Monitoring of Microseismicity in Deep Gold Mines in South Africa

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Background

- Deep mining (~3-4 km) in South Africa provides a good opportunity to observe the preparation and generation processes of earthquakes in the vicinity of seismic sources.
- South Africa and Japan has collaborated to study mining induced seismicity since 1994.
- Microseismicity (M<-4) monitoring started in 2007

Objects

- To bridge a scale gap between laboratory experiments (up to 1 m) and natural earthquakes (>100 m)
- To elucidate the preparation processes of faulting in geological structure, in contrast to artificially polished surface in lab.

Context

- Microseismicity before and after an Mw2.2 earthquake
  - Aftershock distribution
  - Earthquake preparation process implied by foreshock activity
- Migrating planar seismicity in front to mining edge (if possible)

Miciroseismicity before and after Mw2.2 earthquake in Mponeng mine

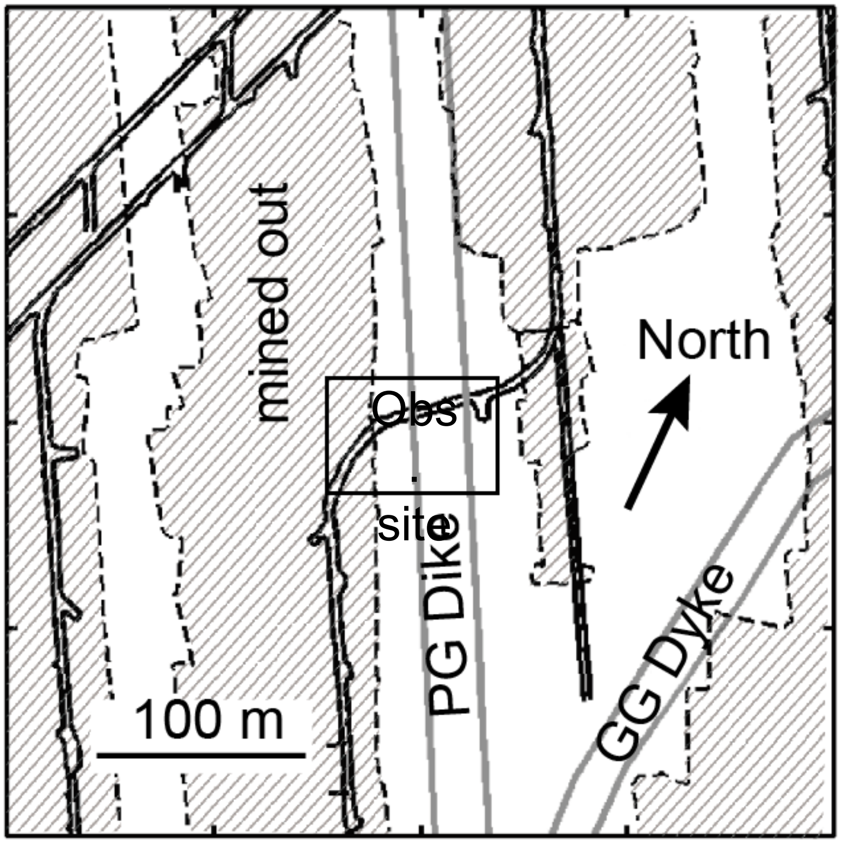
Correction

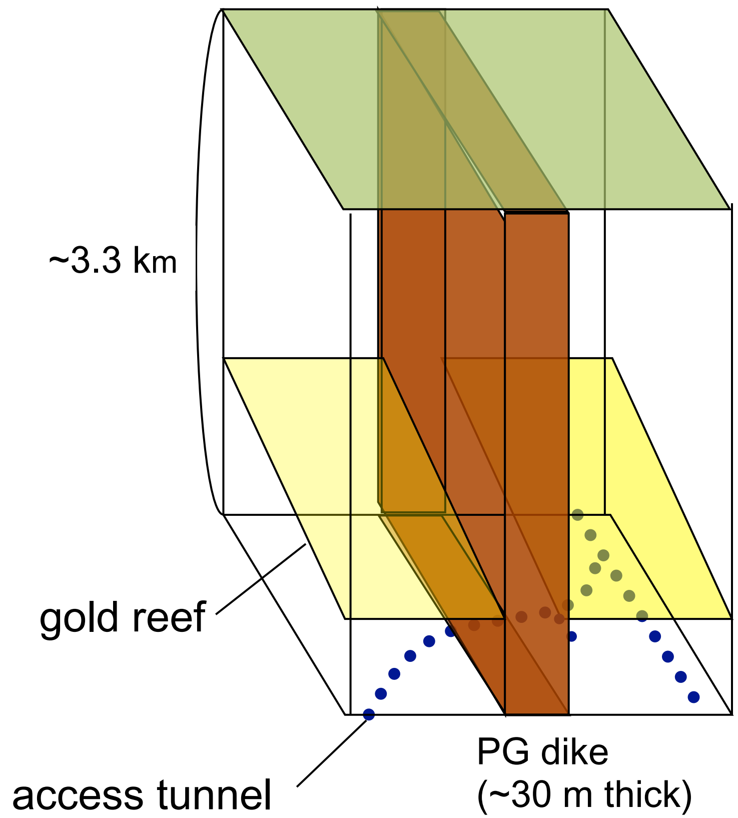
- We found a mistake in data selection after submission of abstract. Some results are different from the abstract.

Mw2.2 earthquake in Mponeng mine

- Observation network was deployed in June 2007.
- On 27 Dec 2007, an earthquake (Mw2.2, mainshock) occurred ~30 m above our network.
- We could record foreshock activity for ~6 months and ~10,000 aftershocks during 150 hr following the mainshock.

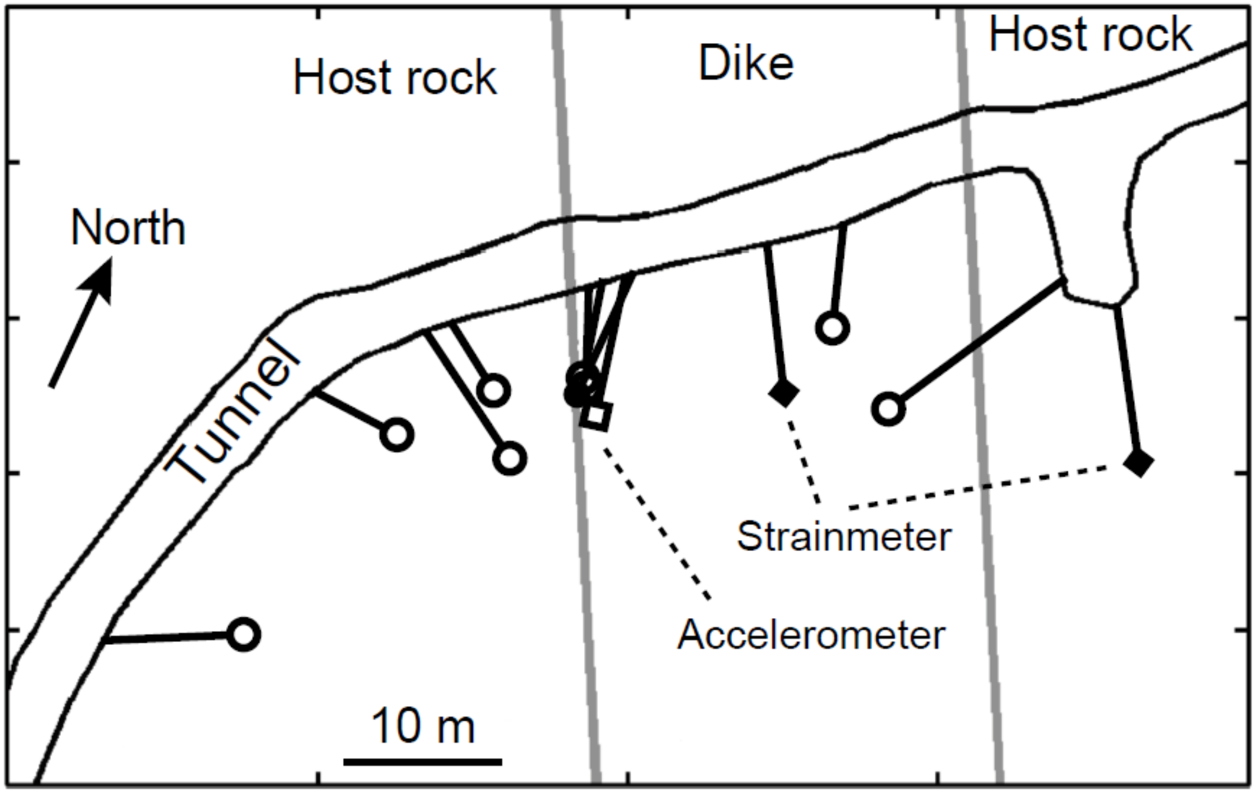
Observation site





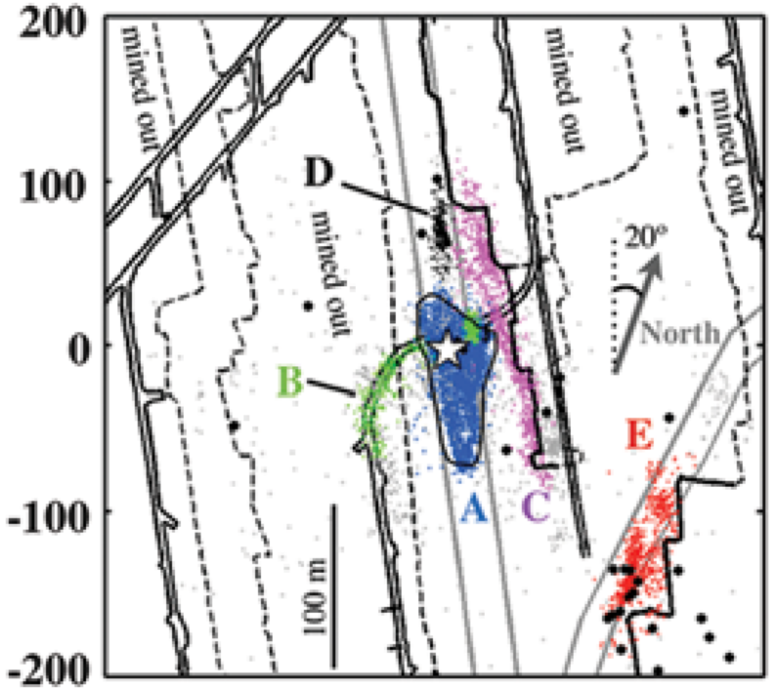
- ✓ Observation site was at a depth ~3.3 km from surface and 90 m below the reef.
- ✓ PG dike (gabbro) was left unmined as a pillar.

