AWE NUCLEAR SECURITY TECHNOLOGIES

Calculating Full Moment Tensor Solutions using Earthquake and Announced Nuclear Test Datasets

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Motivation and Aims

AWE Blacknest needs to characterise sources for events of interest.

There are several event characterisation tools at our disposal:

1. Source depth
2. m_b:M_s
3. Regional high-frequency *P*/*S* amplitude ratios
4. Waveform modelling

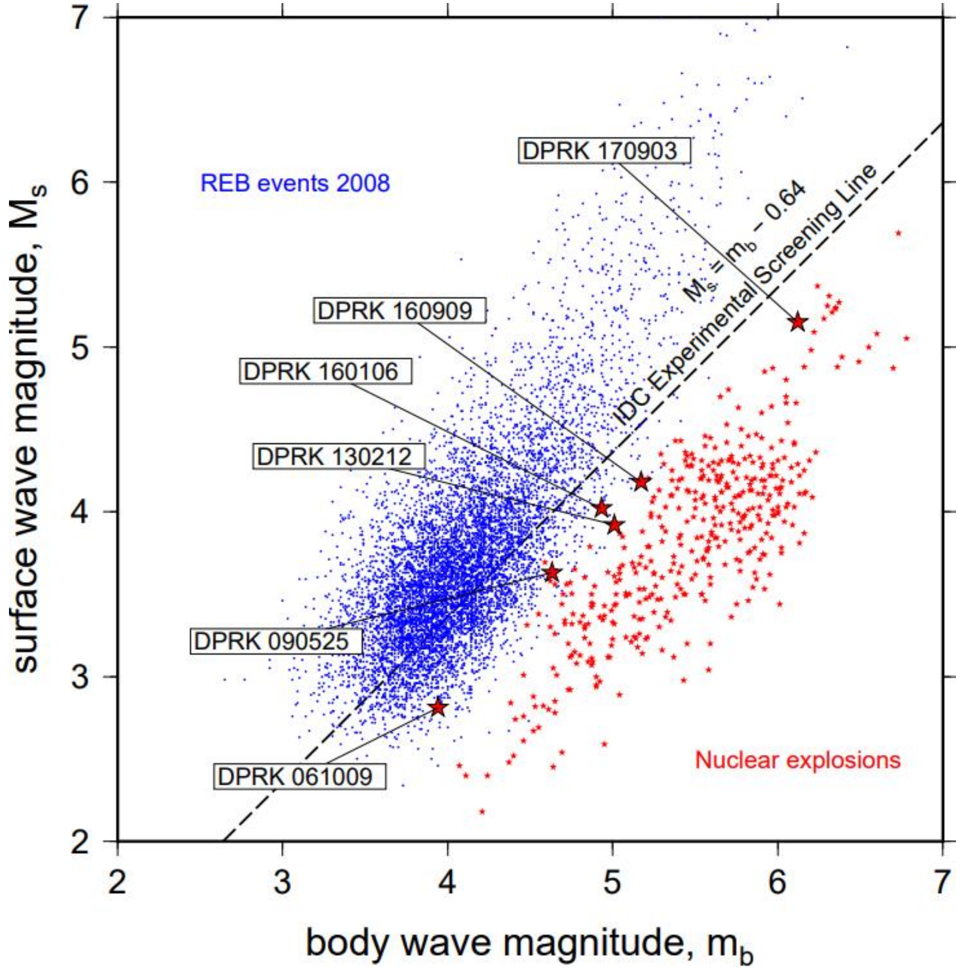
Moment tensor solutions (MTSs) have been viewed as a means of characterising seismic sources (e.g., Jost & Herrmann, 1989).

Project Aims

- Explore moment tensors to characterise seismic sources.
- Compare the capability of publicly available moment tensor inversion codes.
- Understand the trade-off between isotropic (ISO), compensated linear vector dipole (CLVD) and double-couple (DC) components in MTSs.

Challenges with Characterising Events

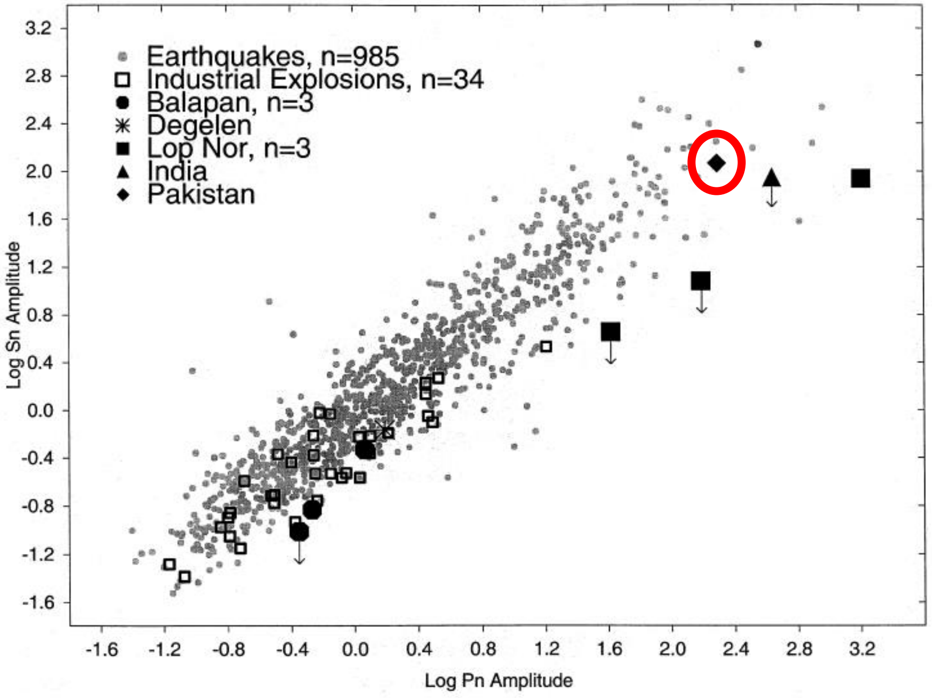
The International Data Centre (IDC) standard seismic event-screening measures (m_b:M_s, depth) screen out many earthquakes, but not all – e.g., m_b:M_s screens out ~40% of events as earthquakes (Selby et al., 2012).



Challenges with Characterising Events

Characterising some events is difficult!

