Monitoring and Numerical Modelling of Induced and Triggered Seismicity in a Deep Sublevel-Stoping Mine

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Objective of the study

Why compare seismic and model data?

Microseismic Monitoring

Real-time monitoring for short-term prevention

Advantages	Limits
Global in site measurements	Precision of detection and location
Real time monitoring	No detection of aseismic deformation
Insight into fractures dynamic	Local measures

Numerical modelling

Optimization of future excavations

Advantages	Limits
Long-term prediction	Needs lots of geo-mechanical information
Simulation of different excavation sequences	High computational requirements
Global view of stress changes	

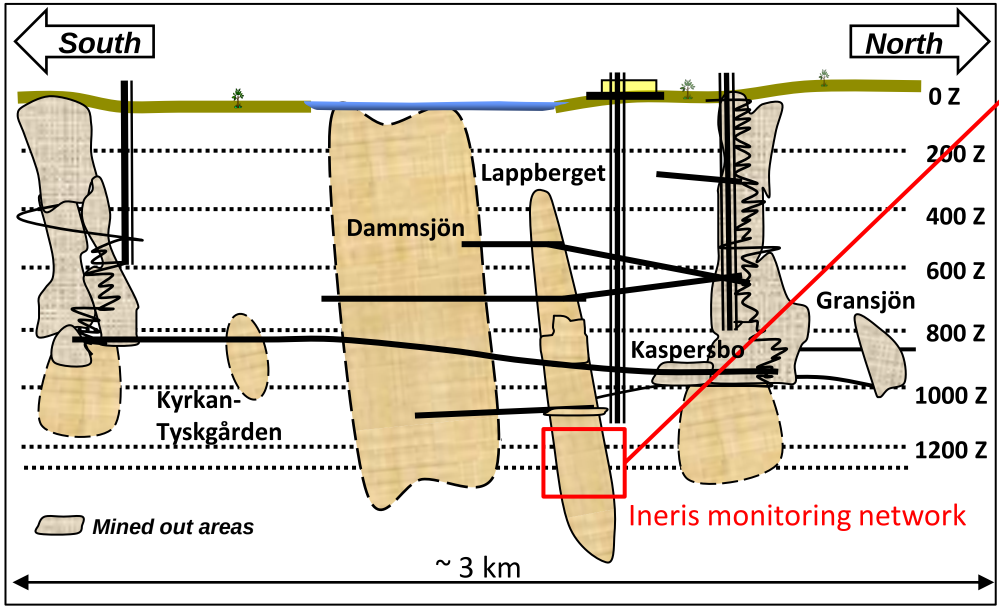
Finding possible links

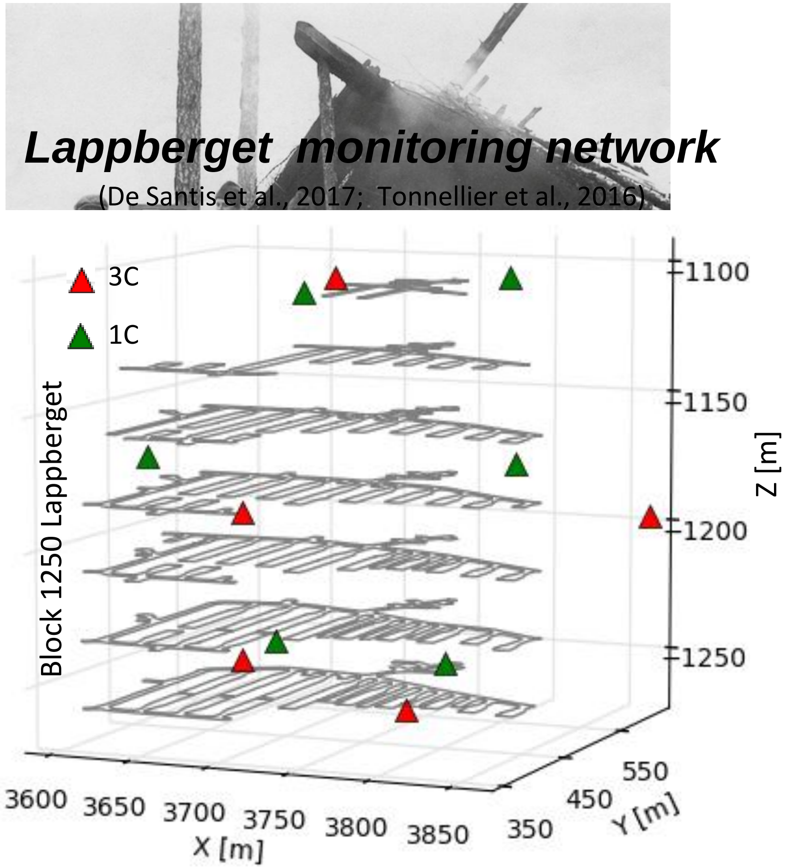
- Better understanding of interactions between stress changes and seismic activity generation
- Gaining additional insights into failure processes
- Improving long-term and short-term prevention

Garpenberg mine

Geographic and Historical context

Schematic vertical profile of Garpenberg mine



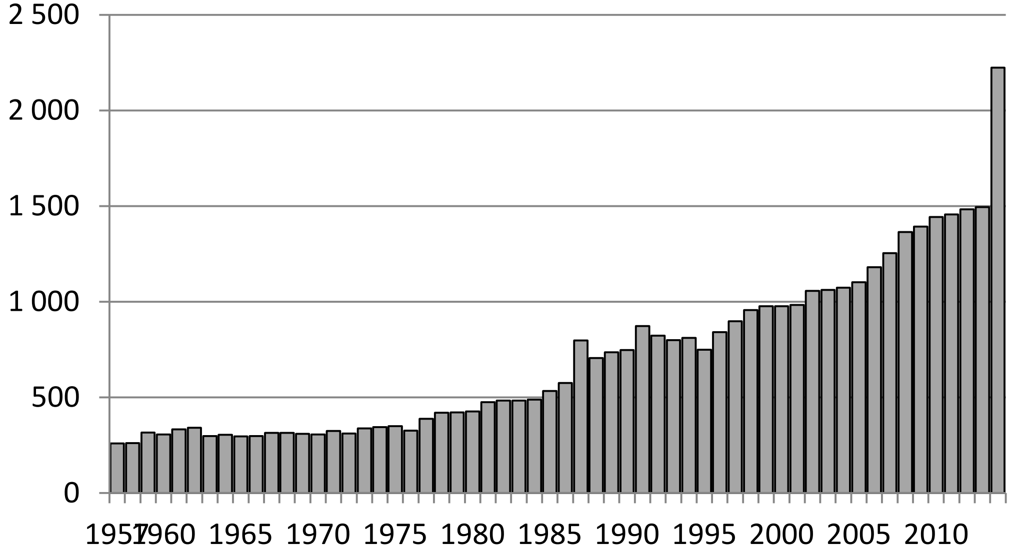


- Sv
- De
- Acquired by Boliden in 1957 (300.000 tonnes/year)
- Discovery of Lappberget orebody in 1998
- Production moved in Garpenberg North in 2004

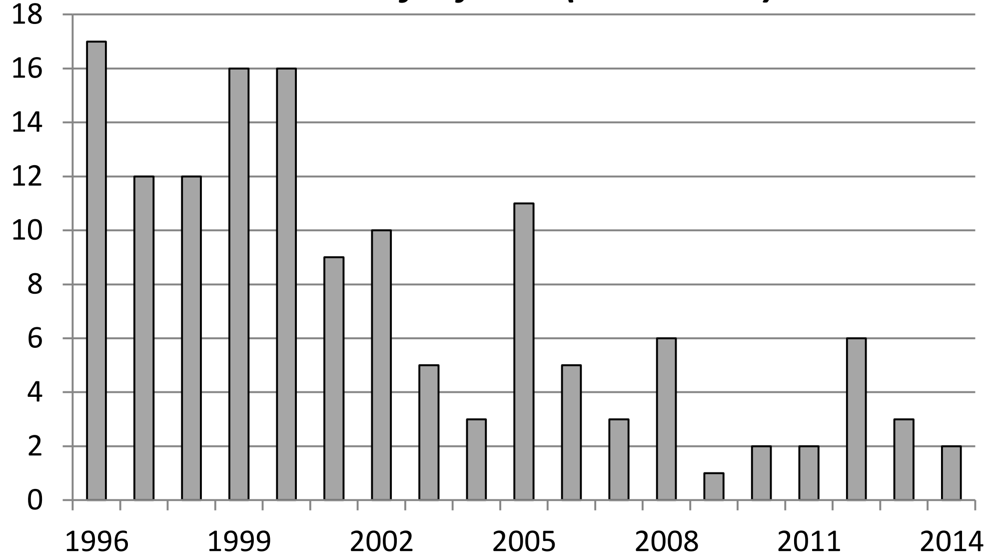
Garpenberg mine

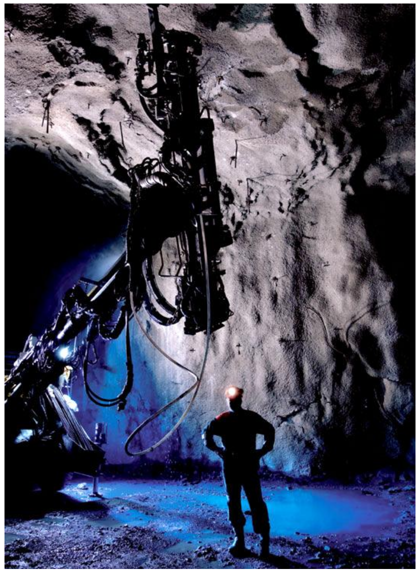
Production & Injuries

Amount of produced ore [kt] (1957-2014)



Number of injuries (1996-2014)





Mass mining methods

Improve automation and digitalization

Microseismic monitoring

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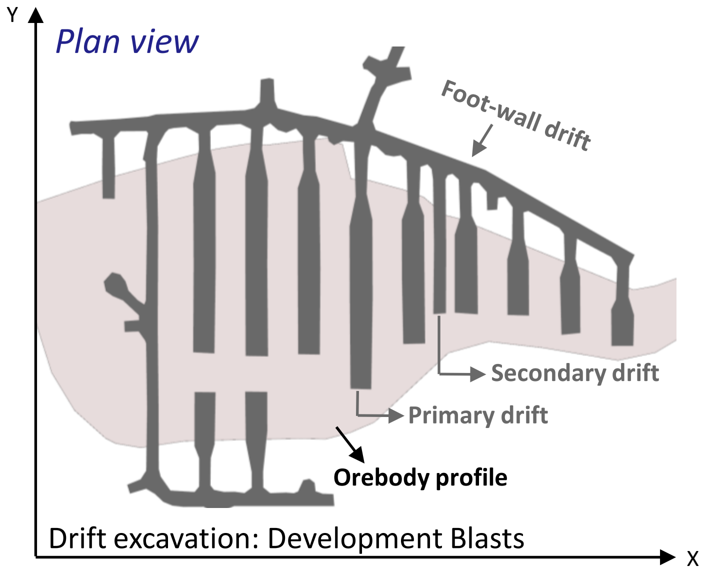
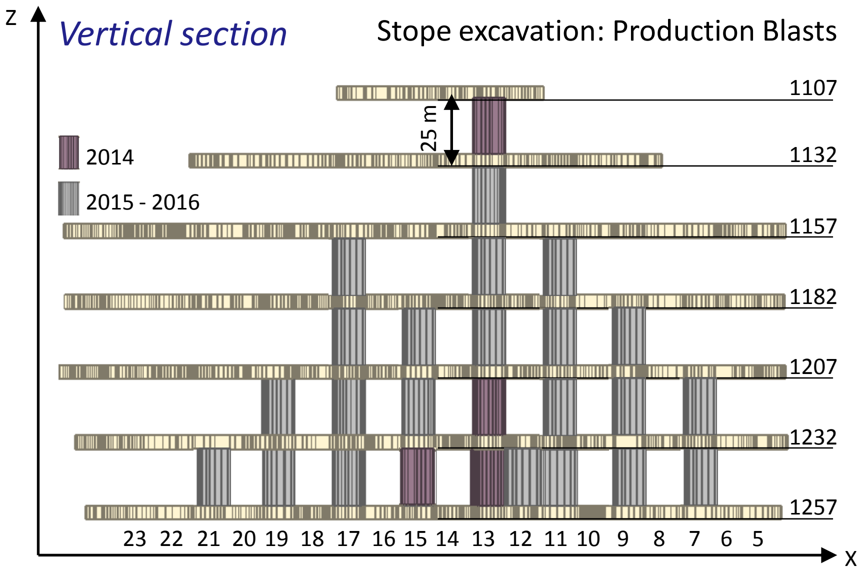
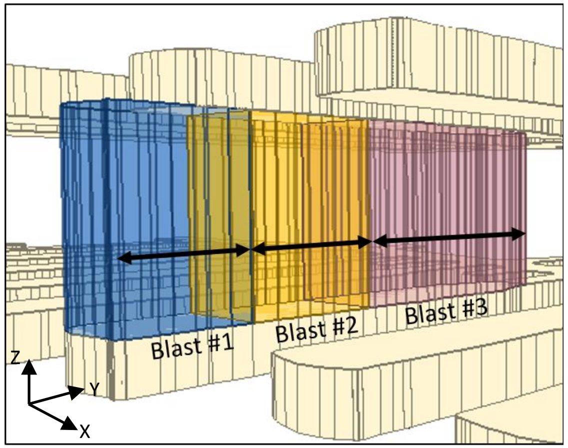
Lappberget orebody

