SELFRAG

HIGH VOLTAGE PULSED POWER TECHNOLOGY

Pre-weakening and Selective Liberation of Rocks using High Voltage Breakage Technology

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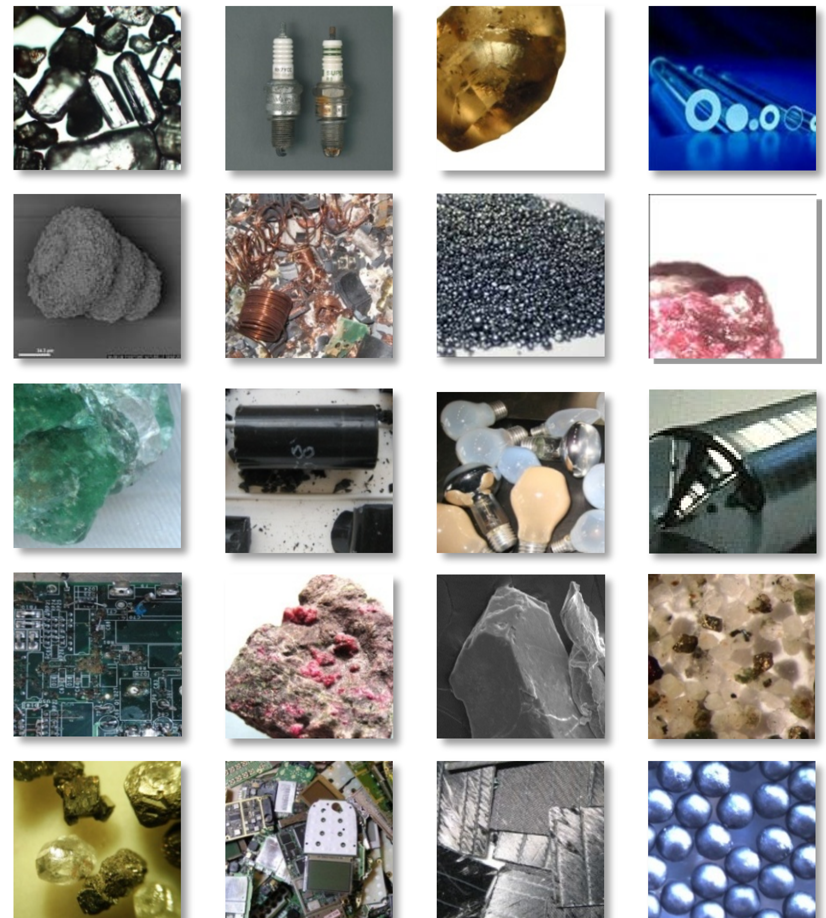
SELFRAG in a nutshell

Technology company focused on high voltage pulse power

At SELFRAG, we develop and commercialize **fragmentation systems** for multiple industries using patented **high voltage** pulse power technologies that **increase the value** of material extracted or recycled.

What can we fragment?

SELFRAG systems fragment **every composite** or **pure material** starting at fist-size down to micron-size.



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A revolutionary fragmentation technology

Focus on targeted applications in three segments

Manufacturing

Add-on to existing product line

Solar grade silicon & quartz glass

Mining

New extraction approach

Base & precious metals, industrial minerals

Recycling

New recycling applications

High purity / value material

Recovery increase + energy savings + ecological process

▶ **Global** and **wide** reach of SELFRAG's technology

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History of high voltage breakage

Old technology, new application

Technical advances		SELFRAG milestones
Erwin Otto Marx invents the Marx generator	**1924**	
Prof. Yutkin describes electrohydraulic crushing	**1955**	
Tomsk Polytechnical University discovers electrodynamic fragmentation	**1960**	
Prof. Andres publishes first paper on HVB	**1977**	
Karlsruhe Institute of Technology (KIT) purchases Russian HVB unit	**1995**	Research at KIT was the first stop towards the foundation of SELFRAG
	2003	Ammann Group (Switzerland) enter license agreement with KIT
	2007	First SELFRAG LAB machine sold
First research into HV-induced weakening of rocks	**2010**	Commissioning of Pre-weakening Test Station
	2014	10 tph pilot plant unit ready for construction

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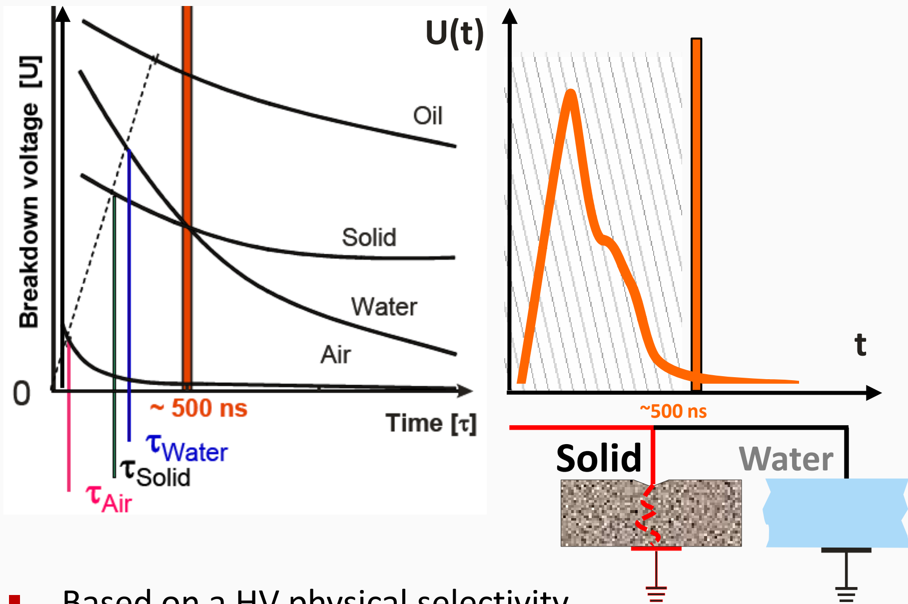
SELFRAG technology:

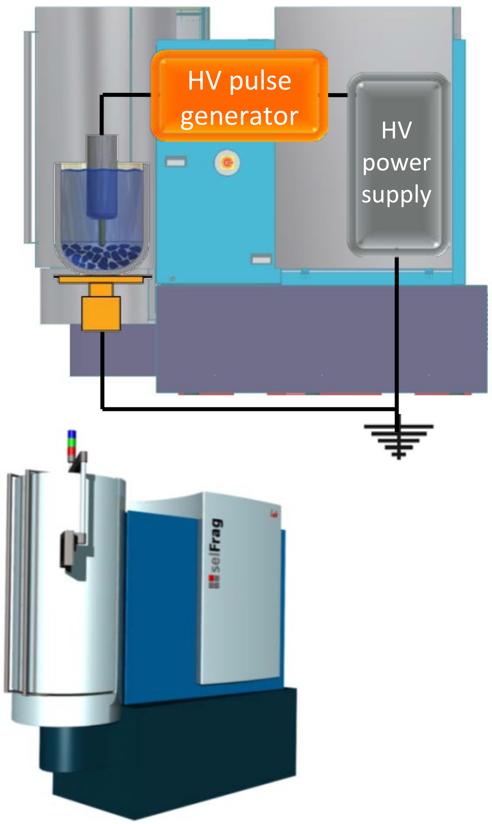
How does high voltage (HV) pulse fragmentation work?

