Applications of seismic monitoring and imaging for hazard management related to volcano eruption, mining and landslide

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Major hazards in Chile (2014-2015)

- Megathrust earthquakes in subduction zone
  - 2014 M 8.2 Lquique earthquake
  - 2015 M8.4 Coquimbo earthquake
- Volcano eruption
  - Villarrica Eruption
  - Calbuco Eruption
- Landslide
  - Tocopilla
  - Atacama
- Forest fire

Source: ONEMI

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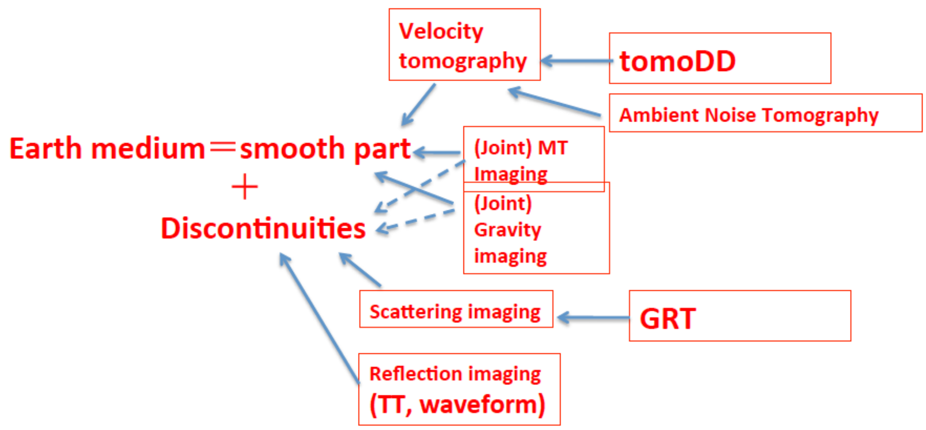
Seismic imaging is a useful tool for these applications

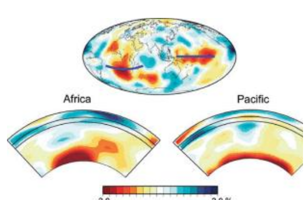
Recent developments of seismic imaging methods

- Wavelet-based multiscale double-difference seismic tomography
  - ✓ Fang and **Zhang**, 2014, GJI
- Near real time seismic tomography
  - ✓ Zhang X. and **Zhang H.**, 2015, JGR
- Seismic anisotropy tomography
  - ✓ **Zhang** et al., 2008, GRL
- Seismic scattering imaging
  - ✓ **Zhang** et al., 2009, GRL
- Joint inversion using seismic body-wave arrival times and surface wave dispersion data
  - ✓ **Zhang** et al., 2014, Pure and Applied Geophysics
  - ✓ Fang, **Zhang** et al., 2016, JGR

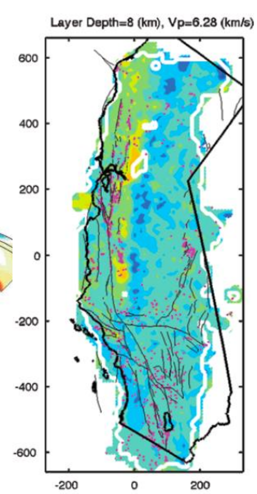
Imaging the Earth' s interior using combined methods and datasets



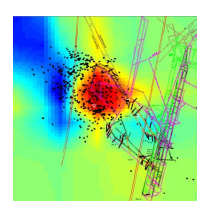
- These seismic imaging tools can be applied from global scales to small scales



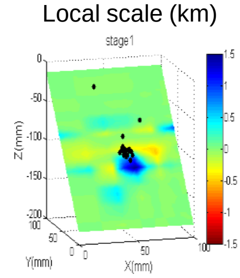
Global scale



Regional scale

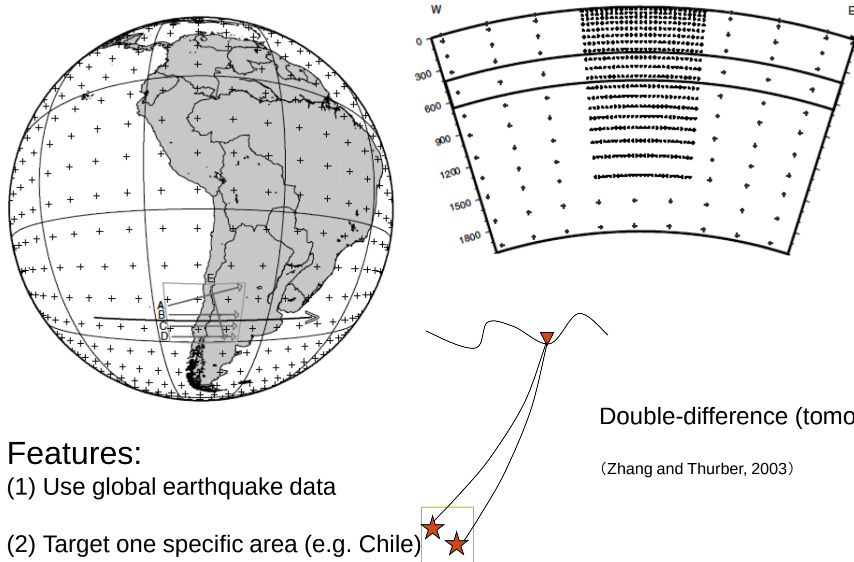


Local scale (km)



Local scale (cm)

Multiscale global tomography



Double-difference (tomoDD)

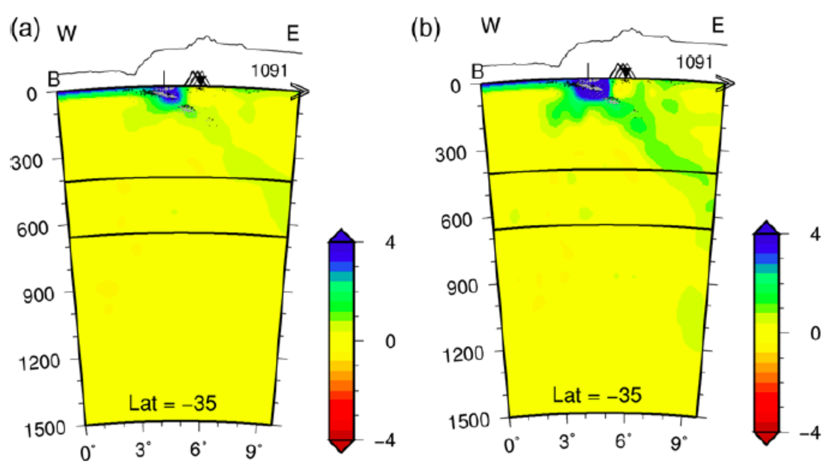
(Zhang and Thurber, 2003)

Features:

(1) Use global earthquake data

(2) Target one specific area (e.g. Chile)
----using differential arrival times

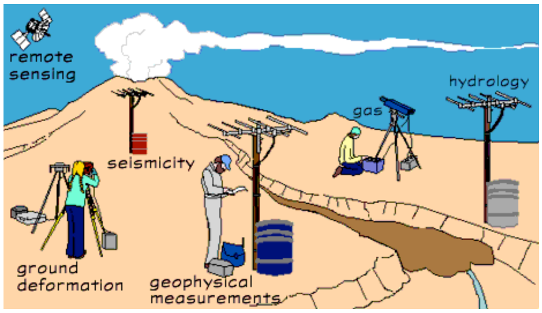
Pesicek, Zhang and Thurber, 2014, BSSA



One iteration **Multiple iterations**

Maule subduction zone, Chile

Pesicek, Zhang and Thurber, 2014, BSSA



Near real time seismic imaging for volcanoes

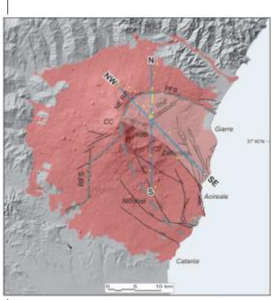
✓ Obtaining temporal velocity changes

✓Near real time seismic tomography based on wavelet and SART

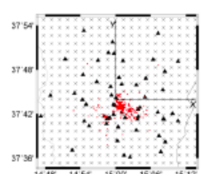
Villarrica volcano, Chile, 2016

Zhang X. and Zhang H., 2015, JGR

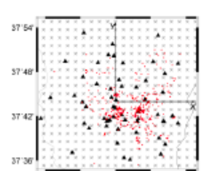
Mount Etna Volcano, Italy



2001 Eruption

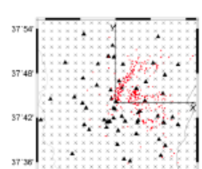


2001 Eruption



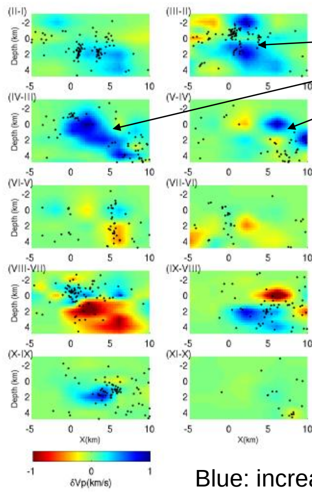
Between 2001 and 2002 Eruptions

2002 Eruption



2002 Eruption

Velocity changes for different time periods (cross section through crater)

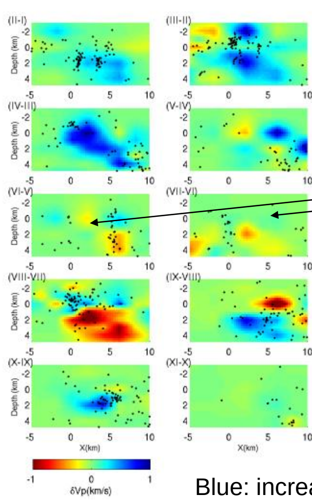


After 2001 eruption:

Velocity increasing, likely due to fracture closure and magma cooling

Blue: increase
Red: decrease

Velocity changes for different time periods (cross section through crater)

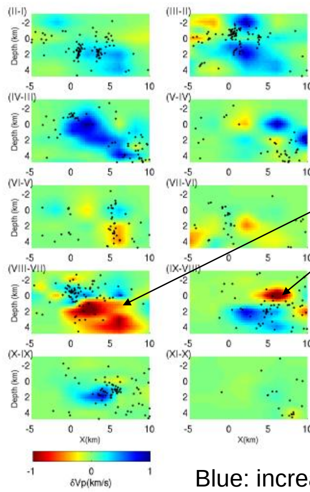


Between 2001 and 2002 eruptions:

Velocity decreasing, likely due to magma recharge

Blue: increase
Red: decrease

Velocity changes for different time periods (cross section through crater)

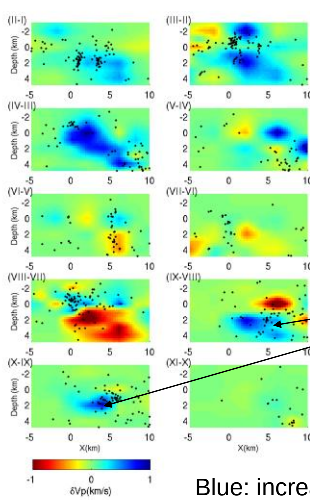


During 2002 eruption:

Velocity decreasing, likely due to magma migration and fracturing development

Blue: increase
Red: decrease

Velocity changes for different time periods (cross section through crater)



After 2002 eruption:

Velocity increasing, likely due to fracture closure and magma cooling

Blue: increase
Red: decrease

Damages caused by landslide

Landslide in Fujian, China

Landslide in Wenchuan, China

Mudflow in Gansu, China
(>**1300 death**)

Damages caused by mining

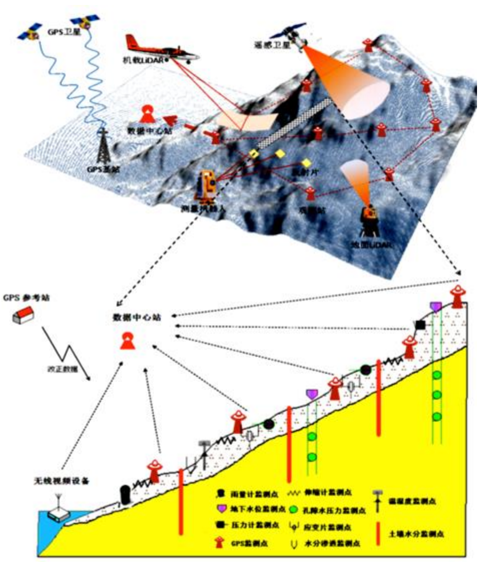
Rockburst

Gas outburst

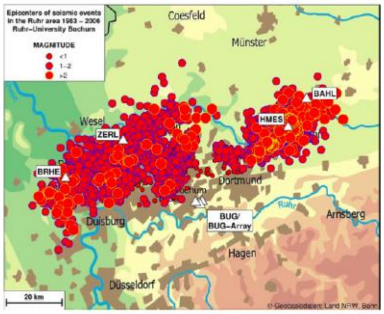
Roof fall

Causing a lot causality and property losses in China each year

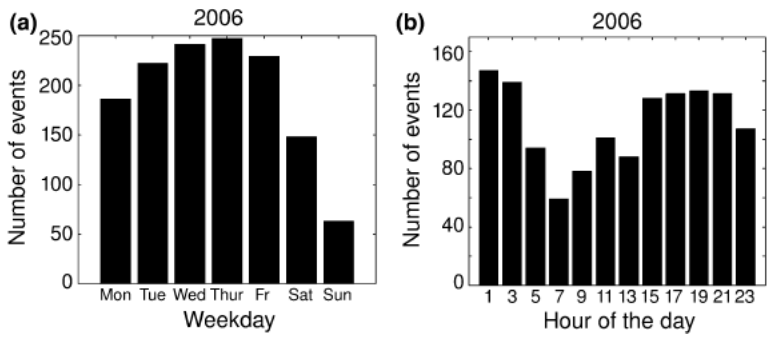
Chile mine rescue of 2010

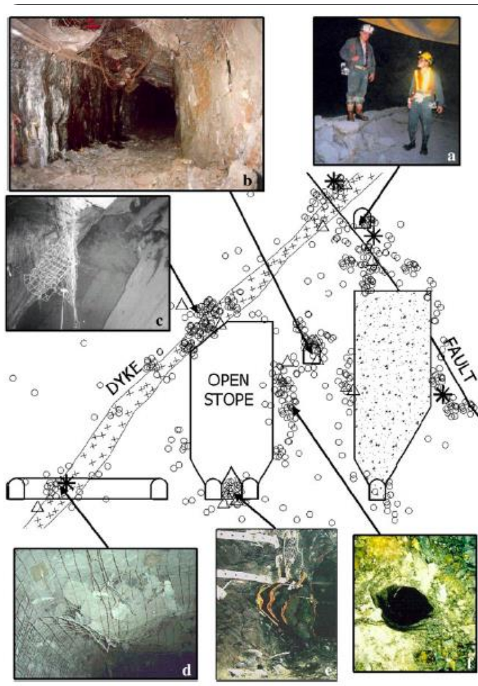


Finding effective ways for monitoring mining related hazards and slope stability is necessary!