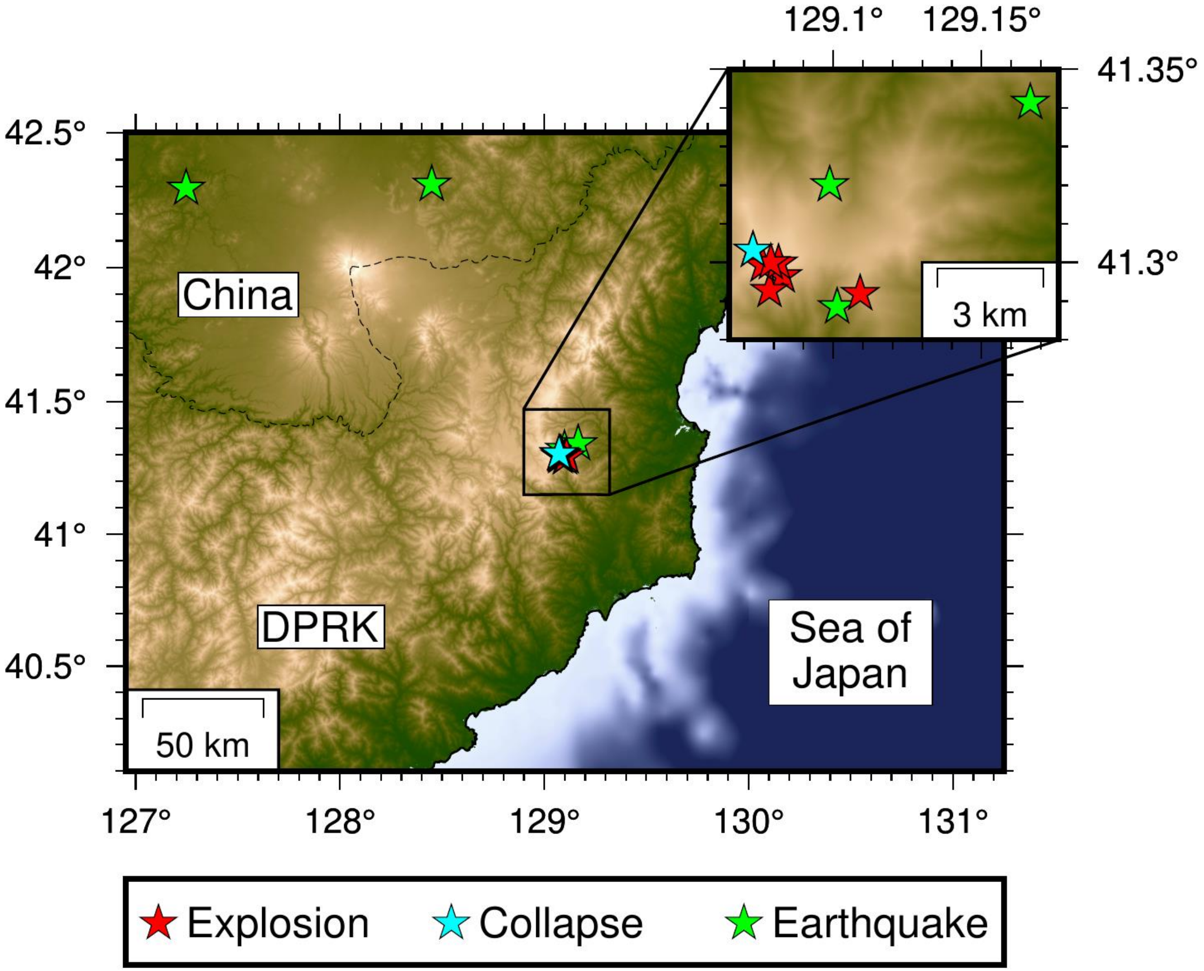
- Chinese explosion identified as an earthquake (e.g., Levshin & Ritzwoller, 2001).
- Misidentifying local earthquake arrivals as a Pakistan explosion (e.g., Jenkins & Sereno, 2001).
- Existing screening criteria difficult to unambiguously determine an earthquake (e.g., Lop Nor, Selby et al., 2005).
- Reverse polarity surface waves from underground explosions (e.g, Shagan River test site; Rygg, 1979; Cleary, 1980).
- Shallow, dip-slip thrust earthquakes can have explosion-like m_b:M_s, simple teleseismic waveforms, and generally positive first-motion P-waves – they look very explosion like.



Jenkins & Sereno, 2001

Dataset

- Six DPRK announced nuclear tests and one "collapse" event (Myers et al., 2018).
- Five earthquakes from the International Monitoring System (IMS) Reviewed Event Bulletin (REB) and Late Event Bulletin (LEB).
- Three of the earthquakes are located within 10km of the Punggye-ri Nuclear Test Site.
- Two earthquakes located at distances of 150km and 200km NW of the test site, in China.
- m_b ~3.4-3.8 for the five earthquakes.
- Synthetic Green's functions generated using wavenumber integration (Herrmann, 2013) with the MDJ2 1-D velocity model (Ford et al, 2009).

