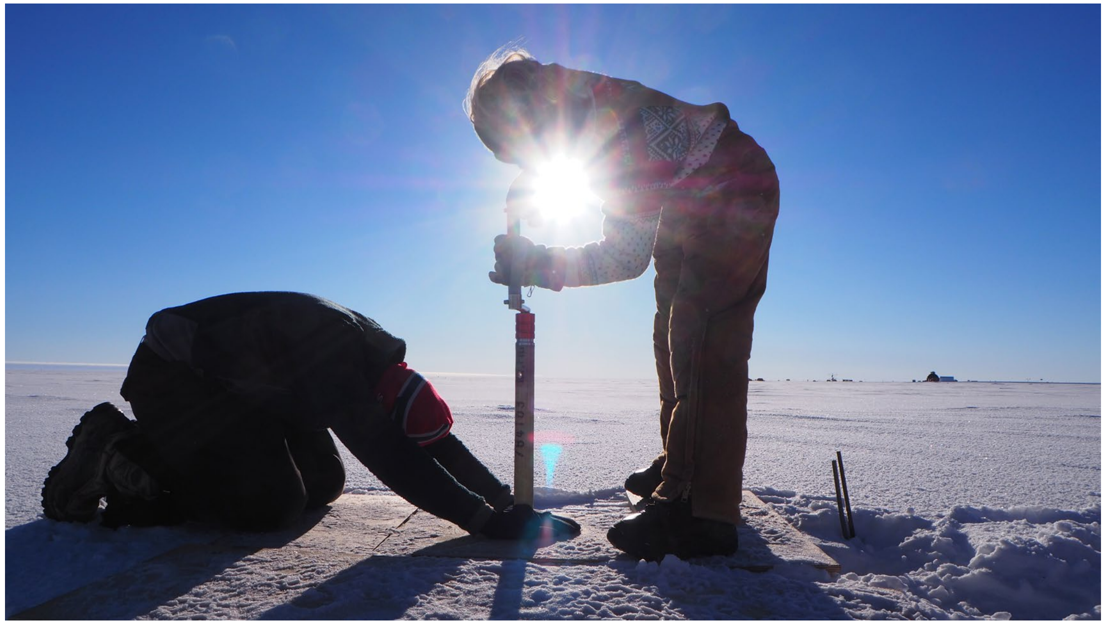
Ice core memories

The first ice cores were drilled during the Cold War in Greenland and in Antarctica. Through their analysis, it was possible to obtain an initial insight into the Earth's past climate. In the years that followed, ice cores were also extracted from glaciers at the lowest latitudes, which, together with the advancement of scientific investigation techniques, enabled us to improve our knowledge of the Earth system.

The Cold War was colder in some areas of the planet than elsewhere. In a remote area of Northern Greenland, about 220 km away from Thule, the US Army installed the first Arctic station ever built under the ice between 1958 and 1959: Camp Century. The official goal of Camp Century was to evaluate different construction techniques on the Greenlandic plateau, as well as carry out scientific investigations into the physical properties of snow and ice and to test the ability to adapt and react in such a hostile environment in case of military attack by the Soviet Union. In an environment where the average annual temperatures were around −24°C, the field was equipped with every comfort. A 1.5 MW nuclear reactor produced the energy needed for everyday activities. 32 buildings were dug underground, and they included offices, a radio station, a garage, shops, a hospital, a fitness centre, a canteen, a cinema, a library, a church and several bars. The structures were connected to each other by galleries that all flowed into a 'main street'.
It was in these environments that, between 1963 and 1966, the first deep ice cylinder in history was extracted. Scientists call these cylindrical portions 'ice cores', and that of Camp Century was 1390 meters deep. Thanks to the intuition of Danish scientist Willi Dansgaard, this long ice core was entirely analysed, thereby giving birth to a new scientific discipline: the chemical analysis of ice cores. While Dansgaard focused his scientific interest on the analysis of stable isotopes to reconstruct the temperature variations of the last 100,000 years, other ice cores collected in different glaciers were studied by scientists for a wide variety of parameters. By way of example, the analysis of the gas content trapped in the ice enabled us to reconstruct the variations in carbon dioxide, methane and other greenhouse gases over hundreds of thousands of years, while the chemical composition of the ice helped in the understanding of other aspects related to the chemistry of the past Earth's atmosphere. The dust concentration in the ice allowed us to discover the frequency and intensity of sandstorms, while the acidity of the ice, together with other elements such as sulphates and iron, gave us an insight into past volcanic eruptions, thereby highlighting their important role in cooling the Earth's climate.
From the first glacio-chemical investigations that took place in the late 1960s and early 1970s, deep core drilling

