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06.05.19

institute of mine seismology

29th Mine Seismology Seminar

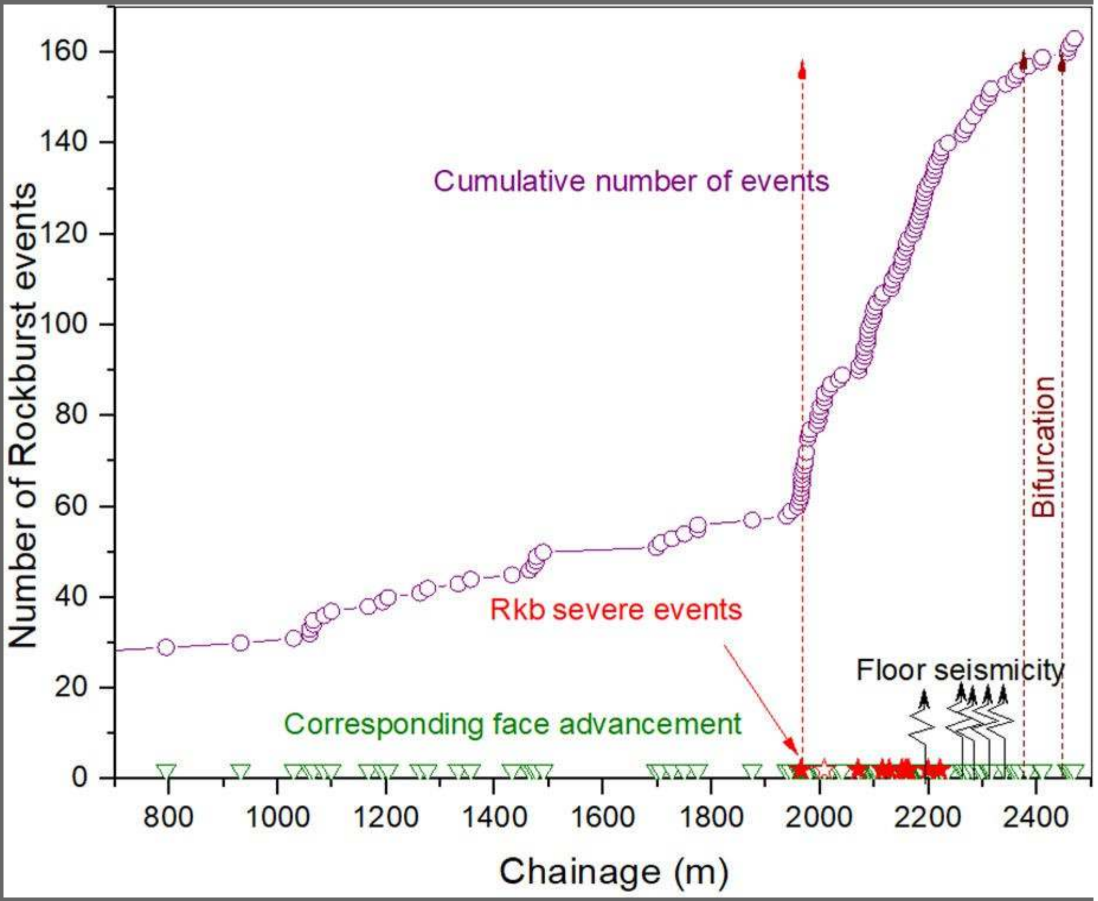
Severe rockburst occurrence during construction of a complex hydroelectric plant

Giordano Russo

Severe rockbursts occurred during the on going construction of a complex hydroelectric plant in the Andean region in Chile, with **serious support failures** and **prohibitive work conditions**

Video	Rockburst
1	Chile site C_1
2	Chile site C_2

The severity and frequency of seismic events dramatically increased while excavating one of the access tunnels to a powerhouse, just after a lithological contact between pyroclastic tuff and andesitic lava, with about 800 m of overburden



Cumulative number of rockburst events in one of the access tunnel. Red dotted line coincides with lithological contact

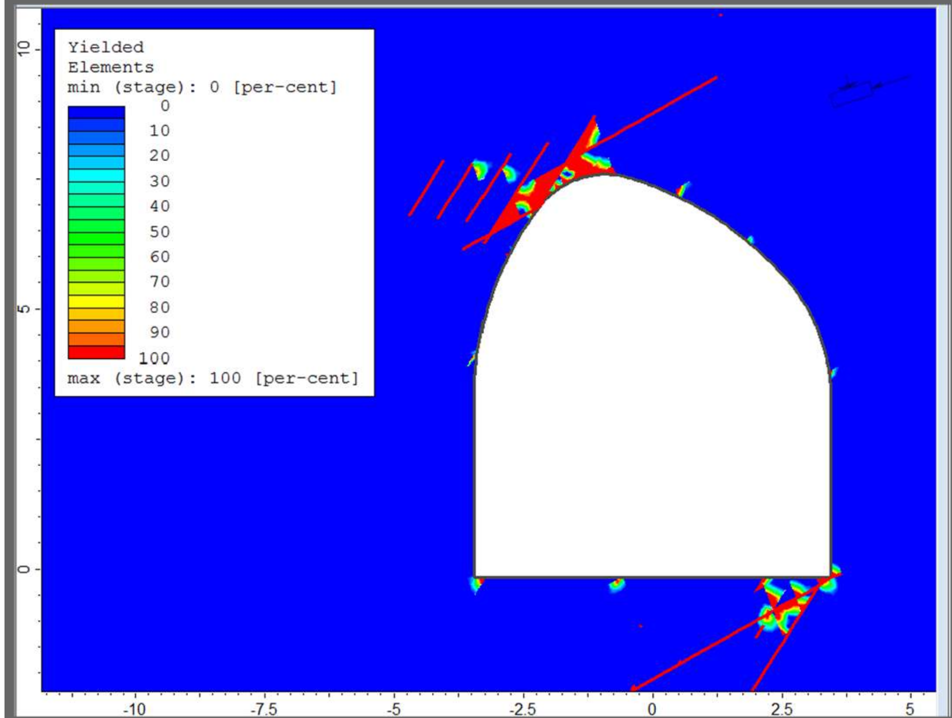
Technical attempts for controlling rockburst initially (by a specialist team) included also modifications of the excavation shape by following overbreaks

The support system was based on PM16/24 Swellex and Shell Anchored bolts alternated with D-Bolts, in combination with FRS shotcrete and weld-mesh

Technical solutions were not able to control the damage from a **very violent rockburst** event about 100m later (930m overburden), resulting in severe support failures at about 10m from the tunnel face and damages up to about 30m from the face

Estimate Energy released: 20-30kJ/m²

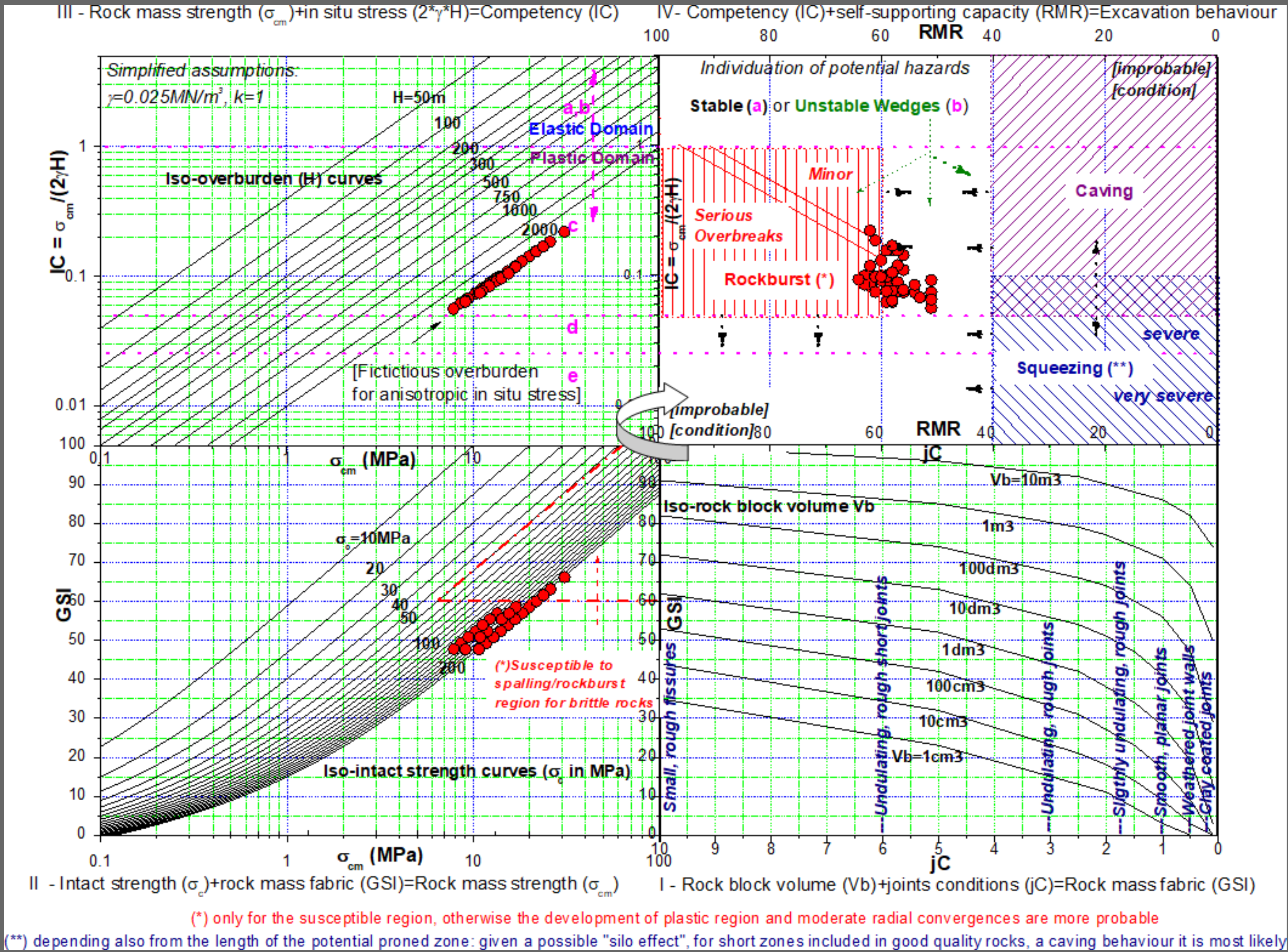
[→Reference Energy Demand for new Design]



Numerical modelling by Joint Network

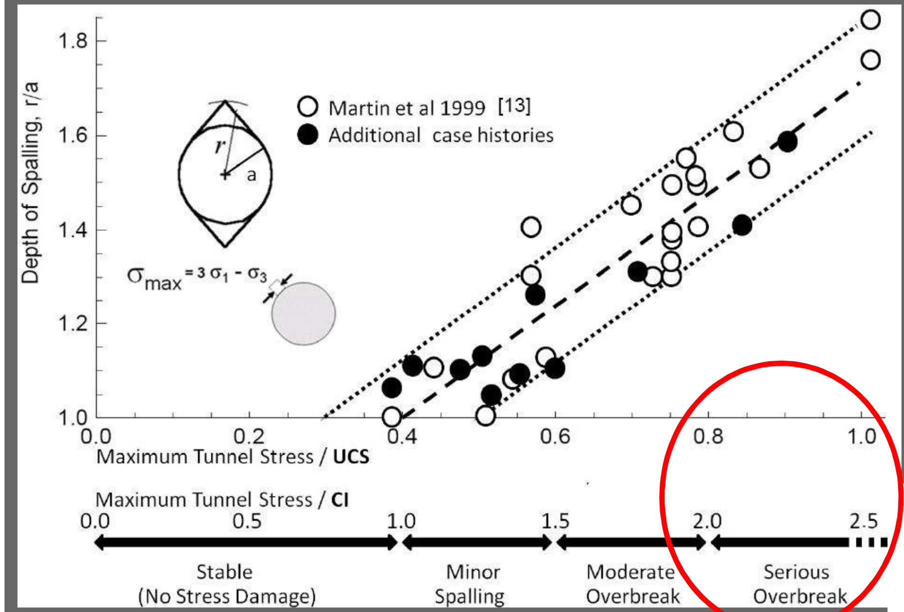
Note alsothe joint in the shotcrete in tunnel crown for reducing stress concentrations

