SnT 2023

CTBT: SCIENCE AND TECHNOLOGY CONFERENCE

HOFBURG PALACE - Vienna and Online

19 TO 23 JUNE

# Seismic source characterization and screening for three mining events in Sweden, eastern United States, and NW Russia

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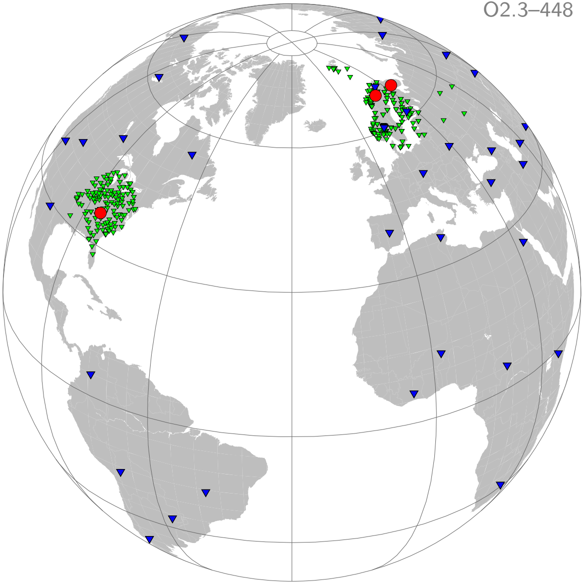
O2.3–448

Tue. 20 June 2023

NORSAR

# Outline

- Motivation
- Three minequakes
  - Sweden
  - USA
  - Russia
- IDC screening
- Moment tensor analysis
- Screening with moment tensors
- Conclusion



**Motivation:** We would like to routinely and robustly differentiate among explosions, earthquakes, collapses (+volcanic, landslides, meteors, induced, and any possible seismic sources)

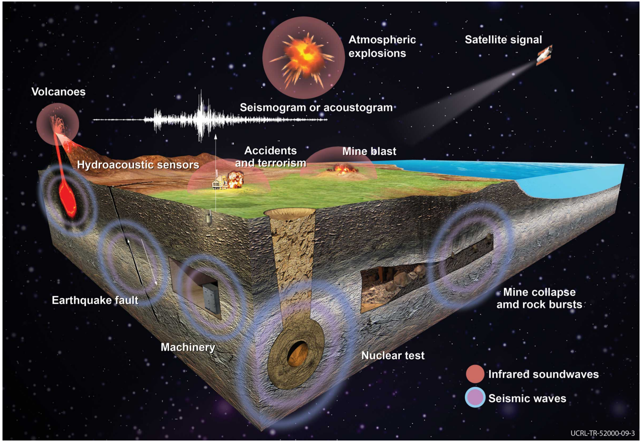
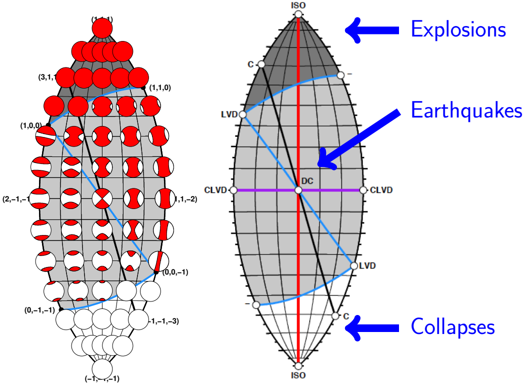


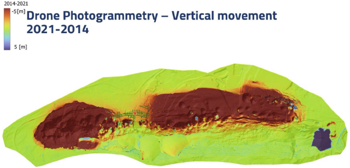

Figure from *Sleuthing seismic signals* (Walter, 2009, *LLNL S&T Mag.*)




The source-type lune (Tape & Tape, 2012). Different seismic events separate into different parts on the lune

## Kiruna, northern Sweden

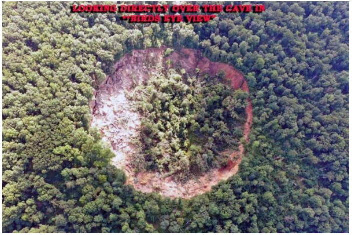
- 2020-05-18 01:11:56.20
- Kiirunavaara iron mine, underground
- mb 4.7 (IDC, nsta 39)
- Ms 3.9 (IDC, nsta 71)
- 253 geophones (not openly available)
- 80,000 aftershocks $-3 < \mathrm{M} < 2.0$