projects multiplied both in Greenland and Antarctica. Among the most important ones, witness NEEM (in Greenland), which made it possible to reconstruct the climatic past of the northern hemisphere with regard to the last 120,000 years, and EPICA (in Antarctica), which described the evolution of the climate during the last 800.000 years. The EPICA ice core showed that, during the last 800.000 years, the climate has fluctuated eight times between glacial periods (colder and with carbon dioxide concentrations around 280 ppm – the current concentration being above 400 ppm) and interglacial periods (warmer, with carbon dioxide concentrations not exceeding 300-320 ppm) with a 100,000 years cyclicity. Coring projects are currently underway in Greenland (East Grip,) and in the near future, the most impressive core drilling campaign ever carried out in Antarctica will begin: Beyond Epica. It is a project funded by the European Union that aims at reconstructing the Earth's past climate of the last 1.5 million years, a scientific and technological challenge that will keep paleoclimatologists and engineers busy for the next decade. Polar locations, thanks to their low temperatures throughout the year and their high depth (up to 3 km), are ideal for reconstructing the climate of the past on a global or hemispherical level. However, they fail in trying to reconstruct events at lower spatial scales, for example as linked to local sources of pollution. From this point of view, the alpine sites, which are less deep and have a more limited temporal extension (around 10,000 years of history), are particularly suitable and enable the identification of the environmental impact of anthropogenic activities – with a high degree of spatial detail – or the monitoring the temporal variability of crops through the analysis of pollen. These are ice archives complementary to the polar ones and, given their being located at lower latitudes, they are much more at risk of melting, with consequent mixing and loss of the climatic information they hold. They are a scientific, cultural and historical heritage to be safeguarded and protected.

Figure 3: Aerial view of Camp Century (Credits: US Army)



Dirty ice

The elements or molecules that can be analysed in the ice are innumerable, and each of them contains valuable information for understanding the past climatic and environmental system. The Colle Gnifetti site has been extensively studied with regard to some pollutants, thereby resulting in a free, independent, ideal scientific observatory for assessing the anthropogenic impact on the environment.