Induced seismicity associated with mining activity in the Ruhr area, Germany

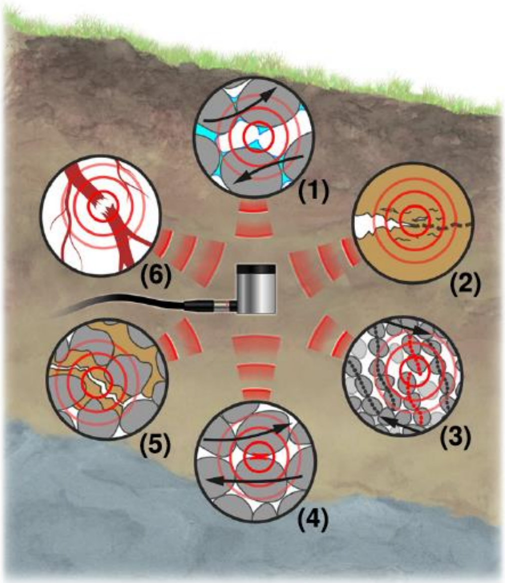




Processes causing microseismic events (or acoustic events) for mining

Fig. 2 Schematic seismic sources or local rock mass failure caused by stress change and different geological conditions: **a** fault movement, **b** stress change causing rock mass fracturing near an excavation, **c** stope overbreak, **d** contrast in rock mass properties causing strain bursting, **e** crushing of mine pillars, **f** stress increase causing rock mass deformation (Hudyma 2008)

Source mechanisms proposed for the generation of acoustic emissions related to slope instability

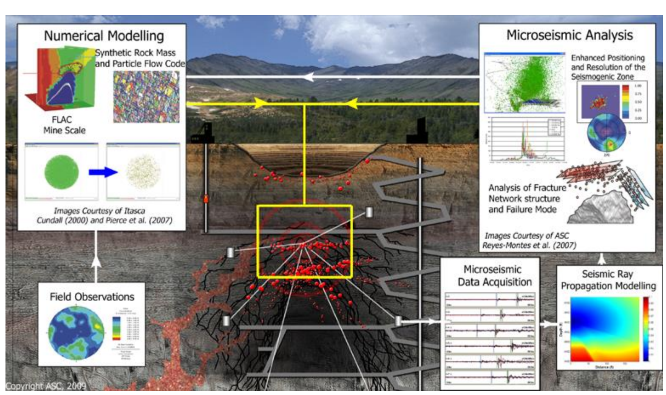


(1) liquid bridge rupture
(2) crack development
(3) release of force chains
(4) grain friction
(5) grain cementation fracture
(6) rupture of soil fibers.

Michlmayr et al., 2012
Earth-Science Reviews

Purposes of microseismic monitoring

- Using high-resolution microseismic data to monitor, manage, and hopefully forecast the risks associated with large seismic events, and rockburst and slope instability.



Microseismic data processing

- Microseismic event detection
- Microseismic event location
- Microseismic source properties
- **Microseismic velocity imaging**

Microseismic data processing

- <u>Microseismic event detection</u>
- Microseismic event location
- Microseismic source properties
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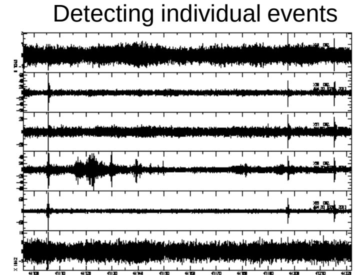
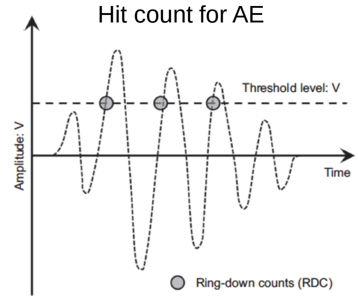
Detecting individual events

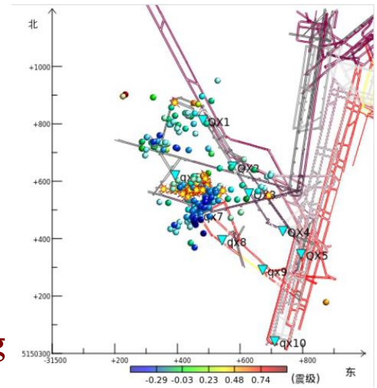


Hit count for AE



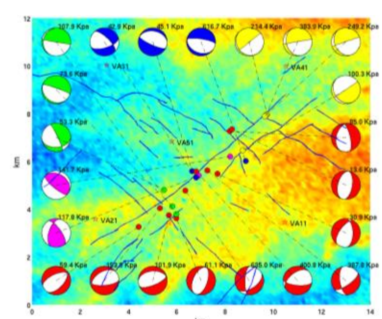
Microseismic data processing

- Microseismic event detection
- <u>Microseismic event location</u>
- Microseismic source properties
- **Microseismic velocity imaging**



Microseismic data processing

- Microseismic event detection
- Microseismic event location
- <u>Microseismic source properties</u>
  - Focal mechanism
  - Source radius
  - Stress drop
  - Magnitude

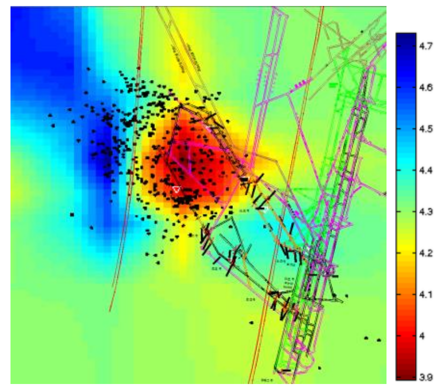


- **Microseismic velocity imaging**

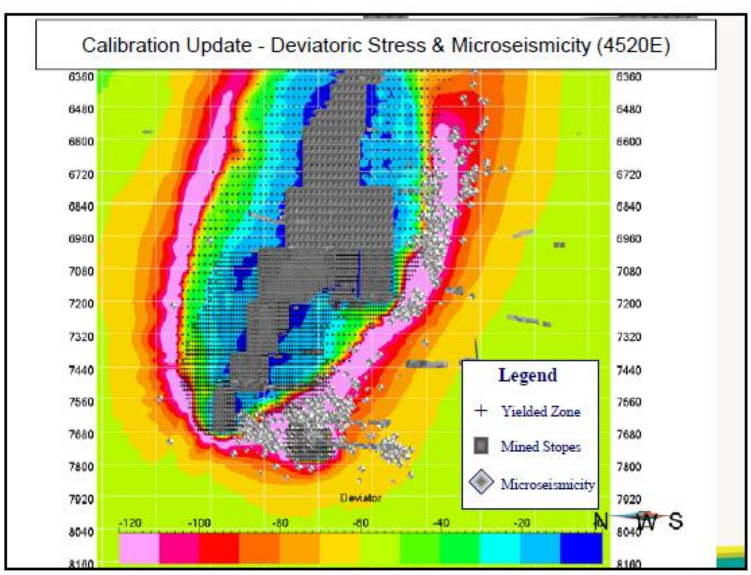
Microseismic data processing

- Microseismic event detection
- Microseismic event location
- Microseismic source properties
- Microseismic velocity imaging

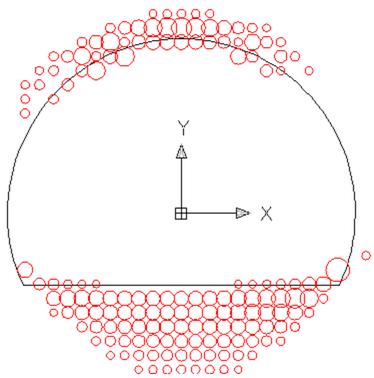
Vp at Z=0.4 km



Rock mechanics modeling shows that the induced seismicity is located in the high stress zone



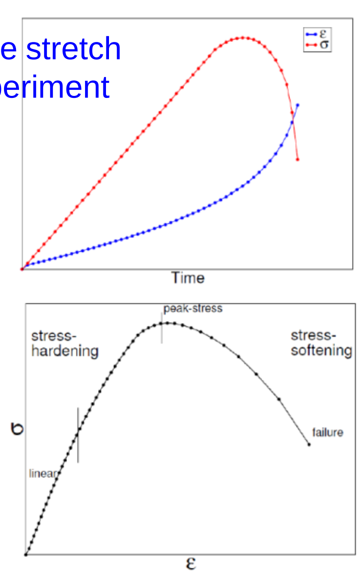
AE activity associated with rockburst

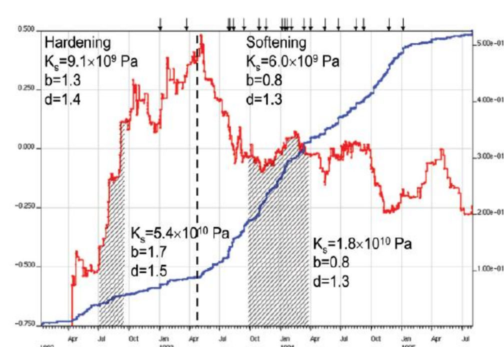


It is obvious that acoustic emission activity is active around the boundary of cavern, where stress is high.

