

Iberulite fall and formation mechanism during a Sahara dust event in Switzerland in February 2021

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Abstract. Saharan dust events can produce micrometer-sized spherical mineral aggregates called iberulites, typically found on the Iberian Peninsula. To our knowledge, iberulites have not yet been reported from Central Europe. Two formation mechanisms—in-cloud and below-cloud scavenging—have been proposed. A strong iberulite fall (IF) was observed in Switzerland in February 2021, when large amounts of dust were transported from the Moroccan-Algerian border toward Central Europe during a Saharan Dust Event (SDE). Unlike previous IFs observed on the Iberian Peninsula, this IF occurred under low-temperature conditions near the freezing point, both in the cloud and at the surface. The relative humidity in the first 1000 meters below the clouds dropped from 70% to 40%. Comparison of the particle-size distribution (PSD) of the iberulite constituents with the dust PSD in the free atmosphere revealed a deficit of particles in the 0.1–0.3 μm range relative to the dust in the free atmosphere. The meteorological conditions and the microstructure of the iberulites suggest that frozen hydrometeors act as scavengers, and that below-cloud scavenging is the most probable formation mechanism. Further discoveries of iberulites in Swiss SDE samples indicate that this phenomenon is widespread and not limited to regions near the dust source.



1 Introduction

Sahara Dust Events (SDEs) occur 10–40 times each year over the Alps, greatly increasing aerosol levels. They peak from February to June and from October to November (Coen et al., 2004; Flentje et al., 2015; Mauro et al., 2019). Since 2020, SDEs in February and March have become more frequent, especially in the Western Euro-Mediterranean region (Cuevas-Agulló et al., 2024), leading to higher dust concentrations. This trend is driven by westerly wind blockages shifting poleward due to blocking highs and the development of cutoff subtropical lows. During these events, aerosol levels often exceed European, Swiss, and WHO PM₁₀ standards (24-hour limit: 50 µg/m³ (European, Swiss), 45 µg/m³ (WHO); during events: 55 µg/m³), with ground-level concentrations during SDEs exceeding the limits by a factor of 2. Desert dust has been associated with adverse health effects, including increased cardiovascular mortality and respiratory issues, although impacts vary by the dust's geographic source (Fussell and Kelly, 2021; Tobias et al., 2019). In Europe, dust accounts for over 40,000 deaths annually (Wang et al., 2020). To date, 150 countries are affected, with more than 100 classified as non-dust-source regions (Li et al., 2025). Due to the growing threat of sand and dust storms, international agencies have prioritized mitigation efforts over the past twenty years (UNCCD, 2022). Dust also influences climate and ecosystems (Buseck and Pósfai, 1999; Lian et al., 2025) by affecting Earth's radiative balance (Heald et al., 2014), degrading air quality (Proestakis et al., 2025), supplying nutrients to marine and terrestrial ecosystems (Kellogg and Griffin, 2006), reducing snow and ice albedo to accelerate melting (Francis et al., 2018), and adsorbing trace gases, altering their physical properties (Tan et al., 2024). Saharan dust notably impacts hail formation in Europe (Brennan and Wilhelm, 2025). Limited research exists on the economic impact of desert dust, and no standardized data collection or analysis (Middleton, 2017). Annual dust-related damages in Iraq and Iran are estimated between \$1.0 billion and \$1.4 billion (Meibodi et al., 2015). In the U.S., costs related to dust and wind erosion reached \$154 billion in 2017, more than quadrupling since 1995 (Feng et al., 2025).

A distinct type of dust particles is spherule-shaped aggregates measuring between 50 and 200 µm, called iberulites, a term originating from their first discovery in southern Spain (Díaz-Hernández & Párraga, 2008). Iberulites have also been identified in Mallorca (Fiol et al., 2005; Fiol & Guijarro, 2000) and in Tenerife (Spain) (Cuadros et al., 2015), but no sightings have been reported north of 42°N. Iberulites found in Spain display flow textures, including typical depressions (vortices) and a shell structure with a coarse-grained core and a dense, fine-grained surface layer (Díaz-Hernández & Párraga, 2008; Párraga et al., 2021). The iberulite constituents consist of minerals such as silicates, carbonates, sulfates, halides, oxides, and phosphate-vanadate's, along with plant material, silica shells, plankton, and probably viruses. This mineral composition suggests the Sahara and Sahel as primary mineral sources, while other minerals such as gypsum and alunite-jarosite are likely formed in the atmosphere (neof ormation), probably via atmospheric pollutants during transport (Díaz-Hernández & Párraga, 2008; Párraga et al., 2021).

Two mechanisms are proposed for creating these aggregates (Díaz-Hernández & Sanchez-Navas, 2016; Párraga et al., 2021): 1. Coalescence of droplets within a cloud increases condensation nuclei within a single droplet, known as in-cloud scavenging (ICS) or 'nucleation scavenging,' and 2. an increase in concentration through collisions between particles and falling drops, called below-cloud scavenging (BCS) or impaction scavenging (Pruppacher & Klett, 2010). The efficiency of a drop in coalescing or collecting particles is called Number Scavenging Efficiency (NSE) for ICS (Yang et al., 2023) and collection efficiency (CE) for BCS (Laakso et al., 2003; Slinn, 1977, 1983; Volken & Schumann, 1993). If CE were unaffected by factors

such as drop and particle properties or environmental conditions, the grain-size distribution in iberulite would match the dust-size distribution in the cloud (ICS) or the volume of air passing through (BCS). However, ICS depends on aerosol activation, which is influenced by particle size, composition, coatings, and atmospheric water saturation. Dust particles with soluble coatings are highly effective cloud condensation nuclei (CCN) (Levin et al., 2005). Small amounts of soluble material greatly increase the CCN activity of fine dust particles (Kelly et al., 2007). Larger dust particles can act as giant CCN, forming efficient collector drops (Feingold et al., 1999; Levin & Cotton, 2009). Recent evidence shows that insoluble species, such as freshly emitted mineral dust, can also serve as CCNs, even with little soluble material, especially if they contain soluble ions or have strong water vapor adsorption on their surfaces (Herich et al., 2009; Koehler et al., 2009; Kumar et al., 2009). Mineral dust's contribution to CCN levels decreases at lower supersaturations because insoluble aerosols are less hygroscopic and need higher supersaturation to activate compared to soluble particles. Nonetheless, since dust particles are coarser, coated particles can activate at lower supersaturations than smaller human-made aerosols. At 0.2% supersaturation, mineral dust accounts for up to 30% of CCN, increasing to 35% at 0.4%. NSE, or water adsorption efficiency, varies with particle type, size, and supersaturation. For dust particles between 0.3 and 1 μm , NSE remains around 0.2 (Yang et al., 2023). For particles larger than 1.0 μm , NSE increases, whereas particles between 0.1 and 0.3 μm are often removed by impaction, reducing NSE to about 0.1. For BCS, the capture efficiency depends on particle size and the capture mechanism. If a drop with radius R falls vertically, e.g., without deviation by wind, the maximum number of possible collisions N along a trajectory l within the dust layer with particle radius r , mass density M_d , and particle density d can be calculated.

$$N = \frac{3}{4} \frac{2\pi M_d R^2 l}{\pi r^3 d} \quad (1)$$

For particles larger than 1 μm in diameter colliding head-on with a droplet, bouncing is unlikely, and the sticking efficiency is assumed to be 100%. However, for particles with radii between 0.3 and 1.0 μm , the CE, defined as the ratio of the total number of collisions given by eq. 1 to the number of particles captured by the droplet, is less than 1. This occurs because of the airflow around the falling droplet. Particles in this size range, although on collision trajectories, tend to follow the flow lines and are diverted around the droplet. Larger particles, due to their inertia, cross the flow lines and impact the droplet directly, resulting in a CE of 1 (capture by impaction). Small particles (< 0.3 μm) that follow the flow lines may be pushed by Brownian motion into the droplet's wake and deposited on its rear end (Brownian capture), making the CE also close to 1. Capture can also occur through thermophoretic and diffusiophoretic forces. Thermophoretic forces push aerosol particles toward a frozen drop during evaporation and away from it during vapor deposition. During diffusive crystal growth, a flow known as Stefan's flow exists near the hydrometeor surface, exerting a force on nearby aerosol particles that pulls them toward the surface. Particles, regardless of their size, can follow flow lines, but at some point these lines approach the droplet's surface more closely than the particle's radius. The particle then contacts the droplet's surface and sticks to it (capture by interception). This process has a relatively low capture efficiency. For particles with radii between 0.3 and 1.0 μm , none of the preferred capture processes are effective, and the CE decreases by two orders of magnitude. This reduction in CE was first described by Greenfield (1957), and the absence of particles in the 0.3–1.0 μm range is called the Greenfield gap. Both formation mechanisms lead to a depletion of particles in the 0.3–1.0 μm range in the iberulites relative to the dust cloud concentration, but the decrease is much more pronounced for BCS. The particle size

distribution (PSD) inside an iberulite, compared to the PSD in the free atmosphere, can therefore indicate the formation mechanism of the iberulite.