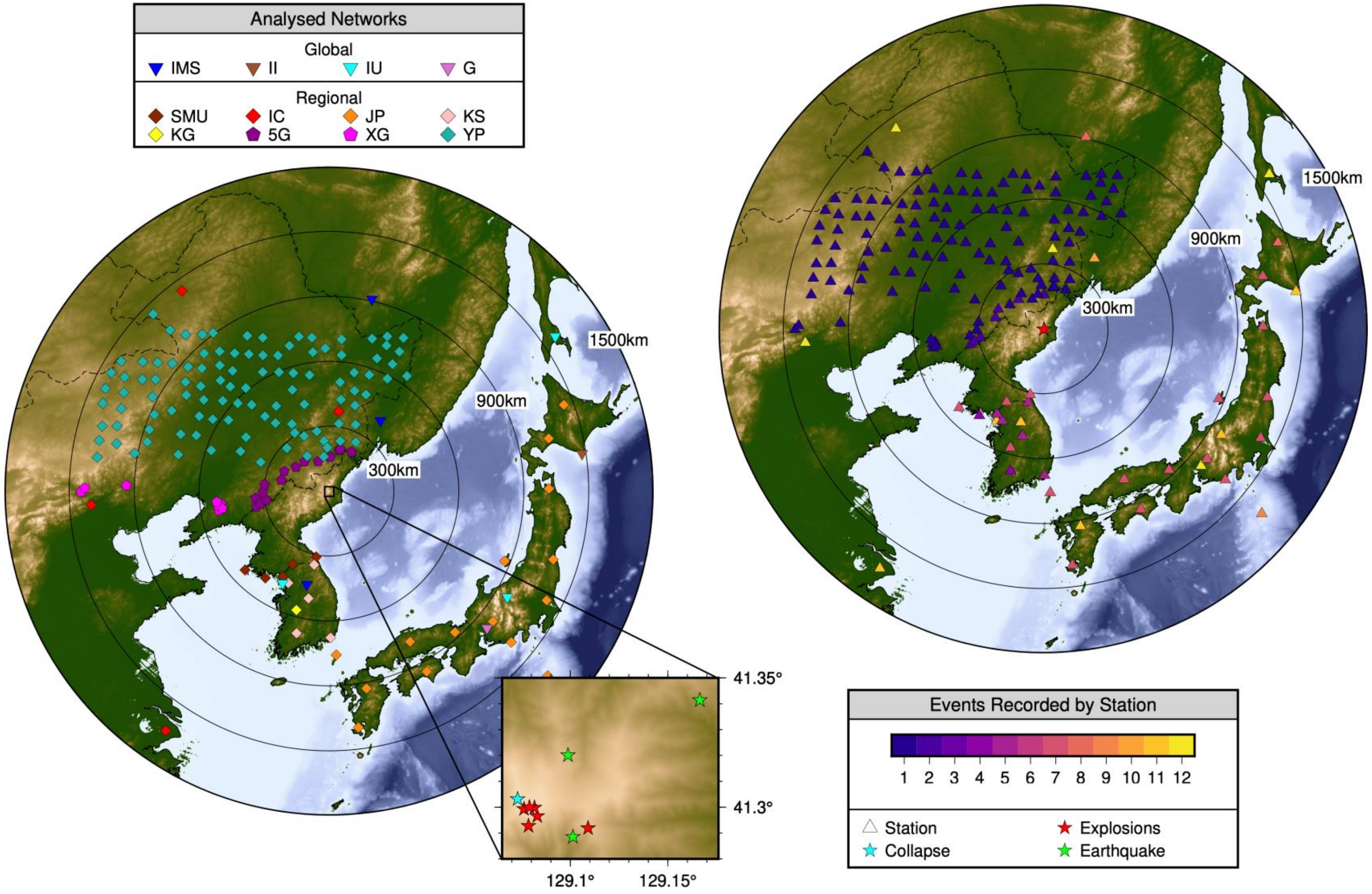


Dataset

Four global and eight regional seismograph networks with stations <1500km distance.

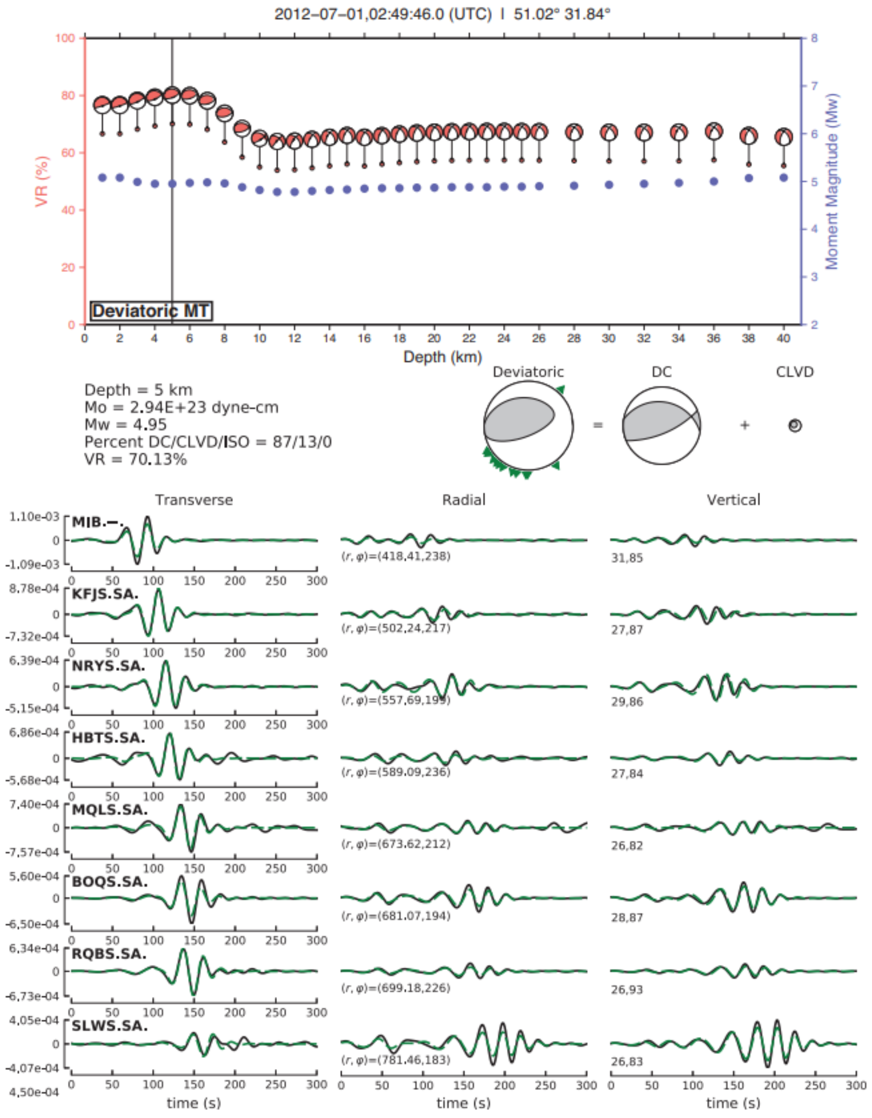
Data sources:

- IDC International Monitoring System (IMS),
- Earthscope, International Federation of Digital Seismograph Networks (FDSN) node,
- Southern Methodist University (SMU; Park et al., 2023) released raw data for five arrays along the southern side of the Korean Demilitarized Zone.



