El Gordo breakdown: research & experiment

– responses from Claude AI to prompts by Juan Corrin, 3/11/2025

JC: Are there any published scientific studies that have looked at this "grain rain" phenomenon?

Based on my search, here's what I found regarding published scientific studies:

The Short Answer: Limited Direct Studies

The specific phenomenon of visible fine particle "rain" from cave ceilings doesn't appear to have a widely recognized name in the scientific literature, though the underlying process - **granular disaggregation** or **granular disintegration** of sandstone - is extensively documented ScienceDirectResearchGate.

What HAS Been Studied:

1. Granular Disaggregation/Disintegration

Research shows that sandstone disintegration occurs through grain-by-grain loss, with studies documenting "small mounds of loose sand at cliff bases, sand deposits in cavities, or sand cones and sheets emerging from fissures" ScienceDirect. Multiple experimental studies have confirmed that granular disintegration is the dominant mechanism of sandstone deterioration, with cement dissolution reducing binding forces between grains ResearchGateSpringer.

A comprehensive review by Turkington & Paradise (2005) in *Geomorphology* traces sandstone weathering research over the past century, noting a progression from description to process-based explanations ScienceDirectResearchGate.

2. Cave Breakdown Monitoring

The U.S. National Park Service explicitly identifies "stability-breakdown, rockfall and partings" as a vital sign to monitor in caves, recommending recording the "date and location of each new piece of breakdown" U.S. National Park Service. However, this focuses on larger rockfall events rather than continuous fine particle loss.

3. Airborne Sedimentation in Caves

Interestingly, cave monitoring literature discusses "airborne sedimentation" - the sedimentation of dust and lint in caves due to natural cave processes such as airflow U.S. National Park Service. This recognizes that particles do fall through cave air, though it's typically studied in the context of human-caused dust rather than roof weathering.

4. Sandstone Cave-Specific Studies

Studies document that grain-by-grain recession occurs "along deep fractures or on the walls of underground conduits" ScienceDirect, but most research focuses on surface outcrops rather than cave interiors.

Research in Spanish sandstone caves (Albarracín Cultural Park) has documented that salt and wetting-drying weathering cause granular disintegration and flaking in cave environments Springer, though this studied rock art deterioration rather than the visible particle fall phenomenon.

5. Roof Failure Precursors

Studies on underground mining establish that structural damage leading to collapse "takes a long time, even years, to occur, and that there is a gradual progression in time, intensity, and appearance of recorded precursors" ScienceDirect. Recent research using microseismic monitoring shows that "numerous tensile fracture events occur" during the development stage of collapse ScienceDirect.

The Gap in Literature:

What's Missing: A specific study documenting and characterizing the continuous, visible "rain" of fine particles (10-100 micrometers) from sandstone or mixed lithology cave ceilings as:

- A diagnostic feature
- A potential warning sign
- A quantifiable weathering rate indicator

The phenomenon you're observing sits at the **intersection** of several research areas (sandstone weathering, cave breakdown, airborne particles) but doesn't appear to have been studied as a distinct, named phenomenon in the speleological literature.

Why This Gap Exists:

1. Sandstone cave research is relatively underdeveloped compared to limestone caves, partly due to "the widespread belief that weathering of sandstone is a relatively straightforward case of physical breakdown" ScienceDirect
2. The particles are only visible under specific lighting conditions, making them easy to miss during standard cave surveys
3. Most cave breakdown research focuses on dramatic collapse events rather than slow, continuous grain loss

Recommendation:

Your observation may represent an **under-documented phenomenon** that could be valuable to characterize scientifically, especially given the presence of recent block falls. The combination of visible particle rain with fresh breakdown in an interbedded sequence could provide insights into failure precursors that current literature doesn't adequately address.

If this cave is significant, documenting the spatial distribution of particle density, correlations with weather, and any temporal changes could contribute genuinely novel data to cave geomorphology literature.

JC: Given that, in this chamber, not only rock particles are falling but that water droplets may also fall after percolating through the overlying rock. Devise a full experimental method (which may last a year or two) to measure the rate of particle fall, or the mg/sq.m that may fall annually. This may involve some form of sticky 'tape' set up in a number of places scattered across the chamber.

This is an excellent question that requires a practical, rigorous experimental design for measuring particle fall rates in a cave environment. The user wants to quantify both rock particles and potentially separate them from water droplets. Let me think through a comprehensive experimental protocol.

Key considerations:

1. Long-term deployment (1-2 years)
2. Multiple sampling locations across the chamber
3. Need to distinguish rock particles from water droplets
4. Cave environment - humidity, potential for human disturbance, minimal impact
5. Need to quantify mass per area per time
6. Should account for spatial variability
7. Should be able to distinguish particle types (sandstone vs limestone)
8. Should not damage the cave environment

I should design:

- Collector types
- Sampling strategy
- Data collection protocols
- Analysis methods
- Quality control
- Safety considerations

Let me create a comprehensive experimental protocol that would actually work in practice.