Constructing “stress-strain curves” based on microseismic monitoring data

Wire stretch experiment



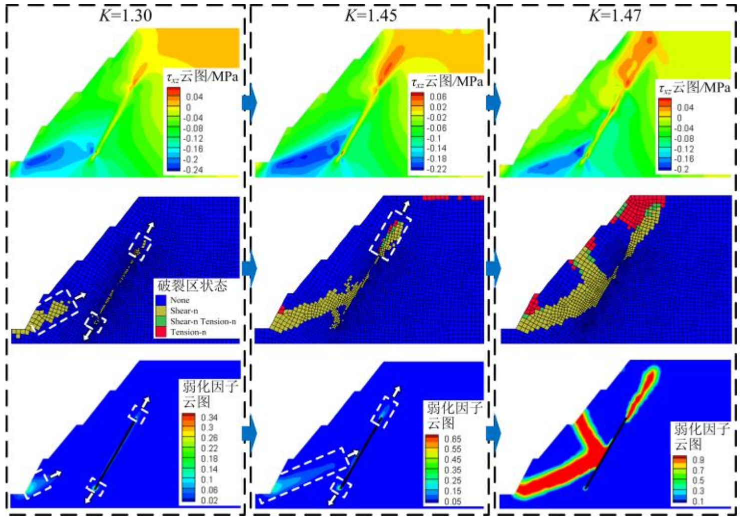


Real mining case

Courtesy of Dr. Rebuli of IMS

Slope instability modeling using SRM

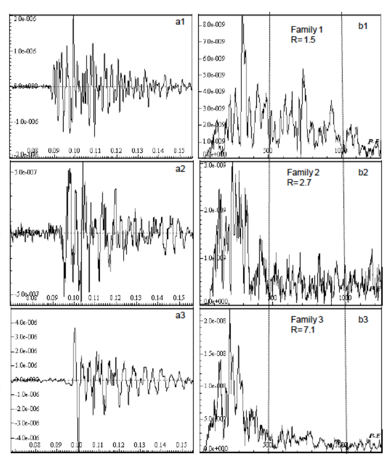
- Stress concentration
- Fracture initiation
- Fracture development
- Slip weakening
- Fracture coalescence



Ke Zhang, Kunming University of Science and Technology

Different microseismic signals at different stages of cliff collapse

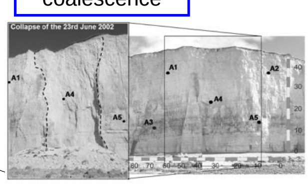
- Stress concentration
- Fracture initiation
- Fracture development
- Slip weakening
- Fracture coalescence



Family 1

Family 2

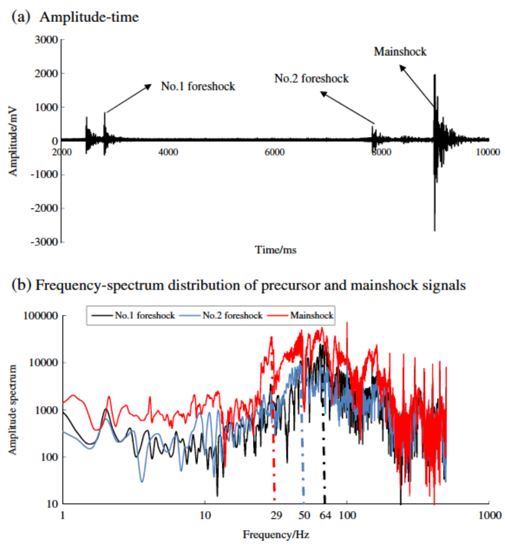
Family 3



Mesnil-Val,
NW France

Senfaute et al., 2009, NHESS

Using microseismicity as a precursor for bursting failure and rock fall



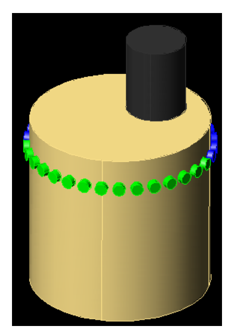
Before the rock failure, there is a tendency that the frequency band becomes wider and the predominant frequency-spectrum moves to lower-frequency band.

micro-cracks to macro-fracture.

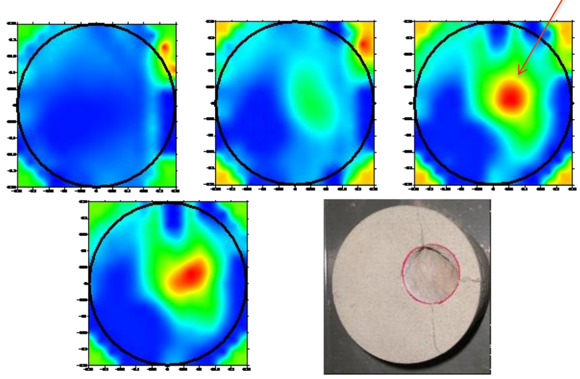
Lu et al., 2012, Applied Geophysics

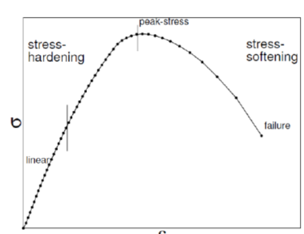
Using velocity changes as a proxy for stress variations

- ‘Stress’ vs. seismic velocity



Velocity increase

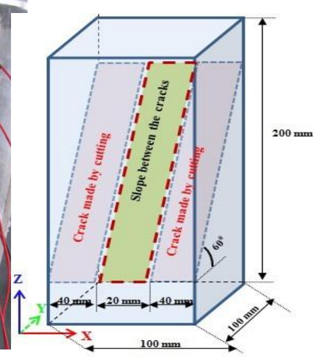




Courtesy of Erik Westman of Virginia Tech

Acoustic emission experiment

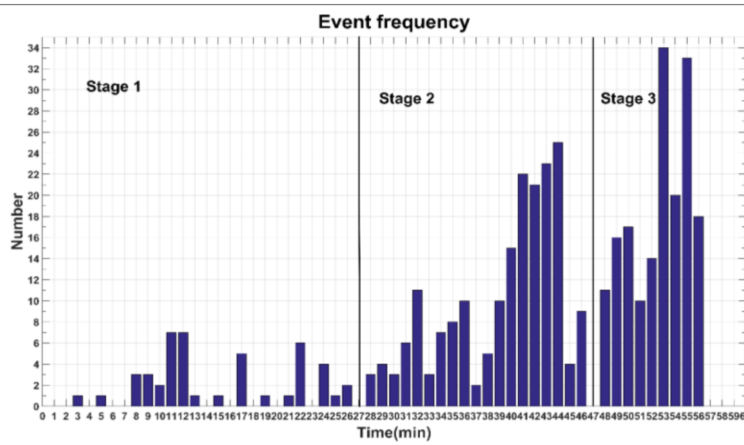
- ✓ Temporal and spatial distribution of AE events
- ✓ Temporal velocity changes