Geomechanical conditions



Russo, 2014

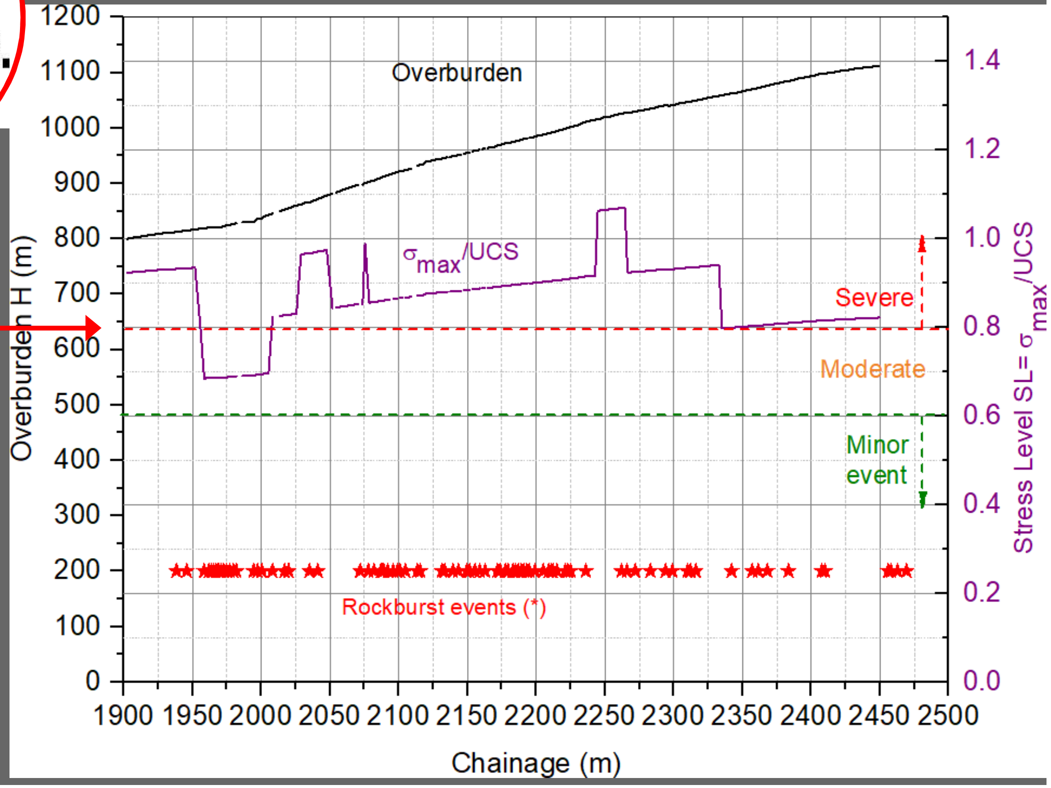
Application of the GDE Multiple graphs for the adit stretchonsid. Note that fictitious overburden in top-left quadrant allows for deriving the effective max tangential stress related to k≈2÷2.5 (from in situ tests).



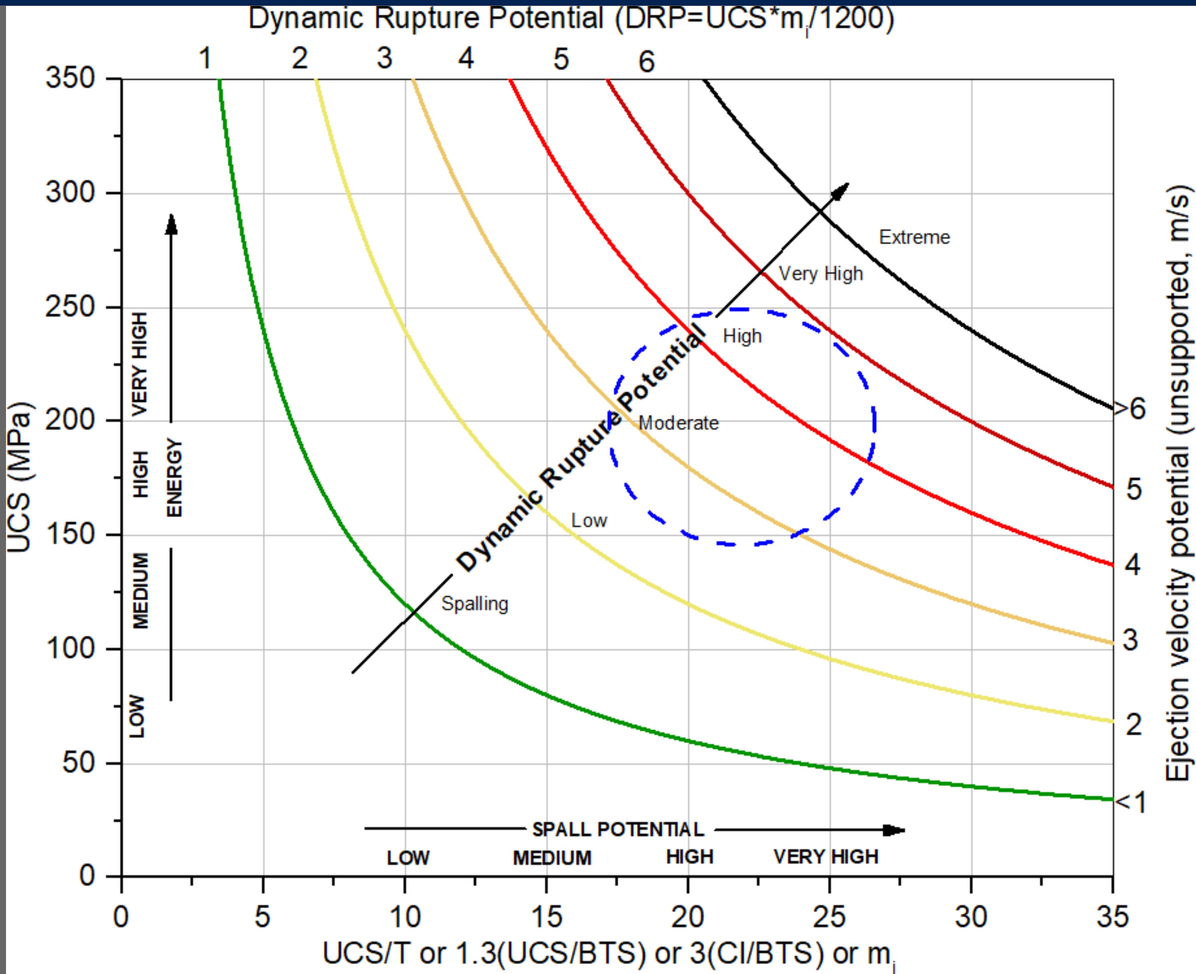
↑**Empirical prediction of Depth of Failure (Dof) for Stress Level SL=σ_{max}/UCS**

CI=Crack Initiation Threshold↑
(CI=0.4*UCS in the graph)

Relation between rockburst events and the calculated Stress Level SL=smax/UCS



[Diederichs et al., 2010, based on Kaiser, 1996 and Martin et al., 1999]

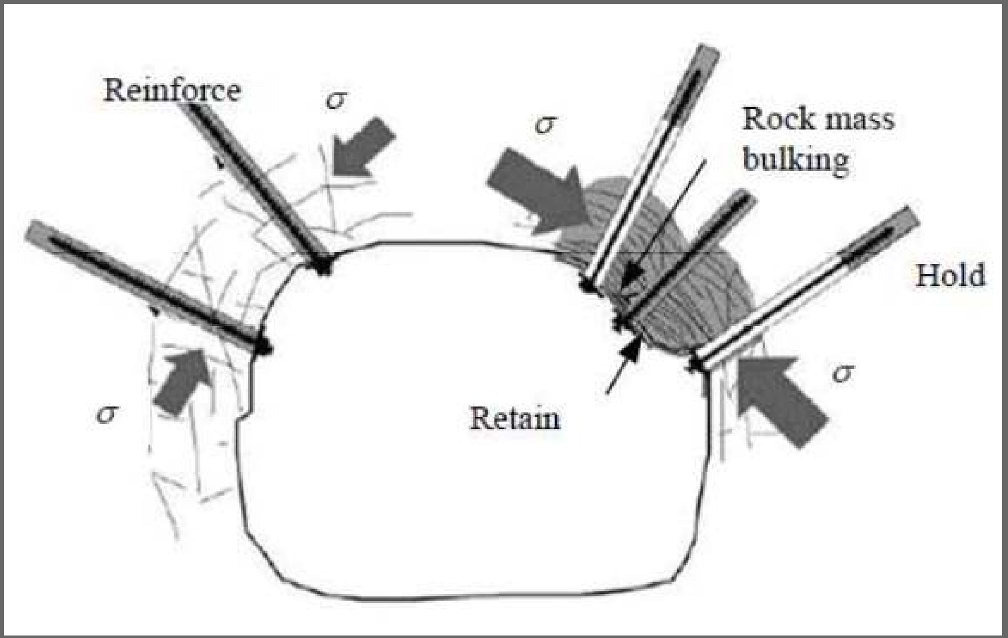


Dynamic Rupture Potential (DRP) for massive rock (Diederichs, 2016) with approximate indication of typical Andesitic Lavas properties

In 2016 the Contractor involved Geodata Engineering (GDE) to find an adequate and safe technical solution

Key elements

- Special bolting equipment for the **automatic installation of steel mesh and bolts** without any exposure of the workers;
- Implementation of accurate **seismic monitoring**
- Innovative **"double-layer" support system**
- Cautious definition of **Factor of Safety (FS)**

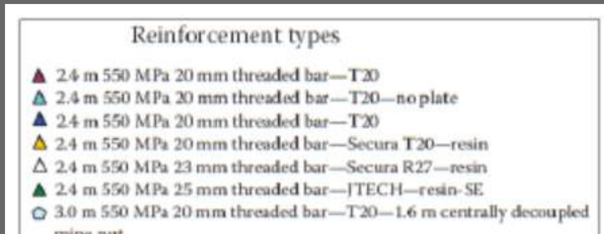


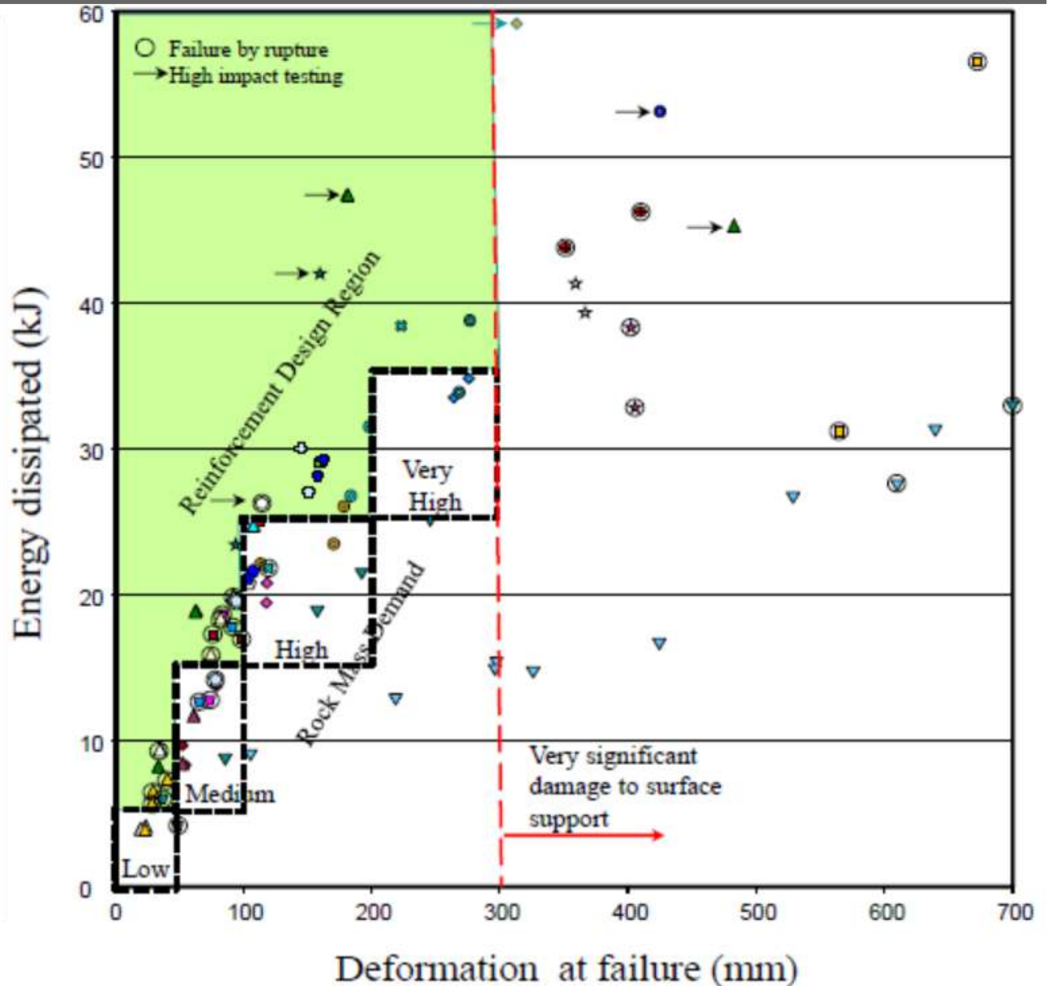
Applied approach for severe Rockburst design

Rockburst Energy Demand	Reinforcement Capacity*	Surface Support Capacity*
E_D	$\geq 2E_D$	$\geq E_D$
High Energy (Severe Event)	n.2 orders of high capacity grouted elements	n.2 FRS+high capacity chain link mesh layers

