Exploring the Vanoise Karst: Marble Caves Beneath Active Glaciers

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Abstract

The Vanoise Massif (French Alps) presents a unique setting to investigate interactions between glacial dynamics and karstic processes. Recent speleological surveys (2022–2024) focused on high-altitude carbonate formations in the Col de la Vanoise syncline, where Jurassic and Cretaceous marbles exhibit complex karstification driven by ~1,000 m of glacial retreat since the early 20th century. The exploration and mapping of 2.6 km of galleries across 18 caves, with depths reaching 135 m, revealed subglacial losses, moulins, and fossil conduits, enabling the tracing of groundwater pathways to lower-altitude emergences. Hydrogeological analyses confirmed links between glacial meltwater infiltration and karstic outflows, while speleothem records provided insights into paleoclimate variability in glacial environments. A major discovery, Arcelin Cave, extends >2 km and hosts an active subglacial river, representing a pioneering example of such systems in the Western Alps and globally. These findings highlight the significance of glacially influenced karst networks and their role in high-mountain hydrology under accelerating climate change.

1. Introduction

The Vanoise massif, located in Savoie in the French Alps, is a remarkable natural area for its geological diversity, complex topography and karstic systems. Reaching a peak of 3,855 m at the Grande Casse, the massif is home to peaks exceeding 3,000 m, numerous glaciers and a wide variety of geological formations. Geographically, the Vanoise serves as a crucial transitional zone between the Briançonnaise coal zone and the lustrous shale (ELLENBERGER, 1958). The area surveyed generally consists of massive Jurassic (Malm) marbles and chlorite marbles from the Upper Cretaceous to the Paleocene. These marbles are mostly underlain by Triassic quartzites (lower impermeable level); the thickness of the marbles is variable and sometimes unknown.

The speleological history of the Vanoise is characterised by a succession of contributions since the 1970s. Since the inaugural explorations by the Spéléo Club de Pommard in 1976, and the subsequent detailed investigations conducted by the SGCAF and the Forez speleologists in the 1980s (DUCLUZAUX, 1993), there has been a gradual increase in the discoveries of karstic sinkholes and losses. Of particular note is the documentation of the areas surrounding the Col de la Vanoise refuge and the Arcelin plateau, which has revealed intricate underground water flows and conduits that are often challenging to penetrate due to glacial deposits (HOBLEA, 1997). From 2022 to 2024, a new speleological exploration campaign was conducted in the syncline of the Col de la Vanoise, located south of Pralognan-la-Vanoise, at an altitude ranging from 2,600 to 3,000 meters. The marble layers, though altered and karstified, are partially covered by recent glacial deposits. The sub-glacial losses, bedières and moulins observed in this area are indicative of karstic activity influenced by the glacial retreat of almost 1,000 m since the beginning of the XXe century, exposing ancient fossil conduits and beheaded caves. Tracing carried out from the losses near the Col de la Vanoise refuge has confirmed the hydraulic connection between the sub-glacial losses and the emergences located between 1,500 and 1,800 m, near the place known as 'Les Fontanettes' (RAMPNOUX and NICOUD, 1979; DUCLUZAUX, 1993).

This recent work, including tracing in 2024, has enhanced our comprehension of the groundwater dynamics in this karstic system. Continuous glacial melt, in conjunction with periods of warming, exerts a pivotal influence on the evolution of the caves and the formation of speleothems, the dating of which offers valuable insights into the reconstruction of Alpine paleoclimates. The objective of this publication is to present the results of the explorations carried out between 2022 and 2024, while building on previous work. The study of karst systems in the Vanoise massif, through the analysis of losses, sinkholes and underground circulation, offers new perspectives on the interactions between karst and glacial dynamics in a context of climate change.