Dust from potential source areas has been characterized by bulk chemistry and mineralogy (Kandler et al., 2007; Scheuvs et al., 2013). Mineralogical fingerprints include phyllosilicates, such as the ratio of illite to kaolinite concentrations (I/K) (Caquineau et al., 1998; Chester and Johnson, 1971; Scheuvs et al., 2013). In Northern Africa, I/K generally increases from south to north and from east to west. High carbonate content (>10 wt.%, calcite > dolomite) also serves as a fingerprint of dust from northwestern Africa (Avila et al., 1997). As with illite, carbonate content decreases steadily toward the south (Paquet, 1984). The high carbonate content of dust emitted from the northern regions within and near the Atlas Mountains reflects the geology of those areas (Grousset et al., 1992).

A major SDE struck Switzerland on the afternoon of February 6th, 2021, making it one of the strongest since systematic monitoring began in 2001 (Collaud Coen et al., 2025) at the Jungfraujoch laboratory (JFJ, inlet altitude 3585 m above sea level). Due to its elevation and low local emissions, JFJ is ideal for studying long-range transport processes. A record PM₁₀ concentration exceeding 700 µg/m³ was recorded (NABEL, BAFU/Empa). The iberulite fall (IF) was observed by the authors in Saint-Légier (Vaud), Fribourg (Fribourg), and Geneva. This study aims to characterize the collected iberulites and examine the aggregation mechanism in detail, using well-documented meteorological conditions during the fall.

2 Methods

2.1 Iberulite collection

The fall of iberulites was observed early in the afternoon on February 6th in St. Légier (46.471° N, 6.877° E), Fribourg (46.717° N, 7.083° E), and Geneva (46.204° N, 6.143° E) (Fig. 1, Table 1). Iberulites were collected at all three sites. The city of Fribourg (500-700 m ASL) is 50 km NNE of Lake Geneva on the Swiss plateau, and the village of St. Légier (576 m ASL) is on the northern central shore of the same lake. The geology around both sites is dominated by calcareous mountains (Jura, Préalpes) (Matzenauer, 2011). In St. Légier and Geneva, iberulites were collected from the ground with tweezers, and in Fribourg, an aluminum foil sheet was laid on the ground, from which samples were collected with a fine spatula. The iberulites were gently placed on the head specimen mounts. Dust particles sampled on the same foil were also collected and dispersed onto a particle filter (Millipore type AAWP, 47 mm, pore size 0.8 µm, nitrocellulose). Collecting dust on aluminum foil is not a common method, but because the IF was unexpected, standard sampling equipment, such as a sampling head with an impactor and a pump, could not be set up in time. Aluminum foils are used to collect interstellar dust (Kearsley et al., 2010) and to identify laboratory sources of microplastic and nanoplastic contamination (Jones et al., 2024). Loss of particles during dispersal on the foil is negligible.



Figure 1: Locations in Western Switzerland mentioned in the text (Swisstopo, 2025).

Table 1 Sampling sites and analyses done (iber.: iberulite; opt.: binocular imaging)

Site	Sampling	Dust PSD	Iber. PSD	Dust XRD	Dust SEM	Iber. Opt.	Meteo
Fribourg	x		x	x	x	x	
St. Leger	x		x	x	x	x	
Genève	x				x		
Jungfrauoch		x					x
Payerne							x

2.2 Observational data

Meteorological data were collected from radiosonde balloons launched by the Federal Office for Meteorology and Climatology of Switzerland (MeteoSwiss) station in Payerne (46.817° N, 6.933° E, Fig. 1) twice daily at 11:00 and 23:00 UTC. Payerne is located 17 km west and 47 km north of the collection sites in Fribourg and St. L  gier, respectively. The station is equipped with a Raman lidar, ceilometers, and a Doppler radar to measure precipitation, aerosol concentrations, and wind profiles. On February 6th, the ceilometer profile series from Payerne showed gaps in the morning and smaller gaps in the afternoon due to ground fog. The area is also covered by two weather radars: one on La Dole Mountain (46.425° N, 6.099° E), west of St. L  gier and near Geneva, and the other on Plaine Morte (46.383° N, 7.500° E, Fig. 1), in the central Bernese Alps southeast of the two collection sites.

The size distributions of fine- and coarse-mode aerosols in the dust cloud were measured at the high-altitude Alpine station Jungfraujoch (JFJ, 7.98° N, 46.55° E; 3580 m ASL, Fig. 1) in the Bernese Alps. Its remote location, far from local human sources, makes it ideal for monitoring background atmospheric conditions over central Europe. Jungfraujoch hosts a comprehensive long-term in situ monitoring program for aerosols and trace gases as part of the World Meteorological Organization (WMO) and is included in the Swiss National Air Pollution Monitoring Network (H  glin, 2021). Aerosol measurements were conducted using a custom-built Scanning Mobility Particle Size Spectrometer (SMPS) (Wiedensohler et al., 2012; Jur  nyi et al., 2011) and a white-light optical particle size spectrometer (FIDAS, Palas GmbH, Germany) (Brem et al., 2023; Fischer and H  glin, 2024).

2.3 Dust trajectory analysis

The dust RGB product, based on three infrared channels from the Spinning Enhanced Visible and Infrared Imager (SEVIRI) on EUMETSAT's second-generation MSG-11 satellite (Schmetz et al., 2002), was used to identify the sources of afternoon dust arriving over western Switzerland (Schepanski et al., 2009). The dust detection method relies on brightness temperature differences at 12.0 μm minus 10.8 μm and 10.8 μm minus 8.7 μm , as well as on 10.8 μm (Sokolik, 2002). The plume's path was tracked using satellite images (supplement) following the approach described by Ashpole and Washington (2013). The visually identified dust routes were confirmed using forward- and backward-trajectory calculations with the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPPLIT) model, developed by NOAA's Air Resources Laboratory (Draxler and Rolph, 2003). HYSPLIT uses archived three-dimensional meteorological data from ground and satellite observations, along with short-term forecasts. For this study, the Global Forecast System dataset from the National Centers for Environmental Prediction at 0.25° resolution was employed for back-trajectory calculations. The SEVIRI images and the backward trajectories trace the dust's origin for an arrival time over Fribourg at 2000 meters above ground level (AGL), between 12:00 and 18:00 UTC on February 6, roughly coinciding with the period of highest cloud density, to the Algerian-Moroccan border. The dust source meteorological data were obtained via the Real-time Environmental Applications and Display System (READY) from the archived Global Data Assimilation System (Rolph et al., 2017). The data were collected for the center of the main dust source observed in the satellite image, located at 33.8°N, 1.5°W.