* At ~100-(150)mm of radial displacement

Energy Capacity of Reinforcement elements



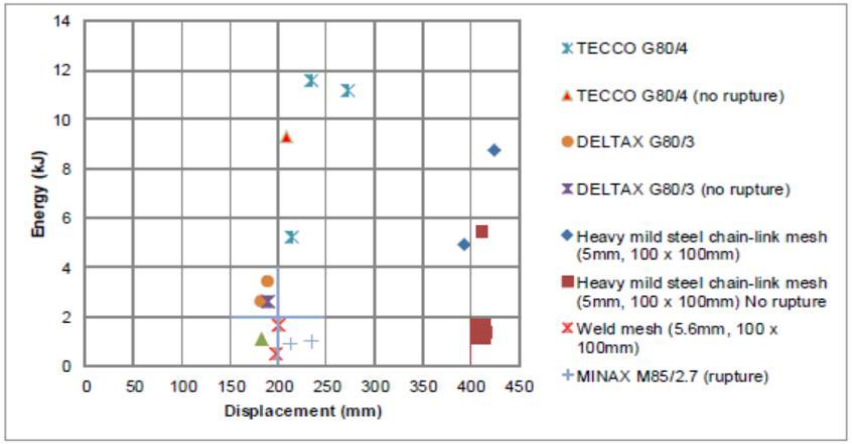


Test for 25mm threadbar

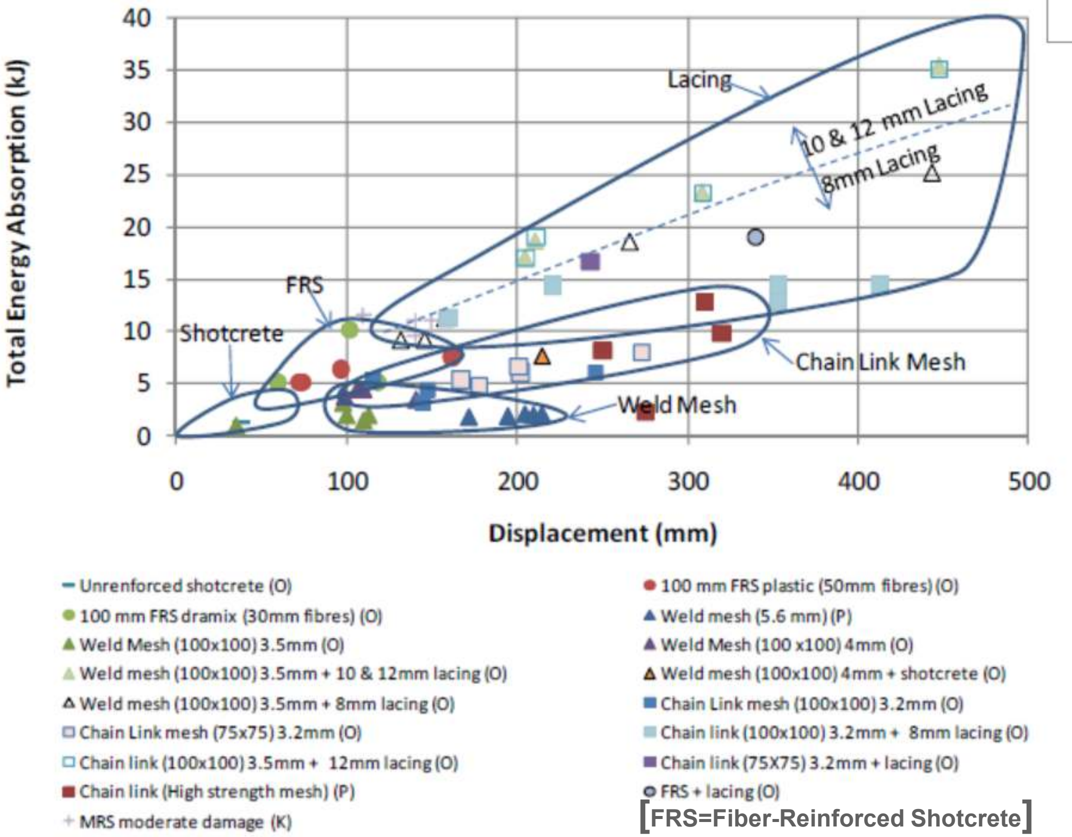
Input Energy 36kJ →97mm

Example from Villaescusa et al. 2015-2016, WASM Dynamic Test Facility

Energy Capacity of Surface support

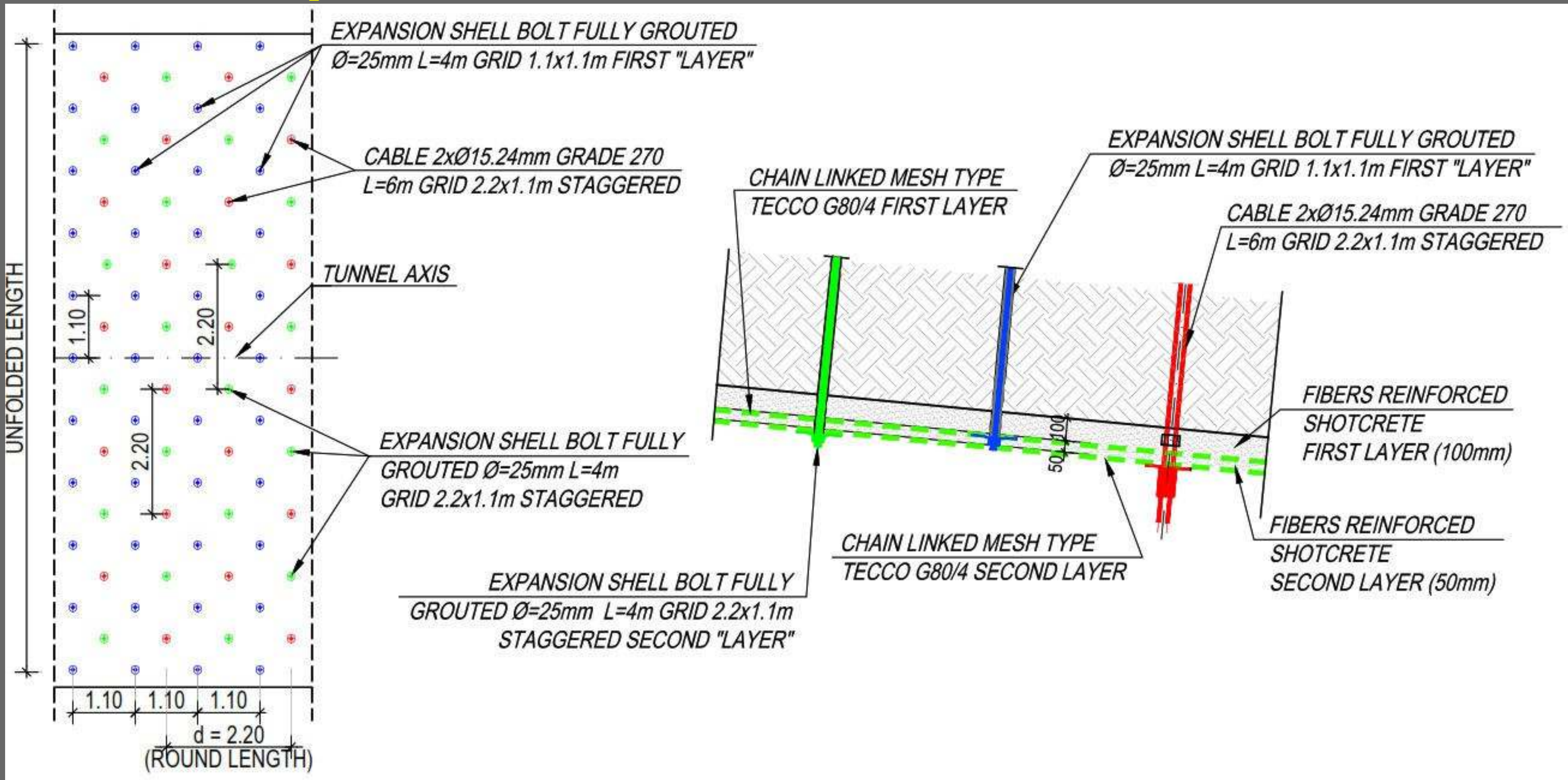


↑**Steel mesh dynamic test results**
[Villaescusa and Player, 2015]



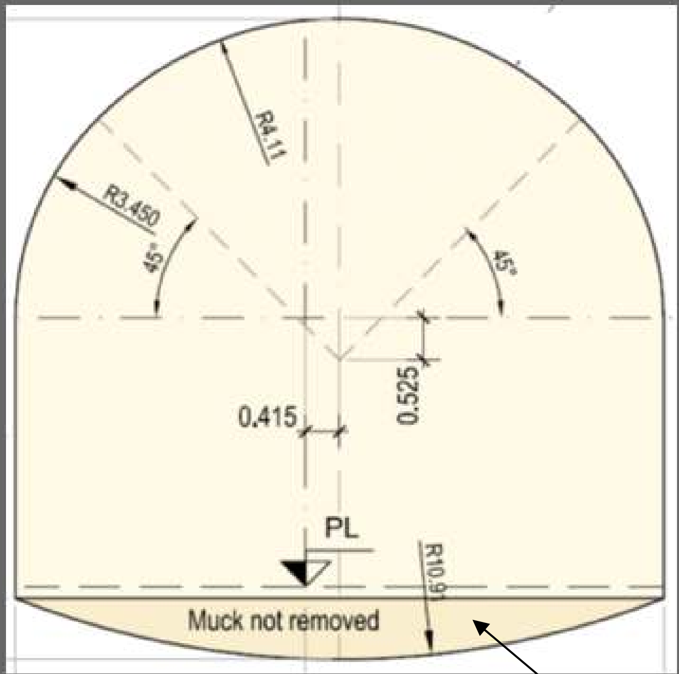
Potvin et al. 2010

Double-layer solution for severe rockburst occurrence



The double-layer solution involves two retention system components: Fibre-Reinforced Shotcrete (FRS) and high capacity chain-linked steel mesh (Tecco G80/4). Each component is combined with a radial reinforcement by fully grouted 25mm expansion shell threadbars or twin-(15.2mm) strand cables (as partial alternative holding element for the second order).

Upgraded design solution



Video	Rockburst
3	Chile site C_3
4	Chile site C_4

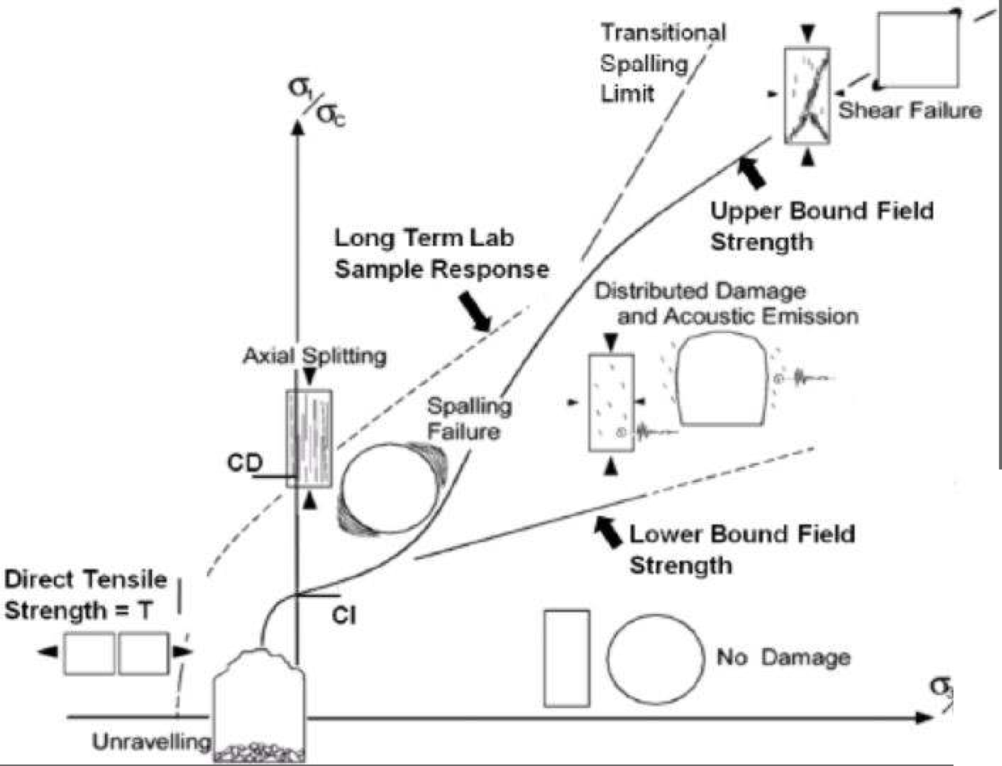
As a measure for some controlled dissipation of seismic energy was recommended to leave temporarily on site the muck (blasted rock) of the invert