2. Context

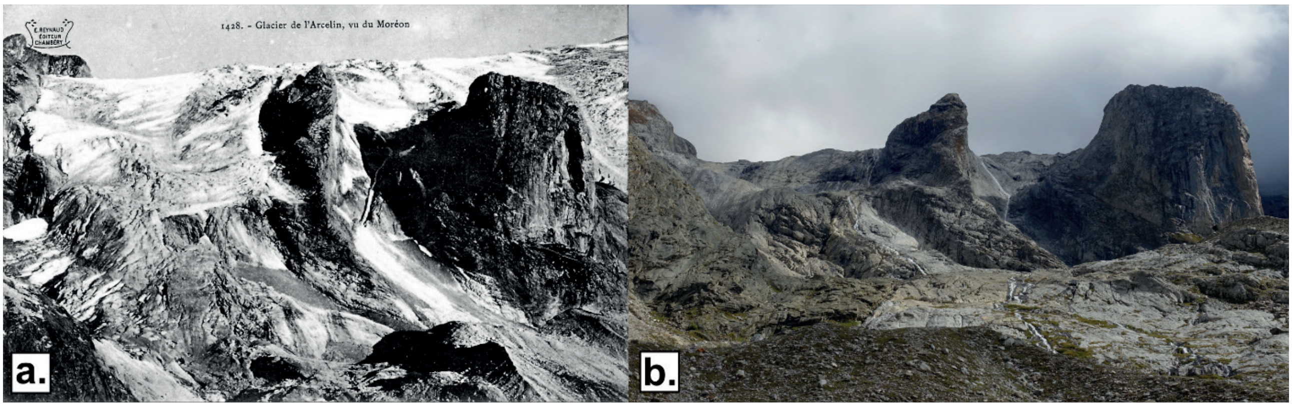

Figure 1: *a. The Arcelin glacier at the beginning of the 20th century. b. Contemporary photograph showing the same view of the slabs at the front of Arcelin Glacier. Both pictures are from Bernard Vion.*

Since 2022, a series of speleological expeditions have been undertaken in the Vanoise massif with the objective of enhancing our comprehension of high mountain karsts, with a particular emphasis on the repercussions of recent glacial changes. This endeavour has been informed by systematic surveys, exploration of new caves, and an integrated scientific approach encompassing hydrogeological studies and speleothem analyses. The rapid retreat of glaciers, as illustrated by the evolution of the Arcelin Glacier over the past century (Fig. 1), underscores the urgency of these investigations.

Glacial retreat and link with karstic environment

The interaction between karst landscapes and the cryosphere—Earth's ice-covered regions, such as glaciers and snowfields—is crucial for understanding environmental dynamics in high mountain regions. In high-altitude karst areas, the cryosphere directly affects underground hydrology, cavity formation, and landscape evolution. Glaciers and perennial snowfields act as water reservoirs, releasing meltwater that infiltrates karst systems through sinkholes and shafts, altering underground hydrological flows in a seasonal and sometimes unpredictable manner. The freeze-thaw cycle also causes cryoclasty, widening limestone fissures and promoting the development of lapiaz and dolines. Subglacial and periglacial cavities are influenced by glacier fluctuations, which can lead to the widening of galleries or the temporary clogging of conduits by sediment or ice.

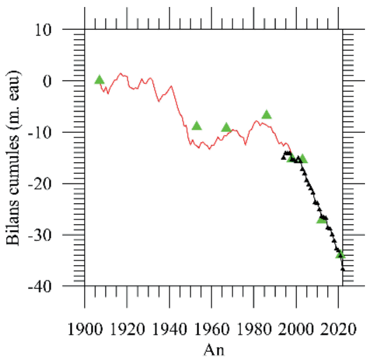

Figure 2: *Reconstructed mass balance of the Gebroulaz Glacier (1905–2022). Data and figure: GLACIOCLIM.*

Studying karst-cryosphere interactions is essential for understanding geomorphological processes in high mountains and the impacts of climate change on glacier stability, water resources, and karst network evolution.

The Vanoise mountain range, particularly the Gebroulaz Glacier (as an example), has been studied for years, with monitoring beginning in 1995 (Fig. 2). The mass balance of the Vanoise glaciers, like those across the Alps, shows a significant deficit. Given the projected disappearance of glaciers by 2050 (VINCENT et al., 2019), it is essential to understand their current hydrogeological functioning to anticipate potential regime shifts in the coming decades.

Origin of the project

The project was launched at the initiative of mountaineers, speleologists, local guides, and rangers from the Vanoise National Park (PNV) in 2021. A review of existing work, notably the synopsis by HOBLEA (1997), was undertaken, leading to the identification of key karstic regions of interest through a series of field observations.

These areas, which are primarily situated in the vicinity of the Col de la Vanoise, are characterised by the presence of sinkholes, losses and moulins, which have been exposed due to the retreat of the glaciers (Fig. 1).

