Electro-Fragmentation of Rocks
From Laboratory Testing to Numerical Modeling

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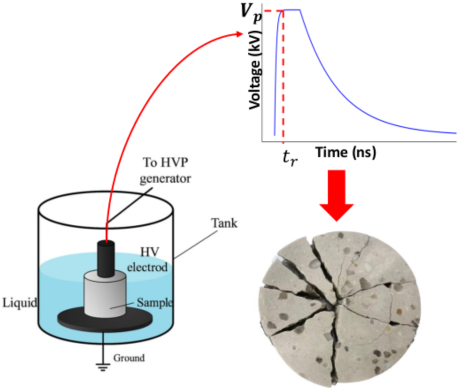
CFMR Jeunes Technical Workshop

THMCE: multiscale and coupled processes in evolving geomaterials

May 28, 2026

What is High-voltage Pulse Fragmentation (HVPF)

High-voltage Pulse ⇒ Plasma Channel ⇒ Rock Fragmentation



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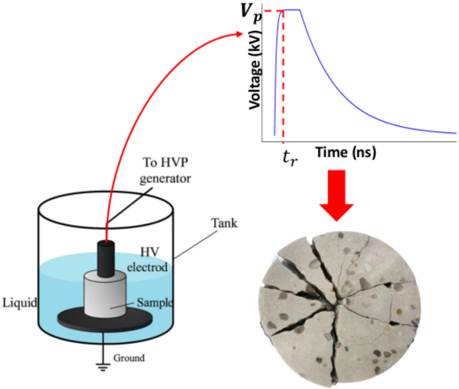
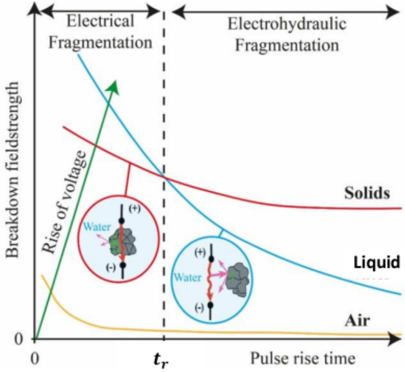
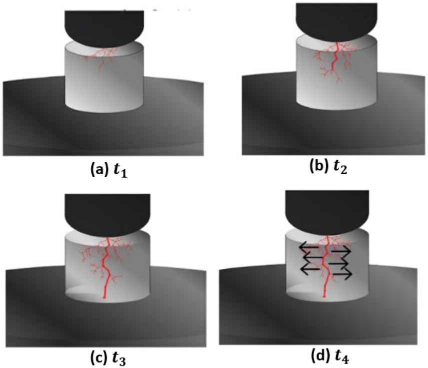


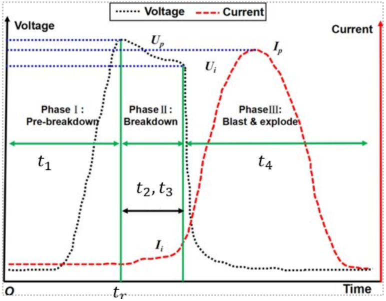
Influence of the media



What happens during HVPF?



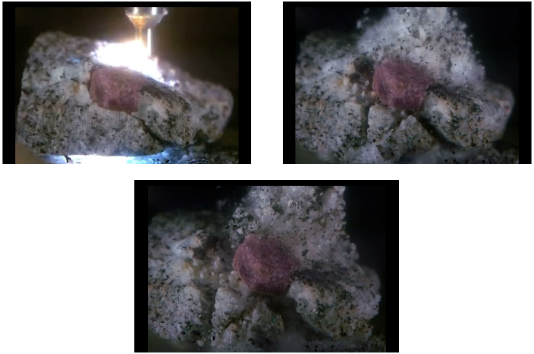
Gradual electro-pulse breakdown of a rock (the red filaments represent streamers) [Li et al., 2021c].



Waveforms of voltage and current during HVPF process.

