Observational studies in South African mines to mitigate seismic risks: challenges & achievements

Ray Durrheim
University of the Witwatersrand, South Africa

Mining-related earthquakes

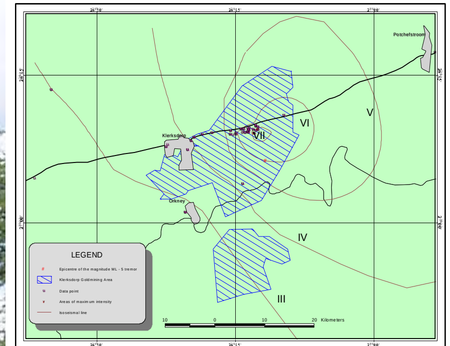
M=5.2
Welkom,

8 December 1976

Photograph: The Star

Mining-related earthquakes

Photograph: RJ Durrheim



Photograph: RJ Durrheim

M=5.3, Stilfontein, 9 March 2005

The event and aftershocks caused serious damage to several buildings, and minor injuries to 58 people.

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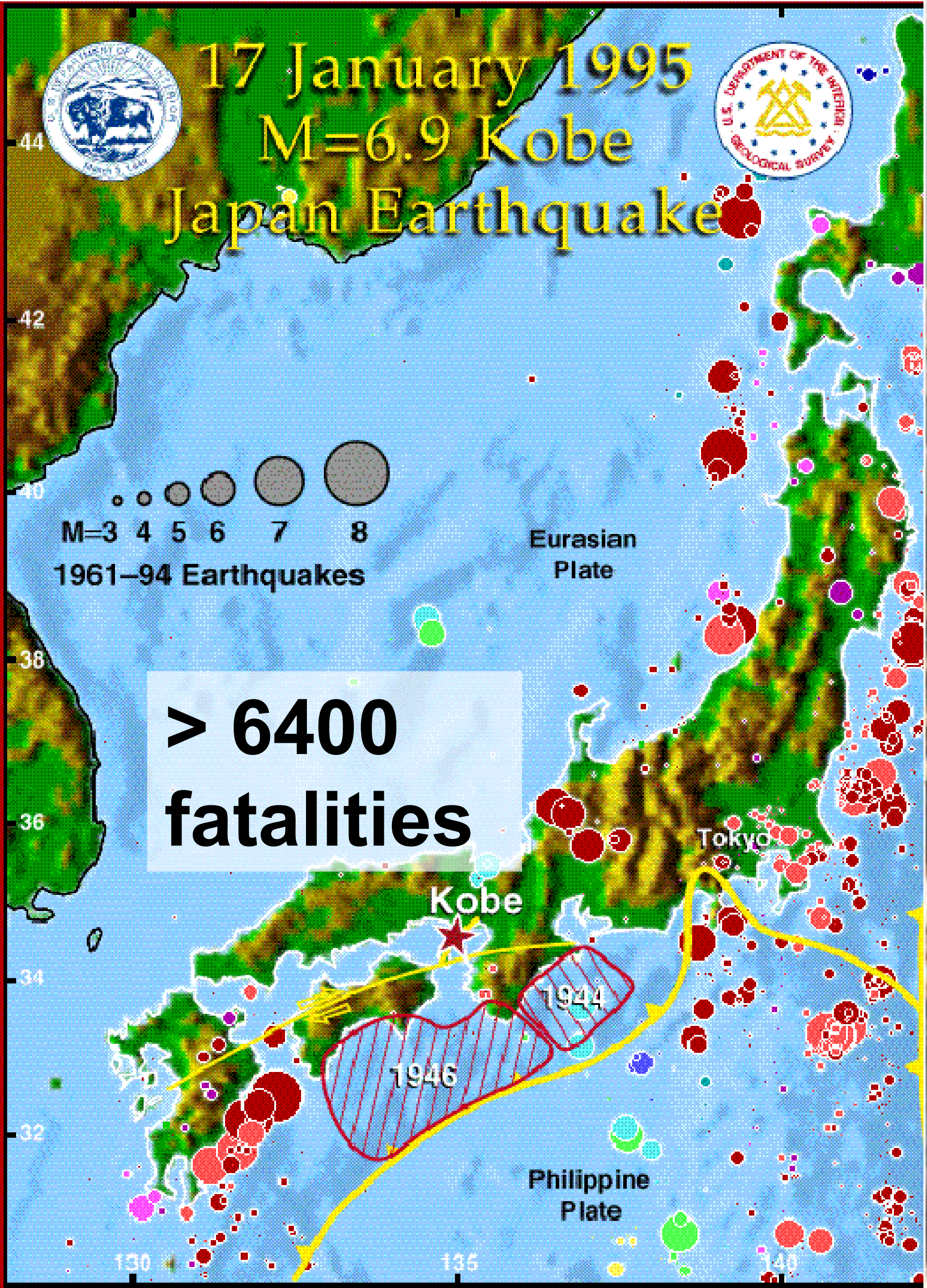
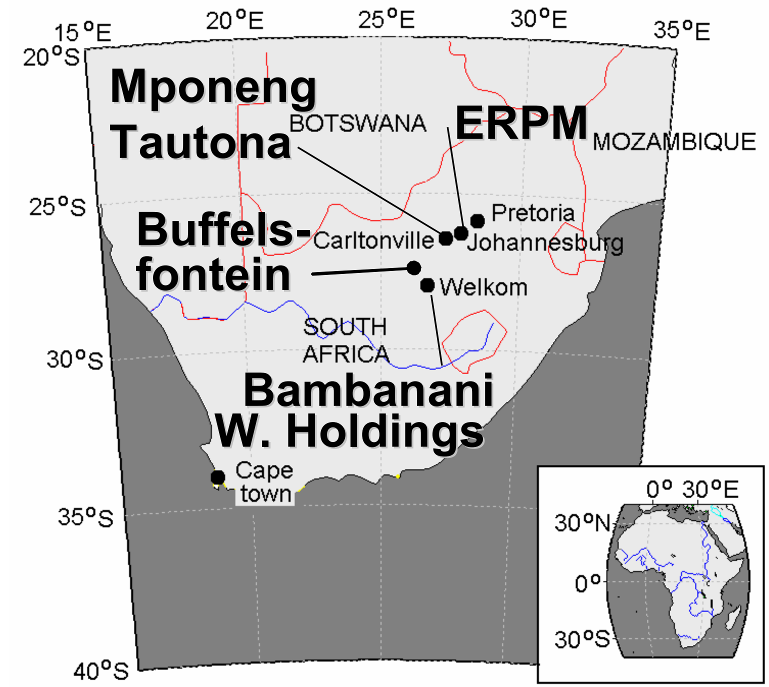
Damage to dwellings in Khumo caused by Orkney M_L5.5 earthquake, 5 August 2014

Failure of cantilever wall


17 January 1995
M=6.9 Kobe
Japan Earthquake
M=3 4 5 6 7 8
1961–94 Earthquakes
Eurasian Plate
> 6400 fatalities
Kobe
Tokyo
1944
1946
Philippine Plate
44
42
40
38
36
34
32
130
135
140

SeeSA 1995-2009



1995 **W. Holdings**

1996 **WDL <100m,** 9 accel.

1997

1998 **Bambanani**

1999 A single strainmeter < ~10m from an M2 fault

2000

2001

2002 **Mponeng** Proximal two strainmeters < ~10 m from fault gouge

2003 Tau Tona

2004

2005

2006 **Flooded mines**

2007

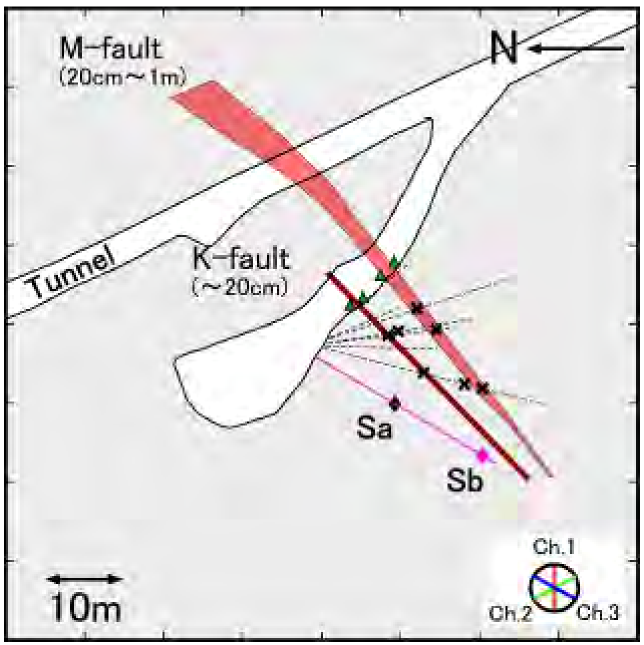
2008 Near a dyke, AE, on-fault accelerometers and proximal two strainmeters

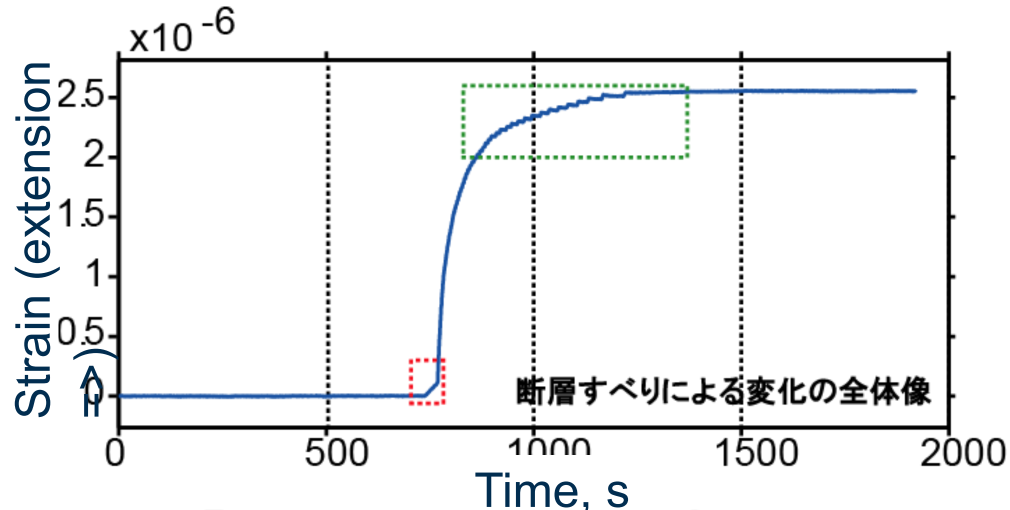
SeeSA 1995-present

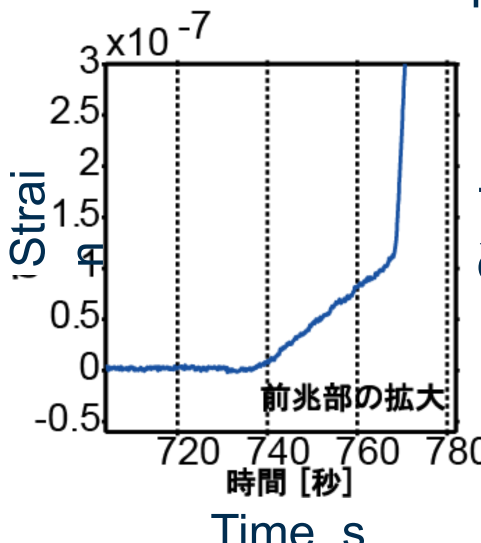
Clear forerunner found prior to a M-1 slow event

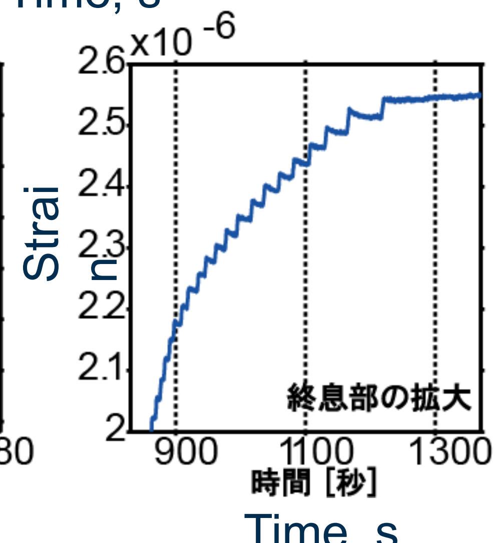
Mponeng mine at a 2.9km depth

(2003-2005)