Mining method and sequence

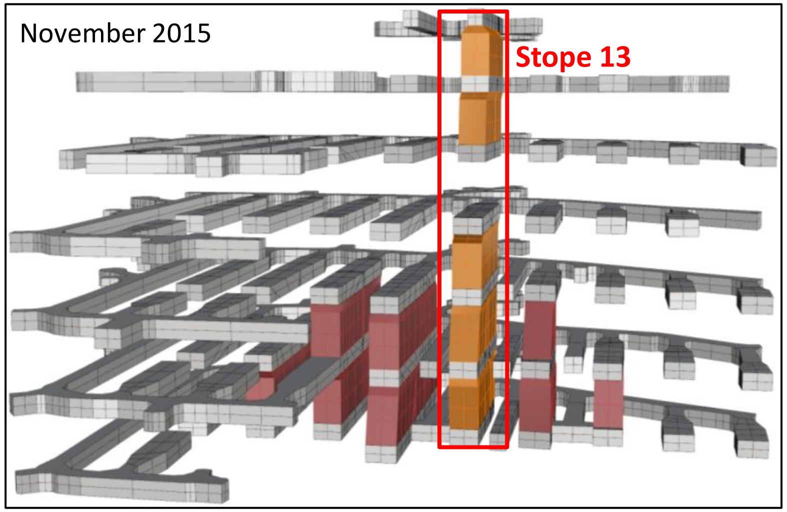
Sublevel stoping method with backfilling

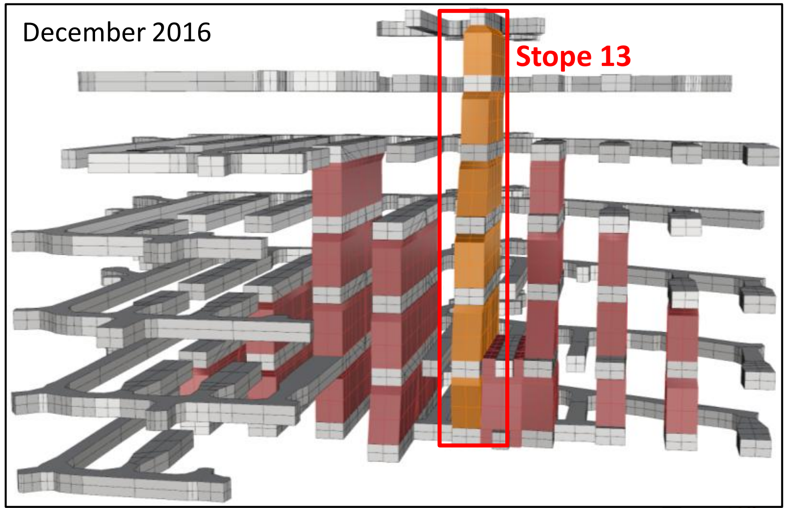






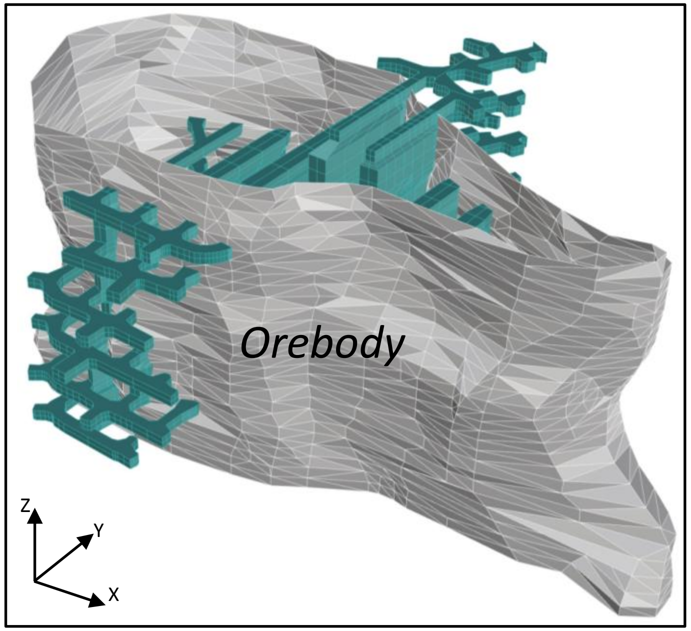
Mining sequence

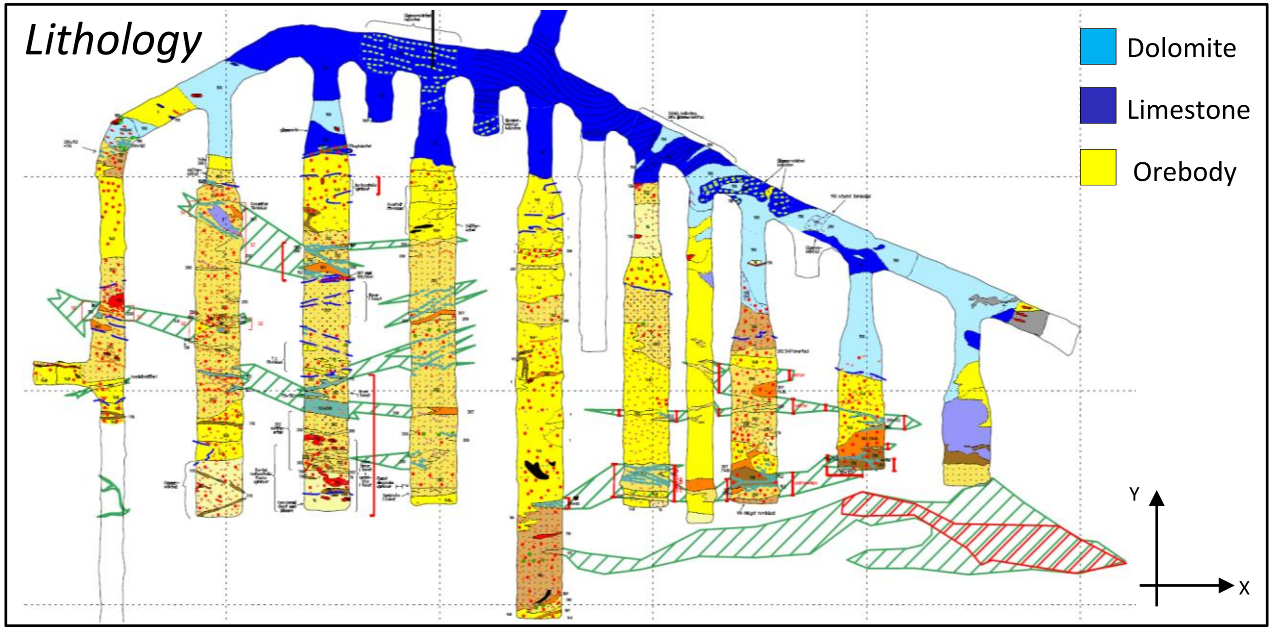


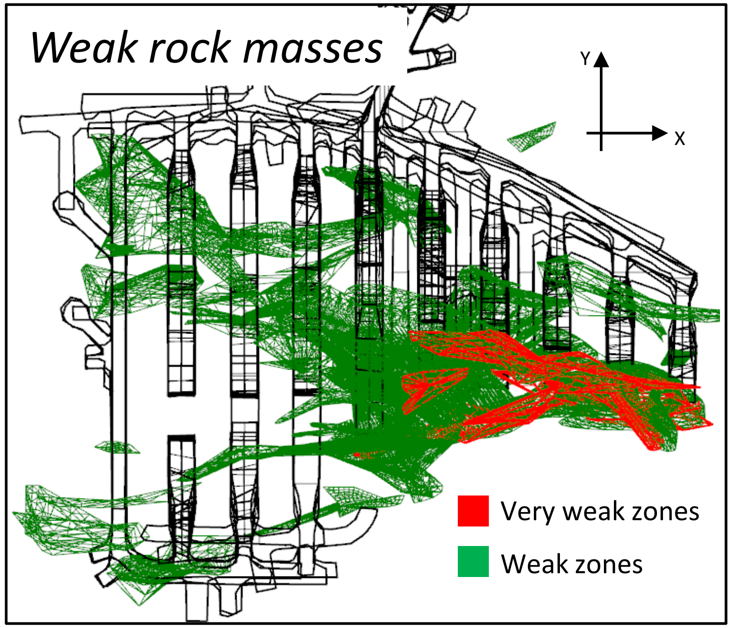


Lappberget orebody

Local geology







Mechanical properties

Materials	*Young modulus E [MPa]*	*Poisson's ratio ν*	*Density ρ [kg/m^3]*
Ore	66000	0.2	3030
Limestone	57000	0.18	
Weak	20000	0.3	
Very weak	2000	0.4	

Lack of data:

- Characteristics of fractures, joints or faults
- Mechanical properties of rock types
- No 3D information except for the orebody

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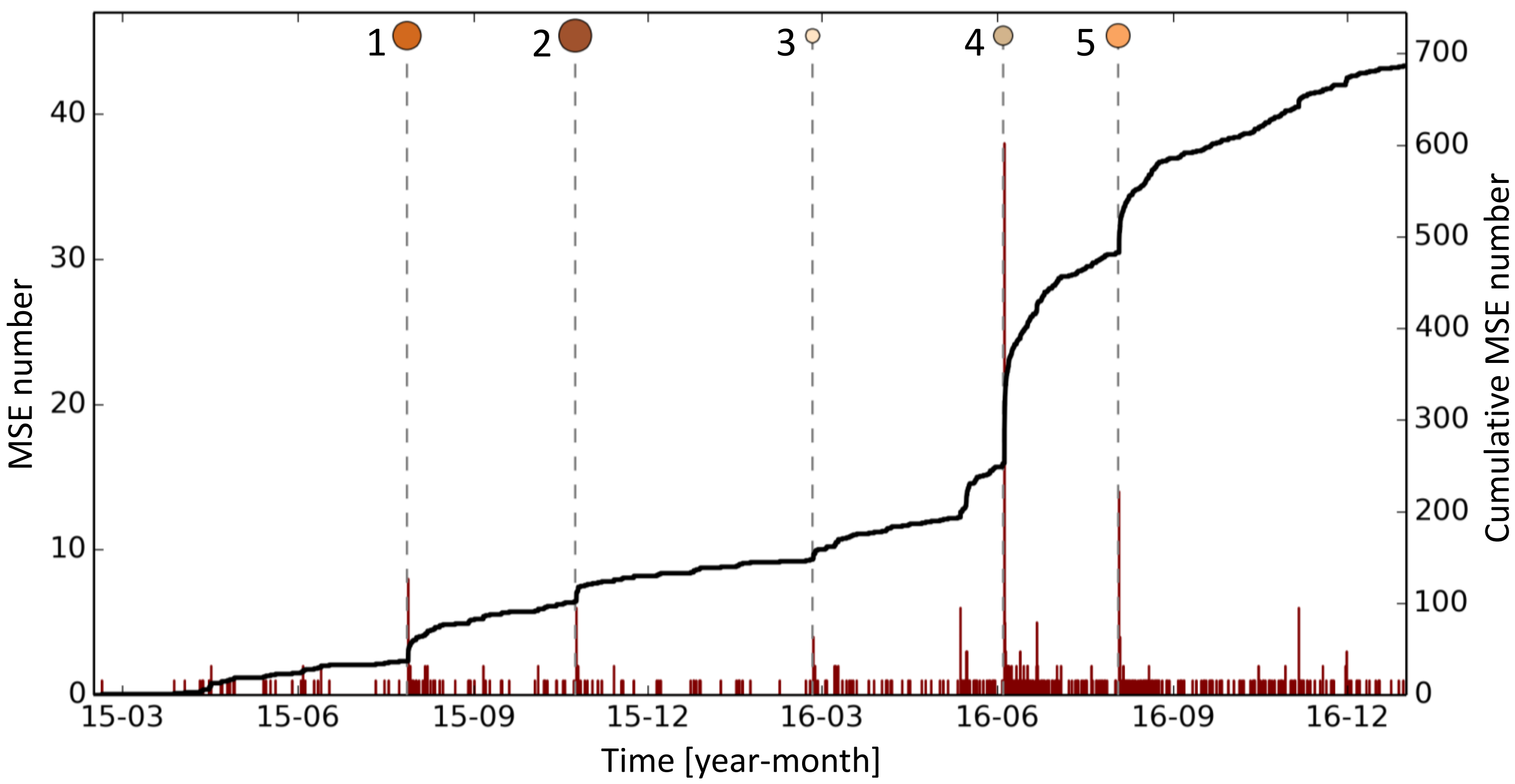
Analysis of Lappberget Microseismic Activity between 2015 and 2016