HV pulse power technology



- Based on a HV physical selectivity
- At short pulse rise time water is more isolating than solids
- Discharge occurs through solid, causing strong internal shockwaves resulting in selective breakage

Industrialized and patented



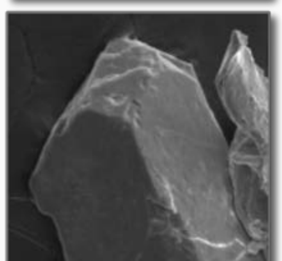
Our product portfolio addresses different applications

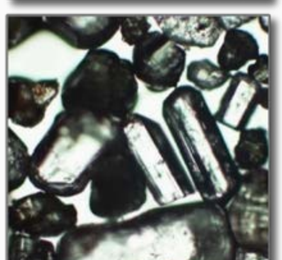
Technology has been mastered in a lab and continuous system

	Lab system (batch)	Low-throughput continuous system	Container based system	Scalable high-throughput system
				
Capacity	Batch	100kg – 1tph	10tph	100 – 2’000tph
Value proposition	Purity Selectivity Batch	Purity Selectivity Continuous process	Recovery increase Energy saving	Energy saving Selectivity High throughput
Applications	Sample preparation	High purity glass recycling Silicon crushing Mining exploration	Recycling Mining Pilot planting Available 2014	Mining E-scrap recycling Concrete recycling Available 2016

SELFRAG's USP for the laboratories

Enables unmatched quality in sample preparation for laboratories



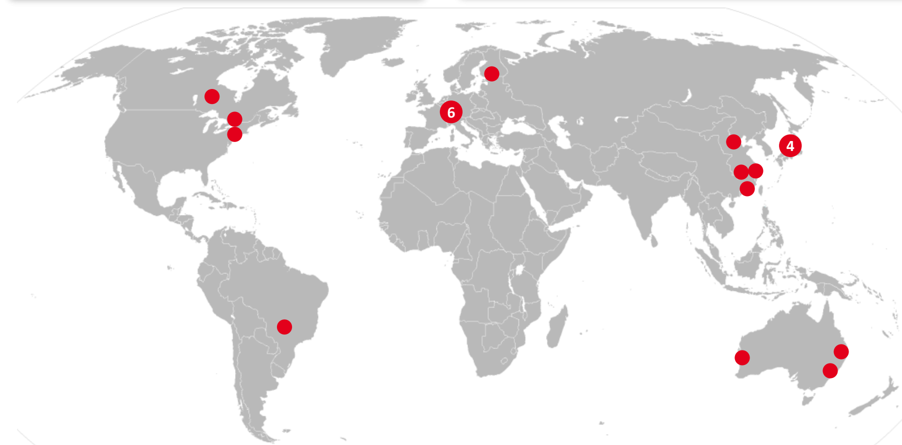


Industry status

- Fragmentation done by hand, old crusher or sometimes impossible
- Quality of the sample is limited and cross-contamination is an issue
- Time consuming and dirty process

Value proposition SELFRAG

- Fragmentation along grain boundary
- No cross-contamination
- Fragmentation of all materials
- Fast and clean process



Our clients today: 22 top tier universities around the globe

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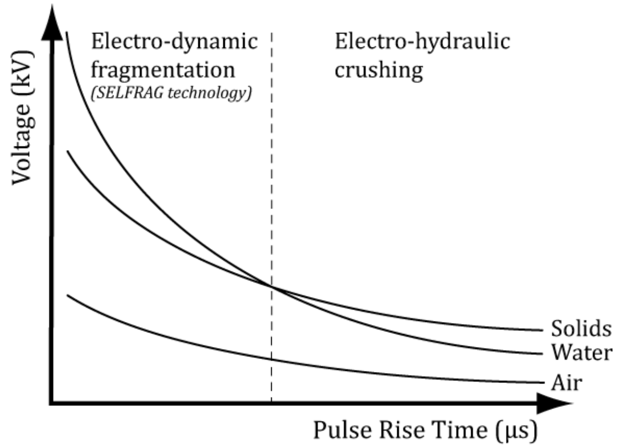
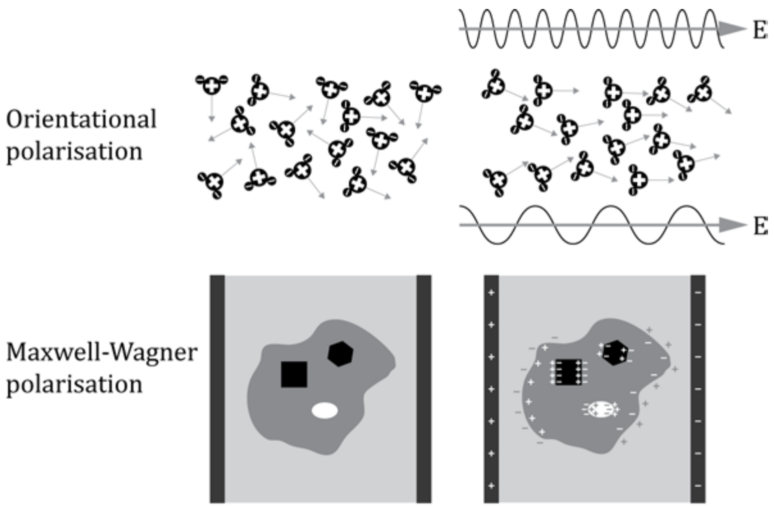
Electrical Breakdown

Water acts as an insulator

Electrical breakdown occurs when a material is not conductive enough to fully accommodate electricity flow, yet not resistive enough to completely inhibit it either

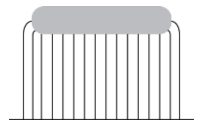
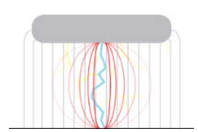
Differences in polarization mechanisms make breakdown more likely in rocks than water at the right conditions





High Voltage Breakage
Discharge/fragmentation process

Electrical breakdown causes extensive plasma and shockwave damage

Discharge process *Common analogue - lightning*		Fragmentation process *Common analogue - blasting*
Formation of the electrical field		
Plasma streamer creation and growth		Streamers get attracted to areas of strong field distortion (i.e. sulphides, oxides)
Plasma streamer(s) bridge the gap between electrodes and create a discharge		
Very rapid plasma channel expansion due to Ohmic heating		Localised crushing near plasma channel, circumferential/radial fracturing and spalling in periphery
Plasma channel collapse		Shockwave emission causes tensile fracturing enhanced by plasma percolation into fractures