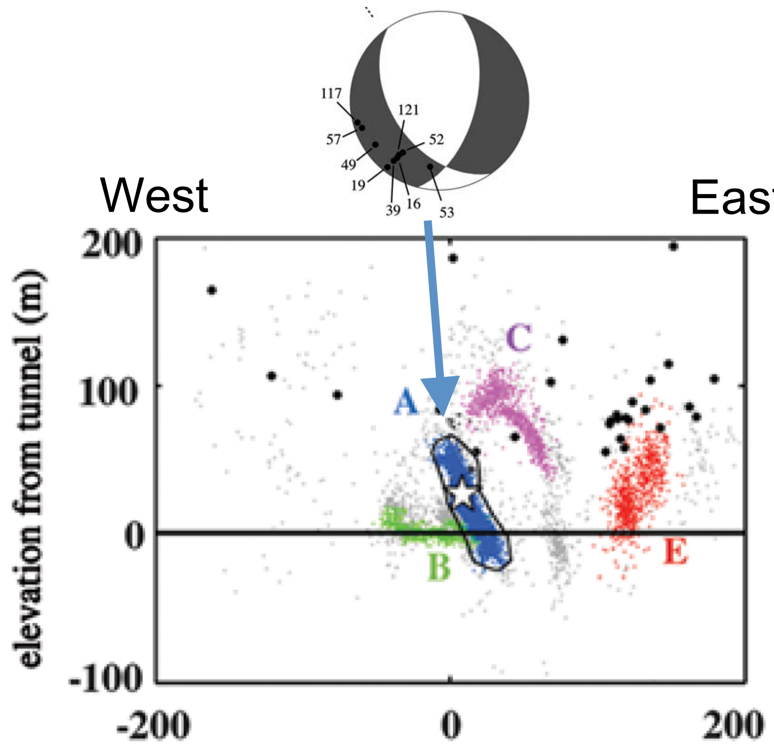
Observation network



Observation network consisted of 7 AE sensors, 1 triaxial accelerometer and 2 strainmeter.

Aftershock distribution

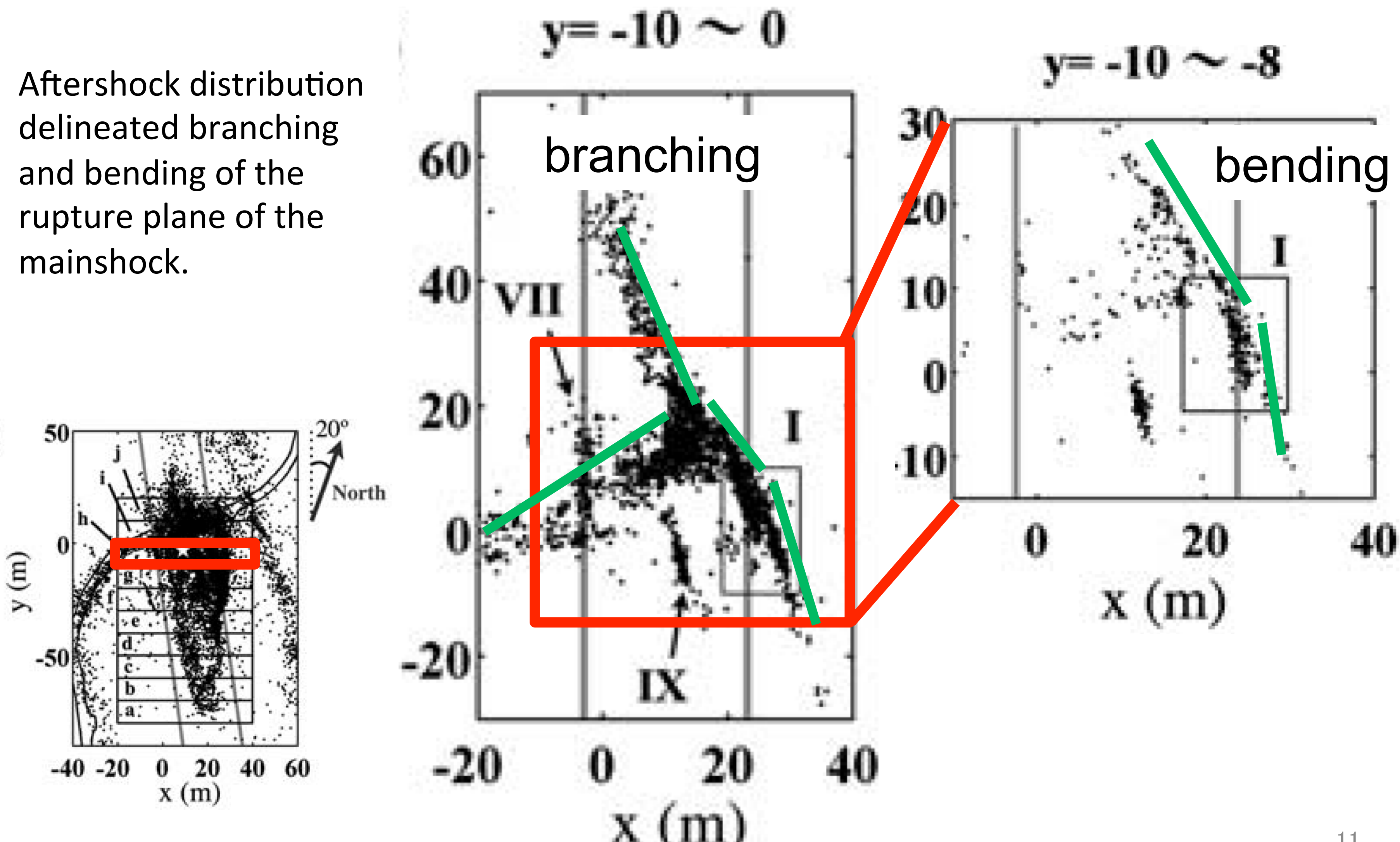




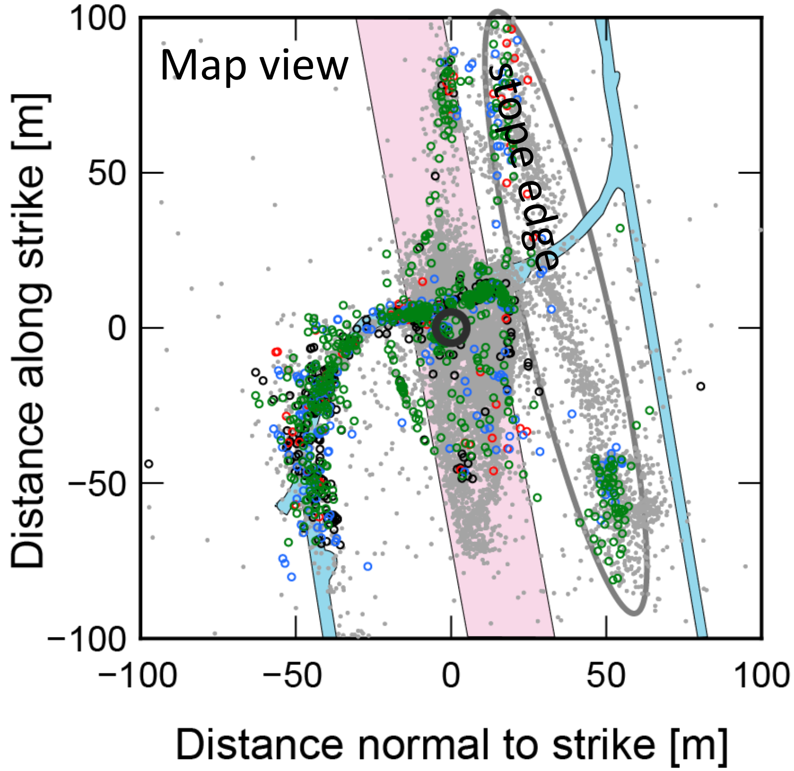
- ✓ Microseismicity for 150 hr immediately after the mainshock can be classified to 5 clusters.
- ✓ The mainshock hypocenter was located on a plane of cluster A.
- ✓ Cluster D was on a northern extension of the plane of cluster A, but showed clear discontinuity from cluster A.

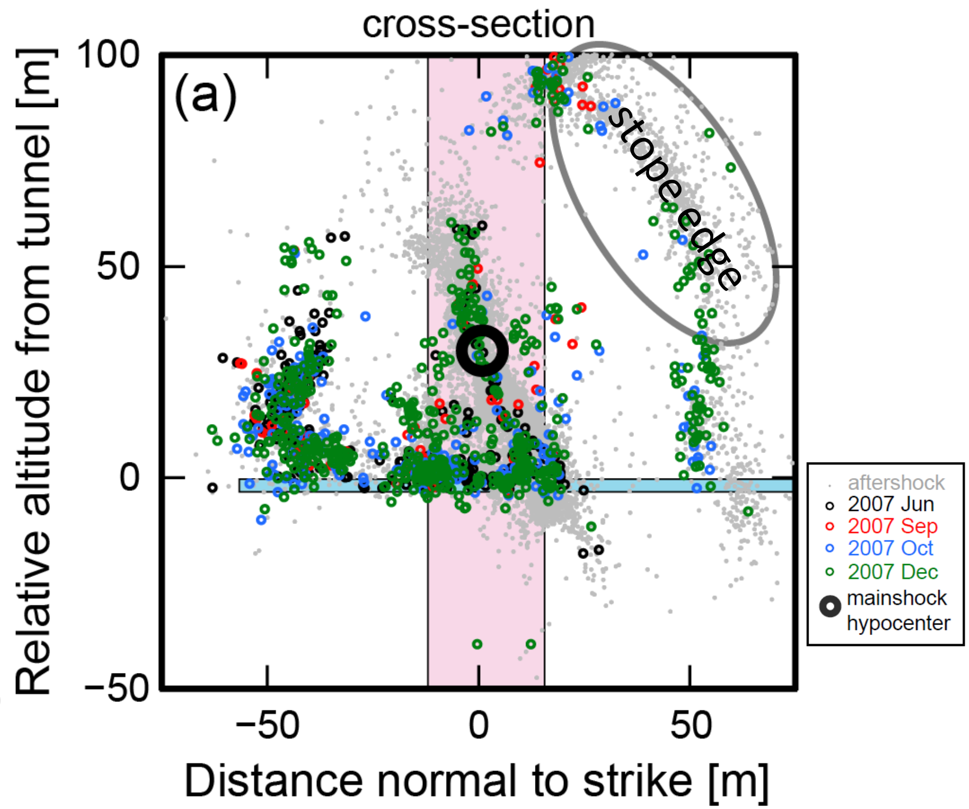
Fine structures of the rupture plane of the mainshock

Aftershock distribution delineated branching and bending of the rupture plane of the mainshock.