- At t_1: Discharges appear, $I = 0\,\text{kA}$, $V \uparrow$
- At t_2 and t_3: One or two conductive channels form $\rightarrow I \uparrow$, $V \downarrow$
- At t_4: Electrode bridging releases energy $\rightarrow$ sample fragmentation

Why HVPF is Gaining Attention



HVPF discharge and rock fragmentation —
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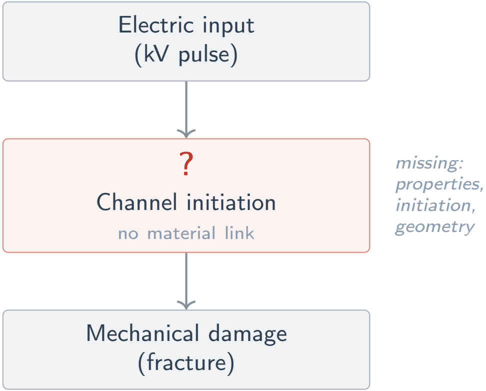
Advantages over conventional crushing

- **Selective** — cracks follow grain boundaries ⇒ **Preserved minerals** — no damage ⇒ **Better liberation**
- **Energy efficient** — up to 30% savings
- **No tool wear** — contactless process

Driven by critical mineral demand, geothermal drilling, and net-zero targets.

Research Objectives & Methodology



Electric input
(kV pulse)

?

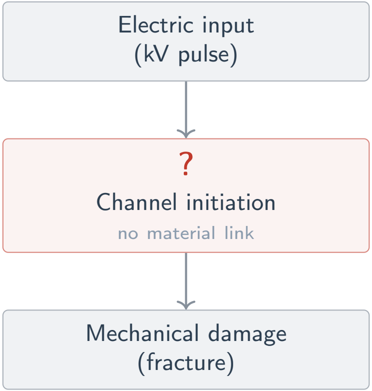
Channel initiation

no material link

missing: properties, initiation, geometry

Mechanical damage
(fracture)

Research Objectives & Methodology


Electric input
(kV pulse)

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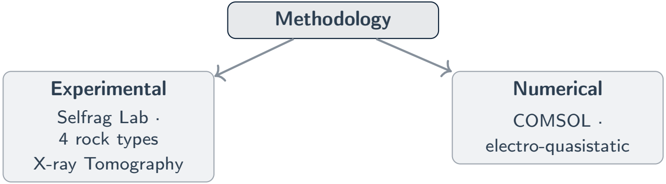
no material link

Mechanical damage
(fracture)

missing: properties, initiation, geometry

- Understand better the HVPF phenomena and its physical mechanism.
- Determine the sensitivity of the process to the operating parameters.
- Develop a new approach that predicts the rock breakdown and associated damage.

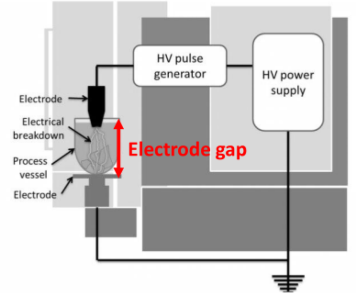

Methodology

Experimental
Selfrag Lab ·
4 rock types
X-ray Tomography

Numerical
COMSOL ·
electro-quasistatic

Experimental Setup & Materials

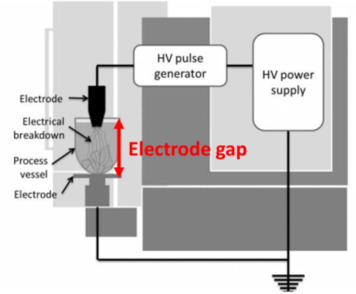
Selfrag Lab — key parameters



Parameter	Range
Voltage	90–200 kV
Energy/pulse	140–750 J
No. of pulses	1–999
Electrode gap	10–40 mm

Experimental Setup & Materials

Selfrag Lab — key parameters



Parameter	Range
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Machine & specimen photos

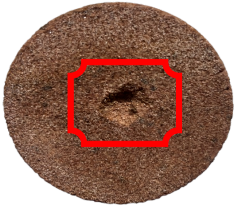
≈300 Specimens with their height ranging from 40mm-10mm

Material	UCS (MPa)	Por. (%)	ε_r	σ S/m
Sandstone	40	20	3–5	10^{-3} - 10^{-1}
Cement	51	27	2	10^{-3} - 10^{-2}
Concrete	53	25	6	10^{-3} - 10^{-1}
Granite	150	<1	4–6	10^{-5} - 10^{-3}