Methods – MTTime - COPYRIGHT

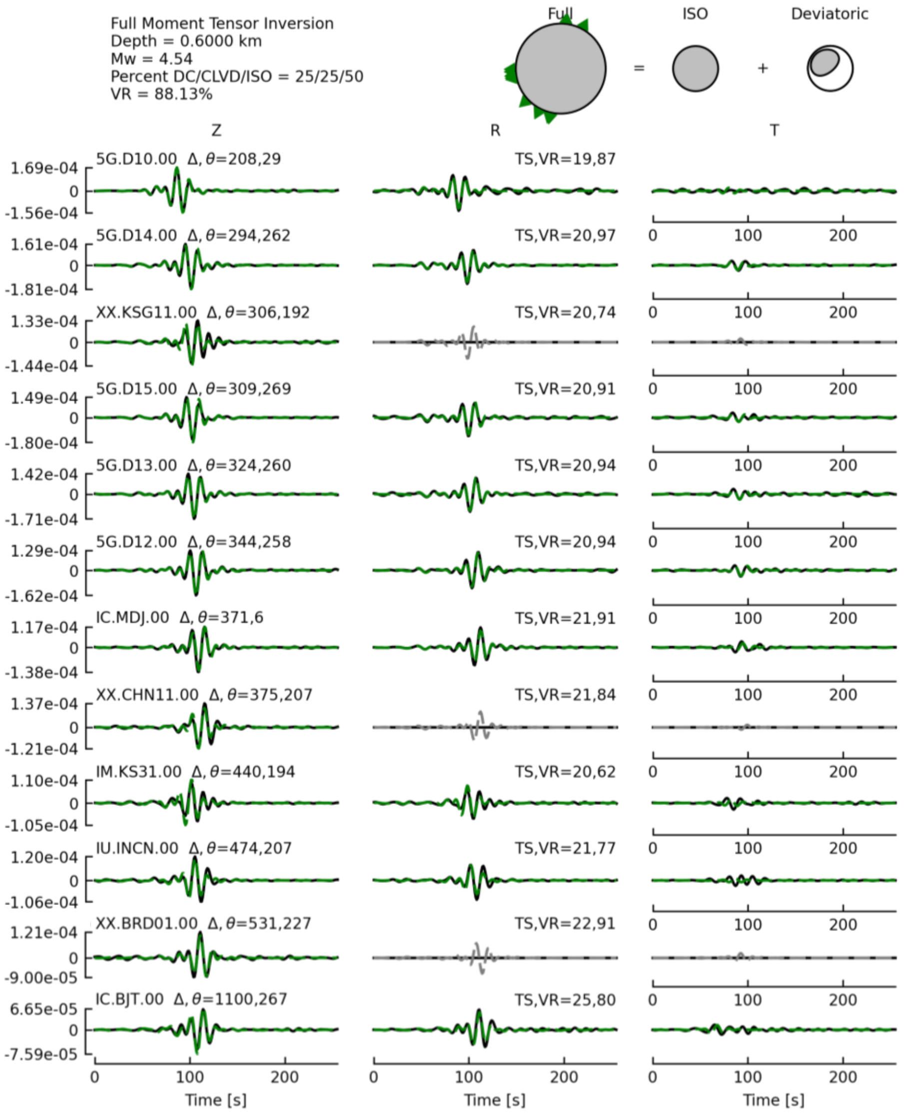
- Time Domain Moment Tensor Inversion in Python (MTTime) is a well-documented and computationally cheap method to produce full MTSs (Chiang et al., 2021).
- Synthetic displacement seismograms are calculated as a linear combination of the basis Green's functions weighted by the MT.
- Least-squares inversion method with Gauss-Jordan elimination.
- Best fitting MTS when variance reduction (VR) is maximised.
- User can manually shift waveforms to account for an inaccurate velocity model. Total time shift (TS) = Δt (user defined, ≤±7s) + constant (numerical lag-time, 20s here).
- Noisy components can be removed from the inversion if they are clearly fitting incorrectly.



(Chiang et al., 2021)