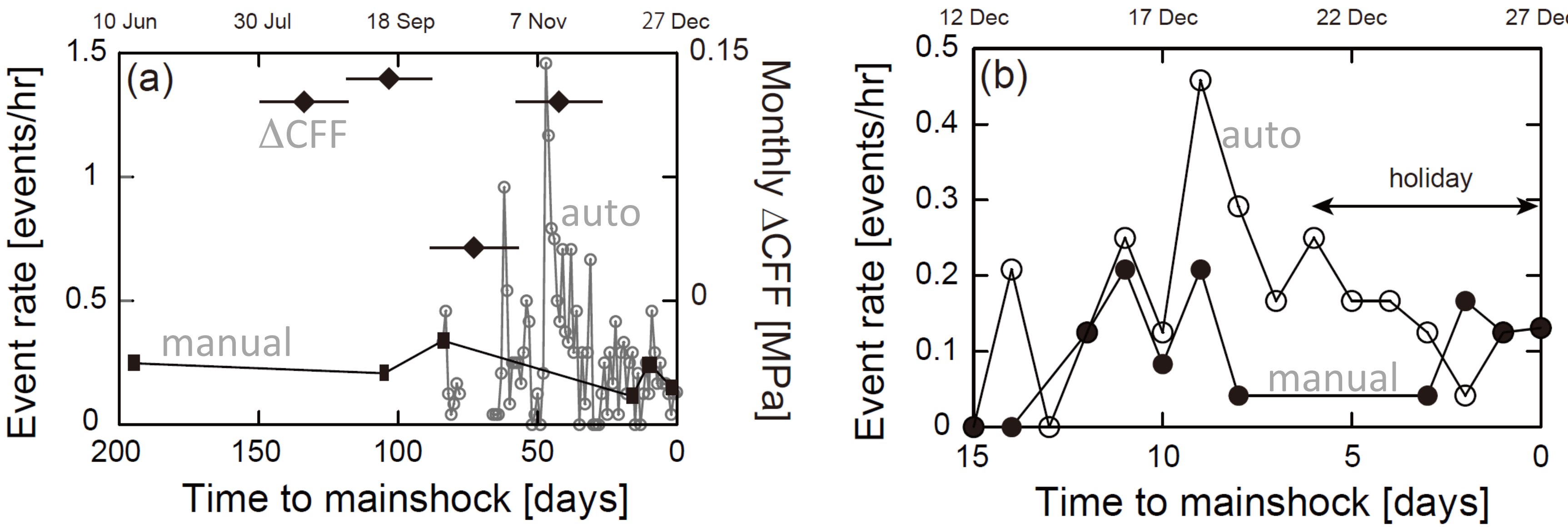
Microseismicity before and after the mainshock





- ✓ Even before the mainshock fault, seismicity can be recognized on the mainshock fault for 6 months.

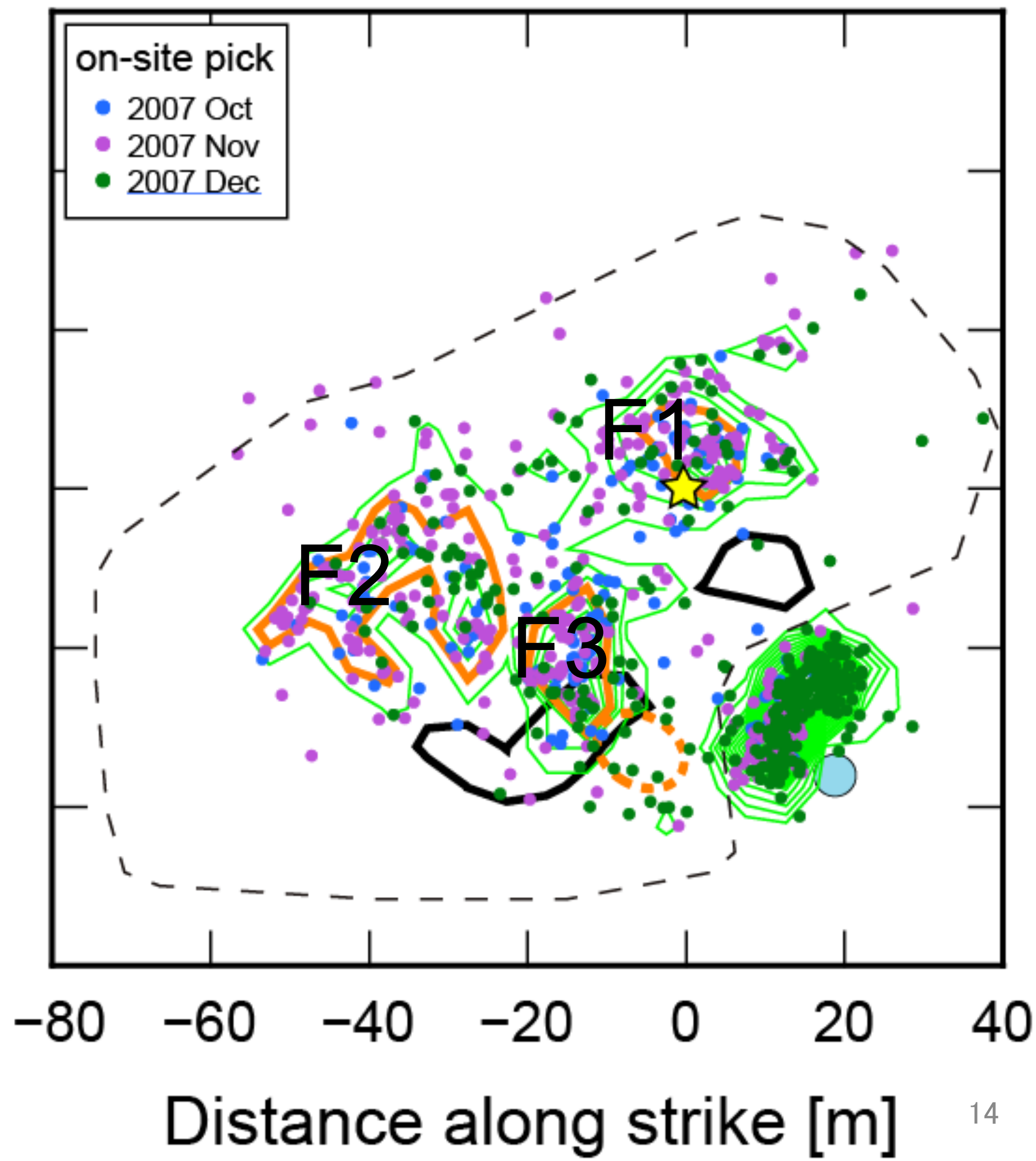
Long- to intermediate-term whole foreshock activity



- ✓ Long-term (months) foreshock activity was modulated by stress perturbation associated with mining.
- ✓ Neither long-term nor intermediate-term (weeks) foreshock activity as a whole showed acceleration prior to the mainshock.

Foreshock distribution on the fault

- ✓ Foreshocks concentrated to fixed 3 clusters irrelevant to mining activity, suggesting that foreshock clusters might occur at weak patches.
- ✓ Foreshock clusters and aftershock clusters merely overlap to each other.
- ✓ The mainshock hypocenter was neighboring to the cluster F1.



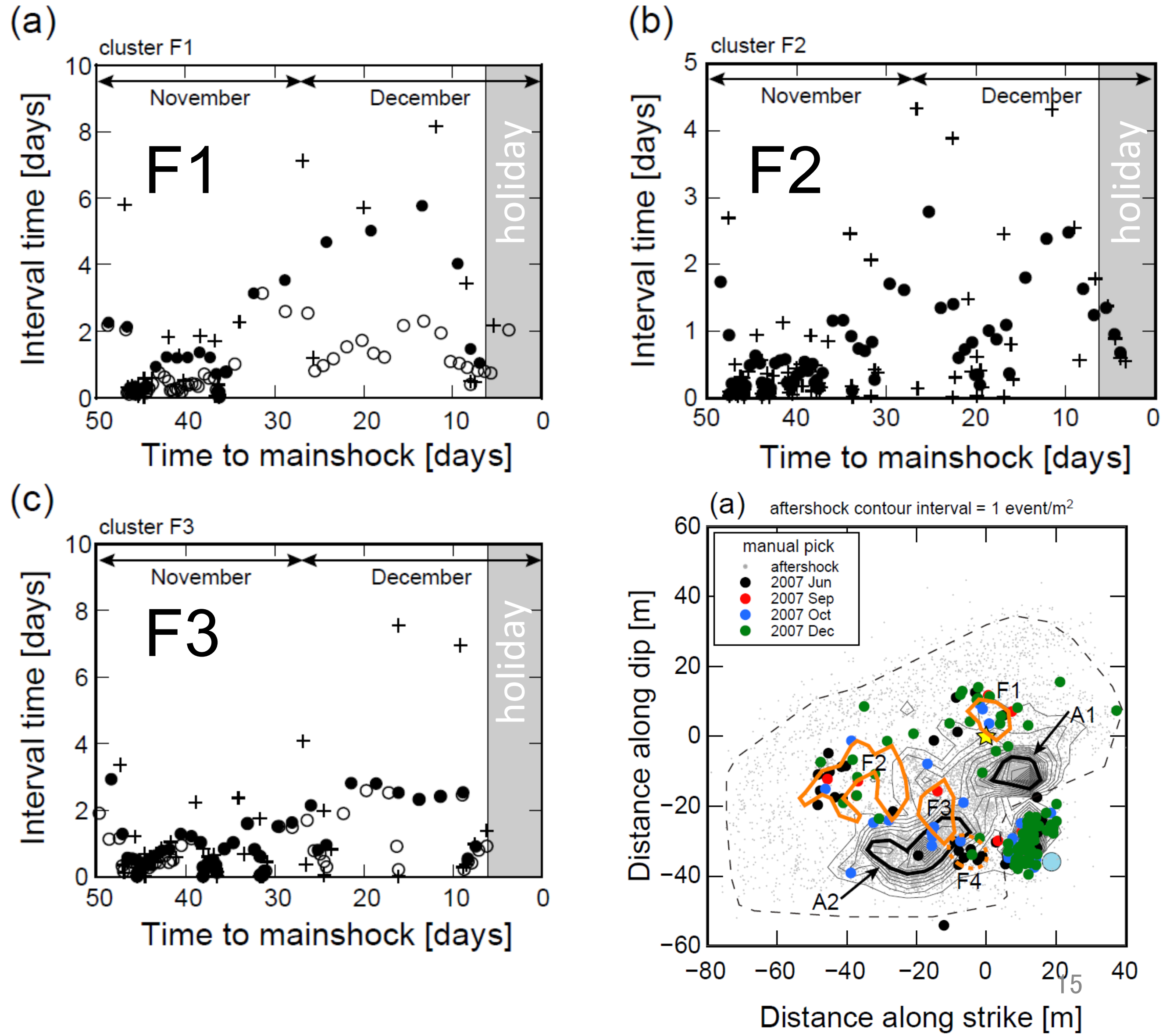
Long-term activity in each cluster

Long-term activity in each cluster was modulated by mining activity, as well.

When the holiday started, activities in F1 and F3 ceased.

Activity in F2 became higher even after the holiday started.

Slip patch at F2 reached its criticality about 10 days before the mainshock?