*The Kiruna seismic event: important insights from the geotechnical model (Mawson et al., 2022)*

## Tennessee, USA

- 2021-08-13 11:57:34.970
- Crab Orchard Mine and Mill, limestone, underground
- mb 4.0 (IDC, nsta 2)
- Ms N/A (IDC, nsta 0)
- ML 3.7 (IDC, nsta 2)

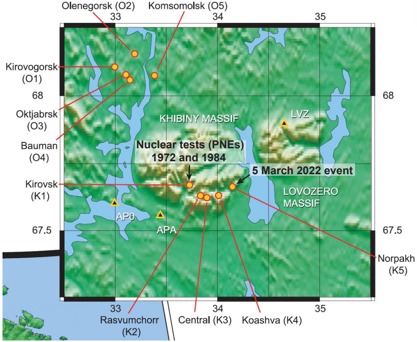



www.crossvillenews1st.com

www.therobotreport.com/how-robots-helped-a-collapsed-mine-get-back-in-operation/

## Norpakh, Kola Peninsula, Russia

- 2022-03-05 00:13:25
- Apatite mine, open pit (?)
- mb 4.0 (IDC, nsta 18)
- Ms 3.6 (IDC, nsta 27)
- Near nuclear test sites

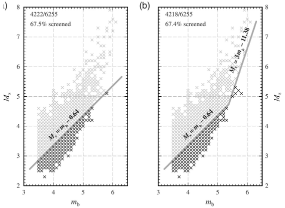



Harris & Kvaerna (2010)

# Screening explosions at IDC using Event Screening Criteria



- **Not screened out if Score<0**
  (i.e. could be an explosion)




Event screening line

Ford & Walter (2014) (left: Selby et al., 2012)

$$m_b - M_s + 1.96\sigma_M < 0.64^*$$

* Eq. 43, IDC/OPS/MAN/001/Rev.3, Sec. 7.3.2

WGB report, Session 34 of the Preparatory Commission, CTBT/PC-34/WGB/1

- Kiruna Event 18914909 (mb 4.7, Ms 3.0)
  **[NS] NOT SCREENED OUT. Score –2.03**

EVENT SUMMARY BLOCK

| Category | Score | Dscore | mscore | Rscore | Hscore | Smaj_sc | Smin_sc | Depth | Sdep | mbms | Smbms | Foffsh | MinWD | Clr |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| NS/Onsh | -2.03 | 0 | -2.03 | 0 | 0 | 6.1 | 4.3 | 0 | 0 | 0.76 | 0.12 | 0 | 0 | 0 |

- Tennessee Event 20919773 (mb 4.0, Ms N/A)
  **[IS] INSUFFICIENT DATA. No Ms**

EVENT SUMMARY BLOCK

| Category | Score | Dscore | mscore | Rscore | Hscore | Smaj_sc | Smin_sc | Depth | Sdep | mbms | Smbms | Foffsh | MinWD | Clr |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| IS/Onsh | 0 | 0 | 0 | 0 | 0 | 21.3 | 13.7 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

- NW Russia Event 21879684 (mb 4.0, Ms 3.6)
  **[SO] Screened out. Score 0.23**

Magnitude Block | Phase Block | Event Summary Block | Hydroacoustic Block | Regional Block

Copy Print

| Category | Score | Dscore | mscore | Rscore | Hscore | Smaj_sc | Smin_sc | Depth | Sdep | mbms | Smbms |
|---|---|---|---|---|---|---|---|---|---|---|---|
| SO/Onsh | 0.23 | 0.0 | 0.23 | 0.0 | 0.0 | 6.7 | 6.2 | 0.0 | 0.0 | 0.42 | 0.18 |

# Methodology

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JGR

**Journal of Geophysical Research: Solid Earth**

RESEARCH ARTICLE
10.1029/2017JB015325

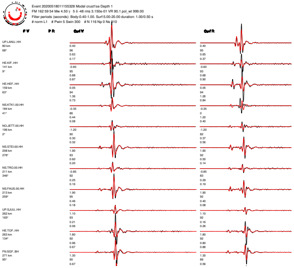
**Estimation of Full Moment Tensors, Including Uncertainties, for Nuclear Explosions, Volcanic Events, and Earthquakes**