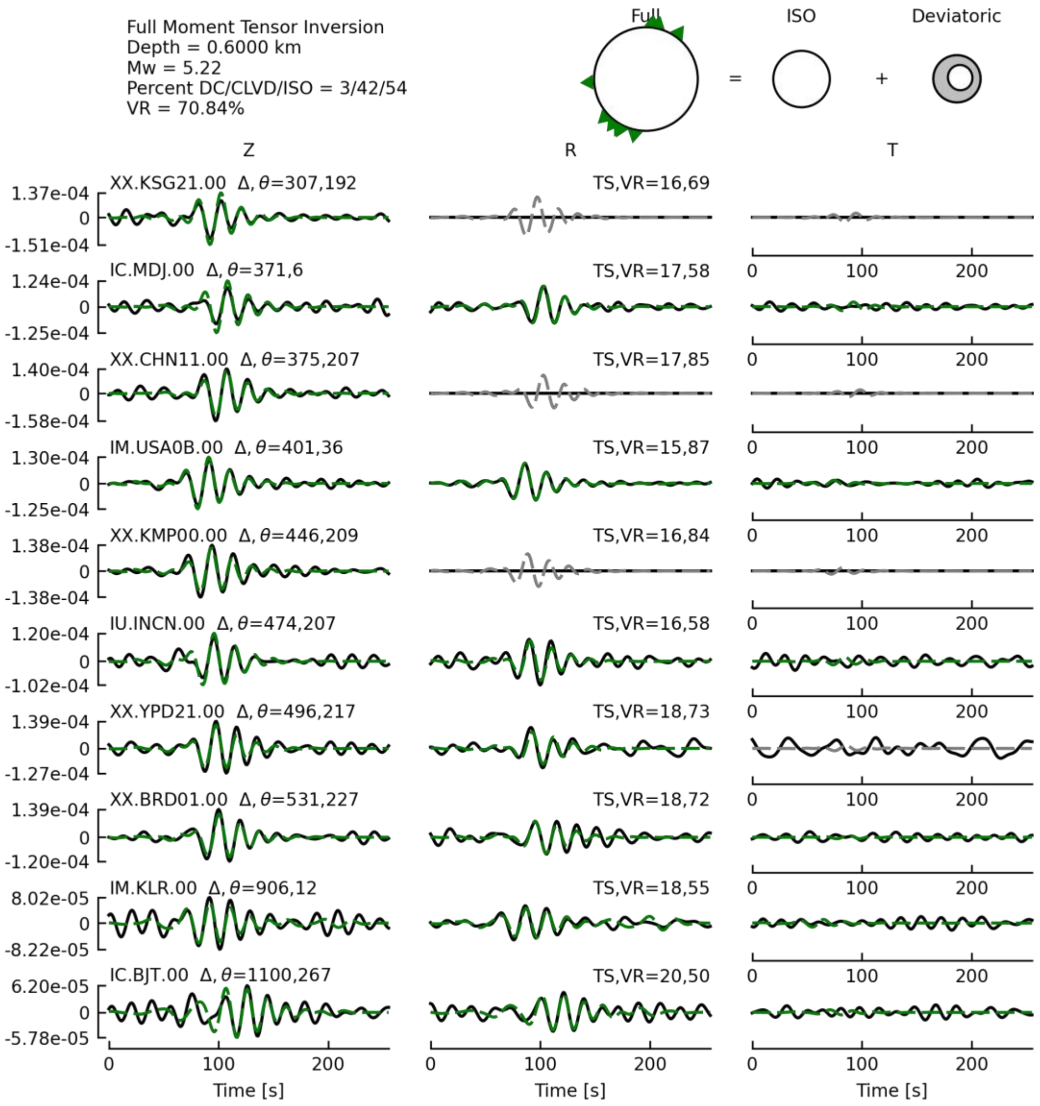
Results – DPRK Explosions

- Hypocentre information from Myers et al. (2018) – DPRK 2 shown right.
- Fixed depth (Chiang et al., 2018) of 1km (DPRK 1) or 0.6km (DPRK 2 - 6).
- Bandpass filter 0.04 - 0.1Hz (DPRK 1 – 2), 0.02 - 0.1Hz (DPRK 3 – 6).
- Large amplitudes on the vertical (Z) and radial (R) components compared to the tangential (T). Suggests Rayleigh waves are being generated efficiently whereas Love waves are not.
- >=50% positive isotropic component for all explosions – source mechanism dominated by volume expansion at the source – i.e. an explosion.
- Very good waveform fits (61-88%), largely due to good signal-to-noise ratio and good azimuthal coverage.
- Δt consistently +/-1s for most stations, ~6s for HIA and BJT (inaccurate velocity model at 1100km distance?).



Results – DPRK “Collapse”

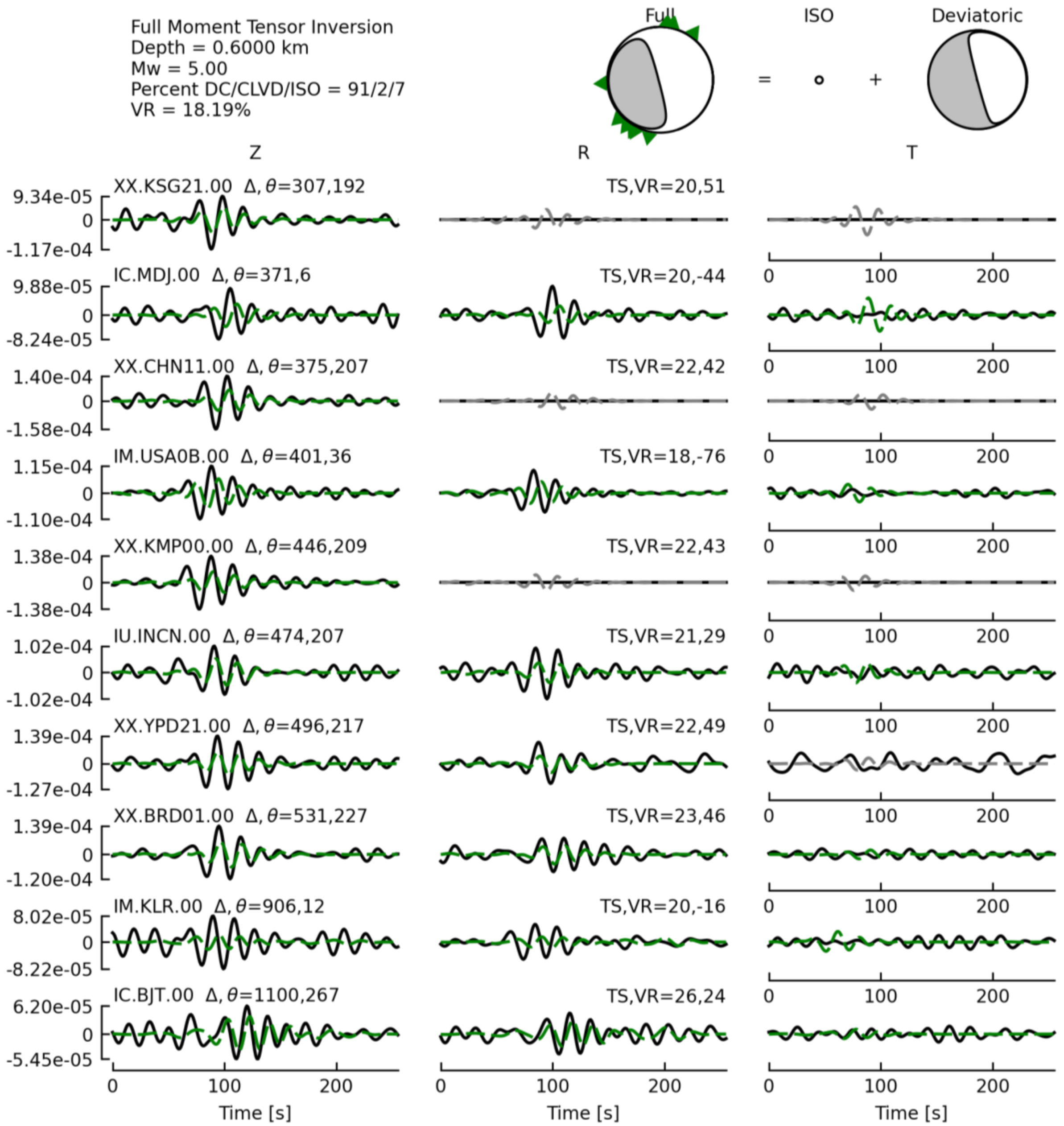
- Fixed depth of 0.6km (Chiang et al., 2018).
- Bandpass filter 0.02 - 0.06Hz.
- Reduced SNR for the surface waves from the “collapse” event.
- 54% negative isotropic component, 42% CLVD component – source mechanism is consistent with a horizontal closing crack.
- Station time-shift (Δt) values are all ~4s smaller than for DPRK 6: origin time uncertainty for this “collapse” event?
- Applying the same Δt’s as for DPRK 6 produces an explosion dominated MTS – cycle skipping, origin time uncertainty, or problematic inversion method?



Alternative ‘Collapse’ MTSs

- Using the same Δt values as for the DPRK6 explosion produces a predominantly double couple MTS.
- Waveform fits (VR = 18%) are significantly worse.
- Origin time related to the body wave hypocentre (Myers et al., 2018) differs from that of the surface waves?