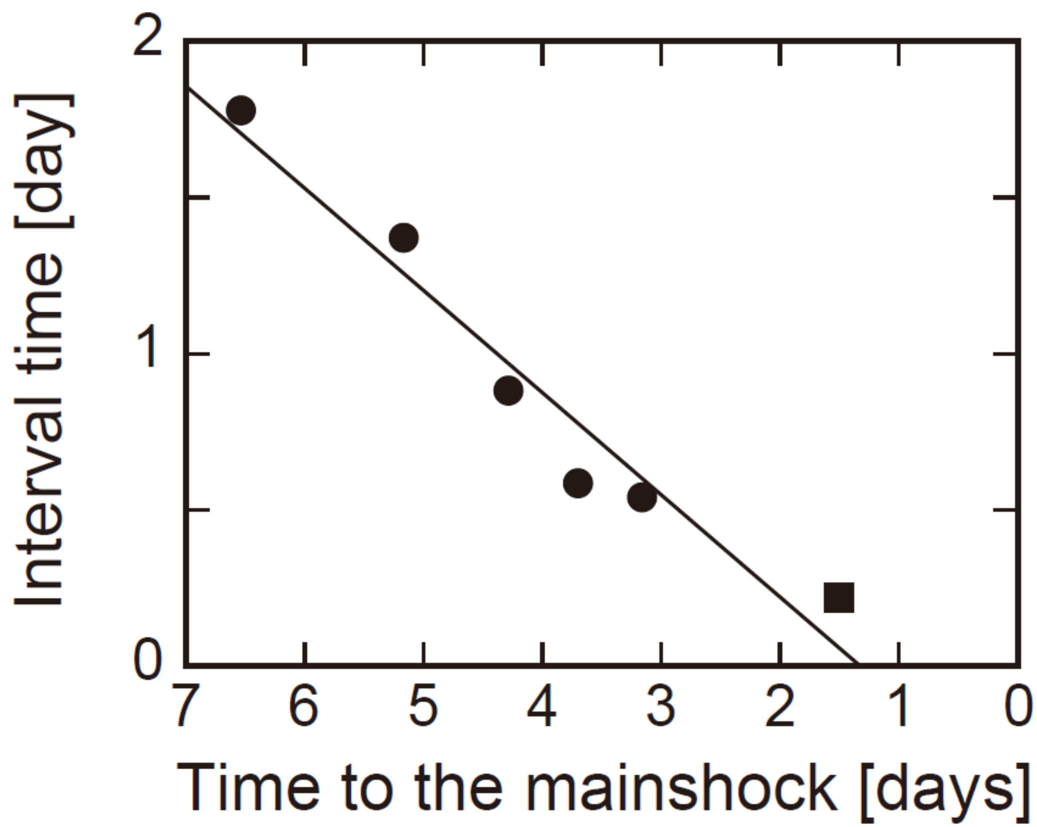


Foreshock activity in F2 immediately before the mainshock

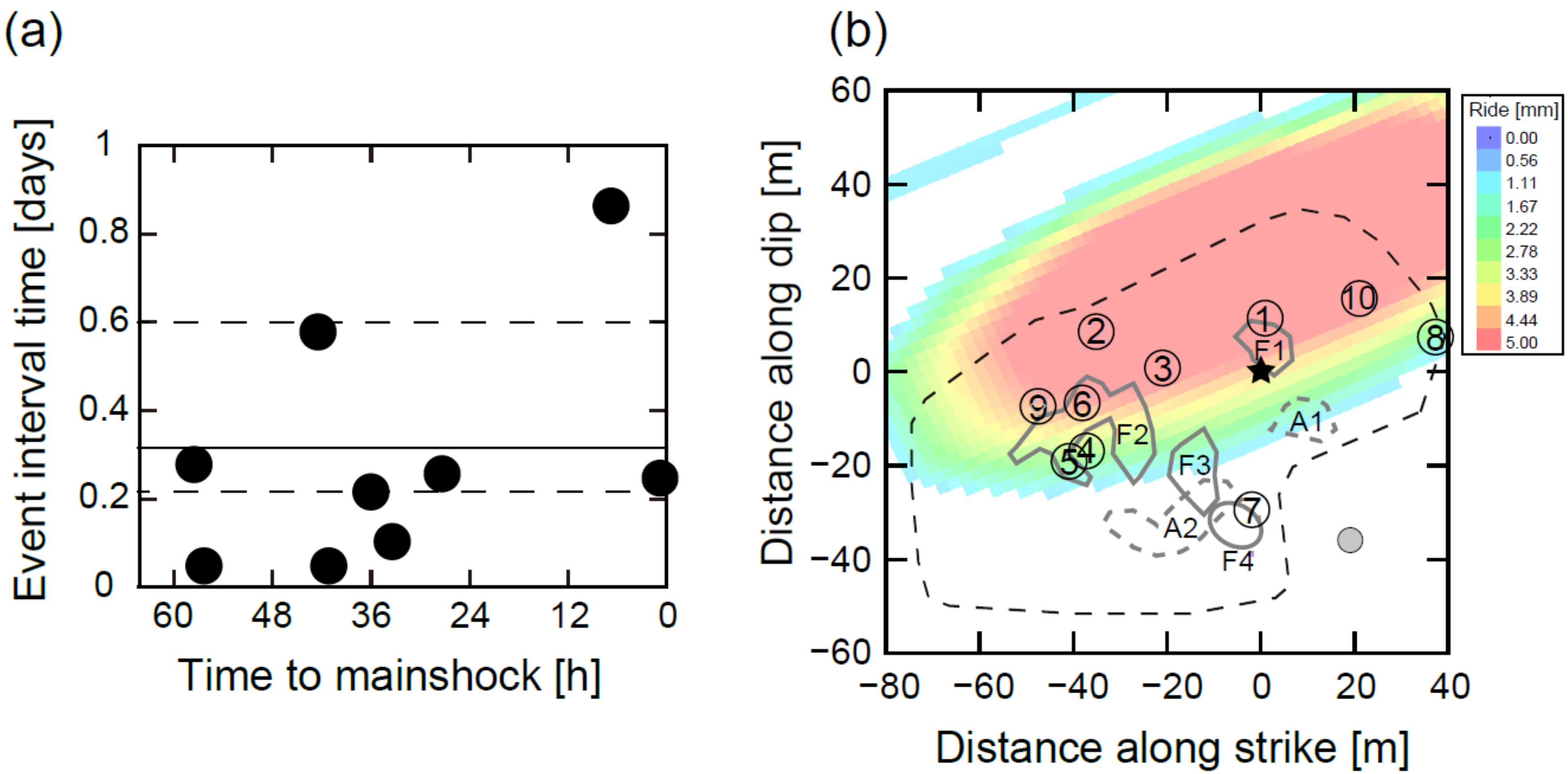
Because of mine's holiday, no stress perturbation for 7 days before the mainshock.

Interval time of foreshocks in F2 showed a monotonic, linear decrease with time to the mainshock.

Linear extrapolation predicted time of the mainshock 1.3 days before the actual occurrence time of the mainshock.



Foreshocks for 64 hr before the mainshock



- ✓ 9 of 10 immediate foreshocks within a few days before the mainshock occurred within high CFF area on the pre-existing plane of weakness.
- ✓ Immediate foreshock activity also did not show acceleration.
- ✓ The foreshock #1 occurred 50 minutes before the mainshock.

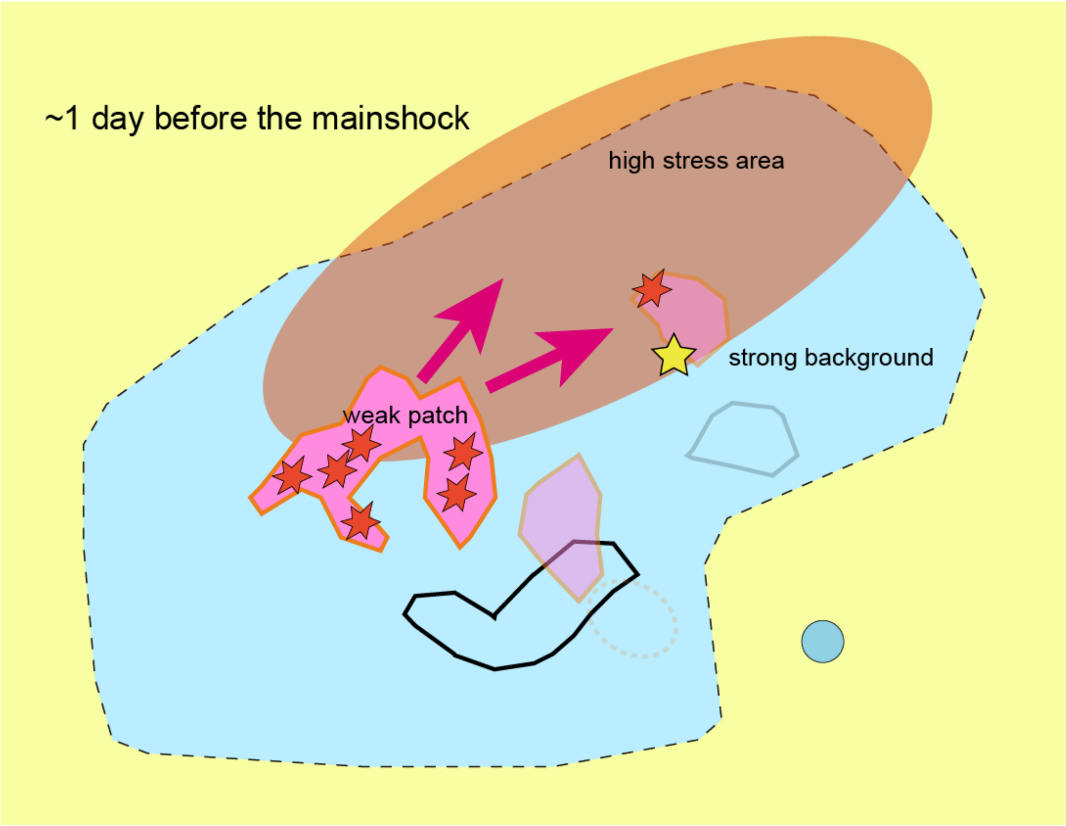
Implicated preparation process

- More than 3 months before the mainshock
  Persistent foreshock activities (localized preslip) initiated at weak patches F1-F3.

- 1.1-1.3 days to the mainshock
  Slip patch at F2 became critical and had been quasi-dynamically expanding. However, its expansion was decelerated by high strength around F2.