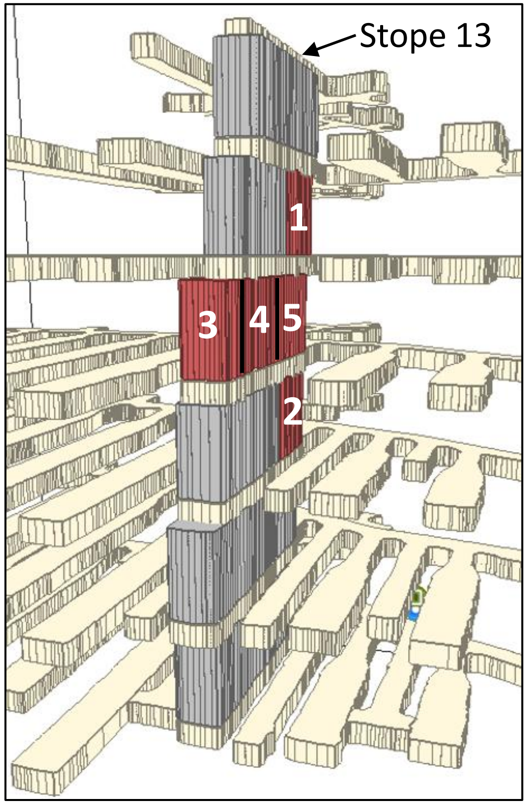
Mining Production & Microseismic Activity

Space-time distribution

Microseismic swarms



Mined Stopes



Extracted rock mass volume:

1000-3000m³ · 3000-4000 m³ · 4000-5000 m³ · 5000-6000m³ · ≥ 6000 m³

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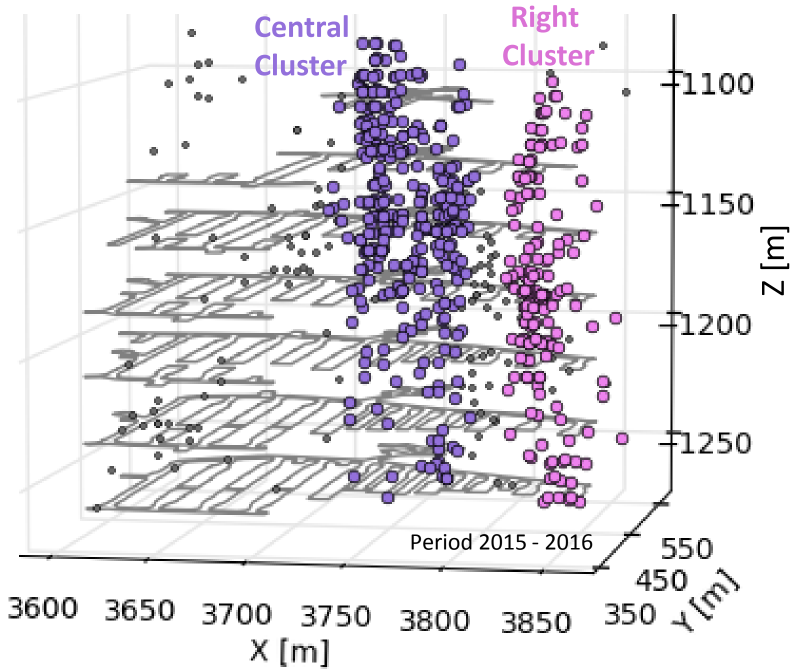
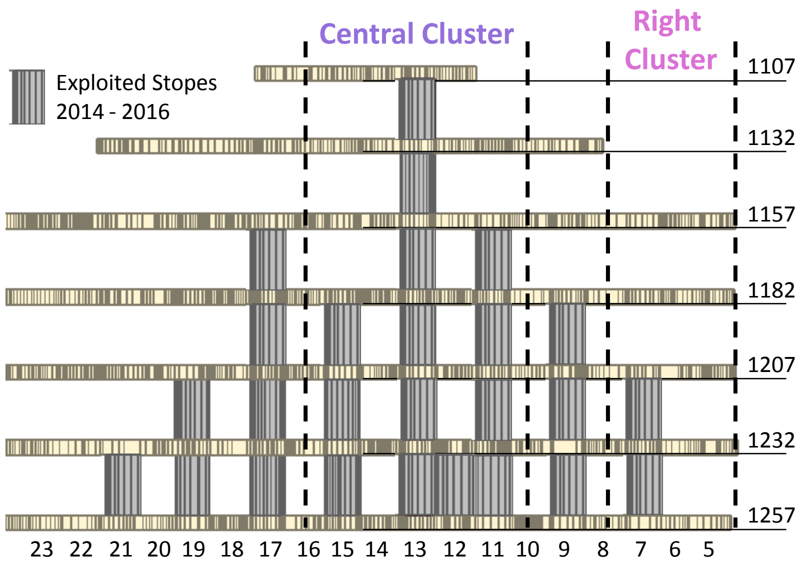
Mining Production & Microseismic Activity

Cluster of MSE

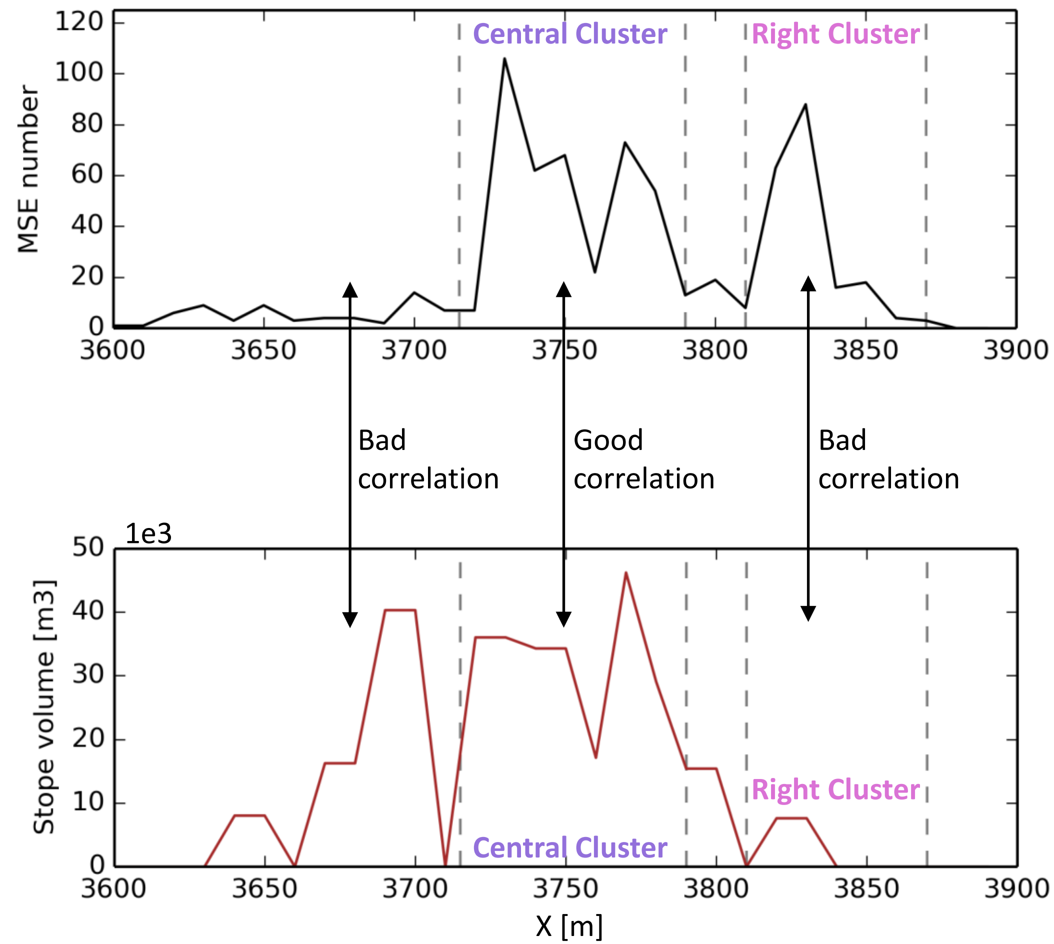
Microseismic activity



Mine production



MSE number & stopes volumes on a sliding window along X direction



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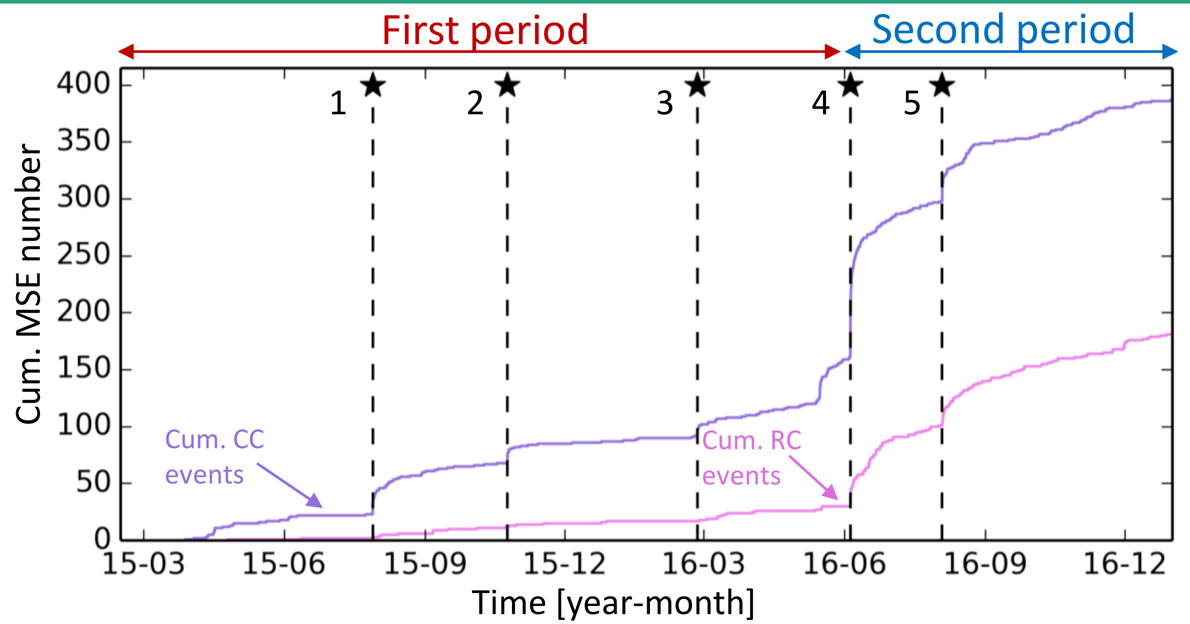
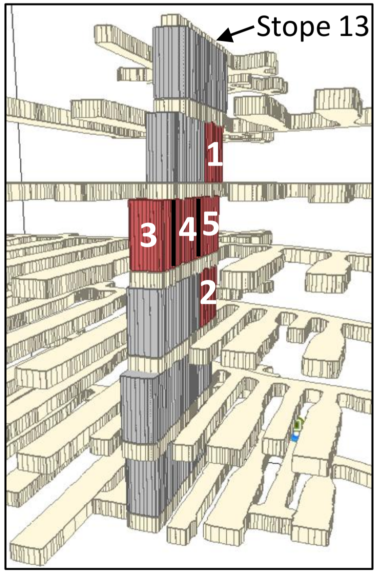
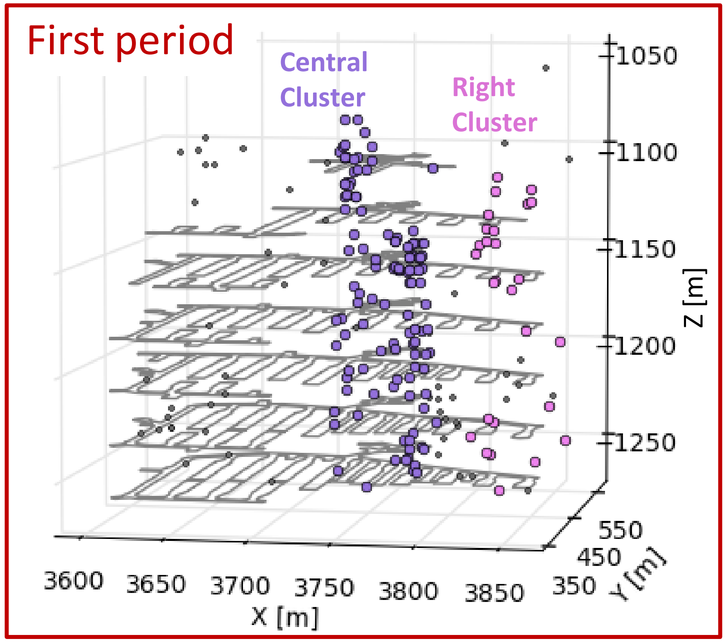
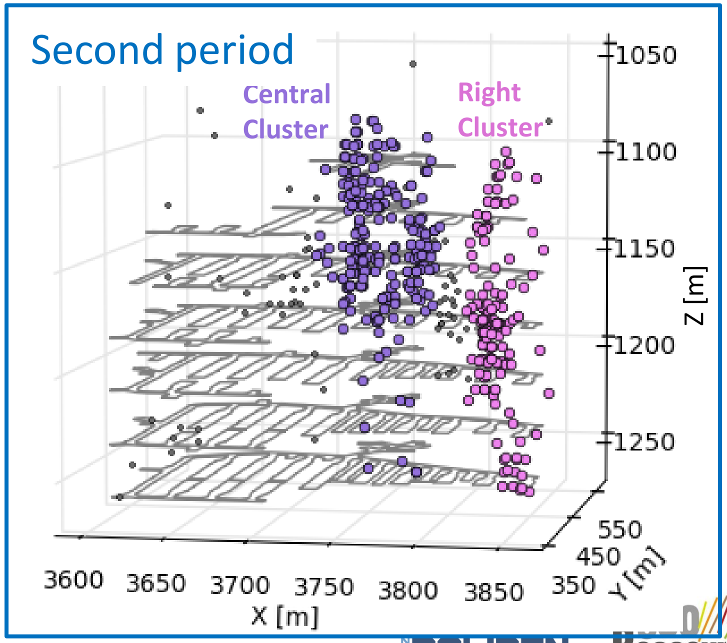
Mining Production & Microseismic Activity