2.4 Scanning Electron Microscopy (SEM) and Optical Polarization Microscopy (OPM) analyses

Single particles and iberulites were isolated from samples collected on the ground in St. Legier and Geneva, as well as from aluminum foil in Fribourg. A selection of iberulites was gently placed onto a ½-inch pin stub (Ted Pella, Redding, CA, USA) and examined using an Olympus SZX12 binocular microscope (Tokyo, Japan). All single particles collected on the foil in Fribourg were dispersed onto a carbon pad-covered 1-inch pin stub and analyzed using automated SEM/EDX single-particle analysis (Computer-Controlled SEM, CCSEM). During CCSEM, particles are identified based on their Back-Scattered Electron (BSE) contrast, and images, along with Energy-Dispersive X-ray (EDX) spectra, are acquired. For this, a FEI Sirion FEG microscope equipped with an Oxford X-MAX EDX detector with a 150 mm² sensor size, a four-quadrant BSE detector, and AZtecFeature software (Oxford Instruments) was used at the Department of Geoscience of the University of Fribourg (Fribourg, Switzerland). Analyses were conducted at 20 kV. Particles were identified by simple gray-value (BSE intensity) thresholding. EDX analyses were performed for each identified particle. The AZtec software automatically applied a ZAF correction (PAP version of the $f(\rho z)$ formalism (Pouchou and Pichoir, 1985)—considering atomic number (Z), absorption (A), and fluorescence (F)—to the raw data for elemental concentrations. Quantification was based on factory-calibrated standards. The ZAF correction assumes homogeneous samples with smooth surfaces perpendicular to the beam and thicknesses greater than the excitation volume—conditions not met by these particles due to their rough surfaces and small sizes. However, studies (Weinbruch et al., 1997; Meier et al., 2018; Kandler et al., 2018) have shown that for particles larger than 1 µm, the relative standard deviation of the corrected major-element concentrations is approximately 2%. For minor elements, the deviation is higher. Since only particles >1 µm in diameter were included in further data processing, ZAF-corrected concentrations were used without additional corrections. The standard deviation of ZAF-corrected concentrations measured in particles increases proportionally with the acceleration voltage (equivalent to increasing excitation volume). Several blank analyses of empty substrates have shown that, under the applied analytical conditions, the substrate surface contains, in an area of ca. 1 mm², a maximum of five particles on unexposed substrates. These particles are organic in nature and most likely hair follicles.

2.5 Particle size and microstructure analysis

Images from both the optical microscope and the SEM were used to characterize the particle-size distribution of the total dust and iberulites, as well as their microstructure, using Avizo software (Thermo Fisher). Selected iberulites were placed in a 1-inch round container and filled with impregnation resin. The resulting cylindrical samples were polished on the side containing the iberulites and then examined by electron microscopy. A BSE image of a polished iberulite section was also segmented in Avizo software (Thermo Fisher), enabling the counting of individual particles and the determination of their equivalent spherical diameter d_{ve} , defined as the diameter of a sphere with the same volume as the particle:

$$d_{ve} = \frac{1}{P^2} \sqrt{64\pi B^3} \quad (2)$$

where B is the area the particle covers on the sample substrate and P is the particle perimeter. Due to the resolution of the segmentation process, only particles larger than 0.05 µm can be detected and counted. To compare the SMPS with the SEM-derived PSDs, the mobility diameter d_m obtained by SMPS must first be converted to the volume-equivalent diameter d_{ve} (Decarlo et al., 2004):

$$d_{ve} = \frac{C_c(d_{ve})}{C_c(d_m)\chi} d_m = CF d_m \quad (3)$$

with $C_c(dm)/C_c(dve)$, the Cunningham slip correction factor ratio between the mobility and volume equivalent diameters, CF the conversion factor, and the dynamic shape factor χ :

$$\chi = \frac{F_P}{F_{ve}} \quad (4)$$

which is defined as the ratio of the drag force on the nonspherical particle F_P to the drag force on its volume equivalent sphere F_{ve} when both move at the same relative velocity with respect to the gas (Hinds, 1999). The electrical mobility is the velocity v_e of a sphere ($\chi = 1$) with the same velocity as the measured particle:

$$v_e = \frac{neC_c(d_m)}{3\pi\eta d_m} = \frac{neC_c(d_{ve})}{3\pi\eta\chi d_{ve}} \quad (5)$$

From equation (5), the conversion equation (3) follows. $C_c(d_{ve})$ is unknown. The ratio $C_c(dm)/C_c(dve)$ has, to our knowledge, been measured only for salt particles smaller than 600 nm. The latter (extrapolated for particles > 600 nm) was used to convert the volume-equivalent diameter into the mobility diameter. It is always less than one, increases with size, and decreases with aspect ratio. The axis ratios b/a (AR , the ratio of the longest dimension b to the orthogonal width a) and shape factors appear to depend on size, flow regime (Alexander et al., 2016), and orientation (Cheng et al., 1988), ranging from near unity for smaller particles to a value of 3 for the largest particles. The average inside the iberulites is 1.46, close to 1.4 reported for dust particles in the 2 to 10 μm range. Overall, CF is mostly smaller than 1.0. The converted volume-equivalent diameters are smaller than the mobility diameters.

