SnT 2019
CTBT: SCIENCE AND TECHNOLOGY CONFERENCE

Full moment tensor analysis of nuclear explosions and a collapse in North Korea

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FONDS NATIONAL SUISSE
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SWISS NATIONAL SCIENCE FOUNDATION

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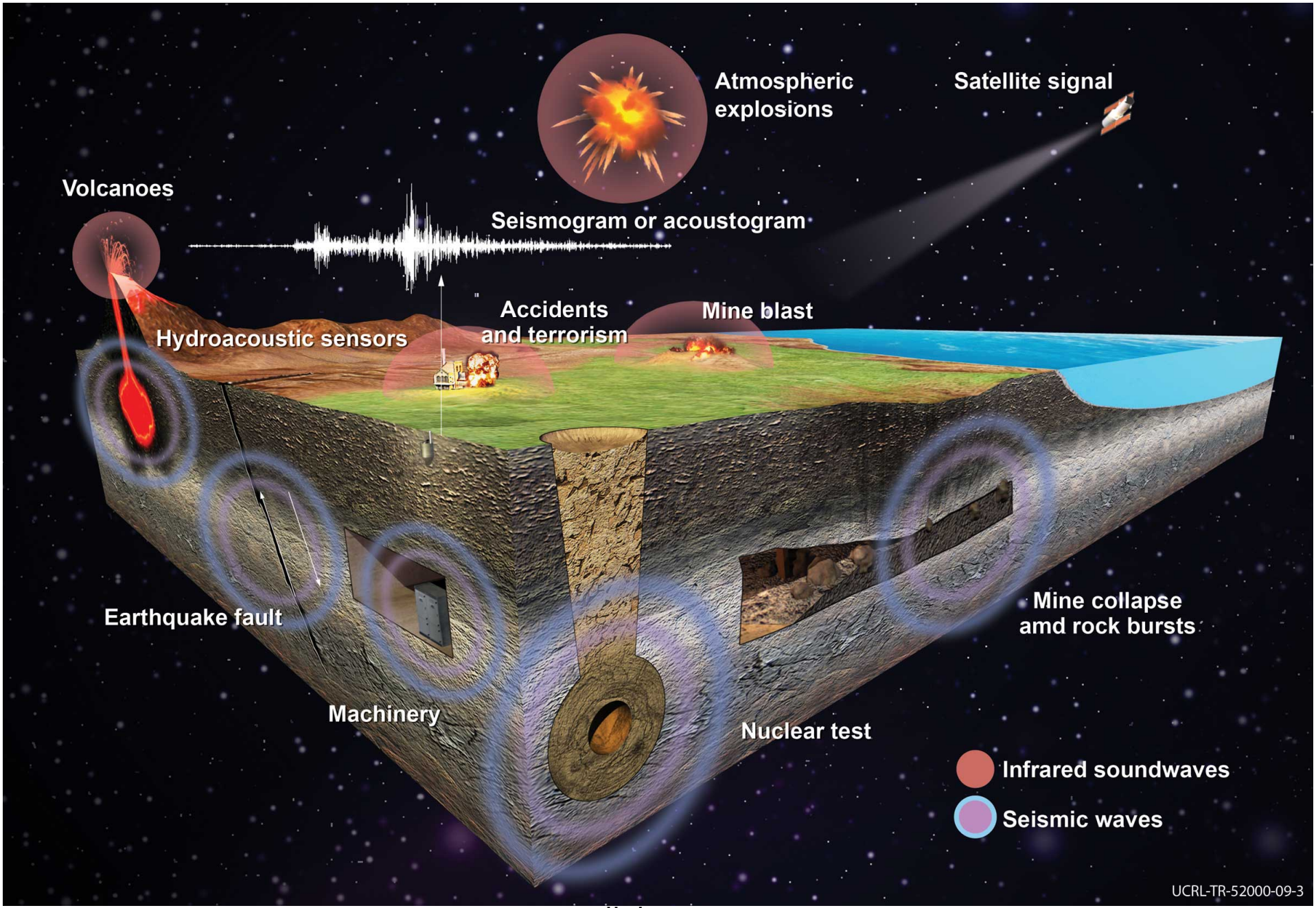
Institut des sciences de la Terre

Goal: differentiate, classify different seismic events



llnl.gov

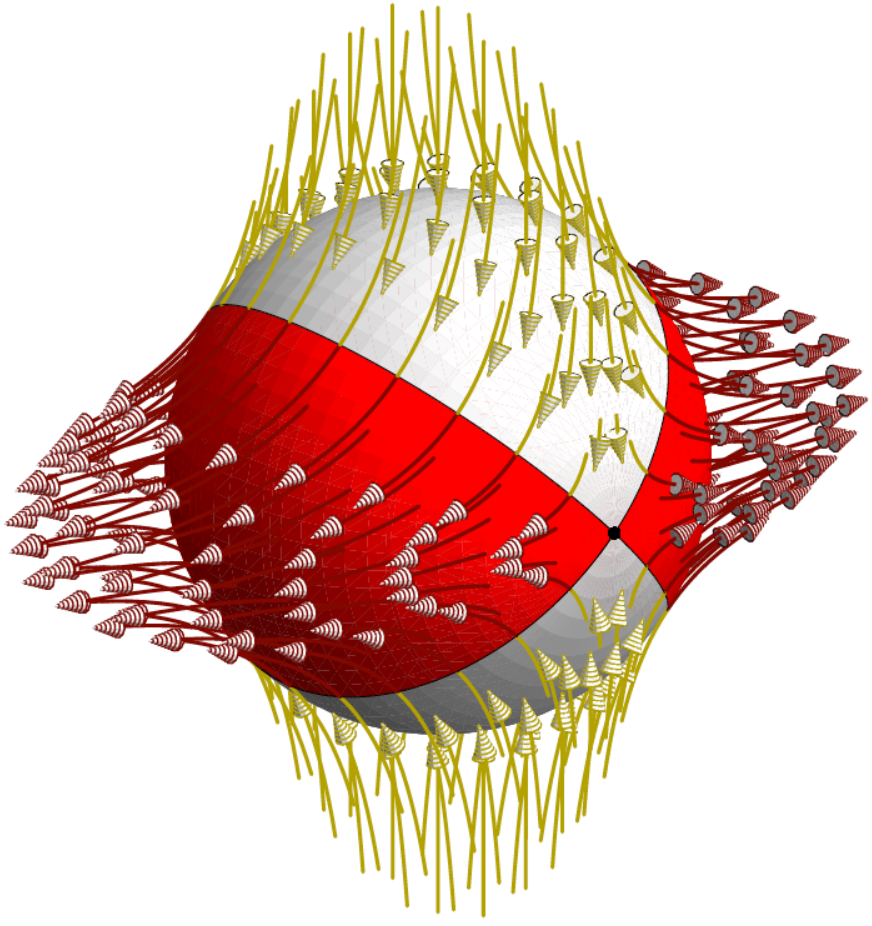
Seismic source representation – moment tensors

- A moment tensor $\mathbf{M}$ is 3×3 symmetric matrix
- U: orientation matrix
- $\mathbf{\Lambda}$: moment tensor eigenvalues

$$\mathbf{M} = U\,[\mathbf{\Lambda}]\,U^{-1}$$

$$[\mathbf{\Lambda}] = \begin{pmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{pmatrix}$$