Plasma Streamers

Lightning as a natural analogue

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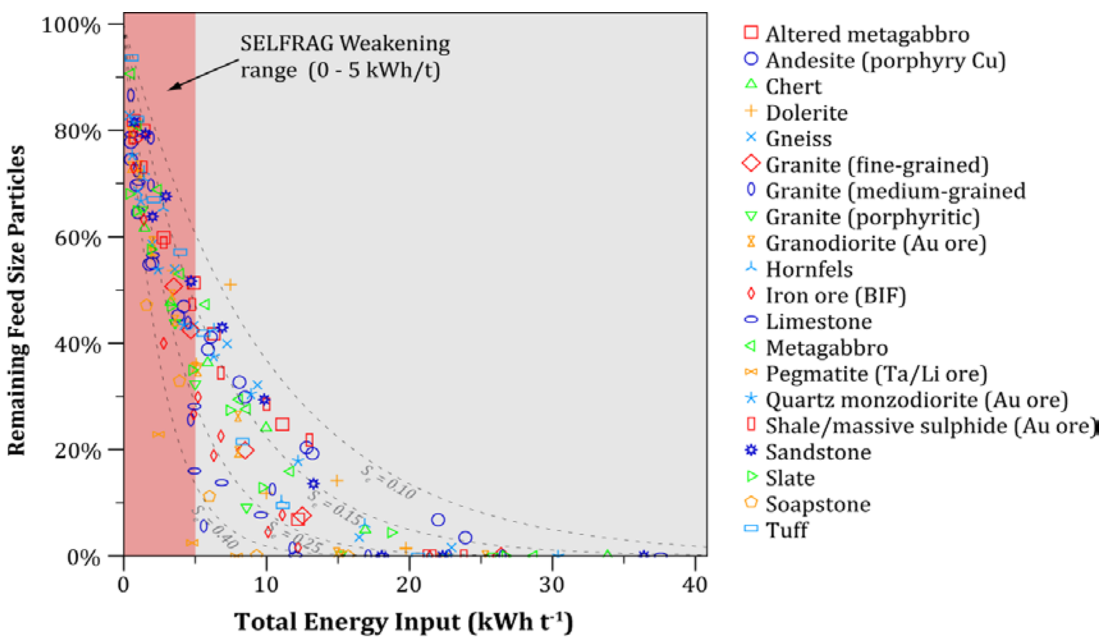
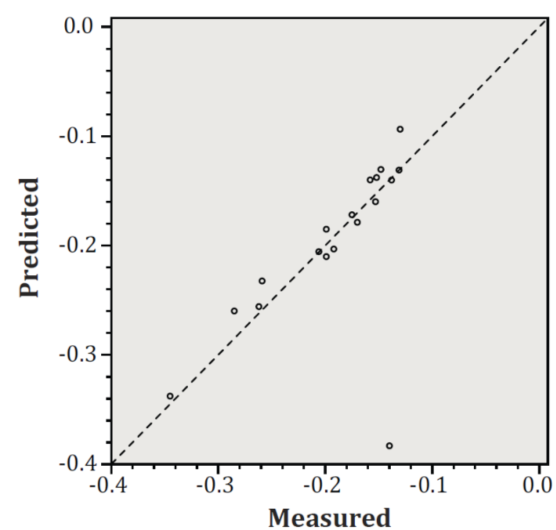
Fragmentation

Extensive experience with a range of rock types

- Exponential decrease of the amount of feed-sized particles remaining after SELFRAG treatment
- Fragmentation can be predicted based on bulk permittivity and tensile strength



$$\% \, Feed \; size \; remaining = \frac{-18.64}{13.98 + \tau\varepsilon_b}$$



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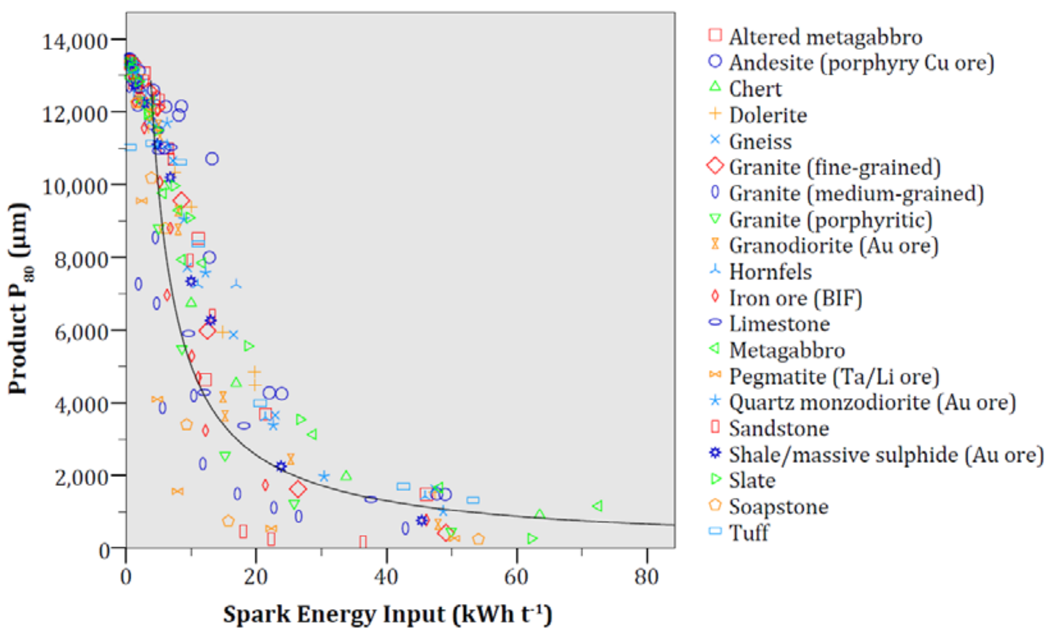
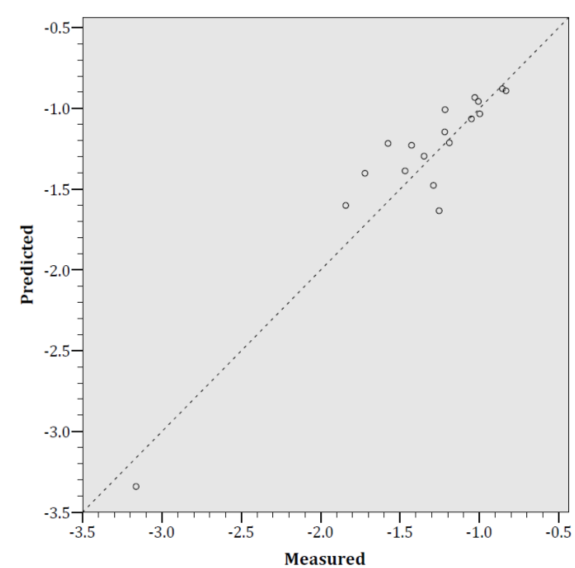
Fragmentation

Extensive experience with a range of rock types (cont.)