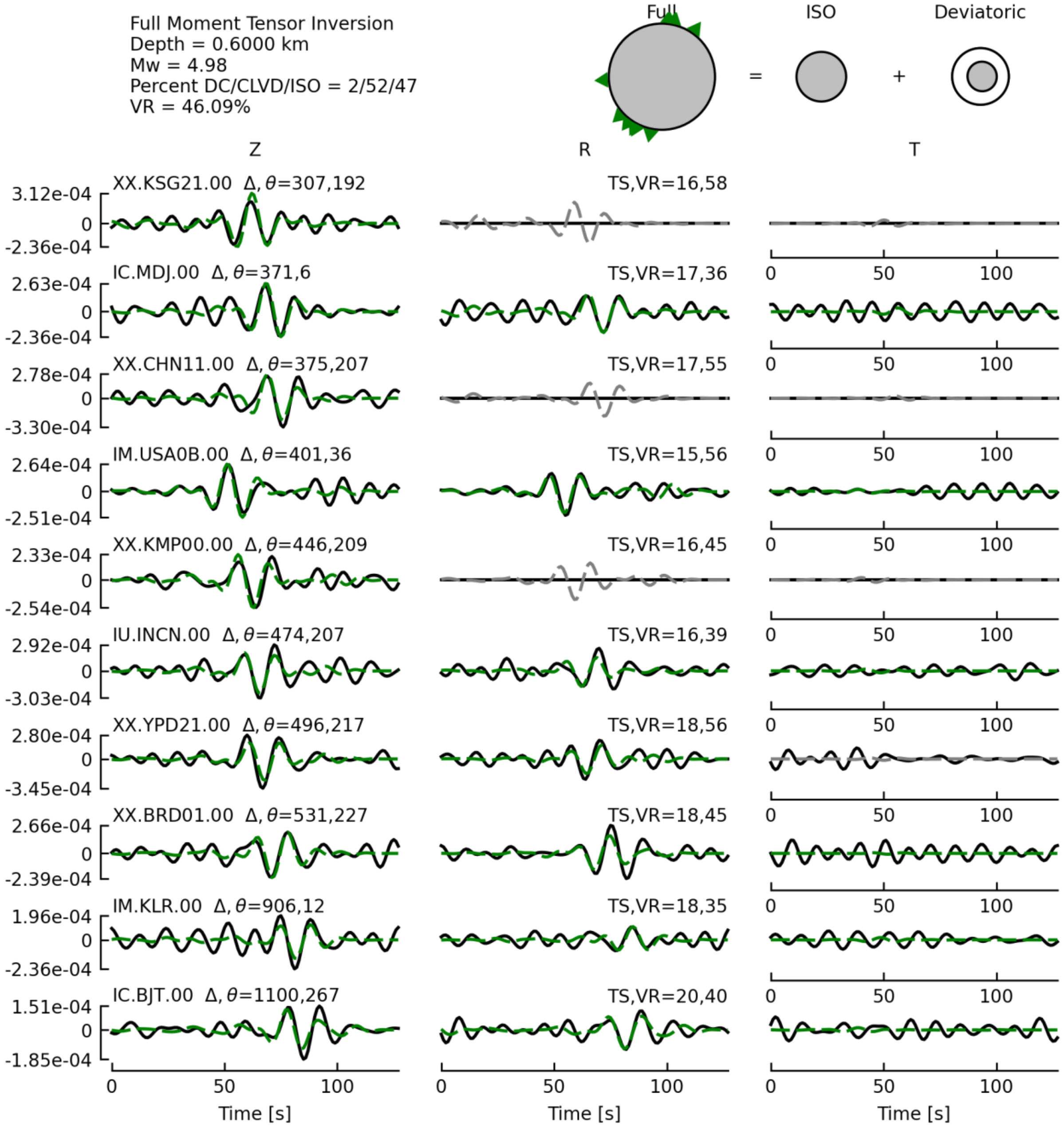
<u>MTSs are sensitive to the station TSs used</u>



Alternative 'Collapse' MTSs

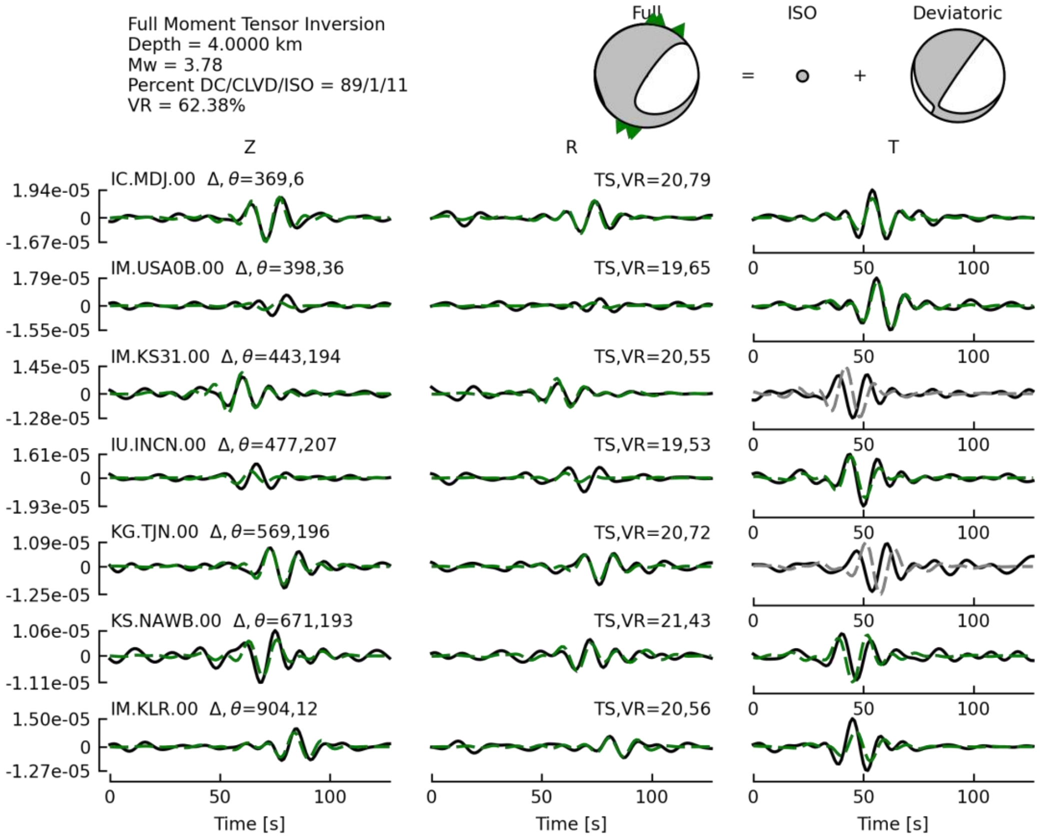
- Higher frequency Butterworth bandpass filter 0.04-0.1Hz.
- Δt's from best-fitting MTS.
- Waveform fit (VR = 46%) lower than the best fitting solution, but not unreasonable.
- A positive isotropic (i.e. explosion-dominated) MTS is calculated.