- **KEY: eigenvalues λ determine coloring of the beachball**



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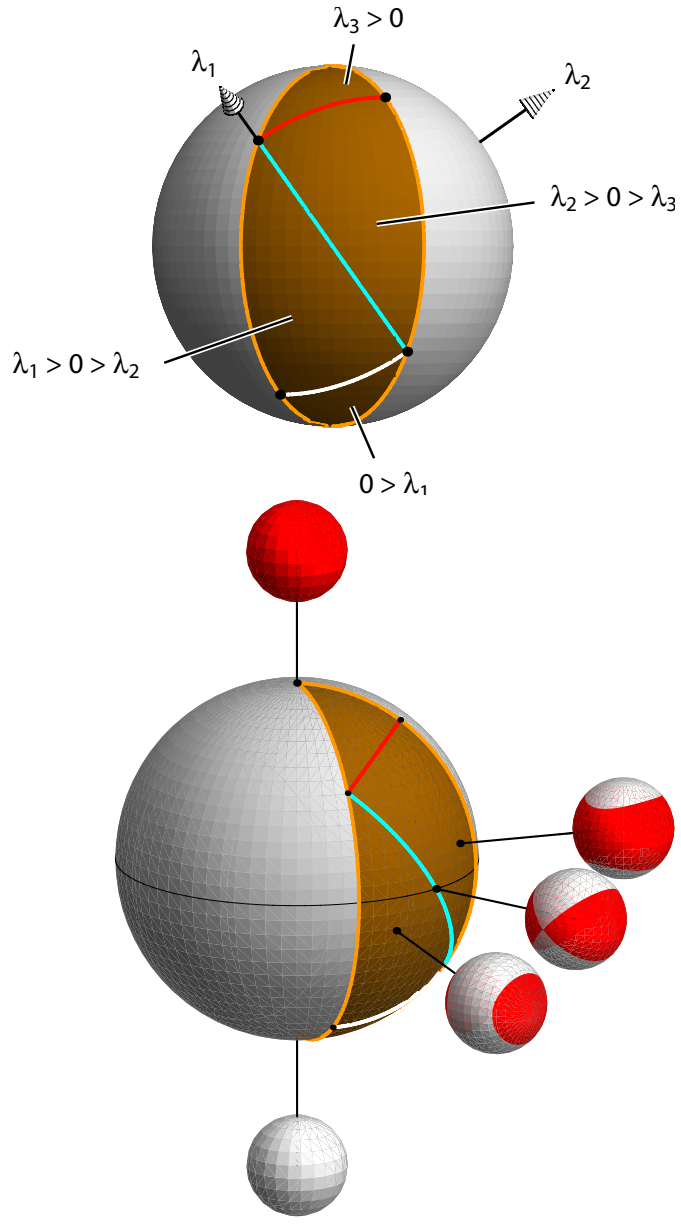
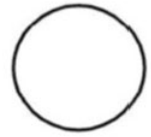
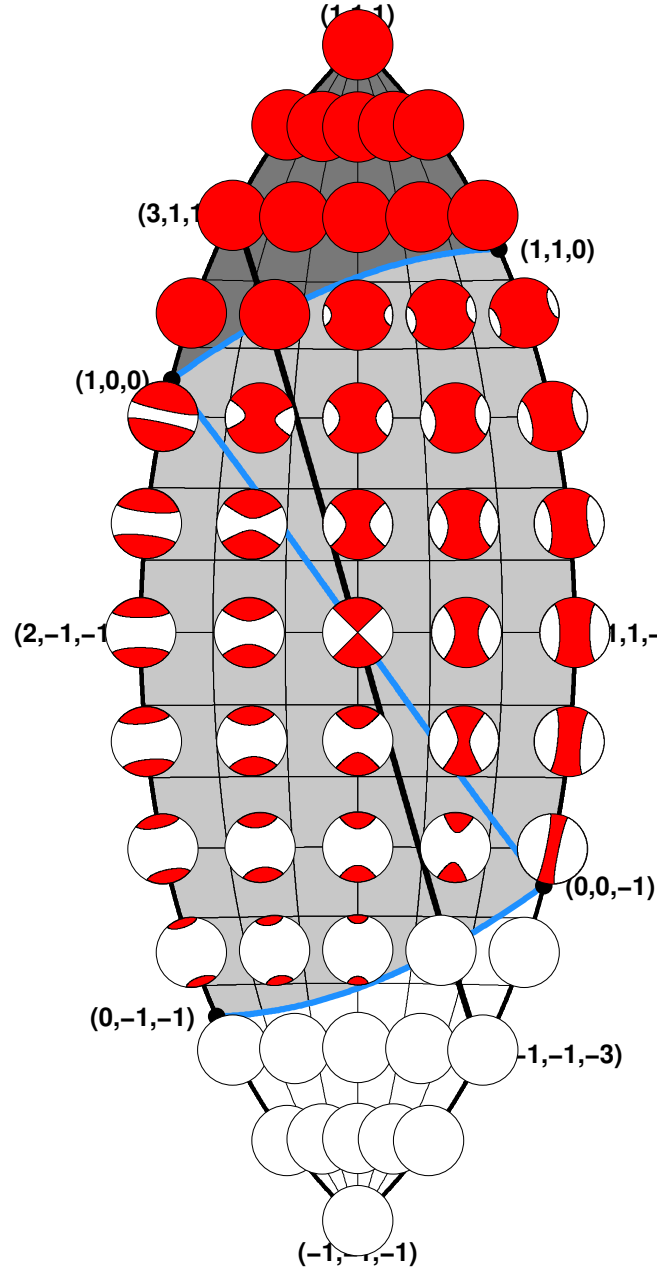


Tape & Tape (2012)

Eigenvalues organize on a **lune** source-type plot

Moment tensor	Beachball	Moment tensor	Beachball
$\frac{1}{\sqrt{3}}\begin{pmatrix}1&0&0\\0&1&0\\0&0&1\end{pmatrix}$		$-\frac{1}{\sqrt{3}}\begin{pmatrix}1&0&0\\0&1&0\\0&0&1\end{pmatrix}$	
$-\frac{1}{\sqrt{2}}\begin{pmatrix}0&1&0\\1&0&0\\0&0&0\end{pmatrix}$		$\frac{1}{\sqrt{2}}\begin{pmatrix}1&0&0\\0&-1&0\\0&0&0\end{pmatrix}$	
$\frac{1}{\sqrt{2}}\begin{pmatrix}0&0&-1\\0&0&0\\-1&0&0\end{pmatrix}$		$\frac{1}{\sqrt{2}}\begin{pmatrix}0&0&0\\0&0&-1\\0&-1&0\end{pmatrix}$	
$\frac{1}{\sqrt{2}}\begin{pmatrix}-1&0&0\\0&0&0\\0&0&1\end{pmatrix}$		$\frac{1}{\sqrt{2}}\begin{pmatrix}0&0&0\\0&-1&0\\0&0&1\end{pmatrix}$	
$\frac{1}{\sqrt{6}}\begin{pmatrix}1&0&0\\0&-2&0\\0&0&1\end{pmatrix}$		$\frac{1}{\sqrt{6}}\begin{pmatrix}-2&0&0\\0&1&0\\0&0&1\end{pmatrix}$	
$\frac{1}{\sqrt{6}}\begin{pmatrix}1&0&0\\0&1&0\\0&0&-2\end{pmatrix}$		$-\frac{1}{\sqrt{6}}\begin{pmatrix}1&0&0\\0&1&0\\0&0&-2\end{pmatrix}$	



A geometric parameterization for moment tensors

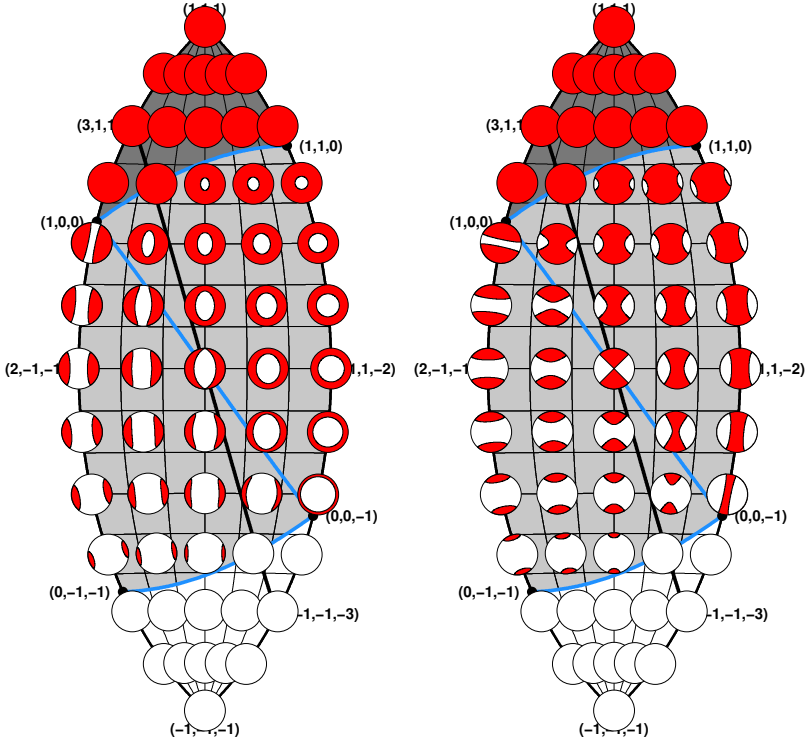
(Tape & Tape, 2012)

$$\mathbf{M}(\gamma, \delta, \kappa, \theta, \sigma) = [\mathbf{\Lambda}(\gamma, \delta)]_{\widehat{U}(\kappa, \theta, \sigma)}$$

- (γ, δ) describe location on the lune
- (κ, σ, θ) describe the beachball orientation
- Magnitude $\propto ||\mathbf{\Lambda}||$

Goal: Find moment tensor that best fits observations, estimate MT uncertainties

lune longitude	$-30 \leq \gamma \leq 30$
lune latitude	$-90 \leq \delta \leq 90$
strike	$0 \leq \kappa \leq 360$
dip	$0 \leq \theta \leq 90$
rake	$-180 \leq \sigma \leq 180$
magnitude	



Grid search
full moment tensor space

Algorithm to estimate full moment tensors + uncertainties

Journal of Geophysical Research: Solid Earth

RESEARCH ARTICLE
10.1029/2017JB015325

Estimation of Full Moment Tensors, Including Uncertainties, for Nuclear Explosions, Volcanic Events, and Earthquakes

Key Points:
- We estimate full moment tensors for 116 events: nuclear explosions,

Celso Alvizuri[1,2], Vipul Silwal[1], Lion Krischer[3], and Carl Tape[1]

Moment tensor estimation

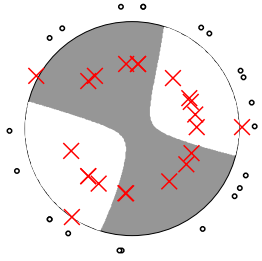
- Efficient grid search FMT space (5D, 30M+ solutions)
- For each MT compute synthetic waveforms (local 1D model)
- Evaluate misfit between observed and synthetic
- Each event requires careful analysis of waveforms & parameters

Uncertainty estimation

- Homogeneous distribution of solutions in moment tensor space
- Assess full ensemble of MTs evaluated in grid search
- Find best orientation at each point on the lune
- Confidence measure for MTs
- Probability for source types