Less than ten years after the Camp Century coring, glaciers in the lower latitudes also began to attract the interest of the scientific community. The Alps, for example, are a natural 'reservoir' of ice, with more than 5100 glacial bodies for a total area of about 1600 km^2 (2017). However, despite this great abundance, the number of glaciers actually useful for paleoclimate studies is drastically low. In order to be used for such purposes, a glacier must satisfy some basic requirements, including a) good accumulation during the winter period and poor melting, or ablation, during summer; b) a general absence of deformations and therefore mass movements at the drilling site and c) a depth enabling the extraction of a sufficiently old and cold ice.
While the majority of polar locations satisfy all the characteristics listed above, unfortunately the same is not true for alpine glaciers. Many of them are located at altitudes affected by strong melting during summer, which implies a mixing of the climatic information contained in the ice. As a consequence, it is not possible to reconstruct the variation in chemical parameters over the years. Furthermore, many of them are characterised by relatively high movements on all the different areas of the glacier, which prevent the achievement of a well-preserved and defined stratigraphy. Finally, even if all the above criteria were respected, the glaciers may not be deep and cold enough to go sufficiently back in time. The presence of cold ice is closely linked to the altitude and exposure of a glacier; while on the northern slopes it is possible to find cold ice already above 3400 m a.s.l., on those facing south the probability of finding cold ice below 4200 m a.s.l. it is almost non-existent. From the shortlist of more than 5000 candidates, therefore, the ones that can be used for our scientific purposes come down to a few dozen. The Colle Gnifetti, together with the Col du Dome, the Fiescherhorn and a few others, is perhaps the best alpine site to perform paleoclimatic investigations.
It is located at high altitude, the oldest ice is estimated to be around 10.000 years old, there are scarce mass movements, and it is relatively easy to reach thanks to the presence of the nearby Capanna Margherita. For these reasons, more than 10 ice cores have been taken from Colle Gnifetti in the last 30 years, making this site one of the most studied in the Alps.
When it comes to studying an ice core, the first challenge that researchers need to face is that of dating, that is, the association of a depth to a certain period. This is crucial for a correct interpretation of the climate record, as well as for making comparisons with ice cores collected elsewhere. In order to obtain a precise dating, there are different techniques, which are divided into 'relative' and 'absolute'. Relative dating is based on the principle that some ions, such as calcium (Ca^{2+}) or ammonium (NH_4^+), tend to be more concentrated during the spring-summer period. Therefore, by 'counting' the number of times these elements reach their maximum concentration, it is possible to go backwards in time. Valid allies in this relative dating process are stable isotopes, the same ones that Dansgaard analysed from the Camp Century core. An enrichment of heavy isotopes ($\delta^{18}O$ towards less negative values) corresponds to higher temperatures, and therefore summer. Therefore, similarly to calcium and ammonium, the 'Dansgaard isotopes' can be used to manually count the years and date an ice core. However, this methodology can only be used for the most superficial portions of the ice samples.
In fact, as the depth increases, the ice is compressed by the upper layers, with several consequences. The first is that, after a certain depth, it is not possible to count the calcium, ammonium and stable isotope peaks; the second, which linked to the first, is that temporal resolution will decrease. In other words, if a year was compressed in a meter of ice at surface, centuries can be enclosed in the deepest meter of ice. In the case of Colle Gnifetti, on a total depth of 80 meters, in the first 60 meters it is possible to find the climatic information dating back to 300 years ago, while in the last 20 said information can reach up to 10,000 years ago.
Absolute methods aim at identifying well-defined time horizons that serve as checkpoints for relative dating. Among these horizons, we find volcanic eruptions (for example the Laki in 1783), the tritium horizon, which is linked to nuclear experiments in the atmosphere (1963), and the Saharan dust horizons (1977, 1937 and 1901 for example), all recognisable thanks to a precise chemical fingerprint. In recent years, an innovative methodology has been developed at the Paul Scherrer Institut and at the University of Bern for the ice core dating through the analysis of carbon-14. This is an 'absolute' methodology that enables the characterisation of even the deepest layers. Thanks to this technique, we know that the deep ice at Colle Gnifetti is about 10,000 years old.

The Colle Gnifetti ice cores were analysed for different chemical elements and molecules, with the main aim of reconstructing the environmental impact of

human activities.
Sulphates, i.e, SO_4^{2-}, are produced by the oxidation of SO_2, a gaseous pollutant emitted by the combustion of fossil fuels including coal and oil. The analyses conducted on the Colle Gnifetti ice cores have enabled us to reconstruct the evolution of this ion from the pre-industrial period (1760) to present day, highlighting how, since the beginning of the twentieth century, sulphate concentrations have increased until reaching a peak between 1963 and 1981. This is a more than 10-fold increase compared to the pre-industrial period and demonstrates how economic activities and the combustion of coal and oil, predominantly from the regions of Switzerland, France and West Germany, have had a relevant environmental impact also at the high altitudes of Colle Gnifetti. The high degree of detail of the climatic information kept in the ice of Colle Gnifetti also makes it possible to evaluate how the environmental impact has changed between the two World Wars and at the end of the Second. In the years immediately following the First and Second World War, the concentration of sulphate decreased