Cluster of MSE





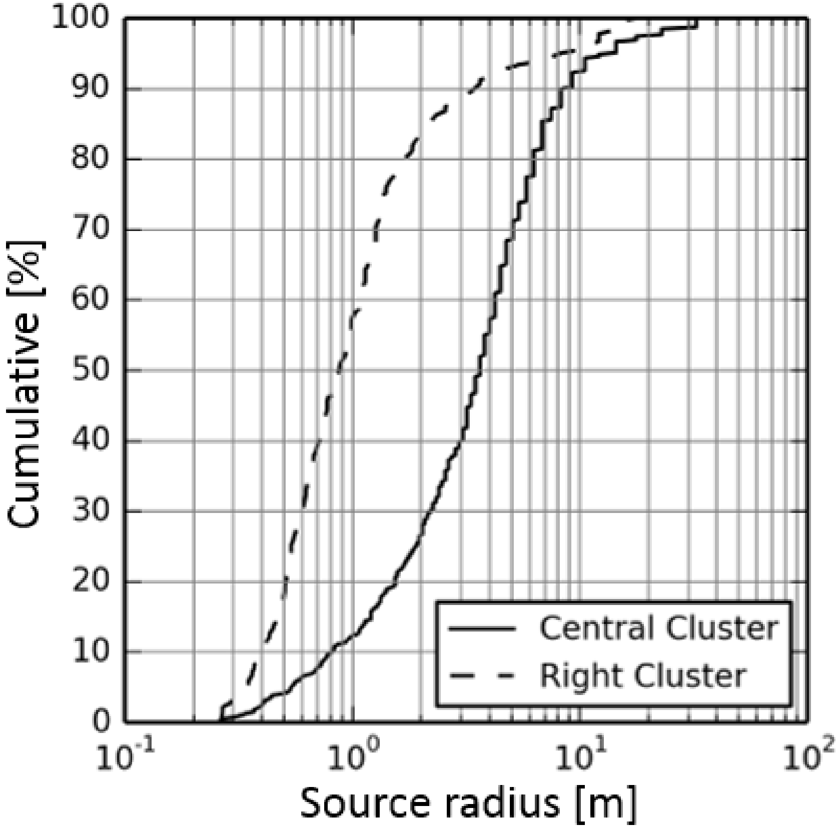




Seismic source characteristics

Fracture size and Apparent Stress

Fracture dimension



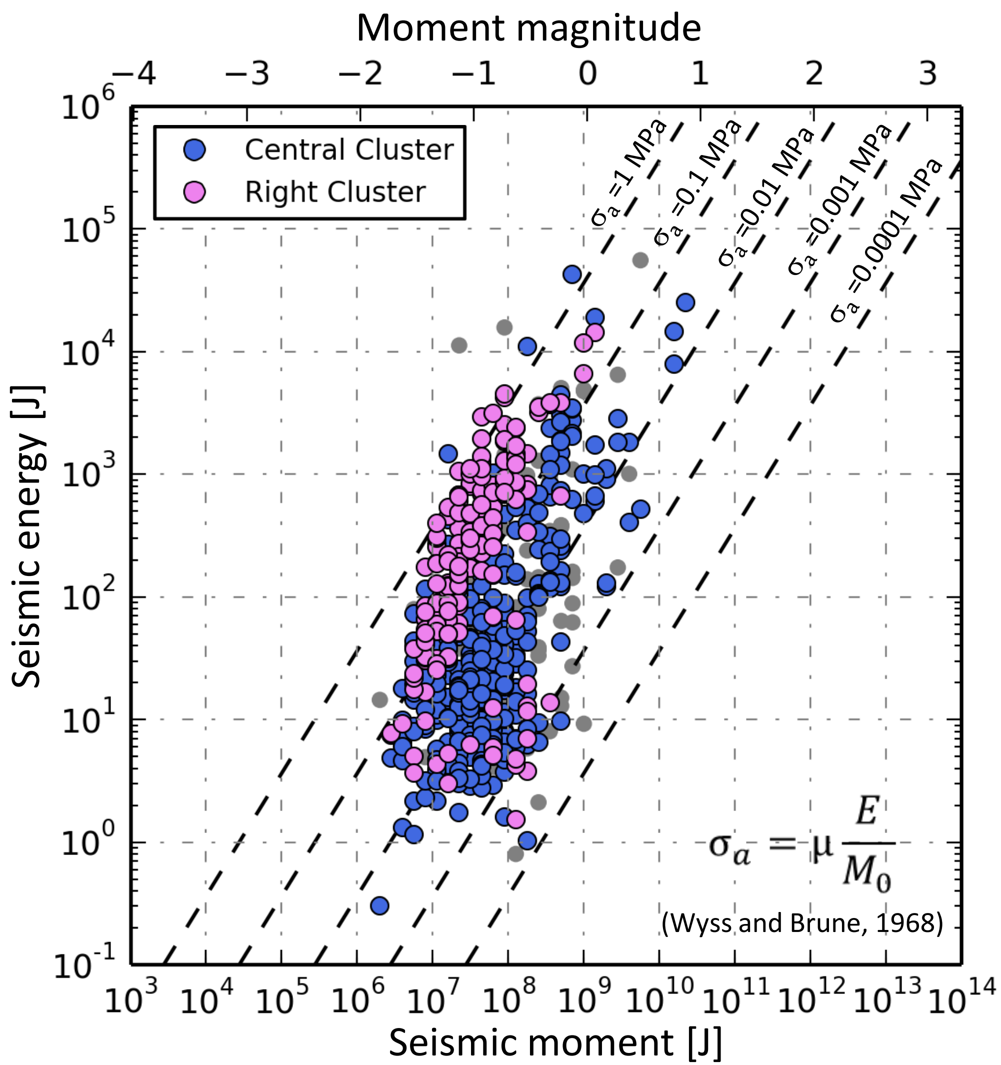
$$f_c = k_c \frac{V_S}{r}$$

$k_c = constant$ [-]

$r = source\ radius$ [m]

$V_S = S\ wave\ velocity$ [m/s]

- Source radius ⇒ from 0.3 m up to 32 m
- Median RC radius = 0.9 m
- Median CC radius = 3 m



- *Apparent stress* ⇒ measure of stress release at a seismic source
- Bigger stresses in the Right Cluster area

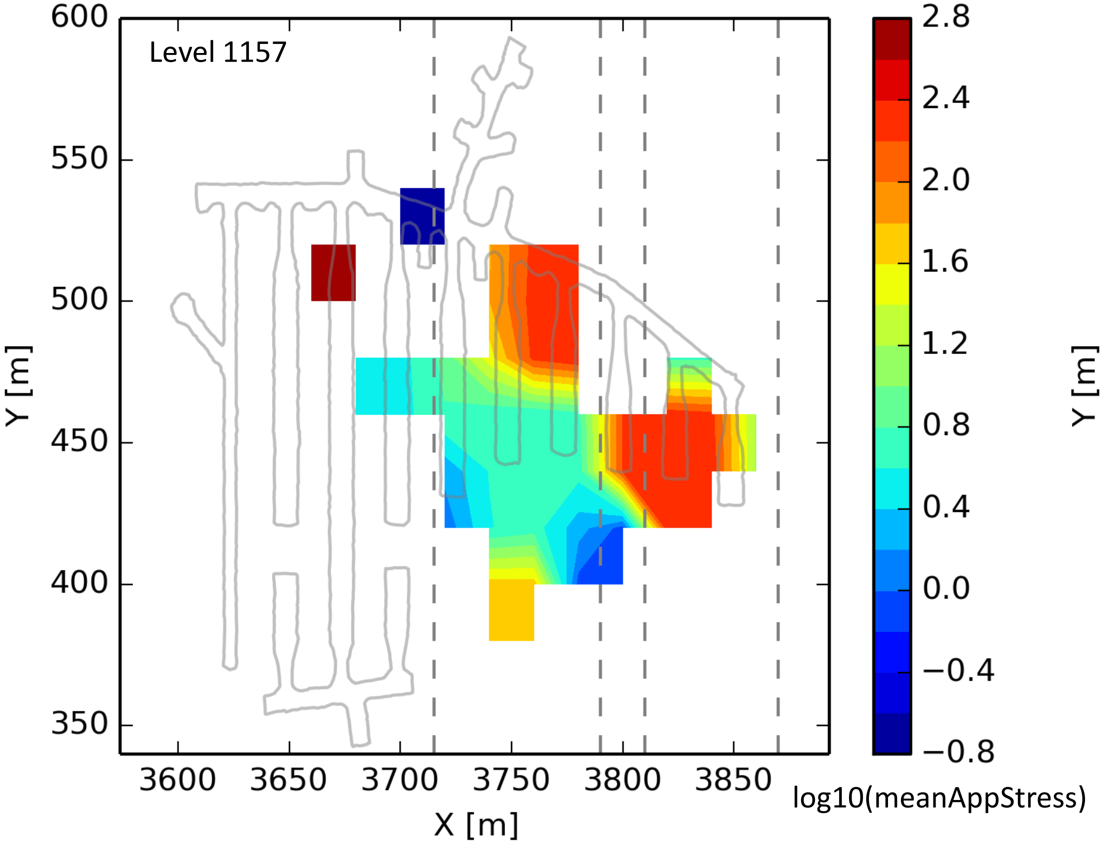
Seismic source characteristics

Apparent stress

Contour maps of apparent stress

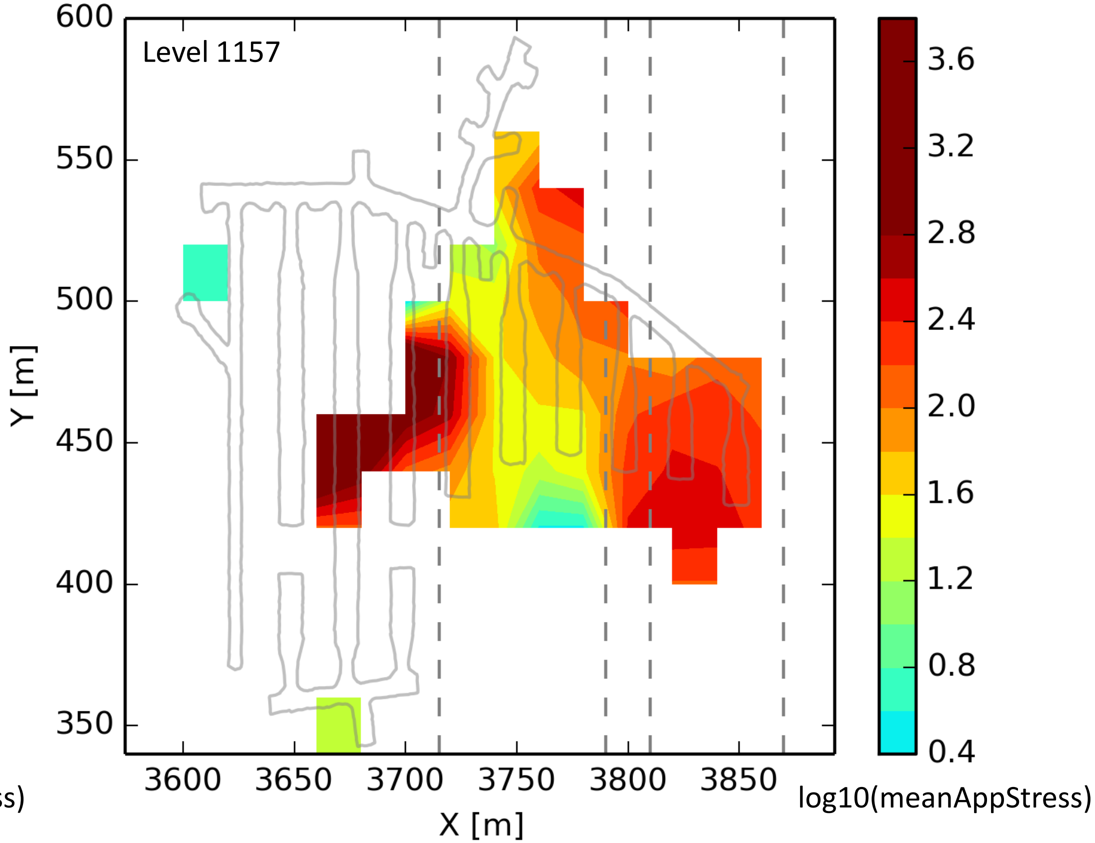
First period

February 2015 - May 2016



Second period

June 2016 - December 2016



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Conclusions on seismic data analysis