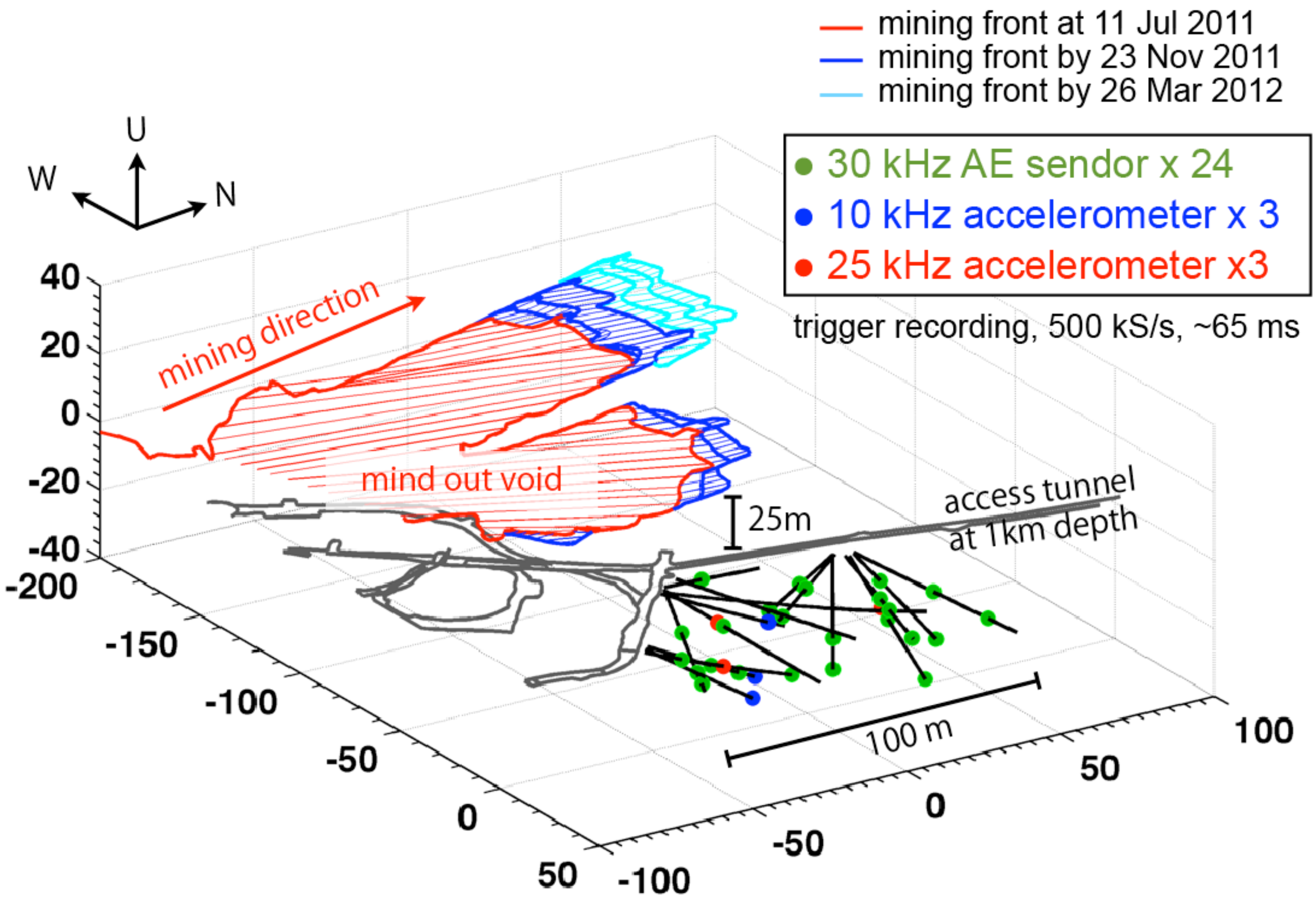
- 50 minutes to the mainshock
  The slip patch expanded from F2 coalesced with a slip patch at F1.

- The occurrence of the mainshock at 15:15 on 27 Dec 2007.

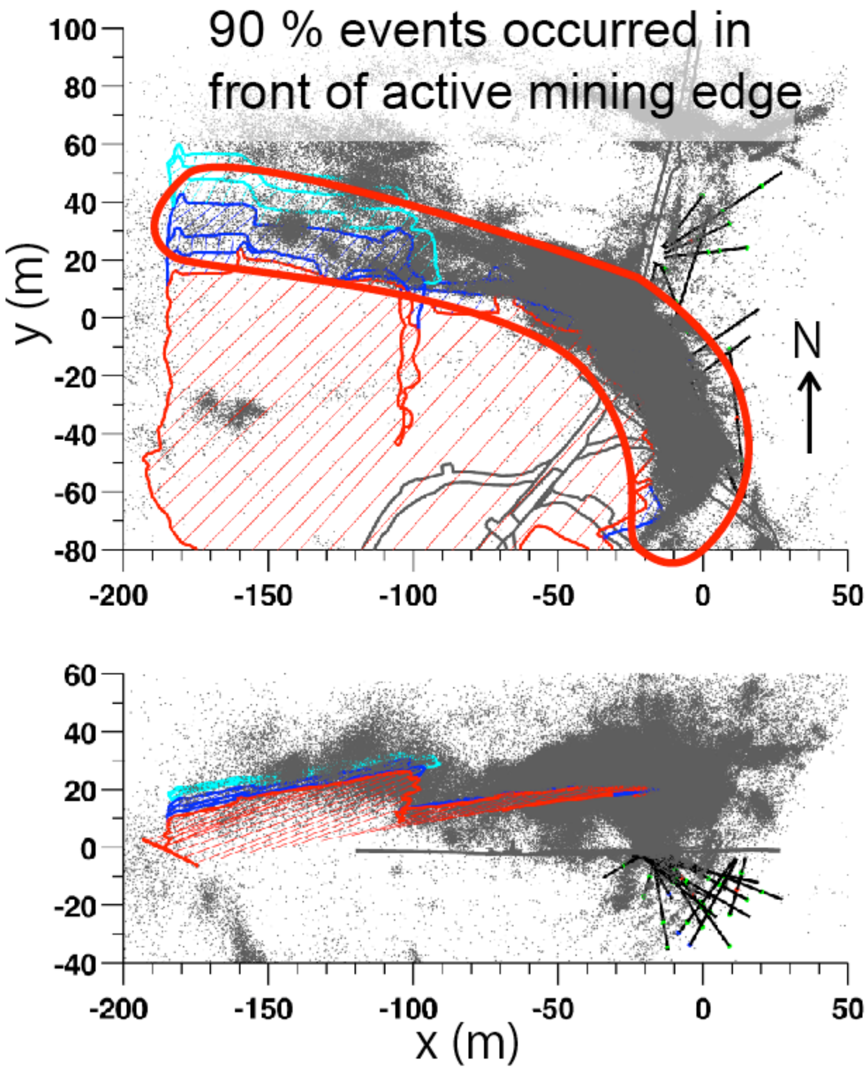


Migrating planer microseismicity in Cooke4 mine

Observation network in Cooke4



Seismicity for 9 months

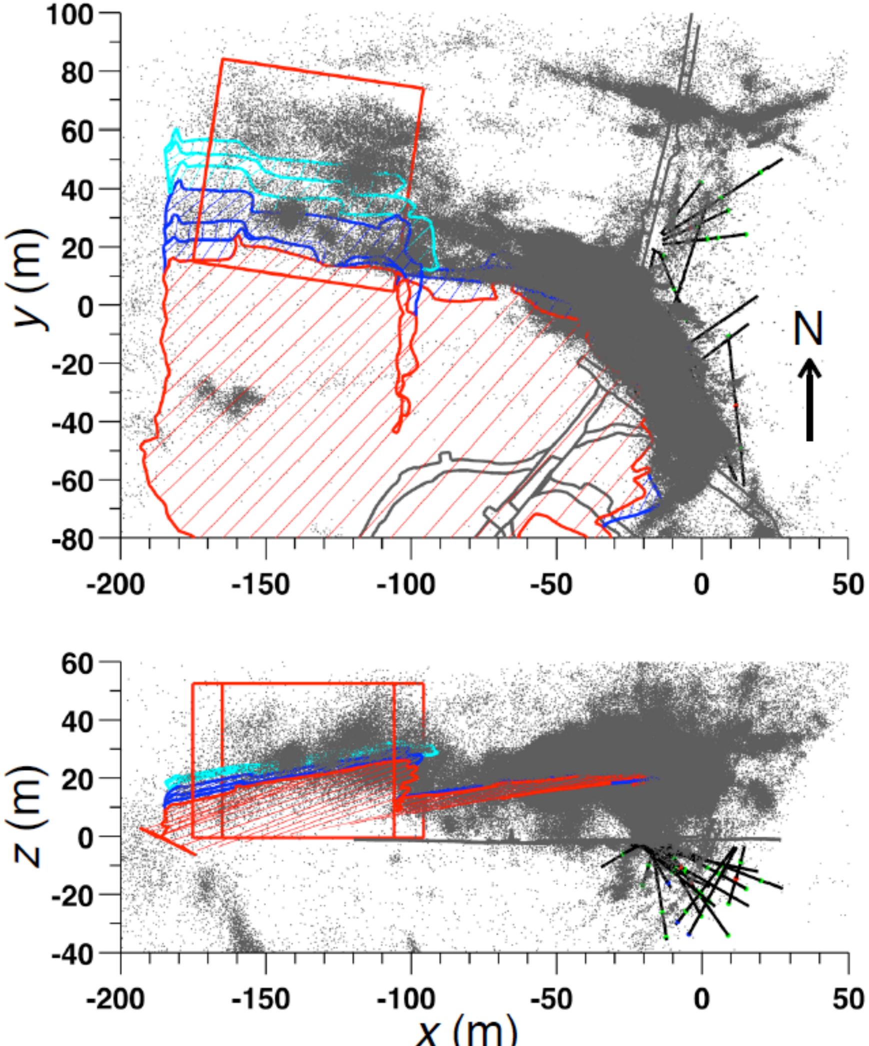


Automatically picking P arrivals

P arrivals ≧ 10
rms arrival time residual ≦ 0.2 ms

About 1 million events with -5.3 < Mw < 0.1 for Jul 2011-Mar 2012 were located.