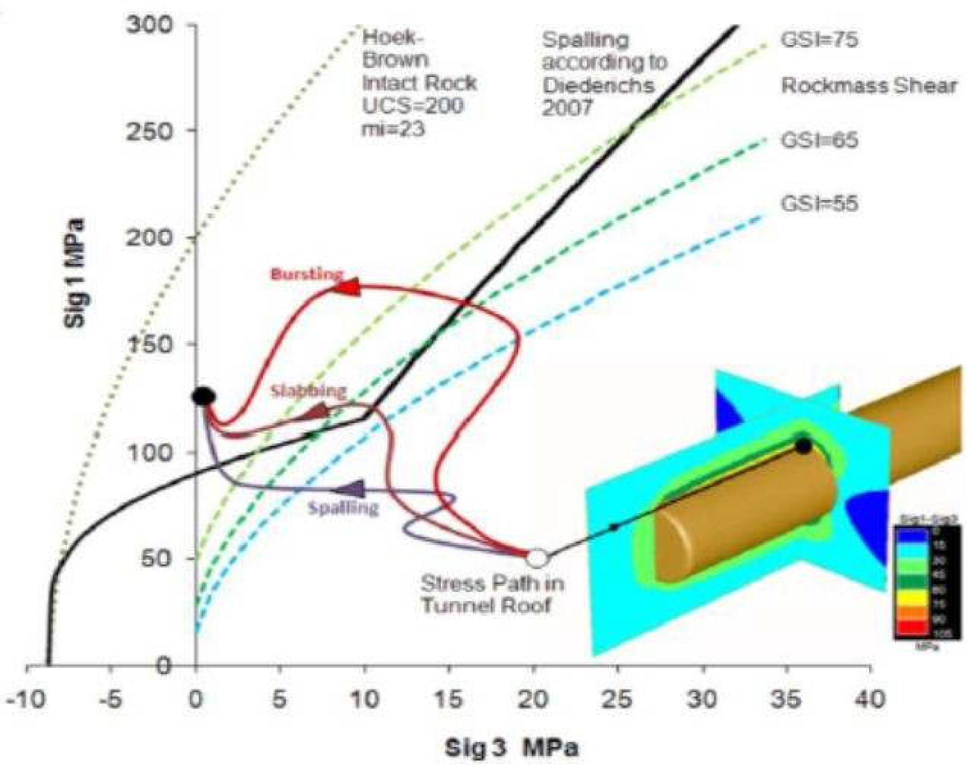
Upgraded design solution

← **Application of the Double-layer solution**

Tunnel face control→

Multi-phase envelope for simulating brittle (spalling) failure in hard rocks (DISL Damage Initiation Spalling Limit)





Shear or spalling failure depends on the relative envelope intercepted by the stress path

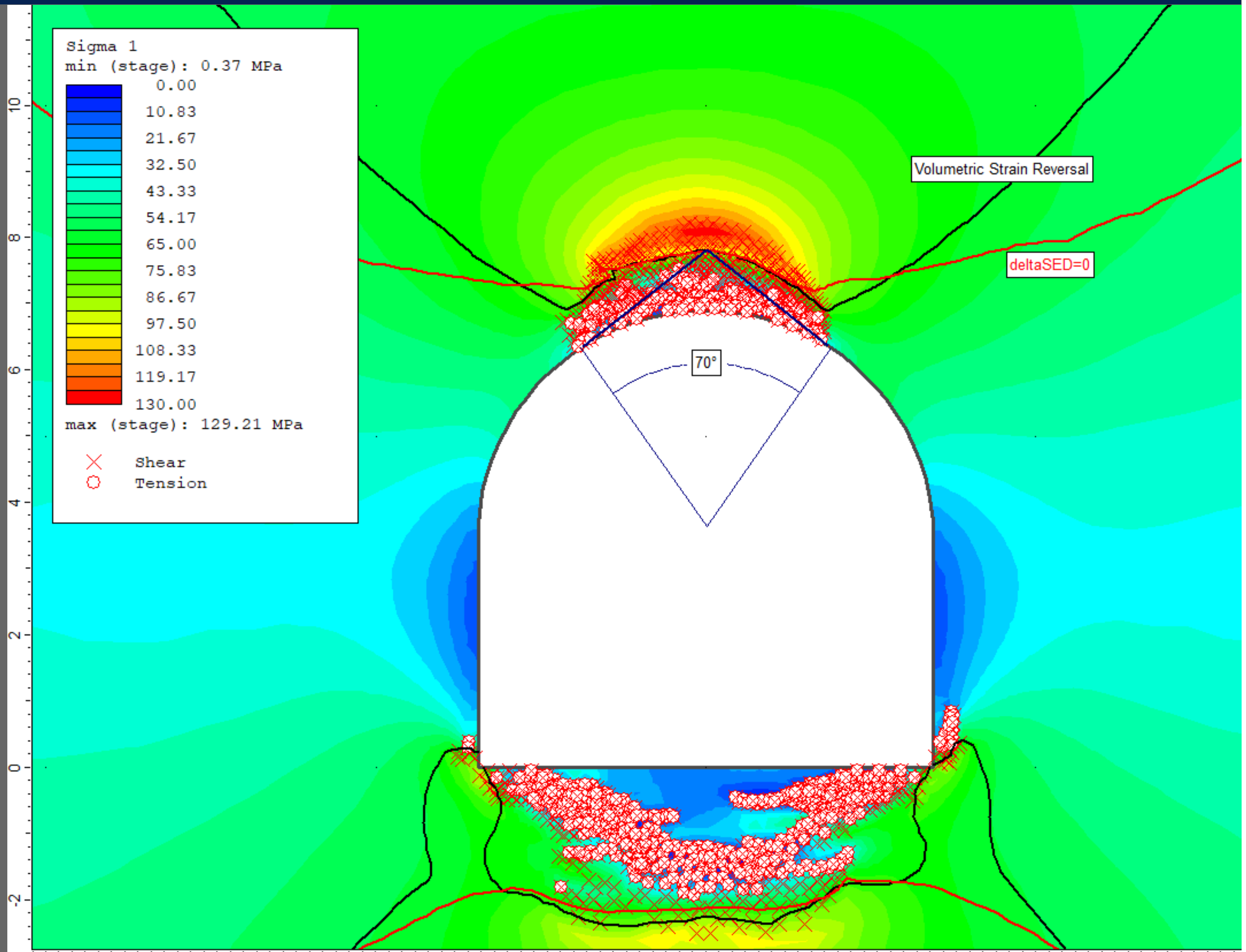
(Diederichs, 2005-2014)

Insight from Numerical Modelling

Result of numerical modelling by Rs2 in terms of:

- **Sigma 1**
- **Yielding zones**
- **Volumetric Strain Reversal (VSR)**
- **Potential brittle failure notch**

- **[Iso-line ΔSED=0]**



→ VSR: Limit between Volumetric strain expansion and contraction.
(→mean DoF → spalled notch or failed material, Martin et al., 1999)

[→ ΔSED=0: Limit between the zones in which Strain Energy Density (SED) reduces (close excavation) or increases from peak to post-failure condition]

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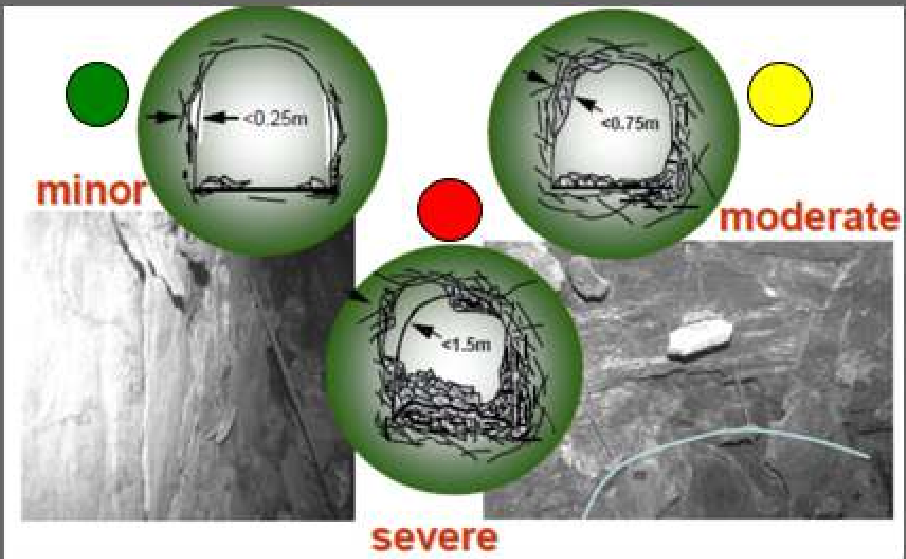
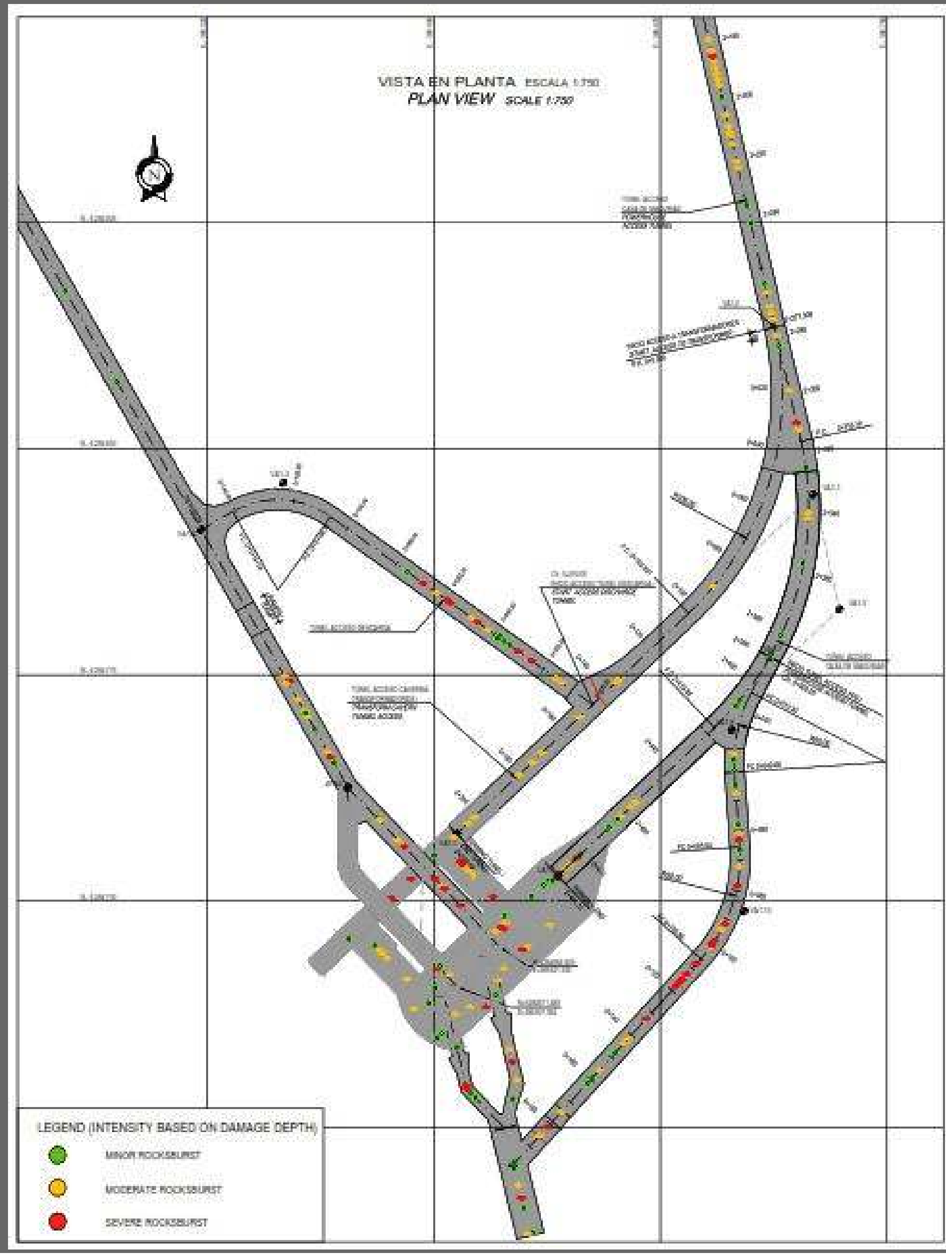
Performance of the new support system