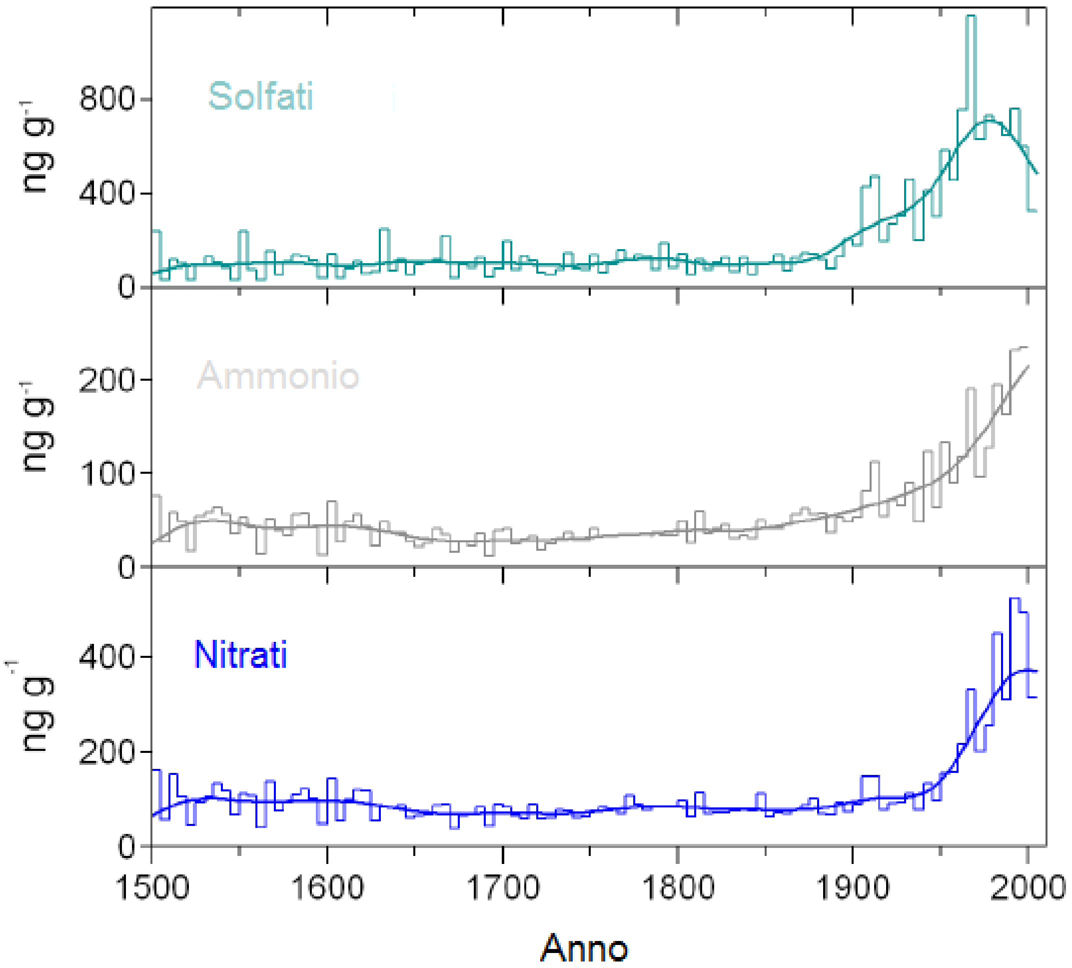


Figure 4: Concentration profile for some pollutants analysed from the Colle Gnifetti ice cores: sulphate, ammonium and nitrate (Graphics by Margit Schwikowksi)

significantly and then grew again from 1955, a behaviour that well represents both the conditions of economic stagnation recorded at the end of both conflicts and the subsequent rapid economic growth that has characterised the European continent since the 1960s. Another indicator that confirms this interpretation is a class of persistent organic pollutants: polycyclic aromatic hydrocarbons (PAHs). PAHs are generated mainly because of combustion processes. Through an analysis of ice core samples from Colle Gnifetti, a sharp drop in the concentration of these contaminants was observed at the end of the First World War due to the economic crisis and the slowdown in production processes. Around the mid-1930s, the economic recovery on the European continent led to an initial doubling of the concentrations of PAHs compared to the previous period, which was followed by a contraction by about 5 times at the end of the Second World War. A rapid increase followed until 1975, tracing the years of the economic *boom*.
The concentration of PAHs is currently increasing again likely because of the increased use of biomass combustion for domestic heating, stressing the urgency of adopting more stringent environmental policies. From this point of view, therefore, alpine glaciers are important independent tools for monitoring environmental quality from which it is possible to not only study and reconstruct the climatic past of our planet, but also to evaluate the effectiveness of environmental policies.
If the Cold War gave us the first ice core in history, it also left an indelible imprint on the ice. Indeed, between the 1950s and 1963, there were more than 500 nuclear tests conducted in the atmosphere by the US and USSR, some of which, such as the explosion of the Tsar thermonuclear bomb, had a devastating environmental impact. One of the main consequences of these tests was the contamination of the sites where the bombs were detonated (e.g., the Semipalatinsk nuclear polygon in today's Kazakhstan or the desert regions of Nevada). The analysis of ice cores taken at a great distance from the test sites (such as at Colle Gnifetti) highlighted the global dimension of these events. As a matter of fact, in the ice it is possible to spot a layer of plutonium and tritium directly connected to the nuclear tests performed in the atmosphere, an indelible trace that should make us think about the global impact of nuclear tests.

