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THE PRESERVATION OF VANISHING GLACIERS ARCHIVES

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EDITOR-IN-CHIEF: Laurent Mayet

REVISED BY: Lesley Jessop (USA).

GRAPHIC DESIGN AND LAYOUT: Stéphane Hergueta, Guillaume Sciaux.

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Ice Memory: a global sanctuary of ice cores in Antarctica

The delivery in January 2026 of ice cores from Alpine glaciers to a devoted sanctuary in Antarctica marks an important step in a unique international programme which is aimed at preserving world vanishing glacier archives.

Glacier melt is one of the most visible indicators of climate change, but glaciers themselves are remarkable archives of the Earth's atmosphere, climate and environmental history. Season after season, snowfall encapsulates atmospheric aerosols, from sub-nanometric to micrometric sizes. As snow compacts into ice, *firn* layers ("perennial snow undergoing densification and metamorphism with depth") trap atmospheric gases in the open porosity, forming tiny air bubbles that serve as fossil capsules of past atmospheric composition. Analysis of these allows us to reconstruct the evolution of greenhouse gas concentrations; the isotopic composition of water molecules which reveals past temperatures and air mass origins. As well, chemical analysis of trace elements in snow and ice layers documents precipitation history, volcanic eruptions, desert dust storms, biomass burning, and the evolution of anthropogenic pollutants like heavy metals, acids, radioactivity, persistent organic pollutants and much more.

Figure 1 – Excavation work for the construction of the Ice Memory storage cave. A snow trench was dug to a 10 meter depth with a snow blower. *Credit: Rocco Ascione, ENEA-UTA, Italy.*

> ***'With Ice Memory, we connect all latitudes and generations via science and diplomacy, establishing Antarctica as a unique universal repository'***

Over millennia, glacial strata preserve a detailed memory of the atmosphere, biogeochemical cycles and climate, capturing regional features thanks to the global distribution of glaciers. Although ice-core science is relatively young, having emerged in the late 1950s, it has fundamentally transformed our understanding of the climate system. Analyses of ice cores from Greenland and Antarctica demonstrated the unprecedented rise in greenhouse gases since the Industrial Revolution and quantified the CO_2 -temperature interplay over glacial-interglacial cycles, forming one of the scientific foundations for the Intergovernmental Panel on Climate Change reports.

However, the glaciers preserving this memory are disappearing. Mountain glaciers and small polar ice caps are retreating rapidly due to anthropogenic warming. Meltwater percolation through the snowpack has already altered original signals in deeper layers. Some glacier archives are irreversibly degraded. The Kilimanjaro glacier in Tanzania, for example, is losing mass through *sublimation* ("the transition of a substance directly from the solid to the gas state"). Scientists face a race against time to save this unique scientific treasury. It was in this urgent context, the creators of the Ice Memory initiative had to build a global library of ice cores from endangered glaciers, safeguarding them for future generations and future scientific discoveries. Future technologies and ideas will likely to expand the scientific potential of ice cores. Microbiological content (bacteria, virus, spores) is currently difficult to study due to technological barriers and future analyses could unlock new antibiotics and aid global healthcare (bioprospection).

The Ice Memory initiative was not born from a conference but rather from a warning issued by the scientific community. In February 2010, the Working Group on Snow and Ice of the Intergovernmental Hydrological Programme for Latin America and the Caribbean (IHP-LAC) met in Valdivia, Chile. A resolution was adopted there highlighting the urgent need for extracting ice cores from vanishing Andean glaciers.

In October 2013, at an Andean glaciology workshop in Porto Alegre, Brazil, I proposed to South American colleagues a project to store and preserve such safeguarded ice samples in Antarctica. The principle was simple: no commercial freezer can guarantee safe storage for decades or centuries[1]. On the other hand, the East Antarctic plateau offers naturally cold temperatures year-round, without energy input, ensuring preservation for centuries despite global warming. Moreover, the Antarctic Treaty System provides a unique legal

[1] Usually, ice cores drilled in mountain glaciers and ice caps are stored in commercial freezers located in the vicinity of ice core research laboratories. In Grenoble for instance, ice cores are stored in facilities handled by the private company *Stef Logistique*, pending analysis in the laboratories of the *Institut des Géosciences de l'Environnement* (IGE).

framework where territorial claims are frozen and decisions are taken by consensus among 58 State Parties, a unique framework for discussing and establishing best practices for the preservation of this world heritage of scientific raw material.