- Fractal law describes product P_{80} increase with SELFRAG energy input
- Product P_{80} is related to acoustic impedance and porosity



$$Product\ P_{80} = -2.7 + 1.07 \times 10^{-7} z - 14.5\Phi$$



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Fragmentation
Selectivity

Selectivity of SELFRAG process arises from two sources:

1. Field enhancements are strongly dependent on electrical properties of minerals.
2. Shockwave interaction with acoustic properties of minerals.

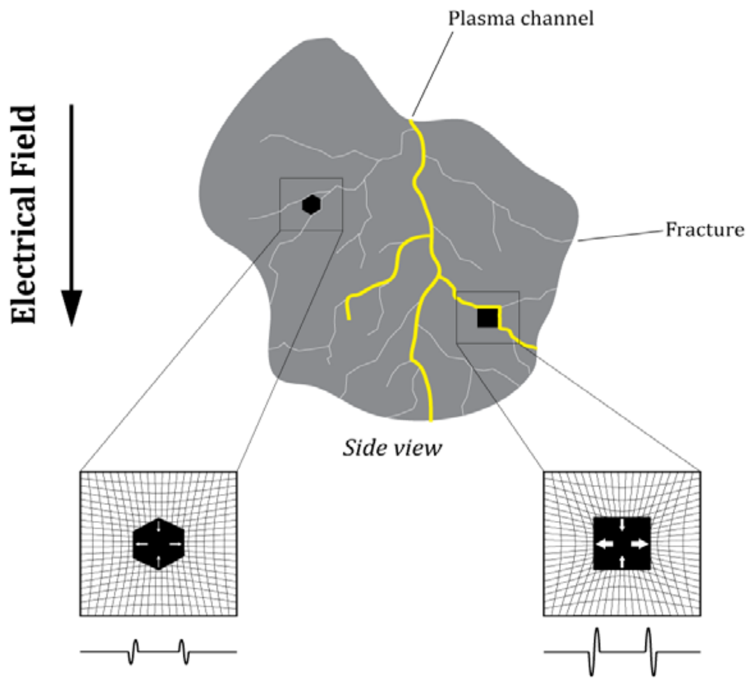
SELFRAG processing causes two types of selective fracturing:

1. Inter-granular selective fragmentation, i.e. preferential fracturing along grain boundaries.
2. Intra-granular selective fragmentation, i.e. preferential fragmentation of certain mineral phases (most notably quartz).

Fragmentation

Selectivity (cont.)

Electrical selectivity



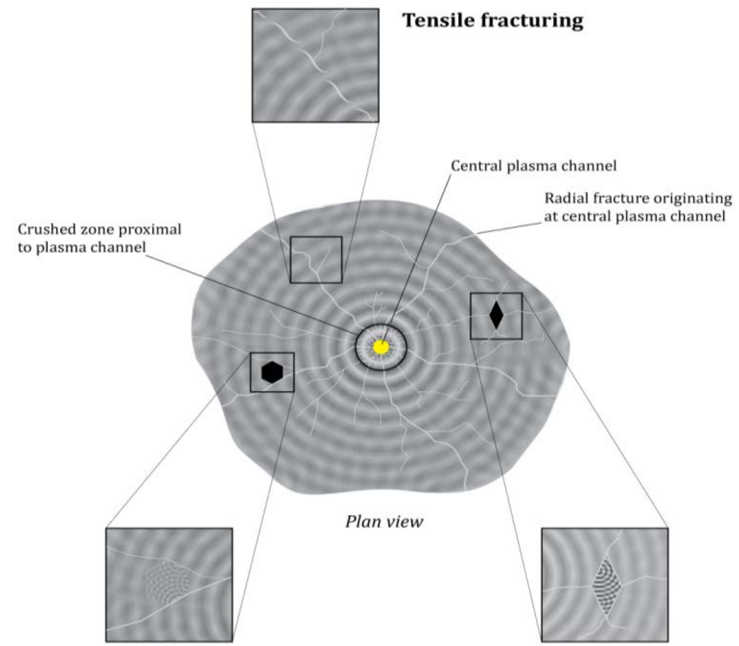
Low permittivity contrast

- *Weak field distortion along grain boundary*
- *Limited electro-strictional tension*

High permittivity contrast

- *Strong field distortion along grain boundary*
- *More pronounced electro-strictional tension*

Shockwave selectivity



Low contrast in acoustic impedance between inclusion and matrix

- *Weak wave interactions in particle*
- *Limited fracturing along grain boundaries*

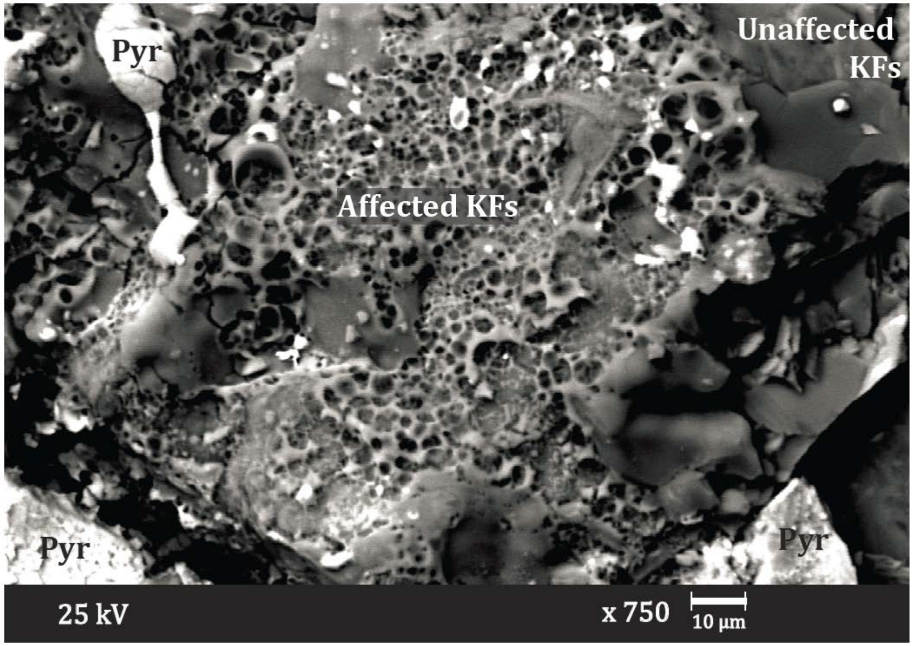
High contrast in acoustic impedance between inclusion and matrix