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

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

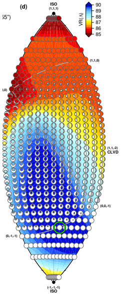
## Moment tensor estimation

- Propose focal mechanism
- Compute synthetic seismograms
- Compare observed:synthetic
- Repeat 40M times



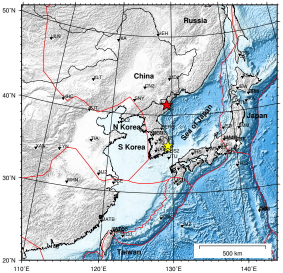
## Source type and uncertainty characterization

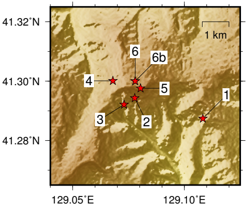
- Appraise ensemble solutions (40M)
- Probabilities for source types
- Sample moment tensor space
- Source types and uncertainties
- Source models (single, multiple processes)



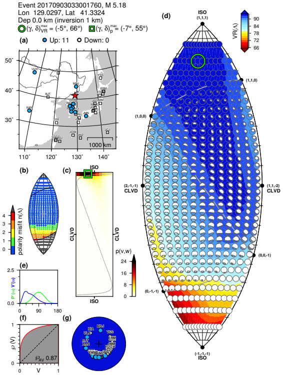
# Application to the 6 North Korea nuclear explosions

**Full Moment Tensor Analysis of Nuclear Explosions in North Korea (Alvizuri & Tape, 2018a, SRL Special Issue)**

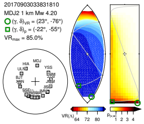


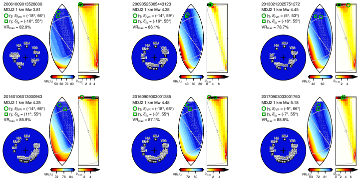

- The 6th nuclear event 2017-09-03T03:30:0176 Mw 5.18 (NK6)



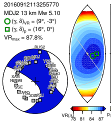

A collapse mechanism 8 min after NK6



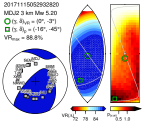

- The 6 nuclear tests



2016 Gyeongju

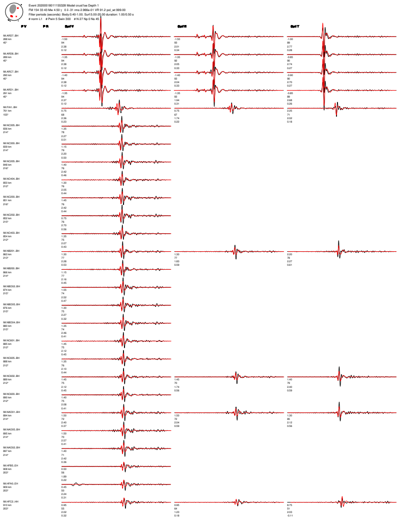



2017 Pohang



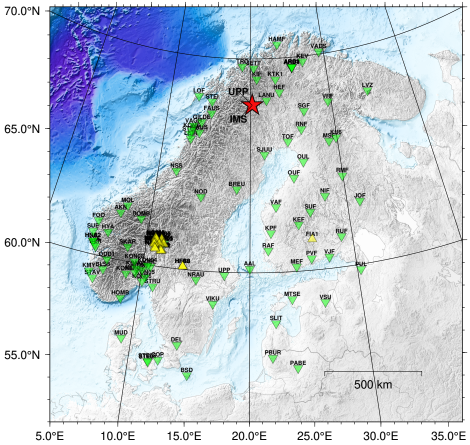
# **Kiruna event**: Moment tensors and waveform fits