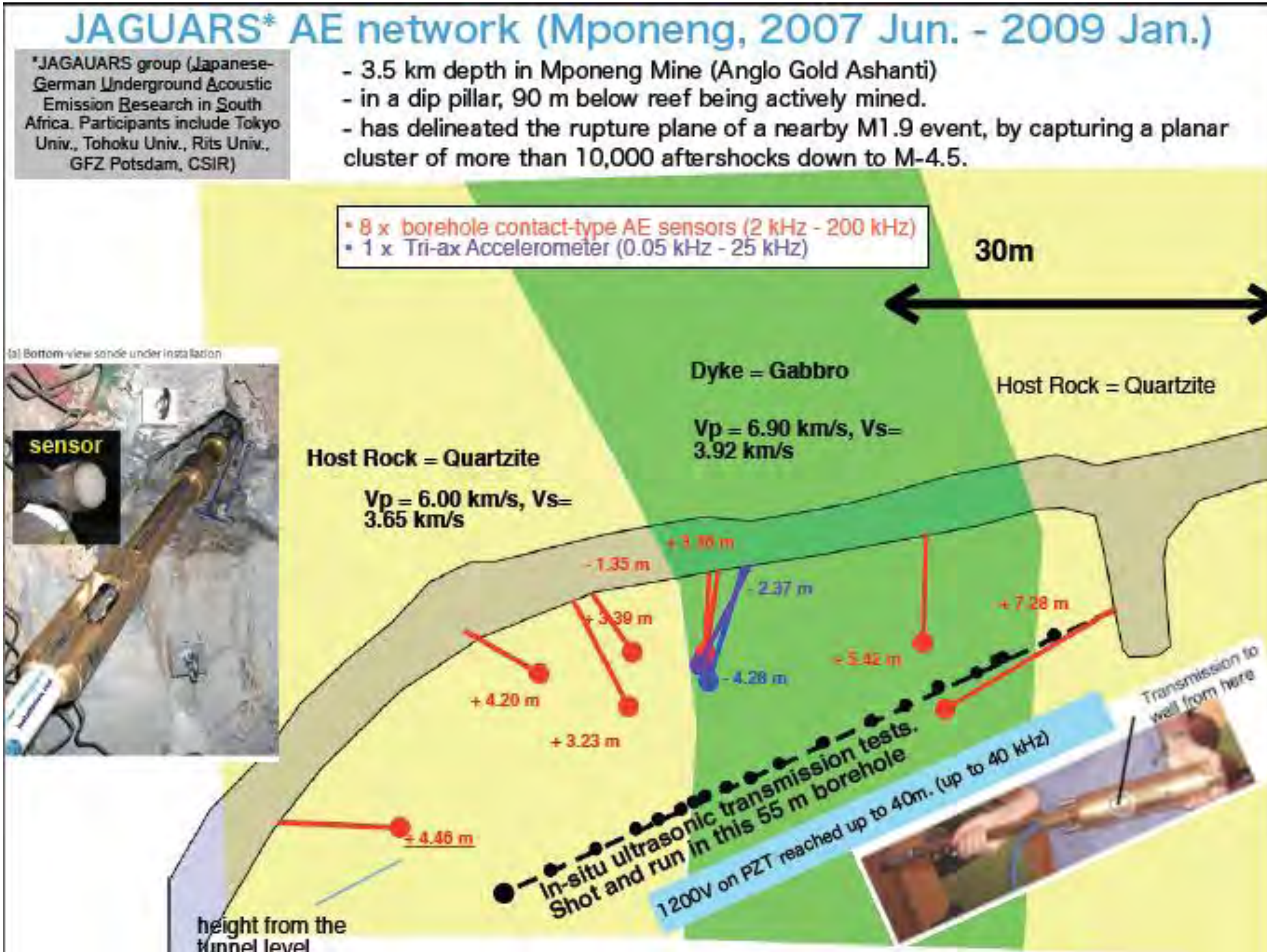


Ishii sensitive strainmeter x 2

Within several meters from fault gauge

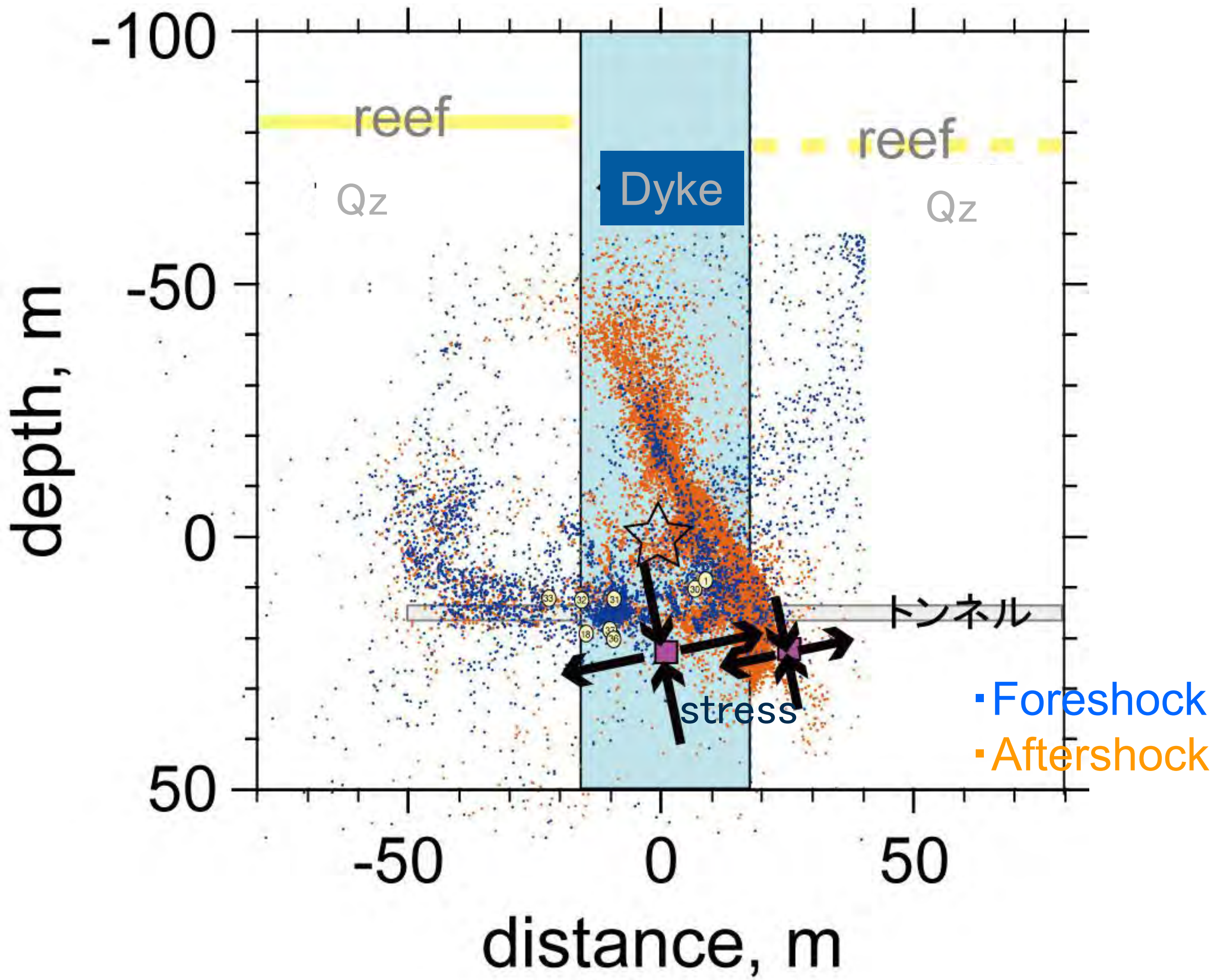
JAGUARS collaboration

(Japanese-German Underground Acoustic emission Research in South africa)



SeeSA 1995-present

Foreshock AEs delineated M1.9 mainshock fault



Strain monitoring

Stress change in dyke
= 1.5 x stress change
in host rock.

AE monitoring
>1,000 foreshocks
for 3 months showed
mainshock fault.

CSIR
our future through science

Project launch: August 2010

OBJECTIVES

1. To learn more about earthquake preparation and triggering mechanisms.
2. To learn more about earthquake rupture and rockburst damage phenomena.
3. To upgrade the South African national seismic network.
4. To develop human, technical and infrastructural capacity in South Africa.

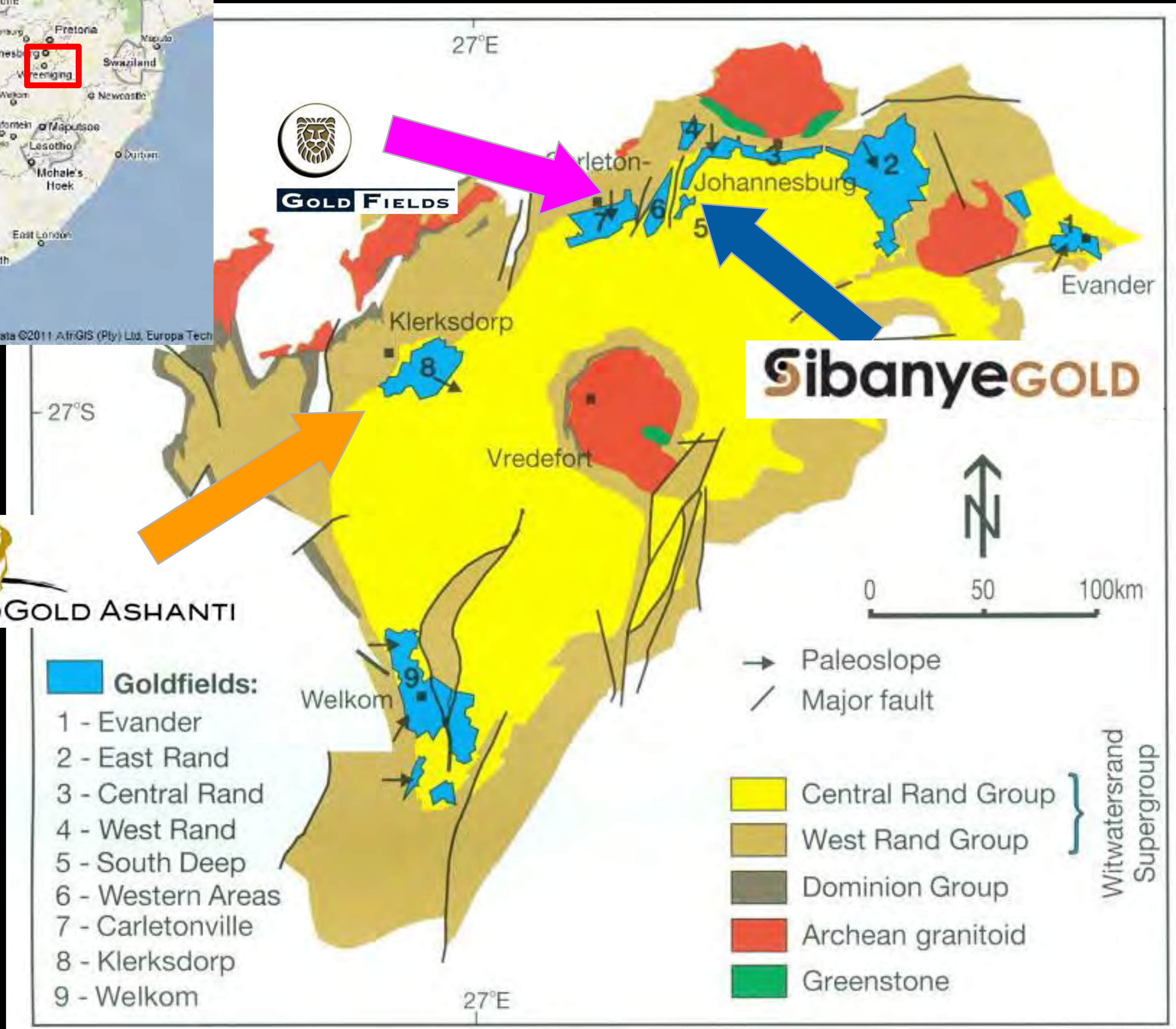
Project team

11 March 2013 SATREPS seminar at West Wits Conference Centre sponsored by JICA. About 80 people from JICA, JST, Japanese research organizations, from CSIR, CGS, and Wits. Univ. and from Anglogold Ashanti, Gold One, Sibanye Gold, Ground Work, IMS, OHMS, SRK, Seismogen and others joined.

TASKS

1. Investigation of the rock mass and target faults
2. High-sensitivity studies of the earthquake preparation zone
3. Hazard assessment
4. Strong motion studies
5. Upgrading of the South African National Seismograph Network (SANSN)


Botswana
Mmadinare
Mahalapye
Gaborone
Pretoria
Johannesburg
Vereeniging
Swaziland
Welkom
Newcastle
Bloemfontein
Maputsoe
Lesotho
Durban
South Africa
Mohale's Hoek
East London
Port Elizabeth
Cape Town
©2011 Google - Map data ©2011 AfriGIS (Pty) Ltd, Europa Tech

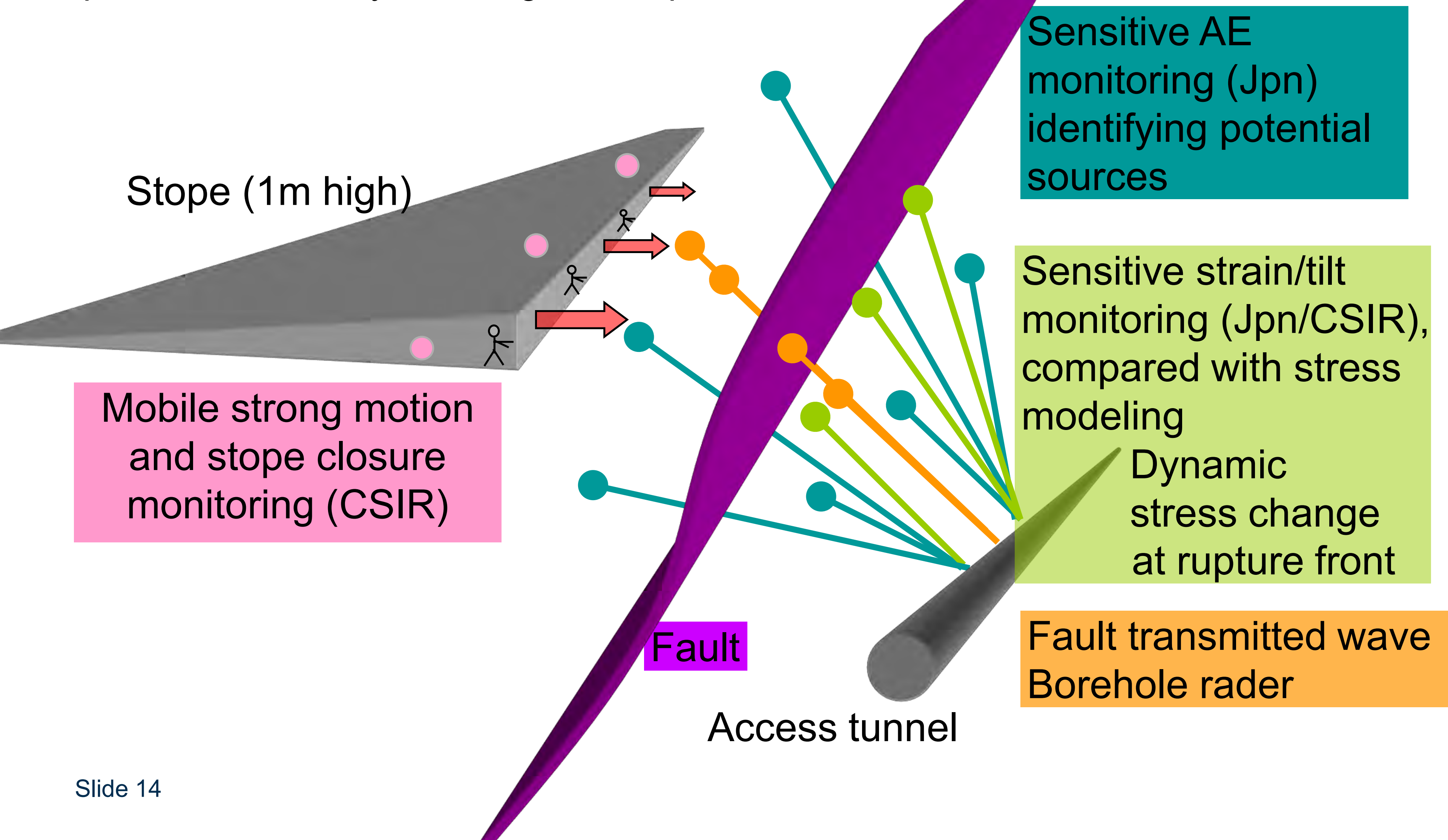

GOLD FIELDS
SibanyeGOLD
ANGLOGOLD ASHANTI
27°E
27°S
Carleton-
Johannesburg
Evander
Klerksdorp
Vredefort
Welkom
1
2
3
4
5
6
7
8
9
0
50
100km
N
Goldfields:
1 - Evander
2 - East Rand
3 - Central Rand
4 - West Rand
5 - South Deep
6 - Western Areas
7 - Carletonville
8 - Klerksdorp
9 - Welkom
Paleoslope
Major fault
Central Rand Group
West Rand Group
Dominion Group
Archean granitoid
Greenstone
Witwatersrand Supergroup