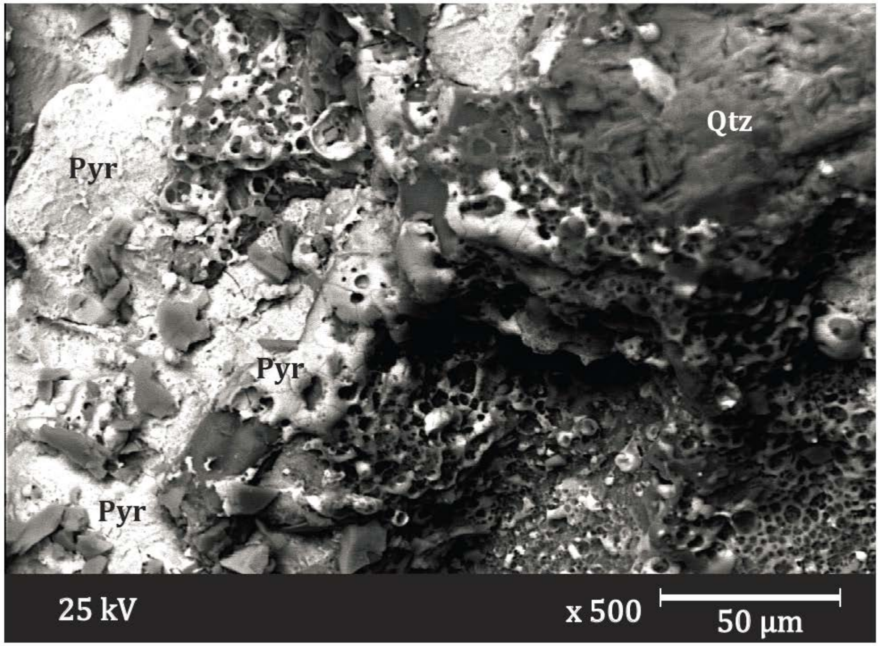
- *Strong wave interactions in particle*
- *Considerable fracturing along grain boundaries*

Plasma channel effects

Very localised melting

- Melting effects are observed but volumetrically negligible
- Volumetrically negligible, no negative effects on flotation/dating/other mineralogical attributes

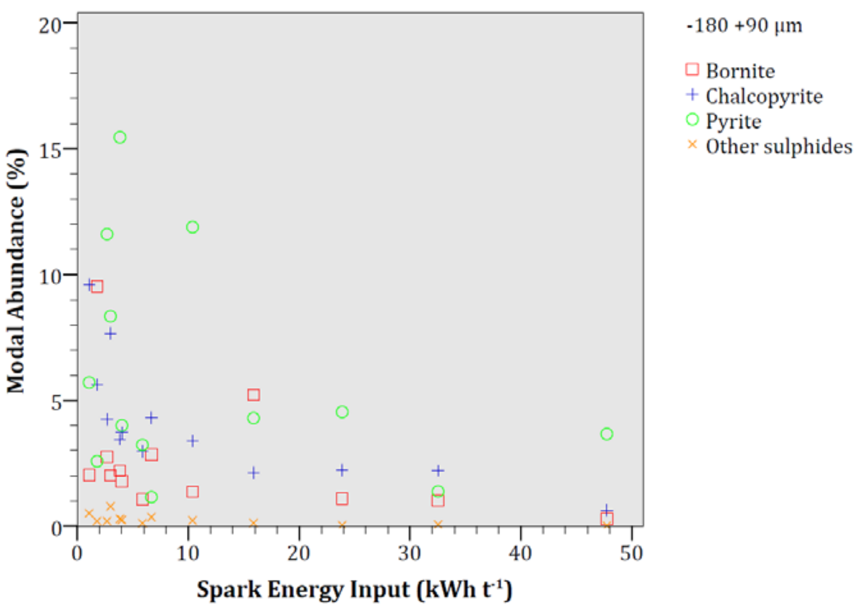


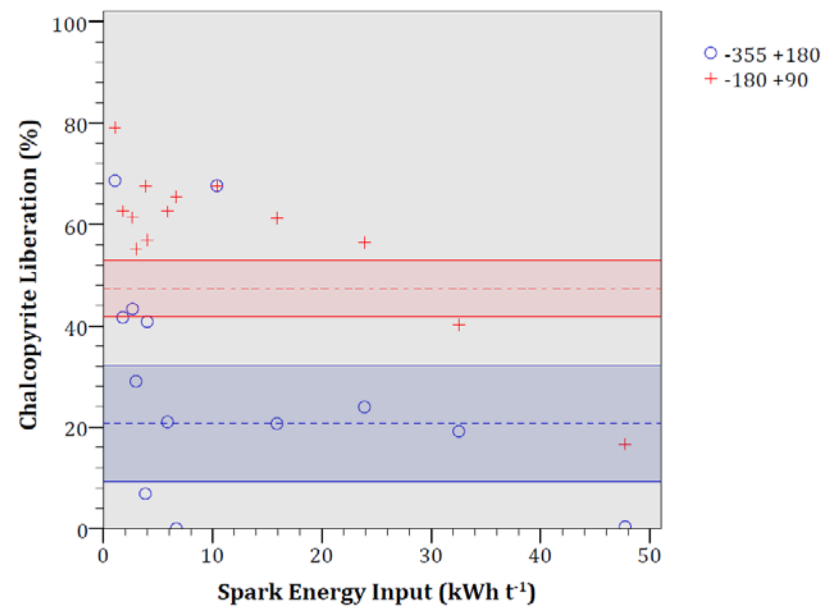


Fragmentation

Improved liberation

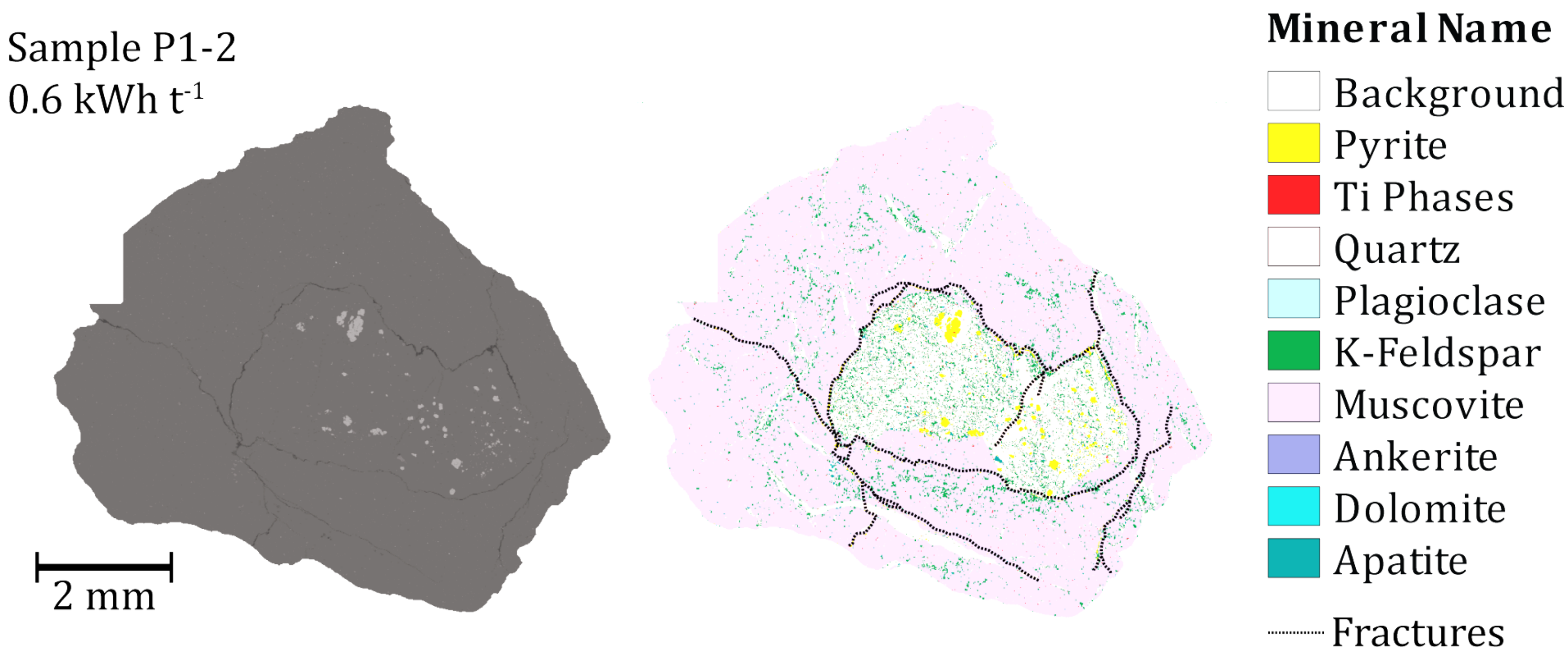
- 1.8% Chalcopyrite in feed upgraded to >10% at SELFRAG energies in 0 – 5 kWh/t range
- Liberation/modal abundance advantages coincide with weakening energy range