Example moment tensor result

2016 Pawnee, Oklahoma (USA)

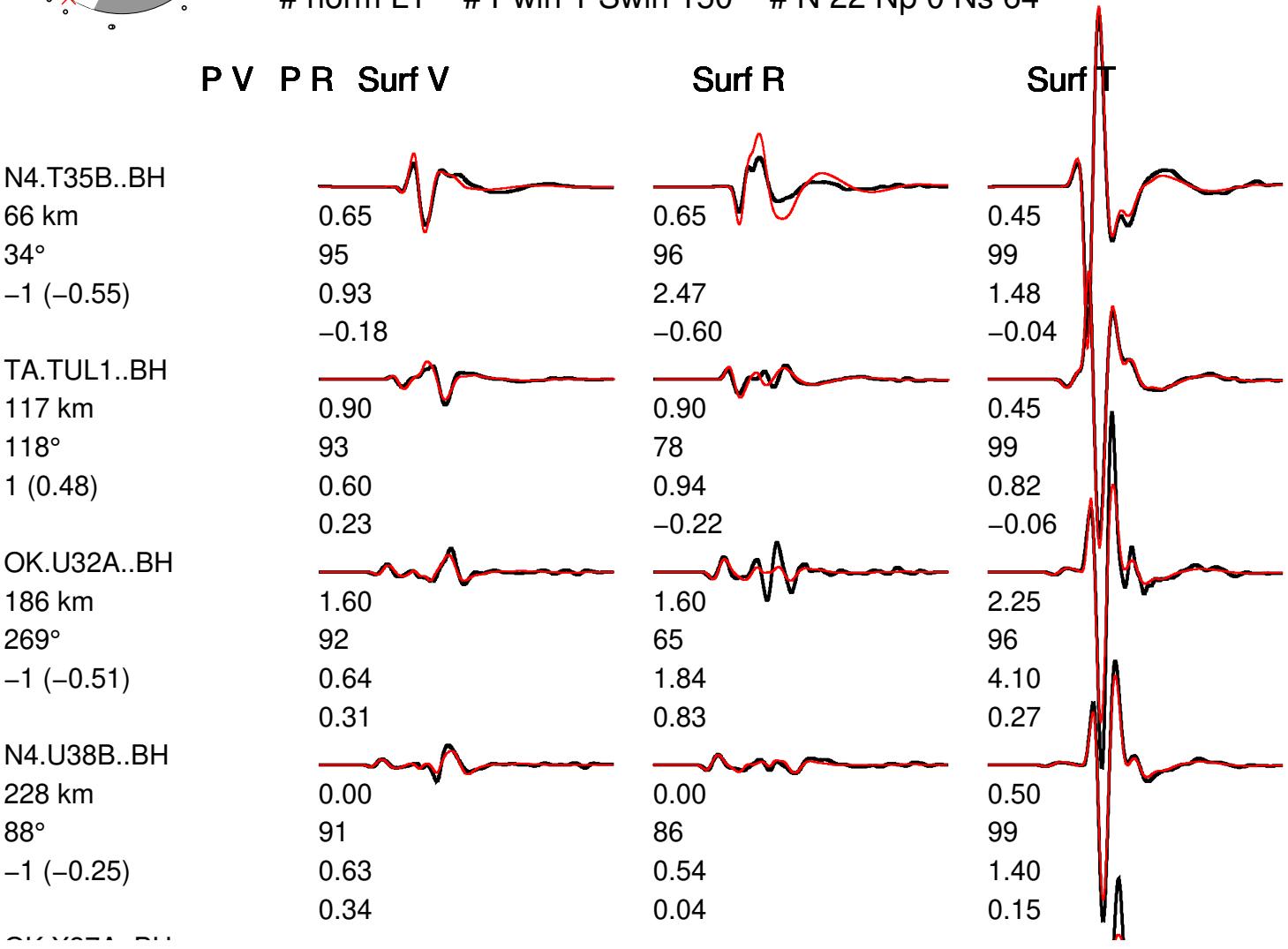


Event 20160903120244400 Model cus Depth 6

FM 106 89 5 Mw 5.60 γ 0 δ 3 rms 2.080e−01 VR 95.7 pol_wt 0.20

Filter periods (seconds): Body:0.50–3.33. Surf:10.00–50.00 duration: 2.00/1.

norm L1 # Pwin 1 Swin 150 # N 22 Np 0 Ns 64



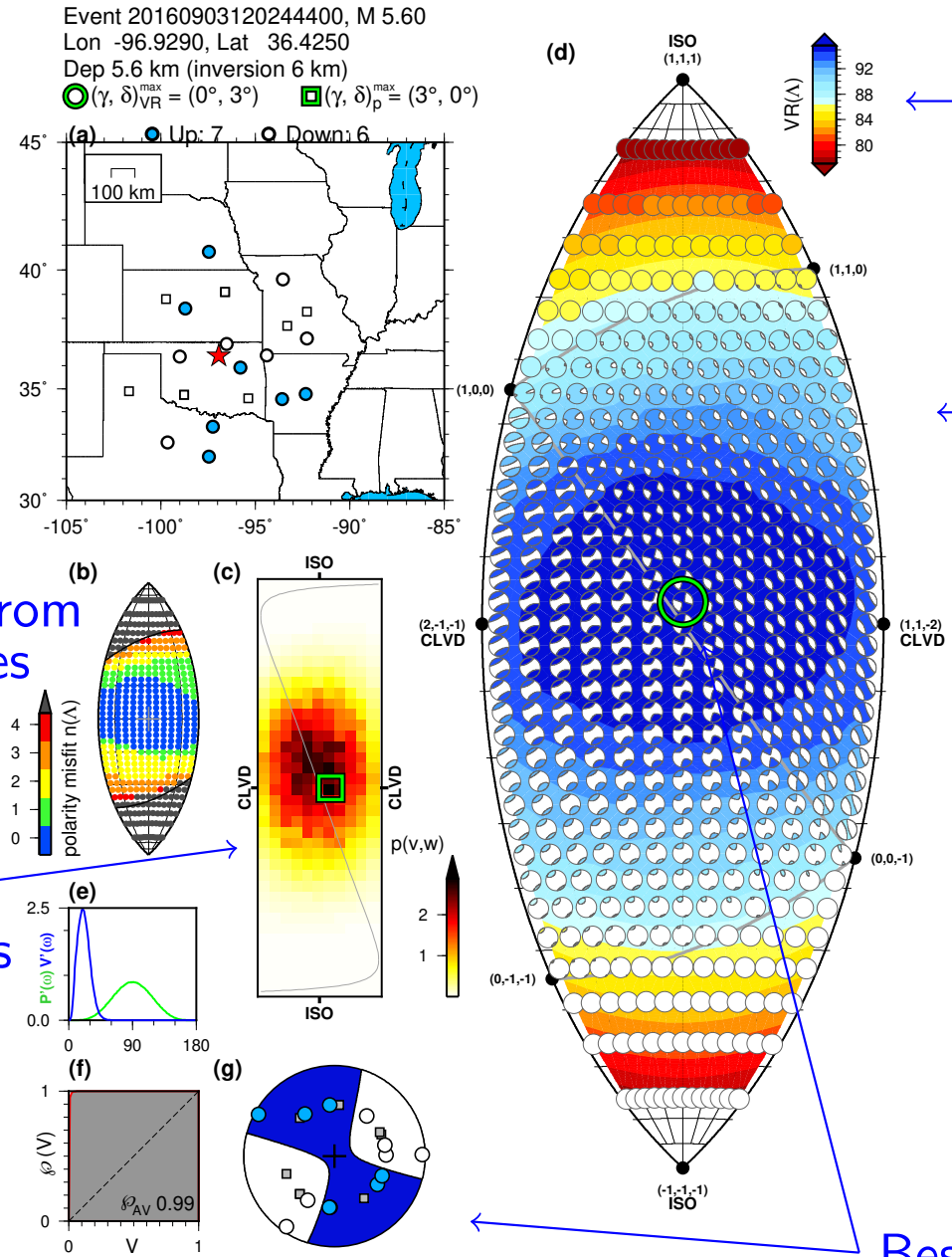
Example moment tensor uncertainty analysis

Station map

Permissible solutions from first motion polarities

PDF for source types

Confidence params.