Comprehensive Experimental Protocol for Measuring Cave Ceiling Particle Fall Rates

EXPERIMENTAL DESIGN OVERVIEW

Duration: 24 months (2 annual cycles to capture seasonal variation) **Target Precision:** ±5% measurement error **Primary Metric:** mg/m²/year of dry particulate matter **Secondary Metrics:** Particle size distribution, mineralogical composition, spatial variation, temporal patterns

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PHASE 1: PRE-EXPERIMENTAL SETUP (Months 0-1)

1.1 Site Characterization & Mapping

Ceiling Survey:

- Create detailed map of chamber ceiling at 1:50 scale
- Mark all visible fractures, bedding planes, and the mineral vein
- Document areas of visible particle rain intensity (light/moderate/heavy zones)
- Photograph ceiling from multiple angles with scale bars
- Record ceiling height at each proposed collector location

Environmental Baseline:

- Install 3-5 temperature/humidity data loggers (placed strategically around chamber)
- Set to record every 2 hours
- Install simple rain gauge at entrance to correlate with percolation events
- Document prevailing air flow patterns using smoke tubes

1.2 Collector Grid Design

Stratified Random Sampling Approach:

Create three strata based on observed particle rain intensity:

- **Stratum A (Heavy):** Areas with visibly dense particle fall - 8 collectors
- **Stratum B (Moderate):** Intermediate zones - 8 collectors
- **Stratum C (Light):** Areas with minimal visible particles - 6 collectors
- **Stratum D (Control):** Areas under overhangs or protected - 2 collectors

Total: 24 primary collection stations

Additionally:

- 4 "mobile" collectors for targeted studies
- 6 duplicate collectors (co-located with primaries for QA/QC)

PHASE 2: COLLECTOR DESIGN & CONSTRUCTION

2.1 Primary Collector System: "Dual-Layer Trap"

Design Specifications:

Layer 1 - Dry Particle Collector (Top Layer):

Materials:

- 20cm × 20cm (400 cm²) aluminum foil tray (pre-weighed)
- Coated with petroleum jelly or specialized adhesive (PTFE-based like Tangle-Trap)
- Alternative: Microscope slide-grade glass with thin silicone grease coating
- Raised edges (2cm) to prevent lateral loss

Purpose: Capture airborne particles that fall slowly through air

Layer 2 - Water Separator (Bottom Layer):

Materials:
- 25cm × 25cm collection funnel
- Fine nylon mesh (50 µm pore size) suspended 5cm below Layer 1
- Drainage tube leading to graduated collection bottle
- Bottle contains biocide (0.1% sodium azide) to prevent algal growth

Purpose: Capture water droplets and any particles carried by water
Allows differentiation between dry fallout and water-borne particles

Mounting System:

- Adjustable tripod stand (stainless steel or PVC)
- Height: 1.5m above cave floor (human impact avoidance)
- Level bubble indicator built in
- Protective cage (optional: 40cm diameter wire mesh hemisphere) to prevent human contact while allowing particle entry
- ID tag: unique alphanumeric code + QR code

2.2 Control & Calibration Collectors

Sealed Reference Collectors (n=4):
- Identical to primary collectors but sealed with fine mesh cover
- Measures contamination from lateral air movement only
- Helps quantify background dust vs. ceiling-derived material

Laboratory Control:
- Maintain 2 identical collectors in lab conditions
- Track handling contamination and adhesive degradation

PHASE 3: DEPLOYMENT PROTOCOL (Month 1)

3.1 Installation

Pre-deployment:

1. Clean all collectors with filtered compressed air in clean lab
2. Weigh all components to 0.1mg precision (analytical balance)
3. Photograph each collector with scale bar and ID tag
4. Record GPS coordinates and distance/bearing to permanent cave features
5. Document ceiling characteristics directly above each collector

Deployment checklist per station:
- Level collector using spirit level (±1°)
- Record exact height above floor
- Photograph station from 4 orthogonal directions

- Mark position on cave floor with discreet permanent marker
- Record ceiling height above collector
- Document any drip points or obvious fractures above

3.2 Documentation System

Create field datasheet recording:

- Station ID
- Date/time of installation
- Collector height
- Ceiling height
- Distance from nearest wall
- Distance from entrance
- Local environmental conditions
- Photographs taken
- Observer name
- Any anomalies

PHASE 4: MONITORING & MAINTENANCE (Months 1-24)

4.1 Collection Schedule

Primary Collections:

- **Monthly:** Months 1-3 (establish baseline variability)
- **Quarterly:** Months 4-24 (long-term monitoring)

Why this schedule?