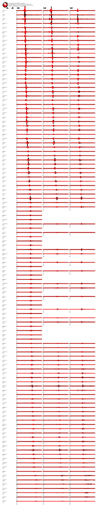
**IMS only:** ARCES, NOA, FINES, HFS

Total stations: 27, 288–910 km




**IMS + open:** 3R DK EE FN GB GE HE II IU NO NS PL QE UP

Total stations: 116, 80–1439 km



# **Kiruna event**: Moment tensor and source type analysis, IMS only

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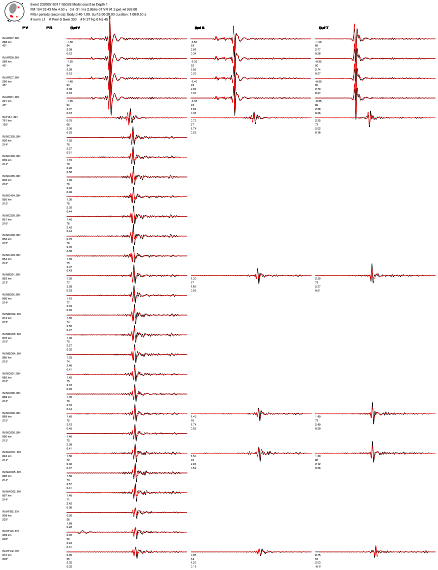
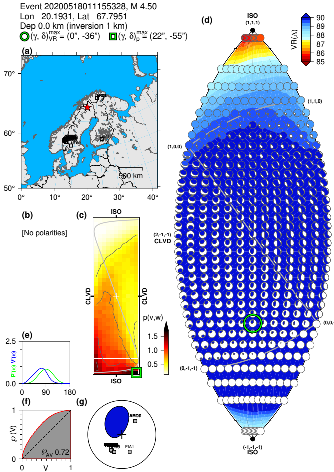
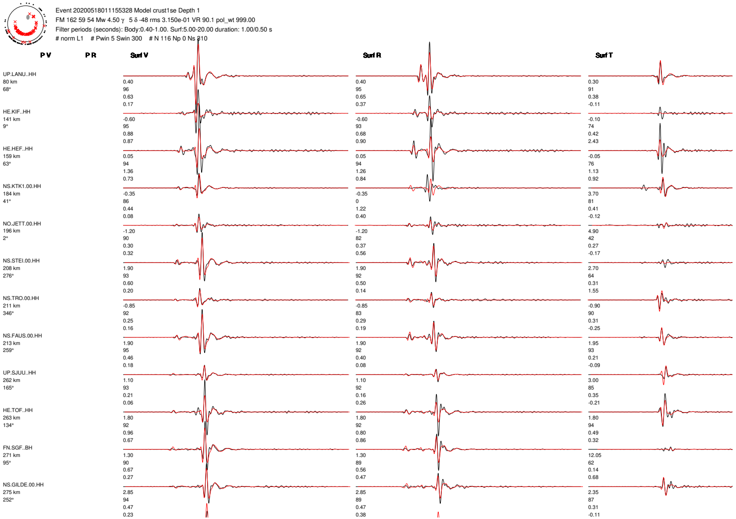
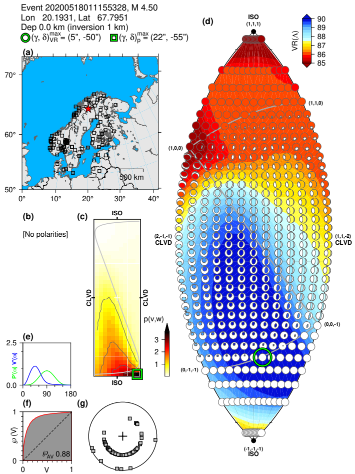