← Variance Reduction

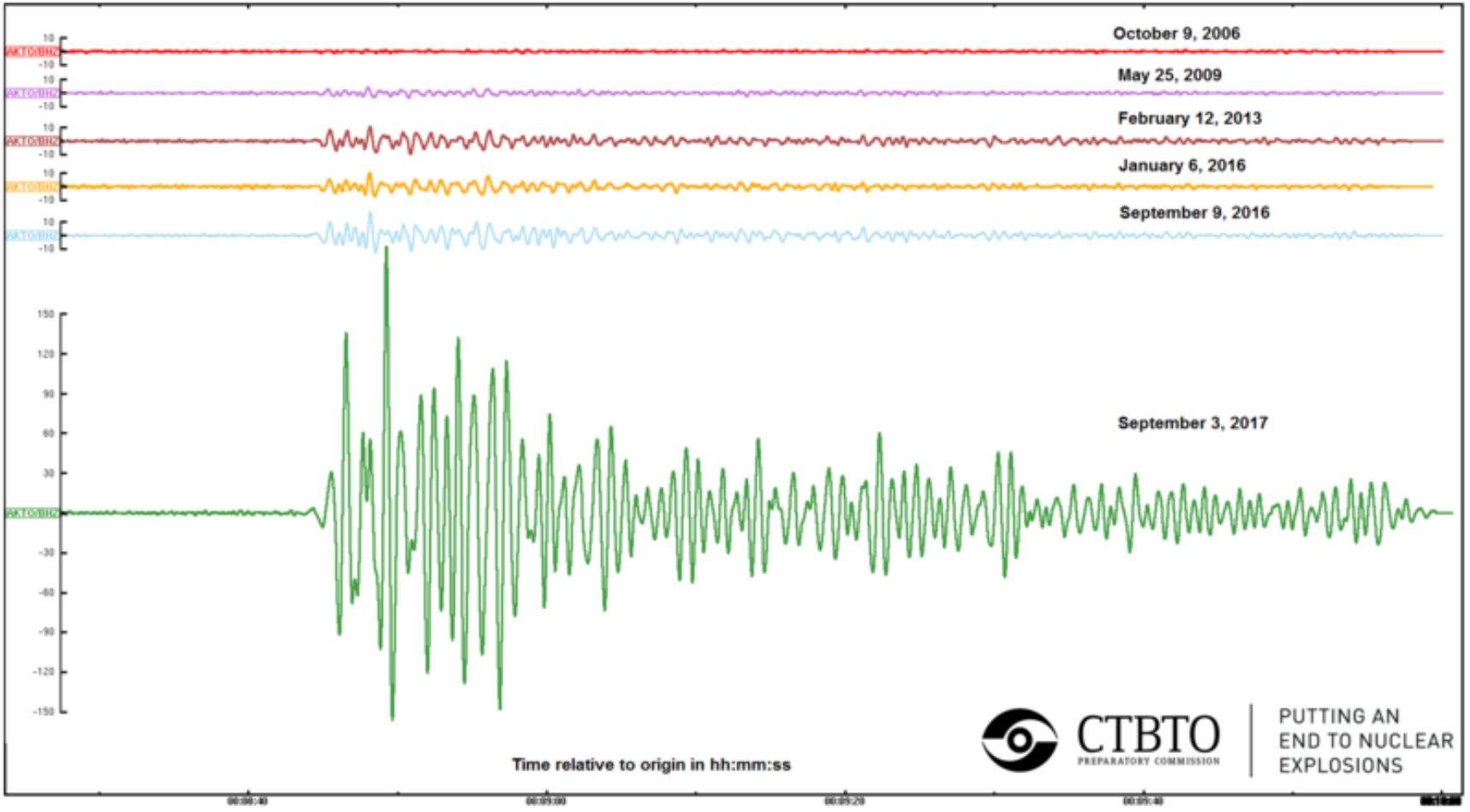
← VR by source type

Best mechanism

Application: The North Korea events

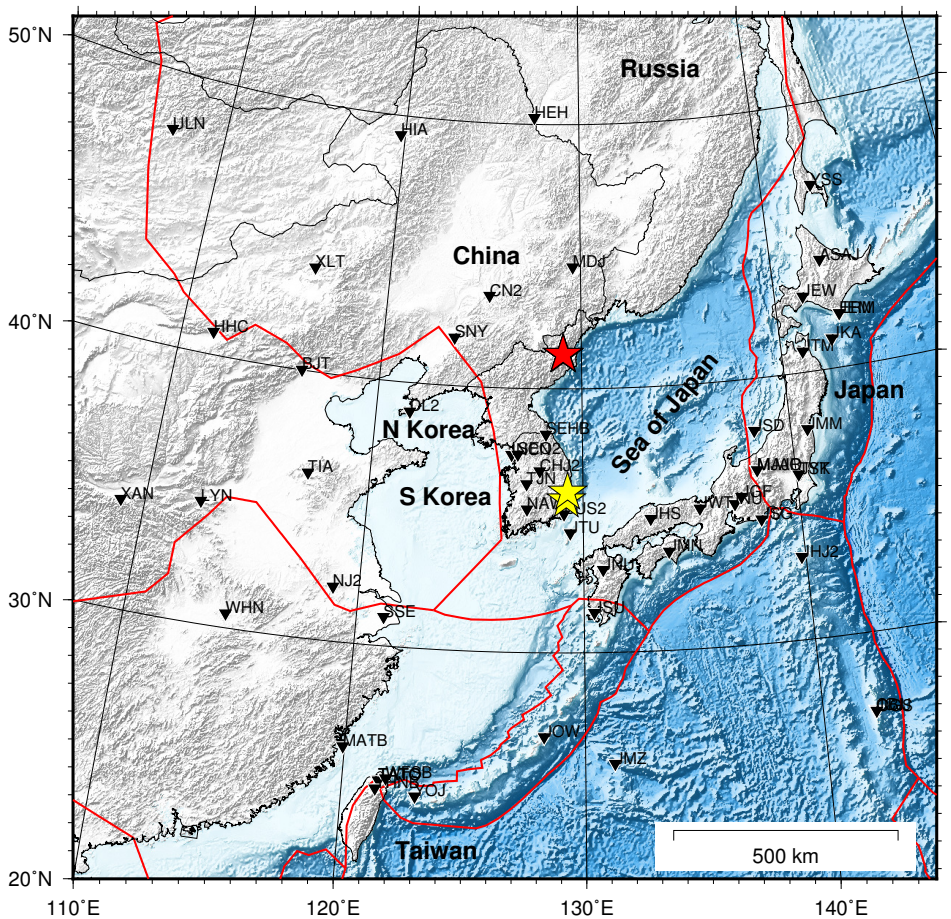
September 3, 2017 CTBTO press statement

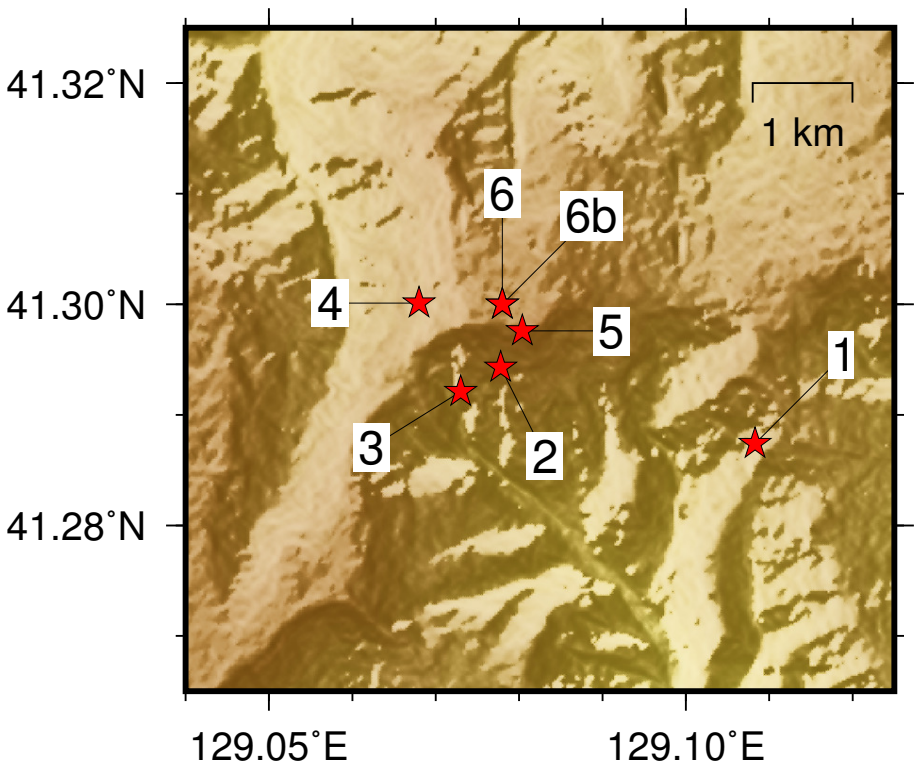
"Our monitoring stations picked up an unusual seismic event in the Democratic Peoples Republic of Korea (DPRK) today at 03:30 (UTC)..."



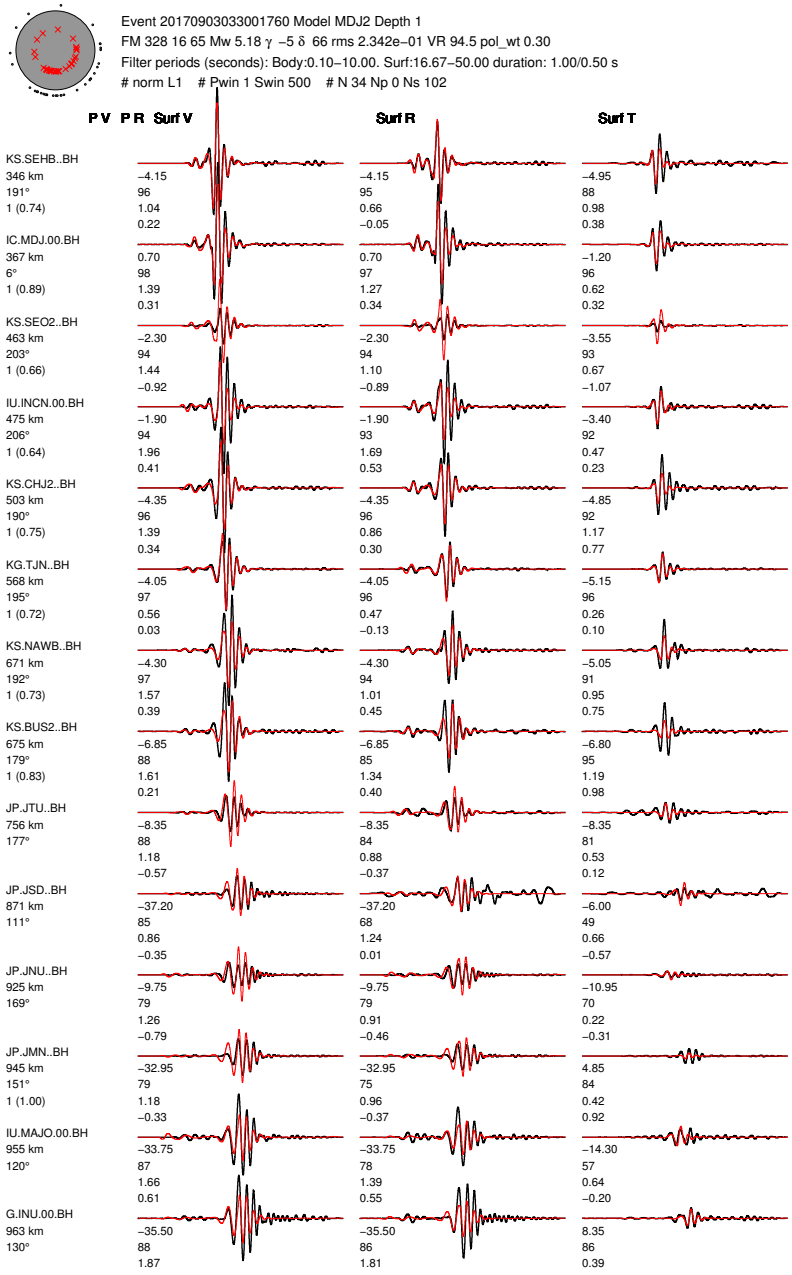
Study: Full Moment Tensor Analysis of Nuclear Explosions in North Korea (Alvizuri & Tape, 2018, SRL special issue)