Damage Modes Depend on Microstructure

Sandstone – grain gaps (≈100μm)

- Large craters at electrode faces and Few radial cracks



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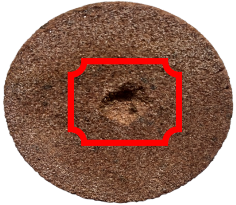
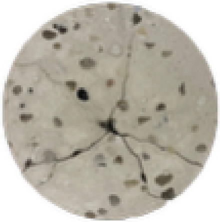


Concrete – grain gaps (<1μm)

- Prominent radial cracks and Smaller craters



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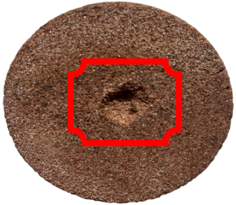

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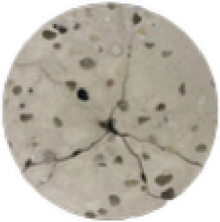
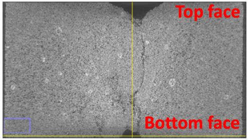
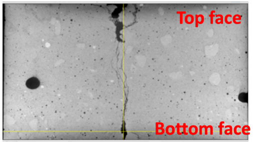


Internal damage channel



X-Ray tomography for sandstone tested with 1 pulse

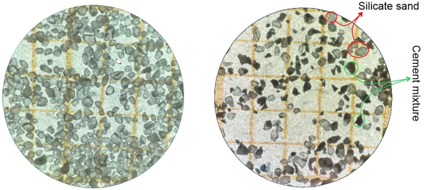


X-Ray tomography for concrete tested with 1 pulse

> Microstructure governs the spatial pattern of damage.
> Fragmentation occurs in Direct Damage Modes.

Heterogeneity Controls Cracks — Concrete & Sand

Sand microstructure



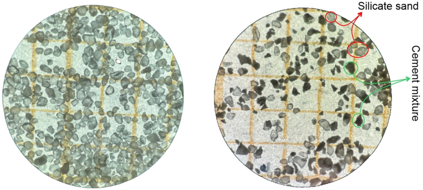
Before *After*

Gravel liberation

Before *After*

Heterogeneity Controls Cracks — Concrete & Sand

Sand microstructure



Before *After*

Gravel liberation

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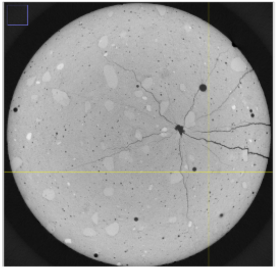


X-ray tomography — internal crack network

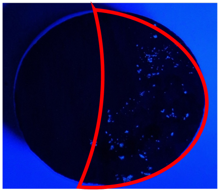
- Gravel inclusions liberated after few pulses
- Crack follows inclusion boundary

> Cracks follow grain boundaries — selective liberation without over-grinding.

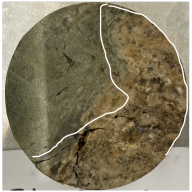
Heterogeneity Controls Cracks — Skarn (Scheelite)

Before & after HVPF — visible and UV light

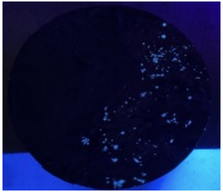
Before (visible)



Before (UV)



After (visible)



After (UV)

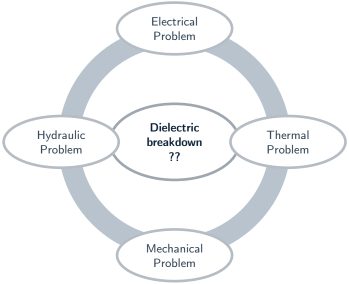
Selective liberation along ore layers

- Scheelite-rich zones fluoresce under UV
- Cracks concentrate in mineralogically rich zones
- Selective fragmentation after a single pulse

> HVPF follows electrical & mechanical contrasts — coinciding with grain boundaries.