Crack formation in front of active mining edge

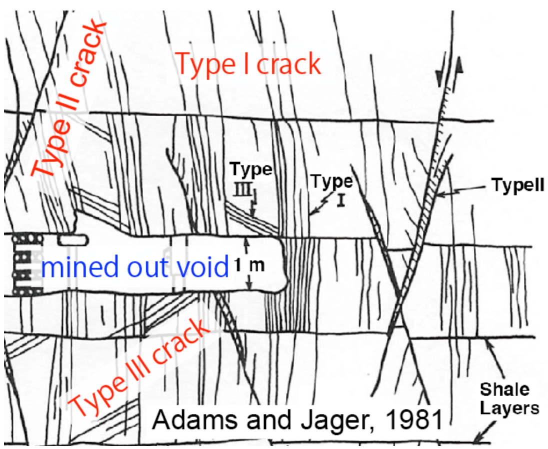


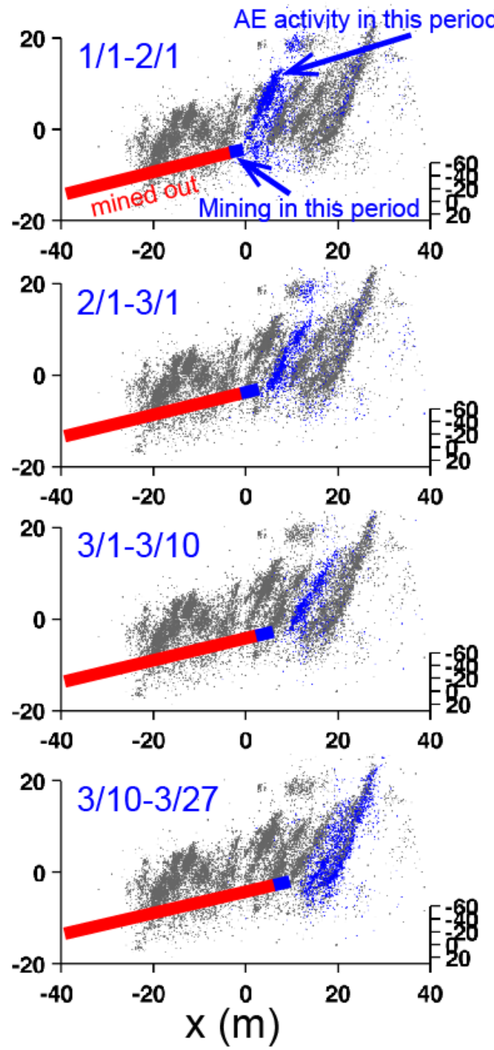
- ✓ Target area; in front of relatively linear mining edge (red box)
- ✓ Time window; 1 Jan-27 Mar 2012
- ✓ Precise picking by waveform correlation
- ✓ Relocation by DD method

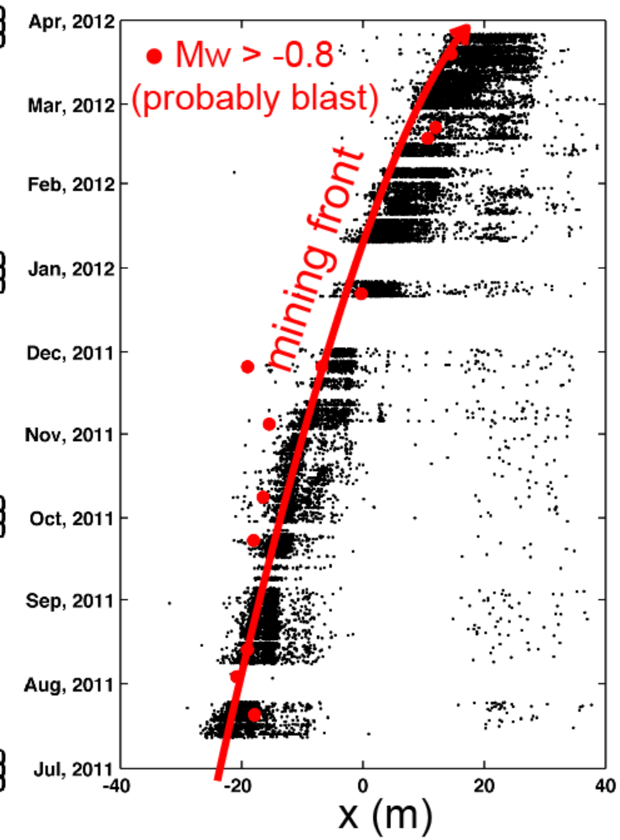
- ➢ 98 % of 24787 events can be well relocated.

Migration of planer activity

- ✓ Regularly spacing ~10 planer structures
- ✓ Dipping by 60~70° to south
- ✓ Sub-parallel to the mining edge
- ✓ Location of planer activity migrated with active mining front.
- ✓ The planer structure may represent nucleation of Type II crack.



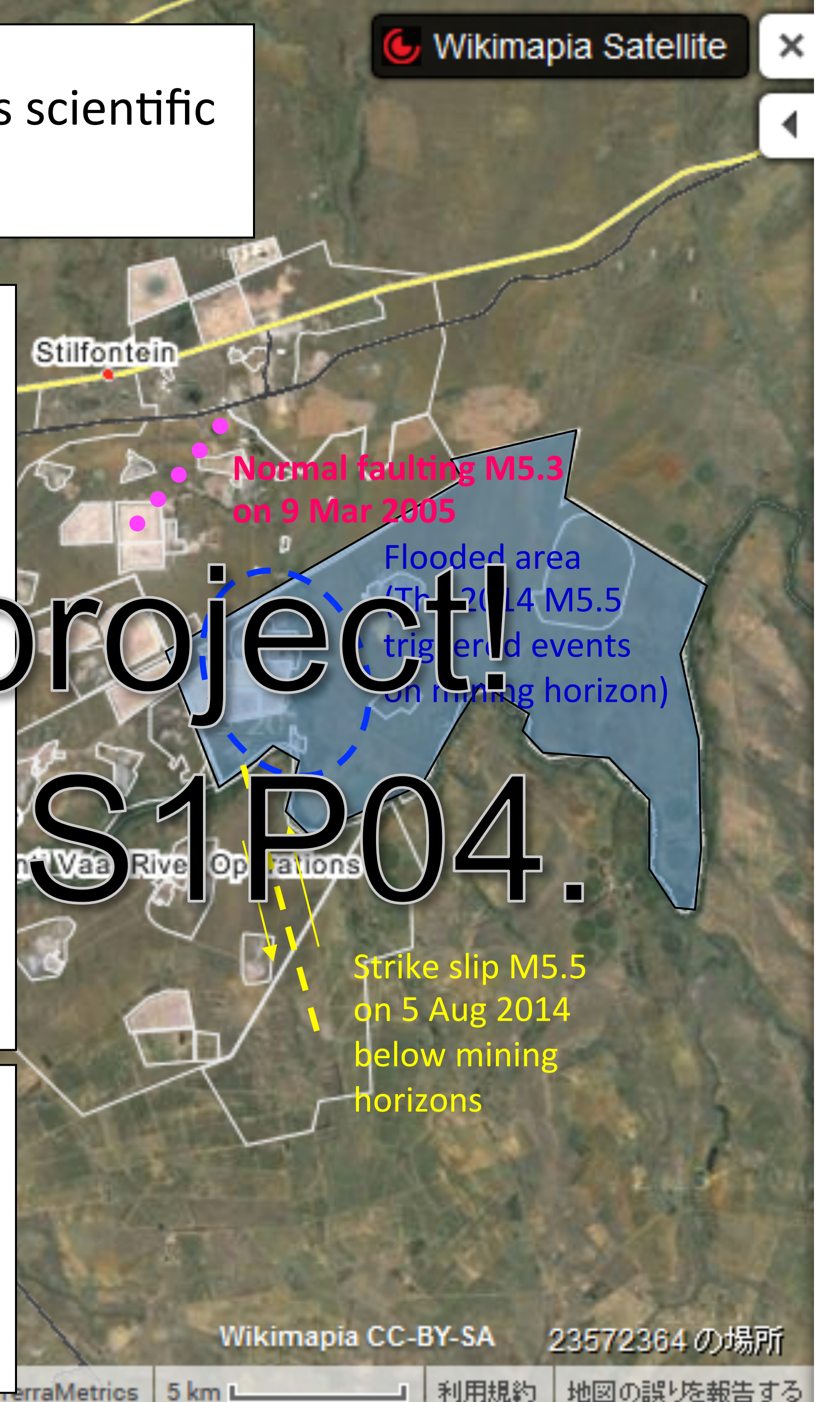




Summary

- AE observation has abilities of
  - monitoring preparation processes of faulting.
  - delineating fine structures of faults and joints buried in rock mass.
  - detecting nucleation of newly generated cracks.

Let’s hope ICDP allows us a workshop to discuss scientific objectives and the best strategy



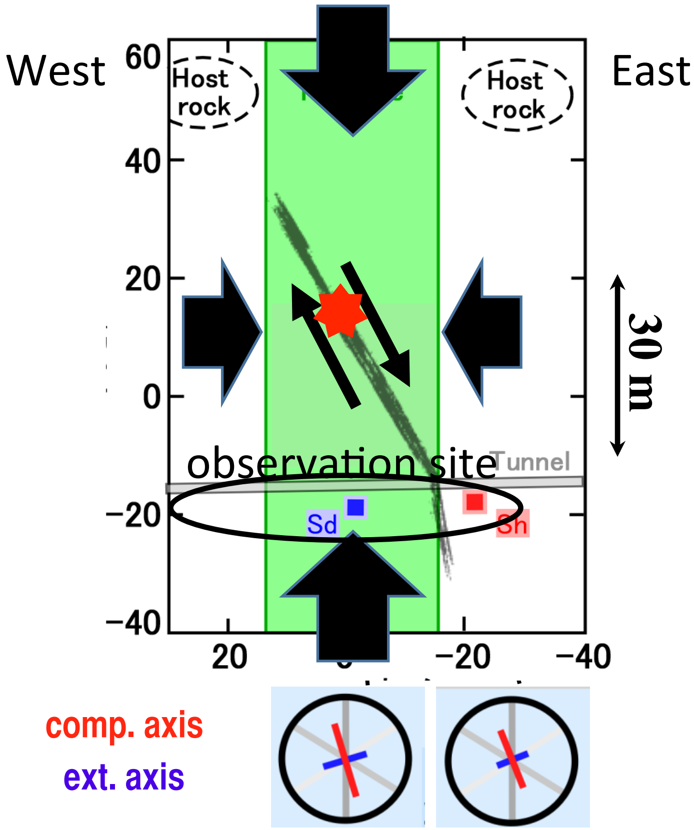
Our new project!
Visit poster S1P04.