The project was further strengthened thanks to the involvement of my colleague, Prof. Carlo Barbante from Università Ca'Foscari Venezia, Italy, who had been considering a similar project for Alpine glaciers in 2012. Dr. Patrick Ginot, from the Institut de recherche pour le développement, IRD, who co-signed the 2010 Valdivia resolution, joined this small group. The next step was to find financial and political support. Research funding is typically a short-term commitment, while Ice Memory Programme is clearly a centennial legacy investment. In addition, the initiative can target specific glaciers where short-term scientific objectives are not a priority.

Figure 2 – Building the snow arch of Ice Memory storage cave. A 35-m long balloon is inserted in the snow trench, inflated, and snow is blown back on top of it. After deflating the balloon, the cave has a snow roof modifying slowly over time, without need of any construction material and providing optimal storage conditions at a constant -52°C temperature. *Source: Rocco Ascione, ENEA-UTA, Italy.*

A pivotal meeting occurred in Grenoble, France, in November 2014, when Prince Albert II of Monaco paid a visit to the Laboratoire de glaciologie et géophysique de l'environnement (LGGE now known as IGE) where I was conducting my research. A storm grounded his flight back to Nice, extending a brief encounter into a long discussion on the fragility of the cryosphere followed by my presentation to the Prince of the Ice Memory project. Anne-Catherine Ohlmann, Director of the newly born Université Grenoble-Alpes Foundation, became aware of our conversation and offered to help Patrick Ginot and I to make this dream a reality. In spring 2015, Barbante, Ginot, Ohlmann and I turned this concept into a structured programme and submitted the plan to the

Prince Albert II Foundation, which, alongside other donors[2], mobilized the private resources needed to launch the initiative.

With initial funding and in-kind support from French and Italian institutions (Université Grenoble-Alpes, Centre national de la recherche scientifique, Institut de recherche pour le développement, Ca'Foscari University of Venice and Consiglio Nazionale delle Ricerche), we managed to conduct the first field demonstration on Mont Blanc' slopes in the French Alps. In August 2016, on an expedition led by Patrick Ginot, three ice cores were drilled to bedrock at 128 m depth on the Col du Dôme glacier (4,300 m of altitude), one of them was meant to go to the ice core sanctuary in Antarctica.

Figure 3 - Ice Memory operations conducted between 2016 and 2026. White frames: drilling operations, achieved or unachieved. Blue frame: transfer of the first heritage ice cores to Antarctica. *Copyright: Ice Memory Foundation.*

Following the 2016 success, a more ambitious drilling occurred in Spring 2017 on the Nevado Illimani glacier, Bolivia at an altitude of 6,300 m. Patrick Ginot again coordinated the operation in collaboration with the University of La Paz, retrieving two ice cores down to bedrock (a depth of ~135 m), where ice dates back to the last glacial maximum 18,000 years ago. In 2017, UNESCO joined as a strong advocate of the initiative. An international

[2] At the time of writing these are: Findus, Claude Lorius (the founder of ice core science in France), Didier et Martine Primat Foundation, Thermo-Fisher Scientific, Air Liquide Foundation, Tupack Group, BNP Paribas, Petzl Foundation, Richard Lounsbery Foundation, Elcom, Alizentt, Decathlon, GMM, Pressario, Lexinnov Avocat, Aku, Karpos, Polibox.

workshop at its headquarters in Paris in March gathered scientists from twelve countries. The UNESCO executive board issued two declarations urging U.N. Member States to support the initiative. Switzerland also joined the management group of four members via Prof. Margit Schwikowski from the Paul-Scherrer Institute (PSI). As a legal entity became necessary for international representation and coordinated decision-making processes, the five founding members established the Ice Memory Foundation (IMF) in 2021, Prince Albert II of Monaco acting as Honorary President. Its seven founding members (Université Grenoble-Alpes, CNRS, IRD, Università Ca'Foscari Venezia, CNR, PSI and the French polar institute IPEV) adopted several key principles:

- Select glaciers of major scientific value;
- Prioritize sites under immediate threat;
- Recover parallel cores where possible;
- Preserve at least one untouched "heritage" core;
- Create open-access scientific databases;
- Ensure long-term international governance.

This framework revealed a core difficulty: balancing support for current science while preserving samples for future generations.