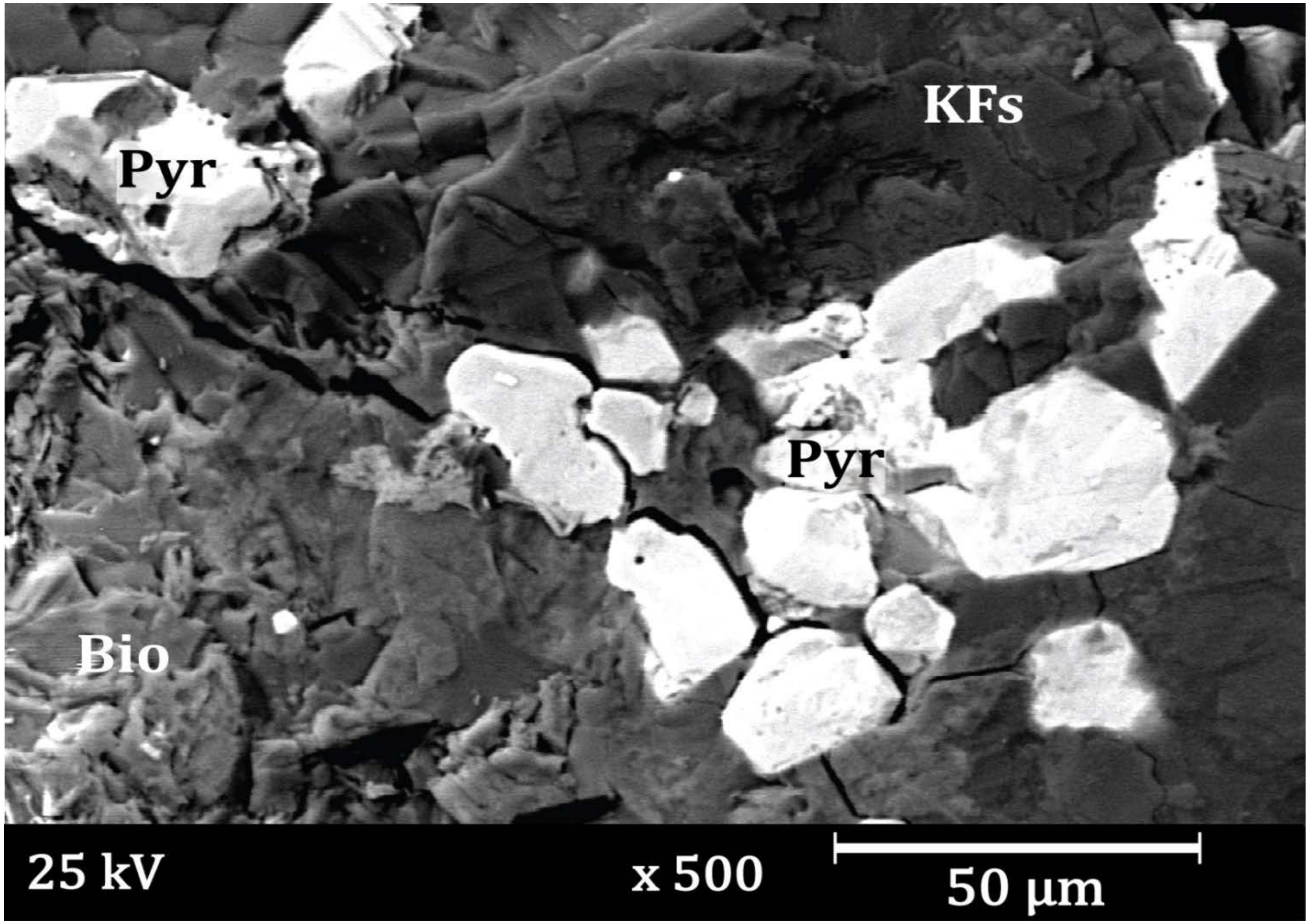
Fragmentation

Weakening and liberation



Fragmentation

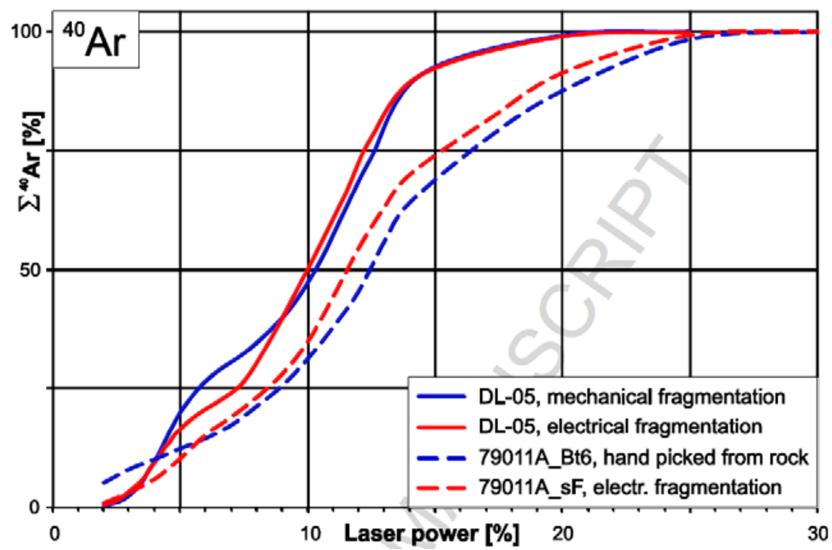
Weakening and liberation



Liberation for Geological Research

Improved geochronology results

- Vastly superior zircon/apatite liberation combined with quicker, dust-free sample preparation
- No negative effects on fission track, $^{40}Ar/^{39}Ar$, ^{40}Ar degassing curves, other thermochronology methods[1,2]