Preliminary surveys, encompassing a visit to the Grand Marchet resurgence and the cave on the Arcelin glacier front, signified the project's inaugural stages. These investigations culminated in the establishment of an inaugural caving camp in 2022.

Constraints and terrain conditions

The Vanoise massif imposes significant climatic and logistical constraints, which must be considered when planning fieldwork in this area. In winter, the caves and moulins are often blocked by snow, making access perilous, and in spring and early summer the melting snow can disrupt explorations by saturating the caves.

Consequently, late summer and autumn are the optimum periods for prospecting, with more stable conditions and minimal snow cover.

Access to the exploration areas is possible via a three-hour walk and a 1,000-metre ascent from the Fontanettes car park in Pralognan-la-Vanoise. The proximity of the Col de la Vanoise refuge facilitates extended stays, thereby maximising the effectiveness of fieldwork.

2023: Further exploration

The encouraging results obtained in 2022 led to an extension of activities for the following year, with the primary objective being to continue prospecting the moulins and subglacial cavities, while deepening exploration of the identified sinkholes. Closer collaboration with the Vanoise National Park enabled the validation of the scientific approach and the sampling authorisation for calcite samples. These samples were collected as part of Alexandre Honiat's PhD thesis, which focused on the formation of speleothems in a glacial environment. Prior to the main camp in 2023, two scouting trips were conducted: In July 2023, the Petit and Grand Marchet cirques were explored, and the topography of the loss of the Petit Marchet was studied, along with the identification of new entrances in the marbles. In August 2023: Surveys on the Col de l'Arcelin and the Vanoise glacier, locating several caves, including those explored in the 1980s (AR1, AR2 and AR3). The data collected enabled the search areas to be extended, particularly around the Pointe du Dard.

2024: New discoveries and further scientific research

In 2024, the focus of explorations was directed towards the Arcelin cave, where promising prospects had been identified in the preceding year. Despite the occurrence of initial snowfall, which rendered extensive prospecting challenging, the October camp was dedicated to climbing and topography within this cave. Concurrently, two scientific themes were initiated:

1. Hydrogeological tracing: This involved the implementation of artificial tracing between August and September 2024, with the objective of elucidating the subterranean circulation between glacial losses and karstic outcrops. The outcomes of this endeavour, meticulously documented in a dedicated report, substantiate the correlation between these elements.
2. Speleothem studies: The process of sampling and instrumentation within the Arcelin cave has facilitated the investigation of speleothem formation conditions within a subglacial environment. This research aims to reconstruct the glacial paleoclimates of the Alps.

3. Exploration

Name	X	Y	Z	Development (m)	Height Difference (m)
Arcelin 1988					
colAR1	325525	5027289	2600	41	26
colAR3	325440	5027344	2565	129	62
Arcelin 2022 (AR)					
AR1 **Arcel1**	325573	5027449	2530	2022	135
AR3	325991	5027256	2791	14	13
Arcelin 2023					
AR12	325909	5026904	?	21	12
Rocher du Génèpy 2022 & 2023 (G)					
G1 **Marbrimba**	326617	5027246	2946	131	117
G2	326528	5027262	2875	19	18
G3	326196	5027362	2793	23	22
G4	326115	5027348	2791	56	42
G8	326055	5027677	2665	35	42
G9	326083	5027653	2743	10	10
G11	326061	5027632	2725	6	6
G13	326077	5027637	2731	11	10
G14	326073	5027628	2737	17	15
G17	326075	5027281	2799	8	7
G18	326068	5027239	2855	8	8
Col de la Vanoise (CV)					
CV3	326432	5028768	2475	26	15
CV5	326829	5028478	2505	10	3
	Total Cave Development:			**2587**	
Moulins 2022 (M)					
M1	326772	5026609	3043	35	30
M2	326614	5026804	2987	75	42
M4 M5 M6	326017	5027115	2862	517	64
Moulins 2023					
M11	326985	5026342	3055	65	60
M12	326090	5026478	3055	89	51
	Total Development:			**3368**	