<u>MTSs are also sensitive to the filter bandwidth used</u>



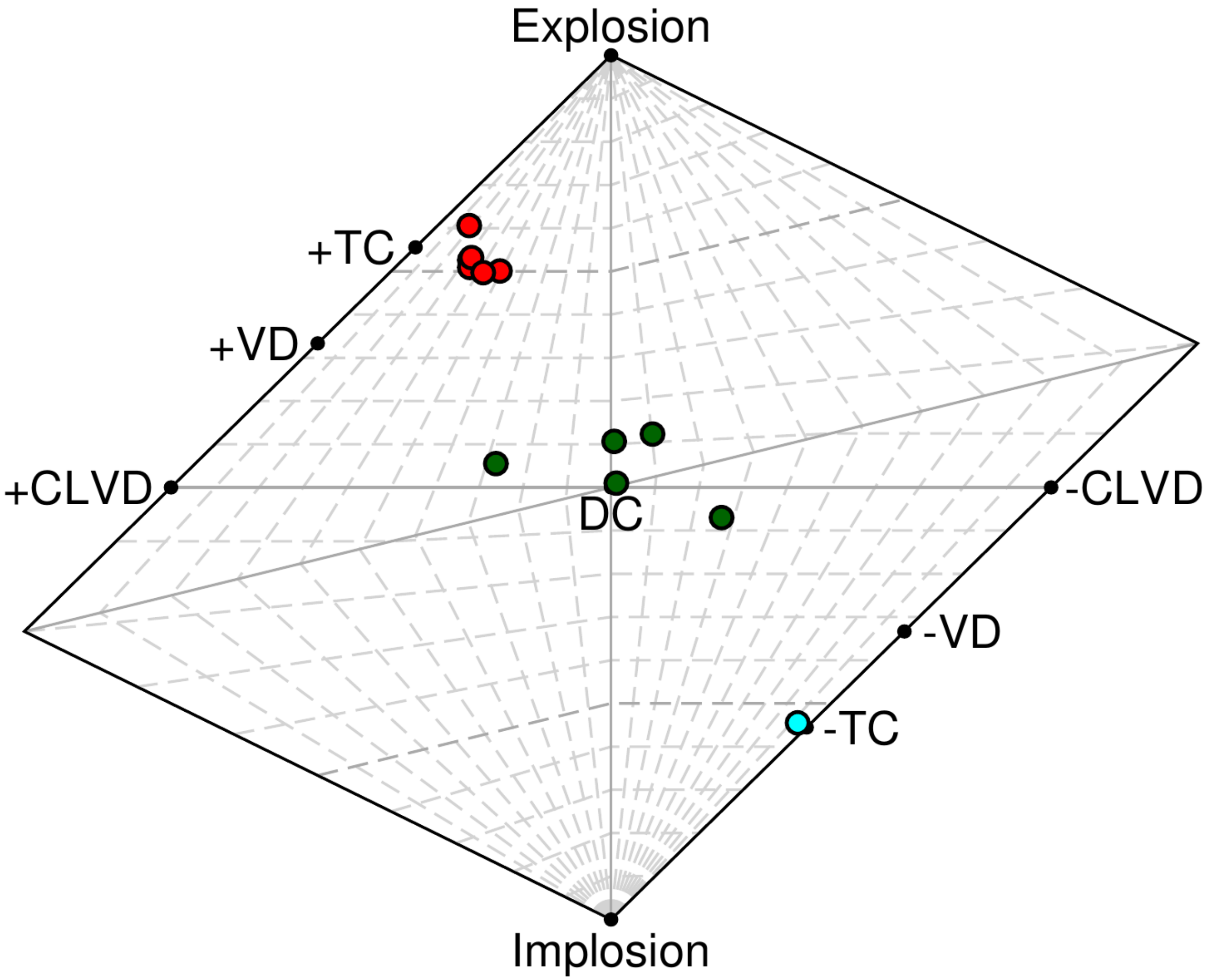
Results – DPRK Earthquakes

- Hypocentres of five earthquakes from IDC REB and LEB catalogues.
- Bandpass filter 0.04 - 0.1Hz.
- Earthquakes are dominantly DC MTSs.
- One DPRK event (right) has 89% DC, and 62% waveform fit, but has an unusual vertical dip-slip/shallow dipping strike-slip focal mechanism.
- Two events in China are well-constrained (high VR) as strike-slip earthquakes, however depth is not well constrained.
- Station distribution is not ideal for DPRK earthquakes - stations are in two clusters north and south.
- Not possible to fit Love waves correctly for some stations (e.g., T component for stations KS31 and TJN, see right).



Results – Event Characterisation

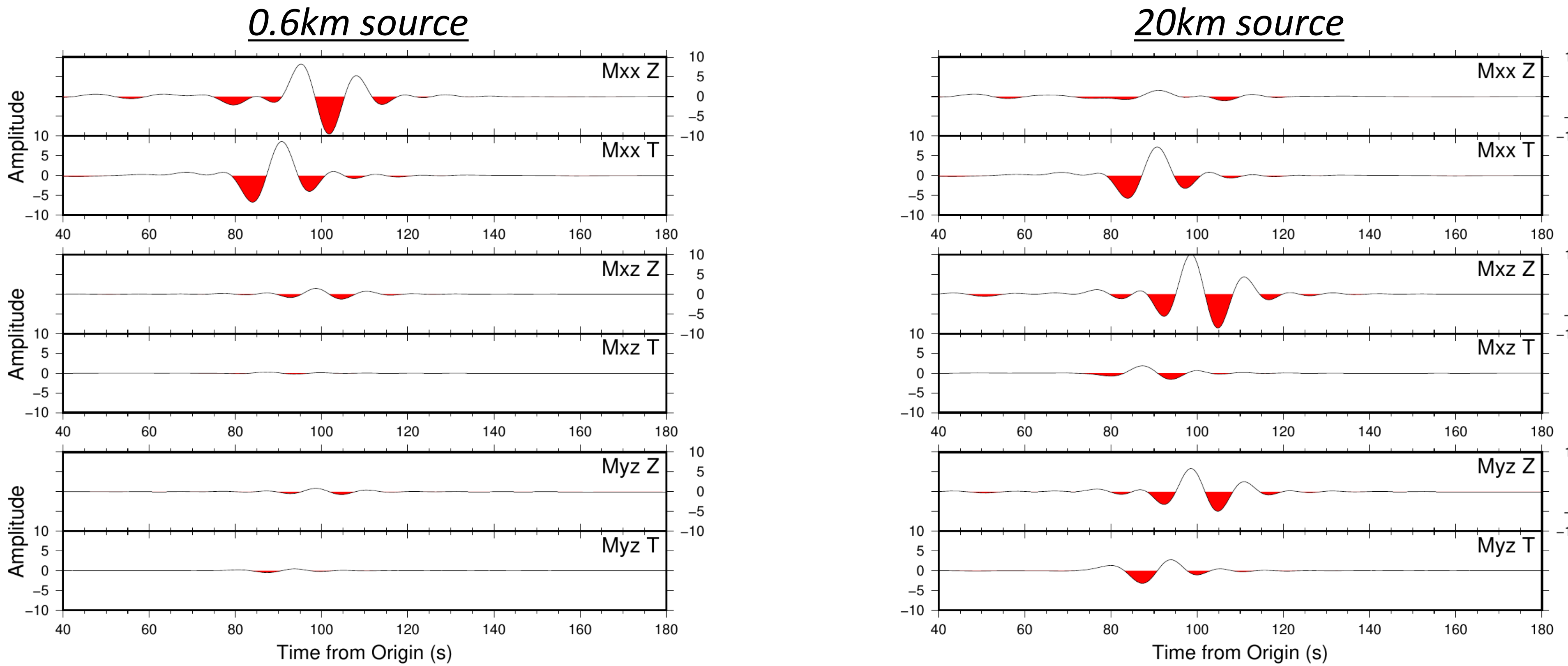
- Source-type of the MTSs can be plotted on a Hudson plot.
- Isotropic MTSs towards the top and bottom of the plot. DC sources plot in the centre of the x-axis and CLVD sources are at the x-axis extremities.
- Explosions (red), collapse (cyan) and earthquake (green) sources for DPRK are all in separate, distinct clusters – event discrimination may therefore be possible.
- Earthquakes plot in the centre of the Hudson plot.
- Explosions plot in the positive isotropic space (i.e., increasing volume) and the collapse event plots near the closing crack source mechanism (-TC).