Central Cluster	Right Cluster
In agreement with production in the area	Linked with remote blasting in stope 13
Active since the beginning of the monitoring	Activated at final stages of stope 13 exploitation + Influenced by local geology
Bigger fractures	Smaller fractures
Lower apparent stress values	High apparent stress values

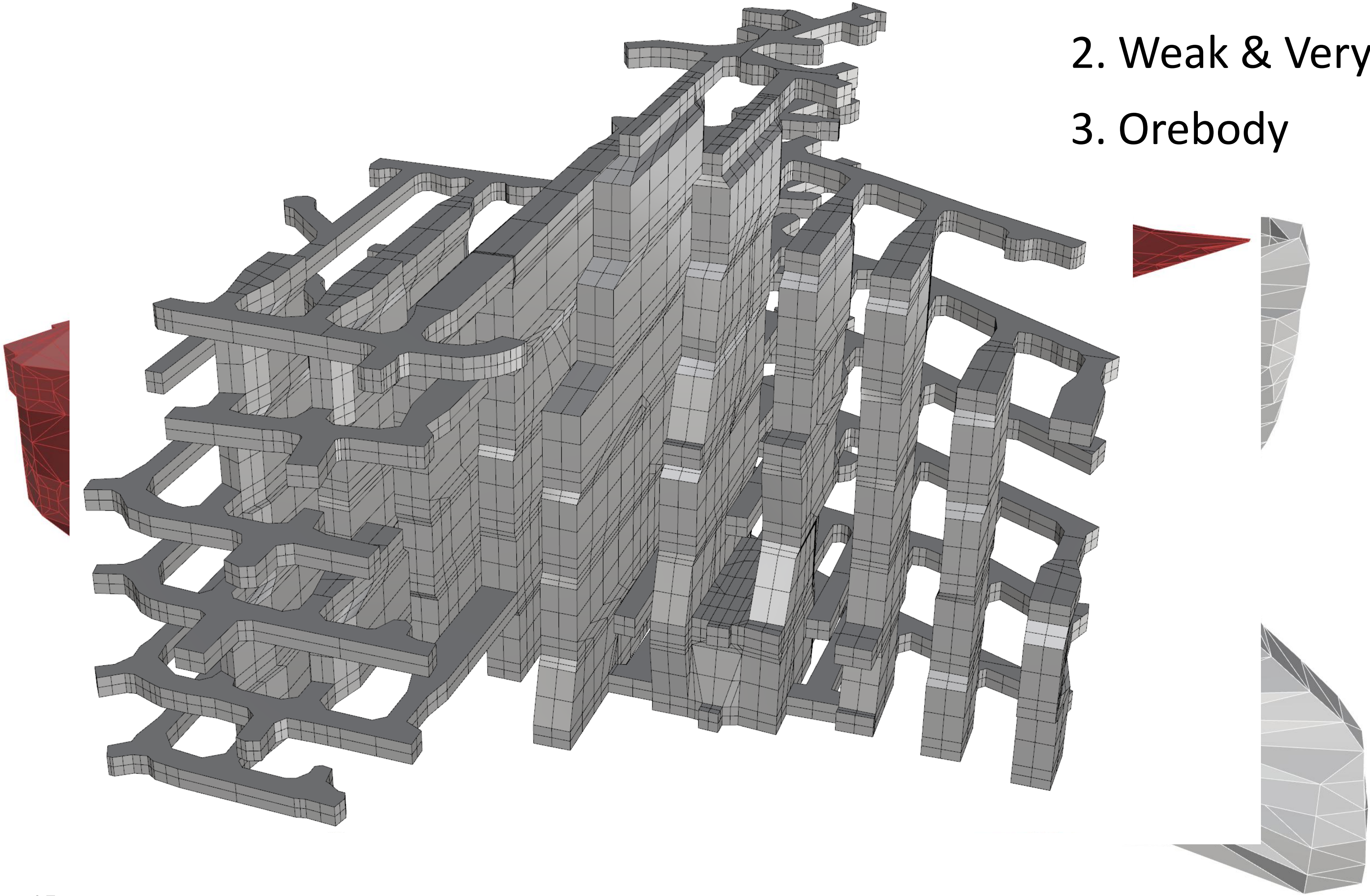
Numerical Modelling

Simulation of the exact mine sequence between 2015 and 2016

Numerical Model

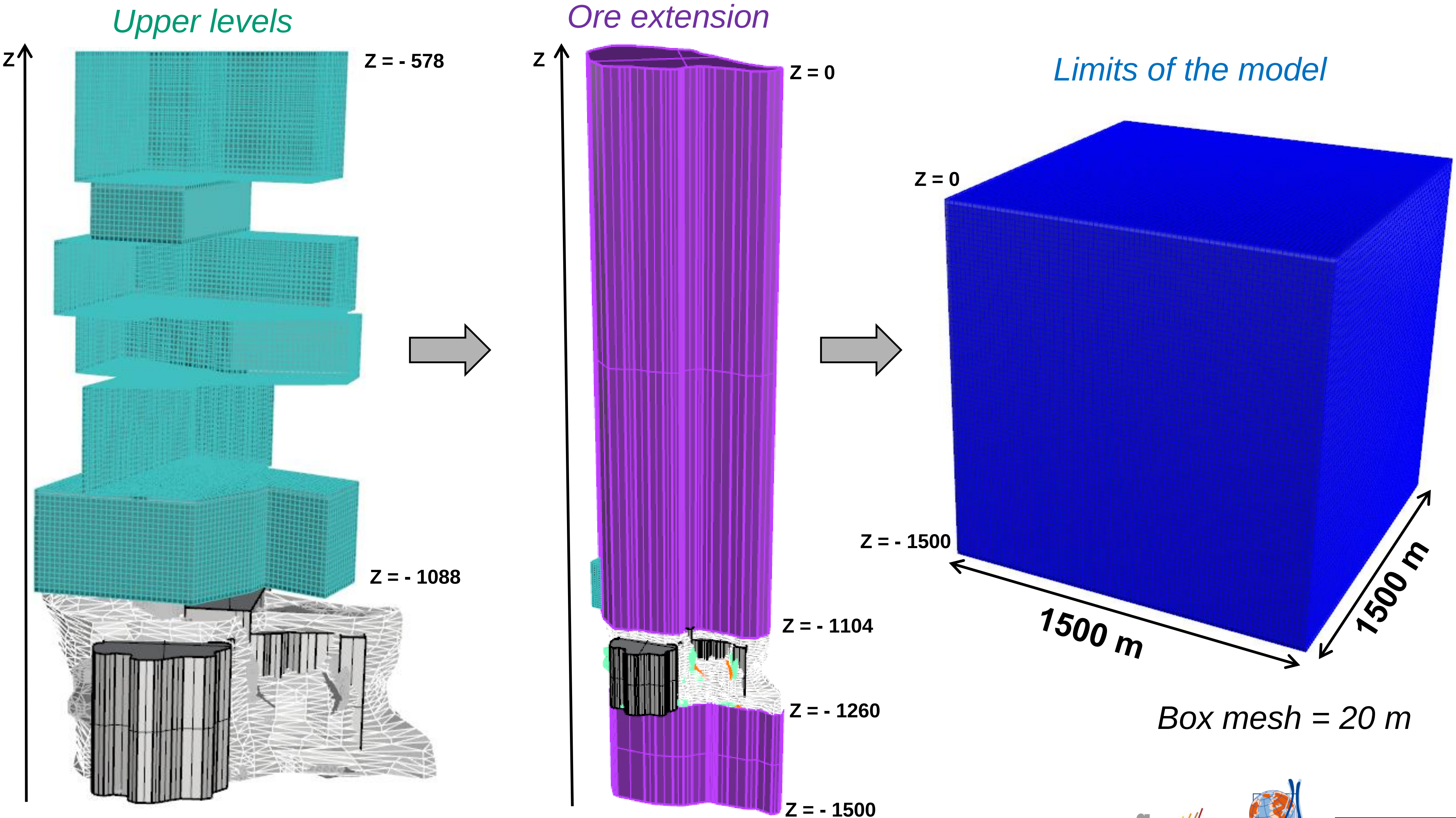
Geometry & Meshing

1. Galleries & Stopes
2. Weak & Very weak zones
3. Orebody



Numerical Model

Geometry & Meshing



Upper levels mesh = 5 m

Box mesh = 20 m

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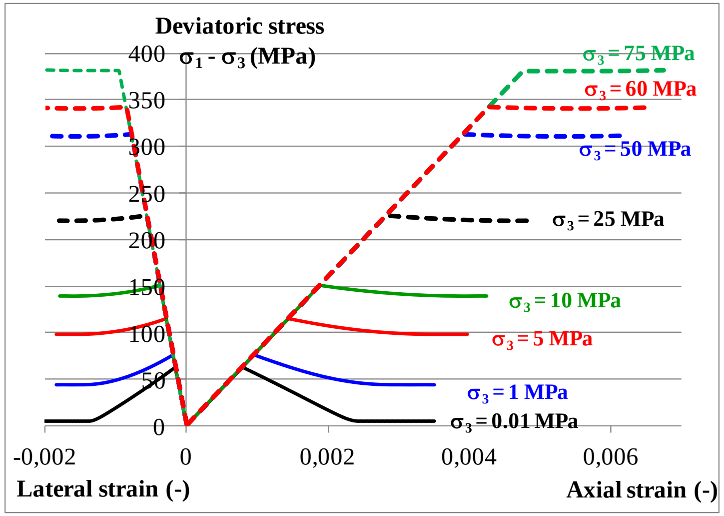
Initials & Boundary Conditions

$$\sigma = f(z) = \rho g \begin{pmatrix} k_X \\ k_Y \\ 1 \end{pmatrix} z \quad \begin{cases} \sigma_X = 44.3\ MPa \\ \sigma_Y = 47.3\ MPa \\ \sigma_Z = 34\ MPa \end{cases}$$

Failure criteria

Hoek-Brown failure criteria $\Rightarrow \dfrac{\sigma_1}{\sigma_C} = \dfrac{\sigma_3}{\sigma_C} + \sqrt{m\dfrac{\sigma_3}{\sigma_C} + s}$

Brittle failure criteria



(Souley et al., 2018)

	Elastic parameters		***Hoek-Brown parameters***			
Materials	*Young modulus E [MPa]*	*Poisson's ratio ν*	*m*	*s*	*σ_C [MPa]*	*Density ρ [kg/m³]*
Ore	66000	0.2	10	0.112	188	3030
Limestone	57000	0.18	10	0.112	110	
Weak	20000	0.3	1	0.001	30	
Very weak	2000	0.4	0.63	0.00024	10	
Paste	500	0.2	-	-	-	2000

	Brittle failure criteria parameters					
Materials	m_r	σ_3^{b-d}	s_r	ξ_r	β_m	b_1
Ore	2	$\sigma_C * (s)^{1/2}$	s*1e-5	0.0025	tan(15°)	750

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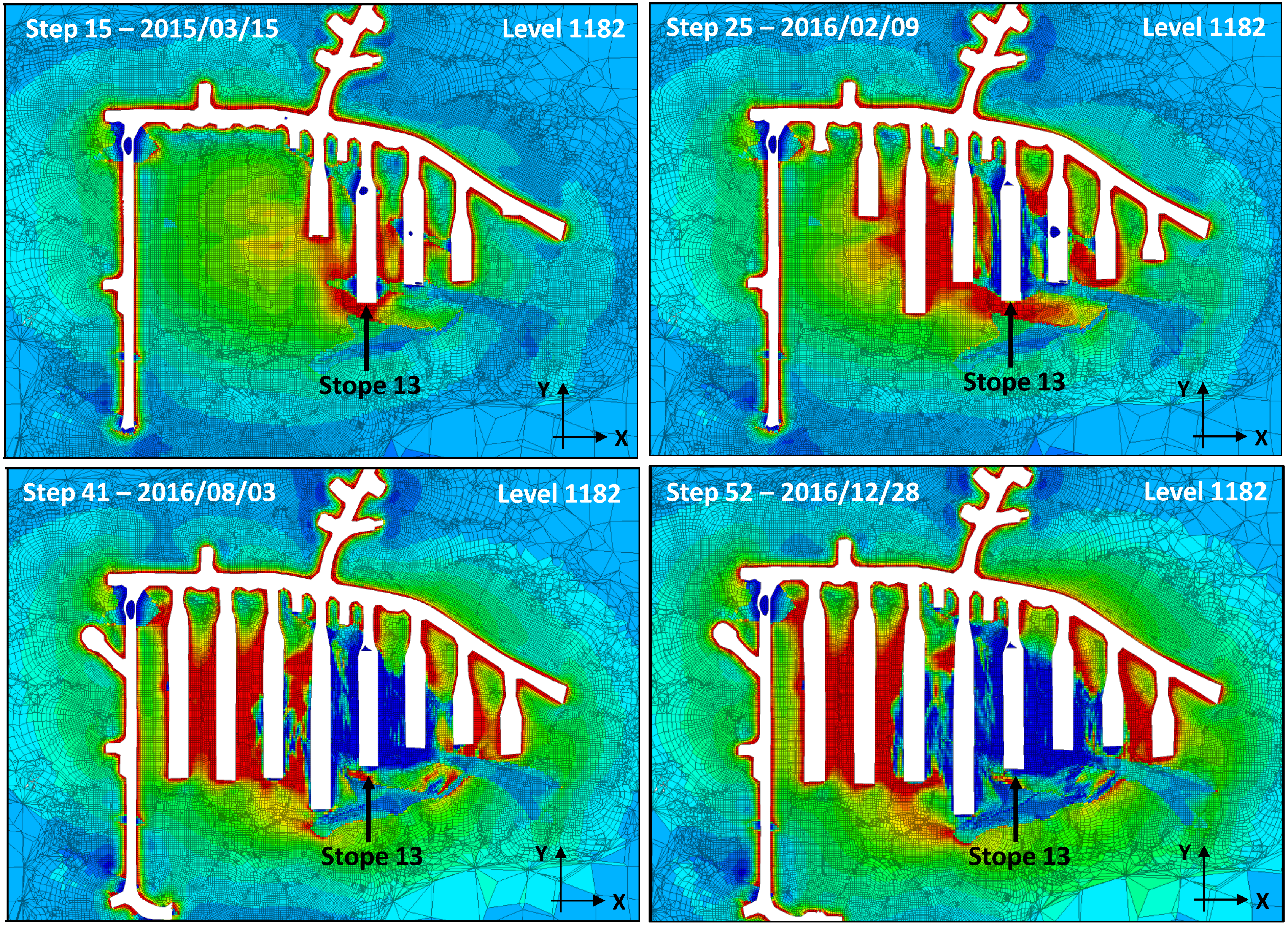
Numerical Model