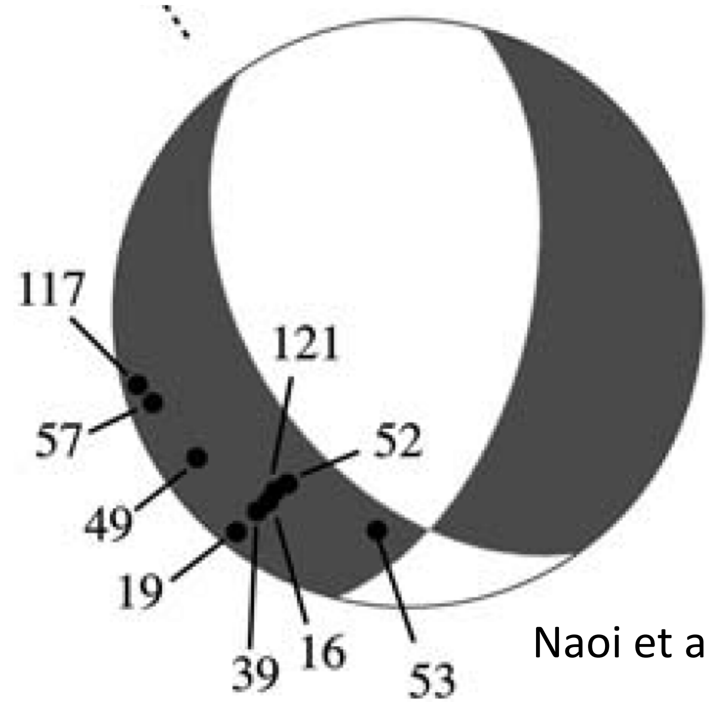
1972 M4.7	1982 M4.6	1984 M4.1	1996 M4.2
1973 M4.8	1983 M5.1	1986 M4.8	1997 M4.4
1977 M5.2	1983 M4.3	1987 M4.9	1997 M3.8
1978 M4.5	1983 M4.0	1987 M4.5	1997 M4.0
1980 M4.9	1983 M4.0	1988 M4.3	2001 M4.2
1981 M4.8	1984 M5.0	1988 M4.4	2004 M4.9
1981 M4.9	1984 M4.8	1989 M4.4	2005 M5.3

Geophone only before 2010

2010 DMR CGS strong motion meters
SATREPS
2014 M5.5

Mainshock as a Mohr-Coulomb failure in the PG dike

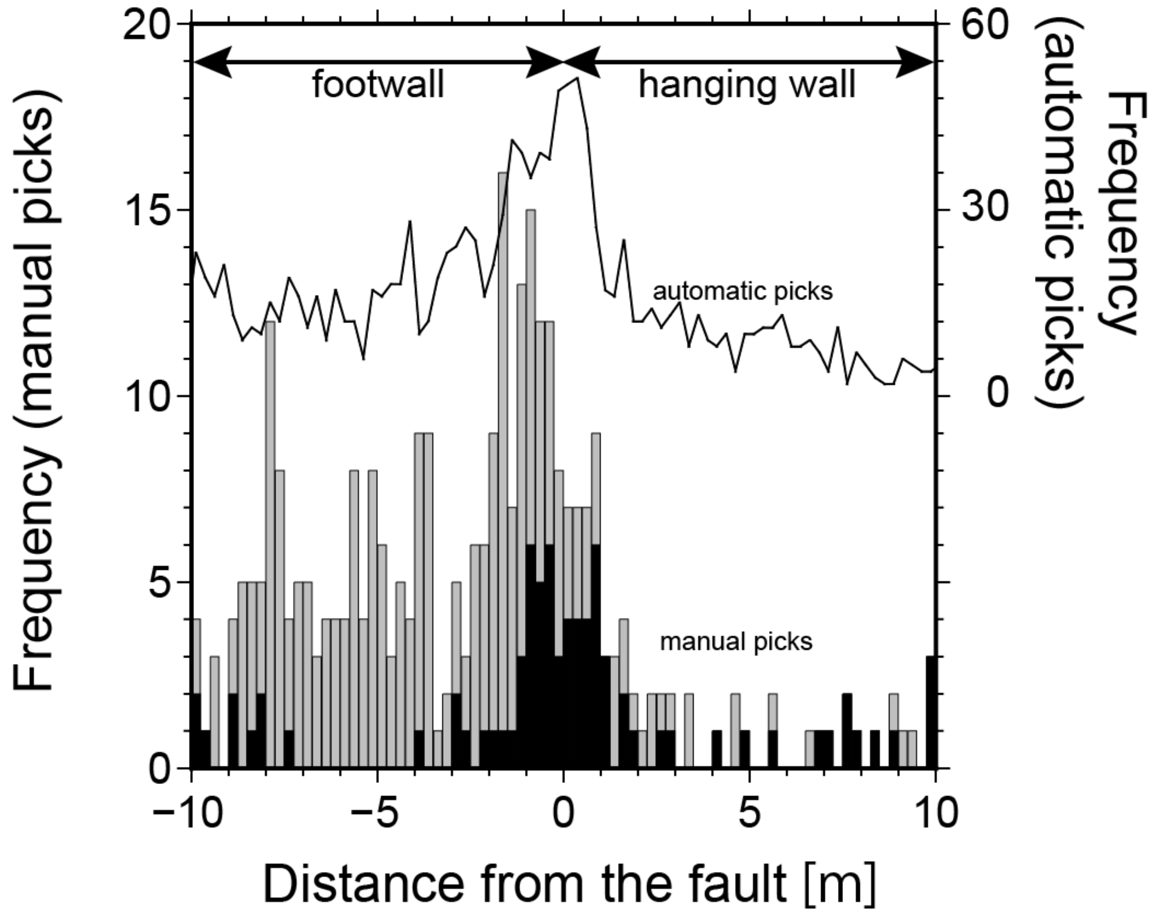




Naoi et al. (2011)

- ✓ Strain monitoring revealed ~20 MPa increase in sub-vertical axial compression for 9 months prior to the mainshock.
- ✓ A nodal plane of the mainshock focal mechanism was an optimum plane for the Mohr-Coulomb failure in the PG dike under sub-vertical compression.

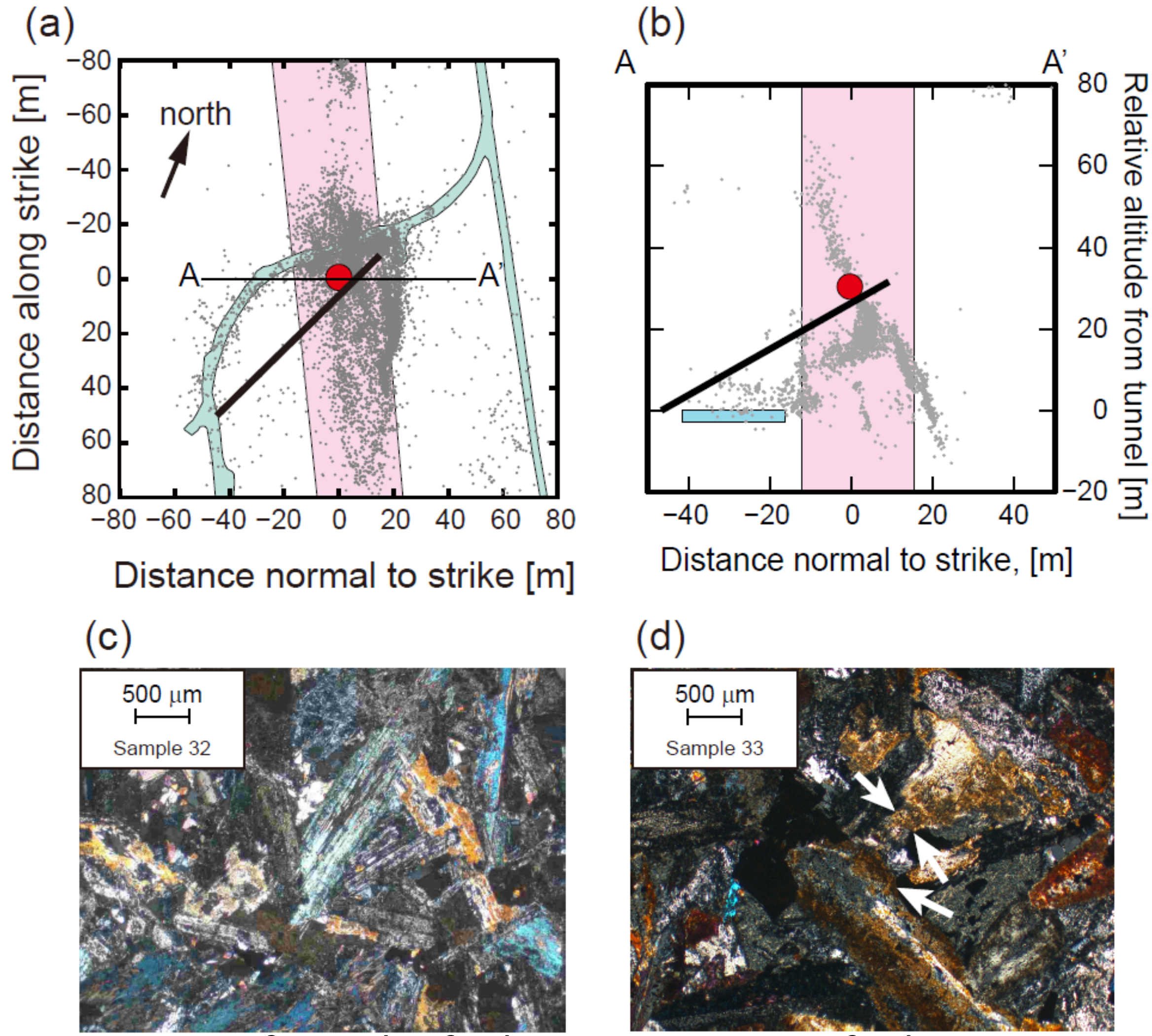
Concentration of AE activity before the mainshock to the fault



Clear concentration within 1.2 m from the mainshock fault.

The mainshock occurred on a pre-existing plane of weakness.

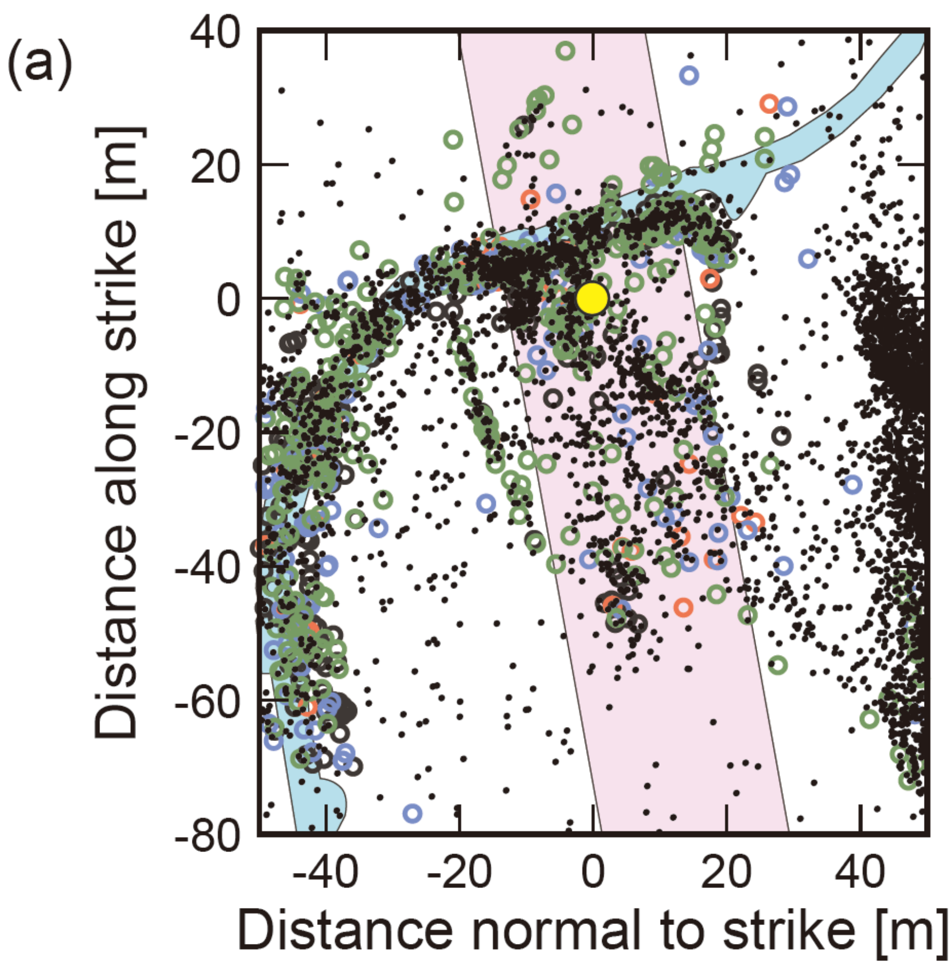
- ✓ A borehole passing through the mainshock fault was drilled ~1.5 yr after the mainshock.
- ✓ Alteration by ancient thermal activity was found only in a sample recovered on the mainshock fault.
- ✓ The mainshock occurred on a pre-existing plane of weakness.