19

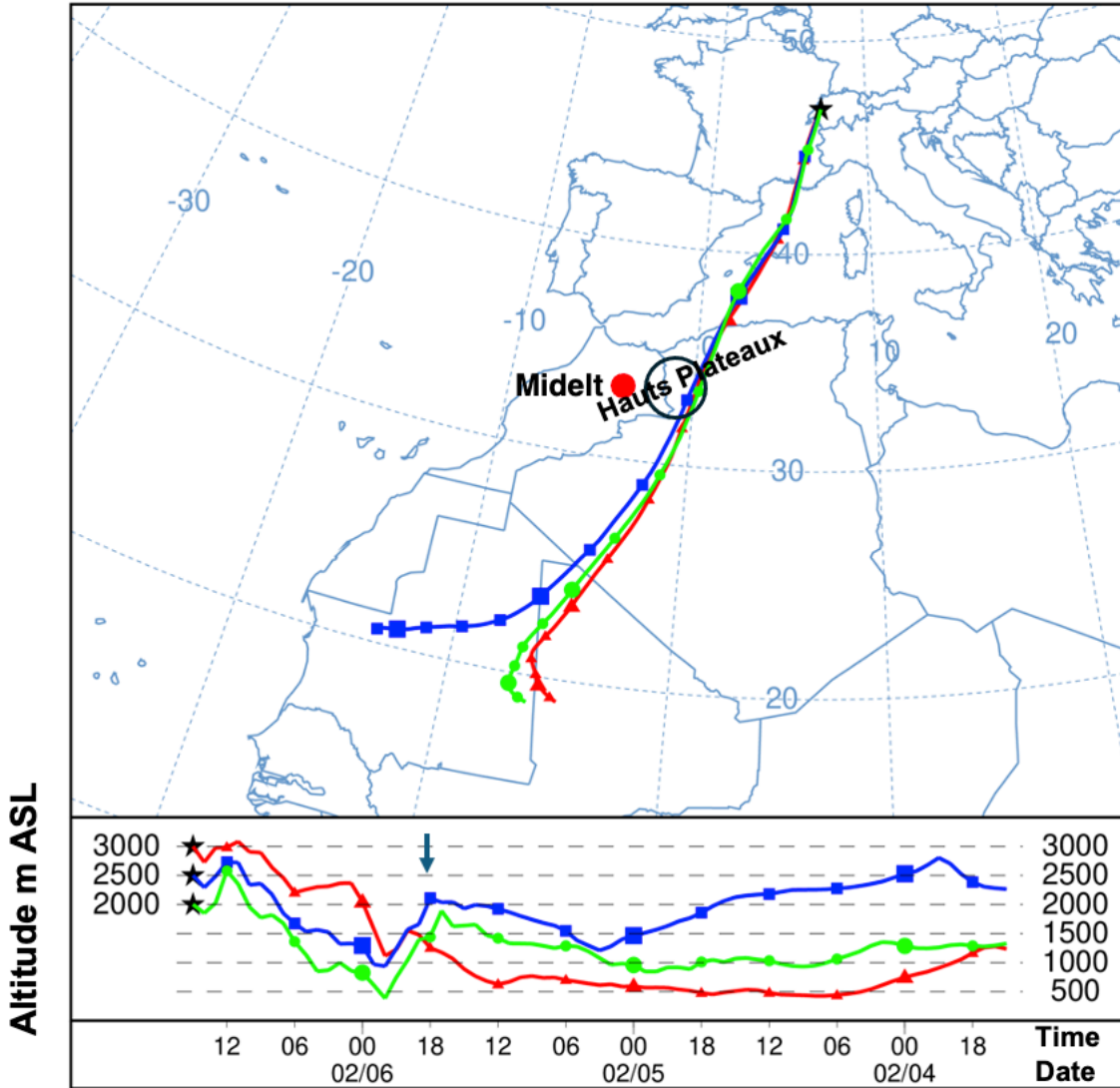
20 2.6 X-ray diffraction

21 A loose, single dust particle sample, lacking iberulites but collected simultaneously with the iberulites that fell in
 22 Fribourg, was analyzed using a Rigaku Ultima IV diffractometer equipped with a position-sensitive detector (PSD).
 23 Diffractograms were recorded from 5° to 70° 2 θ in step-scan mode (0.02°/step and 1 min/°). The copper X-ray tube was
 24 operated at 40 kV and 40 mA. The Cu K α radiation was filtered through a nickel foil. Quantitative phase analysis via
 25 Rietveld refinement (Bish and Post, 1993) was performed on the recorded patterns using the PDXL2 software package
 26 (Rigaku). The refined instrumental parameters included the zero shift, sample displacement, and peak shape, modeled with
 27 a Pseudo-Voigt profile. Structure parameters for the phases in the sample were sourced from the International Center for
 28 Diffraction Data database; only the scale factor, unit-cell parameters, isotropic overall temperature factor, and, in some cases,
 29 the preferred orientation parameter (phyllosilicates, calcite) were the structural parameters refined using the March-Dollase
 30 formalism (Dollase, 1986). Phase fractions were determined through the scale factors. Atomic positions and site occupancies
 31 remained fixed during refinement. Multiple iterations were performed until the process converged.

32 3. Results

33 3.1 Dust source and trajectory

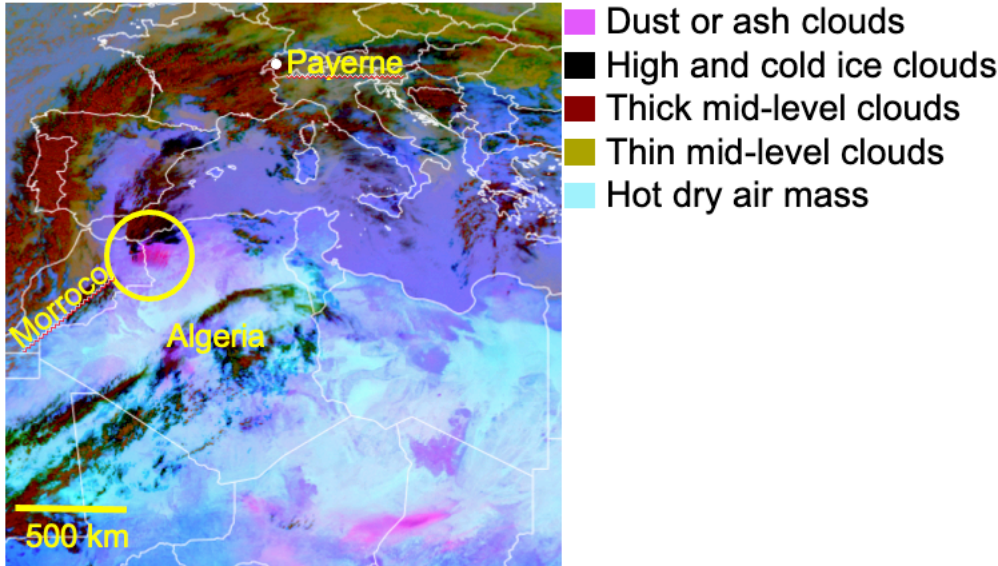
34 For air masses arriving at 2000, 2500, and 3000 m ASL over Fribourg in the early afternoon of February 6th, HYSPLIT back-
 35 trajectory calculations were performed for hourly arrival times from 9:00 to 15:00 h.



36
 37 **Figure 2: Back trajectories for air masses arriving over Payerne at 15:00 UTC, February 6th. The black circle shows the location**
 38 **of the first appearance of the dust plume entrained across the Mediterranean Sea towards central Europe. The black arrow**
 39 **points to the location markers inside the black circle.**

40 The dust originated in northwest Africa (Fig. 2), between the southern Moroccan border and northwestern Algeria. Satellite
 41 images showed a dust plume forming in a region called "Hauts Plateaux" (also known as "Hautes Plaines") between the Pre-
 42 Sahara and the Tell Atlas (Fig.3). The air masses arriving over the Hauts Plateaux during the early afternoon of February 5th
 43 were at altitudes ranging from 1500 m to 3500 m ASL, which is within the Planetary Boundary Layer (PBL; calculated

14 with the READY software (Rolph et al., 2017)), spanning from 2600 to 4500 m. Surface wind velocity (at 10 m above
15 ground) increased from 40 km/h to approximately 70 km/h.



16
17 **Figure 3: Satellite RGB image (5.2.2021, 22:00 UTC) from the SEVIRI dust product. The dust plume transported to Central**
18 **Europe is seen east of the Moroccan – Algerian border (center of yellow circle).**

19 Weather stations in the Atlas Mountains recorded hurricane-force gusts (e.g., 117 km/h on 05.02.21 in Midelt, Morocco (Fig.
20 2) (Hoshyaripour 2021). This exceeds the threshold wind speed for dust emissions defined for western Algeria (Marticorena
21 et al., 1997). The dust plume was transported northeastward toward the Mediterranean Sea, where a low-pressure system
22 developed. The associated warm conveyor belt lifted the dust to higher altitudes and carried it with the polar jet across the
23 Mediterranean toward the Alps, a process known as an "atmospheric river" (Francis et al., 2022; Rautela et al., 2024).
24 Source sensitivities (the probability that an air mass originates from a given source along a certain path) for Saharan dust (fine
25 mode) arriving at JFJ were calculated using FLEXPART to generate backward trajectories and assess the general surface
26 contact of air masses over the Sahara Desert (Collaud Coen et al., 2025). The sensitivities indicate that the most common
27 pathway is from the Sahara, over the Mediterranean, directly to the Alps.

58 3.2 Local meteorology

59 **Ground temperature measurements and T/RH profiles from the radiosonde released at 11:00 UTC in Payerne showed**
60 **relatively high temperatures for February 6th in Western Switzerland (4°C at the ground and a 0°C level at 2800 m ASL),**
61 **along with a typical inversion situation (Fig. 4). Compared to conditions during previous IFs over the Iberian Peninsula**
62 **(Diaz-Hernandez and Sanchez-Navas, 2016), the temperature was much lower. The vertical profile of relative humidity (RH)**
63 **was complex: RH decreased from 97 % at ground level to a low 48 % at 1000 m, then increased to 61 % at 3200 m ASL**

(Fig. 4). RH remained between 48 and 55% up to an altitude of 4300 m ASL, where it began to increase to 97 % resulting in a 100 m thick layer between 5000 and 5100 m ASL with temperatures below the frost point.

The Payerne ceilometer time profile (Fig. 5) shows a cloud base at 5000 m ASL at midnight, with reflections above about 2500 m (the 0°C level), which may be due to aerosol (SDE) or ice particles. Reflections from ice particles and dust are generally difficult to distinguish. Early in the morning, the cloud base lowered to 4000 m, and the reflections extended down to 2500 m. Below 2500 m ASL, the temperature is above 0°C and rises quickly; therefore, it is very unlikely that the reflections below 2500 m ASL are from ice particles. The below-cloud reflections appear streaky in the ceilogram. After a large gap in ceilometer recordings between 9:00 and 11:00 UTC due to ground fog blocking the laser, a reflection wall extending to the ground appeared. These strong dust particle reflections persisted throughout the day. The cloud base lowered from 4000 m to 2000 m during the evening. Around 22:30, three short periods with very strong reflections were observed; during these times, precipitation was recorded on the ground. After 23:00, the reflections became less intense.