Model Results



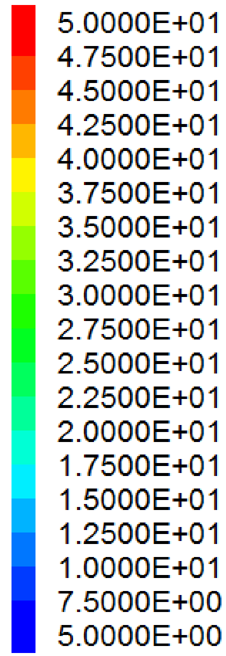
$q^{ini} = 12.1\ MPa$

$\sigma_x^{ini} = 44.3\ MPa$

$\sigma_y^{ini} = 47.3\ MPa$

$\sigma_z^{ini} = 34\ MPa$

Deviatoric stress* [MPa]



$^{*}\ q = \sqrt{3J_2} = \sqrt{\frac{1}{2}[(\sigma_1-\sigma_2)^2 + (\sigma_1-\sigma_3)^2 + (\sigma_3-\sigma_2)^2]}$

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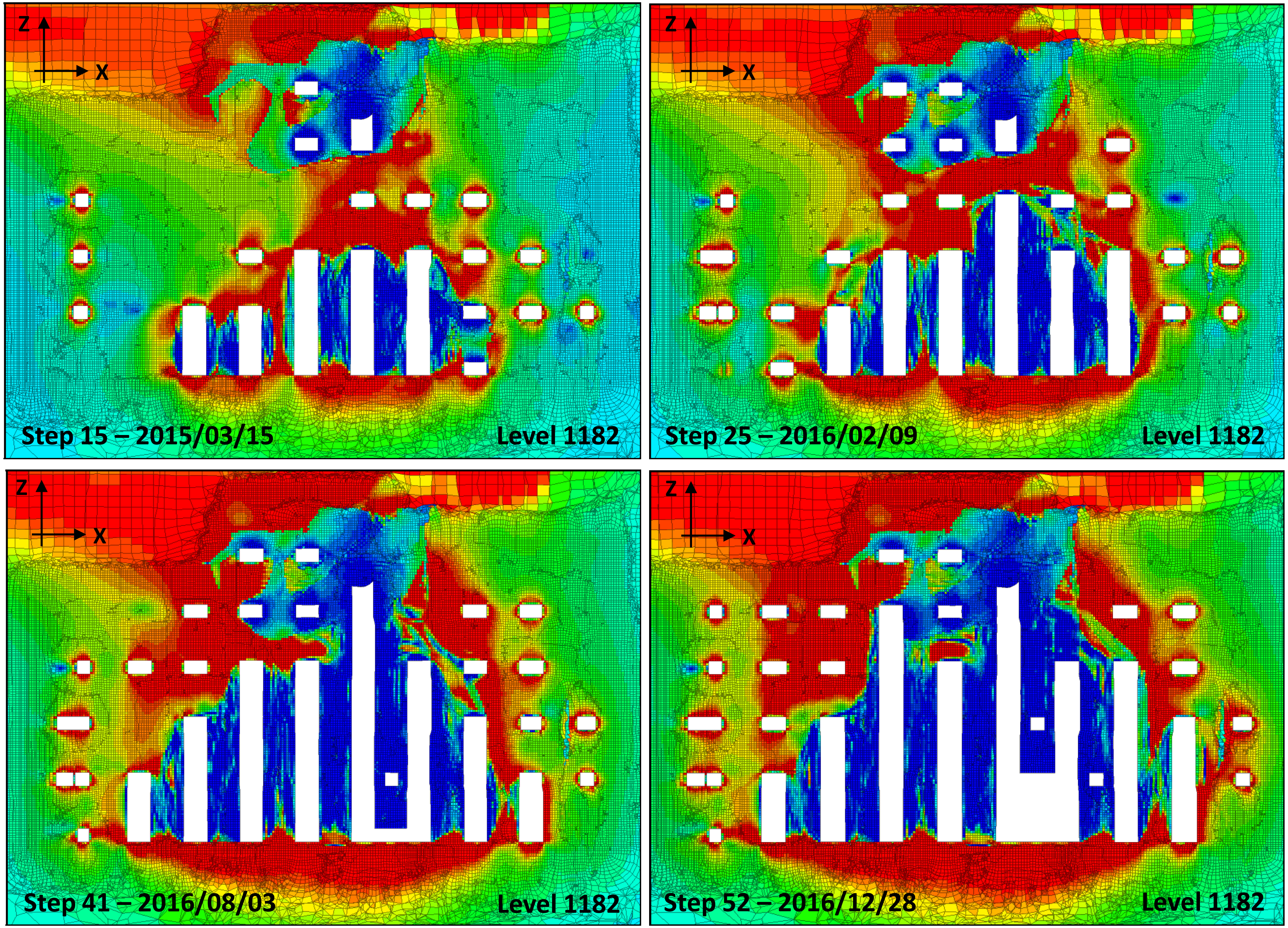
Numerical Model

Model Results



$$q^{ini} = 12.1\ MPa$$

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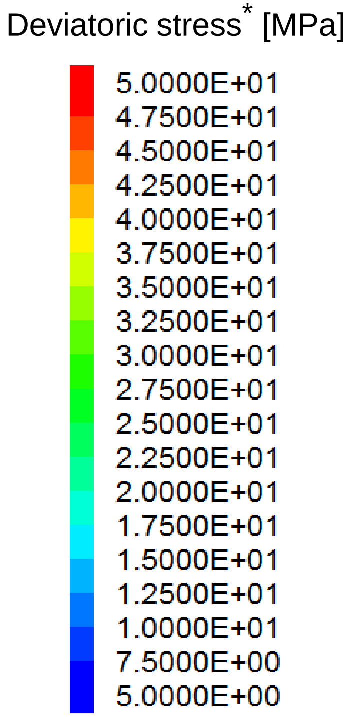
$$\sigma_z^{ini} = 34\ MPa$$



Seismic Data and Model Data comparison

Seismic Data & Model Data

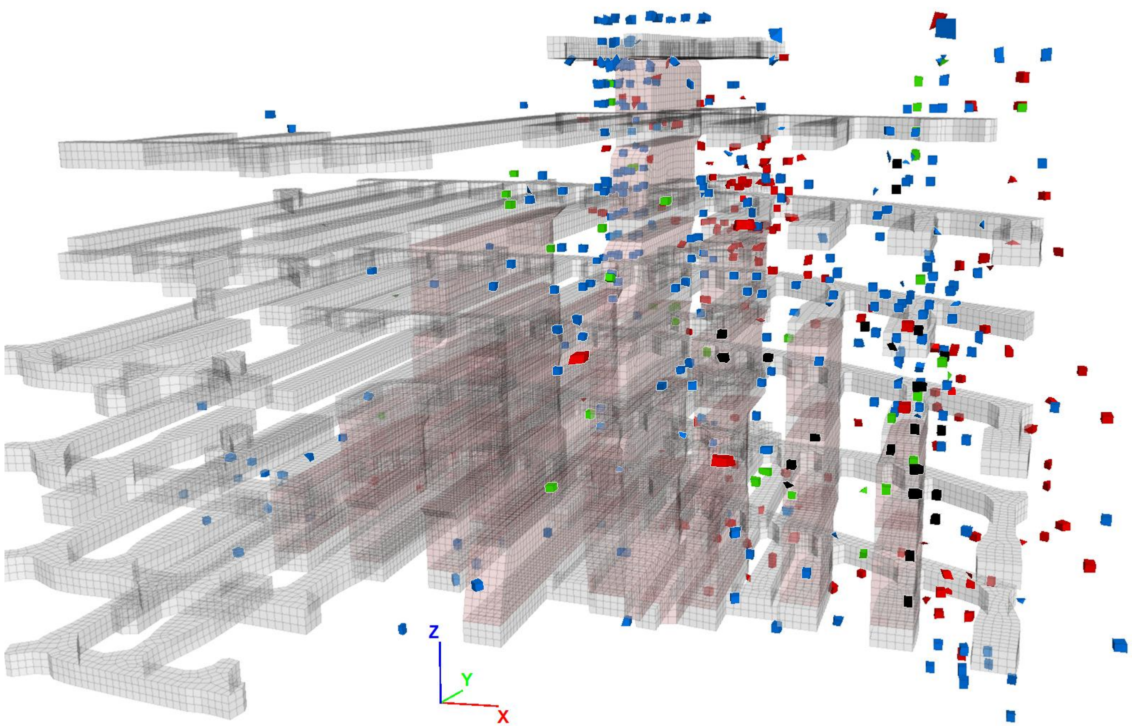
1st approach of comparison: individual measures