# **Kiruna event**: Moment tensor and source type analysis, IMS + open



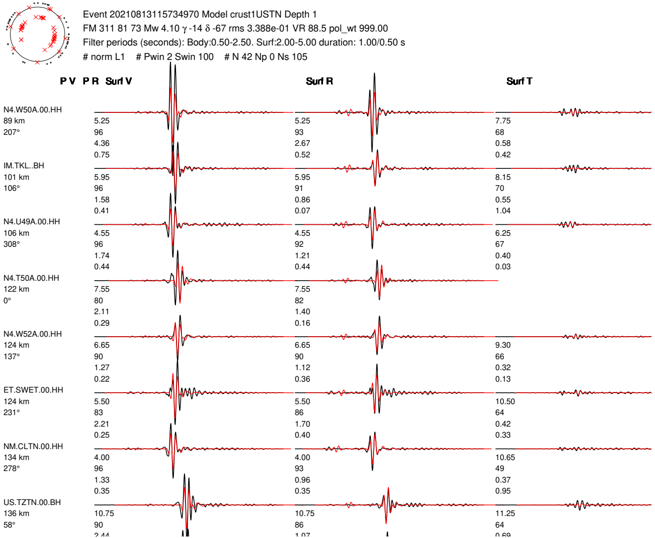


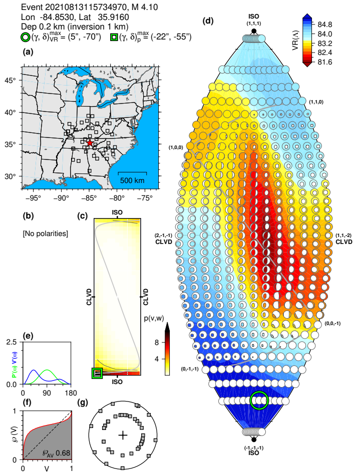




Total stations: 116, 80–1439 km. Snippet 80–275 km

# **Tennessee event**: Moment tensor and source type analysis, IMS + open

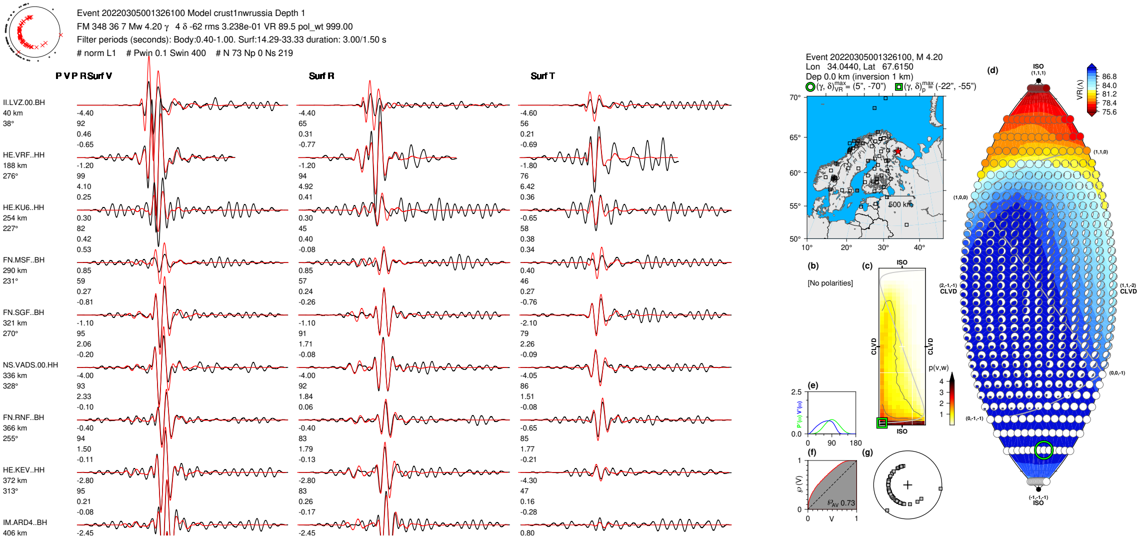





Total stations: 42, 89–677 km. Snippet: 89–136 km

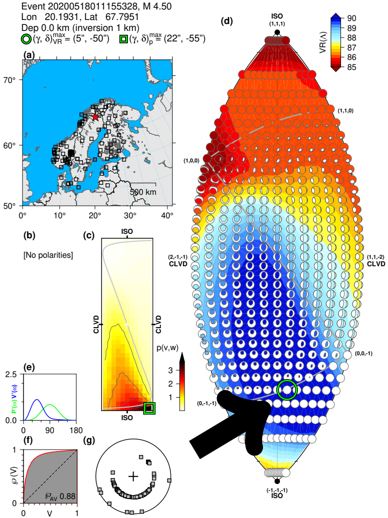
# **NW Russia event**: Moment tensor and source type analysis, IMS + open