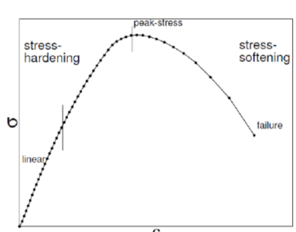


Before compression

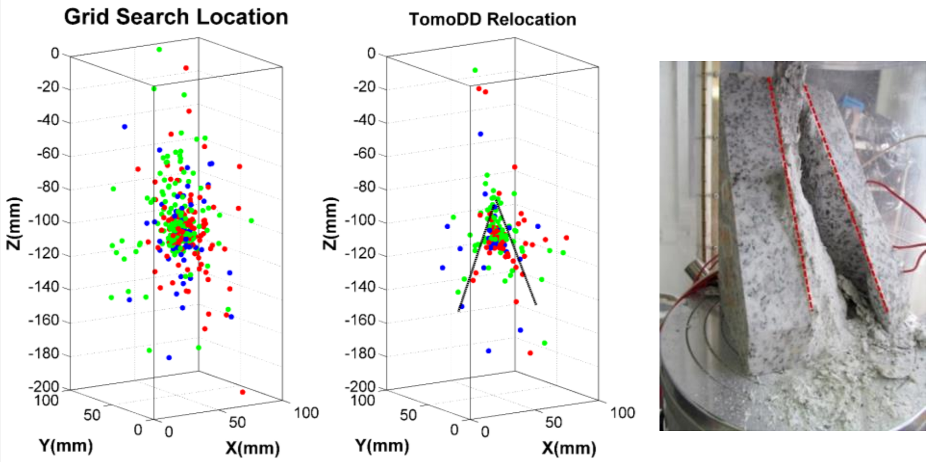
After compression

Collaboration with Erik Westman

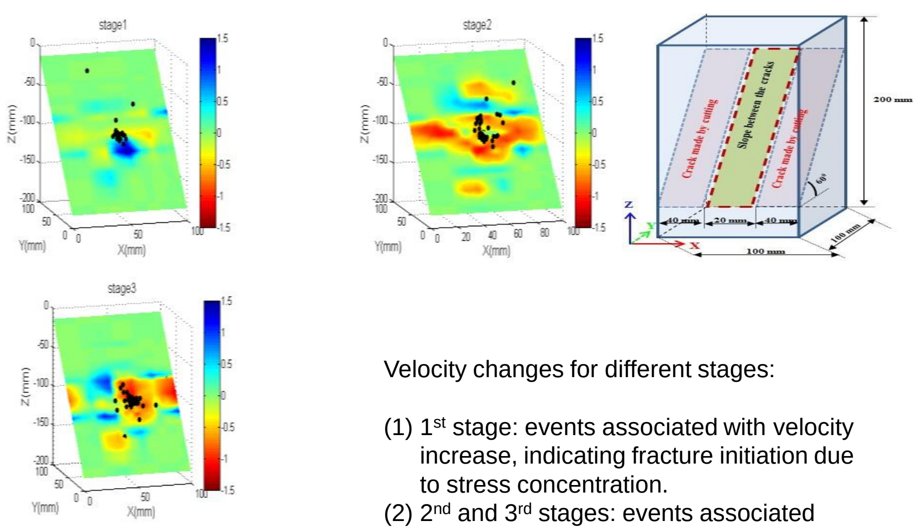




Microseismic events (AEs) are grouped into 3 stages according to temporal distribution.



Better event location method (tomoDD) is helpful for improving location accuracy.

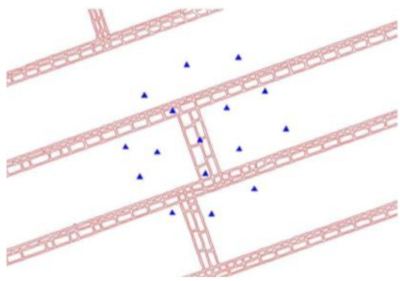


Velocity changes for different stages:

(1) 1st stage: events associated with velocity increase, indicating fracture initiation due to stress concentration.
(2) 2nd and 3rd stages: events associated with velocity decrease, indicating fracture development.

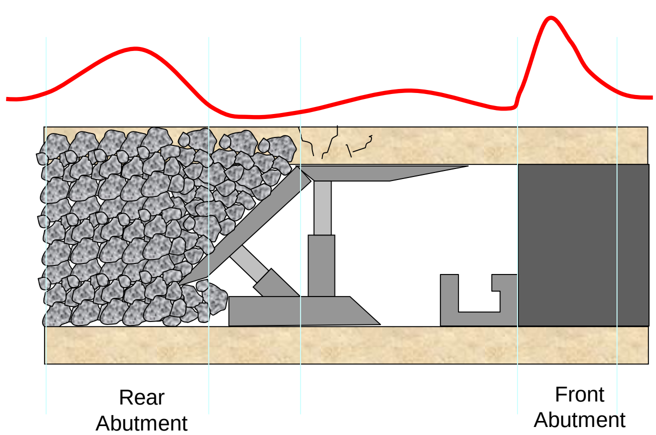
Time-lapse microseismic imaging for a coal mine

- 1200 ft deep seam, 1500 ft by 1500 ft area
- 16 surface geophones
- 18 days of monitoring
- Typical frequency of 30 Hz, wavelength of 140 m

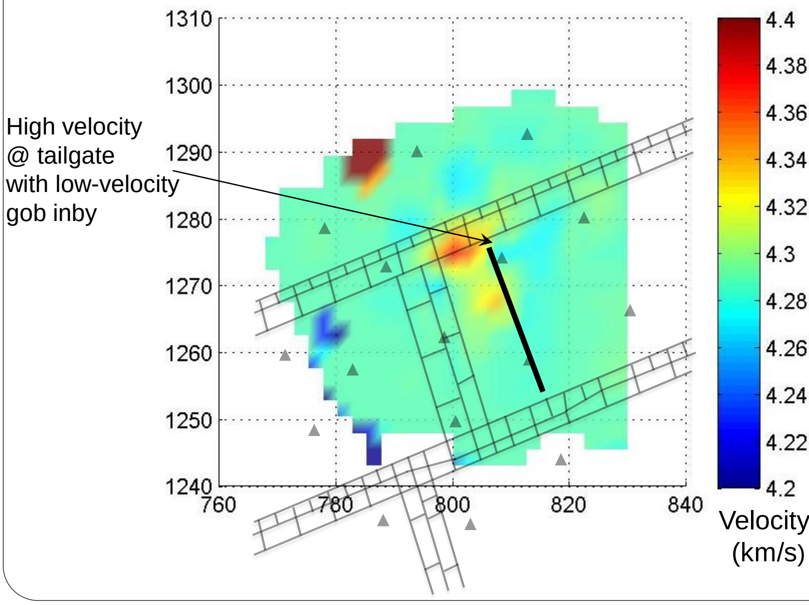


Collaboration with Erik Westman of Virginia Tech

The stress changes induced by coal mining



Jul 25


High velocity
@ tailgate
with low-velocity
gob inby
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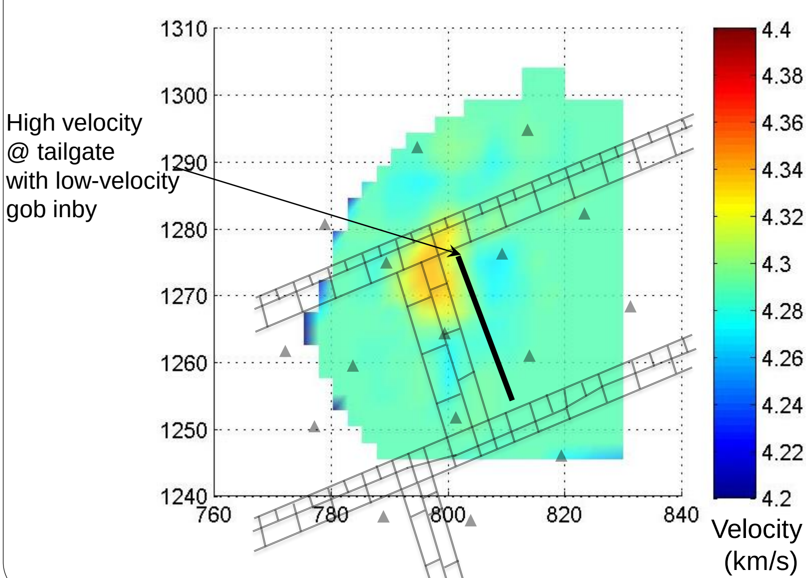
4.22
4.2
Velocity
(km/s)