- Monthly initially captures seasonal onset patterns
- Quarterly reduces disturbance while maintaining temporal resolution
- Provides 8 quarterly samples over 2 years

4.2 Collection Procedure (Critical Protocol)

Before entering chamber:

1. Don clean lab coat and powder-free nitrile gloves
2. Prepare pre-weighed replacement collectors in sealed containers
3. Bring field kit: forceps, sealable sample bags, labels, camera, datasheet

At each station:

1. Photograph collector in situ (note any obvious changes)
2. Record visual observations (unusual debris, damage, water pooling)
3. Carefully remove Layer 1 (dry particle trap):
   - Use wide forceps to avoid touching collection surface
   - Slide immediately into pre-labeled rigid container
   - Seal container (avoid jarring that could dislodge particles)
4. Record water volume in Layer 2 bottle
5. Remove bottle, seal, label
6. Install fresh pre-weighed collector
7. Re-level and photograph
8. Record time of collection

Post-collection:

- Transport samples in rigid container to prevent disturbance
- Store at consistent temperature until analysis
- Never stack samples

4.3 Quality Assurance During Monitoring

Field blanks:

- Deploy 2 collectors that are opened for 5 minutes then immediately sealed
- Quantifies contamination during handling (do this quarterly)

Duplicate sampling:

- 6 stations have co-located duplicates
- Calculate relative percent difference: RPD = |A-B|/((A+B)/2) × 100
- Target: RPD < 20%

PHASE 5: LABORATORY ANALYSIS

5.1 Gravimetric Analysis (Primary Measurement)

Procedure:

1. **Drying Phase:**

   - Allow samples to equilibrate to lab conditions (24h, 20±2°C, 50% RH)
   - Place in desiccator for 48h
   - Re-weigh collection surface to 0.1mg precision

2. **Gross Mass Calculation:**

   Gross particle mass = (Sample weight + collector) - (Initial collector weight)

3. **Adhesive Correction:**

   - Weigh control samples (never deployed) after same storage time
   - Calculate adhesive evaporation rate
   - Subtract from gross mass

4. **Water-Soluble Component (Optional Detail):**

   - Rinse collection surface with known volume of distilled water
   - Filter rinse through pre-weighed filter (0.45 µm)
   - Dry filter at 105°C for 24h
   - Weigh to determine water-soluble vs insoluble fractions

5. **Final Calculation:**

   Particle fall rate (mg/m²/period) = Net dry particle mass (mg) / Collection area (m²)

   Annual rate = (Quarterly average × 4) or sum of all periods

5.2 Particle Characterization

Subsample Analysis (every 4th sample or where anomalies observed):

A. Particle Size Distribution:

- Transfer particles to microscope slide
- Use stereomicroscope (40-100× magnification)
- Measure longest axis of 100+ random particles per sample
- Use image analysis software (ImageJ or equivalent)
- Report as size classes: <10µm, 10-50µm, 50-100µm, 100-500µm, >500µm

B. Mineralogical Composition:

- **Visual sorting:** Under stereomicroscope, separate:
  - Clear/translucent grains (quartz)

  - White/calcite-appearing particles
  - Colored/clay-looking material
  - Organic material (if any)

- Weigh each fraction
- Calculate percentage composition

C. Advanced Analysis (Optional, for key samples):

- **X-ray diffraction (XRD):** Definitive mineral identification
- **Scanning Electron Microscopy (SEM):** Particle morphology

  - Distinguish angular (fractured) vs rounded (weathered) grains
  - Look for dissolution features on calcite

- **Energy Dispersive X-ray Spectroscopy (EDS):** Elemental composition

5.3 Water Chemistry (Layer 2 samples)

Analysis of collected percolation water:

- pH (field measurement if possible, else lab within 24h)
- Electrical conductivity
- Total dissolved solids (TDS)
- Major ions: Ca^{2+}, Mg^{2+}, HCO_3^-, SO_4^{2-}, Cl^-
- Turbidity (suspended particulates)
- Filter water through pre-weighed filter, dry, weigh = water-borne particles

Purpose: Correlate water chemistry with particle type and rate

PHASE 6: DATA ANALYSIS & INTERPRETATION

6.1 Statistical Analysis

Descriptive Statistics:

- Calculate mean, median, standard deviation for each stratum
- Range (min-max) and coefficient of variation
- Test for normality (Shapiro-Wilk test)

Spatial Analysis:

- Create interpolated surface map of particle fall rates (kriging or inverse distance weighting)
- Identify hotspots of high particle production
- Correlate with ceiling features (fractures, bedding planes, vein location)
- Use GIS software if coordinates available

Temporal Analysis:

- Plot time series for each collector
- Identify seasonal patterns (ANOVA by season)
- Correlate with:
  - Temperature/humidity records
  - Rainfall data
  - Visitor numbers (if applicable)
- Calculate coefficient of temporal variation

Comparison Testing:

- Compare strata (heavy vs moderate vs light zones)
  - Use Kruskal-Wallis test if non-normal
  - ANOVA if normally distributed

- Compare Year 1 vs Year 2 (paired t-test)
- Compare particle types (sandstone vs limestone)

6.2 Rate Calculations & Extrapolation

Chamber-Wide Estimate:

1. Calculate mean rate for each stratum: $\bar{R}_a$, $\bar{R}_\beta$, $\bar{R}_c$
2. Measure area of chamber ceiling in each stratum: A_a, A_β, A^c
3. Chamber total = $(\bar{R}_a \times A_a) + (\bar{R}_\beta \times A_\beta) + (\bar{R}_c \times A^c)$
4. Express as kg/year for entire chamber

Ceiling Retreat Rate:

If sandstone density = ~2.2-2.5 g/cm³:

Retreat rate (mm/year) = Particle fall rate (g/m²/year) / Density (g/cm³) / 10000 cm²/m²

Example:

100 mg/m²/year = 0.1 g/m²/year
0.1 / 2.3 / 10000 = 0.0000043 mm/year = 4.3×10^{-6} mm/year
= 0.0043 mm/1000 years = 4.3 mm/million years

6.3 Hazard Assessment

Warning Threshold Development:

Compare particle rates to:

- Areas where blocks recently fell (if collectors there)
- Areas showing visible ceiling fractures
- Literature values for "stable" vs "unstable" sandstone surfaces

Develop traffic light system:

- **Green (safe):** < X mg/m²/month
- **Yellow (monitor):** X-Y mg/m²/month
- **Red (avoid):** > Y mg/m²/month

Where X and Y are determined by data-driven clustering analysis

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PHASE 7: REPORTING & DISSEMINATION

7.1 Interim Reports (Every 6 months)

Content:

- Summary statistics (mean rates by stratum)
- Time series plots
- Spatial distribution maps
- Notable anomalies or events
- Preliminary safety assessment
- Any equipment failures or modifications

7.2 Final Report (Month 25-26)

Structure:

1. **Executive Summary**
    - Key findings in 1-2 pages
    - Safety recommendations
    - Chamber-wide particle fall rates
2. **Methods**
    - Full protocol description
    - QA/QC results
    - Any deviations from protocol
3. **Results**
    - Comprehensive statistics
    - All maps and figures
    - Temporal patterns
    - Spatial patterns
    - Particle characterization
4. **Discussion**
    - Comparison to literature values
    - Interpretation of processes
    - Relationship to block fall hazard
    - Environmental controls
5. **Conclusions & Recommendations**
    - Is chamber actively failing or stable?
    - Which areas are highest risk?
    - Recommendations for access management
    - Suggestions for continued monitoring
6. **Appendices**
    - Raw data tables
    - Collector locations (map and coordinates)
    - Photographs
    - QA/QC results
    - Statistical outputs

7.3 Scientific Publication

Consider submitting to:

- *International Journal of Speleology*
- *Geomorphology*
- *Environmental Earth Sciences*
- *Cave and Karst Science*

Novel contributions:

- First quantitative study of particle rain rates in mixed lithology caves
- Relationship between particle fall and structural failure
- Methodology for long-term cave ceiling monitoring

ADDITIONAL CONSIDERATIONS

Safety & Ethics

Human Safety:

- Avoid placing collectors directly under areas with fresh block falls
- Mark collector locations clearly to prevent tripping
- Establish access protocols if cave has visitors

Cave Conservation:

- Minimize foot traffic to collector locations
- Use established paths where possible
- No permanent fixtures (all equipment removable)
- Report unusual biological features encountered

Equipment Budget (Approximate)

Item	Quantity	Est. Cost
Aluminum collection trays	30	$150
Adhesive (Tangle-Trap)	2L	$80
Collection bottles	100	$100
Stainless steel stands	30	$600
Protective cages	30	$300
Temperature/humidity loggers	5	$500
Analytical balance (0.1mg)	1	$3000*
Field kit supplies	-	$200
Storage containers	50	$150
Total		**~$5,080**

*If lab access available, major cost reduced

Contingencies

If adhesive fails:

- Switch to dry collection (weighing empty trays)
- May lose finest particles but capture bulk

If water contamination severe:

- Add raised lip to Layer 1
- Use hydrophobic coating on collection surface

If human disturbance:

- Add lockable protective cages
- Reduce collection frequency
- Focus on least accessible areas

EXPECTED OUTCOMES

Based on literature values for sandstone granular disaggregation:

Predicted range: 10-1000 mg/m²/year

- Lower end: Stable, well-cemented surfaces
- Upper end: Actively weathering, poorly cemented zones

Your observations suggest moderate to high rates, possibly 100-500 mg/m²/year in active zones.

The presence of recent block falls suggests some zones may exceed 1000 mg/m²/year - which would be a **significant finding** indicating active structural failure.

This protocol would provide the quantitative data needed to assess whether the "grain rain" is:

1. **Benign weathering** - slow equilibrium process
2. **Failure precursor** - warning sign of imminent collapse

Would you like me to detail any specific aspect further, such as the adhesive selection, statistical methods, or alternative collector designs?