Research plan

Multidisciplinary proximate sensitive sensor array + assessment

Better understanding of earthquake preparation & generation

Improve the accuracy of strong motion prediction

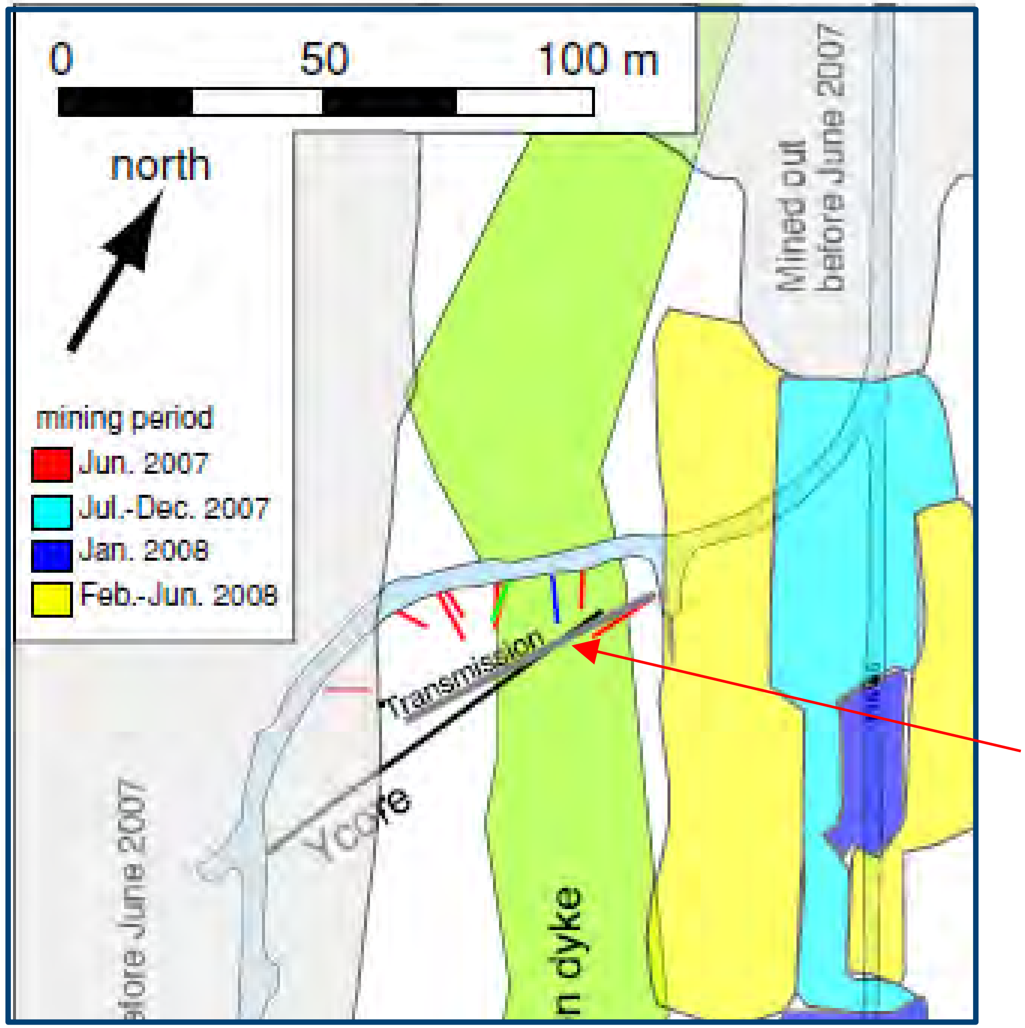


Output 1: Mapping of face, faults, fractures and support

Output 1: In situ observations

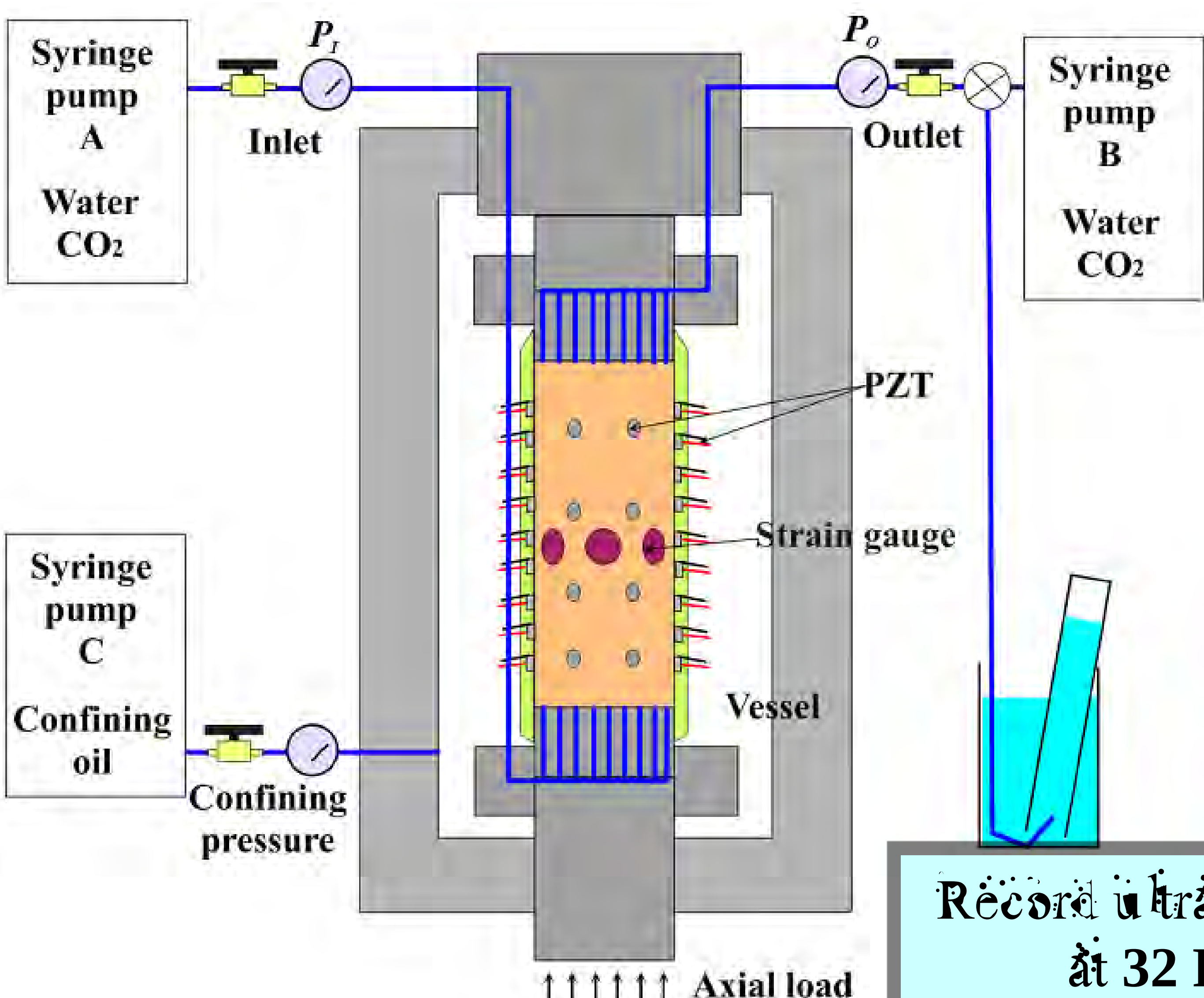
Output 1: In situ observations & lab experiments

Drilled core samples



Gabbro

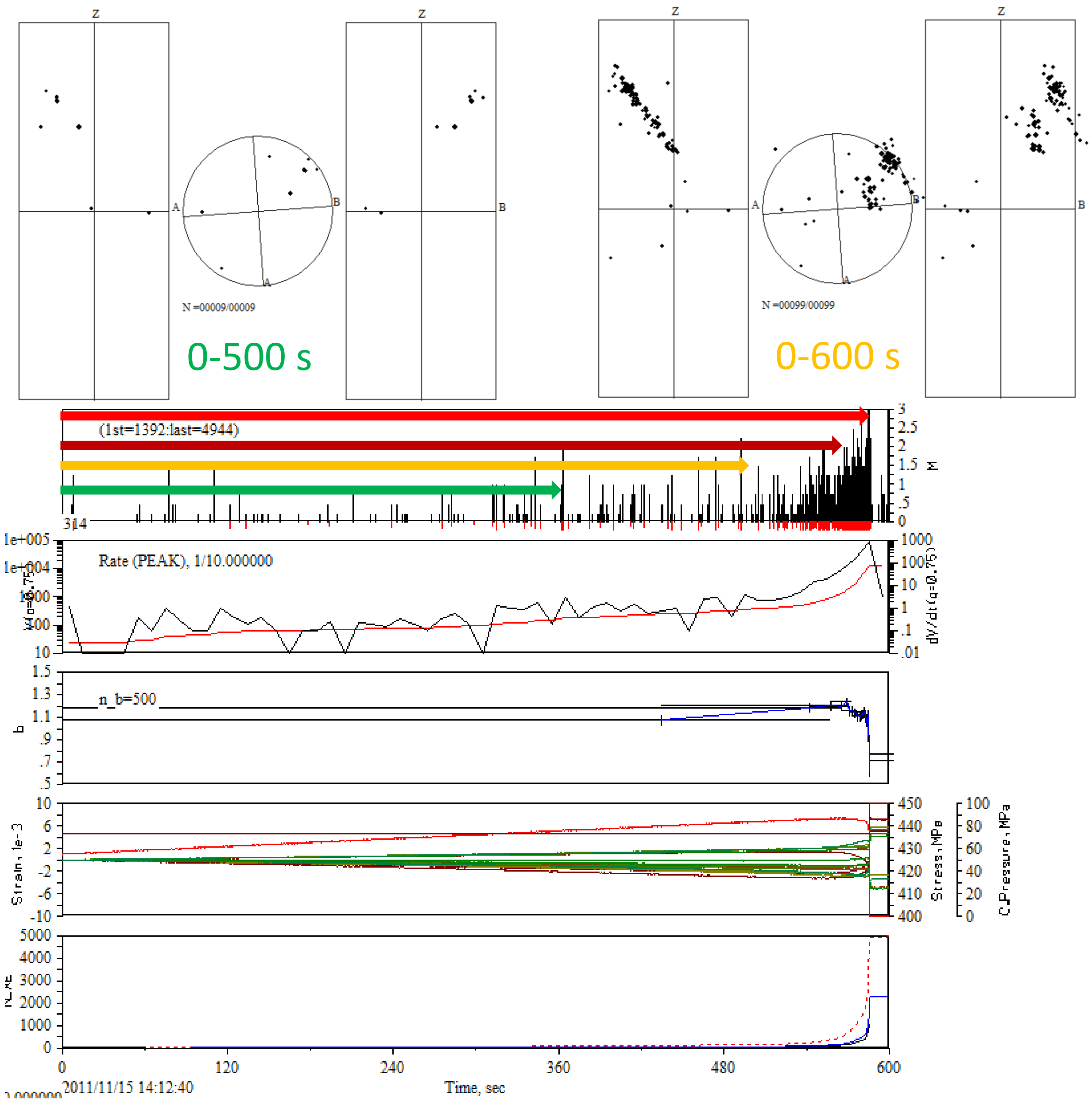
Experimental setup



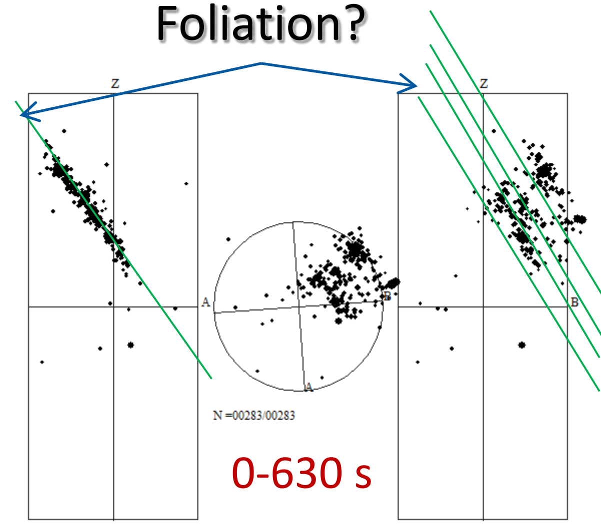
Record ultrasonic waveforms at 32 PZT sensors with 100MHz, 16bit A/D.

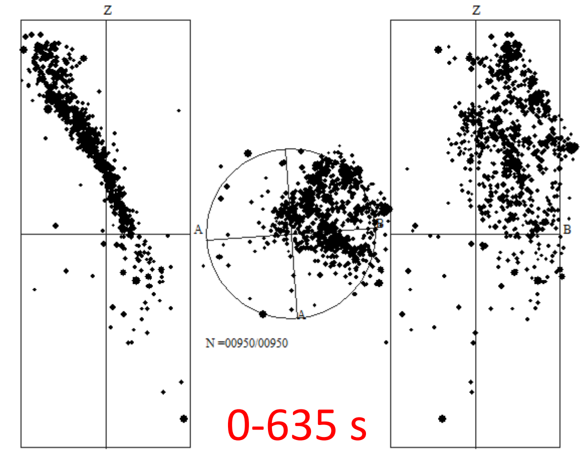
Pc 75MPa; ~1 μstrain/s

Fault nucleation



Foliation?

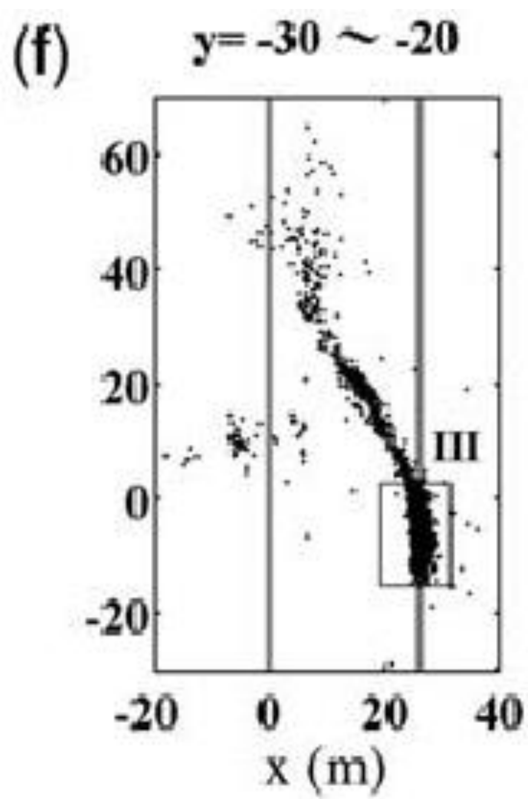




Nucleation dimension:
2x5 cm

M_L1.9

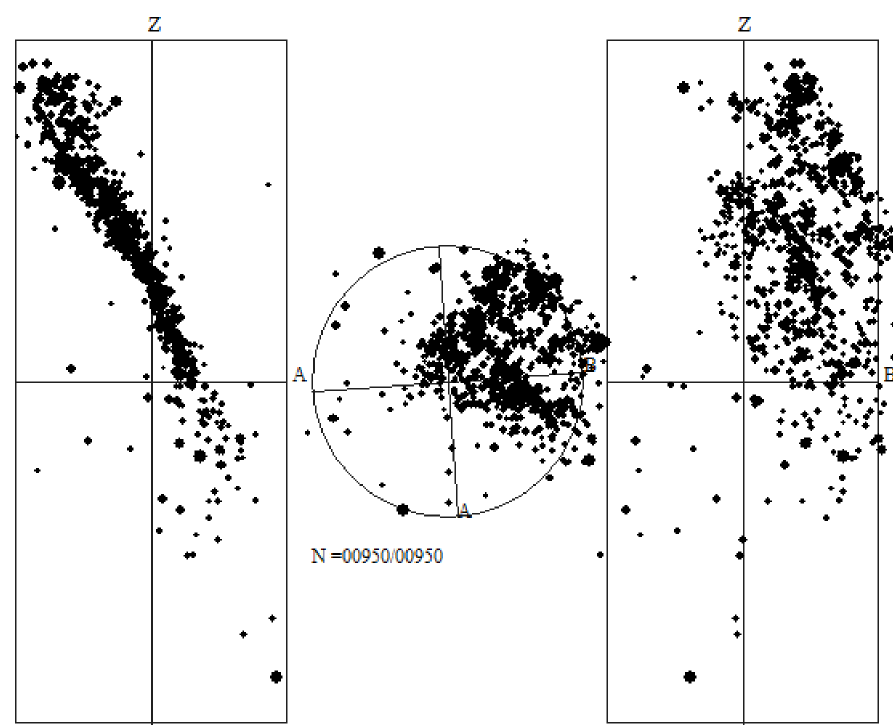
- Loading rate: ~1 μstrain/day
- Found:
  - nucleation (several tens of m)
  - no increase in AE rate just prior to the mainshock
  - strength 160MPa at 75MPa Pc(?) (Hofmann et al. 2012)



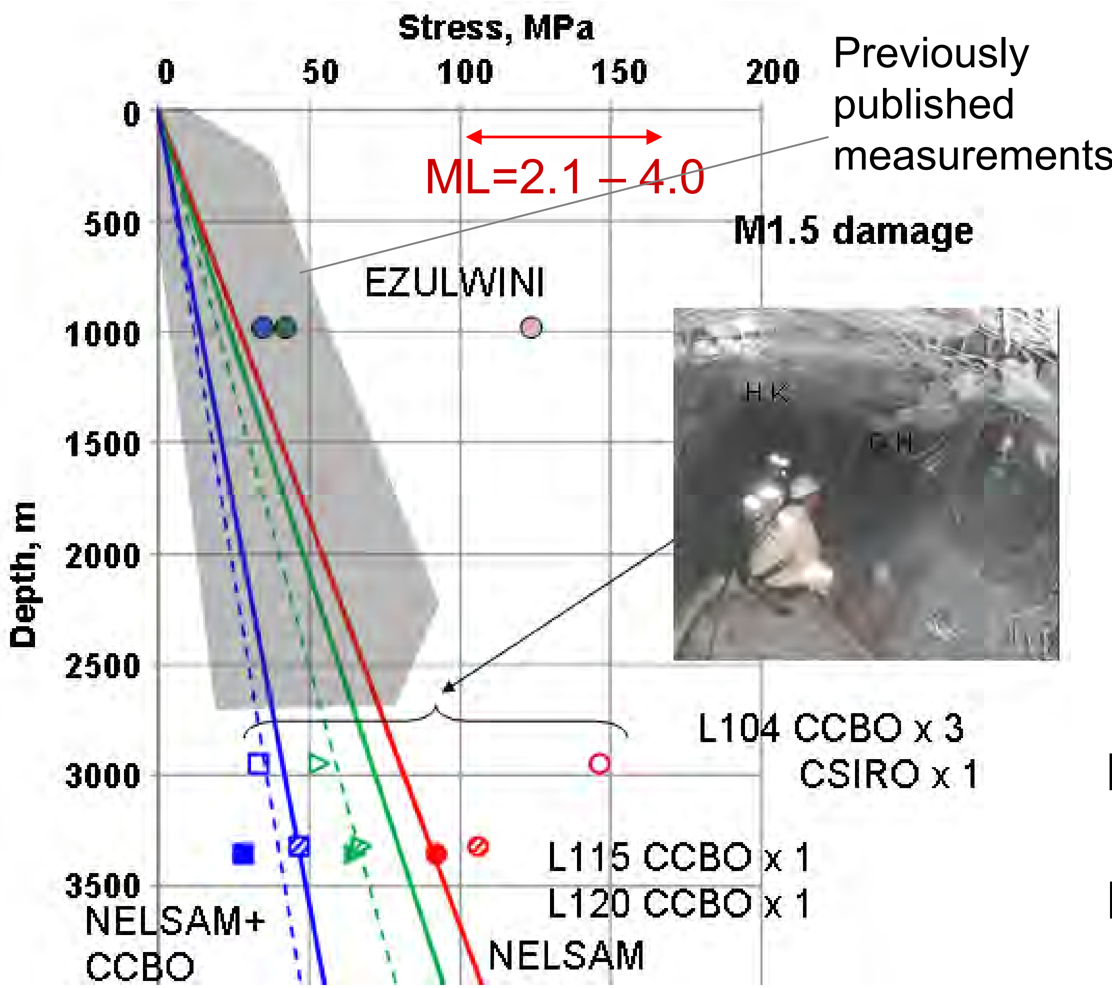
Naoi et al. (2011)