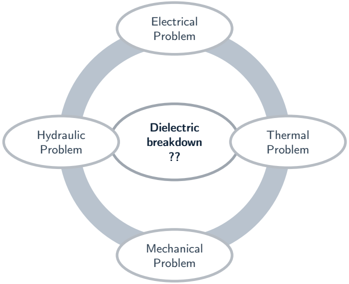
Numerical Approach

Dielectric Breakdown: Governing Physics



Numerical Approach

Dielectric Breakdown: Governing Physics

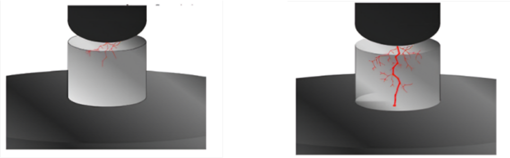

Electrical Problem

Thermal Problem

Mechanical Problem

Hydraulic Problem

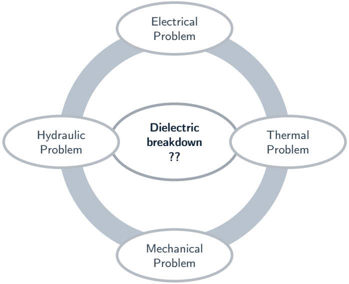
Dielectric breakdown ??

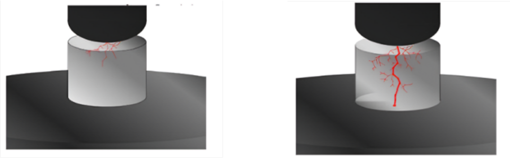

after breakdown

Insulator → *Conductor*

Numerical Approach

Dielectric Breakdown: Governing Physics



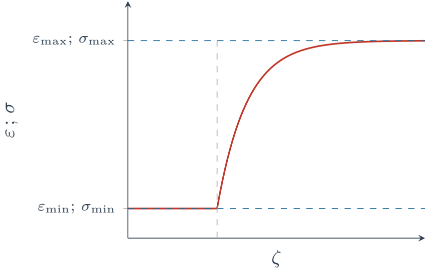


after breakdown

Insulator → *Conductor*

Electrical Problem

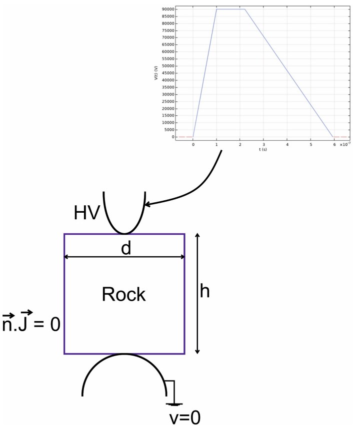
- Electro-quasistatic formulation
- Rock electric properties σ and ϵ_r increases with time



- Damage zones where $\varepsilon = \varepsilon_{\max}$ and $\sigma = \sigma_{\max}$ — mechanical damage most likely occurs here.

Model Assumptions

Trapezoidal input signal



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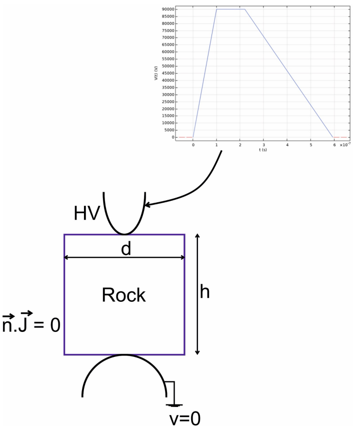
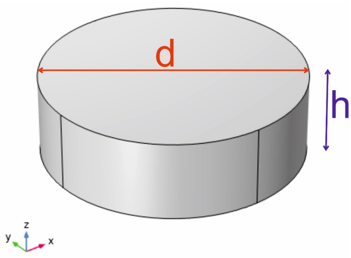


Geometry

Rock modelled as a cylinder:

- Diameter $d = 65\,\mathrm{mm}$
- Height $h \Leftrightarrow$ electrode gap



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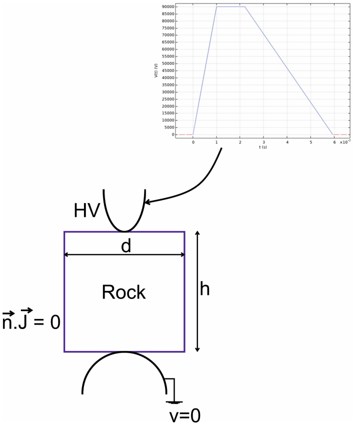