JC: OK. Good start. However, you need more information.
This chamber takes an underground journey of at least 2 hours to reach. The trip involves SRT pitches with some difficult crawls and climbs meaning that the caver arrives at the chamber in a muddy and dusty state. In reality, the chamber might be visited by 2 people, twice a year. They could spend about 4 hours setting out the equipment and the same collecting the items at the end of the underground phase. (A change of clothes preventing contamination would be vital at the entry point to the chamber, where it is possible to stand up. It is also highly likely that movement around the boulder-floored chamber will raise dust.)
Take those factors into account and completely rewrite a simplified but thorough experimental technique.

Simplified Experimental Protocol for Remote Cave Particle Fall Rate Measurement

REALITY CHECK: Critical Constraints

Access limitations:

- 2-hour underground approach with SRT pitches
- Difficult crawls/climbs - cavers arrive muddy
- Maximum 2 people, realistically 2 visits per year
- 4-hour working window in chamber
- Boulder floor generates dust when traversed
- All equipment must be compact, lightweight, robust for underground transport

Revised Strategy: Ultra-simple, self-contained, annual monitoring system

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REVISED EXPERIMENTAL DESIGN

Duration: 2 years minimum (3 visits: deployment, Year 1 collection, Year 2 collection) **Primary Metric:** mg/m²/year dry particle accumulation **Number of Collectors:** 8 primary + 2 contamination controls = **10 total Philosophy:** "Set and forget" - collectors must function unattended for 12 months

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PHASE 1: PRE-DEPLOYMENT PREPARATION (Surface/Lab Work)

1.1 Collector Design: "Bomb-Proof Passive Trap"

Core Design Principle: Simple, robust, zero maintenance

Collector Specifications:

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BASE UNIT (per collector):
- 150mm diameter PVC pipe cap (white/light colored for visibility)
- Depth: 50mm
- Collection area: 177 cm² (0.0177 m²)
- Pre-weighed to 0.01g using lab balance

COLLECTION SURFACE:
- Single layer of glass fiber filter paper (Whatman GF/C or equivalent)
  - 125mm diameter disc
  - Pre-weighed in lab to 0.001g
  - Placed in base of cap
  - Held with 3 tiny dabs of silicone (weighed) at edges only

COVER (prevents lateral contamination):
- 200mm diameter aluminum foil "roof"
- Mounted 100mm above collection surface
- Bent to create gentle slope (sheds water to sides)
- Supported by 3 bamboo skewers glued to cap edge
- Purpose: Blocks lateral dust, allows vertical fall only

MOUNTING:
- Three 10mm holes drilled in base
- Secured to substrate with wire or cord through holes
- Or weighted with pre-weighed rocks placed inside
```

Why This Design:

- Durable enough for 12-month deployment
- Simple enough to deploy/collect in 4 hours total
- No adhesives (eliminates evaporation concerns)
- Filter paper is:
    - Lightweight for transport (30 collectors = 200g)
    - Inert and stable
    - Easy to weigh precisely
    - Can be analyzed for mineralogy later
- Roof prevents most human-generated dust from entering laterally
- White PVC easy to relocate after 12 months

1.2 Pre-Deployment Lab Work

Prepare collectors (1-2 months before deployment):

1. **Label everything:**
    - Engrave each PVC cap base with unique ID: P01-P08 (primary), C01-C02 (control)
    - Write ID on filter paper edge with pencil
2. **Weigh components:**

```
For each collector, record to 0.001g:
- Empty PVC cap weight
- Filter paper weight
- Silicone dabs weight (use same amount each time)
- Cover assembly weight
- Any rocks/weights if using

Record everything in waterproof field notebook
```

11. **Assemble in clean environment:**
    - Install filter paper in cap
    - Add pre-weighed rocks if using as weights (bag them in sealed plastic)
    - Attach covers
    - Wrap each complete collector in plastic bag
    - Pack in rigid boxes (repurposed food containers)
12. **Prepare contamination controls (C01, C02):**
    - Identical to primary collectors BUT
    - Cover is completely sealed (aluminum foil taped all around)
    - These catch only lateral contamination from human activity
    - Deploy near entrance to chamber and in middle of working area
13. **Pack transport kit:**

```
Rigid container 1 (carry in):
- 10 pre-assembled collectors in bags
- Waterproof notebook + pencils
- Camera in waterproof case
- 25m measuring tape
- Compass
- Chalk for marking positions
- LED headtorch (plus spares)

Rigid container 2 (carry out later - empty on entry):
- 10 rigid plastic boxes with fitted lids (for sample return)
- Labels
- Backup bags
```

27. **Prepare clean-room clothing (critical):**

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For each caver:
- Clean coveralls (Tyvek disposable suits ideal)
- Clean overboots or spare clean wellies
- Clean gloves
- All sealed in waterproof bags INSIDE transport bags
```

PHASE 2: SITE SELECTION & MAPPING (Pre-Deployment Surface Planning)

Before the deployment trip:

Use any existing surveys, photos, or cave descriptions to:

1. **Identify target areas** (8 locations):
    - 3 collectors: Under areas with observed heavy particle rain
    - 3 collectors: Under areas with moderate particle rain
    - 2 collectors: Under stable-appearing ceiling (baseline)
2. **Plan layout:**
    - Spread collectors across chamber (avoid clustering)