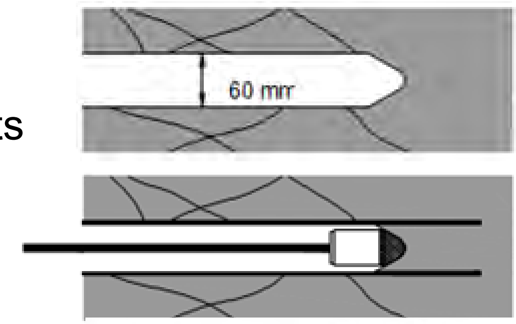
Satoh's laboratory experiment

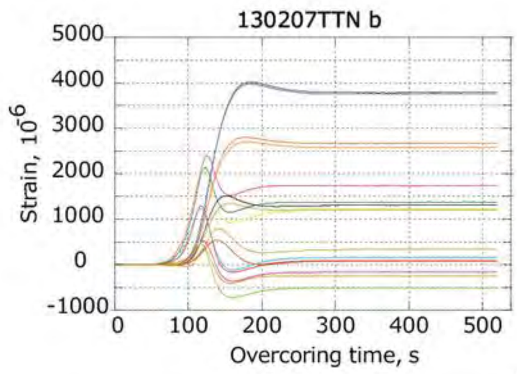
- Loading rate: ~1 μstrain/s
- Found:
  - almost linear stress-strain relationship
  - nucleation (2 x 5 cm)
  - increase in AE rate prior to the failure only
  - strength: ~600MPa at 75MPa CP



Output 1: Compact conical-ended borehole overcoring technique



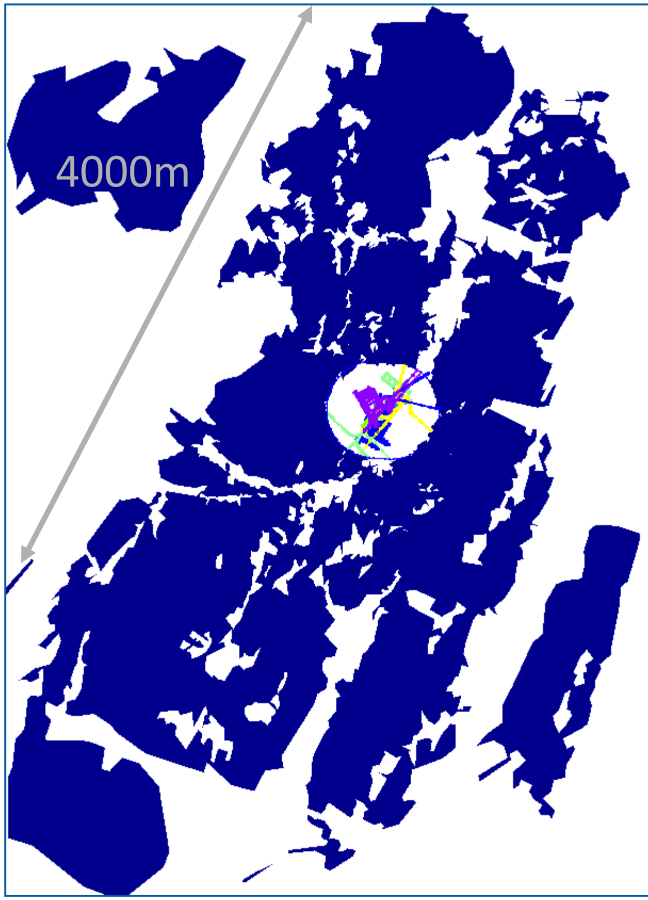


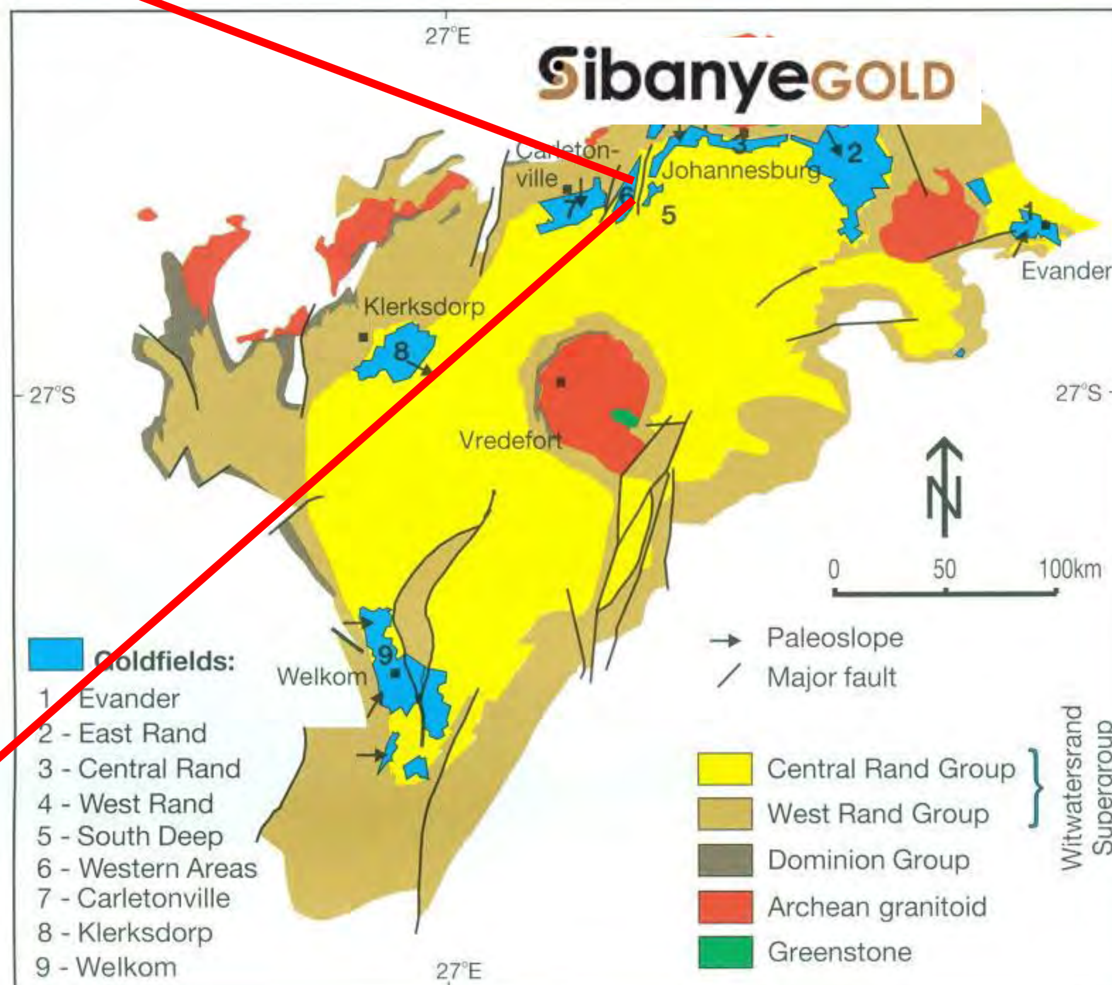


Much easier and faster than CSIRO HI or CSIR triaxial.

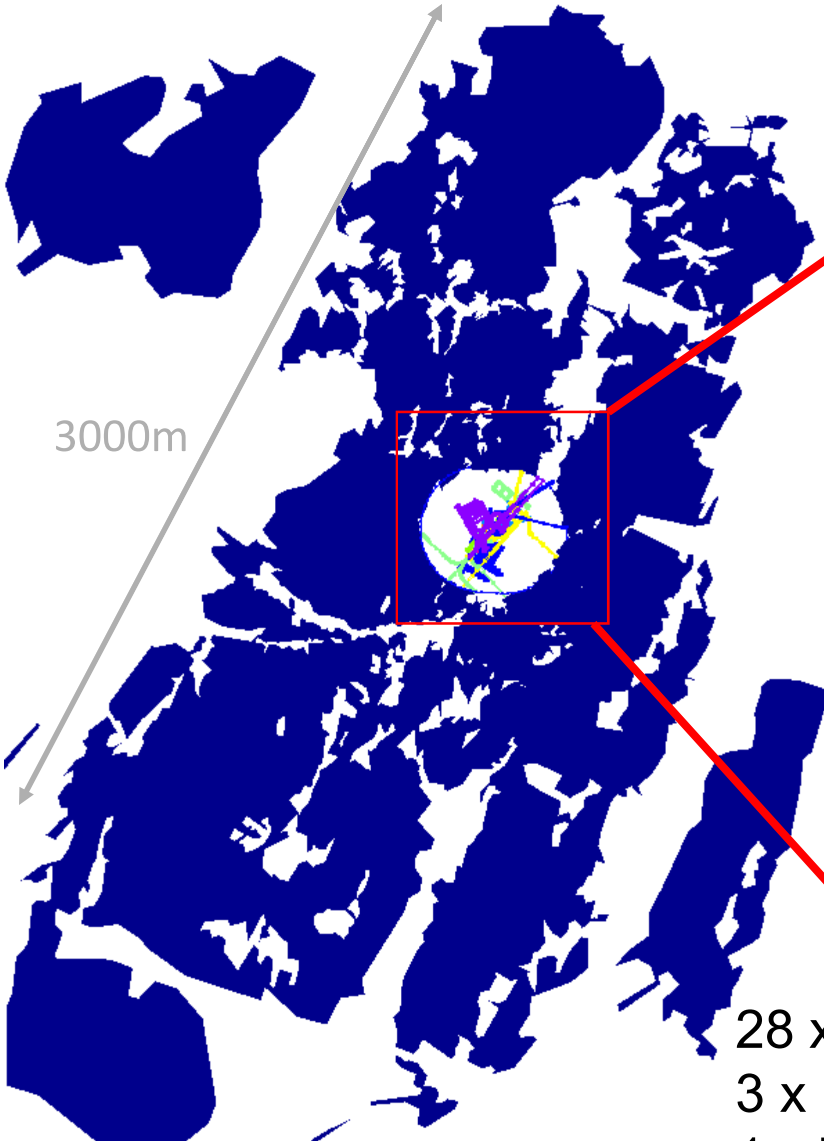
In a standard procedure 3 overcorings are carried out with an interval of about 20cm.

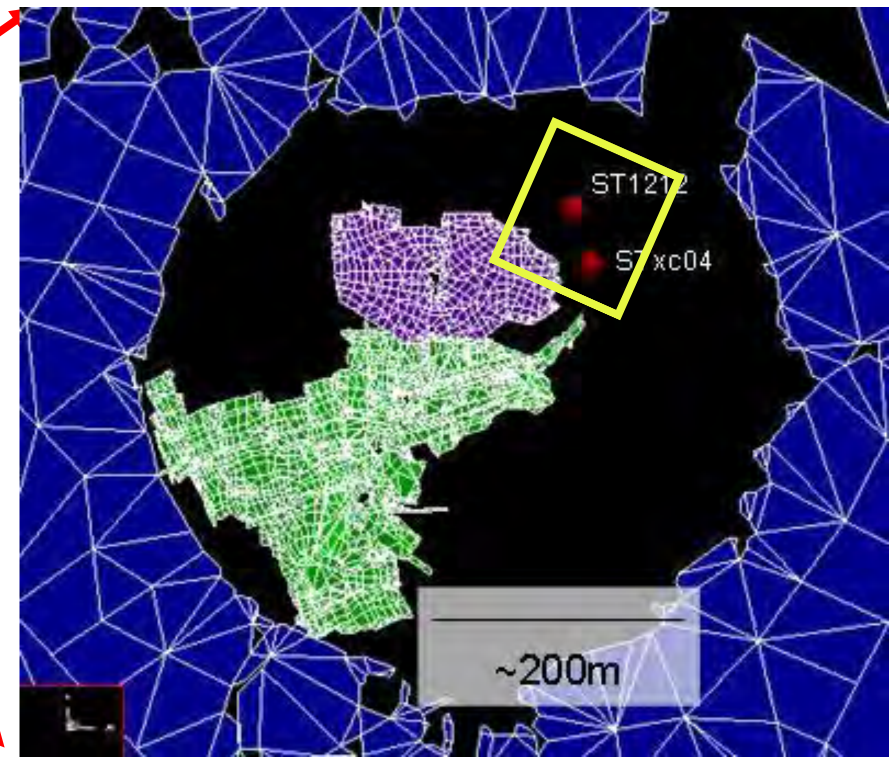
Output 2: Preparation and forerunners of earthquakes





Cooke #4





28 x AE sensors (~100m extent; 3D)
3 x 10kHz & 3 x 25kHz tri-ax accelerometers
1 x Transmission line
4 x Strong motion and fault slip sensors
2 x Strainmeters

Output 2: Preparation and forerunners of earthquakes

Because time evolution can be tracked in AE data, the forthcoming AE research will allow us to describe, in detail, the time evolution of fracturing and stress due to mining.