Jul 27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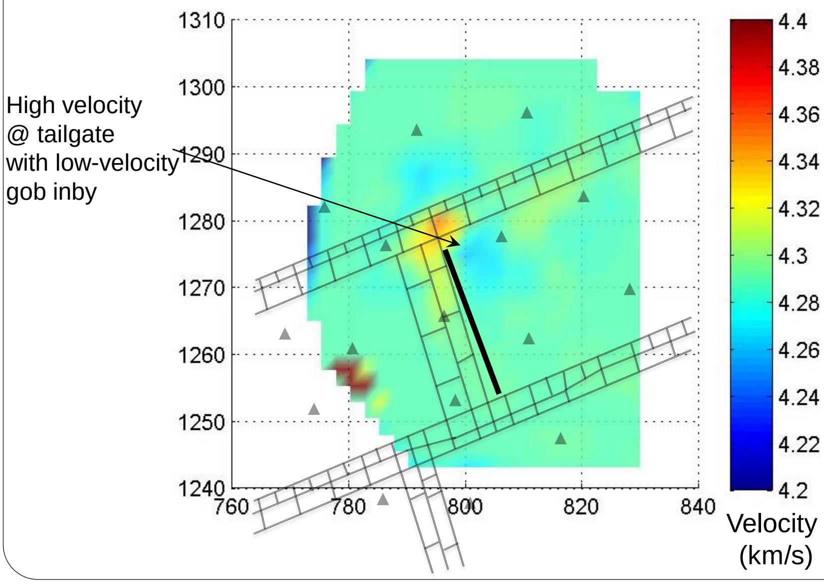
4.2
Velocity
(km/s)

Jul 28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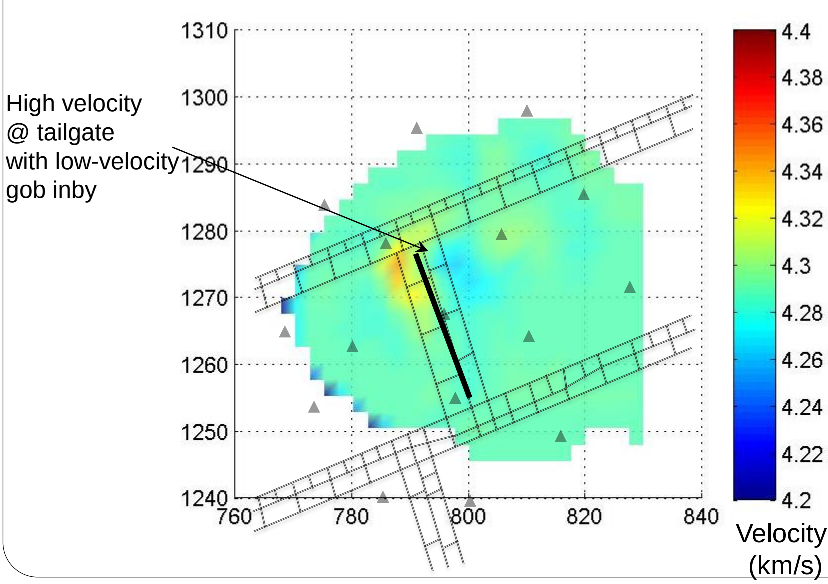
Velocity
(km/s)

Jul 31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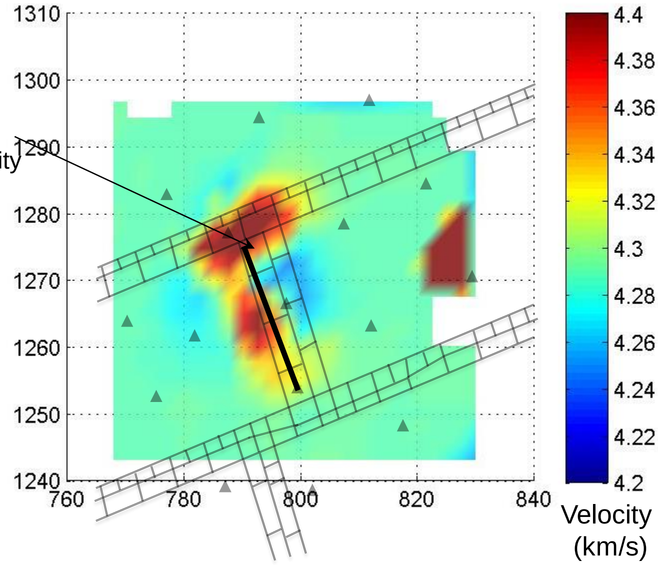
Velocity
(km/s)