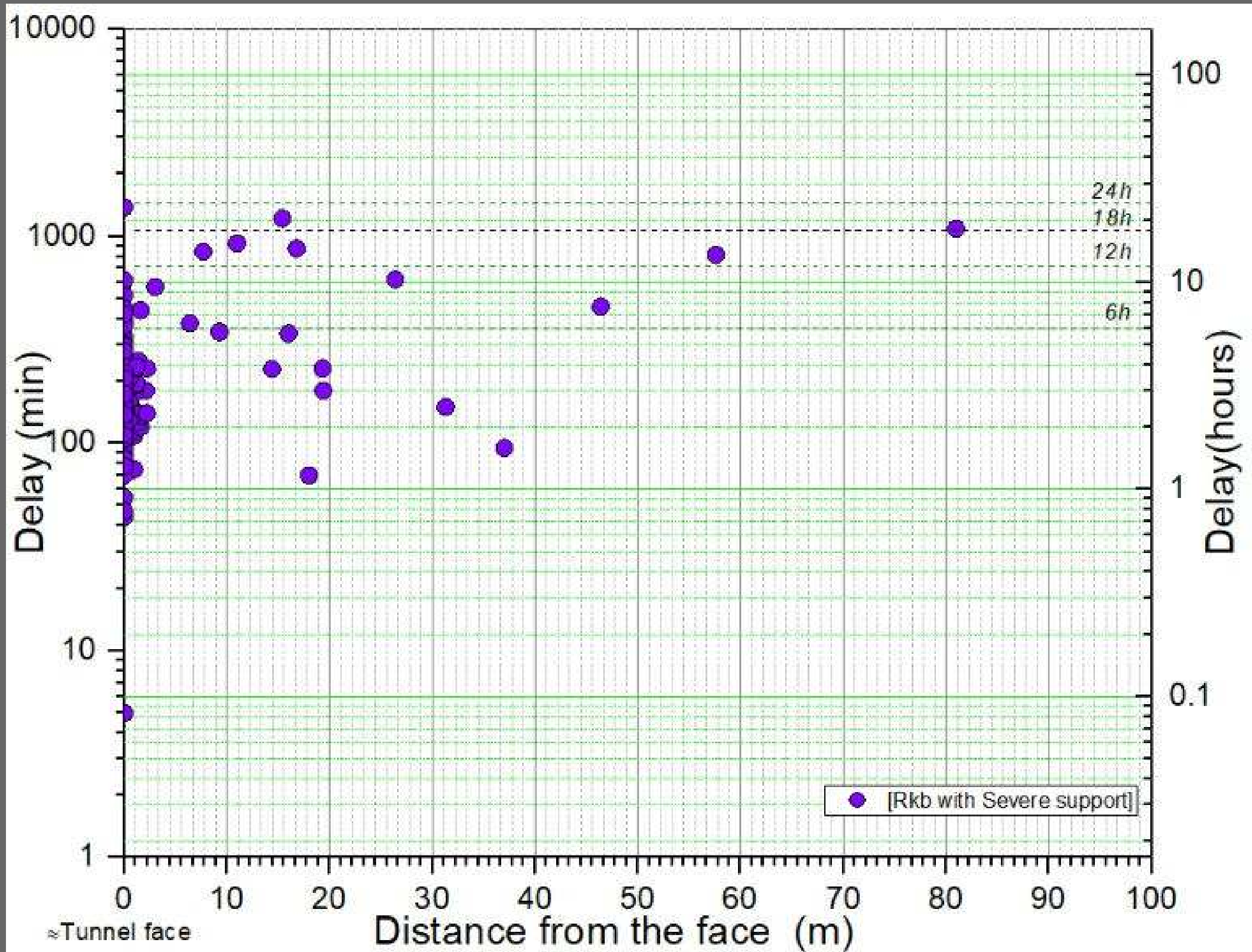
Double-layer solution has been extended for more than 2km to the tunnels and other Designer adopted for the on going caverns construction.

Violent rockburst events persisted with high frequency mainly in the zone of the powerhouse



Kaiser et al., 1996





Time of occurrence (Delay) of rockburst after blasting vs relative Distance from the face (95% <4h & <5m)

Performance of the new support system

The **performance of the double-layer solution** has been **satisfactory**: the support system was able to control very violent events by **limiting the damages**, without critical structural failure.

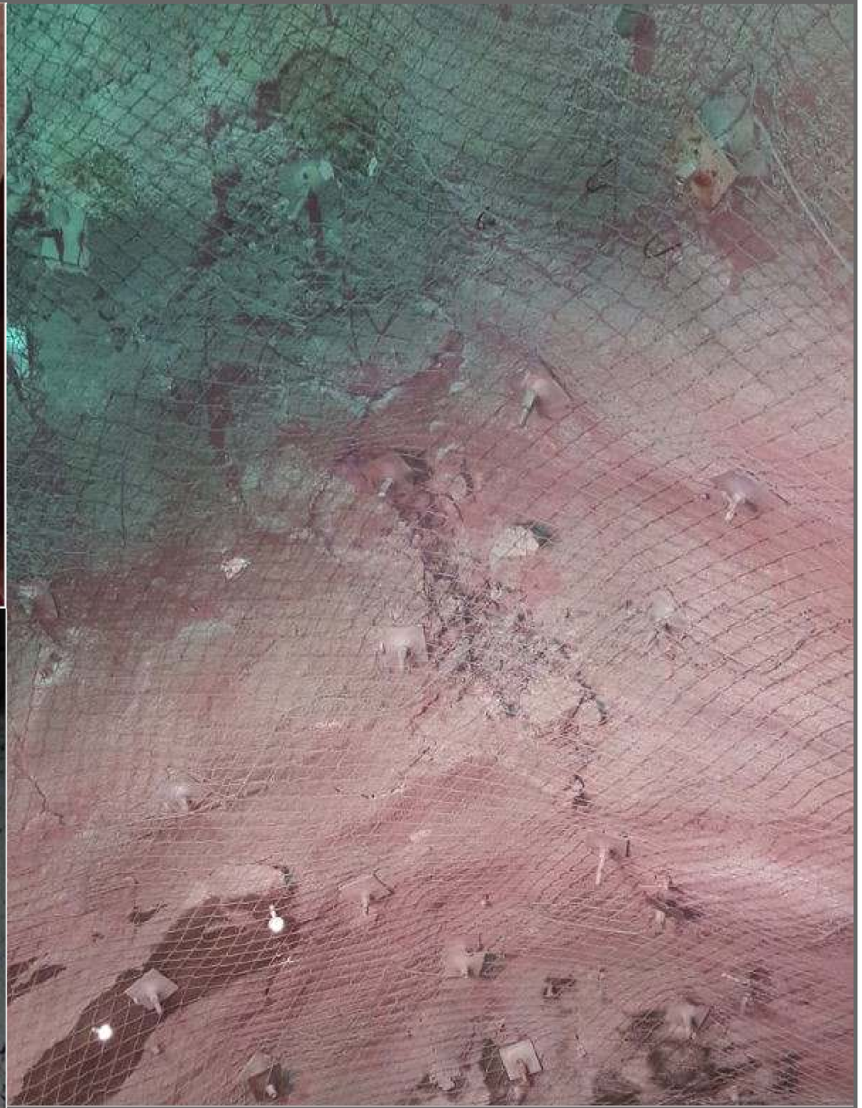
In occasion of the most severe events, the following type of damages have been observed:

- **Fracturing of the shotcrete,** sometime along preferred alignment, without relevant fall-down or ejection of fragments because of the chain-link mesh protection;

- **local shear cut of the threadbars** (at distance <0.5m from the bolt heads; no twin- strand cables shear failures;

- **cracks in the invert zone**, for floor heave and/or very impressive up-down movement

Performance of the new support system



Examples of damage

Rockburst damage scale for support

Rockburst damage scale	Rock mass damage	Damage surface area	Rock support damage
R1	No damage, minor, loose	0	No damage
R2	Minor damage, less than 1 t displaced	< 1 m^2	Support system is loaded, loose in mesh, plates deformed, shotcrete cracked
R3	1–10 t displaced	< 10 m^2	Some broken bolts, mesh bulged, shotcrete fractured
R4	10–100 t displaced	10 to 50 m^2	Major damage to support system; retention capacity severely compromised
R5	100+ t displaced	> 50 m^2	Complete failure of support system

Potvin et al., 2009; modified by Cai and Kaiser, 2018

Comment on type of rockburst (1 of 2)

For the majority of the cases, rockburst event can be classified as Self-initiated/Mining induced strainburst (Kaiser and Cai, 2013)

Anyway, Seismically triggered and even Dynamically loaded strainburst (mainly for large and delayed events) are not excluded as the results of seismic impact of induced fault-slip mechanism.

→Seismic waves may temporarily modify the tangential stress and then the Stress Level, so increasing the Depth of Failure

$$\Delta\sigma^{d}_{max}=\pm 4 * c_s * \rho * PGV_s$$

c_s =propagation speed of shear waves
ρ = density of rock mass
PGVs= Peak (particle) Ground Velocity of the shear waves

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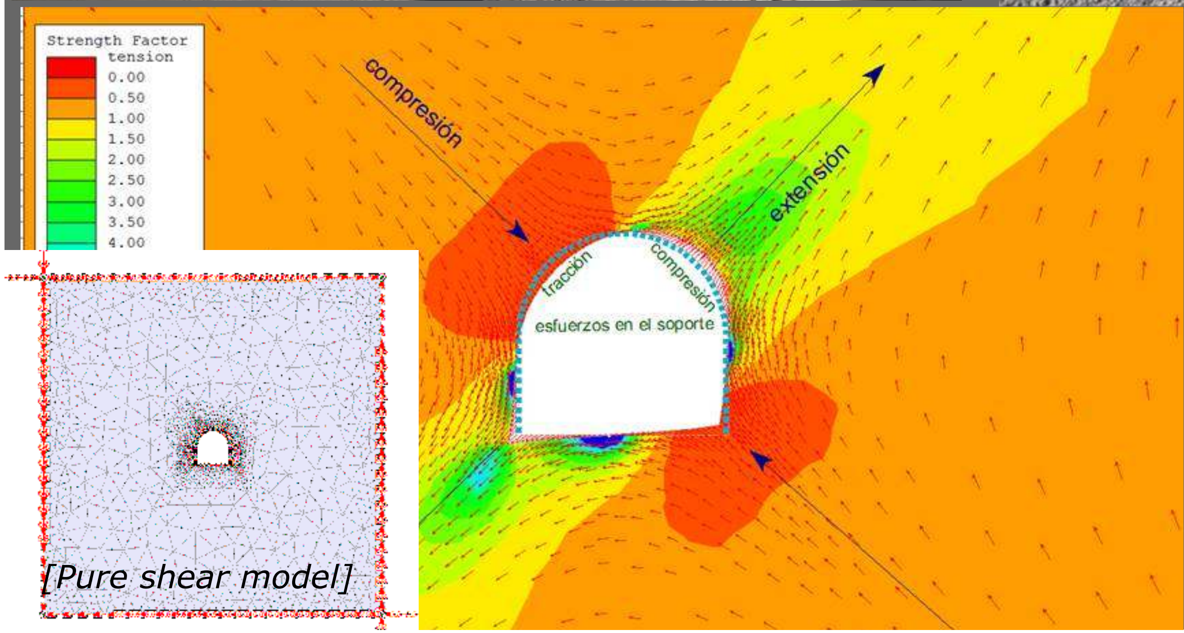
Comment on type of rockburst (2 of 2)



Additionally, in some case, the effect of hoop deformations in terms of distortion of the cross section (Mendecki, 2017) creating stress concentrations could be relevant.

[Example: El Teniente analysis]

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Performance of the new support system

Induced seismicity, violence of rockbursts and support damages increased with the progressive moving closer of excavations (tunnels and caverns) towards the works completion.

This allows for:

- **enhancing local stress concentrations (zone of intersection, etc.);**
- **reducing Local Stiffness of the excavation System and increasing Damage Potential***
- **favoring possible interferences between blasting**

An extremely high seismicity has been observed as resulting from the D&B advancements:

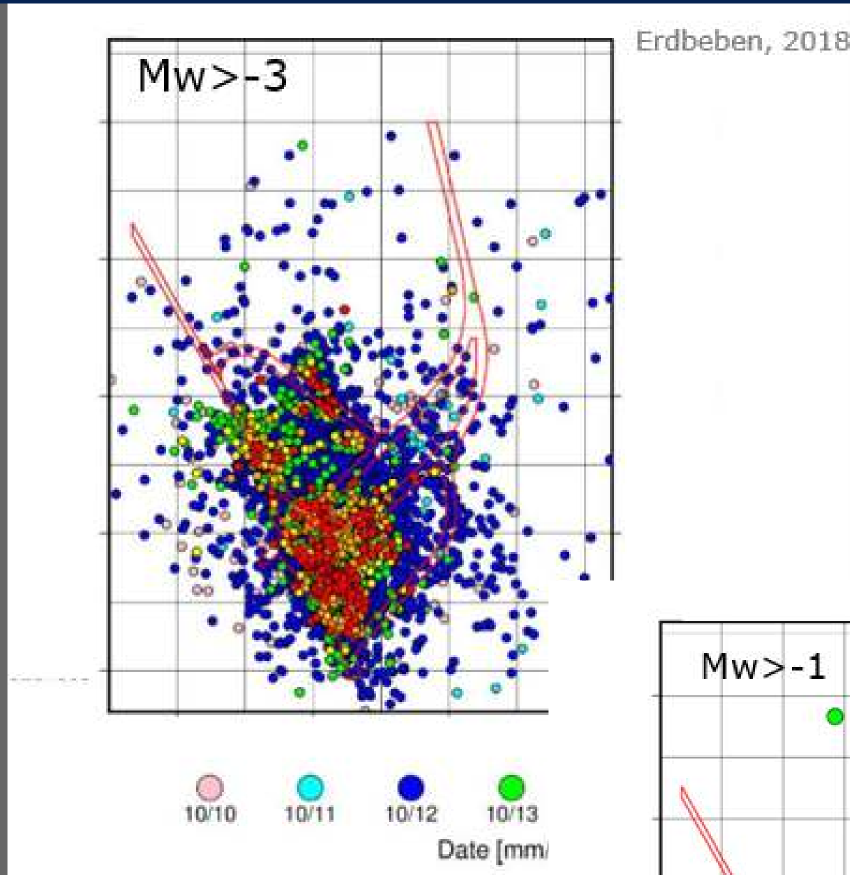
- **even more than 10,000 seismic events per week**
- **some hundred events with moment magnitude Mw > -1**
- **several Mw > 1 events (up to Mw = 1.4)**