Seismic parameters ⇔ *Model parameters*

Punctual measures at seismic events locations — Measures within the whole space

⇩

Model parameters calculated inside meshes at the position of MSE location

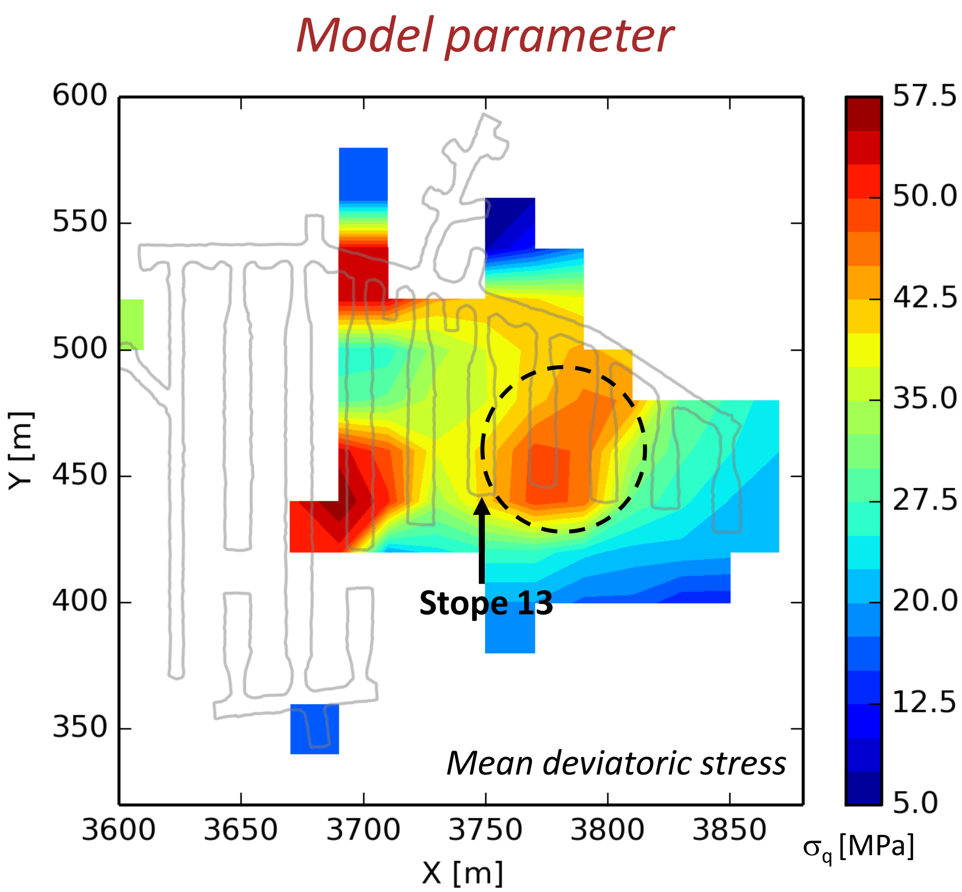


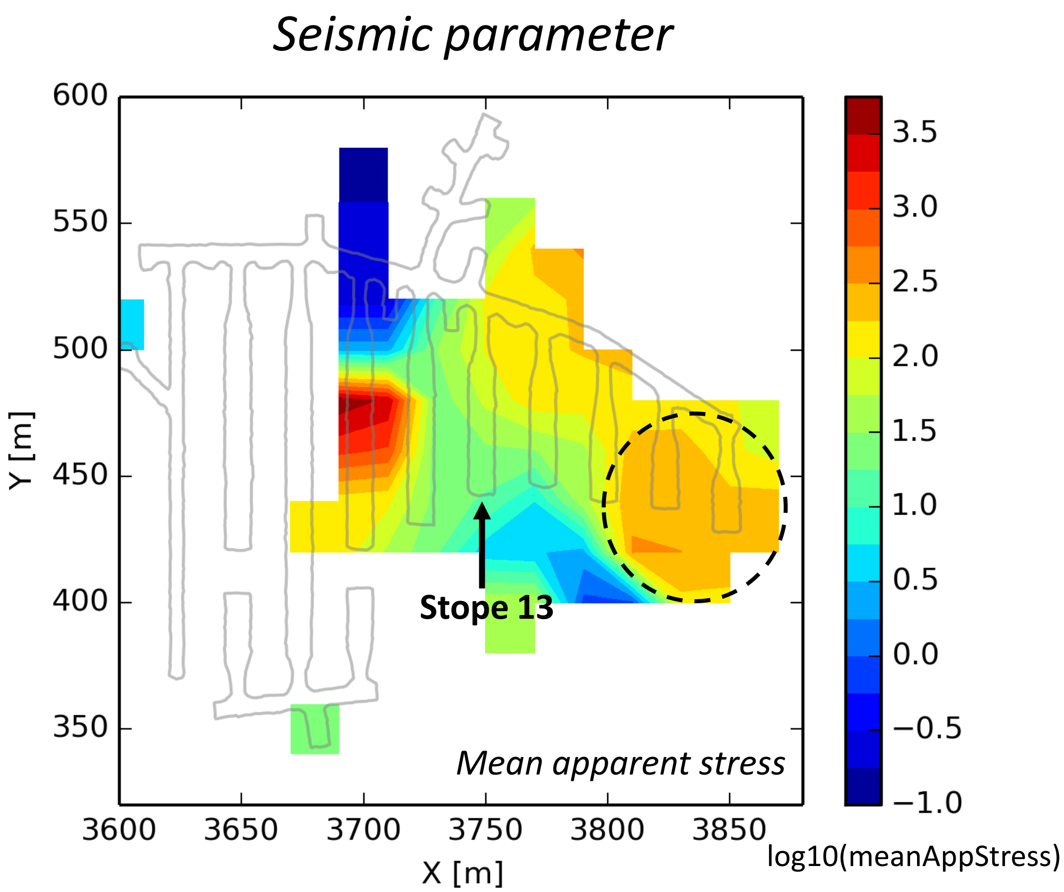
Seismic parameters
E – seismic energy
M_0 – seismic moment
M_W – moment magnitude
f_c – corner frequency
σ_{app} – apparent stress
V_{app} – apparent volume
$\Delta\sigma$ – stress drop

Model parameters	
Stress variables	Strain variables
σ_1 – max. principal stress	ε_1 – max. principal strain
σ_2 – inter. principal stress	ε_2 – inter. principal strain
σ_3 – min. principal stress	ε_3 – min. principal strain
σ_{ij} – stress tensor	ε_{ij} – strain tensor
σ_q – Von Mises stress	ε_q – Von Mises strain

Seismic Data & Model Data

Qualitative Analysis





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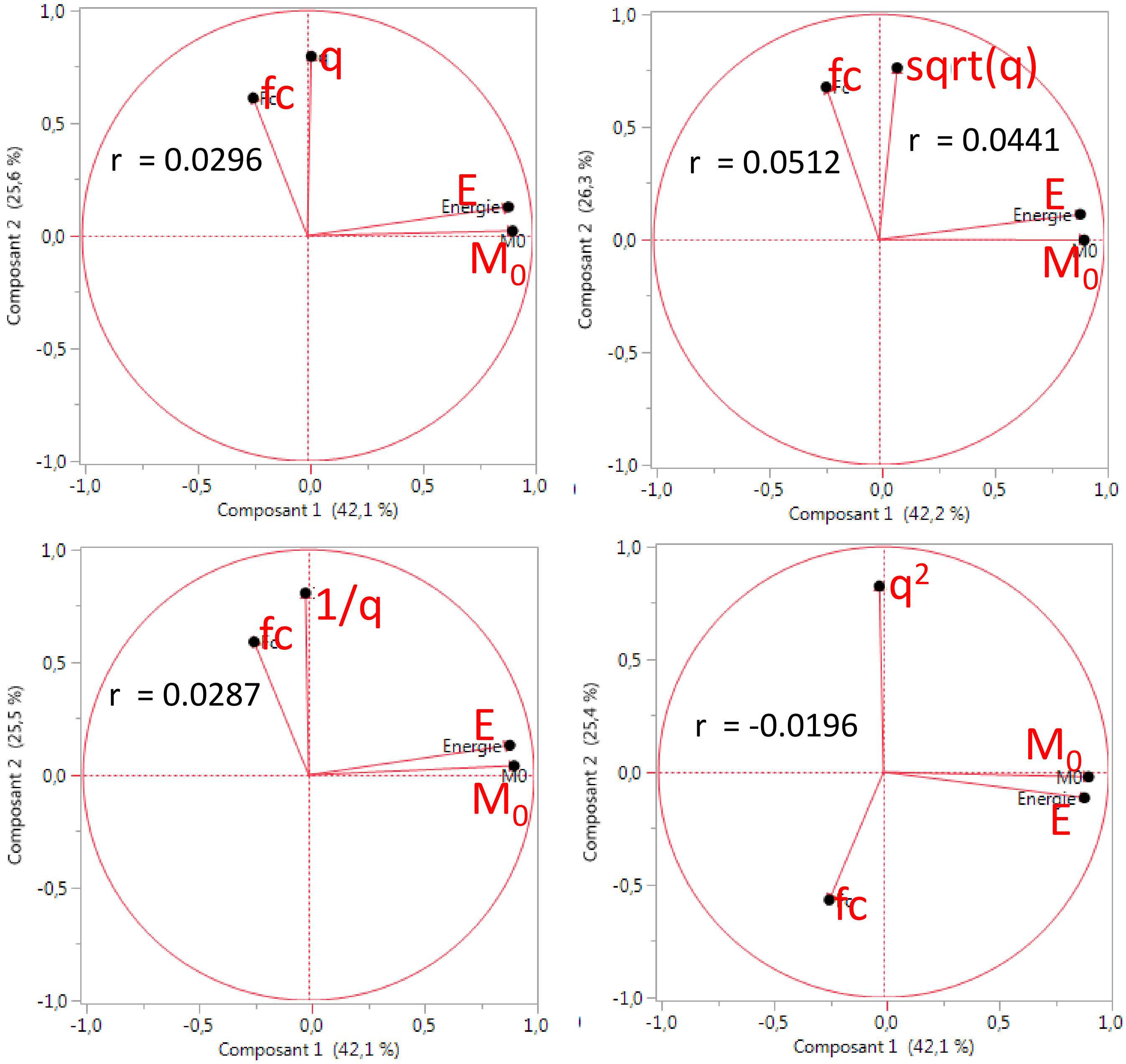
Seismic Data & Model Data

Quantitative Analysis: Principal Component Analysis



Seismic Data & Model Data

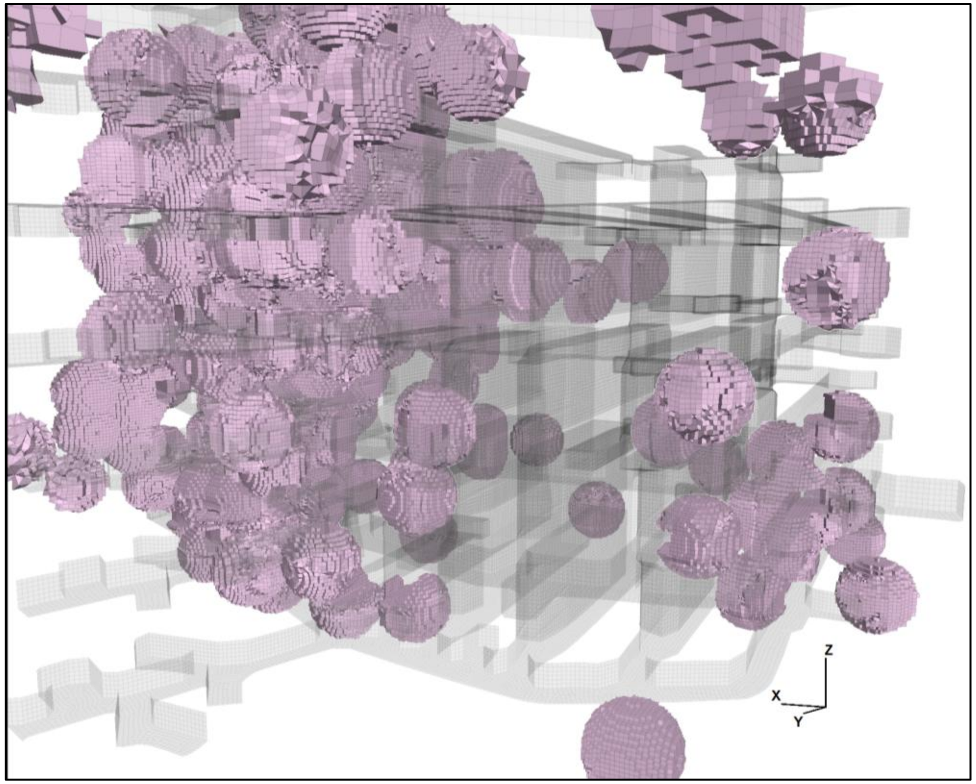
2nd approach of comparison: cumulated measures

Seismic parameters ⇔ *Model parameters*

Punctual measures at seismic events locations — Measures within the whole space

⇩

Cumulated model parameters calculated inside the spheres of 10 m radius around each seismic events location



Seismic parameters
E – seismic energy
M_0 – seismic moment
V_a – max. principal stress
A_s – Source area

Model parameters	
Elastic	Plastic
Volumetric elastic energy	Volumetric plastic energy
Shear elastic energy	Shear plastic energy
Total elastic energy	Total plastic energy
	Plastic volume
Mean Von Mises stress and strain	
Mean of max. shear strain	
Volumetric strain	
Shear strain	

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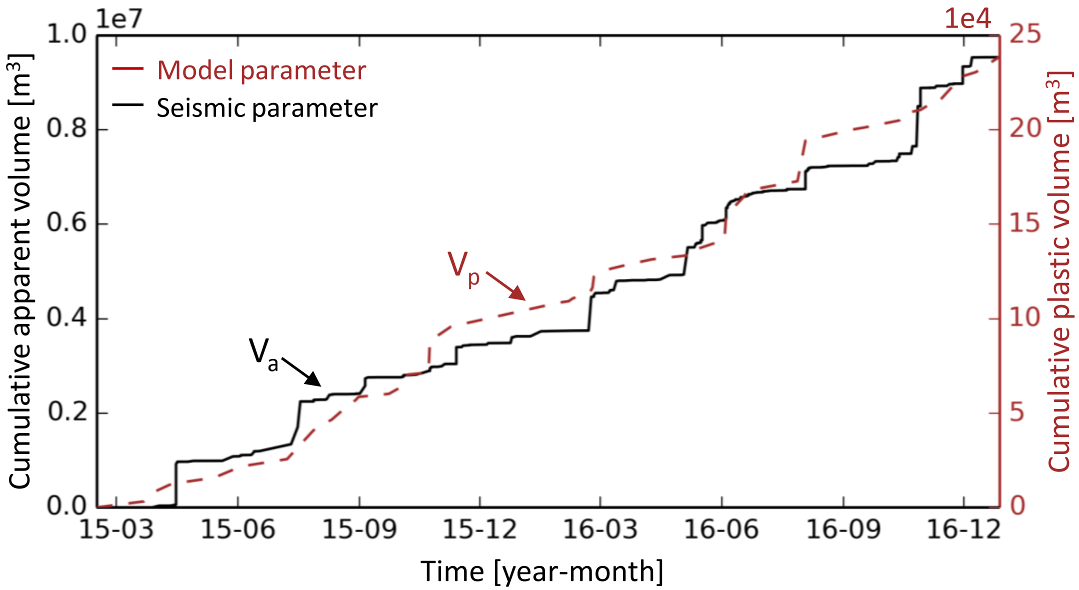
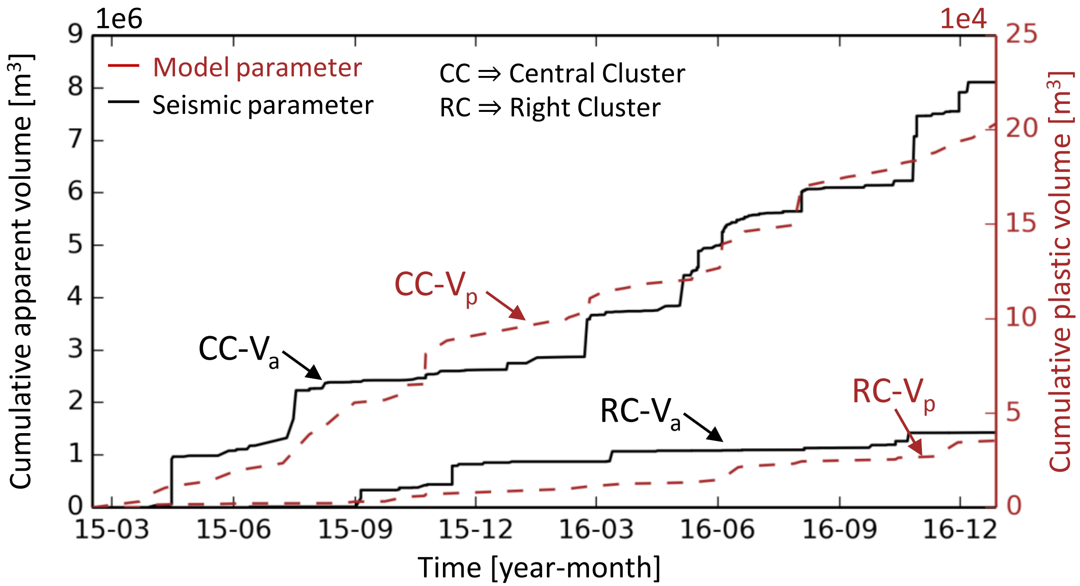
Seismic Data & Model Data