Years of lead

Climate and society have always been closely linked: the great civilizations of the past have thrived thanks to favourable climatic conditions, and various economic and social crises occurred during their worsening. For scientists and historians, ice cores are an archive of information of incalculable value.
On the one hand, they enable the reconstruction of the past temperatures and environmental conditions and, on the other, they offer a complementary perspective to traditional historical sources about the evolution of societies over the centuries.

The materials that surround us are made of plastic: witness computer keyboards, pens and clothes. Plastic is ubiquitous, and its invention has revolutionised humanity.
A somewhat 'similar' element, which was used for the most various purposes, was lead. Indeed, in Roman times, the lead that was extracted as a by-product of silver and gold found application in many objects of common use: from water pipes to cinerary urns and from the production of coins to some uses in building where, once melted, it was used in the welding of stone blocks.
What the Romans ignored, although some began to suspect it, was that lead had particularly toxic properties for humans and could cause mental retardation in children or reduce fertility. Similarly to plastic, whose poor biodegradability and precarious culture of reuse have determined a devastating impact on the environment, the massive use of lead by the Romans was perhaps the first example of environmental pollution in human history.
In fact, part of the lead extracted was inevitably dispersed into the atmosphere and transported over great distances.
Recent studies have highlighted that, during periods of greater prosperity and wealth for the Roman Empire, the concentration of lead in the ice of the polar (Greenland) and alpine regions (Colle Gnifetti and Col du Dome) reached maximum values for that epoch, thereby highlighting both the economically prosperous period and the continental dimension of pollution.
The Colle Gnifetti ice preserves the imprint of the mining activities operated during the Roman era very well, since it is located close to several gold mines such as those of Valsesia and Valle Anzasca. In periods of greater production, these mines employed up to 5,000 slaves. The rocks of those areas have a natural quantity of lead about 250 times higher than the average of the Earth's crust, thus it is not surprising that, precisely

in the years of maximum prosperity of the Roman Empire (i.e., when the extraction of gold, and consequently lead, reached their peak), high concentrations of this element were found in the Monte Rosa ice. The strong intertwining of economic prosperity and lead in the ice was particularly strong at the fall of the Roman Empire: the collapse of economic activities led to a reduction in mining activities, and therefore also in emissions of lead into the atmosphere. Subsequently, when the economy restarted, such as during the Renaissance, the concentration of this metal in the ice did the same.
The history of lead in ice cores is fascinating, especially when it manages to be complementary to the historical reconstructions obtained thanks to traditional sources. A significant example is the plague epidemic of the fourteenth century, also known as the Black Plague. During that bubonic plague pandemic, between 30 and 50% of the European population died. The Colle Gnifetti ice cores recorded that event. In fact, in those years, the researchers observed a marked decrease in the concentration of lead in the ice and related it to the almost total interruption of economic activities, and therefore also mining. The link between the pandemic, the economy and the environment should not surprise us, considering the experience we have gained during the pandemic crisis that we are still experiencing. Indeed, while today the strong limitations on surface mobility and air transport have significantly contributed to the temporary reduction of greenhouse gas emissions into the atmosphere, in the fourteenth century, the collapse of European societies, populations and economies due to the plague similarly caused a 70% decrease in the concentration of lead in the ice compared to the previous and immediately following periods.
It should be noted that this drop in lead