Lidar measurements were taken between 15:00 and 17:00, during the signal's peak values and the average was used to derive a mass-concentration profile (Fig. 6) across the dust cloud. The altitude range of 4000-5000 meters served as the "no aerosol" reference. The profile was created using a lidar ratio of $0.57 \text{ m}^2/\text{sr} \pm 9 \text{ sr}$ at 532 nm (Haarig et al., 2022), an Ångström coefficient of 0.5 for long-range transported dust in northern Europe (Ansmann et al., 2001), and a mass extinction ratio at 532 nm of $0.47 \pm 0.04 \text{ m}^2 \text{ g}^{-1}$ (Nemuc et al., 2013). The profile showed three peaks. The highest concentration of $81 \mu\text{g}/\text{m}^3$ was observed at an altitude of 1675 meters. The second-largest concentration was recorded just above the ground, and a third small peak was located just above the cloud base at approximately 3500 meters.

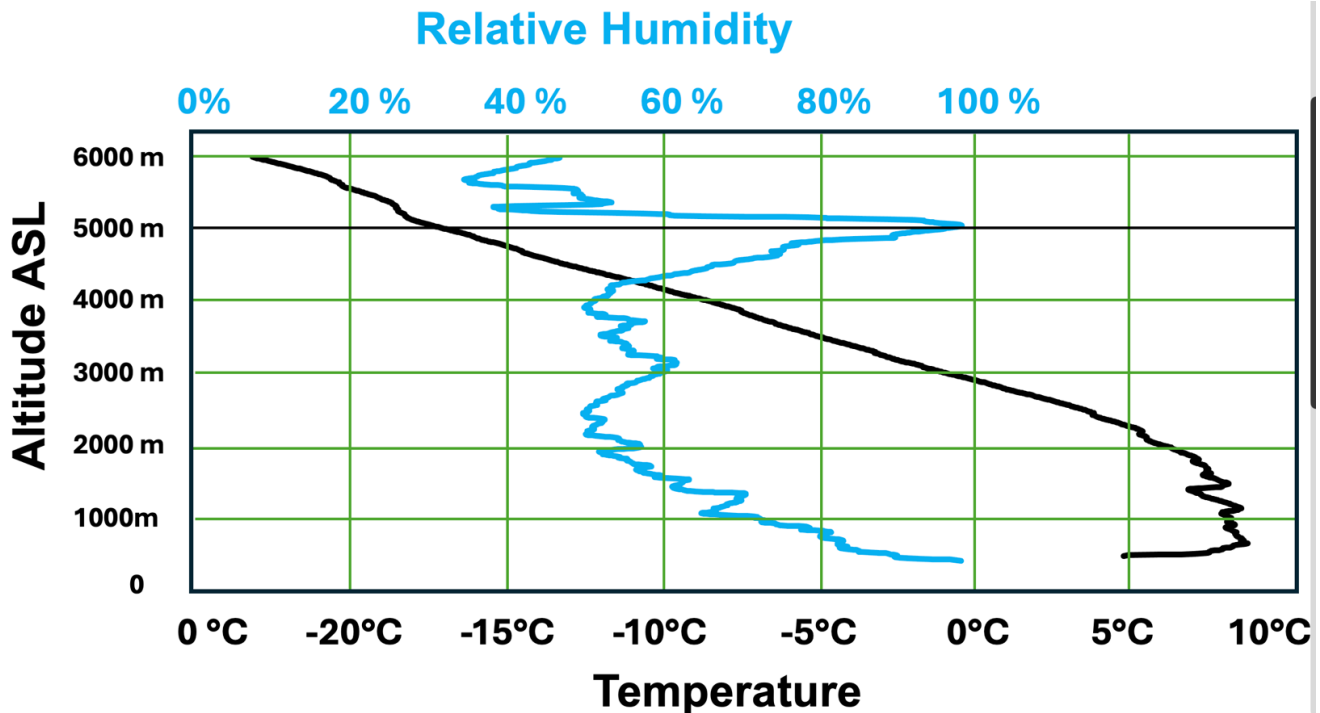


Figure 4: Temperature (black line) and relative humidity (blue line) as a function of altitude from the radio sounding. The balloon was released in Payerne at 11:00 h UTC. The balloon flew 30 km to the NW during the above recording (MeteoSwiss).

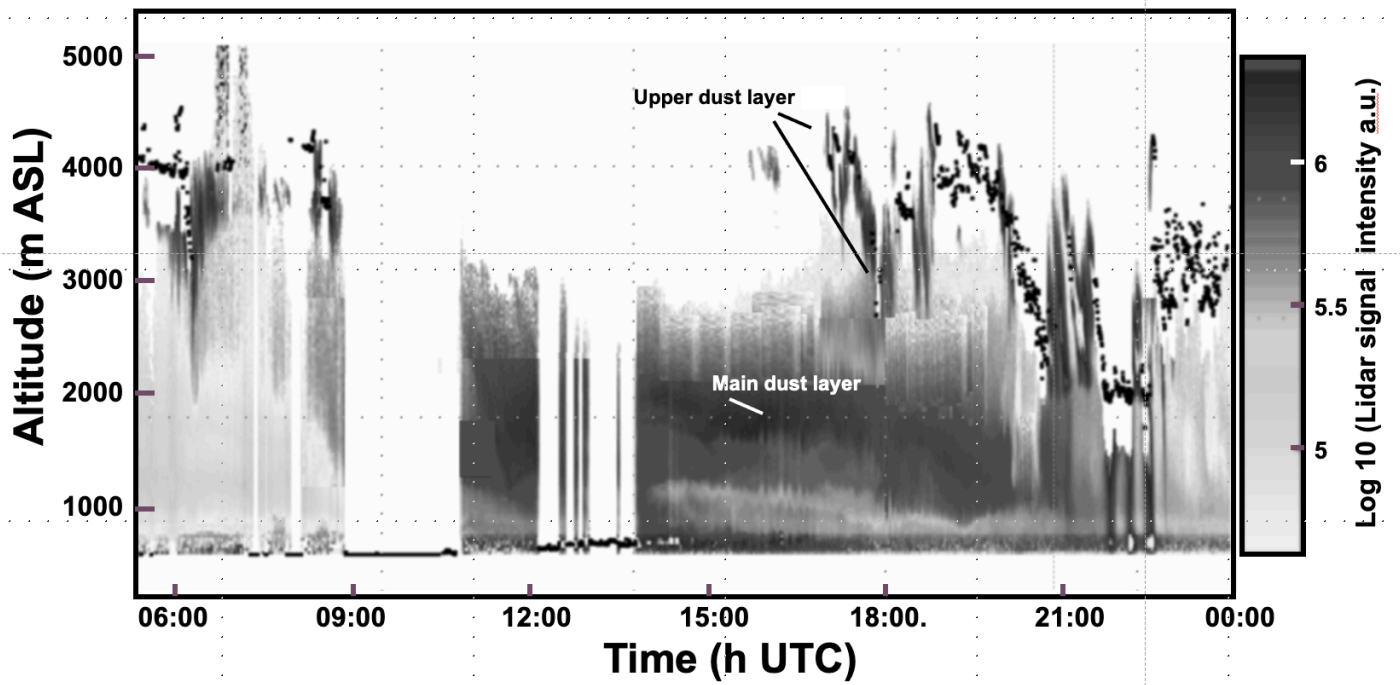


Figure 5: Ceilometer profile for February 6th (MeteoSwiss). The little black dots on top of the reflections show the meteorological clouds' bottom. The white stripes are gaps due to ground fog.