[1]) Sperner, B., Jonckheere, R., Pfänder, J.A., Testing the influence of high-voltage mineral liberation on grain size, shape and yield, and on fission track and 40Ar/39Ar dating, *Chemical Geology* (2014)

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Weakening

Definition of weakening

- Discharge-induced fracture network inside a particle that is:
  1. Sufficiently pervasive to cause a measurable strength reduction
  2. Not pervasive enough to cause full fragmentation of the particle

% Weakening for grindability indicators that increase with softness[1]

- i.e. A*b values
- No maximum weakening

$$\% \, PW = \frac{A*b_{weakened} - A*b_{untreated}}{A*b_{untreated}}$$

% Weakening for grindability indicators that decrease with softness

- i.e. Bond work index
- Maximum weakening of 100%

$$\% \, PW = \frac{BWi_{untreated} - BWi_{weakened}}{BWi_{untreated}}$$

References:
1) Shi, F., Zuo, W. and Manlapig, E. 2013. Characterisation of pre-weakening effect on ores by high voltage electrical pulses based on single-particle tests. Minerals Engineering, 50-51, 69 – 76

Weakening – Energy Relationship

Similarities to drop weight test analysis (1)

- Electrical pulses contain a well-defined amount of energy deposited in a single high strain rate event

- Well-defined and widely recognised models for impact breakage analysis:

JKMRC Prior art model	$t_{10} = A[1 - e^{-bE_{cs}}]$
Vogel and Peukert	$S = 1 - e^{[-f_{mat}xk(E_{cs}-E_{min})]}$
Shi and Kojovic	$t_{10} = M\left[1 - e^{(-f_{mat}xk[E_{cs}-E_{min}])}\right]$

Substitutions: t_{10} → % Pre-weakening

A → H

b → v

$H*v$ as the high voltage equivalent of $A*b$ values

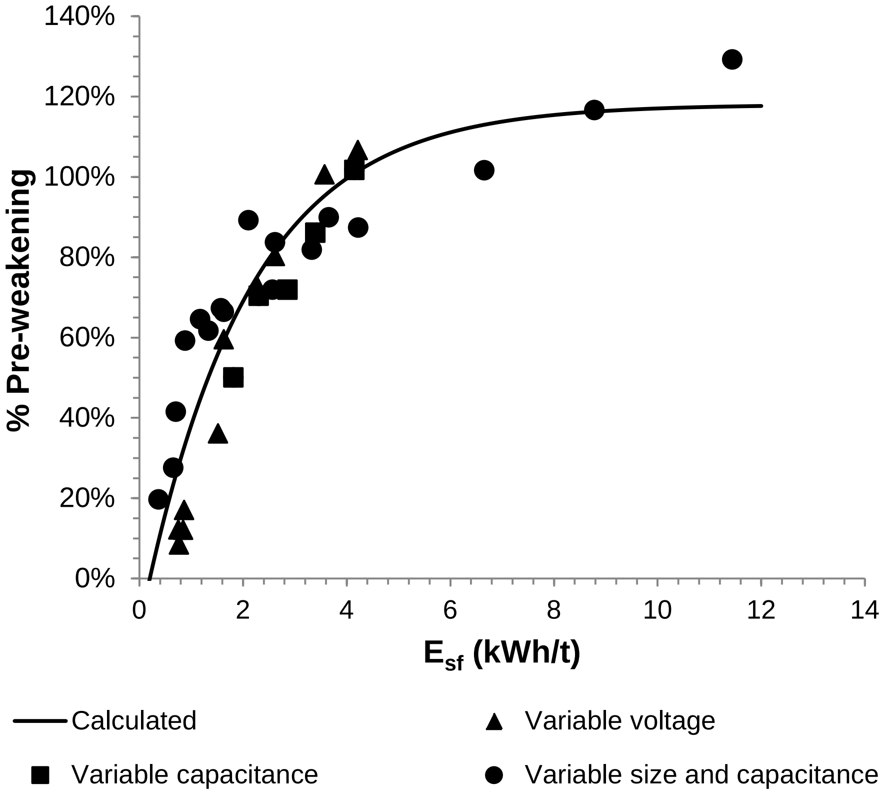
E_{cs} → E_{sf}

Weakening – Energy Relationship

Similarities to drop weight test analysis (2)

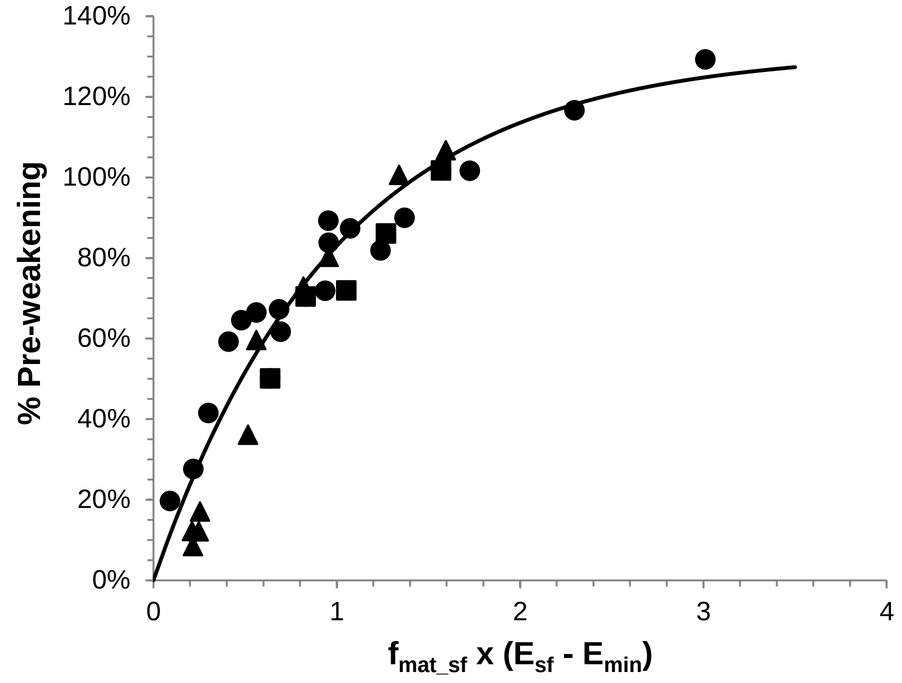
‘Simple’ weakening model

$$\%PW = H\left[1 - e^{-v(E_{sf} - E_{min})}\right]$$



‘Extended’ weakening model

$$\%PW = H\left[1 - e^{-f_{mat\_sf} x (E_{sf} - E_{min})}\right]$$



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Case studies
Introduction

Why care about weakening/selective liberation?