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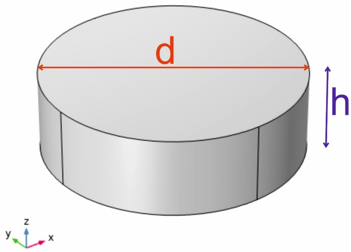
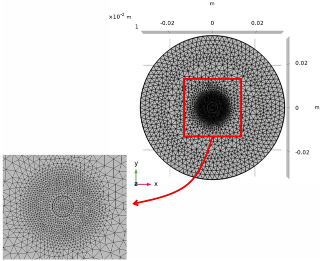


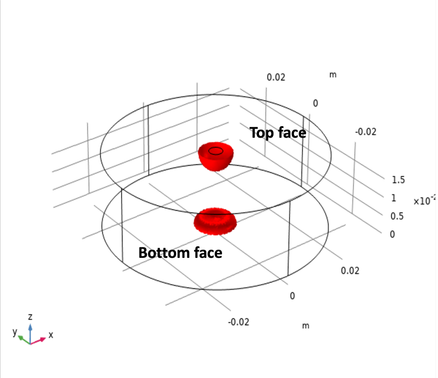
Mesh

- Tetrahedral mesh
- Size: 0.5 mm
- 10× smaller than ground electrode radius



Numerical Results For Homogeneous Sample

Numerical damage zones

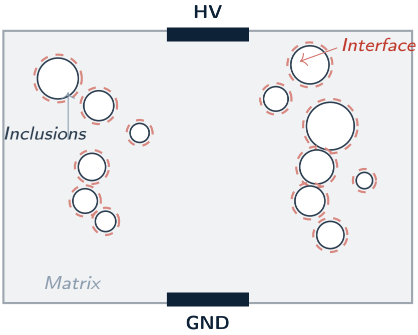


Experimental results — damage zones

Top face *Bottom face*

- Damage zones below HV electrode and above ground — matches crater positions
- Numerical model reproduces all the qualitative experimental trends

Numerical Model — Heterogeneous Materials



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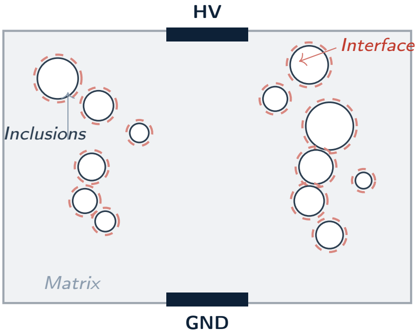


Damage Evolution (per phase i)

$$\dot{\zeta}_i = \frac{1}{\tau}\left\langle \frac{\|\vec{E}\|}{E_{c,i}} - 1 \right\rangle^2$$

$$\sigma_i(\zeta_i) = \sigma_{0,i} + (\sigma_{\max} - \sigma_{0,i})\left(1 - e^{-\beta_1 \zeta_i}\right)$$

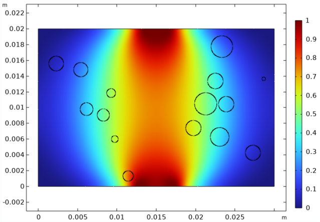
$$\varepsilon_{r,i}(\zeta_i) = \varepsilon_{r,0,i} + (\varepsilon_{r,\max} - \varepsilon_{r,0,i})\left(1 - e^{-\beta_2 \zeta_i}\right)$$

- **Matrix** (vesuvianite): $E_{c,1} = 8\times 10^5$ V/m
- **Interface**: $E_{c,3} = r \cdot E_{c,1} \quad (r < 1)$
- **Inclusion** (scheelite): $E_{c,2} = k \cdot E_{c,1} \quad (k > 1)$

> Each phase evolves independently — breakdown initiates where local $|\vec{E}|$ exceeds $E_{c,i}$.
> Normalized damage zone is when $\zeta_i = 1$.