concentration, though interesting, needs further studying to be confirmed.
However, that of the Black Death is not just a story of lead and mining. The ice cores, and in particular that of Colle Gnifetti, can tell us much more. These climate archives, besides preserving the chemical information of the past Earth's atmosphere, also contain particles, including pollen. Through their analysis, it is therefore possible to reconstruct the species of plants that grew in a specific region and understand how crops have evolved over the centuries. During the years of the plague pandemic, the European climate was changing. In fact, we were entering what was known as the Little Ice Age, which lasted until the mid-1800s. The reduction in temperatures had already caused severe famines on the continent and hypothetically favoured the ideal conditions for the proliferation of the disease. Pollens preserved in the ice of Colle Gnifetti tell us of this climatic transition. The conditions until 1250 were characterised by the mild temperatures of the Medieval Climate Optimum, a period that favoured the progress of agricultural techniques reflected in the prevalence of grass pollen and some fungal spores originating from manure. Later, the decrease of temperatures and the arrival of the Black Death caused a sharp decrease in pollen concentration, indicating the collapse of agriculture and the onset of famines.
The combination of this information with historical sources gives ice cores not only a scientific, but also a cultural relevance that must be protected and safeguarded from global warming.
Going back to lead and fast-forwarding to the last decades, another increase in its concentration was recorded in the perennial snows of Monte Rosa between the end of the Second World War and 1975. In those years, a lead antiknock additive was used in gasoline. Its name was tetraethyl lead. The use of these *super* gasolines in Europe led to the release into the atmosphere of about 40,000 tons of lead per year between 1960 and 1970. Thanks to the implementation of stricter environmental policies that reduced the lead content in gasoline from 0.4 g / L to 0.15 g / L, emissions also decreased. Then, after the ratification of the 1998 Aarhus Protocol on heavy metals, lead in gasolines was definitively banned. Following these actions and other stringent environmental policies, lead emissions in Italy fell by 94%, going from around 4,000 tons in 1990 to 11 in 2013 (ISPRA). Therefore, we can say that the years of lead are definitely behind us.

A future to be written

Sending an email in the early 2000s was not as simple as it is today. You had to have a computer and unplug the telephone line to be able to connect it to the Internet, a past so obsolete and far from us that we have probably already forgotten it.
The study of ice cores has undergone a similar evolution. If one compares modern investigation techniques with those available less than a quarter of a century ago, they will immediately realise what incredible scientific advances have been made. This scientific progress has enabled us to deepen our knowledge on the Earth system and understand how it can evolve in a context of climate change. Among the most significant innovations, there are those related to the study of organic molecules, impossible until the beginning of the 21st century due to their very low concentration in ice, and the quantification of chemical elements. In fact, while until the mid-1990s few elements could be analysed simultaneously and the analysis of a single sample could require up to four hours of work, today the same sample can be analysed for thirty or more elements simultaneously in just a couple of minutes.
This unstoppable evolution of new investigation methodologies, however, clashes with the precariousness of the ice archives. Indeed, regardless of the climatic scenarios, by the middle of this century, about 60% of the volume of all Alpine glaciers will have disappeared, and with it also the precious and unique climatic information they store. In this context, the Ice Memory project aims at 'saving' this ice heritage and storing it in a natural freezer, namely Antarctica, for the future generations of scientists.
It will be thanks to their intuitions and to technological innovation that, through special international calls, this ice will again be available to the scientific community to make discoveries that today are simply impossible.
To show how scientific research in the chemistry, environmental, paleoclimatic and biological fields is experiencing a particularly prolific period, we report some examples of research in progress at the Ca' Foscari University of Venice, the Institute of Polar Sciences of the CNR (ISP-CNR), and the Paul Scherrer Institut (PSI) whose future developments could benefit from the Ice Memory action.
Chemistry, biology and volcanism are intertwined with artificial intelligence in the IceLearning project, of which Niccolò Maffezzoli, researcher at the Ca 'Foscari University of Venice, is the main investigator. The project, which received funding from the European Union as part of the Marie-Skłodowska Curie fellowships, aims at automatically and simultaneously identifying the particles stored in the ice (atmospheric dust, volcanic ash, pollen, micro-organisms ...) through the use of a microscope and machine learning algorithms. The methodology will not only significantly reduce analysis times, but will allow the study of previously unknown or poorly investigated particles. *"An interesting application could be the identification and study of diatoms,"* explains Niccolò *"tiny algae from lakes and oceans that are transported and deposited on glaciers by the wind. Their taxonomic identification and the study of how the various species have*