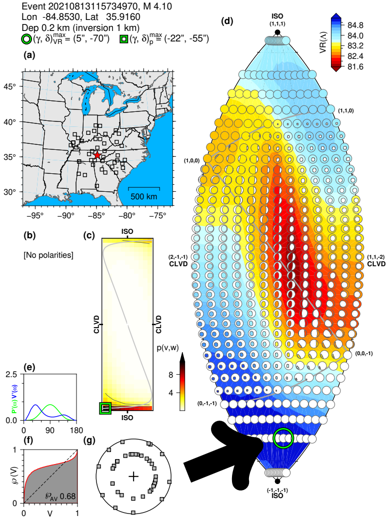

Total stations: 73, 40–1902 km. Snippet: 40–406 km

# Consistent –ISO (collapse) mechanisms for the three events

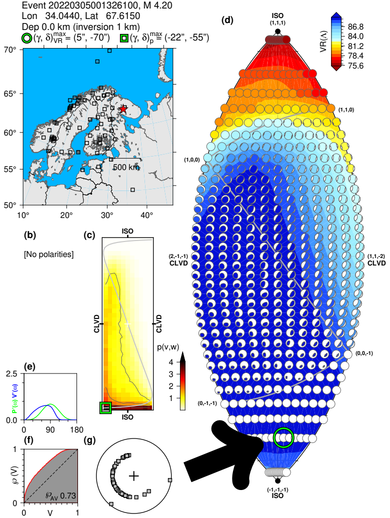
## Kiruna, Sweden

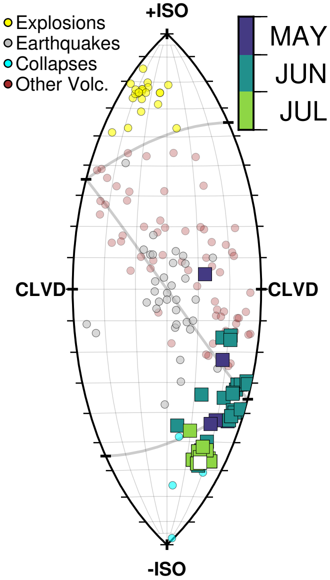



## Tennessee, USA




## NW Russia






*A progression of 54 M∼5 collapses in Kīlauea caldera, Hawaii (Alvizuri et al., 2021, EPSL)*



## Different seismic events separate into different parts on the lune

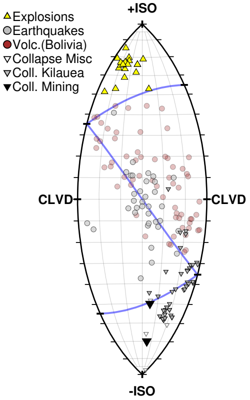
⇒ *Source screening with moment tensors*

- **Explosions** (top)
  Nuclear tests at Nevada Test Site, North Korea
- **Earthquakes** (center)
  Bolivia, Alaska, Europe, Scandinavia, etc
- **Collapses** (bottom)
  Sweden, Russia, USA, Hawaii

# Conclusion



- Three mining related events (M∼4) in Sweden, USA, Russia
- Inconsistent event screening at IDC
- Kiruna collapse screened as explosive
- Estimated moment tensors with waveforms from IMS + open stations
- Consistent collapse mechanisms (–ISO) for all events
- Need to supplement IMS with open stations for event screening




***Screening with moment tensors***

Thank you for your attention!

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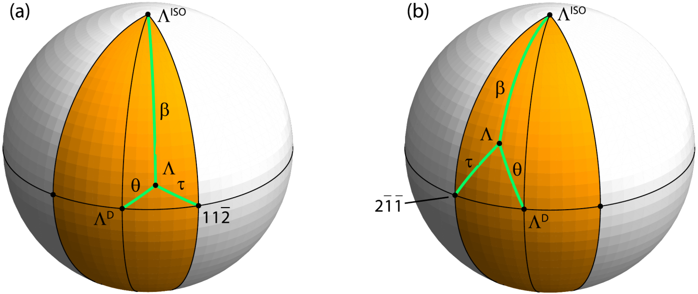
Walter, W., 2009. Sleuthing seismic signals, *Lawrence Livermore National Laboratory, Science & Technology Review, March*