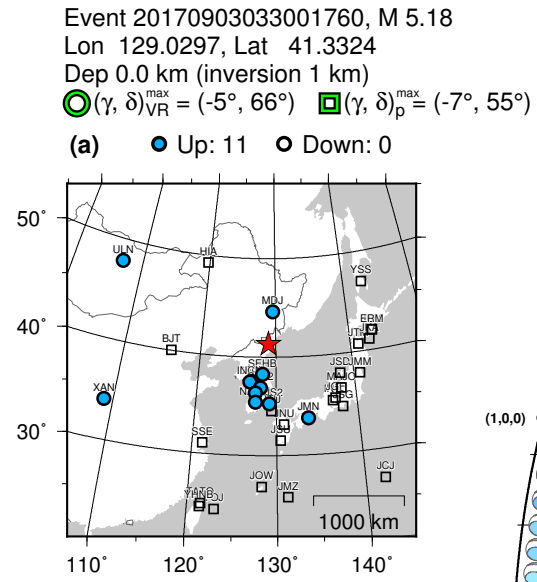
- 6 nuclear tests
- 1 unusual event
- 2 earthquakes in South Korea
- All available broadband stations within 2,000 km radius

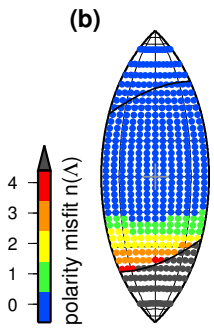


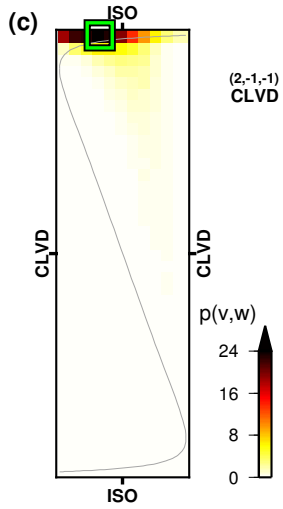


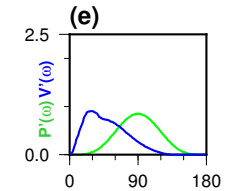
NK6 2017-09-03T03:30:01.760 (UTC) – main event

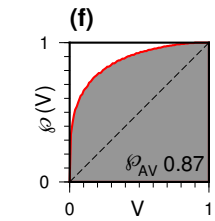


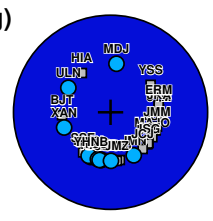


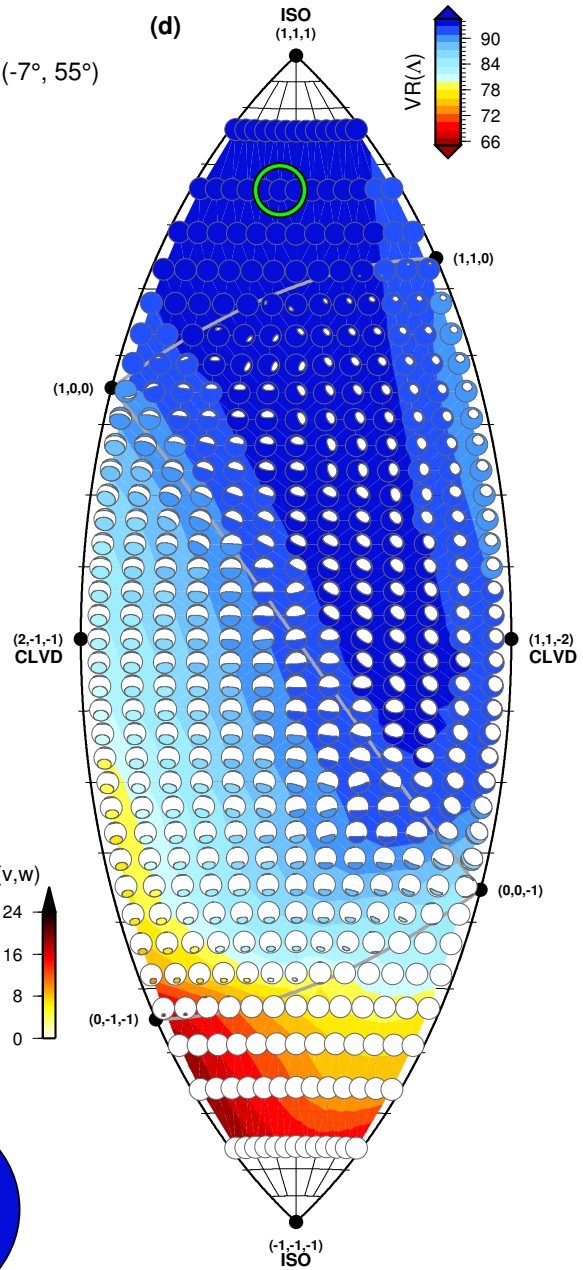




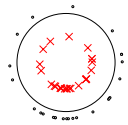




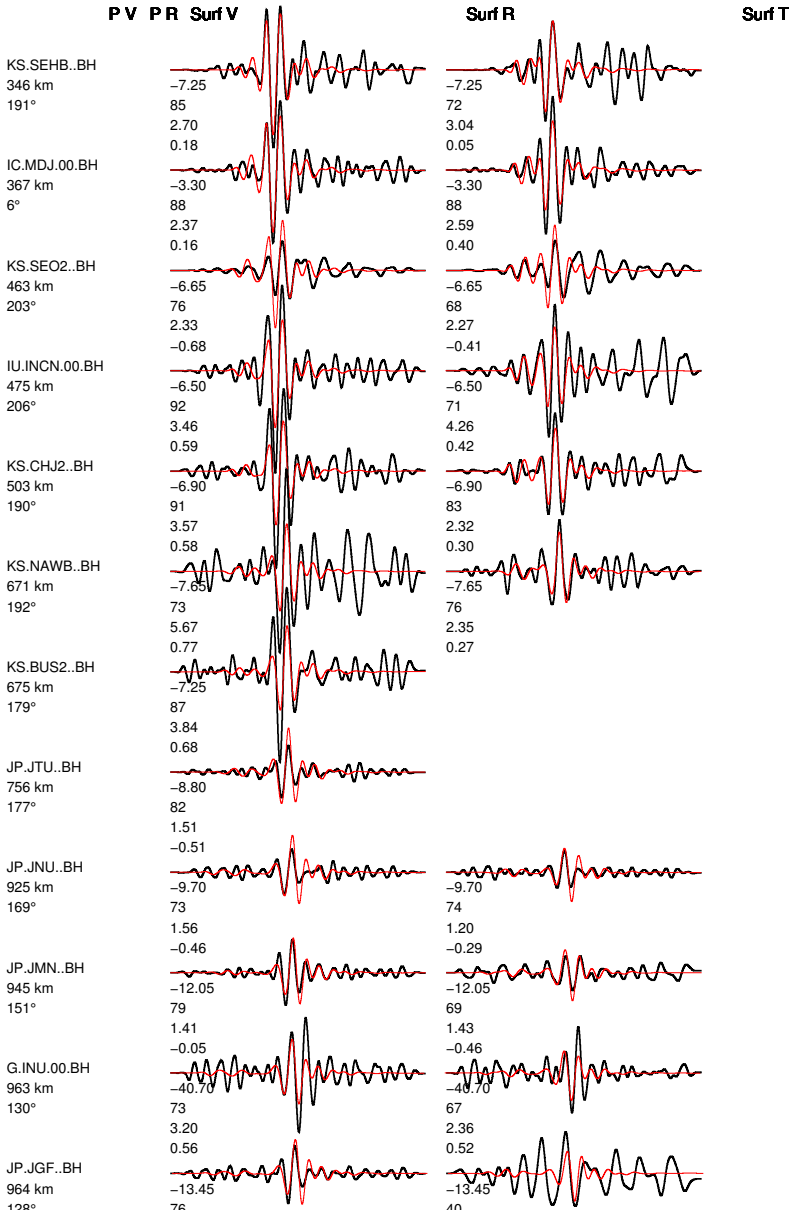




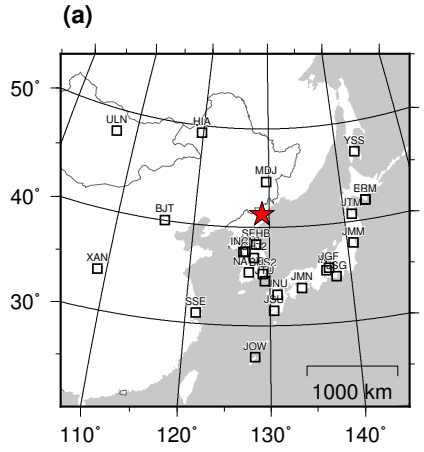
NK6 2017-09-03T03:38:31.810 (UTC) – unusual event



Event 20170903033831810 Model MDJ2 Depth 1
FM 86 37 15 Mw 4.20 γ 23 δ −87 rms 3.898e−01 VR 84.8 pol_wt 999.00
Filter periods (seconds): Body:0.10–10.00. Surf:25.00–50.00 duration: 1.00/0.50 s
norm L1 # Pwin 1 Swin 500 # N 25 Np 0 Ns 41

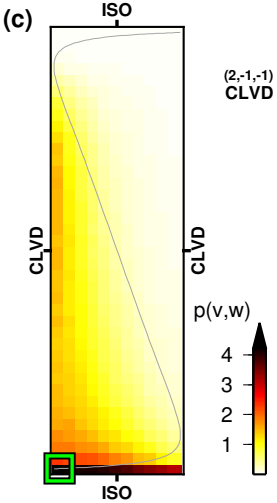


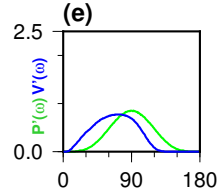
Event 20170903033831810, M 4.20
Lon 129.0310, Lat 41.3340
Dep 0.0 km (inversion 1 km)
$(\gamma, \delta)^{max}_{VR}$ = (23°, -76°) $(\gamma, \delta)^{max}_{p}$ = (-22°, -55°)