Heterogeneous Results

Homogeneous

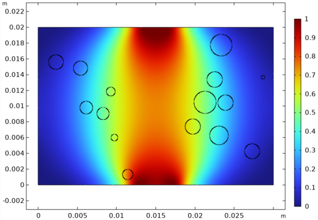


No inclusions

$(r = 1,\ k = 1)$

Heterogeneous Results

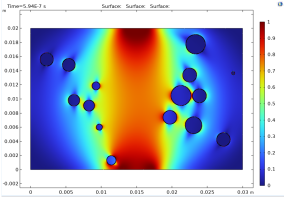
Homogeneous



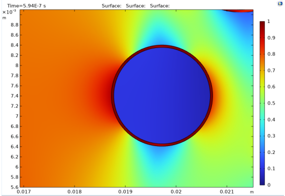
No inclusions

$(r = 1,\ k = 1)$

Heterogeneous $(r = 0.3,\ k = 3)$



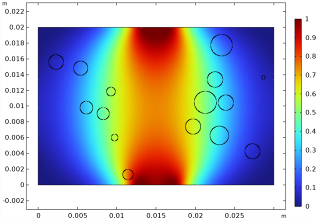
Full domain



Inclusion zoom

Heterogeneous Results

Homogeneous



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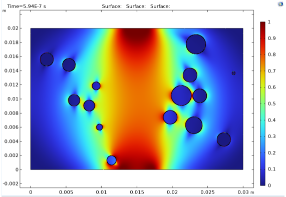

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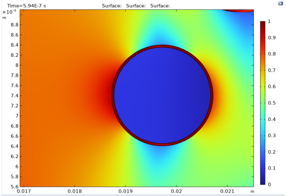

Inclusion zoom

Key findings

- **Interface** ($\zeta_3 = 1$) grain-boundary decoupling
- **Inclusion** ($\zeta_2 \approx 0$) scheelite intact

> HVPF damage is **selective**: interfaces decouple first and inclusions remain intact.

Summary of Main Findings

Experimental

- **Threshold voltage gradient** depends on material properties
- Heterogeneity drives **selective liberation**
- HVPF confirms liberation of minerals without over-grinding

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- All qualitative experimental trends in **homogeneous** materials are reproduced
- **Heterogeneous** model confirms selective damage
- Model provides a framework to understand how operating parameters affect the process

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Numerical

- All qualitative experimental trends in **homogeneous** materials are reproduced
- **Heterogeneous** model confirms selective damage
- Model provides a framework to understand how operating parameters affect the process

> HVPF provides a controlled way to study dielectric breakdown, crack initiation at mineral interfaces, and electro-mechanical coupling in geomaterials — topics central to rock mechanics.

Thank you

Questions & Discussion

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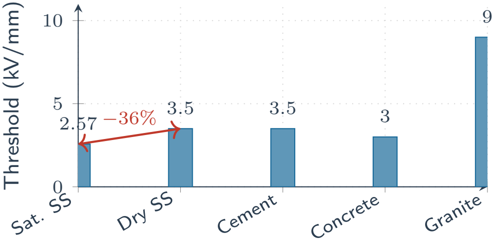
Threshold Voltage Gradient — A Rock-Specific Property

- Creation of channel is not always accompanied by complete fragmentation.
- Channel creation is a prerequisite for the fragmentation of the sample.

- Harder rocks need more voltage
- Saturation reduces threshold by **36 %**

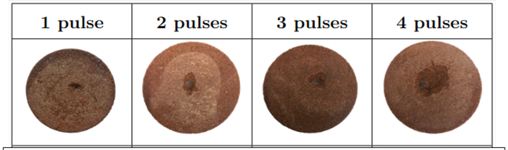
Threshold voltage gradient per material

Material	UCS (MPa)	Threshold (kV/mm)
Sat. sandstone	33	2.57
Dry sandstone	40	3.50
Cement	51	3.50
Concrete	53	3.00
Granite	**150**	**9.00**



The phenomena is sensitive to material physical and mechanical properties.

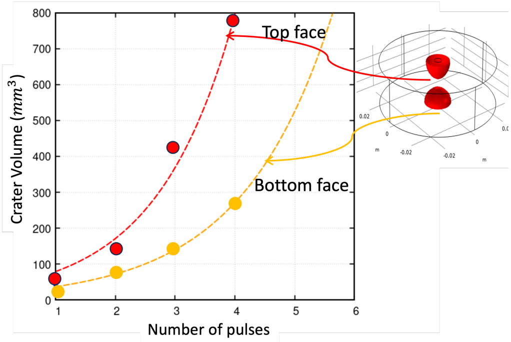
Cumulative Damage Under Repeated Pulses



Observations in 20 mm height sandstone samples, tested under 90kV and several number of pulses (voltage gradient = 4,5 kV/mm)

- Each pulse introduces microscopic cracks
- Crater volume grows **exponentially** with pulse count

Crater volume vs. pulse count



Crater volume of top and bottom faces as a function of number of pulses.