From 2018 to 2025, drilling campaigns expanded to glaciers in the Alps, Caucasus and Altai (Russia), Svalbard and Tajikistan, through the involvement of IMF founding scientists and contributions from other ice core scientists who wanted to contribute with their main research expedition. To date, 11 Ice Memory drilling operations have been organized globally, delivering 9 heritage ice cores (Fig. 3). Ice Memory is halfway to its original target of 20 glaciers drilled in 20 years. Storing endangered glacier archives in Antarctica for centuries to come is a unique dimension of the initiative. Depositing non-Antarctic ice triggered complex legal procedures. The introduction of alien species is ruled by the 1991 Protocol on Environmental Protection to the Antarctic Treaty signed in Madrid. This Protocol prohibits importing alien organisms[3], including bacteria, viruses and spores trapped in glacier ice. Convincing the Parties to the Antarctic Treaty System is not always an easy task. As then Director of the French polar Institute Paul-Émile Victor (IPEV) and member of the French delegation to the 2018 Antarctic Treaty Consultative

[3] Under the terms of the Protocol on Environmental Protection to the Antarctic Treaty, Annex II, Art. 4 (introduction of non-native species and diseases), § 1: "No species of living organisms not native to the Antarctic Treaty area shall be introduced onto land or ice shelves, or into water, in the Antarctic Treaty area except in accordance with a permit." According to art. 4.1, "Non-native species or diseases" include "micro-organisms (e.g., viruses, bacteria, yeasts, fungi) not present naturally in the Antarctic Treaty area." (Editor's note)

Meeting (ATCM) in Buenos Aires, I made a brief presentation of the IM project to the other delegations. This brief presentation led to the creation of a multiyear discussion process. Through following ATCM annual meetings in Prague, Paris, Berlin, and Helsinki, detailed "Information Papers" were submitted to the Consultative Parties with the support of the French and Italian delegations, addressing biosecurity concerns. In 2019, at the ATCM XLII, France and Italy announced they would complete an Environmental Impact Assessment to investigate the impacts of creating a repository at Concordia research station (ATCMXLII, WP41). As mentioned in an Information Paper presented in 2023, at ATCM XLV, "the risk of introduction or redistribution of microorganisms being trapped in ice cores clearly concerns: partial or total melting of ice cores samples, followed by dispersal of the meltwater in the surrounding environment; occurrence of the melting accident during logistic transfer at the Antarctic coast, where endemic animals are located"; "Appropriate procedures will be developed to handle the risks at its origin" (ATCMXLV, IP74). Finally, in March 2024, an Initial Environmental Evaluation signed by the Programma Nazionale di Ricerche in Antartide (PNRA) environmental officer was uploaded to the Antarctic Treaty EIA Database, concluding that the IM programme is estimated to have "a minor or transitory impact" and therefore "may proceed[4].

We selected the high Antarctic plateau, specifically Concordia Station (jointly operated by IPEV for France and the PNRA for Italy). Unlike the South Pole, which suffers from high snow accumulation - risking rapid burial of the Ice Memory vault- Concordia offers a stable, naturally cold environment (–52°C year-round), with minimal snow accumulation (3 cm of water equivalent per year). Inspired by our Danish colleagues who pioneered the methodology in Greenland and supported by Julien Brondex, a postdoctoral researcher in snow mechanics, we designed a snow cave built at 10-meter of depth using an inflatable balloon (Figures 1 and 2). This structure would last several decades before roof deformation would require a two-week rebuilding operation. Executing our vision was an expeditionary marathon. Following high-altitude drilling, ice was transported by helicopter or on the back of porters and mountain guides to the valley, then by freezer trucks from the base camp to commercial freezers or to a maritime reefer container, then

[4] As the Ice Memory Initiative was evaluated by the PNRA as an "activity likely to have no more than a minor or transitory impact, the activity may proceed, provided that appropriate procedures, which may include monitoring, are put in place to assess and verify the impact of the activity" (Madrid Protocol, Annex I, Article 2.2). The Ice Memory initiative presented by the French and Italian delegations never was an ATCM/CEP initiative even though, several national delegations expressed their strong support during the successive ATCM discussions.

traveling the world on a container ship, until the intermediate storage place close to laboratories in Grenoble, Venice and Villigen. In 2025, we seized a unique opportunity: the Italian icebreaker Laura Bassi was in Trieste. We loaded two ice cores (2 tons of ice) from the Swiss and French Alps. The ship carried the cargo across three oceans for weeks without a cold chain break, finally reaching the Italian Antarctic coastal station Mario Zucchelli. From there, a Basler BT-67 ski-equipped plane flew the cores to Concordia[5]. The sanctuary was inaugurated on 14th January 2026, marking the transition from concept to reality. After a decade of fieldwork, legal exploration, and logistical ingenuity, the first ice cores from the Alps were deposited in a 35-m long snow cave at a depth of 10 m.