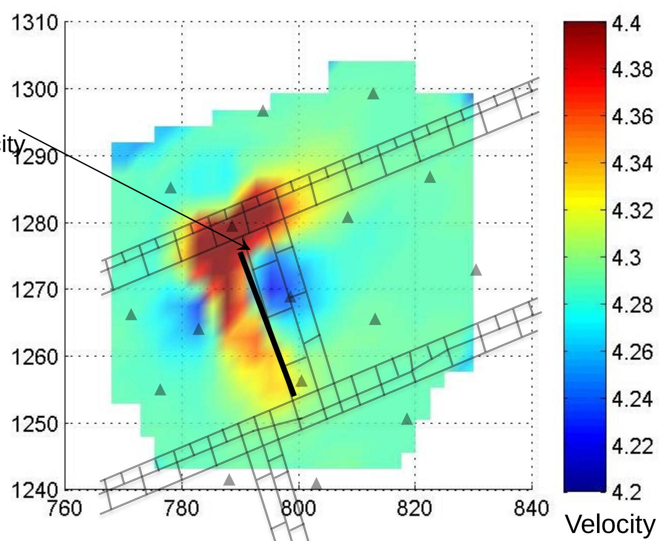
Aug 1

High velocity
@ tailgate
with low-velocity
gob inby

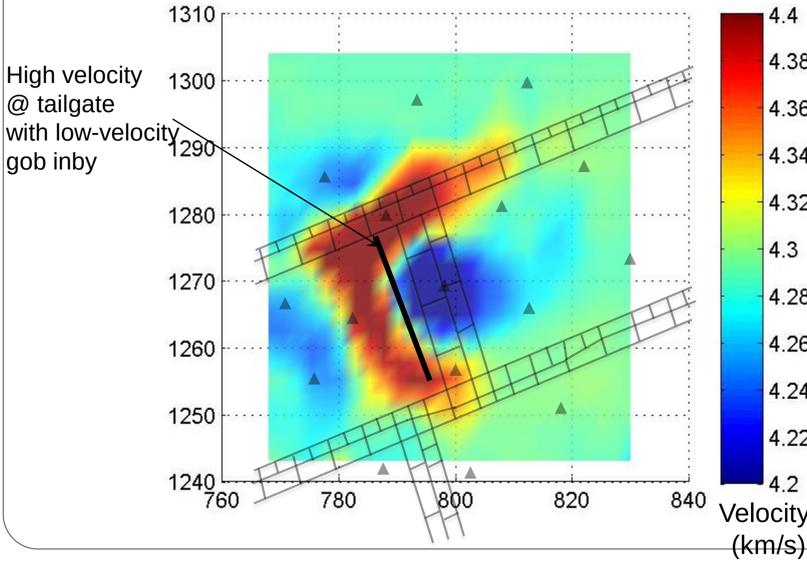


Aug 2

High velocity
@ tailgate
with low-velocity
gob inby



Aug 4


High velocity
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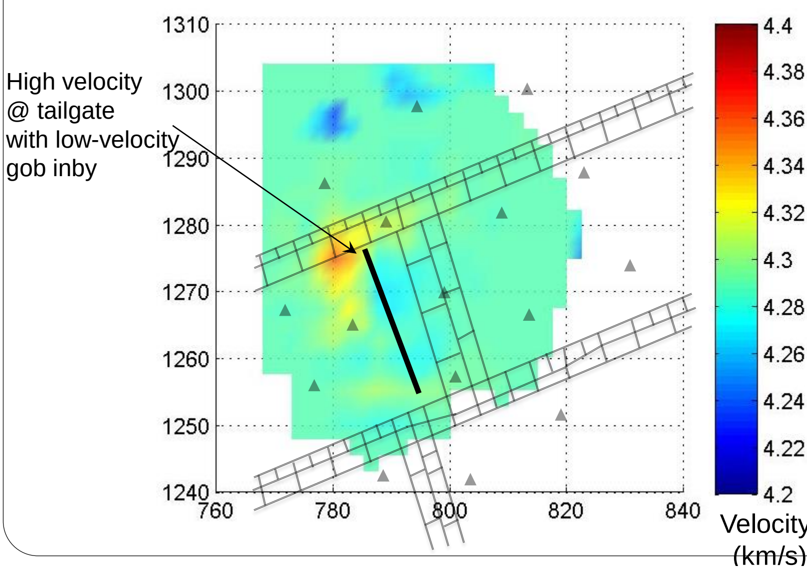
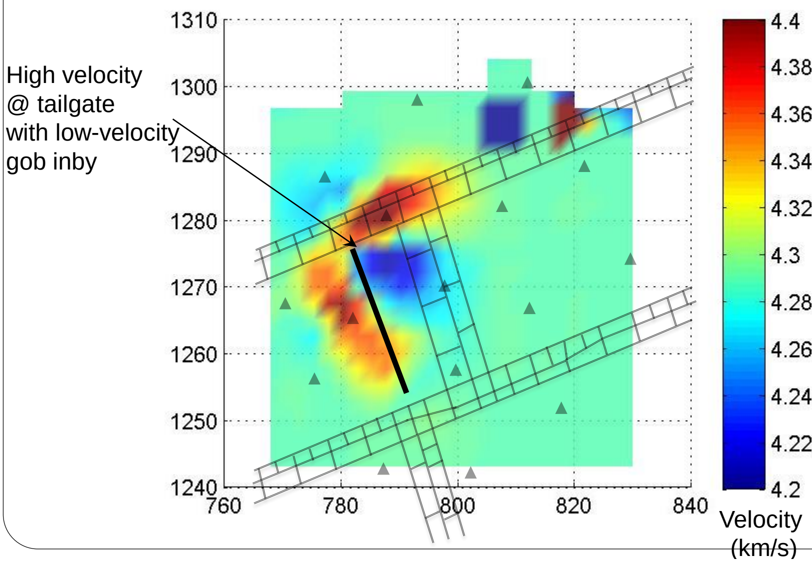
4.26
4.24
4.22
4.2
Velocity
(km/s)

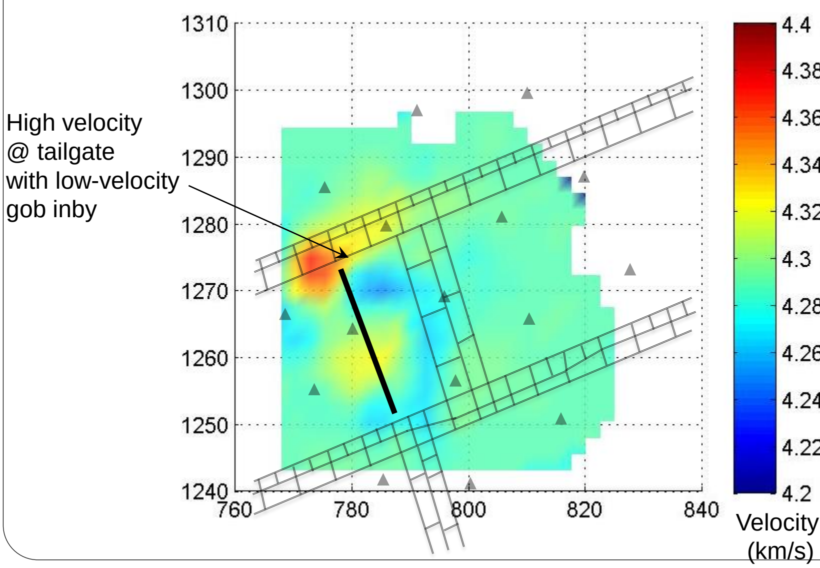
Aug 5


High velocity
@ tailgate
with low-velocity
gob inby
1310
1300
1290
1280
1270
1260
1250
1240
760
780
800
820
840
4.4
4.38
4.36
4.34
4.32
4.3
4.28
4.26
4.24
4.22
4.2
Velocity
(km/s)

Aug 6


High velocity
@ tailgate
with low-velocity
gob inby
1310
1300
1290
1280
1270
1260
1250
1240
760
780
800
820
840
4.4
4.38
4.36
4.34
4.32
4.3
4.28
4.26
4.24
4.22
4.2
Velocity
(km/s)

Aug 7


High velocity
@ tailgate
with low-velocity
gob inby
1310
1300
1290
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760
780
800
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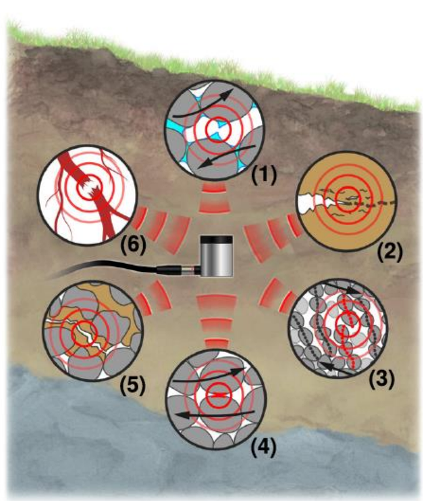
4.4
4.38
4.36
4.34
4.32
4.3
4.28
4.26
4.24
4.22
4.2
Velocity
(km/s)

Observations

- Clear representation of high-velocity zone moving with face retreat
- Consistent low-velocity region behind the face in location of gob

Microseismic velocity imaging could be a valuable tool to understand the stress distribution due to mining for risk assessment.

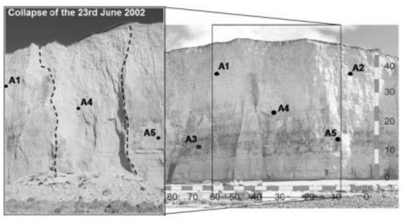
- Review of applications of microseismic monitoring for landslides

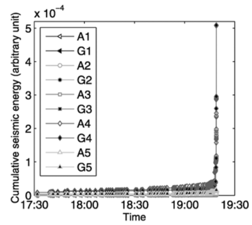


Earthquakes → Landslides

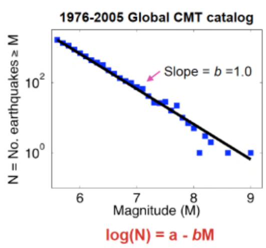
Landslides Slope instability → Microseismic events

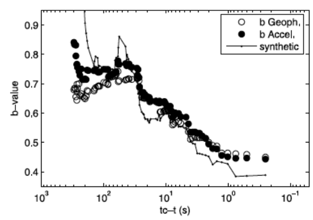
Seismic precursory patterns before a cliff collapse (Normandie ocean shore, Western France)