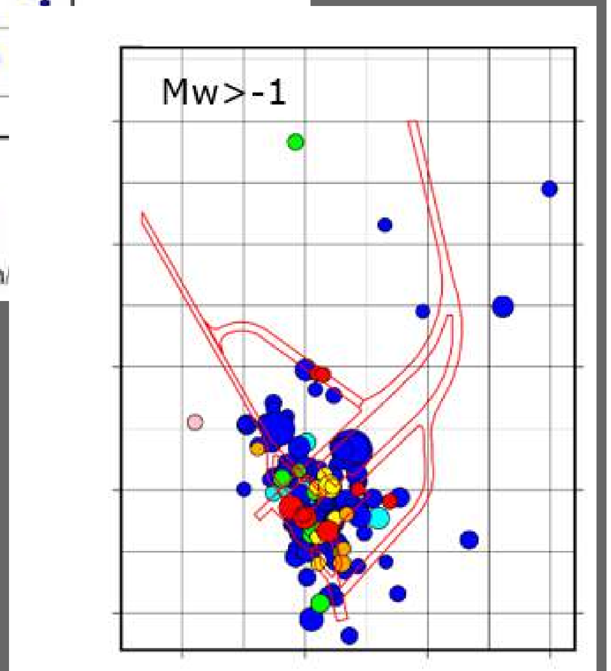
***Cai and Kaiser, 2018**

Example for the week during which some of the most violent rockbusts occurred, simultaneously affecting:

- **n.2 tailraces in proximity to powerhouse,**
- **the powerhouse it-self,**
- **the transformers chamber,**
- **tunnel connections between the two caverns.**

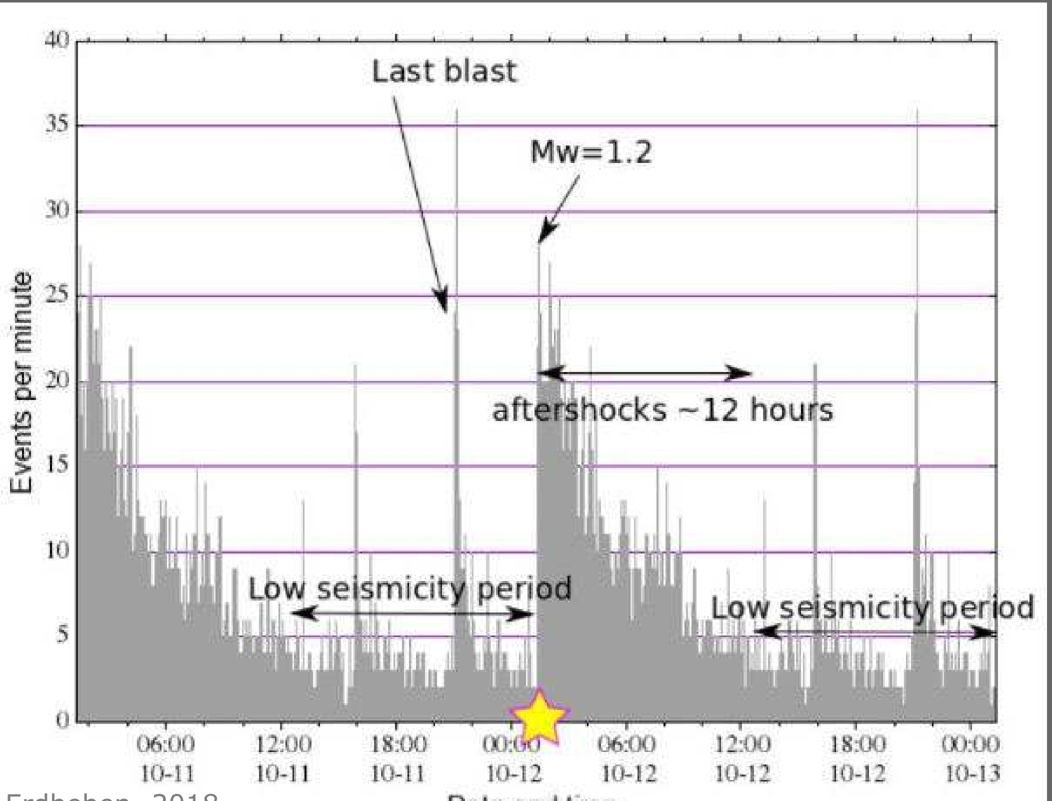
In total, about 270m of these underground structures suffered support damage of the described types





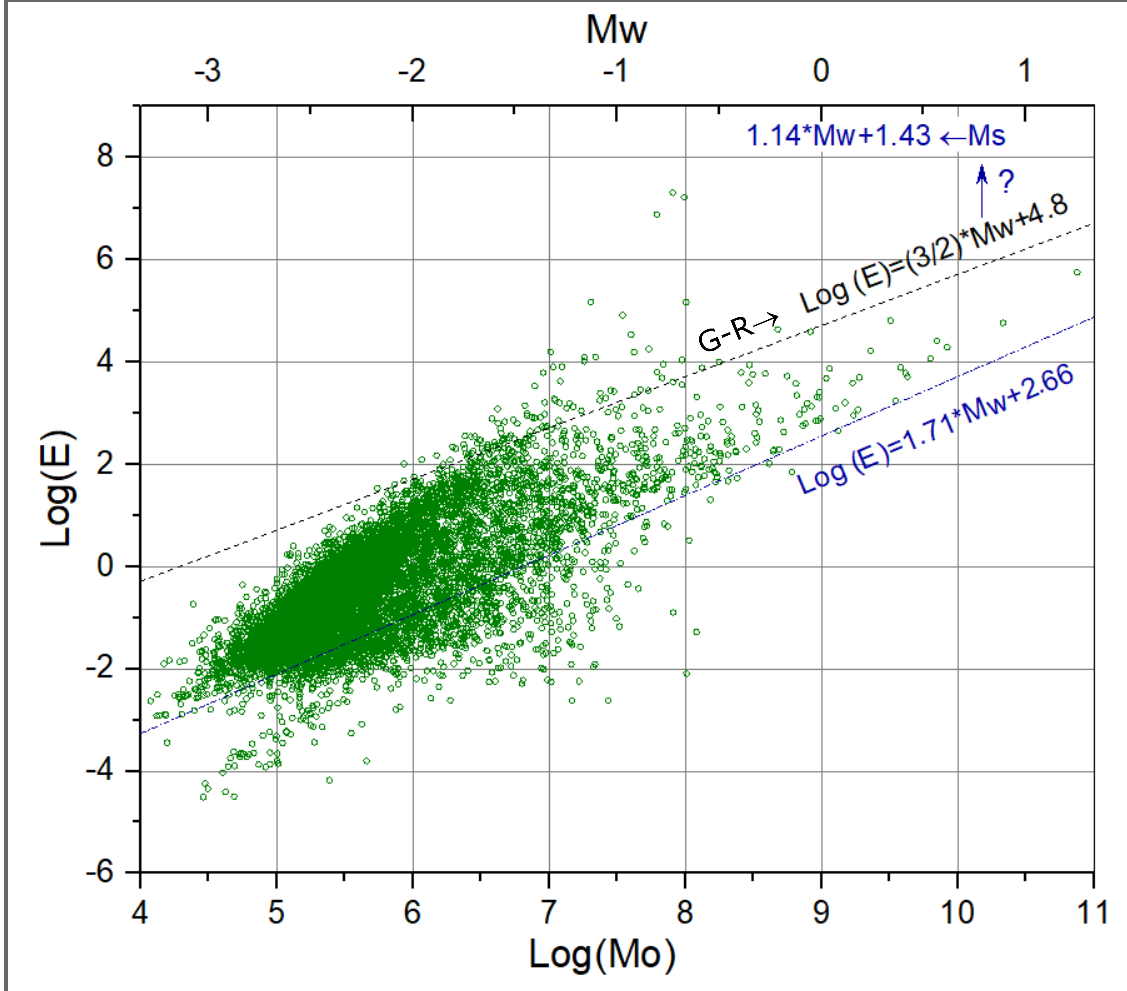
Plan view of the seismicity activity (blue symbols refer to the day of 10/12 rockburst).

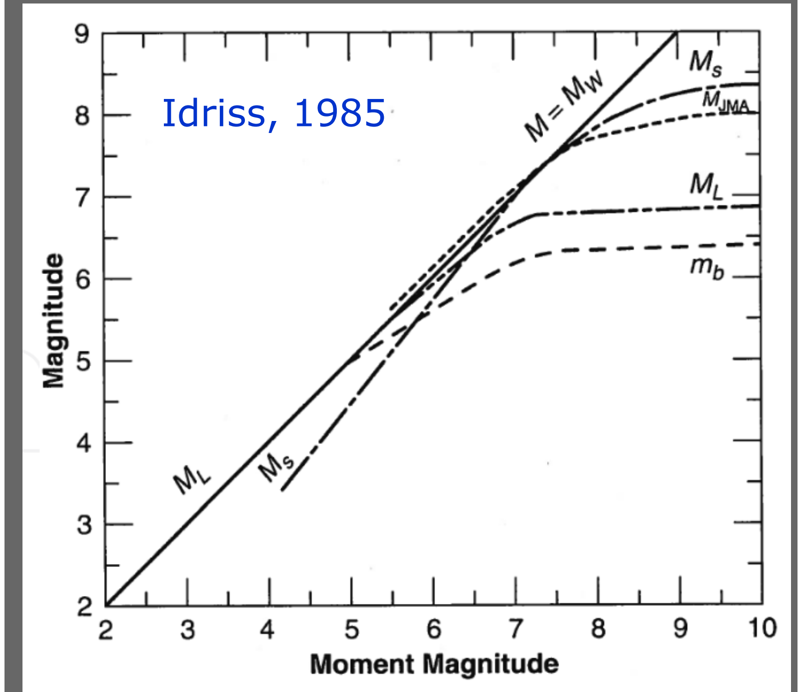
Frequency of events and some basic information.



Erdbeben, 2018

Yellow star indicates the first rockburst affecting one tailrace, some hours later the relative blasting.
Mw=1.2 event occurred about simultaneously at about 50m of distance and probably triggered violent phenomena in other tunnels and caverns.





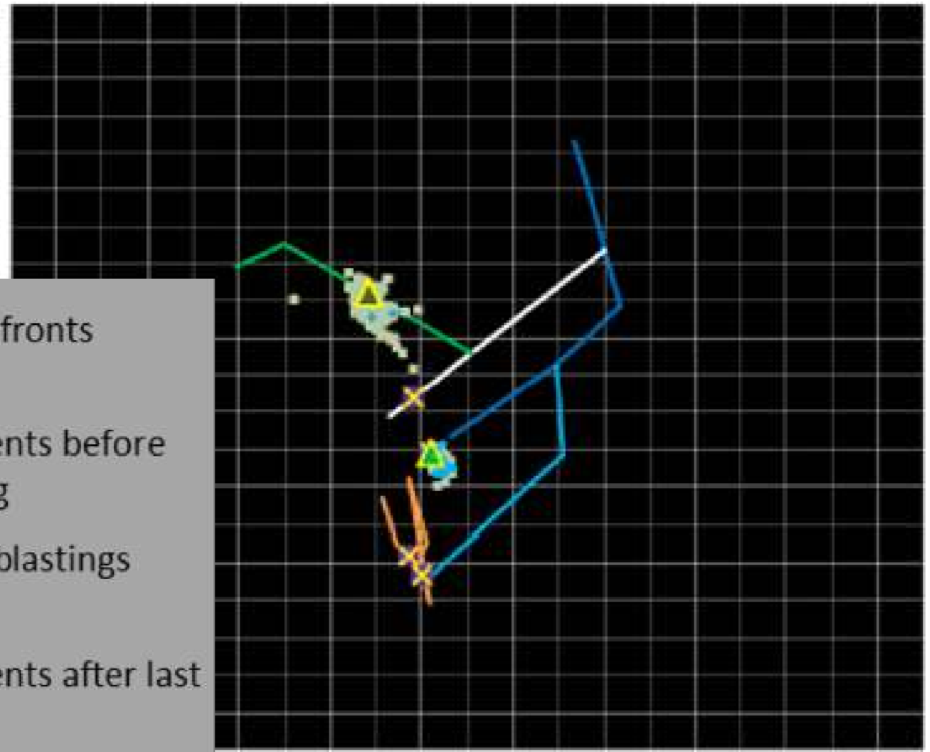
Relations between Log(E) with Mw and Log(Mo) compared with Gutenberg-Richter (G-R; 1956) equation and possible adjustment based on Mw↔Ms(surface wave)

Another case:

Blast in Adit A (h7:20) and rockburst in Adit B at about 100m of distance, after 19hours (h2:10).