# What is a good metric for source screening?



*The eigenvalue lune as a window on moment tensors (Tape & Tape, 2019)*




$\Rightarrow$ Angle or arc length as measure between any two mechanisms

- $\beta = \angle(\mathbf{\Lambda}^{DC}, \mathbf{\Lambda}^{X}) = 90^\circ \Rightarrow$ +ISO (explosion)
- $\beta = \angle(\mathbf{\Lambda}^{DC}, \mathbf{\Lambda}^{X}) = 0^\circ \Rightarrow$ DC (earthquake)
- $\beta = \angle(\mathbf{\Lambda}^{DC}, \mathbf{\Lambda}^{X}) = -90^\circ \Rightarrow$ –ISO (collapse)

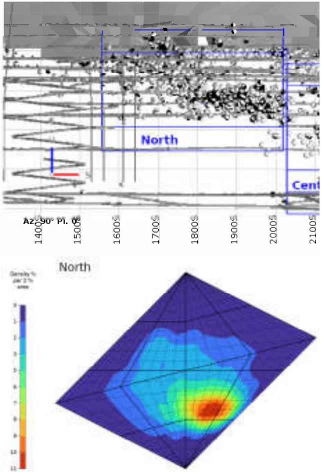
*cf., Ford et al. (2020) $\delta = \cos^{-1}(\mathbf{x}^T \hat{\boldsymbol{\mu}})$ is the angle $\delta$ from a mean explosion population $\hat{\boldsymbol{\mu}}$ to a newly estimated moment tensor $\mathbf{x}$.

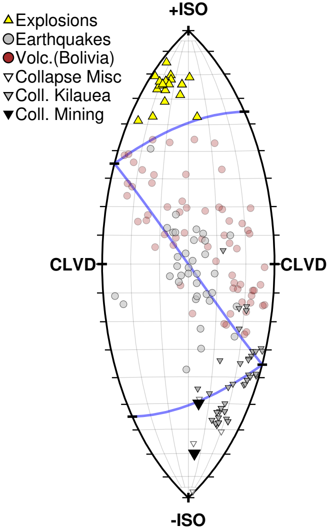
# Ever smaller events resolved with increasing sensor density