1. Comminution is often the biggest single cost factor in a processing circuit, consumes approx. 3 – 5% of global electricity production
2. 95 – 99% of comminution energy is wasted as heat/noise
3. The 1 – 5% remaining energy is used for largely a-selective grinding, significant amounts of energy are consumed grinding finer than strictly necessary

OPEX reduction due to weakening of rocks

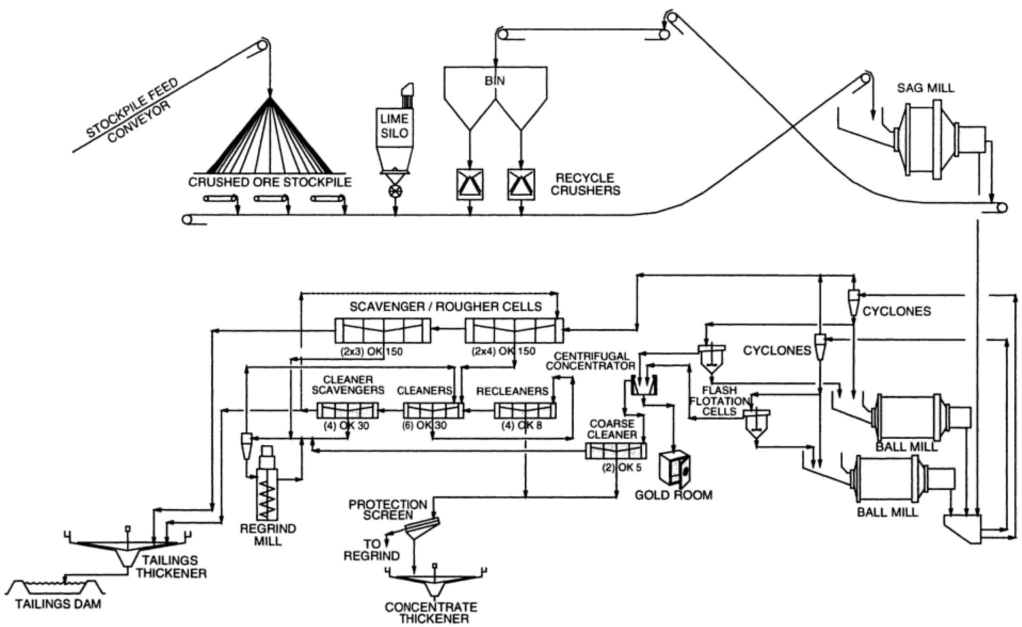
- Brownfield site with escalating production costs
- Investigate potential for cost reduction and revenue increase using SELFRAG technology

Case study

Existing circuit with 19.6 kWh/t input

Target: **OPEX reduction at maintained throughput**

- Extensive weakening study
- JKSimMet simulations were used to quantify benefits
- Close cooperation with mine owner (brownfield site)
- Simulation assumed 72% weakening at 2.6 kWh/t SELFRAG energy

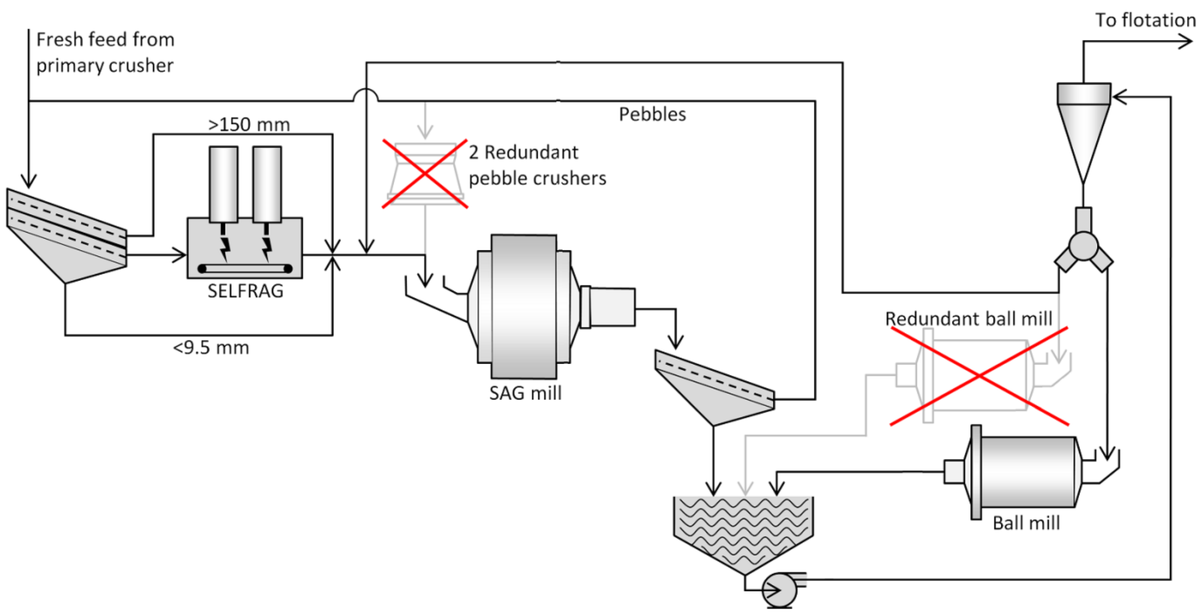


Commodity	Cu/Au
Specific energy input	19.6kWh/t
Throughput	2000 tph
Grindability	A*b = 33.3 BWi = 22.4 kWh/t

Case study

Shutdown of 2 pebble crushers and 1 ball mill is possible[1]

- 25% Specific Energy Saving[1]
- Incidental throughput increase of 6.7%[1]
- Further potential for recovery improvements[2]



[1]) Confirmed by JKSimMet modelling
[2]) JKSimMet suggest grind size decrease from 210 to 148 µm; Circuit originally designed for 150 µm

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Summary

High voltage physics

- Electrical breakdown occurs in rocks before water in SELFRAG units, and causes formation of plasma channels

- Shockwaves emanating from plasma channel, together with plasma percolation and limited direct plasma damage cause extensive weakening and highly selective liberation of SELFRAG technology

- Acoustic impedance and porosity correlate to product size after SELFRAG treatment, tensile strength and permittivity correlate to % remaining oversize after SELFRAG

Summary

Weakening, liberation and case study

- SELFRAG causes extensive micro-fracturing that leads to significant weakening of rocks

- SELFRAG liberates selectively and coarser than conventional comminution technologies

- Case study: OPEX reduction due to weakening of rocks
  - Shut down of one ball mill and two pebble crushers
  - Lower ore strength and reduced milling capacity mean lower grinding media and liner consumption
  - 4.9 kWh/t specific energy reduction at increased throughput
  - Potential for recovery improvements from decreased grind size