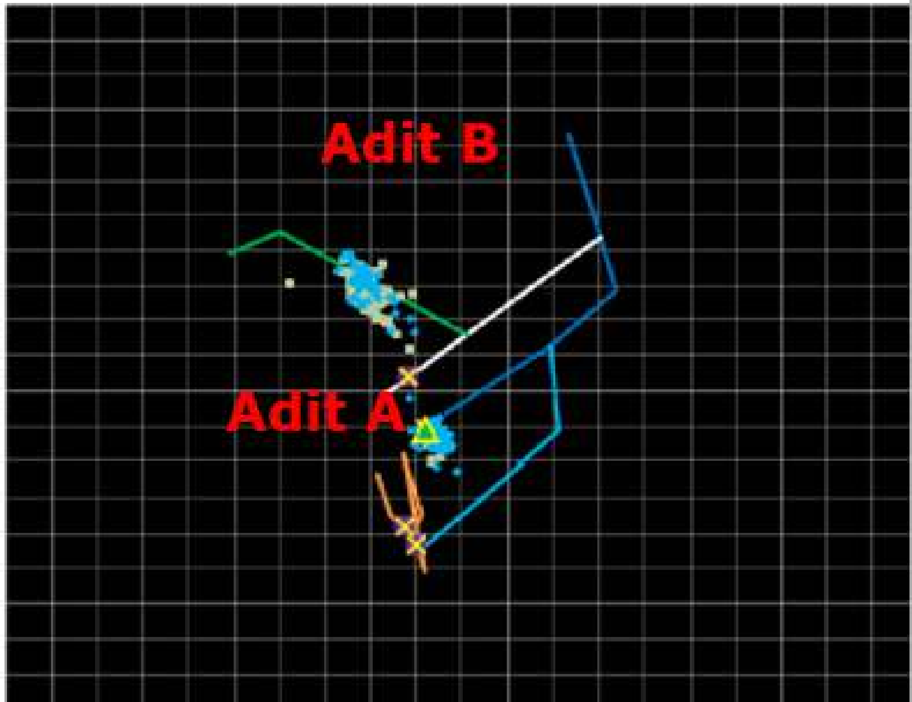
5min after blast in Adit A

1hour after blast in Adit A

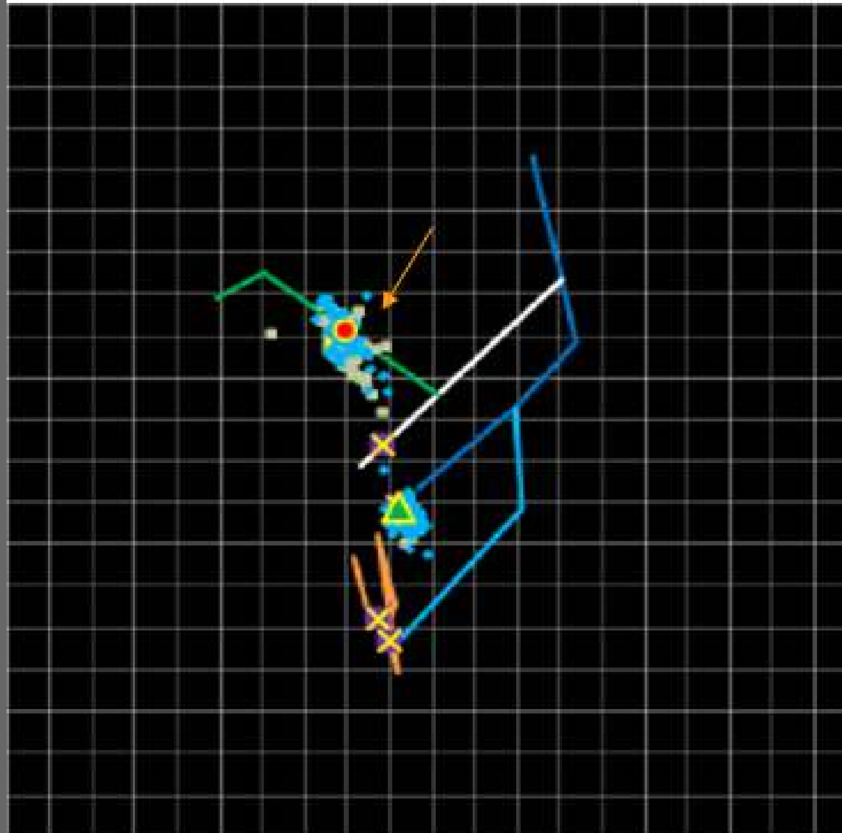


- Excavation fronts
- Seismic events before last blasting
- Precedent blastings
- Seismic events after last blasting
- Last blasting

6hours after blast in Adit A

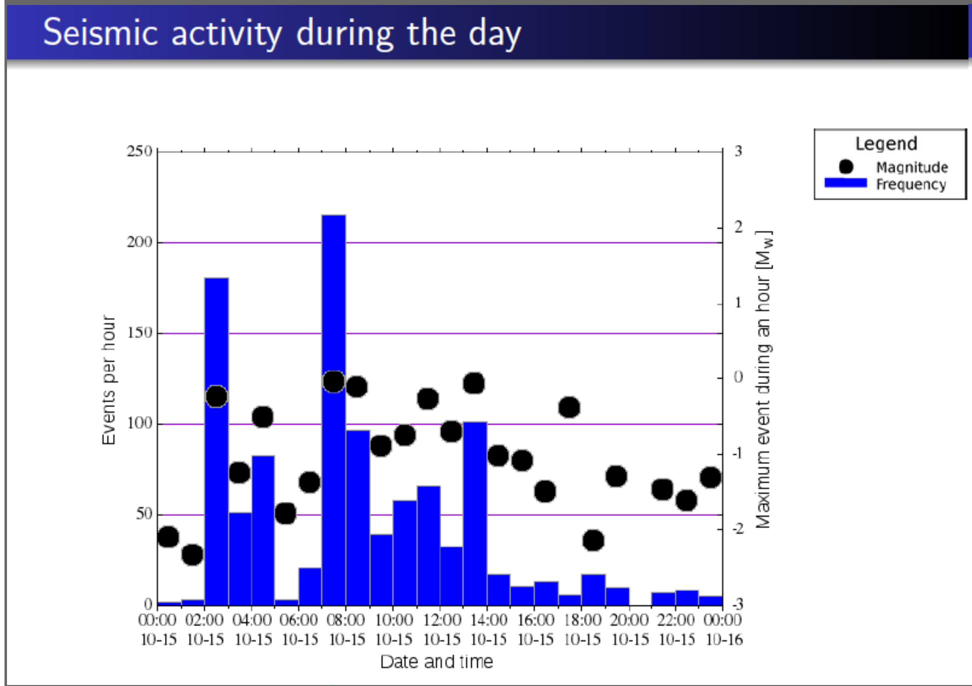


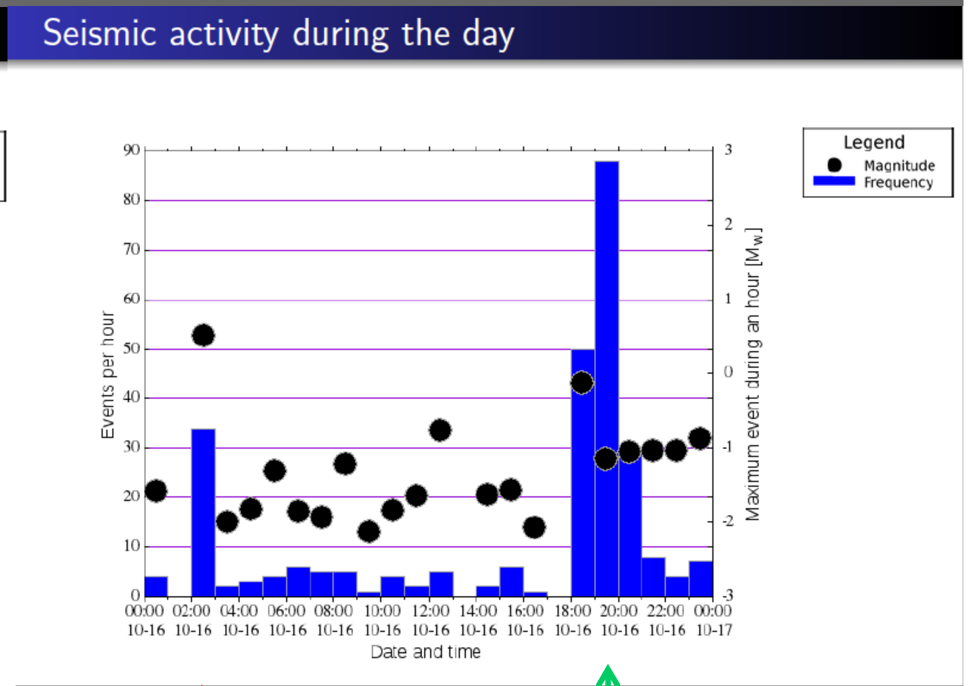
19hours after blast in Adit A



Some new seismicity between tunnels and increase around Adit B (sky-blue points) until rockburst

Seismic rate (events per hour) and max Moment Magnitude (M_W)