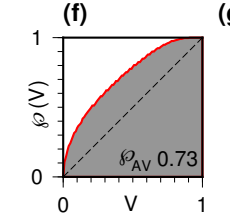


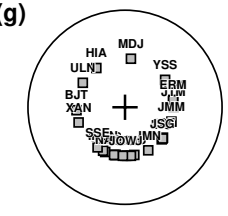
(b)

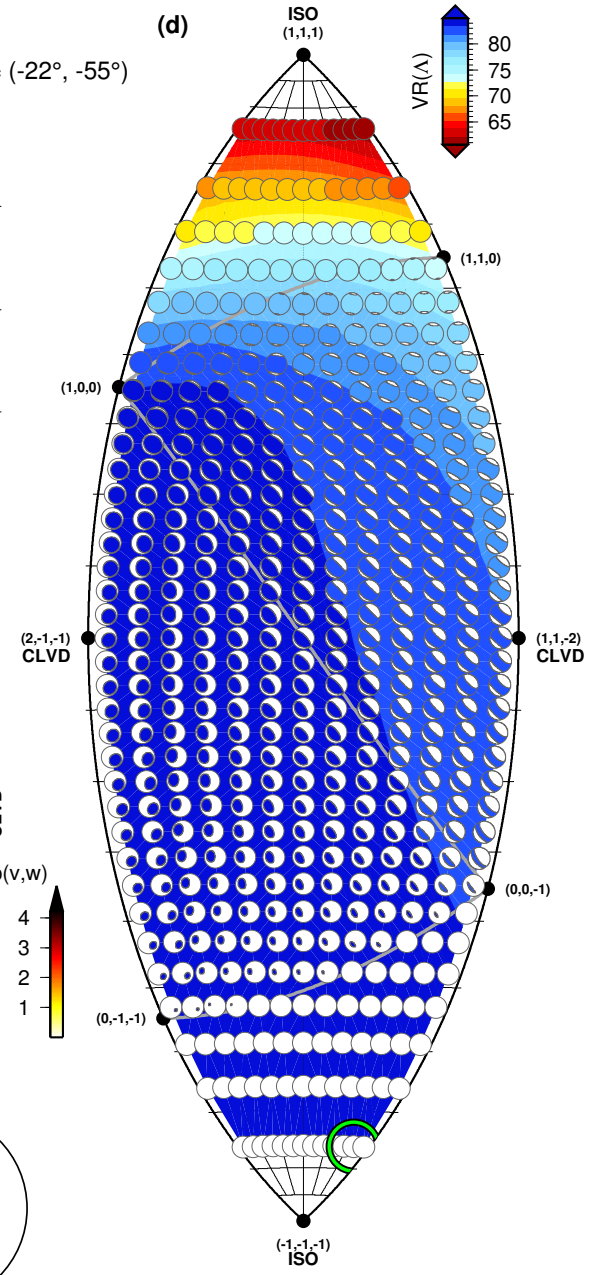
[No polarities]





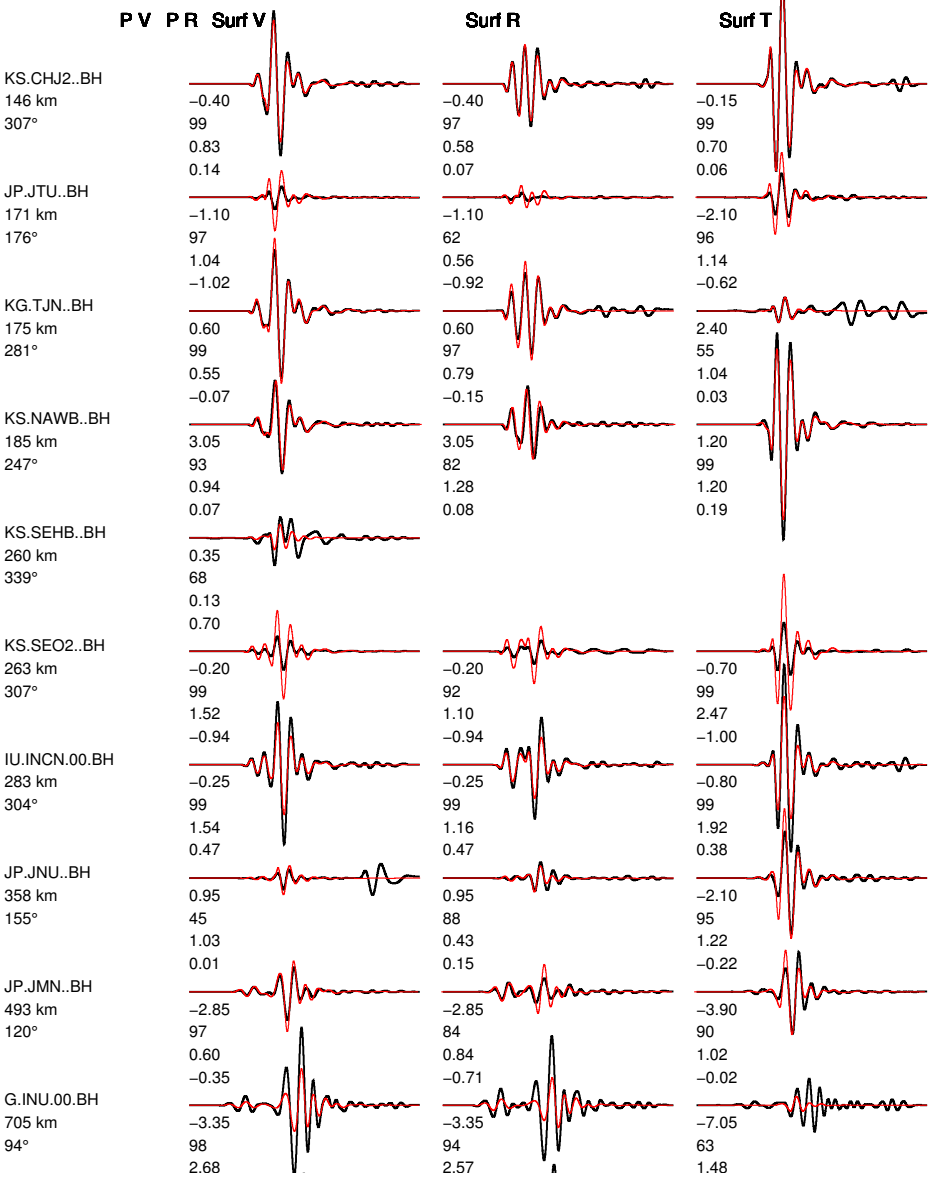




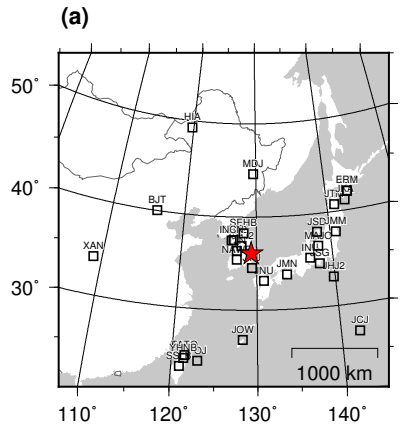


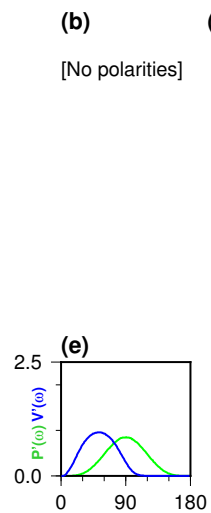
2017-11-15 Pohang

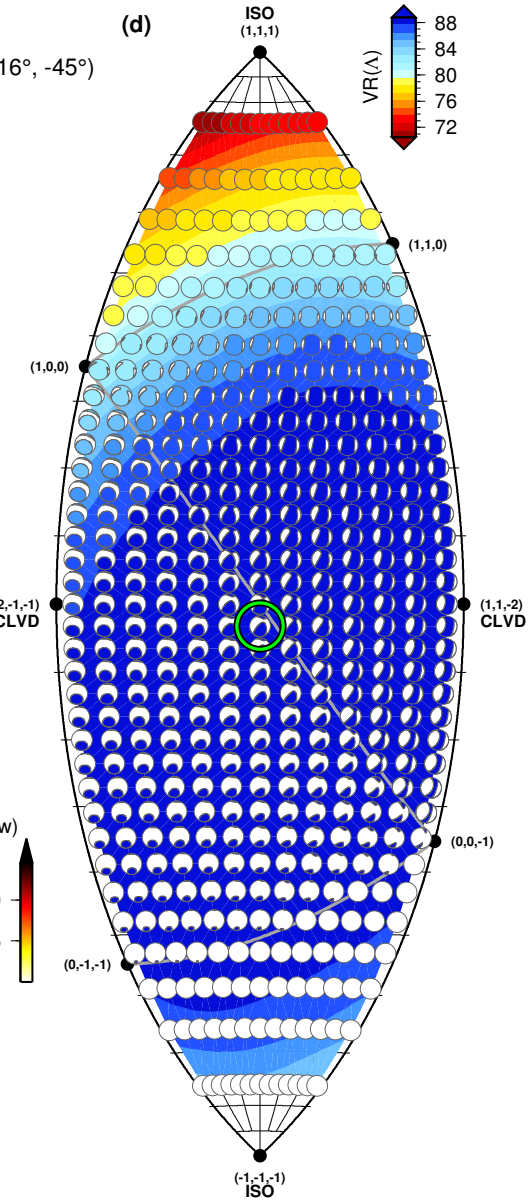
Event 20171115052932820 Model MDJ2 Depth 3
FM 333 42 25 Mw 5.20 γ 0 δ −3 rms 3.346e−01 VR 88.8 pol_wt 999.00
Filter periods (seconds): Body:0.10–10.00. Surf:20.00–50.00 duration: 1.00/0.50 s
norm L1 # Pwin 1 Swin 400 # N 29 Np 0 Ns 82