Intensive seismicity observed on A4 2 hours before collapse





The b exponent continuously decreases toward the collapse

Amitrano et al., 2005, GRL

Different microseismic signals at different stages of cliff collapse

Stress concentration

↓

Fracture initiation

↓

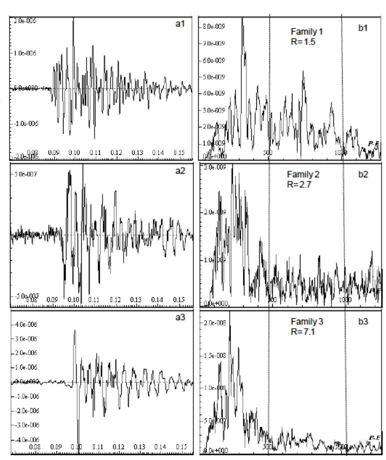
Fracture development

↓

Slip weakening

↓

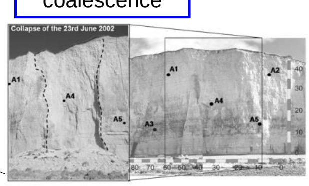
Fracture coalescence



Family 1

Family 2

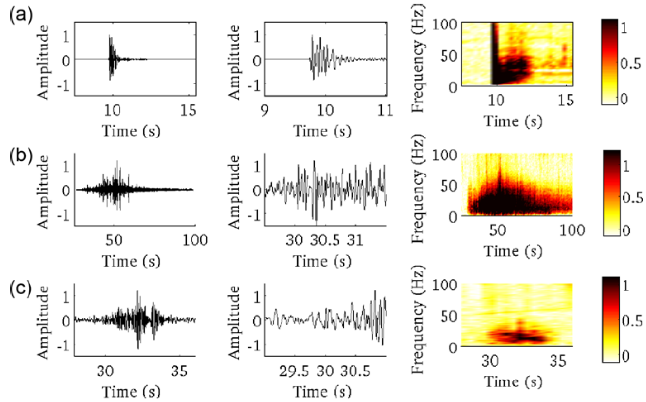
Family 3



Mesnil-Val, NW France

Senfaute et al., 2009, NHESS

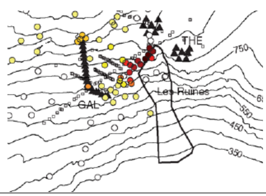
Seismic Signals Associated with Microearthquakes and Rockfalls on the Sechilienne Landslide, French Alps



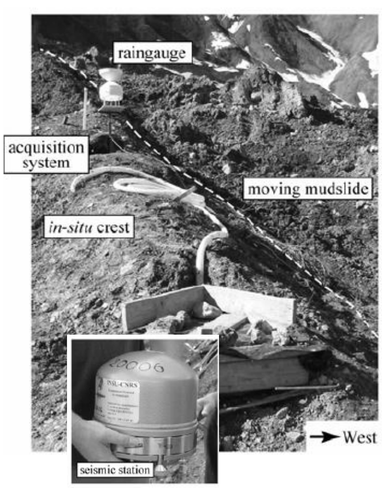
Shot

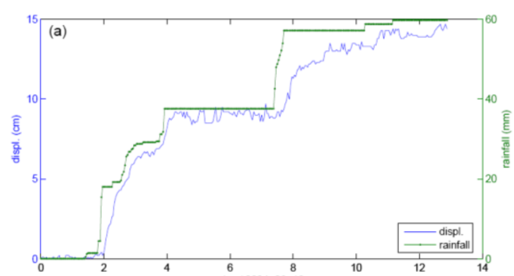
Rockfall

Micro-earthquake

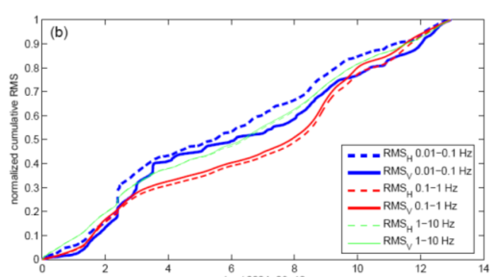


Lacroix and Helmstetter, 2011





Correlation between rainfall and landslide displacement



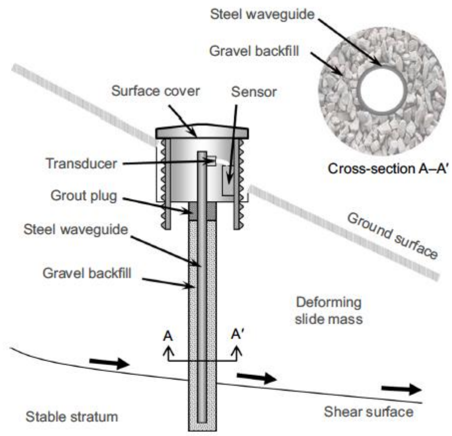
Microseismic monitoring for mudslides

Good correlation between acceleration of landslide movement with seismic activity

Amitrano et al., 2007

Cumulated seismic energy

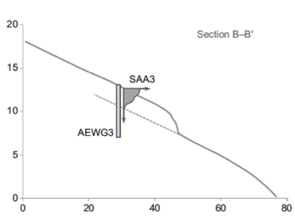
Microseismic monitoring for soil slopes with waveguides

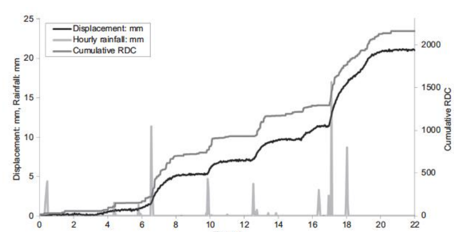


Dixon et al. 2012, 2015

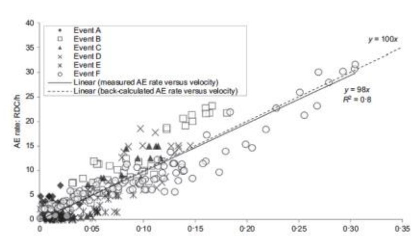
Cheon et al., 2011, Engineering Geology

Acoustic emission monitoring of a soil slope: Comparisons with continuous deformation measurements (Hollin Hill, UK)



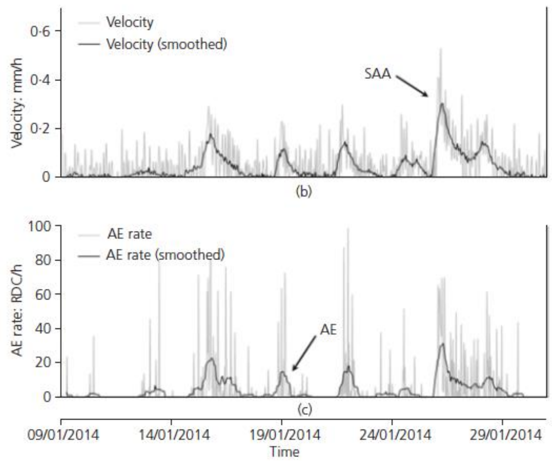


AE monitoring of active waveguides is able to provide continuous information on slope displacements and displacement rates with high temporal resolution.



Smith, A. et al. (2014) Geotechnique Letters

Stability monitoring of a rail (soil) slope using acoustic emission

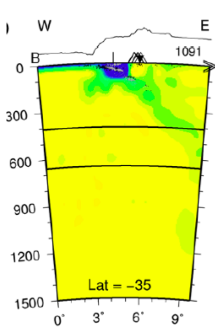


Acoustic emission rates are proportional to the velocity of slope movement and has high temporal resolution.

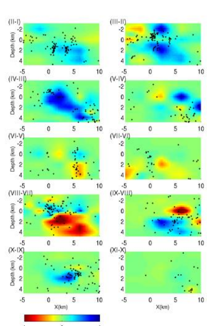
Dixon et al., 2015, Geological Engineering

Summary

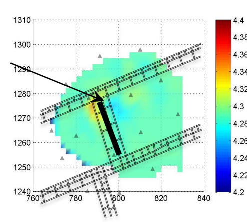
- Seismic monitoring is a useful tool for understanding the processes related to subducting, volcanic eruption, mining and landslide.



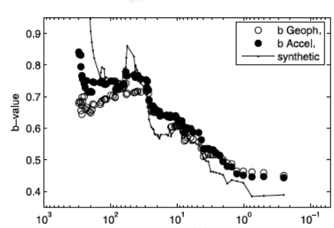
Subduction zone



Volcano



Coal mine



Landslide