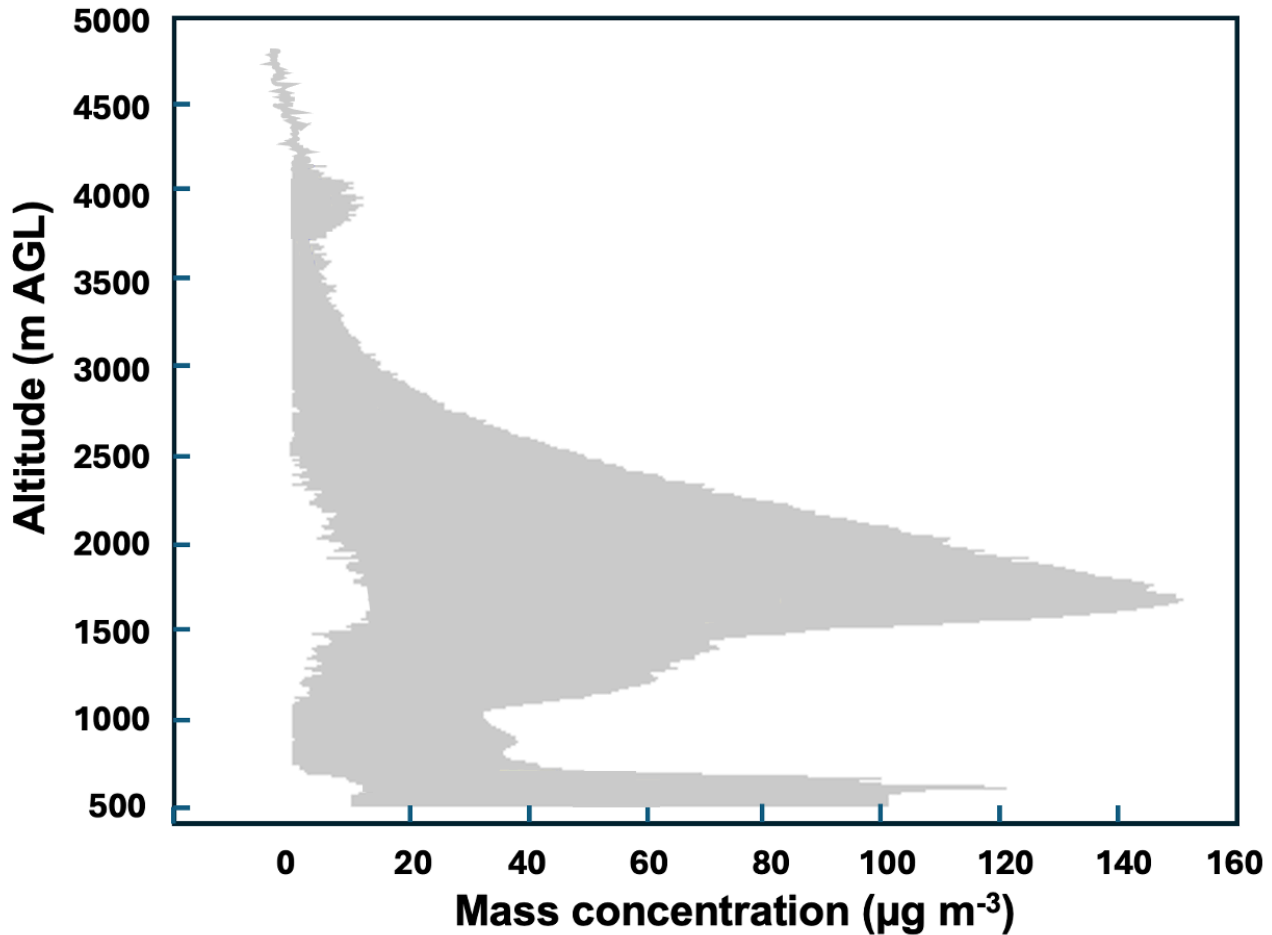


Figure 6: Aerosol mass concentration profile across the dust cloud calculated from the average of Lidar measurements taken between 15:00 and 16:59 h (MeteoSwiss).

3.3 Morphology and microstructure of iberulites

Giant particles were previously observed following long-range transport of Saharan dust. Rapid transport, high turbulence, and electrical forces are thought to counteract the particles' weight. In our case, the large "particles" were not individual particles but multimineral particle aggregates with spherical to slightly ellipsoidal shapes, known as iberulites after their first recording on the Iberian Peninsula (Fig. 7) (Díaz-Hernández and Párraga, 2008). The cores of the iberulites mainly consist of coarser mineral grains (Fig. 8 e,f, and Fig. 9) that have accumulated without a visible cement matrix. Apart from a thin, dense surface layer, the iberulite cores show no internal structure, such as layering or preferred grain orientation. The iberulites collected in St Léger and Fribourg ($n = 425$) are larger than those from the Iberian Peninsula, with an average diameter of 113 μm (range: 43–365 μm).

Most iberulites have smooth surfaces with few large surface pores (Fig. 8 a-d), most likely due to particles ejected from the aggregates. Spherical surface depressions, e.g., could form in the tail of a falling precursor water drops, as observed on Iberian iberulites (Díaz-Hernández and Párraga, 2008), are very rare among the sampled iberulites.

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05 **Figure 7: Light microscopy image of iberulites collected in St Léger.**

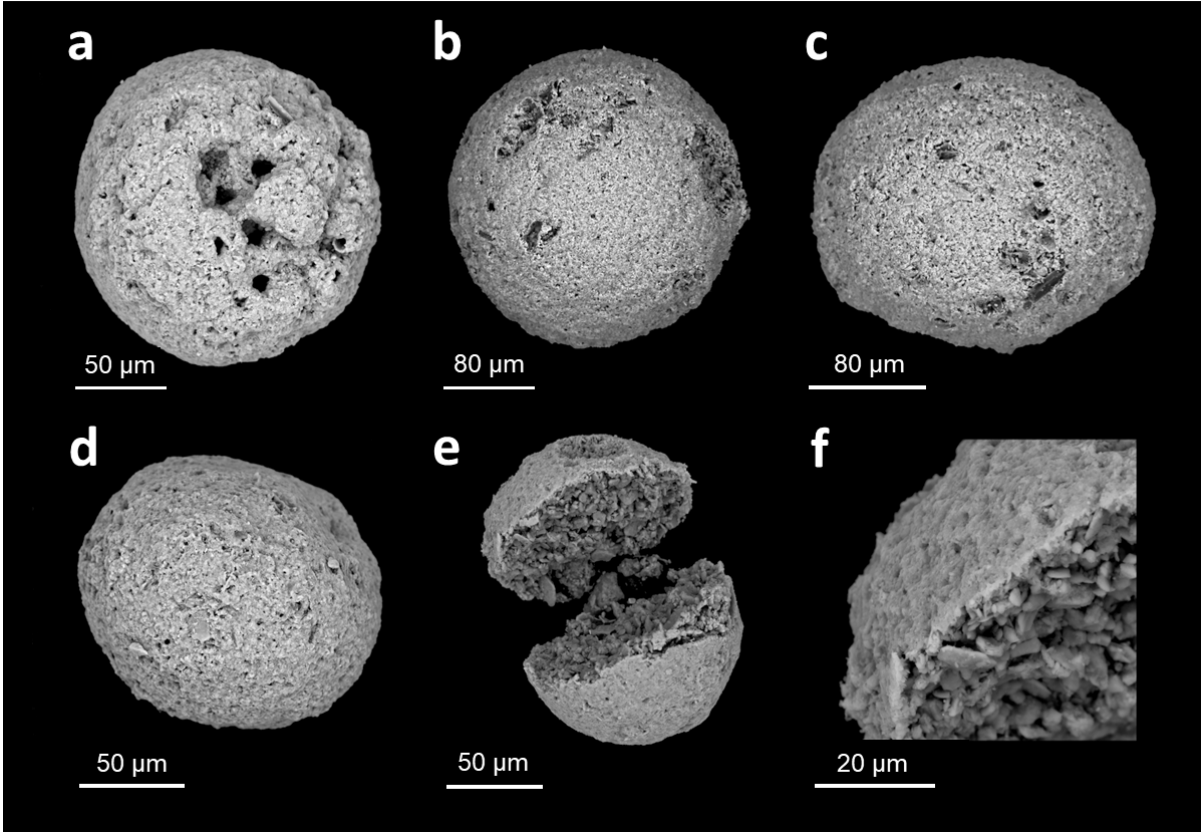


Figure 8: SEM images of some iberulites collected in St Léger on February 6th, 2021. Figure 7f shows the fine-grained rim and the coarse core of an iberulite.