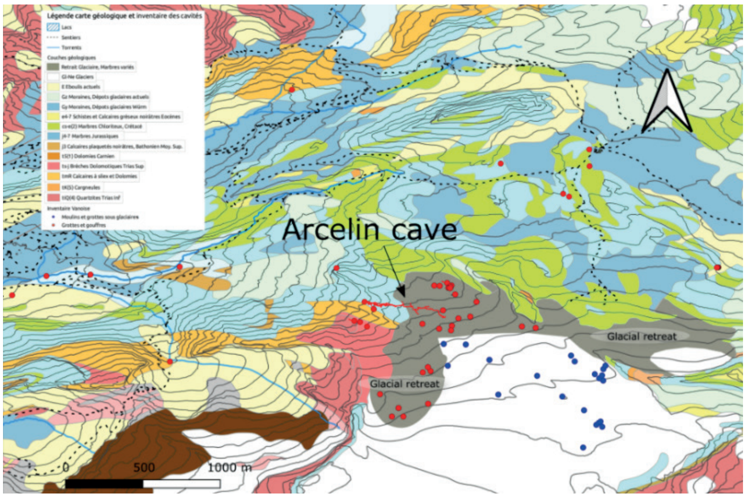

Figure 3: *Table: Summary of cavities explored during the 1988-2022-2023-2024 expedition. Map: Geological map of the prospecting area with the location of the entries identified by the cyan dot. The glacial retreat (interpretation) can be identified in grey and the actual glacier in white. BRGM data.*

Marble and Arcelin caves

A total of 18 caves have been mapped (Fig. 3) and more than 50 entrances have been discovered. The caves in the area are predominantly formed by the fracturing of the marble layers, leading to the formation of numerous single pit blocks by ice and/or sediment. The majority of these caves are vertical in nature, with a maximum depth of -135 recorded for Arcelin and -117 for Marbrimba. There is negligible horizontal development, with the exception of Arcelin.

Arcelin Cave is a fractured alpine karst network characterised by a succession of shafts, meanders and fossil galleries (Map: Fig. 4) Recent explorations have revealed new developments and significant environmental changes, including the disappearance of the fossil ice between 2023 and 2024. From the upper entrance, a series of shafts and meanders descend for more than 60m, culminating in a funnel where a narrow passage discovered in 2023 has allowed further exploration. A fossil gallery displays sedimentary deposits and ancient glacial formations that have now disappeared. The lower entrance opens onto a maze-like network marked by typical forms of erosion and a small temporary lake linked to melting snow.

Exploration in 2024 allowed us to go beyond the previous terminus by crossing a 90° constriction, revealing a gallery with active erosion features, a 30 m deep diaclase and a 9 m shaft leading to a gallery with an unexplored active river from the meltwater of the glacier. This is a major discovery for the western Alps.

Moulins and Ice caves (between the glacier and bedrock)

The Arcelin glacier constitutes the eastern and northern part of the extensive Dômes de la Vanoise ice cap. This glacial plateau, situated at an altitude of between 2,900 and 3,200 metres, is supported by a carbonate bedrock foundation and encompasses an area of approximately 3 km². Exploration of moulins has enabled descent to a maximum depth of 60 metres reaching contact with the bedrock. While few visible emergences are evident at the glacier's forefront, exploratory endeavours have revealed contact caves extending over several hundred metres between the ice and the bedrock. Under-ice karstic losses have also been observed. The caves and moulins under the glacier are undergoing rapid evolution due to the substantial ablation of the glacier.