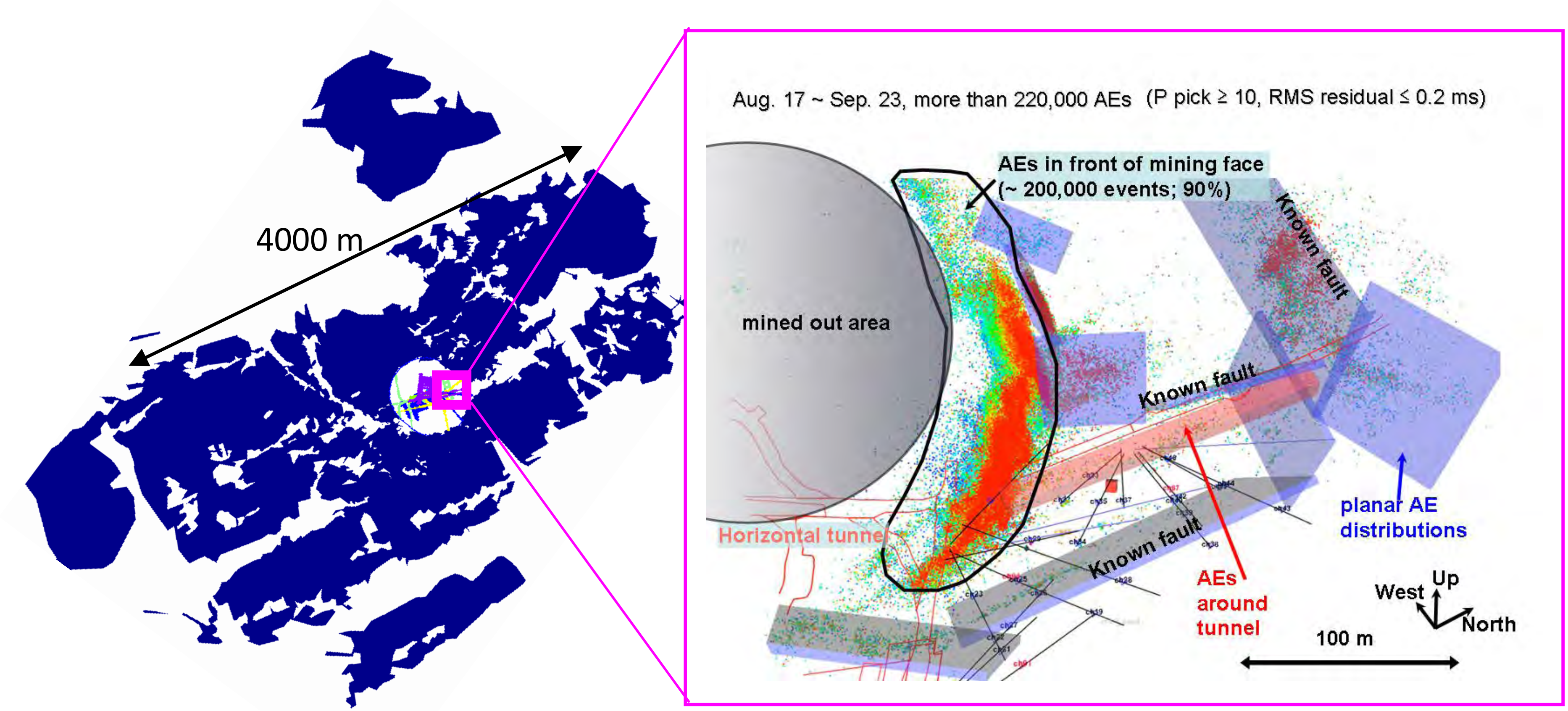
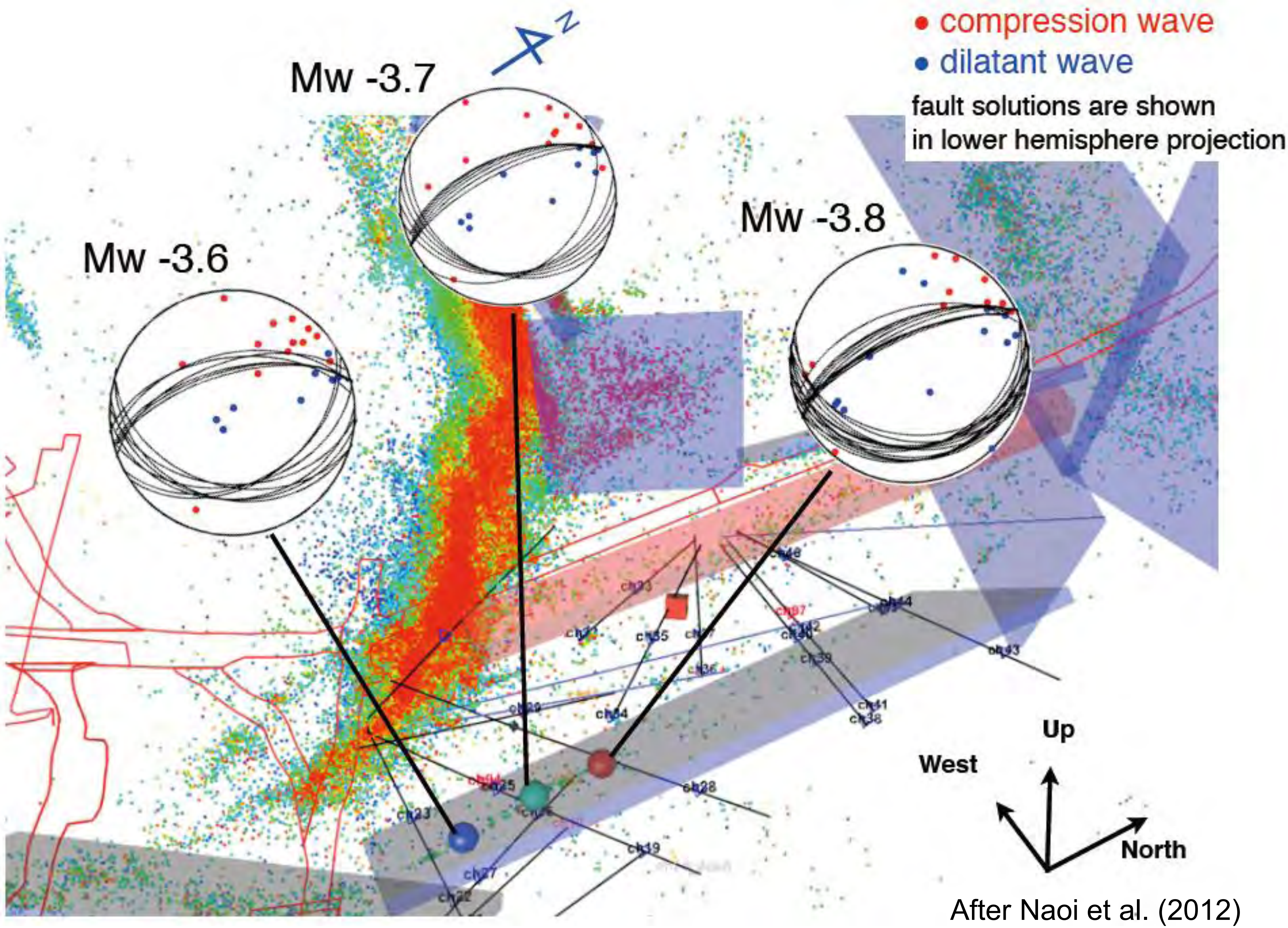
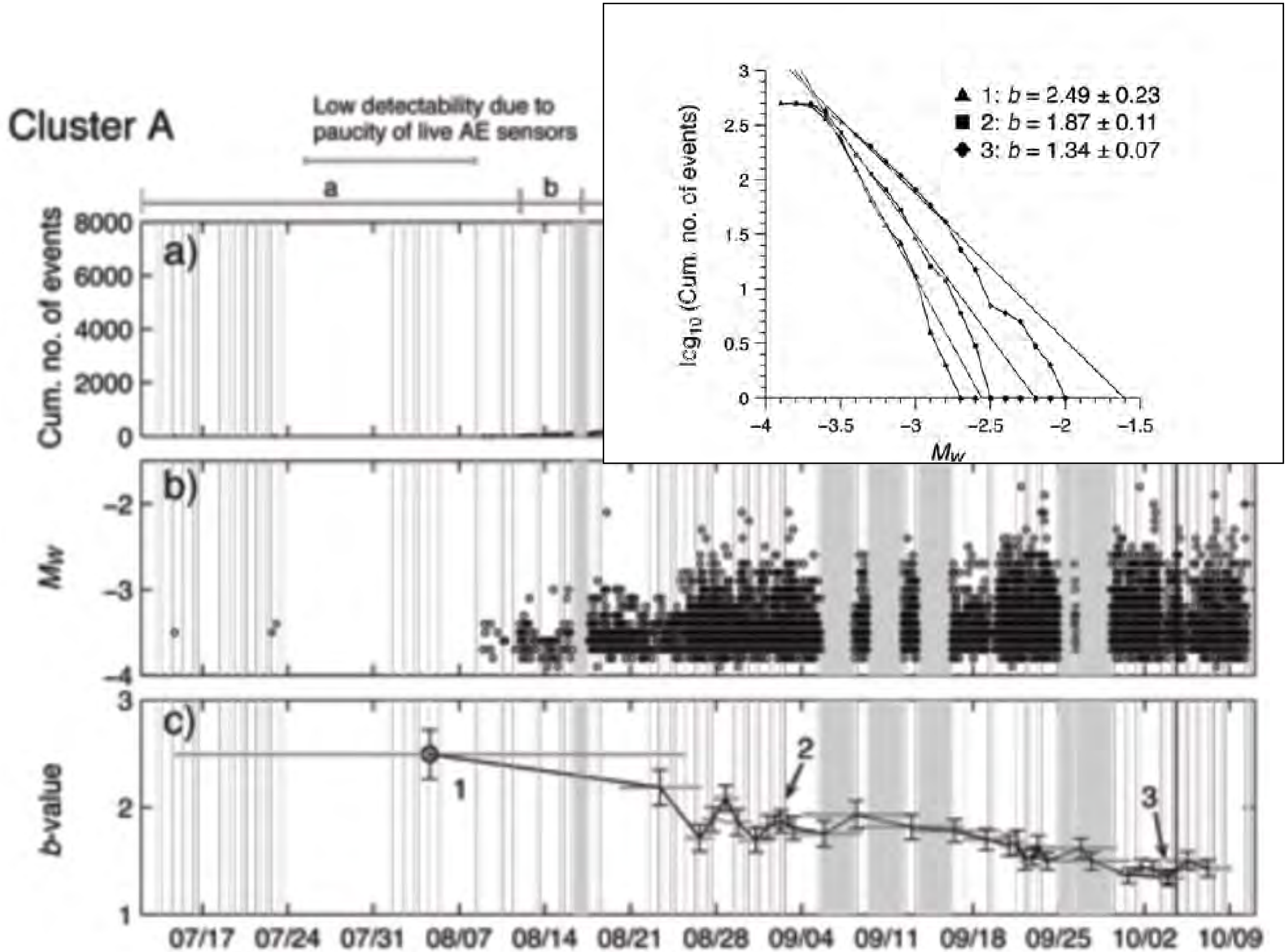


Figure 7 Left: the shaft pillar (white circular area in the middle) currently being mined, is at about 1.0 km depth from surface, surrounded by old stopes not back-filled. The network location of Nakatani (2013) is



After Naoi et al. (2012)

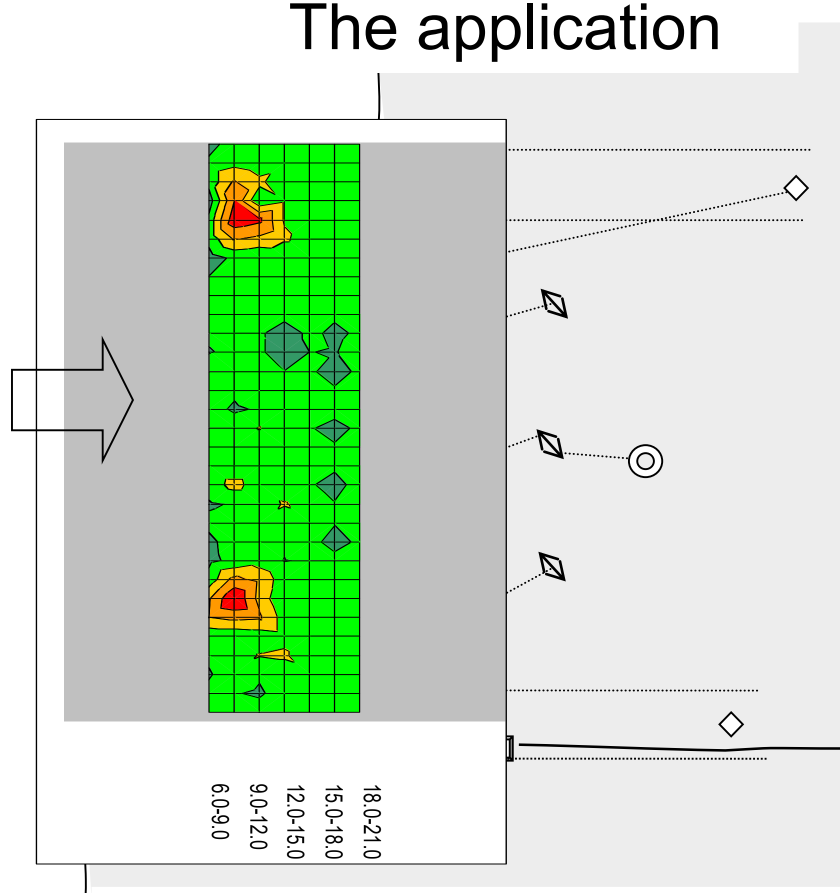


Cluster A
Low detectability due to paucity of live AE sensors
a
b
a)
Cum. no. of events
8000
6000
4000
2000
0
b)
M_W
−2
−3
−4
c)
b-value
3
2
1
1
2
3
07/17
07/24
07/31
08/07
08/14
08/21
08/28
09/04
09/11
09/18
09/25
10/02
10/09
$\log_{10}$ (Cum. no. of events)
▲ 1: $b = 2.49 \pm 0.23$
■ 2: $b = 1.87 \pm 0.11$
◆ 3: $b = 1.34 \pm 0.07$
M_W
−4
−3.5
−3
−2.5
−2
−1.5

Output 3: Assessment of hazard

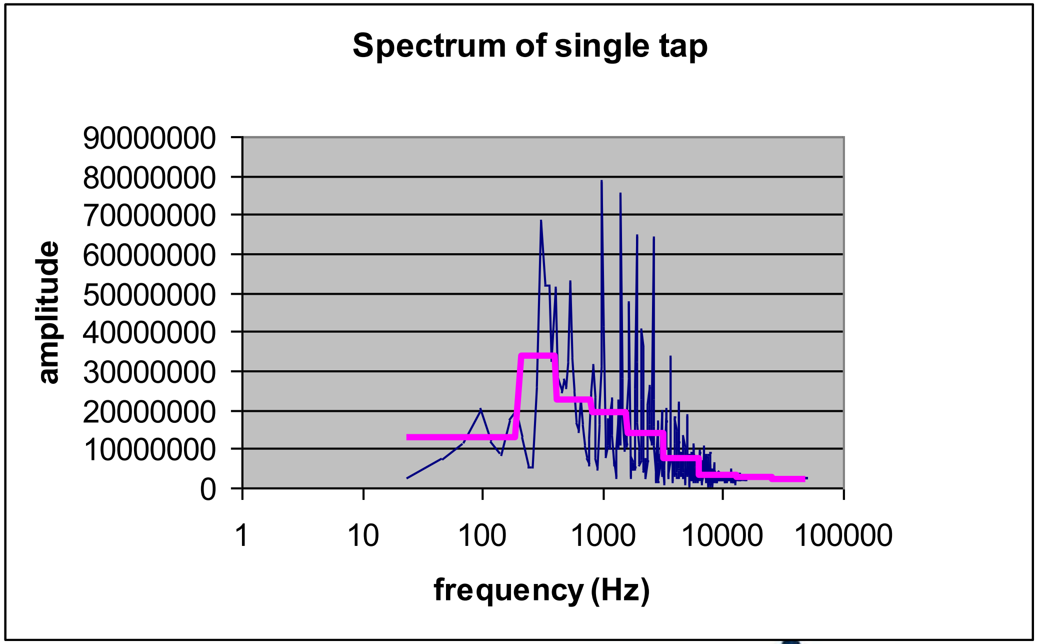
The concept

The application



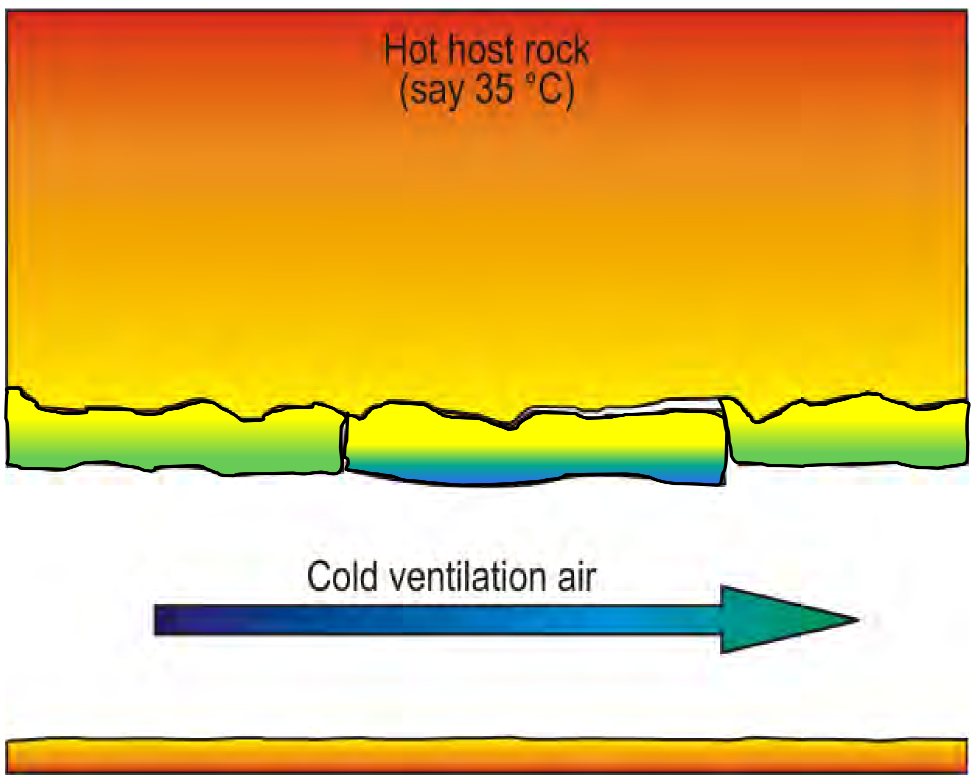
Appropriate Sensing Devices – Acoustic sounding

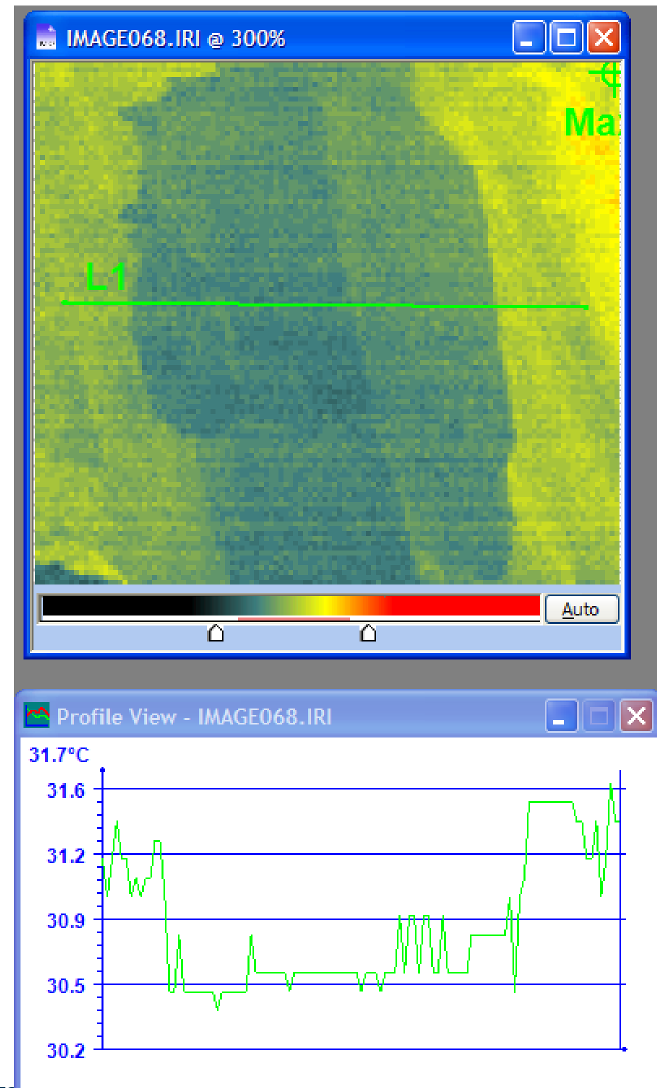
Monitors stability of hangingwall through neural network-based interpretation of the conventional 'sounding'.