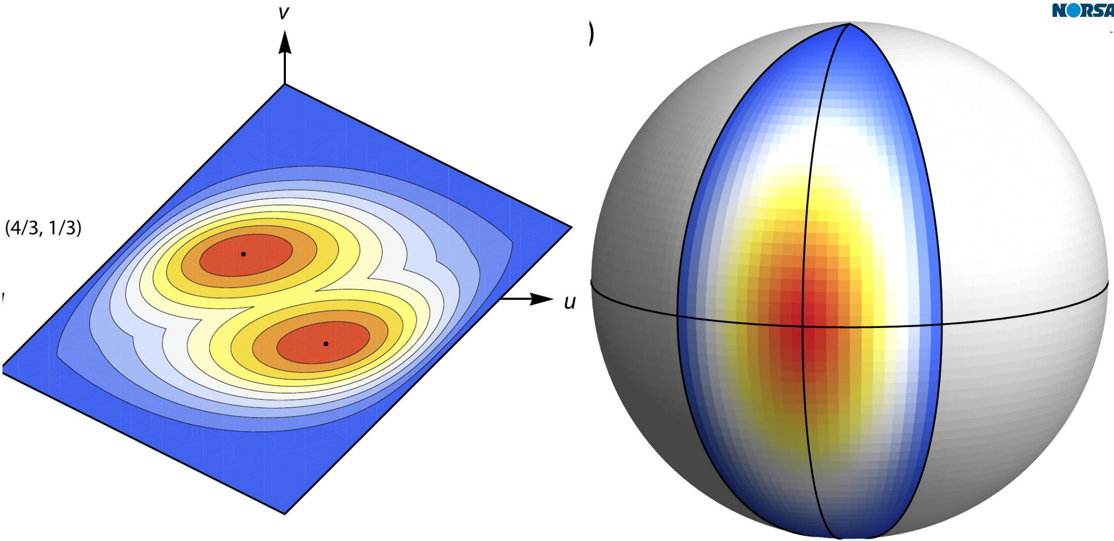


→ ***253 geophones, 80,000 aftershocks*** $-3 < M < 2.0$

*Source mechanisms of aftershocks, Kiruna north section (Dineva et al., 2022)*



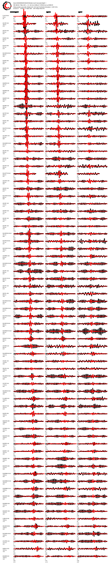


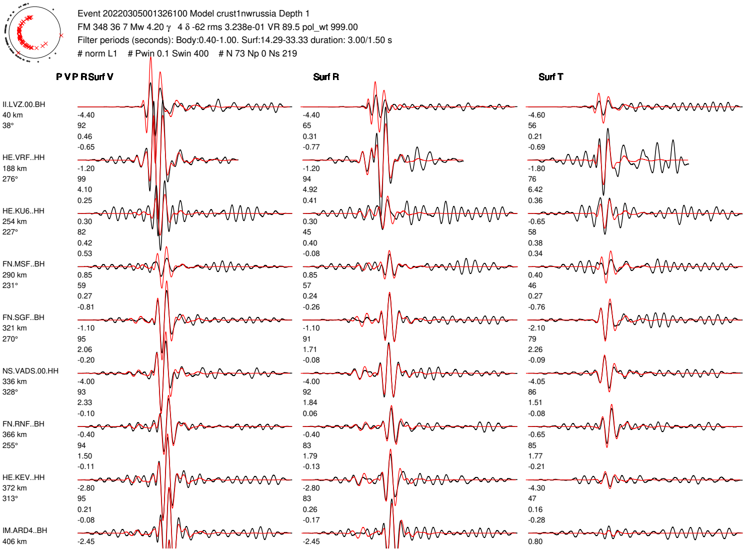

*Homogeneous distributions on the Hudson and Lune diagrams.*

*Figure from The eigenvalue lune as a window on moment tensors (Tape & Tape, 2019)*

# **NW Russia event**: Moment tensor and source type analysis, IMS + open

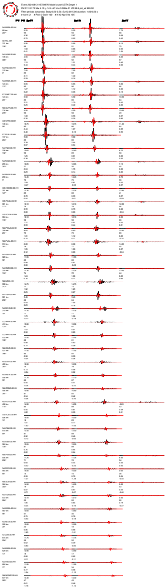


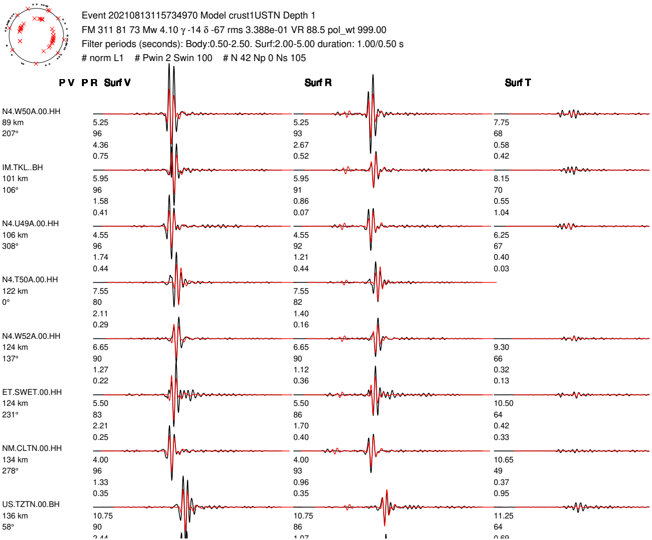





Total stations: 73, 40–1902 km. Snippet: 40–406 km

# **Tennessee event**: Moment tensor and source type analysis, IMS + open

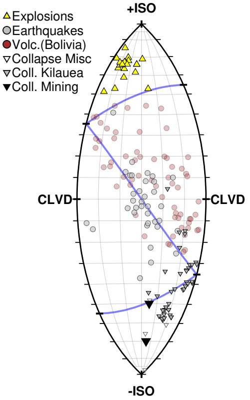





Total stations: 42, 89–677 km. Snippet: 89–136 km

# Perspectives






- Routine ✓ robust ✓ estimation
- Next: real-time screening with moment tensors
- Next: real-time screening and characterization with AI/ML

→ ***253 geophones, 80,000 aftershocks*** $-3 < \boldsymbol{M} < 2.0$

*Source mechanisms of aftershocks, Kiruna north section (Dineva et al., 2022)*