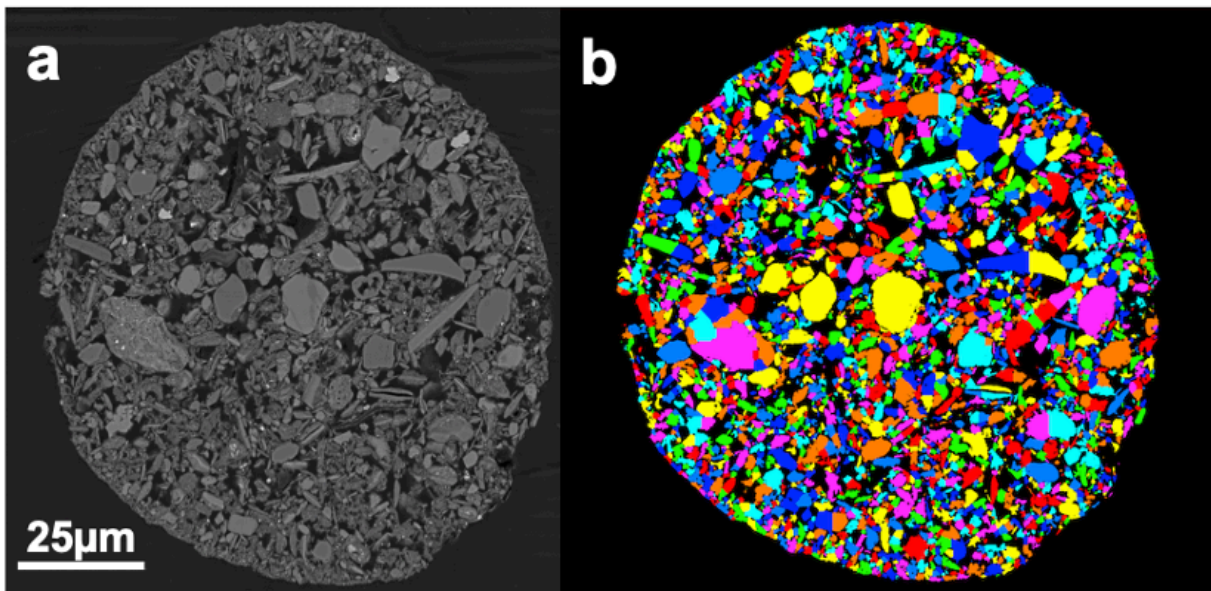


Figure 9: (a) BSE image of a polished section through an iberulite, and (b) the corresponding segmentation obtained from AVIZO. The different colors are used to better distinguish individual particles but do not represent any specific elemental composition.

3.4 PSDs at JFJ and inside the iberulites

During periods when JFJ is cloud-free, above the PBL, and free of Saharan dust, the PSD has two modes: a stronger one near $0.05\text{ }\mu\text{m}$ and a weaker one between 0.15 and $0.4\text{ }\mu\text{m}$ (Fig. 10, green bars). The PSD measured at 11:00 UTC on February 6th, when JFJ was within the Saharan dust cloud, is monomodal, with a maximum near $0.150\text{ }\mu\text{m}$ (Fig. 10, yellow bars). It shows, similar to PSDs observed during previous Saharan dust episodes at JFJ (Chou et al., 2011), much higher concentrations than measurements without SDEs. The PSD of particles within the iberulites is monomodal, with a maximum at $2.5\text{ }\mu\text{m}$ (Fig. 10, blue bars), much larger than that for Saharan dust sampled at JFJ (e.g., $0.2\text{ }\mu\text{m}$). For these dimensions, the PSD of the particles inside the iberulites shows rather a minimum.

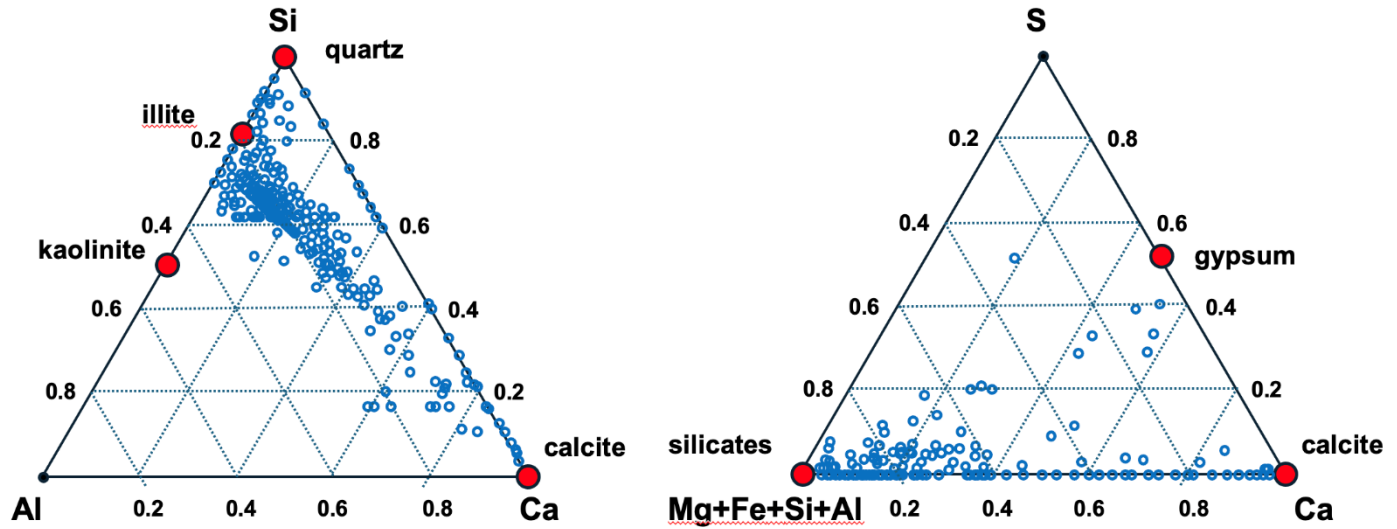
Coarse-mode particles arriving at JFJ were well documented in previous studies of particle volume distributions in dust plumes, with a mode at $1.4\text{ }\mu\text{m}$ (Field, Schwikowski et al., 1995). Saharan dust clouds transported over long distances in dust plumes, such as to Barbados during the SALTRACE campaign (Field, Weinzierl et al., 2017), to Aeronet sites in the eastern Caribbean (Field, Velasco-Merino et al., 2018), over the Mediterranean Sea during the ChArMEx/ADRI-MED campaign (Field, Denjean et al., 2016), and over Cape Verde during the SAMUN2 campaign (Field, Weinzierl et al., 2011), have similar PSDs. The largest particles observed at the Caribbean sites are well above the maximum diameter expected for settling under Stokes' law during transport. The modes observed at JFJ and in the campaigns cited above are similar to the PSDs observed in the source regions (Field, Panta et al., 2023; Bencherif et al., 2022; Dubovik et al., 2006), but are lower in concentration and lack particles $> 30\text{ }\mu\text{m}$.

Figure 10: Jungfraujoch PSD measured in April 2004, when JFJ was above the PBL, cloud-free, and no SDE (green bars); during the SDE of February 6th at 12:00 (yellow bars, shifted 1 bin to the left relative to the original data, see text); and for an iberulite sample collected in St. L  gier (blue bars).

3.5 XRD -results (Rietveld analysis) and EDS - analyses

X-ray diffraction showed that the dust contained phyllosilicates (illite, muscovite, and kaolinite, totaling $34.1\text{ wt}\%$), followed by carbonates ($27.0\text{ wt}\%$ calcite, $4.0\text{ wt}\%$ dolomite) and quartz ($23.3\text{ wt}\%$). The concentrations of gypsum and halite were below the detection limit. Analysis of individual particles within an iberulite confirms the XRD results. EDS analyses on the polished iberulite section have a resolution of $1\text{--}2\text{ }\mu\text{m}$, depending on section thickness and local composition. Compositions of particles $< 1\text{ }\mu\text{m}$ should therefore be interpreted with caution. Trends from the ideal muscovite composition toward the calcite composition, as well as toward the quartz compositions, in the (Mg+Fe+Si+K–Al–Ca) ternary diagram indicate that the particles are mixtures of the three phases (Fig. 11 a). The ternary diagram (Mg+Fe+Si+K–S–Ca), with Mg+Fe+Si+K as the "silicate" corner and Ca as the "calcite" corner (Fig. 11 b), shows measurements mainly along the joint between the silicate and calcite corners, indicating mixed particles between these minerals, with some measurements scattered in the triangle silicates-calcite-gypsum, indicating mixed particles among these phases or the presence of sulfur on other particle surfaces.