One might question whether the transportation and storage in Antarctica entail an excessive carbon footprint. The IMF has evaluated this critical aspect. The primary factor limiting the footprint lies in leveraging the existing logistics of the two polar operators. Ice Memory piggybacks on maritime and air transport that would occur regardless of its association. The ice cores represent only a minor fraction of the total cargo delivered to Antarctica by IPEV and PNRA. Our estimates indicate that transporting 20 heritage ice cores from Europe to Concordia would generate ~100 tons of CO_2, equivalent to the average annual carbon footprint of 15 French citizens. In comparison, operating a commercial industrial freezer for 10 years produces a comparable carbon footprint. Consequently, after a decade of storage in Antarctica, the Ice Memory operation demonstrates a lower carbon impact than alternative storage in commercial freezers.

In mid-2026, the roadmap is clear: complete the collection of heritage ice cores, reinforce governance, and secure funding. The primary challenge is completing drilling on the remaining ten glaciers to achieve global coverage, particularly in underrepresented regions like the Himalayas and Tibetan Plateau, Central Asia, Pacific Ranges along the west North American coast, and parts of the Andes. Each year of delay increases the risk that targeted glaciers will deteriorate beyond the point of yielding a high-quality and chronologically coherent heritage ice core. This requires highly skilled technical and scientific teams, but also funders willing to invest in a global heritage whose returns may

[5] Given that two itineraries are considered in the Initial Environmental Evaluation (French Icebreaker L'Astrolabe-Dumont d'Urville Station-Robert Guillard Station-traverse route to Concordia or Italian Icebreaker Laura Bassi -Mario Zuchelli Station-airborne transfer to Concordia Station), in case of the involvement of French polar logistics and infrastructures in Ice Memory activity, the French part may guarantee, for each transit through French logistical assets, that its activity within the Ice Memory programme comply with environmental regulations, as confirmed by the relevant French national authorities. (Editor's note)

only emerge in a century from now. An unusual prospect in a culture of competitive scientific funding.

A second major challenge lies in governance. How can we ensure binding international agreements, ensuring the long-term preservation of these scientific archives, protecting them against geopolitical tensions? In 2023, the IMF began funding a specific Law and Governance Chair at Université Grenoble-Alpes, led by Prof. Sabine Lavorel, to explore these unprecedented legal questions. For example, who will decide which future scientists have access the heritage cores, under what conditions, and according to which criteria of scientific merit or national equity? The IMF expects to transfer stewardship to an international organization within the next ten years. UNESCO, the World Meteorological Organization (WMO) and the Antarctic Treaty System provide reference frameworks for a potential Ice Memory Treaty. The latter could be signed by State Parties having contributed their frozen heritage, or conducted the safeguarding operations, or the handling of safe storage of this world heritage, or those willing to contribute to the new science based on the stored ice. The United Nations Decade of Actions for Cryospheric Sciences (2025-2034), launched at the Third U.N. Ocean Conference in Nice, June 2025, offers an optimal context for political negotiations and formalization of agreements.

In relation to governance, another challenge concerns the storage capacity in Antarctica. While Concordia can receive many heritage ice cores, a single site could become a limiting factor geopolitically. Parallel storage facilities could be created at other suitable research stations on the East Antarctic plateau, such as Kunlun Station (China), Vostok Station (Russia) or Dome Fuji Station (Japan). Since March 2025, Prof. Thomas Stocker, former IPCC Working Group I Co-Chair, succeeded me as IMF Chair. His experience in science diplomacy, is a major asset to address these challenges. With Ice Memory, we connect all latitudes and generations via science and diplomacy, establishing Antarctica as a unique universal repository.

Jérôme CHAPPELLAZ[6] for POLAR WATCH[7]

[6] Full Professor at École Polytechnique Fédérale de Lausanne, Switzerland; Director of Research at CNRS, France. Co-founder of the Ice Memory initiative and former Chair of the Ice Memory Foundation (2021-2025).

[7] The opinions expressed in this article are those of the author.

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