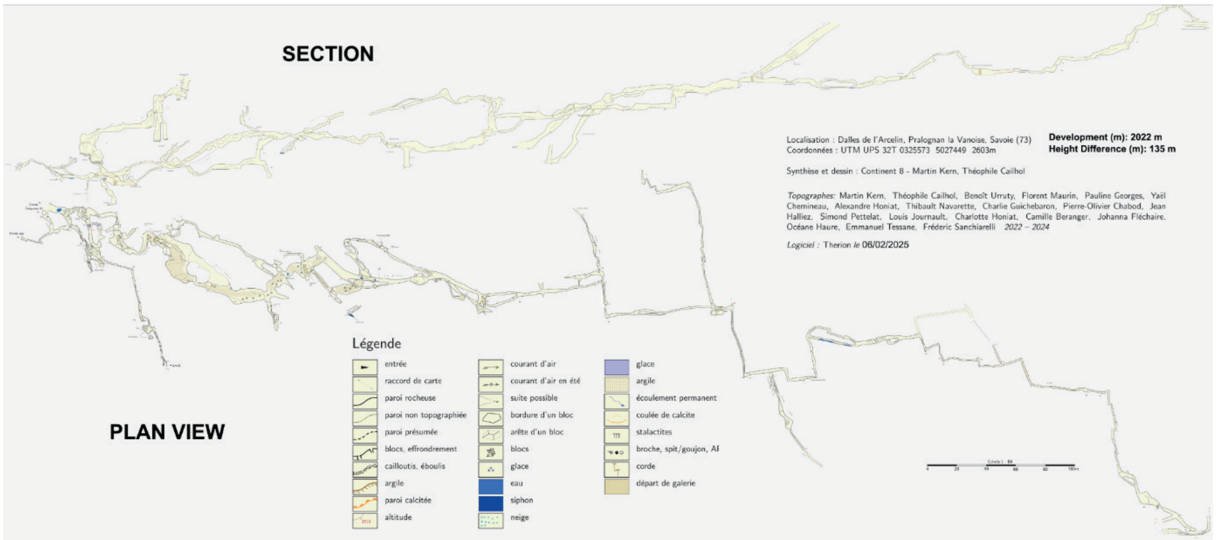

Figure 4: Topography of Arcelin cave. The section on the upper part and the plan view on the lower part are presented.

4. Key scientific work

Karstology and geological observation

The surveyed area includes regions that were previously covered by glaciers, such as carbonate outcrops around the northern edge of the Vanoise glaciers. Between the Pointe du Dard and the Pointe de la Réchasse, the glacier rests on carbonate bedrock (Geological map: Fig. 3).

Glacial deposits are extensive, covering much of the syncline base. Furthermore, sub-glacial calcite crusts (Fig 5.a) and breccias (Fig 5.b) have been exposed by glacial movement at the front of the Arcelin glacier, and karstic conduits have been eroded, forming unroofed caves.

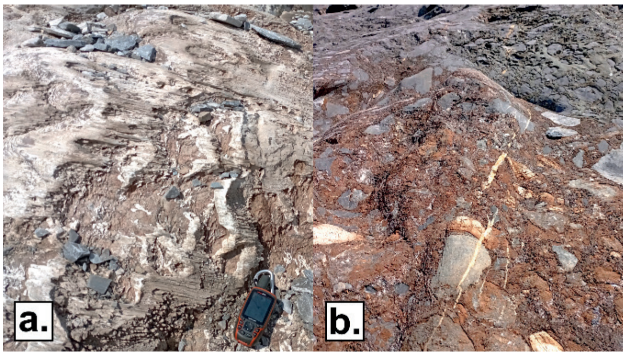

Figure 5: Sub-glacial calcite crusts. b. Breccias.

Subglacial speleothems and paleoclimatology

Subglacial speleothems—carbonate formations within caves overlain by glaciers—challenge conventional assumptions about speleothem growth, typically associated with warm, humid conditions and soil cover. However, evidence from temperate-based glaciers demonstrates their formation beneath ice. This process is driven by sulfide oxidation in the host rock, generating sulfuric acid that dissolves carbonate bedrock (instead of the classical carbonic acid dissolution), leading to calcite precipitation within cave environments. Such mechanisms have been documented in high-alpine caves (SPÖTL et al., 2024), including Milchbach (LUETSCHER et al., 2011), Melchsee-Frutt, Sieben Hengste (Switzerland), Spannagel Cave in Austria (SPÖTL and MANGINI, 2010), and now Arcelin Cave in France (this study).

These formations serve as archives of paleoenvironmental conditions, recording episodes of basal melting beneath temperate glaciers. Their presence indicates past glacier thinning or retreat, enabling meltwater infiltration into underlying karst systems (ATKINSON et al., 1983; SPÖTL et al., 2024).

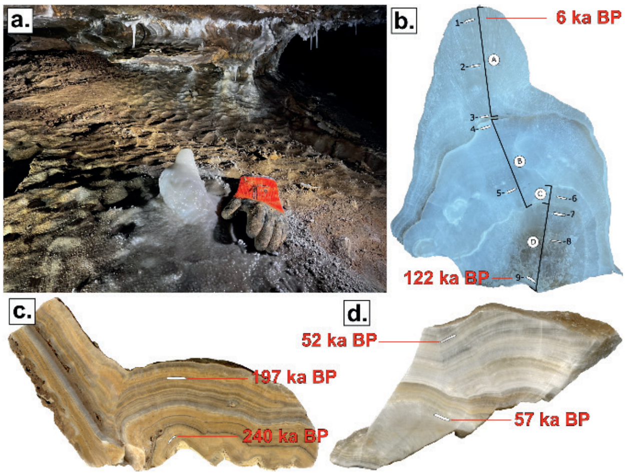

Figure 6: (a)Stalagmite A1S extracted from the terminus room 2023 of the Arcelin cave. (b) Stalagmite A1S. (c) Flowstone AR1. (d) Flowstone AR3. For (b,c & d) Section cut, polished and dated by the U/Th method for the top and bottom (preliminary). The successive growth periods are labelled A, B, C and D respectively (b).