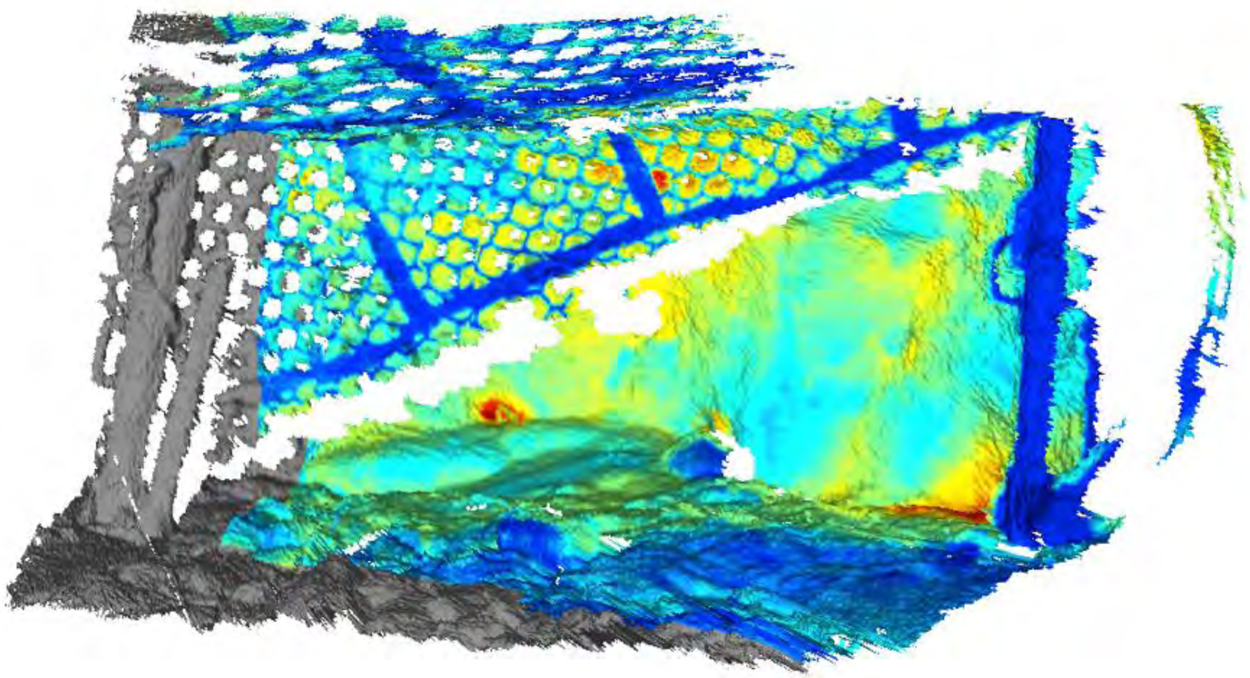
our future through science

Appropriate Sensing Devices – *Thermal imaging*



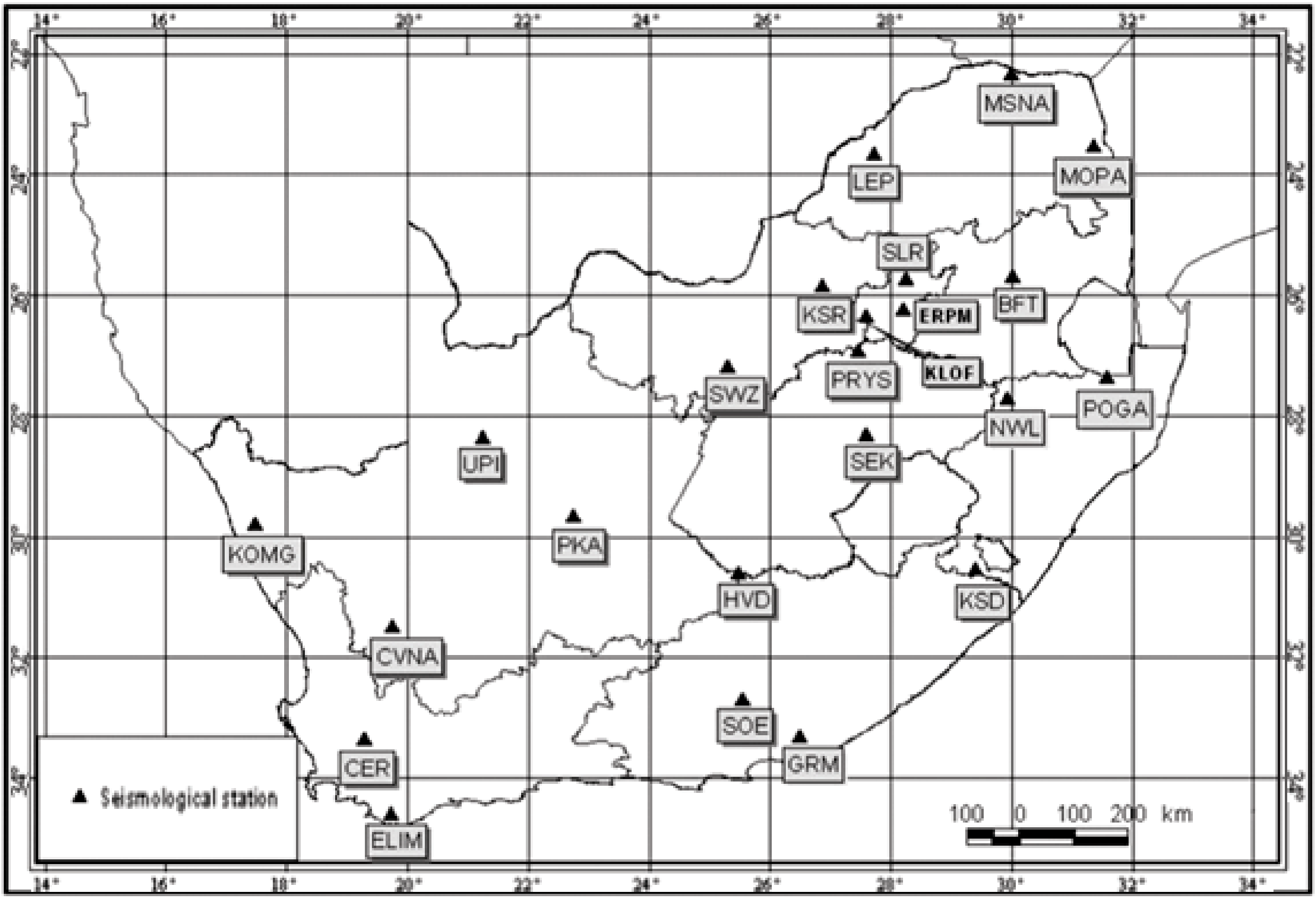


Stope mapping



- Good results from all
- Kinnect is ideal:
    - Fast
    - Cheap

Output 5: Expand national seismograph network



Before 2010 CGS had 23 stations in South Africa, only a few of which were in mining districts.

Surface stations

Figure 4 -1 Far West Rand districts (Carletonville area) with 10 JICA seismic stations (yellow) and two CGS stations (orange).

Outputs

1. Established of research sites in three deep mines
2. Mapped the face, faults, fractures and support elements
3. Logged 70 boreholes and cores (totalling 2.8 km)
4. Measured rock properties in the lab
5. Developed / adapted technologies to:
   - Measure stress,
   - Monitor closure and strong ground motion,
   - Assess the integrity of the hangwall by remote electronic sounding and thermal imaging,
   - Locate seismic events
6. Studies of
   - Precursors
   - Scaling (G-R linear from $-4<M_w<2$)
   - Minimum nucleation size
7. Expanded national seismograph network

DSEIS

icdp INTERNATIONAL CONTINENTAL SCIENTIFIC DRILLING PROGRAM

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Drilling into Seismogenic Zones of M2.0–M5.5 earthquakes in deep South African gold mines

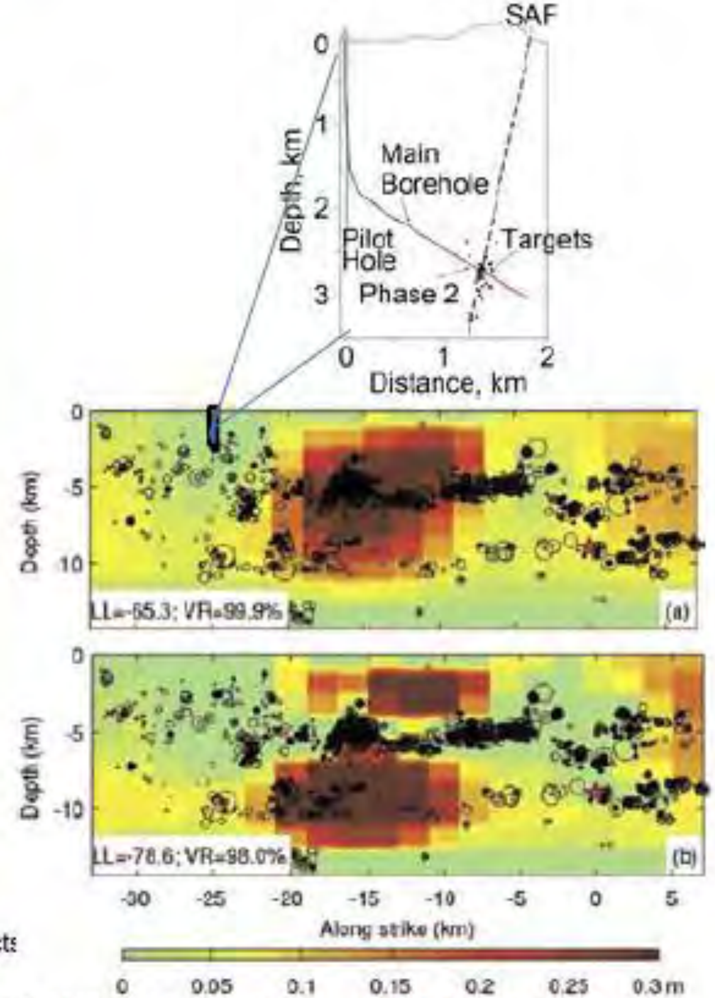
H. Ogasawara[1], R. J. Durrheim[2], Y. Yabe[3], T. Ito[3], G. van Aswegen[4], M. Grobbelaar[5], A. Funato[6], A Ishida[1], H. Ogasawara Jnr[1], S. Mngadi[2], M.S.D. Manzi[2], M. Ziegler[7], A.K. Ward[8], G. Hofmann[9], P. Moyer[10], M. Boettcher[10], P. Dight[11], W. Ellsworth[12], B. Liebenberg[13], N. Wechsler[14], T. Onstott[15], N. Berset[7] and the DSeis Team

1. Ritsumeikan University, Japan 2. University of the Witwatersrand, South Africa 3. Tohoku University, Japan 4. Institute of Mine Seismology Ltd, South Africa 5. Council for Geoscience, South Africa 6. Fukada Geology Institute, Japan 7. ETH, Switzerland 8. Seismogen CC, South Africa 9. Anglogold Ashanti, South Africa 10. University of New Hampshire, USA 11. University of Western Australia 12. Stanford University, USA 13 Independent consultant, South Africa 14. Tel Aviv University, Israel 15. Princeton University, USA

JST JICA SATREPS Science and Technology Research Partnership for Sustainable Development Program 科研費 TOHOKU UNIVERSITY ANGLOGOLD ASHANTI Sibanye IMS CSIR TEL AVIV UNIVERSITY ETH zürich GFZ

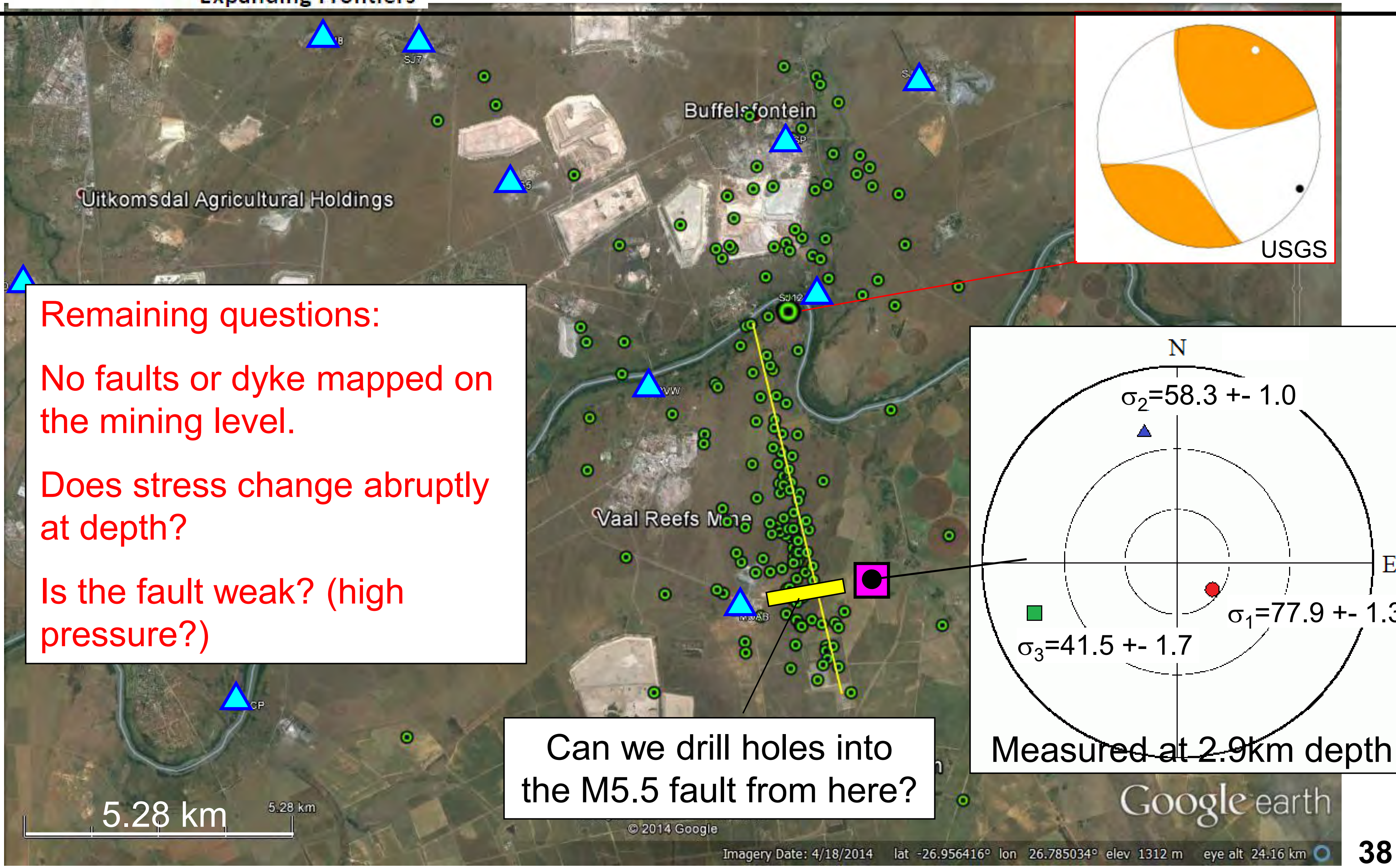
http://www.icdp-online.org/projects naturalhazards/faults/

SAFOD



2004 M6 Parkfield. (a) conventional, (b) anti-aftershock-correlation. (Wang et al. 2012 doi:10.1029/2011JB009017)

Orkney M_L5.5 earthquake, 5 August 2014



Remaining questions:

No faults or dyke mapped on the mining level.

Does stress change abruptly at depth?

Is the fault weak? (high pressure?)

Can we drill holes into the M5.5 fault from here?