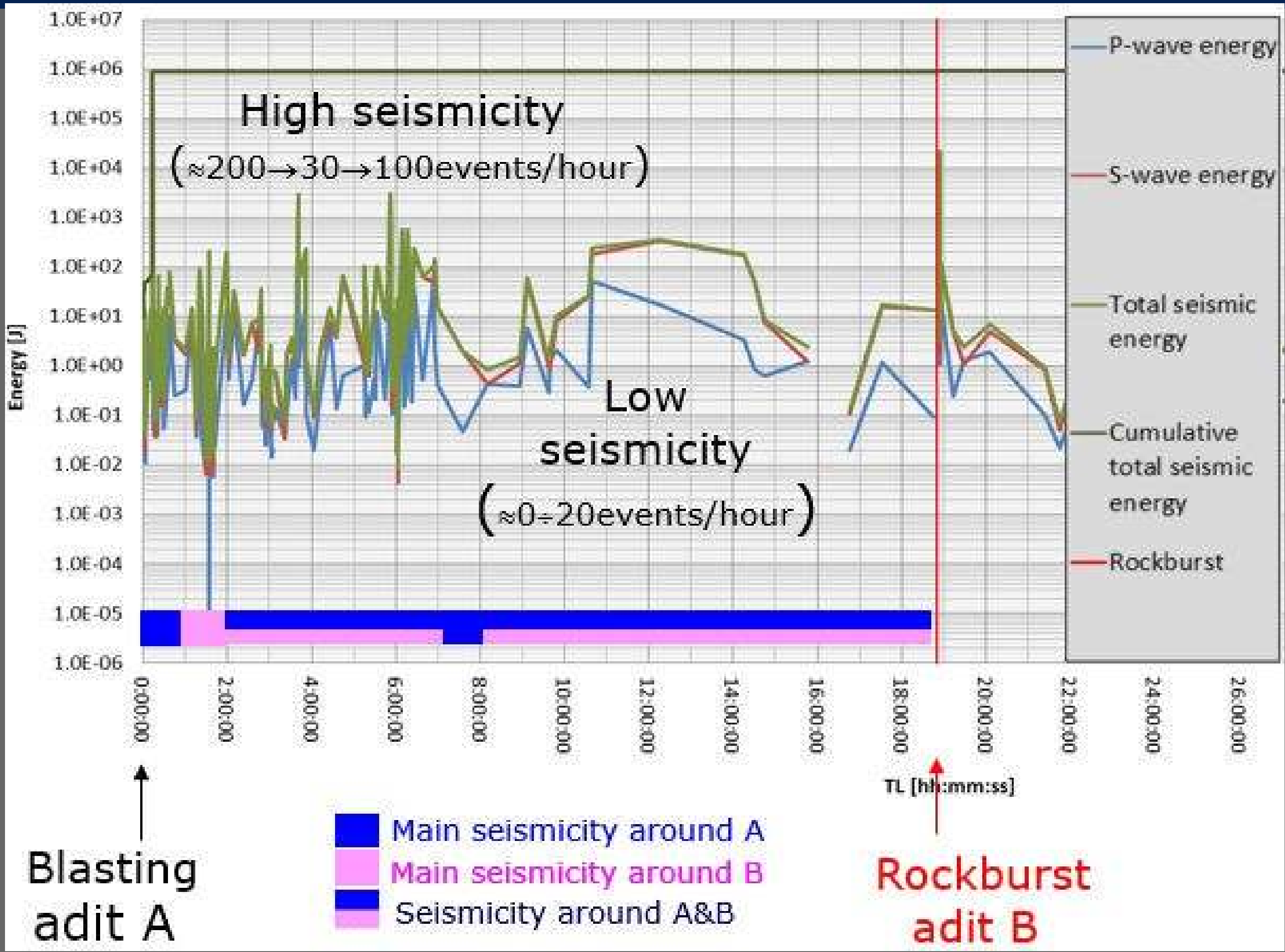




Blast in Adit A (15/10 – 7:20) t=0

Rockburts in Adit B (16/10 – 2:10) t=19h

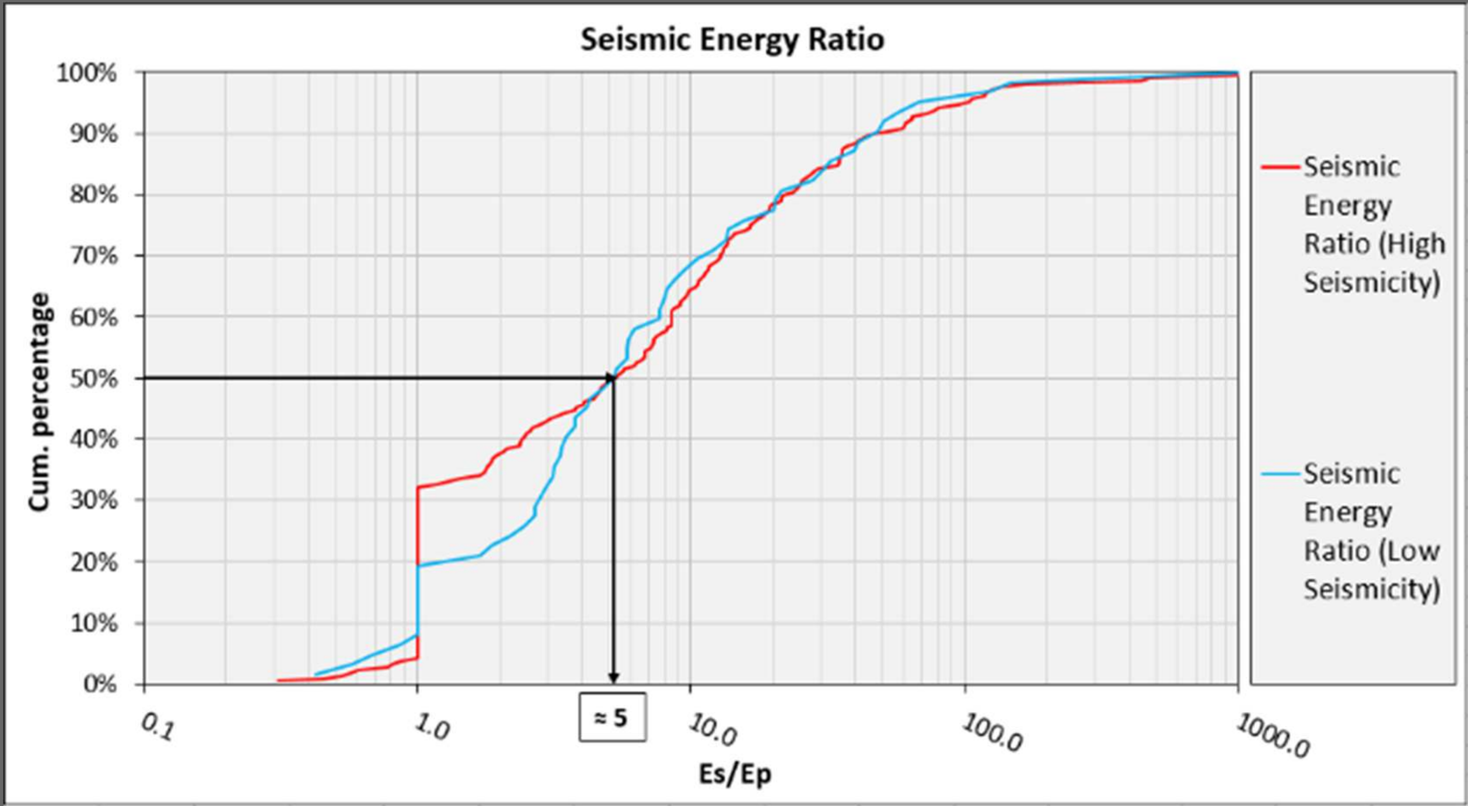
Blast in Adit B (16/10 – 19:00)



Seismic waves energy, with indication of number of events/hours and the dominant localization of events

Analysis of the ratio between S-waves and P-waves energy (Es/Ep)

- **Es/Ep >20 → shear failure and fault- slip mechanism**
- **Es/Ep <10 → non- shear (tensile) failure**

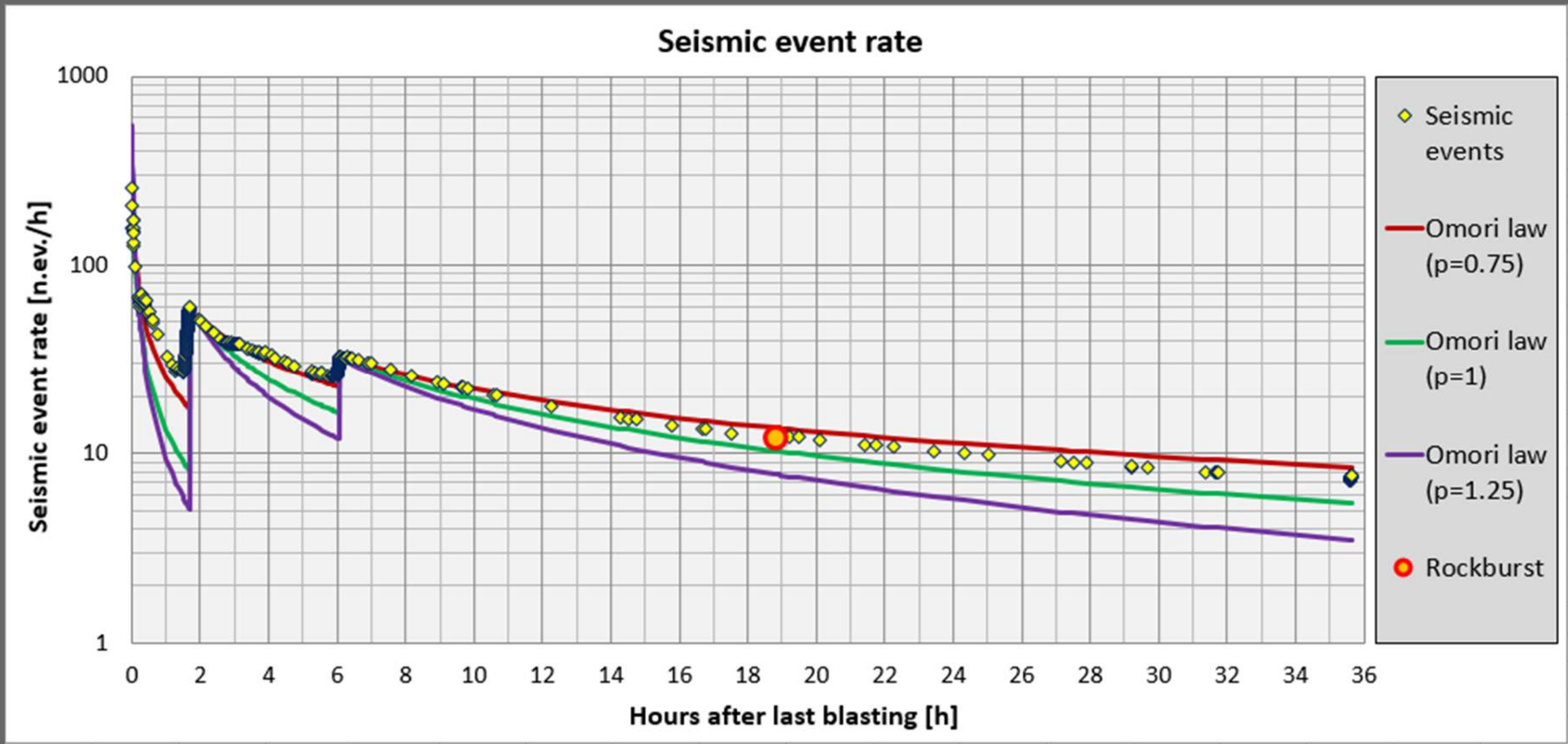


High variability is observed with most frequent values 1÷100 and median ≈ 5
Non-shear failure results the dominant mechanism (≈70%)

Attenuation of seismicity with time according Omori law

$$dN/dt=k/(t+c)^p$$

[N=number of events, t=time, c/k/p=parameters]



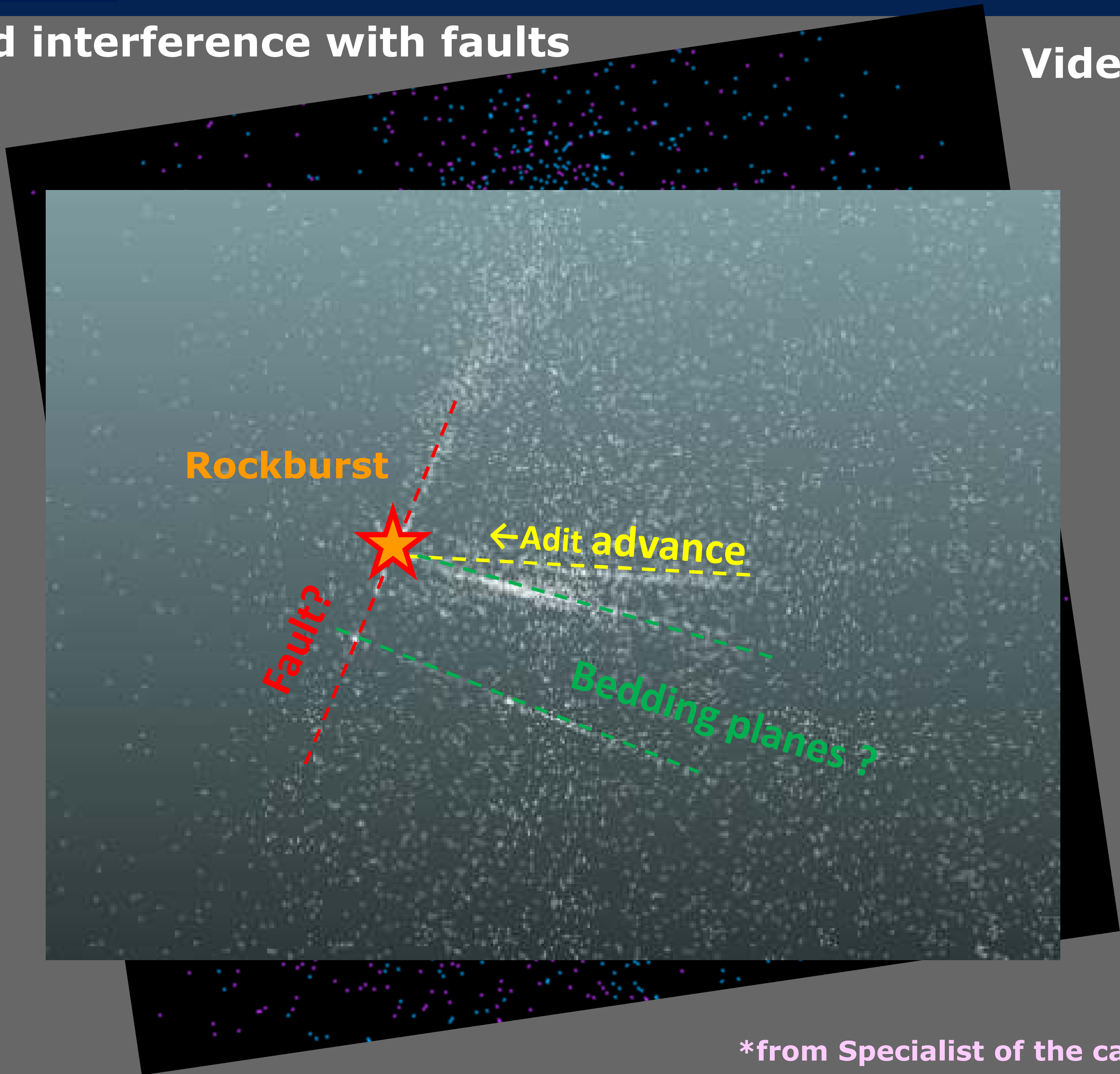
The curves for p=0.75-1-1.25 are reported for comparison:

p=0.7 →stiff system →slow decay

p=1.5 →soft system →fast decay

Suspected interference with faults

Video* →



*from Specialist of the caverns Designer

Some laminated shear bands in the adit face

Conclusive remarks from seismic monitoring:

- Although some statistical tendency, neither the number nor the maximum magnitude of events can be univocally related to the rockburst occurrence and relative severity;
- seismicity around a tunnel can be influenced by blasting in other tunnel, even for distance exceeding 100 m;
- in these case rockbursts can be delayed, even more than one day from time of blasting; otherwise, more than 95% of rockbursts occur in the first 4 hours at <5m from tunnel face;
- several times low seismicity preceded rockburst occurrences;
- the local interference on seismicity and rockburst of fault-slip mechanisms is suspected

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Thank You for Your Attention!