Event 20171115052932820, M 5.20
Lon 129.2800, Lat 36.0735
Dep 10.0 km (inversion 3 km)
$(\gamma, \delta)^{max}_{VR}$ = (0°, -3°) $(\gamma, \delta)^{max}_{p}$ = (-16°, -45°)

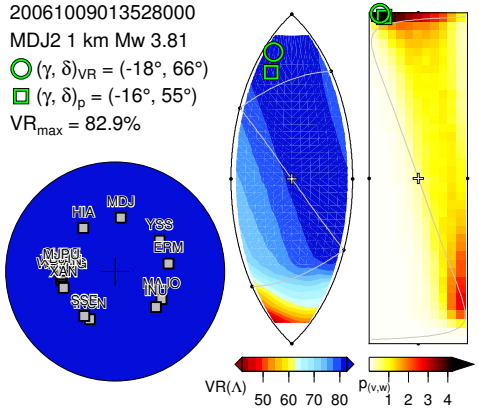






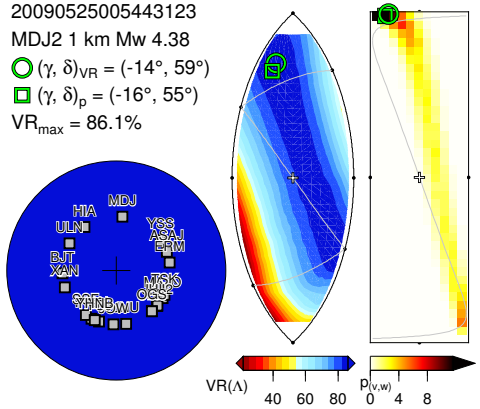
NK1 Mw 3.81

20061009013528000
MDJ2 1 km Mw 3.81
$(\gamma, \delta)_{VR}$ = (-18°, 66°)
$(\gamma, \delta)_{p}$ = (-16°, 55°)
VR_{max} = 82.9%



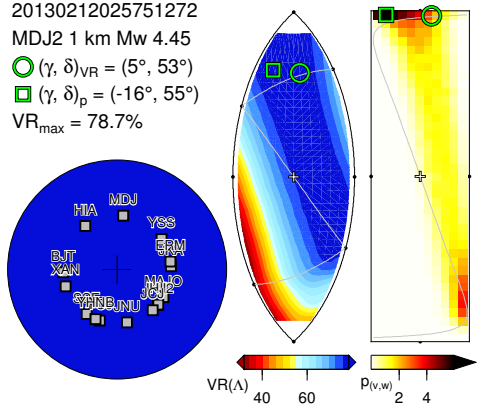
NK2 Mw 4.38

20090525005443123
MDJ2 1 km Mw 4.38
$(\gamma, \delta)_{VR}$ = (-14°, 59°)
$(\gamma, \delta)_{p}$ = (-16°, 55°)
VR_{max} = 86.1%



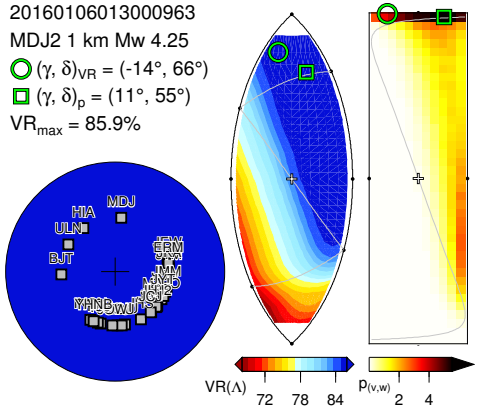
NK3 Mw 4.45

20130212025751272
MDJ2 1 km Mw 4.45
$(\gamma, \delta)_{VR}$ = (5°, 53°)
$(\gamma, \delta)_{p}$ = (-16°, 55°)
VR_{max} = 78.7%



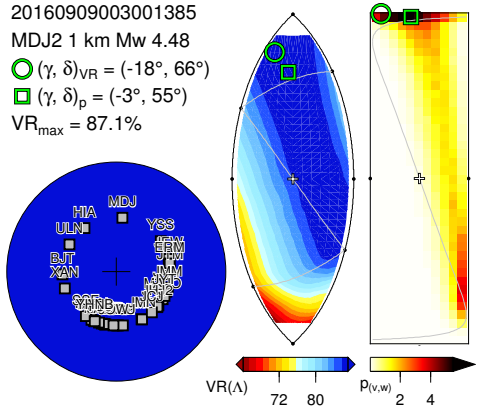
NK4 Mw 4.25

20160106013000963
MDJ2 1 km Mw 4.25
$(\gamma, \delta)_{VR}$ = (-14°, 66°)
$(\gamma, \delta)_{p}$ = (11°, 55°)
VR_{max} = 85.9%



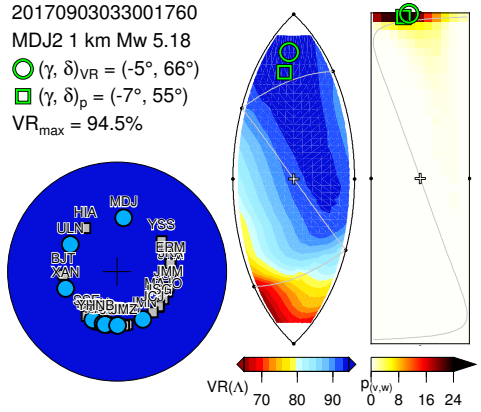
NK5 Mw 4.48

20160909003001385
MDJ2 1 km Mw 4.48
$(\gamma, \delta)_{VR}$ = (-18°, 66°)
$(\gamma, \delta)_{p}$ = (-3°, 55°)
VR_{max} = 87.1%



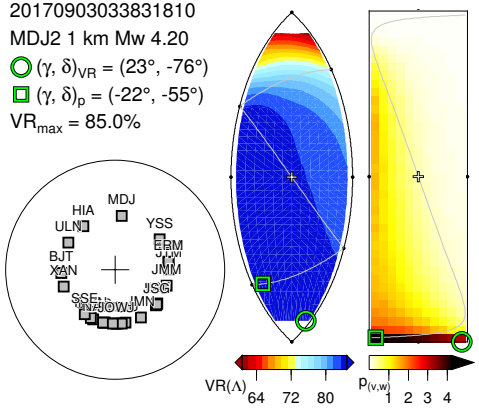
NK6 Mw 5.18

20170903033001760
MDJ2 1 km Mw 5.18
$(\gamma, \delta)_{VR}$ = (-5°, 66°)
$(\gamma, \delta)_{p}$ = (-7°, 55°)
VR_{max} = 94.5%



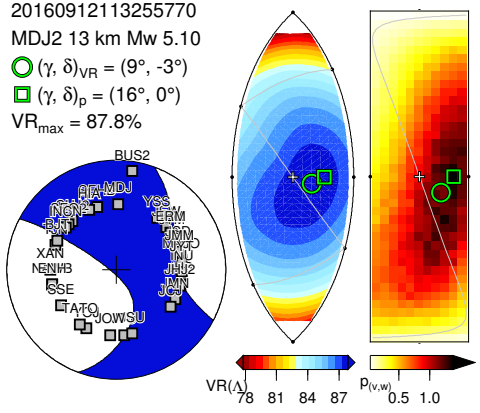
NK6b Mw 4.20

20170903033831810
MDJ2 1 km Mw 4.20
$(\gamma, \delta)_{VR}$ = (23°, -76°)
$(\gamma, \delta)_{p}$ = (-22°, -55°)
VR_{max} = 85.0%



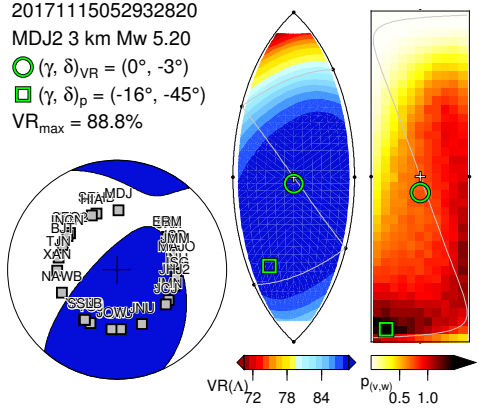
2016 Gyeongju Mw 5.1

20160912113255770
MDJ2 13 km Mw 5.10
$(\gamma, \delta)_{VR}$ = (9°, -3°)
$(\gamma, \delta)_{p}$ = (16°, 0°)
VR_{max} = 87.8%