    - Place away from obvious walking routes
    - Locate near permanent features for relocation
    - Minimum 3m spacing between collectors
    - Draw sketch map showing planned approximate positions
3. **Pre-plan photography:**
    - Decide on photo points for documentation
    - Plan to take systematic photos for later ceiling mapping

Control Placement Plan:

- C01: Near chamber entrance (high human disturbance zone)
- C02: In middle of chamber working area

PHASE 3: DEPLOYMENT VISIT (Year 0 - Autumn)

3.1 Journey In (2 hours)

Pack strategy:

- Person 1: Collector container (lightweight)
- Person 2: Clean clothes bag + return container (empty)
- Distribute items to balance load

Critical: Keep collector container sealed until chamber reached

3.2 Chamber Entry Protocol (30 minutes)

Before entering main chamber area:

1. **Stop at entrance alcove/standing point**
2. **Decontamination:**
    - Remove muddy oversuit, boots
    - Brush/shake off as much mud as possible
    - Change into CLEAN Tyvek suits and clean boots
    - Put muddy gear in sealed bag
3. **Minimize disturbance:**
    - From this point: slow, deliberate movements
    - Step carefully to minimize dust raising
    - One person remains at entrance initially
4. **Open collector container carefully**
    - Check all collectors intact
    - Lay out on clean surface

3.3 Deployment Procedure (2.5 hours for 10 collectors)

Systematic approach - 15 minutes per collector:

Person 1 (Deployer):

1. Carry single collector to target position

2. Clear placement spot of any loose debris
3. Remove collector from bag
4. Level as best possible (use small rocks to shim)
5. Secure with wires through holes OR weight with rocks
6. Mark position with chalk arrow on nearby boulder pointing to collector
7. Photograph:
    - Wide shot showing collector position in chamber
    - Close-up of collector with ID visible
    - Ceiling directly above collector
    - Nearby reference features
8. Record in notebook:
9. `Collector ID: P01Date: 15-Oct-2025Time: 14:30Location: NW corner, 3m from calcite vein, 8m from entranceBearing to entrance: 135°Distance to entrance: 8mCeiling height: ~45m (estimated)Ceiling description: Interbedded limestone/sandstone, visible fractureNearby features: Large boulder with quartz vein on west sidePhotos: 001-004Notes: Moderate particle rain visible in headtorch beamDeployed by: [initials]`

Person 2 (Navigator/Recorder):

- Maintains master map
- Records positions on sketch
- Keeps track of time
- Manages equipment
- Takes backup photos

Deploy in this order:

1. C01 (control at entrance) - FIRST
2. P01-P08 (primaries)
3. C02 (control in working area) - LAST

Why this order:

- C01 captures baseline contamination from initial entry
- Primary collectors deployed while chamber is relatively undisturbed
- C02 captures maximum contamination from entire deployment process

3.4 Final Documentation (30 minutes)

1. **Create master map:**
    - Sketch chamber outline
    - Mark collector positions
    - Note key features
    - Measure key distances with tape
2. **Panoramic photos:**
    - From chamber entrance
    - From chamber center
    - Show overall layout
3. **Final check:**
    - Verify all collectors secure
    - Check all lids are on
    - Verify all photos taken
    - Double-check notebook entries
4. **Leave chamber:**

- Change back to caving gear
- Pack clean clothes for removal
- Minimize disturbance on exit
- One person exits first, other follows 10 minutes later (reduces dust)

3.5 Exit & Surface Work

Immediately upon reaching surface:

- Transcribe field notes to computer
- Download and backup all photos
- Store notebook safely

PHASE 4: COLLECTION VISIT (Year 1 - Autumn - 12 months later)

4.1 Journey In

Same protocol as deployment, including clean clothes

Additionally carry:

- Return container with 10 fitted boxes
- Clean tweezers/forceps (long, for reaching into collectors)
- Backup sample bags
- New set of 10 collectors (if continuing to Year 2)

4.2 Collection Protocol (2.5 hours)

Critical principle: COLLECT CONTROLS FIRST

Contamination Assessment:

1. Collect C01 first
2. Then work through primaries P01-P08
3. Collect C02 last

Per Collector (12-15 minutes each):

Documentation BEFORE touching:

1. Photograph in situ (same angles as deployment)
2. Note any obvious changes:
    - Displaced?
    - Debris on cover?
    - Water pooling?
    - Biological growth?
    - Damage?