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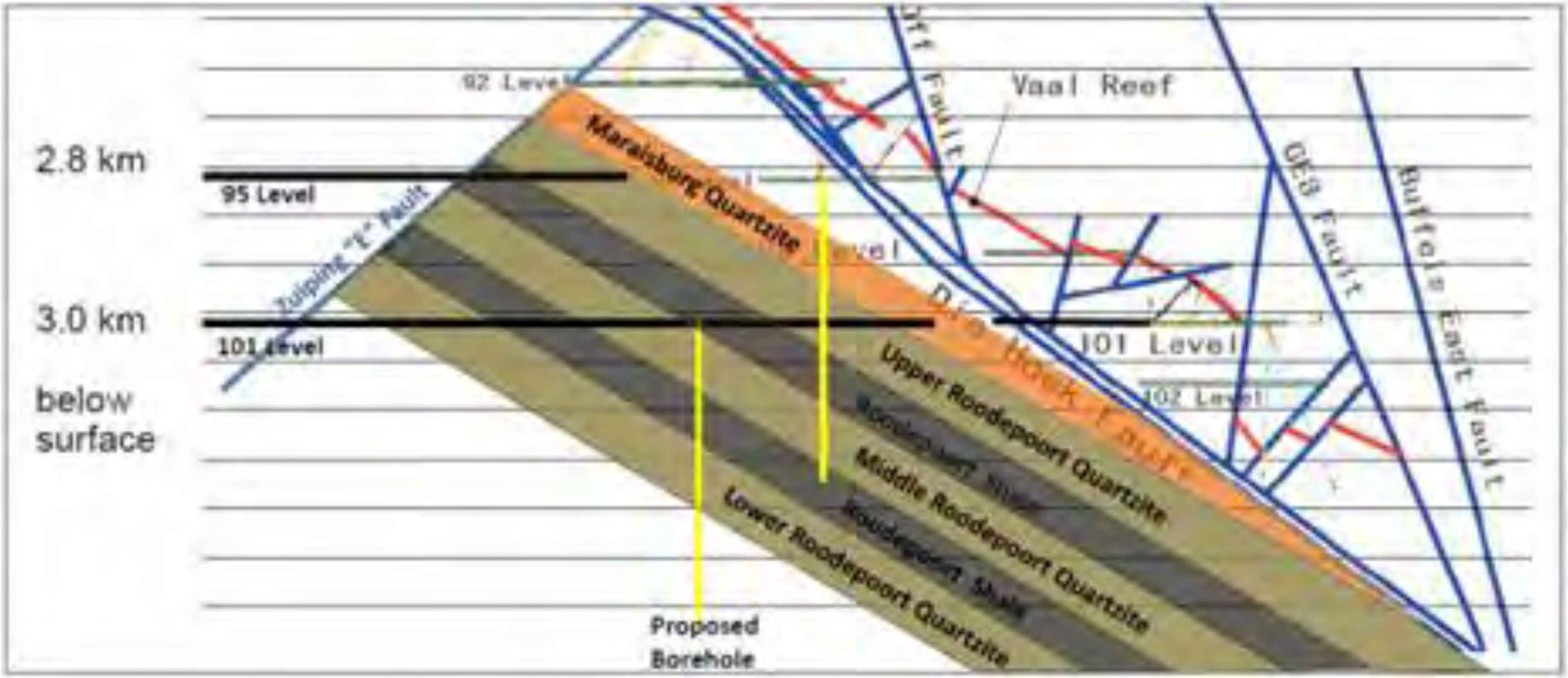
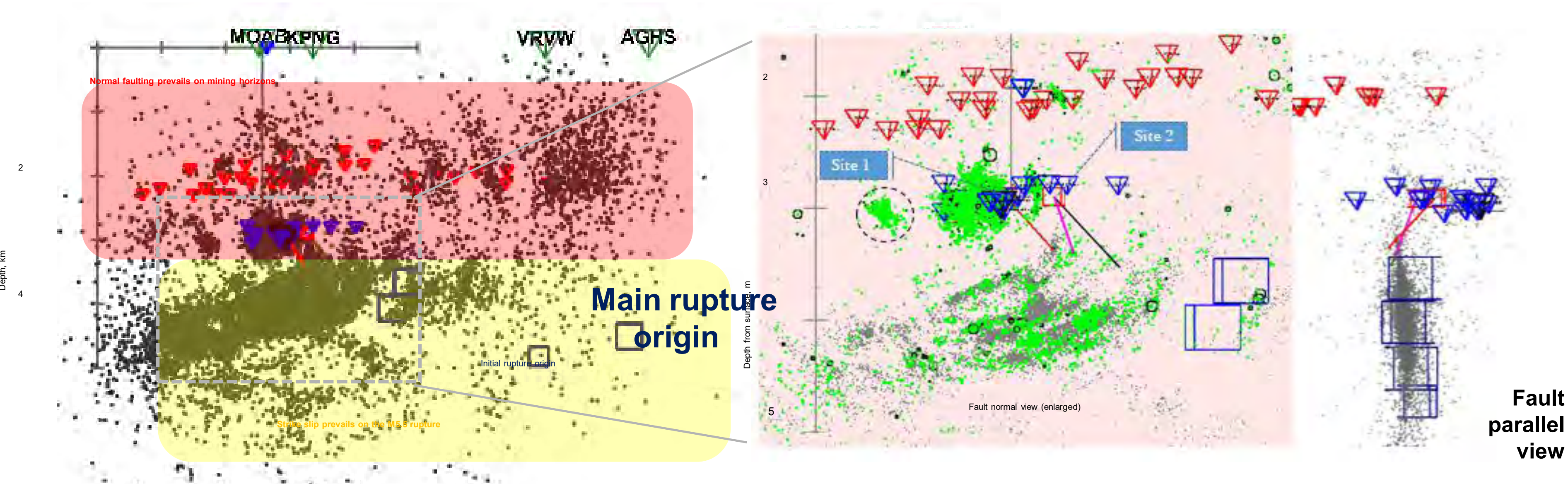


Legend

Witwatersrand Super Group	West Rand	Jeppes town	Maraisburg Formation	75m		Grey medium to coarse grained argillaceous protoquartzite.
			Roodepoort Formation	515m		Dark grey to blackish laminated shale's. (Soft)
						Light grey to grey siliceous to very siliceous orthoquartzite. Glassy look, x-bedded, brittle. (hard)

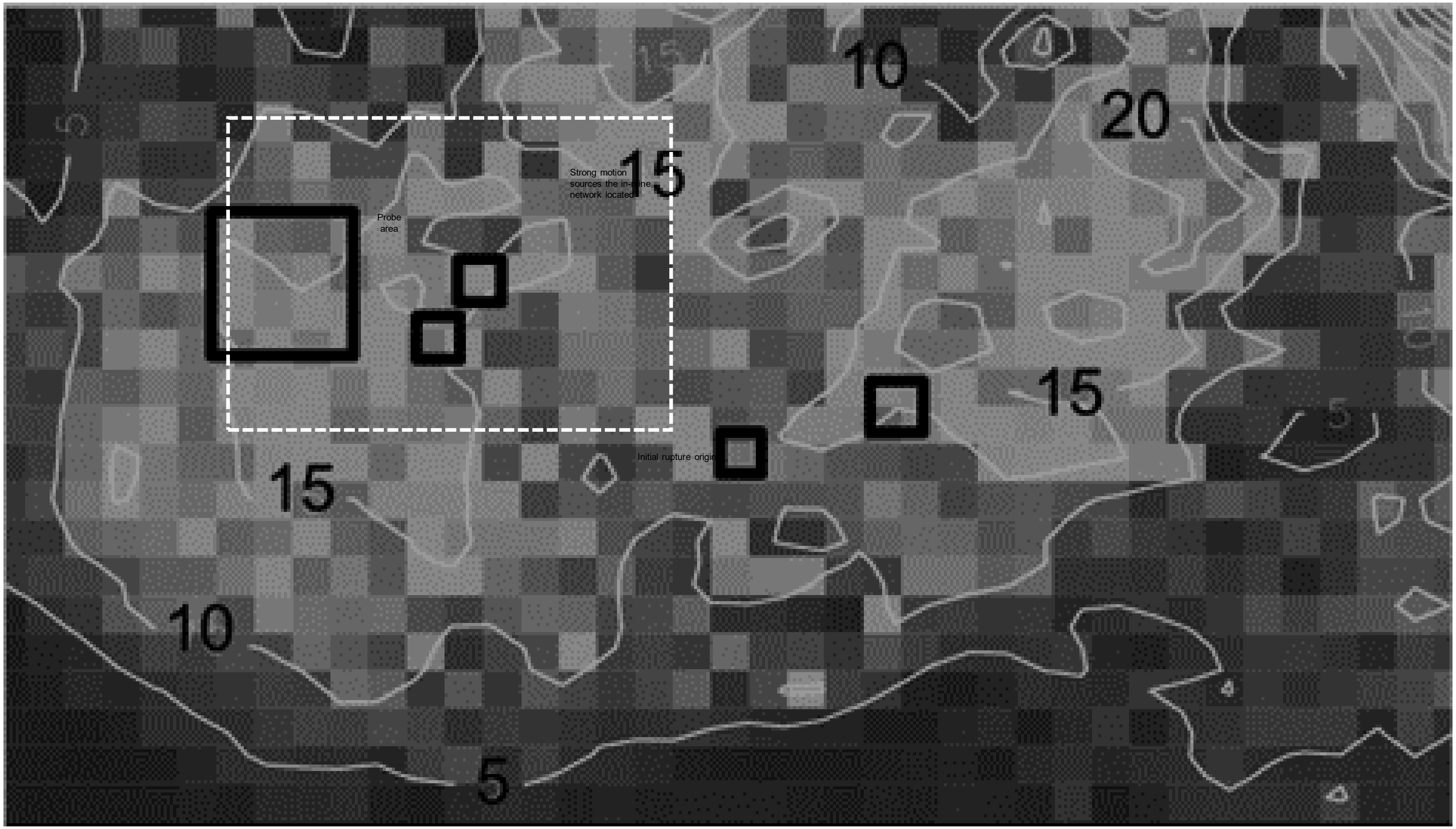
Mine 1: 2014 M5.5 rupture below the mining horizon



>30,000 aftershocks (In-mine catalog; Fault normal view)

Initial 1-month; latest 1-year; 1-month in July 2016.

Mine 1: 2014 M5.5 rupture below the mining horizon



Slip, cm inverted by Ellsworth (Fault normal view)

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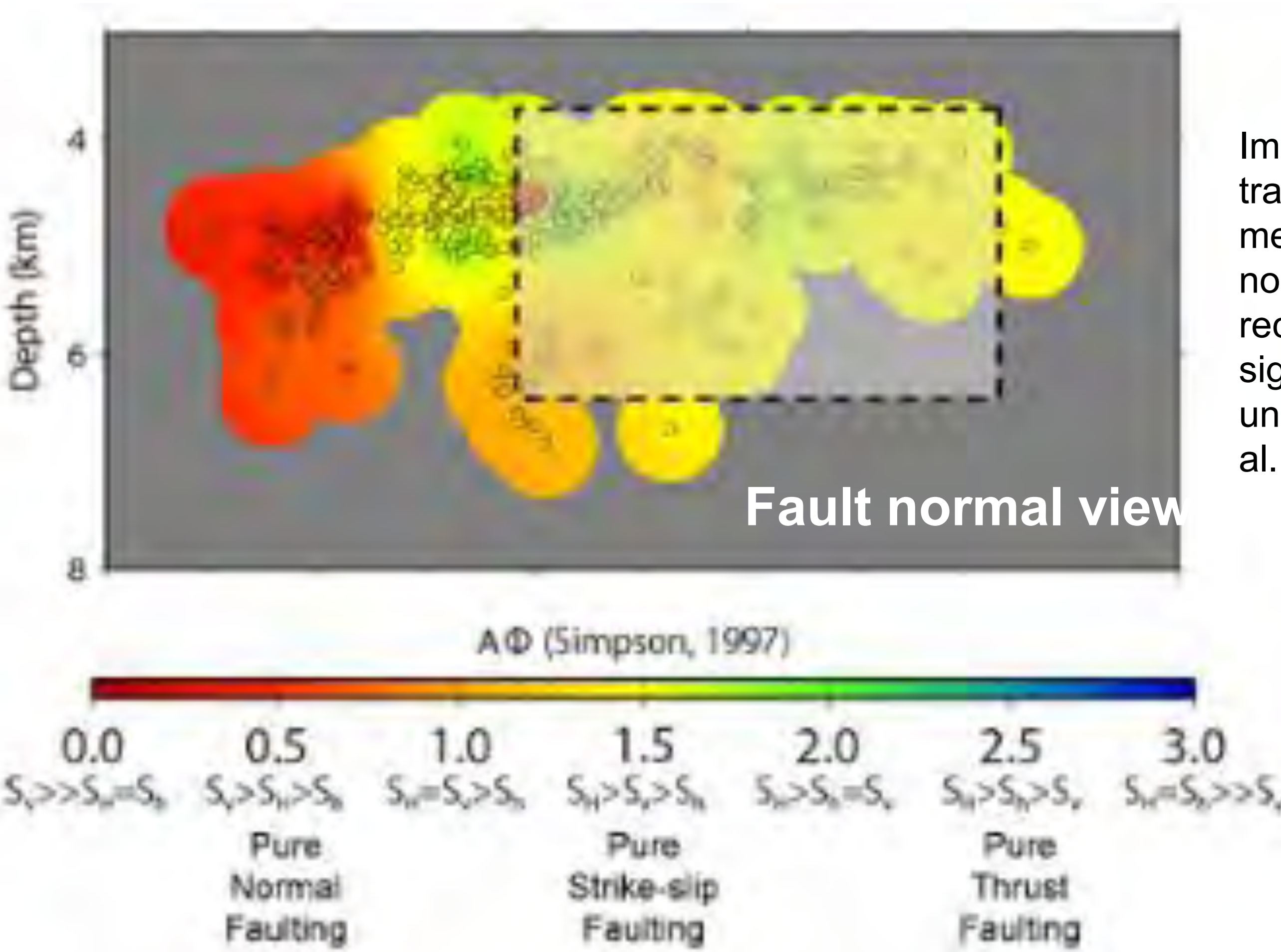


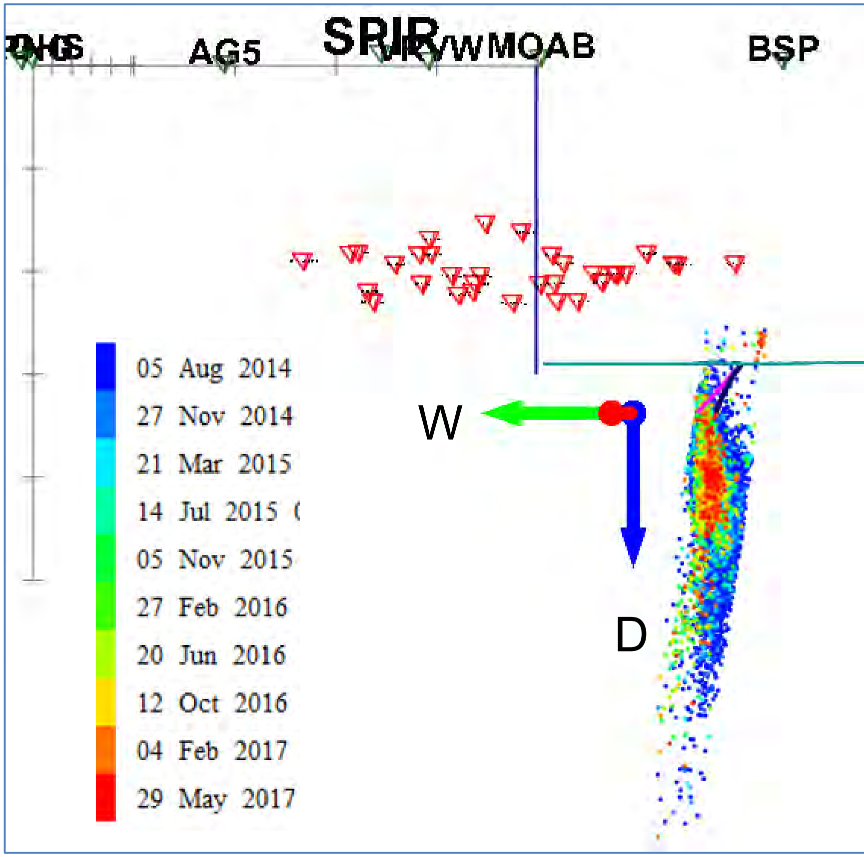
Imanishi et al (JpGU 2016) found a transition in aftershock faulting mechanisms from strike (yellow) to normal slip (orange). A dashed-line rectangle shows the region of significant slip constrained by underground strainmeters (Ishida et al. 2016 JpGU).