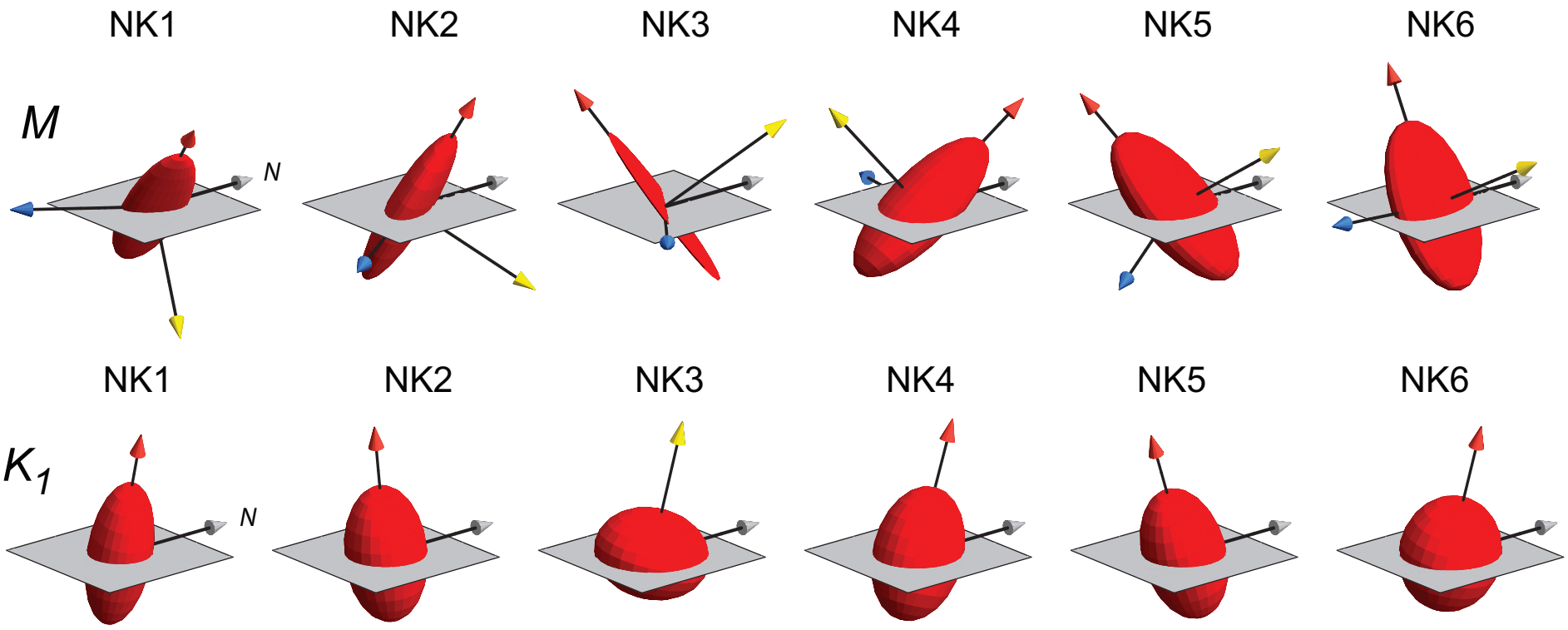


2017 Pohang Mw 5.2

20171115052932820
MDJ2 3 km Mw 5.20
$(\gamma, \delta)_{VR}$ = (0°, -3°)
$(\gamma, \delta)_{p}$ = (-16°, -45°)
VR_{max} = 88.8%



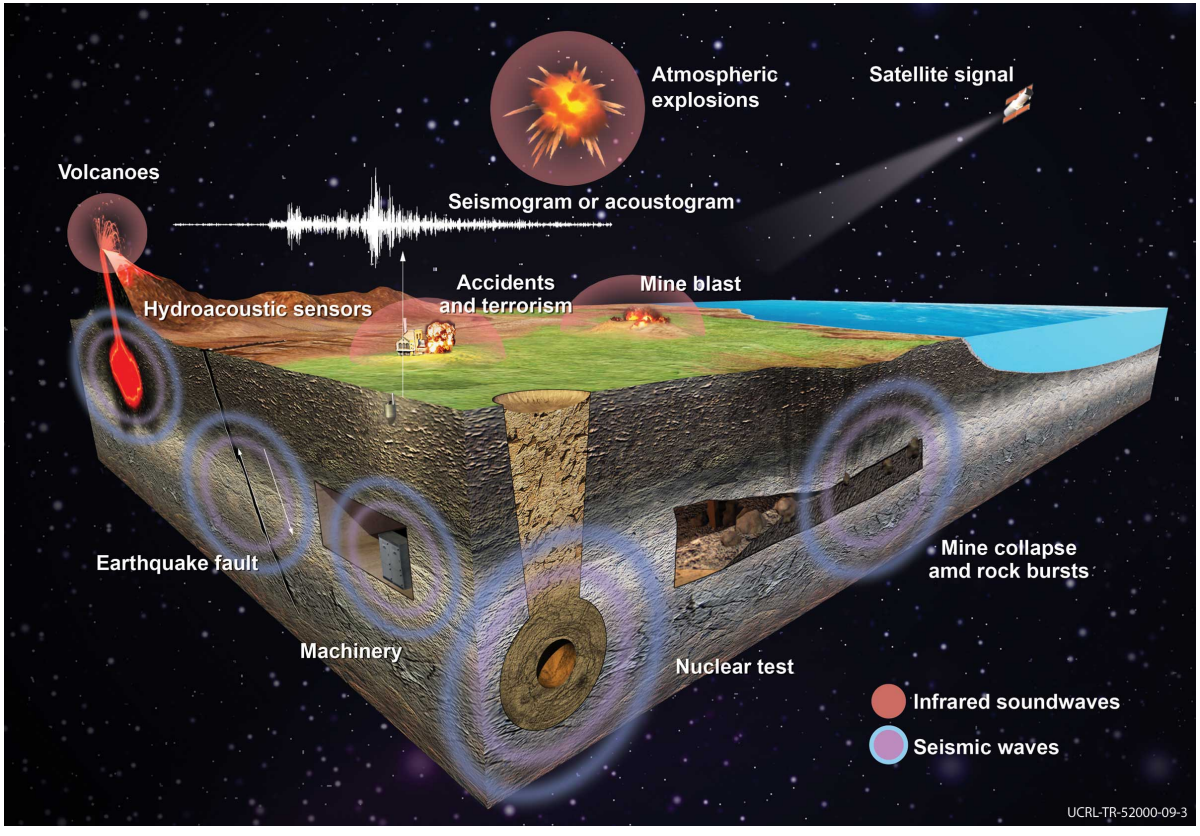
Seismic radiation patterns elongated rather than spherical



Ellipsoids (isocontours) enclosing the vector field associated with a moment tensor
Top: Full moment tensor. Bottom: Crack tensor (M = Crack + double couple)

- Crack tensors also used by others to model nuclear explosions
- Crack tensors for the NK events show near horizontal crack planes
- The double-couple (non-isotropic) radiation varies from event to event. Perhaps can be constrained by ground deformation studies, microseismicity, field mapping

Perspectives



- Uncertainties
  - tradeoffs
  - structure
  - noise
  - limitations
    $\rightarrow$ essential for discussion of physical processes
- Many moment tensor applications
  - Explosions
  - Collapses
  - Volcanic events
  - Landslides (ongoing work)
  - **?**

Conclusion

Methology

- Grid search of full moment tensor space to find mechanism that best fits observed waveforms
- Several parameters to characterize moment tensor uncertainties

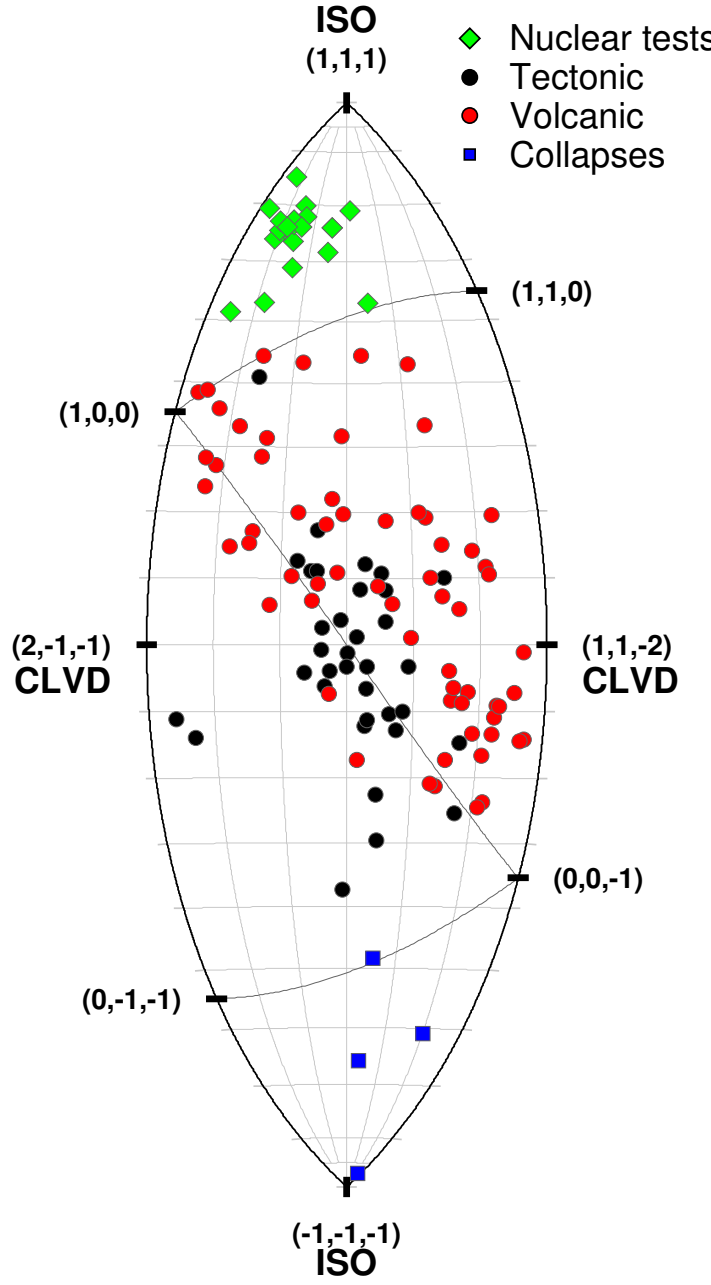
Applications in North and South Korea

- Progression of the NK nuclear tests from Mw 3.81 (NK1) to Mw 5.18 (NK6)
- A collapse event 8 min after NK6

Ongoing & future work

- Landslides
- Moment tensor+uncertainties for 3D structure
- Physical modeling for seismic sources

Thank you for your attention!



Alvizuri & Tape (2016, 2018); Alvizuri et al. (2018)

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