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17 **Figure 11: Ternary diagrams: (a) (Mg+Fe+Si+K–Al–Ca), (b) (Mg+Fe+Si+K–S–Ca).**

18 4. Discussion

19 4.1 Dust composition

20 Dust from potential source areas (PSA) has been characterized by bulk chemistry (Kandler et al., 2007) and mineralogy
 21 (Scheuvens et al., 2013). Mineralogical fingerprints include phyllosilicates, such as the ratio of illite to kaolinite concentrations
 22 (I/K) (Caquineau et al., 1998; Chester and Johnson, 1971; Scheuvens et al., 2013). In Northern Africa, the general trends are
 23 increases in I/K from S to N and from E to W. The value for the present single particles collected in Fribourg is approximately
 24 2.9, consistent with values reported from the Western Sahara, e.g., >2 in NW Algeria and Morocco, the source location for the
 25 SDE determined from the back trajectory calculations and satellite data. High carbonate contents (>10 wt.%, calcite > dolomite)
 26 are also a fingerprint of dust from northwestern Africa (Avila et al., 1997). Similar to illite, carbonate content decreases
 27 continuously toward the south (Paquet, 1984). The high carbonate content of dust emitted from the northern regions within and
 28 adjacent to the Atlas Mountains reflects the geology of those regions (Grousset et al., 1992).

29 4.2 Iberulite formation and insights from internal structure

30 The layer at 5000 m altitude with supersaturated atmospheric conditions is most likely the source of the ice/snowflake
 31 precipitation that led to the formation of iberulites. The temperature at the upper boundary of the dust layer was below 0 °C
 32 and became positive around 2800 m. However, melting of the frozen hydrometeors most likely began at a much lower level
 33 due to low relative humidity, in which the water vapor density of the surrounding air is lower than the equilibrium water vapor
 34 density of frozen hydrometeors at the freezing point; therefore, sublimation of water vapor occurs from the surface of the
 35 latter. Because of this sublimation process, latent cooling can push the surface temperature of the hydrometeor below 0 °C

56 (Matsuo and Sasyo, 1981; Heymsfield et al., 2015). The width of the non-melting layer in the atmosphere increases nearly
 57 linearly as relative humidity decreases, from 120 m at 90% to 700 m at 50%. The relative humidity at the top level of the
 58 main Sahara dust layer is around 50% and remains constant down to an altitude of 1700 m ASL. It is therefore probable that
 59 the melting level is displaced far into the massive Saharan dust layer and that the encounter of dust with the hydrometeors
 60 occurred when the latter was frozen. Although difficult to distinguish from aerosol particles, the reflections just below the
 61 cloud base may originate from frozen hydrometeors. Both solid ice crystals and liquid drops can capture particles. Several
 62 studies on BSC (Feng, 2007; Kyrö et al., 2009; Paramonov et al., 2011) indicate that frozen hydrometeors are more
 63 effective scavengers of aerosol particles than rain on an equivalent water-content basis. The fluttering, zigzagging fall style of
 64 frozen hydrometeors (Hashino et al., 2016; Kajikawa, 1992; Tagliavini et al., 2021; Mccorquodale and Westbrook, 2021;
 65 Stringham et al., 1969) prolongs their trajectories, thereby increasing the probability of collisions with aerosol particles
 66 and, consequently, CE. CE also increases with temperature and relative humidity, although there is a discrepancy between
 67 experimental/natural data and theory (Santachiara et al., 2023). The highest CE has been recorded for mixed precipitation
 68 types at temperatures slightly below and above 0 °C (Miller and Wang, 1989). The temperatures between the likely origin of
 69 the frozen hydrometeors and 2000 m ASL are in this range.
 70 At these temperatures, frozen hydrometeors develop a stickier liquid layer at the surface. The increase in CE at higher RH is
 71 attributable to an increase in collector capacitance (Paramonov et al., 2011). Thus, the conditions for effective scavenging
 72 were met. The Greenfield gap for frozen hydrometeors fall situations was smaller, spanning 0.09-0.3 μm, compared with
 73 the gap observed for rain. This range is also observed in the iberulites collected in the present fieldwork, supporting the
 74 role of frozen hydrometeors as dust scavengers. The increased CE of frozen hydrometeors is probably also responsible for the
 75 larger diameters observed in Swiss iberulites than in Iberian iberulites. When frozen hydrometeors exit the non-melting zone,
 76 they melt or evaporate, exhibiting a wide range of melting behaviors (Oraltay and Hallett, 2005). All frozen hydrometeors form
 77 thin liquid films on the surface and become stickier (Fujiyoshi, 1986; Knight, 1979; Leinonen and Lerber, 2018; Oraltay and
 78 Hallett, 2005). Large frozen hydrometeors increase in size through coalescence in the melting layer (Mcfarquhar et al.,
 79 2007). The behavior of scavenged aerosol particles within melting hydrometeors has not been analyzed to date. Most likely,
 80 they are incorporated into the newly formed raindrops. Within and below the melting layer, due to the very low relative
 81 humidity (45% at 1000 m, at the bottom of the massive dust layer), raindrops will dry very rapidly. A technological analog
 82 of this process is the (spray) drying of a powder suspension, which is used, e.g., in the ceramic, food, or pharmaceutical
 83 industry (Santos et al., 2018). The difference between the drying of a droplet in a spray drier and that of a rain droplet falling
 84 out of a cloud is the temperature difference between the droplet and the drying air stream, which is around 200°C in a spray
 85 drier. Droplets in a spray dryer relax into spherical shapes and are analogous to raindrops. The latent heat of water evaporation
 86 induces a strong heat flux from the droplet surface into the gas stream. This, in turn, drives thermophoretic particle displacement
 87 toward the droplet surface and a specific microcirculation in a layer near the surface, driven by the surface-tension gradient
 88 (Iskandar et al., 2003). This microcirculation entrains particles toward the droplet surface, leading to size- and density-
 89 based segregation. Smaller and/or less dense particles move faster toward the droplet surface, forming a surface layer.
 90 Coarser particles are concentrated in the core. Such a shell-core structure was observed in the present iberulite and has also
 91 been reported in the Iberian examples (Díaz-Hernández and Párraga, 2008; Párraga et al., 2021), with fine-grained
 92 phyllosilicates concentrated in the shell and coarse-grained quartz grains in the core.

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5. Conclusion

To our knowledge, this analysis is the first detailed study of iberulite fall in Switzerland. In contrast to the Iberian cases, the IF fall occurred under much colder conditions, e.g., temperatures around 0° and decreasing relative humidity along the fall trajectory. Iberulites form through the accumulation of particles inside raindrops. A comparison of the PSD inside the iberulites with the PSD measured in the dust cloud at the Jungfraujoch, which encountered the same dust cloud, revealed a Greenfield gap in the iberulite PSD, i.e., a lack of particles in the range between 0.1 and 0.3 µm. The presence of a Greenfield gap within the iberulites supports below-cloud scavenging, i.e., particle capture via collisions with droplets below a cloud, as the mechanism for particle accumulation. The gap arises from particle trajectories in the flow around the falling droplet, which depend on particle size. The freezing temperature, low relative humidity, and ceilogram signals suggest that particle collisions occurred not with raindrops but with snowflakes or ice crystals. These are known to be better scavengers than raindrops.

Author contribution

RJ, FP and JD initiated the research. RJ, FP, JD and NC carried out the measurements. GB, RJ, FP, JVD and NC analyzed the data. SM provided data from Jungfraujoch. GB, wrote the paper. All co-authors proofread and commented on the paper. GB prepared the manuscript with contributions from all co-authors.

Competing interests

The authors declare that they have no conflict of interest.

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