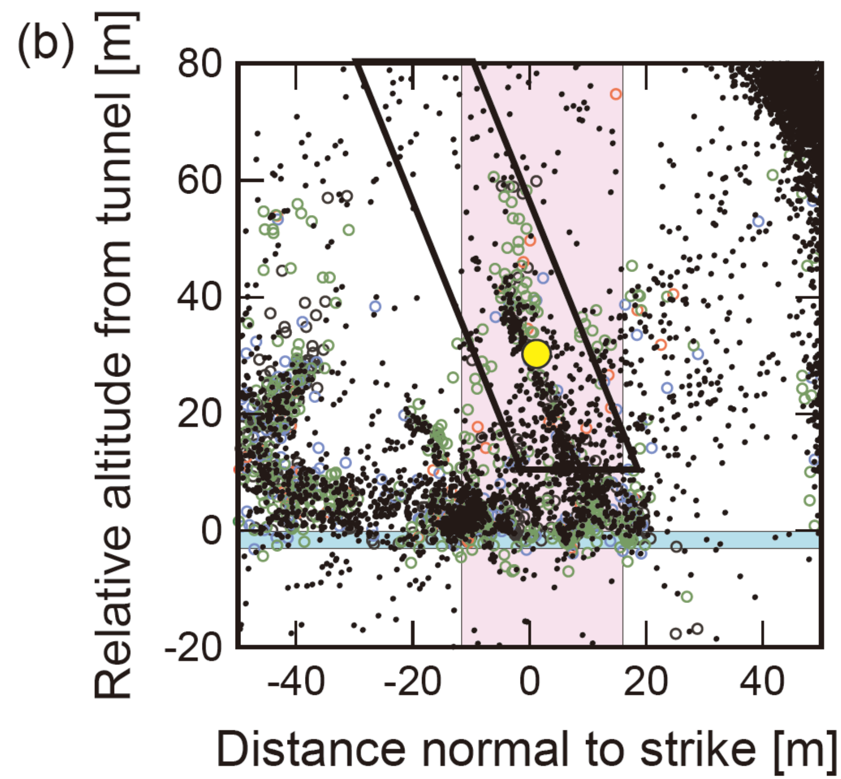


20 cm from the fault

On fault

Comparison of distributions of manually located and automatically located foreshocks



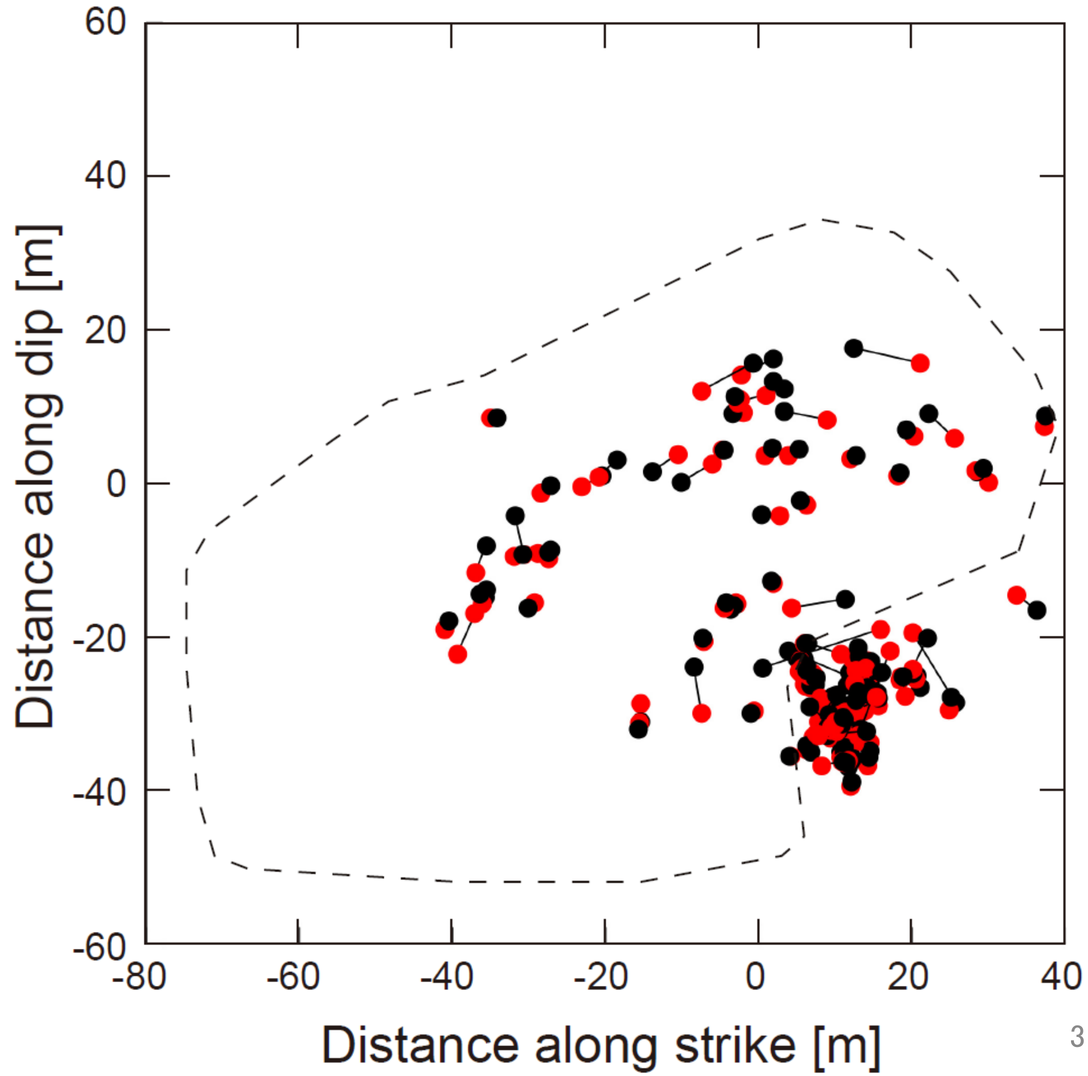


Comparison between manually located and automatically located hypocenters

自動処理（黒丸）と手動検測（赤丸）による震源の位置のずれは2.6±2.5 m.

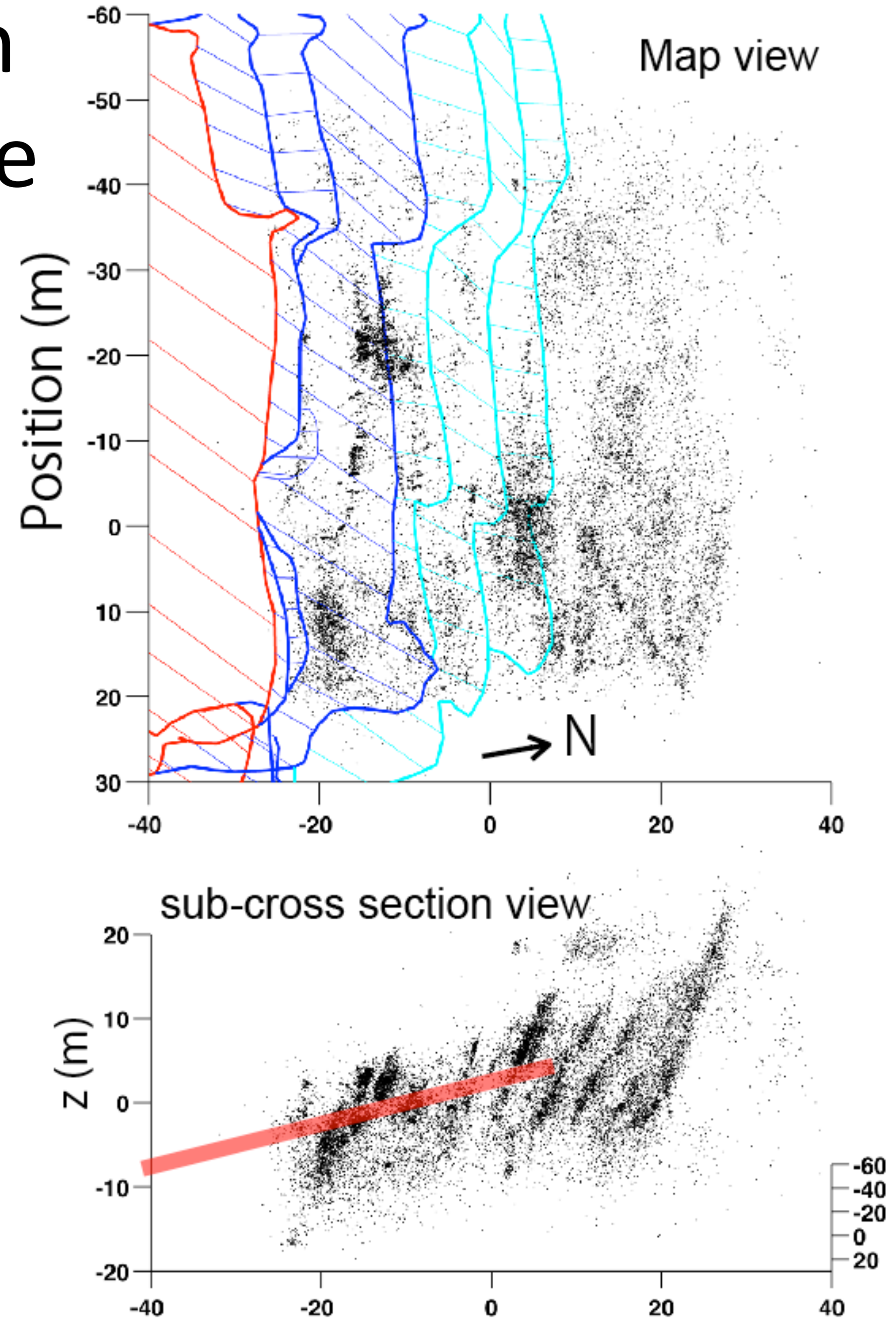
トンネルを中心とした同心円状にずれるが，ずれる方向に傾倒性はない．

ずれる量とトンネルからの距離に関係はない．



Planer AE distribution in front of mining edge

- ✓ Regularly spacing ~10 planer structures
- ✓ Dipping by 60~70° to south
- ✓ Sub-parallel to the mining edge



24404 events, $-3.3 < Mw < -0.5$