evolved over the centuries or millennia could open interesting strands of research". Beatrice Rosso, PhD student in Environmental Sciences at the Ca' Foscari University of Venice, is also interested in particles. Her research, coordinated by Dr. Fabiana Corami of ISP-CNR, focuses on the development of a new methodology for the determination and quantification of microplastics with a diameter of less than 100 μm in ice and snow. *"To date, there is no real standardised procedure for the analysis of microplastics in snow and ice,"* she tells us, a problem that makes the comparison between different sites and analyses very complex. *"I recently obtained funding from the Svalbard Science Forum for the realization of the MICRONESIA project (sMall mICROplastics in sNow and aErosol in Svalbard IslAnds) which aims at identifying the best strategies for sampling and understanding how microplastics are transported in remote environments such as polar ones"*. However, the development of new analytical methodologies requires several years for their validation: *"The time factor is crucial, especially if you think about applying these methods on ice cores"* concludes Beatrice. *"For these reasons, the safeguard action promoted by Ice Memory could be functional to our studies, as it would enable us to have climate archives that are still intact and from which to reconstruct the past atmospheric flows of microplastics, identify their sources and, finally, suggest the adoption of environmental policies aimed at reducing this type of contamination"*.

A rapidly growing disciplinary sector in recent years is that related to the analysis of organic molecules. In fact, there are few studies aimed at their quantification in snow and ice, and all are limited to a restricted selection of molecules. It is from this starting point that the *Organics in Ice* project, funded by the Swiss National Science Foundation, was conceived by Margit Schwikowski, head of the Laboratory of Environmental Chemistry at the Paul Scherrer Institut (PSI). *"I believe that organic molecules are the new frontier of analytical chemistry applied to ice cores"* says François Burgay, post-doc at PSI. *"This is a real and largely unexplored universe that could help us to better reconstruct a number of past climatic conditions, which will significantly contribute to the improvement of current climate models,"* adds Thomas Singer, PhD student in the same research group. The availability of well-preserved climate archives is thus a priority for a better understanding of how the Earth's climate could evolve in the coming decades.

In recent years, another area of scientific research has rapidly evolved, namely microbiology. *"While a routine analysis, such as the genomic sequencing of a micro-organism, required several years of work and a joint effort of several laboratories 20 years ago, today it can be completed in an almost automated way in a few hours"*, says Beatrice Mezzena Lona, PhD student in Polar Sciences at the Ca' Foscari University of Venice. *"The world of microbiology is rapidly expanding, and the interest in the analysis of ice cores is very recent. To date, in fact, there are still no microbiological investigations on alpine cores and only few on polar ice"*. The temporal reconstruction of bacteria, fungi and viruses through the Alpine glacial archives can be fundamental for obtaining climatic and environmental information complementary to those obtainable from traditional chemical proxies: *"the identification of bacterial communities with specific characteristics in the ice core stratigraphy, such as greater resistance to conditions of water scarcity or more intense ultraviolet radiation, could help us better understand the climate of the past and decipher the differences between the current and the pre-industrial periods with a higher degree of detail,"* adds Beatrice. *"However, the precariousness of alpine glaciers can seriously jeopardise all the scientific advances that are being achieved in the field of microbiology: the percolation of liquid water in the ice caused by high temperatures could favour the migration of bacteria into different layers than those in which they were originally deposited, questioning the integrity and reliability of the analyses. For this reason, the timely action of Ice Memory is fundamental: microbiology is a rapidly evolving field, and who knows how much other information is still hidden in the ice which, in a few years, we will finally be able to detect".*

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Biografie

François Burgay (Aosta, 1989) is a postdoctoral research fellow at the Paul Scherrer Institute (Switzerland), where he is developing new methods for the analysis of organic molecules in ice cores. He holds a degree in Environmental Chemistry from the University of Turin and a PhD in Science and Management of Climate Change from Ca' Foscari University of Venice. Burgay has participated in various research expeditions in Greenland, Svalbard and the Alps, where he has contributed to the extraction of several ice cores which enable researchers to "read" the history of the Earth's climate.

Fabrizio de Blasi is a research fellow at the Institute of Polar Sciences (ISP) of the Italian National Research Council (CNR). He holds a degree in Forestry and Environmental Science and a PhD in glaciology/hydrology. His research interests include glaciology, geomorphology and meteorology. In particular, he studies how the glacial and periglacial high-altitude environment evolves as a reaction to climate variability.

Credits

Photos

François Burgay
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