Qualitative Analysis





Apparent volume ⇒ $V_a = \frac{M_0^2}{2\mu E}\ [m^3]$

Plastic volume ⇒ volume of plastic zones in the spheres

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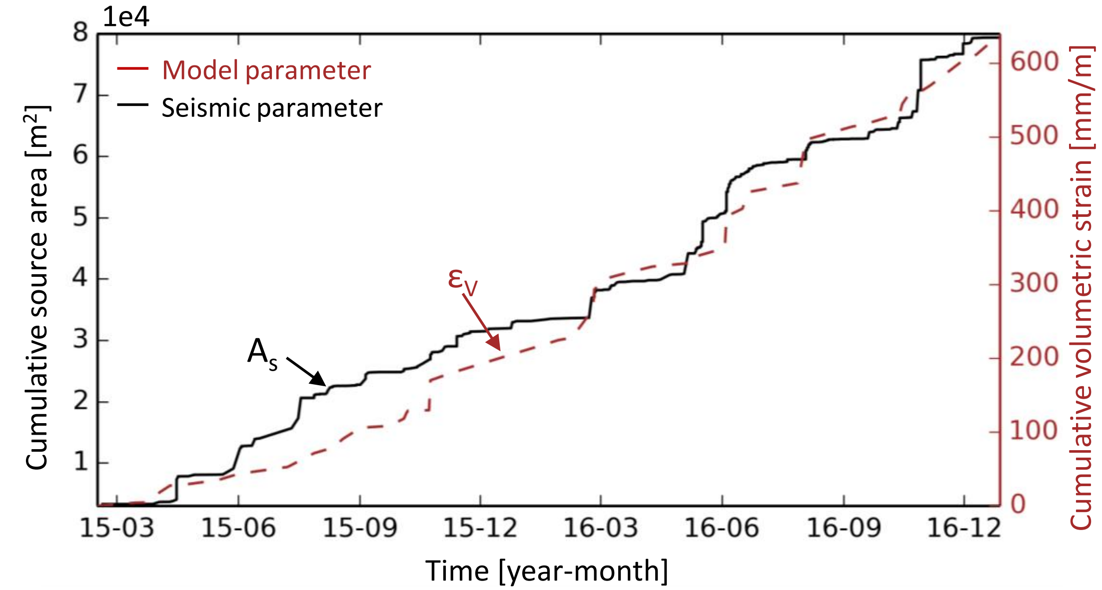
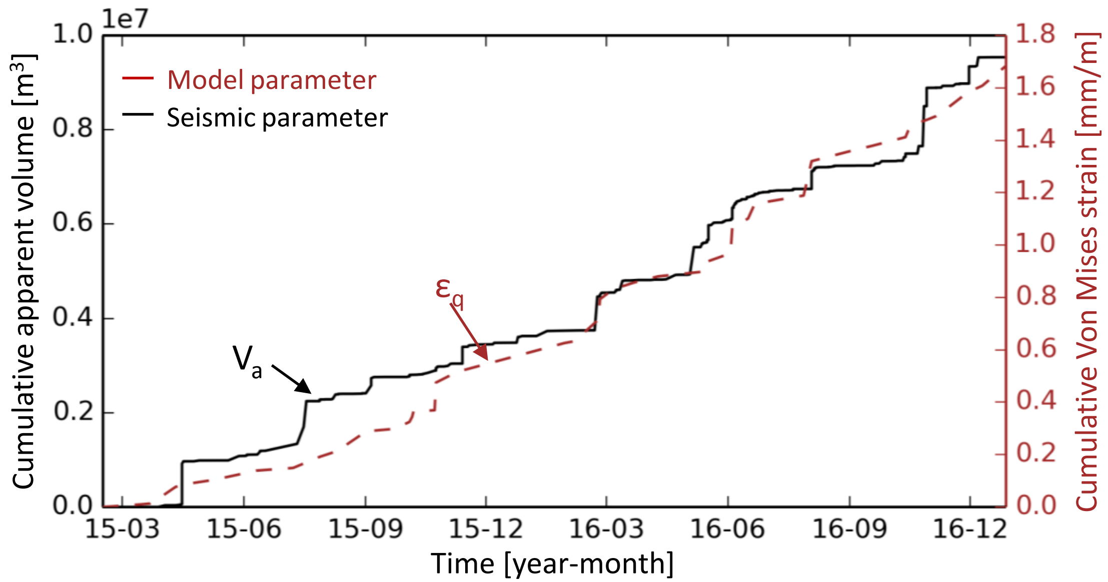
Seismic Data & Model Data

Qualitative Analysis



$$\begin{cases} \textit{Source area} \Rightarrow A_s = \pi r^2 \ [m^2] \\ \qquad r \textit{ determined from } f_c = k_c \dfrac{V_S}{r} \\ \textit{Volumetric strain} \Rightarrow \mathrm{t_r}(\varepsilon) \end{cases}$$



$$\begin{cases} \textit{Apparent volume} \Rightarrow V_a = \dfrac{M_0^2}{2\mu E} \ [m^3] \\ \textit{Von Mises strain} \Rightarrow \varepsilon_q = \sqrt{\dfrac{4}{3} J_2} \end{cases}$$

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Discussion and Perspectives

- Seismic & numerical model shows increasing stresses around the main production area

- Spatialization problem
  - Uncertainties in events location & model uncertainties
  - Reactivation of preexisting structure not taken into account in the model

- Cumulating seismic and numerical parameters in space correlations are improved

  - Improvement of events detection and location
    - Detection: bigger number of seismometers and continuous recordings
    - Location: new location methods based on double difference and multiples analysis
  - Include fractures in the model
    - Bigger fractures of CC may be modeled based on focal mechanism of MSE
    - Smaller fractures of RC cannot be included in the model with the actual mesh
      $\Rightarrow$ reduce mechanical properties of some meshes?
  - Taking creep into account
    - Seismic swarms are long lasting in time (more than 1 month)
    - Stress measurements have sown a differential response of deformations during time

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Questions ?

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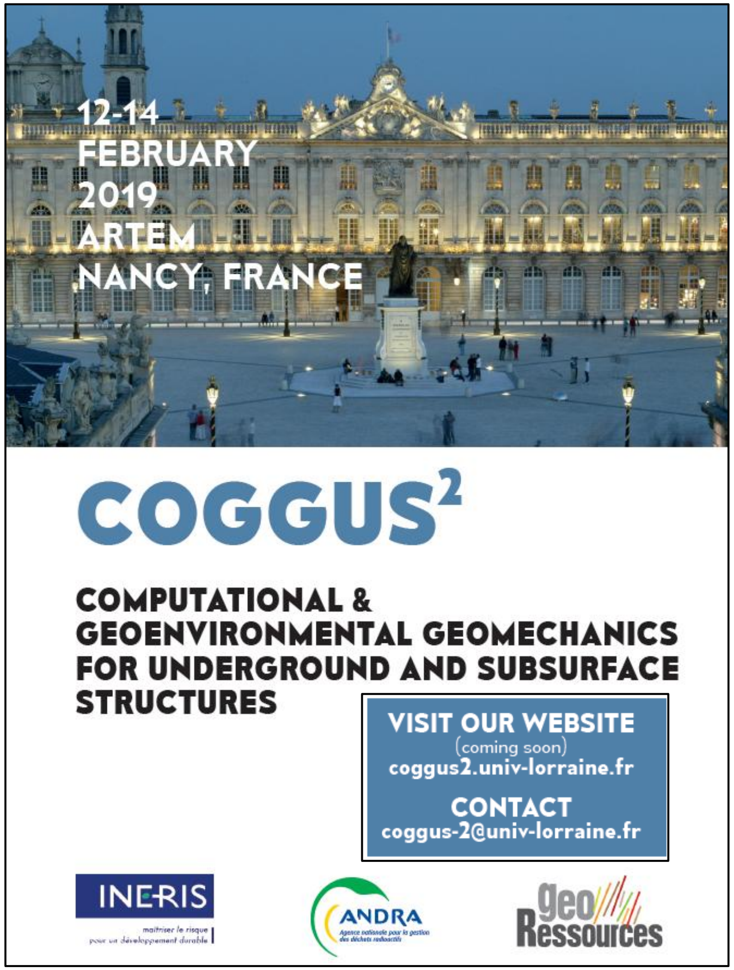
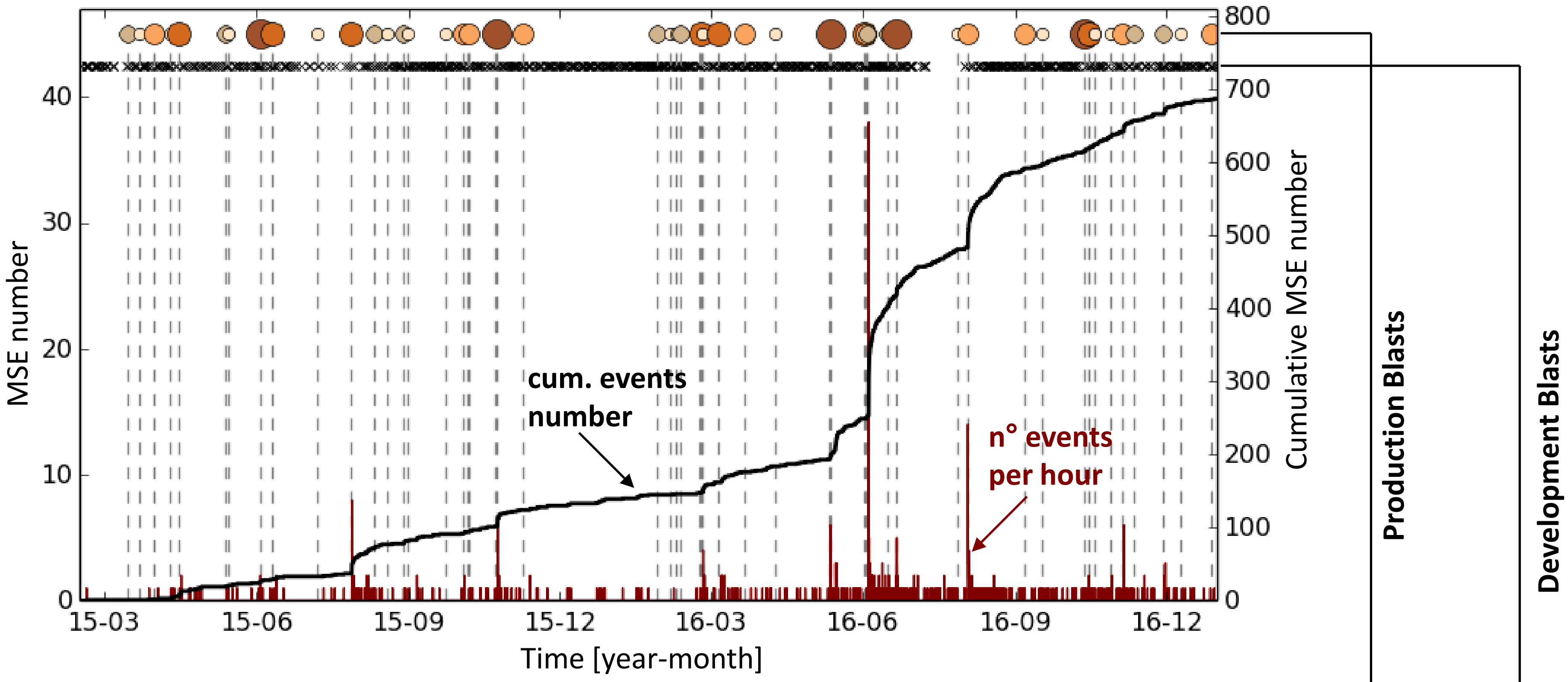


Mining Production & Microseismic Activity

Space-time distribution



Extracted rock mass volume for **Production Blasts**:

1000-3000m^3 3000-4000 m^3 4000-5000 m^3 5000-6000m^3 ≥ 6000 m^3

Extracted rock mass volume for **Development Blasts**:

X ≈ 300 m^3

BOLIDEN GeoRessources IPGP INSTITUT DE PHYSIQUE DU GLOBE DE PARIS INERIS maîtriser le risque pour un développement durable