The 2024 Vanoise expedition builds on previous research, focusing on stalagmite A1S in Arcelin Cave (Fig. 6a, b), which records growth spanning Marine Isotope Stages (MIS) 1–5, punctuated by multiple hiatuses. In 2023, analyses of two flowstones (named AR1 and AR3) revealed continuous deposition during MIS 3/4 (Fig. 6d) and 7 (Fig. 6c), reflecting shifts in glacial and periglacial hydrology. In summary, the growth periods of glaciers occur primarily under favourable climatic conditions, such as interglacial or interstadial periods, where the glacier is able to maintain a stable warm base. These findings serve to confirm the hypothesis that subglacial speleothems are capable of growth in both warm and cold conditions, with the caveat pertinent to the other parameters being the altitude at which they are found. To further investigate these processes, a comprehensive cave monitoring program has been implemented, deploying temperature loggers, drip loggers, and glass plates to track modern calcite precipitation across key chambers in Arcelin Cave.

These new datasets will help our understanding of subglacial speleothem formation and paleoclimatology of glaciated karst environments.

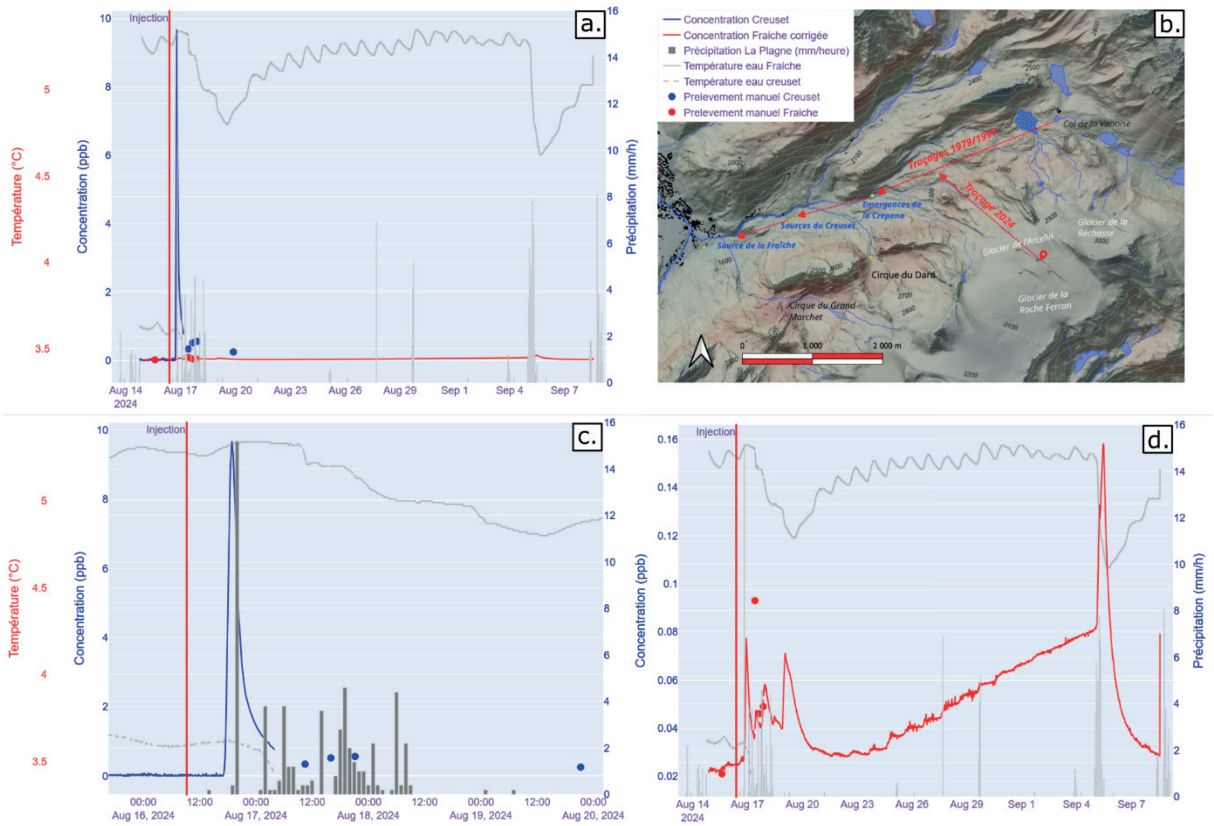

Figure 7: *Tracer Injection and Restitution Data (legend for a, b and c located in the upper left part of the map) a. Tracer concentration curves for the Creuset and Fraîche springs, showing early arrival at Creuset with higher peak concentration. b. Map of the Glacier of Arcelin and the Fontanettes area, indicating the injection site (Moulin M2) and monitored springs with inferred flow paths. c. Temporal distribution of tracer restitution events and their relation to rainfall, showing episodic signals influenced by precipitation. d. Long-term temperature and flow dynamics at the springs, illustrating variations in meltwater contributions and karstic system response over time.*

A hydrological tracer experiment on the Glacier of Arcelin

In August 2024, a hydrological tracer experiment was conducted on the Glacier of Arcelin in Vanoise National Park, France, with the objective of elucidating subsurface hydrological connections between glacial meltwater and karstic springs in the Fontanettes area, with a particular focus on the Creuset and Fraîche springs. This study is of particular importance in the context of climate-driven glacier retreat, which is projected to cause the glacier's disappearance by 2050. On 16 August 2024 at 09:30 AM, fluorescein tracer was injected into Moulin M2, a crevasse reaching the bedrock at a depth of 42 meters. (Fig. 7b). Tracer detection was monitored at six observation points, including the Creuset and Fraîche springs, located 3.5 km and 4.4 km from the injection site, respectively. At Creuset, the