> Damage is non-linear and history-dependent — key for constitutive modelling. Sub-threshold pulses pre-weaken the rock.

Numerical Modelling — Physical Basis

Main properties controlling the transition

- Electric permittivity: $\varepsilon = f(T, |\vec{E}|, \omega(|\vec{E}|), \ldots)$
- Electric conductivity: $\sigma = f'(T, |\vec{E}|, \omega(|\vec{E}|), \ldots)$

Since mechanical damage is induced by $|\vec{E}|$

$$\varepsilon = g(T, |\vec{E}|) \qquad \sigma = h(T, |\vec{E}|)$$

No temperature change observed experimentally

Damage accumulated $\Rightarrow$ internal variable ζ:

$$\varepsilon = g(\zeta) \qquad \sigma = h(\zeta)$$

Evolution law for ζ

$$\frac{d\zeta}{dt} = \frac{1}{\tau}\left\langle \frac{|\vec{E}|}{E_c} - 1 \right\rangle^{\alpha} \qquad \begin{cases} |\vec{E}| \leq E_c \Rightarrow \dfrac{d\zeta}{dt} = 0 \\ |\vec{E}| > E_c \Rightarrow \dfrac{d\zeta}{dt} \neq 0 \end{cases}$$

Theoretical Formalism

Electrical potential in a volumetric domain:

$$\vec{\nabla} \cdot (\sigma \vec{\nabla} V) + \frac{\partial}{\partial t} \vec{\nabla} (\varepsilon_r \varepsilon_0 \vec{\nabla} V) = 0$$

Neumann BC on the surface:

$$\vec{n} \cdot \vec{J} = 0$$

Internal variable — breakdown & damage:

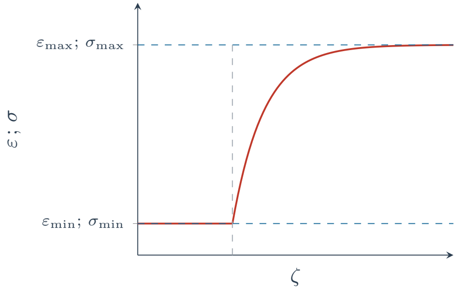
$$\frac{d\zeta}{dt} = \frac{1}{\tau} \left\langle \frac{|\vec{E}|}{E_c} - 1 \right\rangle^{\alpha}$$

Electrical properties during breakdown:

$$\varepsilon(\zeta) = \varepsilon_{\min} + (\varepsilon_{\max} - \varepsilon_{\min})(1 - e^{-\beta\zeta})$$

$$\sigma(\zeta) = \sigma_{\min} + (\sigma_{\max} - \sigma_{\min})(1 - e^{-\beta\zeta})$$

$\varepsilon_{\min}, \sigma_{\min}$ — insulator ; $\varepsilon_{\max}, \sigma_{\max}$ — conductor



> Damage zones where $\varepsilon = \varepsilon_{\max}$ and $\sigma = \sigma_{\max}$ — mechanical damage most likely occurs here.

Numerical Model — Heterogeneous Materials

- **Matrix** (vesuvianite): $E_{c,1} = 8\times10^5$ V/m
- **Interface**: $E_{c,3} = r \cdot E_{c,1} \quad (r < 1)$
- **Inclusion** (scheelite): $E_{c,2} = k \cdot E_{c,1}$ $(k > 1)$

Material Properties

Phase	$\varepsilon_{r,0}$	σ_0 (S/m)	E_c (V/m)
Matrix (vesuvianite)	8.64	10^{-11}	8×10^5
Scheelite inclusion	11.7	10^{-4}	$k\cdot8\times10^5$
Grain boundary	$r\times8.64$	$r\times10^{-11}$	$r\cdot8\times10^5$

All phases: $\varepsilon_{r,\max} = 200$, $\sigma_{\max} = 10^3$ S/m (post-breakdown).