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**Titre du sujet : Tracing anthropogenic ultrafine particles in the Anthropocene using natural archives: development of high-resolution spICP-MS and isotopic fingerprinting in ice cores and peatlands**

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### **Scientific context and rationale**

The Anthropocene is increasingly characterized by the global dispersion of anthropogenic ultrafine particles (UFPs, <100 nm), whose environmental fate, transport mechanisms, and long-term accumulation remain poorly constrained. Emitted by combustion processes, industrial activities and urban infrastructures, these particles are now detected in remote environments, including polar regions, indicating efficient long-range atmospheric transport and deposition in natural archives.

Despite their potential importance for climate feedbacks and ecosystem contamination, UFPs remain largely invisible in classical monitoring frameworks due to analytical constraints linked to their nanometric size, complex composition and extremely low concentrations.

Natural archives such as ice cores and peatlands provide unique records of past atmospheric inputs. Ice preserves high-resolution atmospheric deposition, while peat integrates longer-term continental fluxes. However, these archives have never been systematically exploited for ultrafine particle reconstruction at the particle scale.

This project addresses this gap by combining single-particle ICP-MS (spICP-MS and spICP-ToF-MS) with multi-isotopic tracers (Pb, Sr, Nd, Cu, Zn) and rare earth element (REE) signatures to reconstruct sources, transport and deposition processes of anthropogenic UFPs.

Main hypothesis: *anthropogenic ultrafine particles are efficiently transported through the atmosphere and preserved in ice and peat archives, where they retain diagnostic chemical and isotopic fingerprints allowing reconstruction of their origin and evolution during the Anthropocene.*

O1 — Detection and quantification of UFPs in natural archives: develop and optimize extraction and analytical protocols to quantify ultrafine particles in ice cores and peat sequences.

O2 — Development of selective extraction protocols for peat matrices: design and validate procedures to isolate inorganic nanoparticles from organic-rich matrices while preserving particle integrity.

O3 — Multi-elemental and isotopic fingerprinting of UFPs: combine spICP-MS/spICP-ToF-MS (size, number, composition) with selected isotopic systems (Pb, Sr, Nd, Cu, Zn) and REE signatures to establish robust source attribution frameworks.

O4 — Reconstruction of anthropogenic particle sources and transport pathways: integrate chemical and isotopic tracers to distinguish natural and anthropogenic particles, identify emission sources (industrial, combustion, urban), and reconstruct atmospheric transport and deposition processes.

### **State of the Art and Originality**

Ice-core chemistry has been widely used to reconstruct past atmospheric pollution (e.g., heavy metals, sulfate, black carbon), but ultrafine particulate matter remains almost entirely unexplored due to analytical limitations. Recent developments in single-particle ICP-MS, nano-extraction protocols and ultra-trace isotopic measurements now enable a shift from bulk geochemistry to particle-scale reconstruction of atmospheric contamination.

This project is original in four ways: it targets true ultrafine particles (<100 nm) rather than bulk proxies; it integrates ice and peat archives within a unified framework; it couples particle-scale chemistry with multi-isotopic geochemistry; and it builds directly on methodological advances developed in Arctic and alpine environments, including previous GRAAL experience.

## Methodology

WP1 — Sampling and archive selection: The PhD candidate will participate in field campaigns in Greenland in collaboration with the Greenland Institute of Natural Resources (GINR), the Geological Survey of Denmark and Greenland (GEUS), and Kangerlussuaq International Science Support (KISS). These campaigns will ensure high-quality sampling of ice cores (building on GRAAL experience) and peat sequences, together with stratigraphic control and dating. This step guarantees robust Arctic field training and direct involvement in international collaborations.

WP2 — Development of extraction protocols (key innovation for peatlands): Ice cores will be processed using ultra-clean meltwater filtration and particle preservation methods. For peatlands, a dedicated methodological development will be conducted to separate nanoparticles from organic matrices using density separation and chemical/enzymatic treatments while preserving inorganic fractions. Protocols will be validated using reference materials and spike experiments, ensuring robust UFP recovery from complex matrices.

WP3 — Single-particle chemical characterization: Ultrafine particles will be characterized using spICP-MS (size and number concentrations) and spICP-ToF-MS (multi-element fingerprints). Target elements include Fe, Ti, Al, Pb, Cu, Zn, Sn, Sb, Cr and Ni, depending on source signatures. This will generate time-resolved particle datasets and statistical classifications of particle populations.

WP4 — Isotopic and REE fingerprinting: The same archive levels will be analyzed for isotopic systems (Pb, Sr, Nd, Cu, Zn) and rare earth element patterns. These tracers will allow discrimination between lithogenic and anthropogenic sources and between different industrial or combustion-related emissions. All datasets will be integrated with particle-scale chemical information to build a coherent source attribution framework.

WP5 — Integration and Anthropocene reconstruction: This work package aims to integrate the chemical, particle-scale, and isotopic datasets produced in the PhD project in order to identify the main sources of ultrafine particles recorded in the studied archives and to assess their temporal variability, through the comparison of ice-core (high-resolution atmospheric signal) and peat records (integrated terrestrial signal). This will ultimately lead to the development of a consistent interpretation framework for UFP sources and deposition processes in the context of the Anthropocene.

## Expected Results and Impact

This project will deliver the first reconstruction of ultrafine particle deposition in natural archives and establish a new particle-scale geochemical and isotopic fingerprinting framework. It will provide novel constraints on long-range transport of anthropogenic nanoparticles and significantly improve understanding of atmospheric pollution at the nanoscale. Methodologically, it will advance environmental nanogeochemistry by enabling direct linkage between individual particles and their emission sources.

## Risk Management

Main risks include low particle concentrations, addressed through optimized pre-concentration and ultra-clean procedures; peat extraction complexity, mitigated through iterative protocol development and reference materials; isotopic sensitivity limits, managed by focusing on robust systems (Pb, Sr, Zn); and contamination risks, controlled through strict clean-lab protocols and procedural blanks.

**Conclusion:** *This PhD project proposes a new way of reading the Anthropocene signal preserved in natural archives by targeting anthropogenic ultrafine particles at the individual particle scale. By combining single-particle analytical techniques with multi-isotopic fingerprinting, it establishes a new interface between atmospheric chemistry, nanogeochemistry and environmental archives.*

**Profile of the candidate:** Master's or engineering degree in geosciences, environmental sciences, chemistry or related fields. Strong background in geochemistry, environmental chemistry or Earth surface processes is required. Experience with ICP-MS or isotope geochemistry is an advantage. Interest in analytical development (spICP-MS, nano-analysis) and data processing (statistics, source apportionment) is expected.

The candidate must be autonomous, rigorous and motivated by interdisciplinary research. Participation in Arctic field campaigns (including Greenland) is essential. Excellent written and spoken English is required.

**Training and Skills Developed:** The candidate will acquire expertise in clean geochemistry, trace element analysis, single-particle ICP-MS, multi-isotope geochemistry, environmental archives (ice and peat), and quantitative source apportionment modelling.

**Funding of the PhD project:** The PhD will be supported through the Université Paris Cité Foundation via the GRAAL Arctic expedition ([GRAAL](#)), providing logistical and field support in Greenland. It is also aligned with a submitted ANR Flash project on Arctic environmental archives, which will support analytical and field components if funded. This combined strategy ensures feasibility of both Arctic fieldwork and high-resolution laboratory analyses.