Sample Collection:

```
1. Remove cover carefully (place in bag for return/reuse)
2. Photograph collection surface
3. Visual assessment:
   - Estimate coverage: <10%, 10-50%, >50%?
   - Color: white (calcite), tan (sandstone), mixed?
   - Particle size: dust, sand, gravel-sized?

4. Carefully lift filter paper using forceps:
   - Grasp edge only
   - If particles abundant, slide rigid card underneath first

5. Transfer to rigid collection box:
   - Place filter paper flat in box
   - DO NOT fold or compress
   - Seal box lid
   - Label exterior with collector ID

6. Bag entire PVC cap separately (may analyze residue later)

7. Record collection data:
   Collector ID: P01
   Collection Date: 18-Oct-2026
   Collection Time: 13:15
   Visual estimate: ~30% coverage, mixed white/tan particles
   Condition: Intact, slight water staining on one side
   Photos: 045-047
   Collected by: [initials]
```

If redeploying (Year 2 continuation):

- Place fresh pre-weighed collector in exact same position
- Use same procedure as initial deployment
- Mark "Year 2" on new collector ID

4.3 Exit Protocol

Pack samples with extreme care:

- Rigid boxes prevent crushing
- Pad container with clothing
- Person 1 carries samples (priority cargo)
- Person 2 carries used collectors and covers

On surface:

- Store samples in clean, dry location immediately
- Do NOT open until lab analysis
- Photograph sealed containers
- Update log

PHASE 5: LABORATORY ANALYSIS

5.1 Contamination Baseline (Analyze Controls First)

Controls tell you if experiment valid:

```
Acceptable contamination: C01, C02 < 10% of primary collectors
If controls >> primaries: Human dust contamination too high, data compromised
```

5.2 Primary Sample Analysis

Setup:

- Clean bench space
- Analytical balance (0.001g precision)
- Dust-free environment
- Calm air (no drafts)

Procedure (per sample):

1. **Equilibration:**
    - Let sealed samples equilibrate to lab temp/humidity for 24h
    - Then open and leave in desiccator for 48h
2. **Weighing:**

```
3. Open box carefully
4. Remove filter paper with forceps
5. Weigh on balance: W_final
6.
7. Retrieve original weight from notebook: W_initial
8.
9. Gross accumulation = W_final - W_initial
```

10. **Contamination Correction:**

```
11. Calculate mean control accumulation: W_control_mean
12.
13. Net accumulation = W_final - W_initial - W_control_mean
```

14. **Rate Calculation:**

```
15. Collection period (days) = Date_collected - Date_deployed
16. Collection area (m²) = 0.0177 m²
17.
18. Daily rate = Net accumulation (mg) / Collection period (days) / Area (m²)
19.
20. Annual rate = Daily rate × 365 days
21.
22. RESULT: mg/m²/year
```

5.3 Particle Characterization (Simplified)

Visual/Microscope Analysis:

Under stereomicroscope (40× magnification):

1. **Color assessment** (estimate %):
    - White/translucent particles (calcite/quartz)
    - Tan/brown particles (sandstone/clay)
    - Dark particles (organics?)
2. **Size distribution** (measure 30 largest particles):
    - Fine: <0.1mm
    - Medium: 0.1-0.5mm
    - Coarse: >0.5mm
3. **Morphology:**
    - Angular (fresh fractured) vs rounded (weathered)
    - Grain vs aggregate
4. **Optional** (if budget allows):

- Submit representative samples for XRD (mineralogy)
- Could pool 3-4 samples by zone to reduce cost

5.4 Data Analysis

Simple statistics (Excel/R):

```
For 8 primary collectors:
- Mean particle fall rate
- Standard deviation
- Range (min-max)
- Coefficient of variation (SD/mean)

By zone (if applicable):
- Heavy zone mean
- Moderate zone mean
- Baseline zone mean

Statistical test:
- One-way ANOVA: Do zones differ significantly?
```

Spatial pattern:

- Plot collector positions on chamber map
- Color-code by rate (green=low, yellow=medium, red=high)
- Visual identification of hotspots

Year 1 vs Year 2 comparison:

- If continuing, compare same collector positions
- Calculate % change
- Identify accelerating zones

PHASE 6: SIMPLIFIED REPORTING

6.1 Field Report (Immediately Post-Visit)

Simple document:

- Date of visit
- Team members
- Any issues or deviations
- Photos
- Preliminary observations
- Equipment status

6.2 Annual Data Report

Essential content:

1. **Summary** (1 page):
   - Mean particle fall rate: X ± SD mg/m²/year
   - Range: min - max

    - Chamber total estimate: Y kg/year (if ceiling area measured)
    - Key finding: "Heavy zones show 10× higher rates than baseline"
2. **Methods** (1 page):
    - Collector design
    - Deployment/collection protocol
    - Analysis method
3. **Results** (2-3 pages):
    - Table of all collector data
    - Chamber map with rates
    - Simple bar chart by zone
    - Particle characterization summary
4. **Safety Assessment** (1 page):
    - Which areas show highest rates?
    - Correlation with ceiling features?
    - Recommendation: Traffic light system
        - GREEN zones: <X mg/m²/year (safe)
        - YELLOW zones: X-Y mg/m²/year (caution)
        - RED zones: >Y mg/m²/year (avoid extended stays)
5. **Appendix:**
    - Field notes (scanned)
    - All photographs
    - Raw data

Total: ~10-15 page document, clear and actionable

REALISTIC EXPECTATIONS & LIMITATIONS

What This Method CAN Determine:

✓ **Order of magnitude** particle fall rates (are we talking 10, 100, or 1000 mg/m²/year?) ✓ **Spatial variation** (which areas are most active?) ✓ **Relative hazard** (compare zones within chamber) ✓ **Dominant particle type** (sandstone vs limestone) ✓ **Year-to-year changes** (if study continues) ✓ **Practical safety zones** (where to/not to linger)

What This Method CANNOT Determine:

✗ Precise rates (<±20% error unlikely given contamination issues) ✗ Short-term temporal patterns (monthly, seasonal) ✗ Correlation with specific weather events ✗ Detailed environmental controls ✗ Sub-meter spatial resolution

Known Sources of Error:

1. **Human contamination** (5-20% likely, assessed by controls)
2. **Boulder floor dust** (minimized by clean clothes, slow movement)
3. **Filter paper humidity changes** (±2-5 mg possible, small relative to signal if rates high)
4. **Collector displacement** (document and exclude if occurs)
5. **Biological growth** (unlikely in 12 months, but note if seen)

Expected Measurement Precision: ±15-30%

Good enough for: Hazard assessment, zone comparison, scientific documentation

---

EQUIPMENT LIST & BUDGET

Materials (Deployable Equipment):

Item	Quantity	Cost
PVC pipe caps (150mm)	15	$45
Glass fiber filter papers	50	$80
Aluminum foil (heavy duty)	1 roll	$8
Bamboo skewers	1 pack	$3
Silicone adhesive	1 tube	$6
Wire for securing	20m	$5
Rigid transport boxes	2	$20
Sample return boxes	15	$30
Waterproof notebook	2	$20
Subtotal Consumables		**$217**

Personal Equipment (Per Team):

Item	Quantity	Cost
Tyvek coveralls	4	$40
Clean overboots	2 pairs	$20
Clean gloves	4 pairs	$10
Waterproof bags	4	$20
Subtotal PPE		**$90**

Analytical Equipment:

Item	Cost
Analytical balance (lab access)*	$0-3000
Stereomicroscope (lab access)*	$0-1500
Desiccator	$50
Forceps	$15
Subtotal Analysis	**$65-4565**

TOTAL BUDGET: $372 - $4,872

*Major costs eliminated if university/lab access available

What to Carry Underground (Each Visit):

Person 1 Load (~8kg):

- Collectors in rigid box (3kg)

- Camera (0.5kg)
- Clean clothes (1kg)
- Personal gear (3kg)
- Water/food (0.5kg)

Person 2 Load (~7kg):

- Return boxes + tape measure + notebook (2kg)
- Clean clothes (1kg)
- Personal gear (3kg)
- Water/food (1kg)

Both loads: Manageable for 2-hour approach with SRT

DECISION TREE: Is Study Feasible?

GO (Proceed with study) IF:

✓ Team committed to 2-3 visits over 2 years ✓ Access to analytical balance (±0.001g) ✓ Chamber is genuinely safety concern (worth the effort) ✓ Results will inform access decisions ✓ Budget available (~$400 minimum)

NO-GO (Don't proceed) IF:

✗ Cannot guarantee revisit schedule ✗ No analytical balance access ✗ Chamber clearly unstable (don't return!) ✗ Results won't change management decisions

---

ALTERNATIVE: "Ultra-Minimal" 1-Year Pilot

If even this is too much:

Deploy just **4 collectors:**

- 2 in "heavy" zones
- 1 in "moderate" zone
- 1 sealed control

Single 12-month period.

Answer just one question: "Are particle fall rates high enough to warrant concern?"

If rates >100 mg/m²/year in heavy zones → Yes, concern warranted If rates <50 mg/m²/year everywhere → Probably stable

This takes:

- 2 visits (deploy, collect)

- 2 hours in-chamber each visit
- $150 budget
- Still produces publishable data on understudied phenomenon

PUBLISHABLE OUTCOMES

Even this simplified study would be **scientifically valuable:**

Novel contributions:

1. First quantitative particle fall rates from deep, mixed-lithology cave
2. Methodology for remote cave monitoring
3. Relationship between visible "particle rain" and measured rates
4. Hazard assessment framework for difficult-access caves

Target journals:

- *International Journal of Speleology*
- *Cave and Karst Science*
- *Journal of Cave and Karst Studies*

Title ideas:

- "Quantifying ceiling particle fall rates in a remote mixed-lithology cave chamber, Cantabria, Spain"
- "Grain rain as a rockfall precursor: monitoring sandstone-limestone cave stability"
- "Practical methodology for long-term particle deposition monitoring in difficult-access caves"

This revised protocol is **realistic, achievable, and scientifically sound** given your access constraints. The key compromises are temporal resolution and precision, but you gain feasibility and still answer the critical questions about chamber stability and hazard assessment.

Would you like me to detail any specific aspect further - perhaps the contamination control protocol, the statistical analysis approach, or the safety assessment framework?