Difficulties with Using Surface Waves for MTSs

- Several fundamental challenges posed by using surface waves (0.02-0.1Hz) to calculate full MTSs for shallow (<5km) sources.

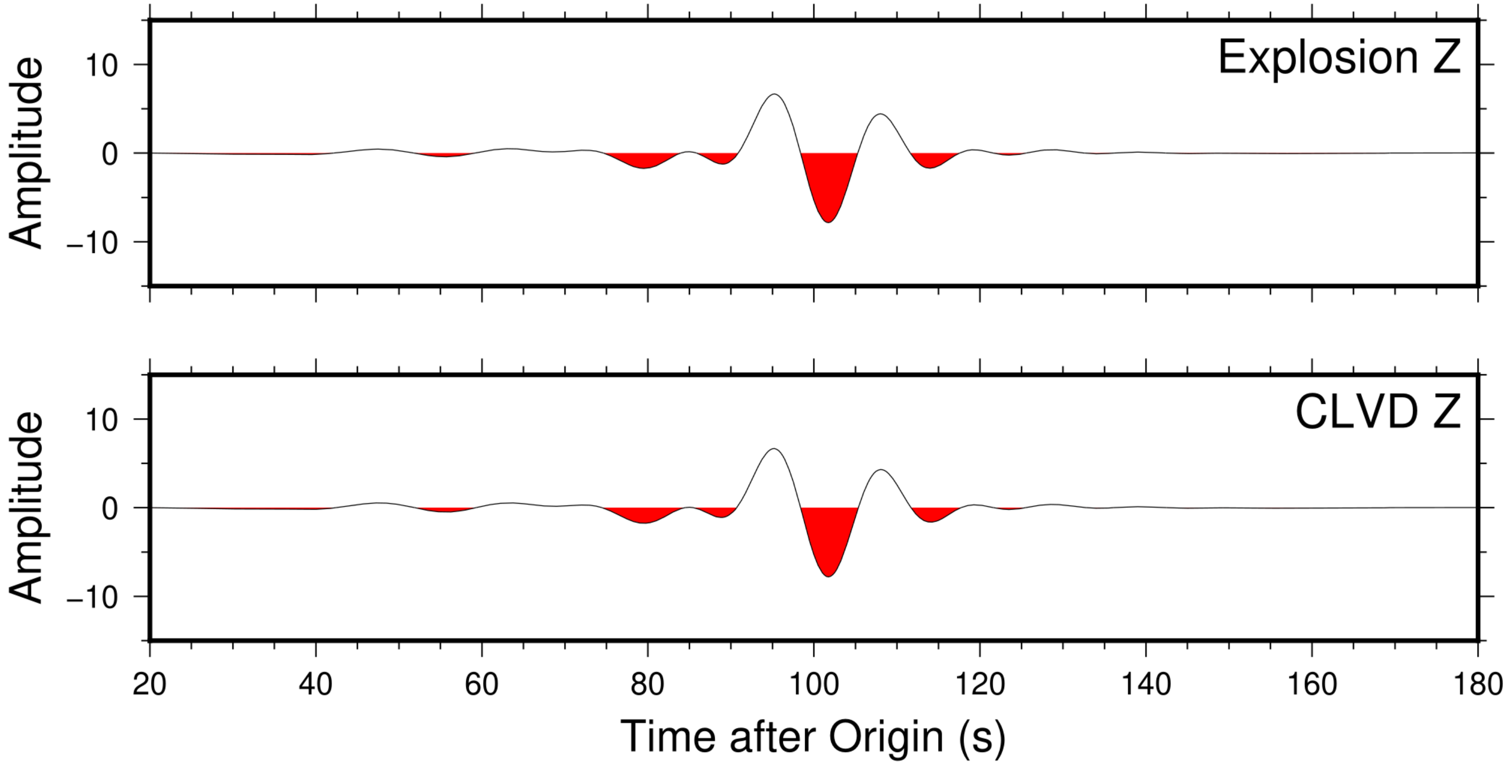
- Mxz and Myz components have near-zero amplitudes and therefore cannot be resolved in the inversion process.



Difficulties with Using Surface Waves for MTSs

- The Mzz and (Mxx + Myy) moment tensor elements are independent of azimuth and cannot be independently constrained for shallow sources.

- Vertical component seismograms generated by explosions or vertically oriented CLVD sources, are visually identical.



Summary

- Event characterisation might be achieved by using MTSs for the DPRK nuclear test site.
- MTTime is sensitive to the waveform filter frequency, event location and station time shifts.

Future Directions

- Use fixed station Δt for all events (approximate path correction) until an improved MTS is found.
- Use “1.5D” fundamental mode surface wave synthetics (Fox et al., 2012) and/or 3D velocity models using SPECFEM3D (Komatitsch et al., 2023).
- Compare MTTime with MTUQ and Bayesian methods (Chiang et al, 2025)
- Can body-wave waveforms and polarities be used to improve MTSs?

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Permissions

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