tracer appeared after 7.5 hours, travelling at a velocity of 470 m/h, with a peak concentration of 10 ppb of fluorescein (Fig. 7a). In contrast, at Fraîche, the tracer emerged after 11 hours, exhibiting a velocity of 398 m/h and a peak concentration that was one order of magnitude lower than that observed at Creuset (i.e., 10 ppb). These findings underscore the pre-eminence of Creuset as the predominant outlet for meltwater, with Fraîche contributing a negligible amount. Temporary outlets such as Crépéna also exhibited episodic tracer signals during periods of high-water levels, thereby highlighting the intricate dynamics of the karst system (Fig. 7c). This experiment emphasises the accelerated infiltration and subsurface transport of meltwater through high-capacity karstic conduits, in addition to the system's vulnerability to external inputs, including precipitation. Long-term discharge and temperature data (Fig. 7d) further elucidate seasonal variations driven by meltwater and rainfall. These findings are of critical importance for the effective management of water resources in Pralognan-la-Vanoise, a region heavily reliant on these springs, and for a comprehensive understanding of the impacts of glacial retreat on alpine hydrology.

5. Conclusion and perspective

The 2022–2024 explorations in the Vanoise massif have significantly advanced our understanding of high-altitude karst dynamics and glacial interactions. During this period, the exploration team successfully mapped 18 caves, discovering over 50 entrances and uncovering a total of 2.6 km of galleries. Of particular note is Arcelin Cave, which has been identified as a remarkable example of karstic phenomena, reaching a maximum depth of 135 meters over an area of 2 km. This cave is notable for its discovery of an active subglacial river, a ground-breaking finding that has significant environmental and scientific implications for the Western Alps and other glacier-covered area. Key findings also include hydrogeological tracing that confirmed subsurface water connections, and the discovery of subglacial speleothems, providing valuable insights into past glacial climates. These discoveries highlight the dynamic role glaciers play in shaping subterranean water systems. As glaciers continue to retreat, the rapid evolution of these caves underscores the importance of ongoing exploration and monitoring. Subsequent expeditions, with a projected duration until at least 2027, will concentrate on first the exploration, then extending paleoclimate research and enhancing our comprehension of alpine hydrology, with a particular emphasis on the pivotal relationship between glaciers, groundwater, and karst networks in the context of climate change.

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