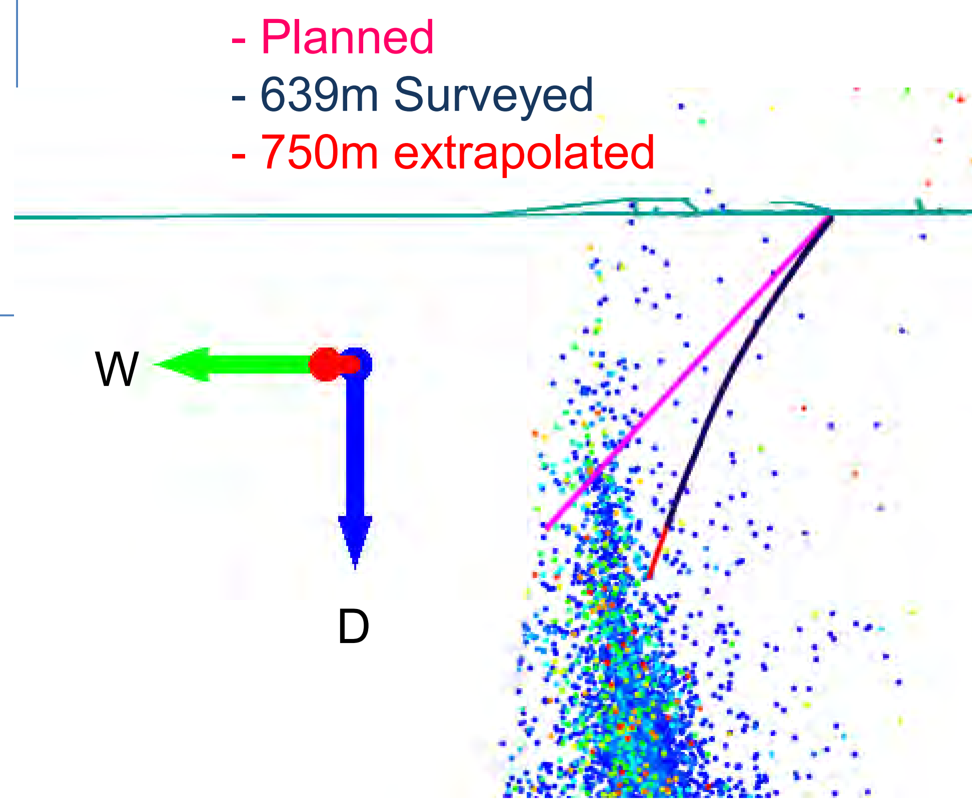
ϕ76mm 750m full-core drilling in line with σ_1 to intersect a M5.5 seismogenic zone. Probe geological, physical, hydrological properties. Recover cores with minimal damage to see stress variation along the hole. Compare those with the main- and after-shock data.

Photo of Site 1 by H. Ogasawara 5 May 2017

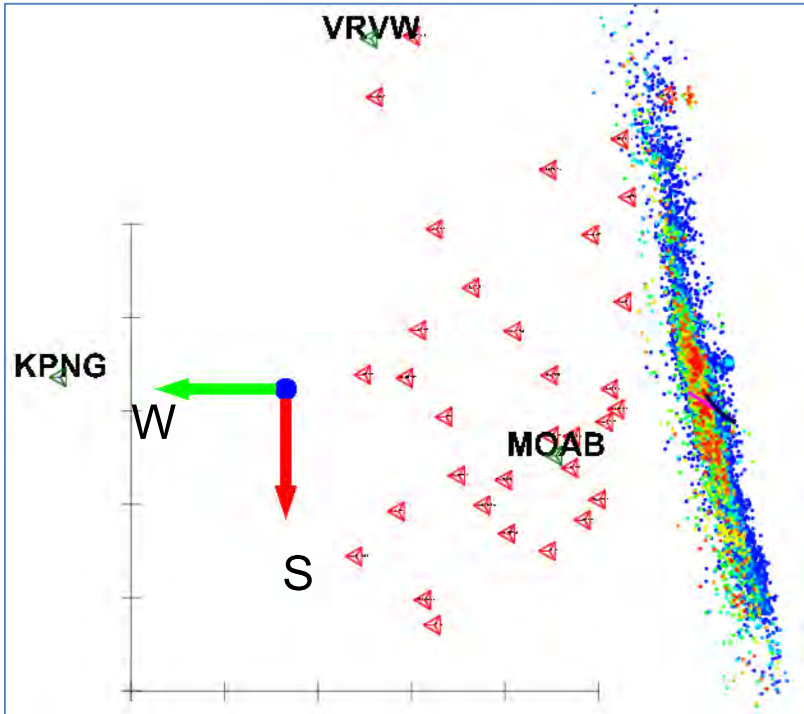
Since February 2017, 6m x 6m x 6m drilling space had been newly excavated at Site 1 at 2.8km depth for DSeis drilling, followed by installation of anchor bolts, mesh & race, ventilation and lights.

Horizontal deflection has caused more difficult intersection with the M5.5 rupture

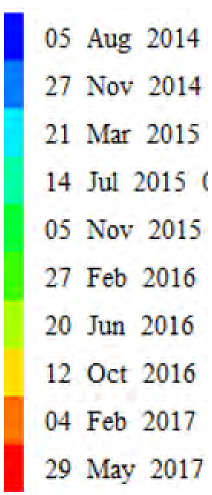


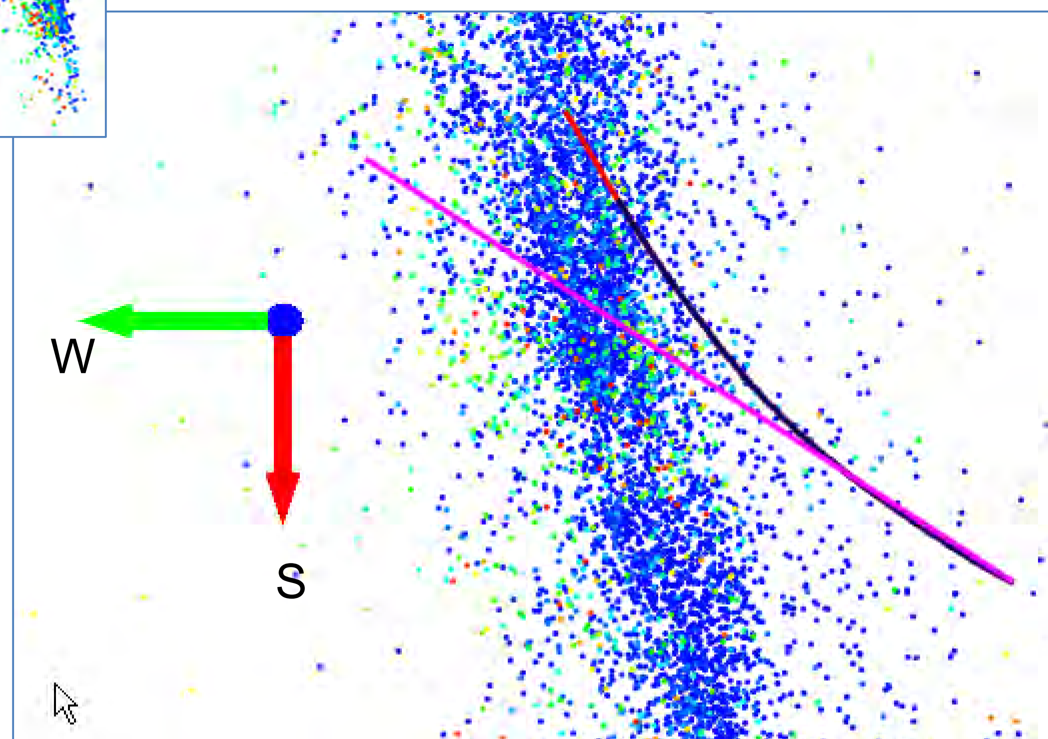


Apparent distance from the M5.5 rupture is mainly caused by change in Hole A trend up to 30 degrees.



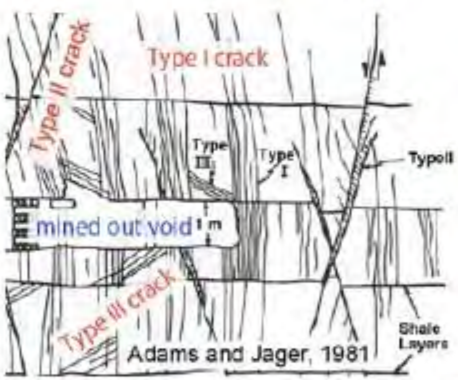
- Planned
- 639m Surveyed
- 750m extrapolated



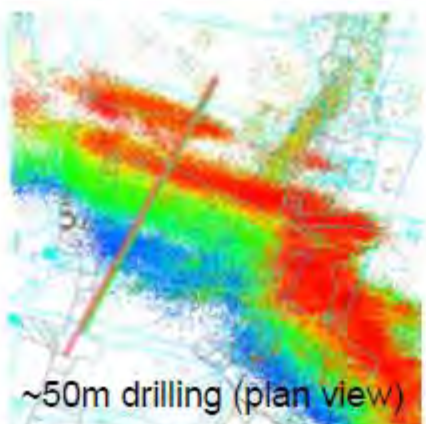


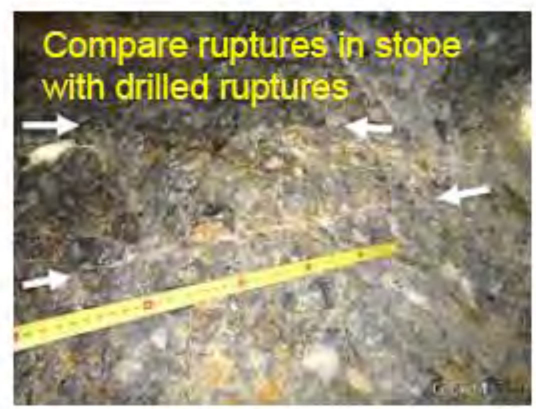
Mine 2: M_w~2 aseismic ruptures ahead of mining fronts

- Quartzite with faults or dykes on mining horizons
  - simpler to interpret
- Targets more than 10 x smaller than the M5.5 can let us
  - probe much larger volume in much less cost,
  - discuss scale dependency,
  - conduct overcoring stress measurement, and
  - compare between ruptures exhumed by mining and recovered by drilling.



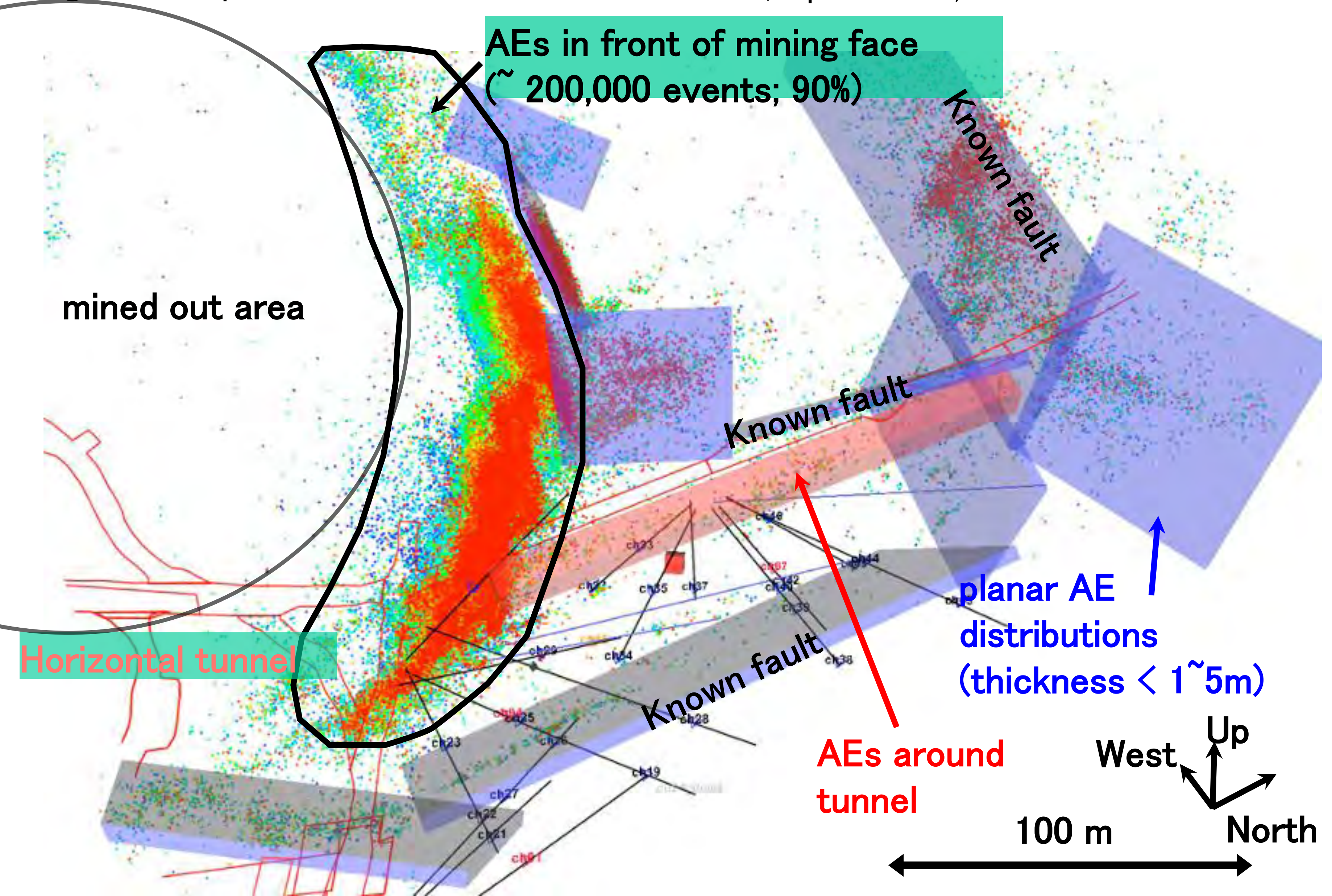
Ruptures ahead of stope (section)

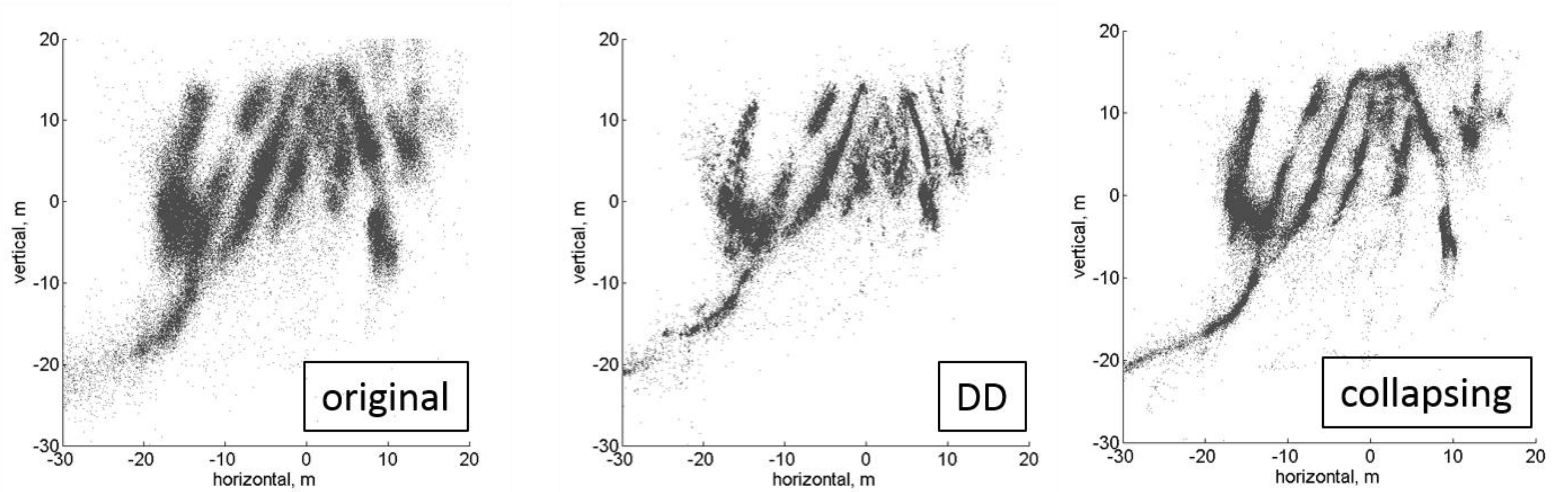




AE monitoring at Cooke 4# (led by M. Nakatani, U. Tokyo)

Aug. 17 ~ Sep. 23, more than 220,000 AEs (P pick ≥ 10, RMS residual ≤ 0.2 ms)





Mine 2: M_w~2 aseismic ruptures ahead of mining fronts

The ICDP DSeis drilling offers a unique opportunity to:

- Compare the directly probed seismogenic zones and those inferred from seismic analyses;
- Investigate the relationship between violent motion and the directly-probed heterogeneity;
- Investigate scale effects and the factors that control seismic rupture;
- Investigate the relationship between seismicity, hydrology, and microbiological activity