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:

- Source depth
- m_b:M_s
- Regional high-frequency P/S amplitude ratios
- 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.

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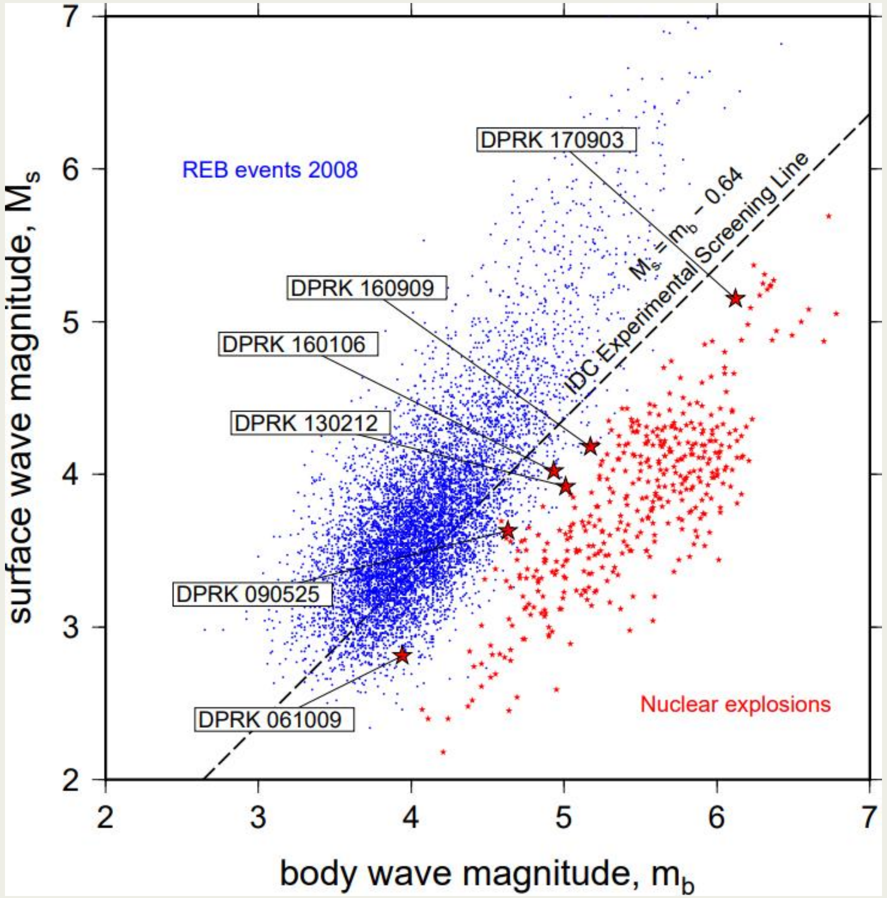
Challenges with Characterising Events

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).



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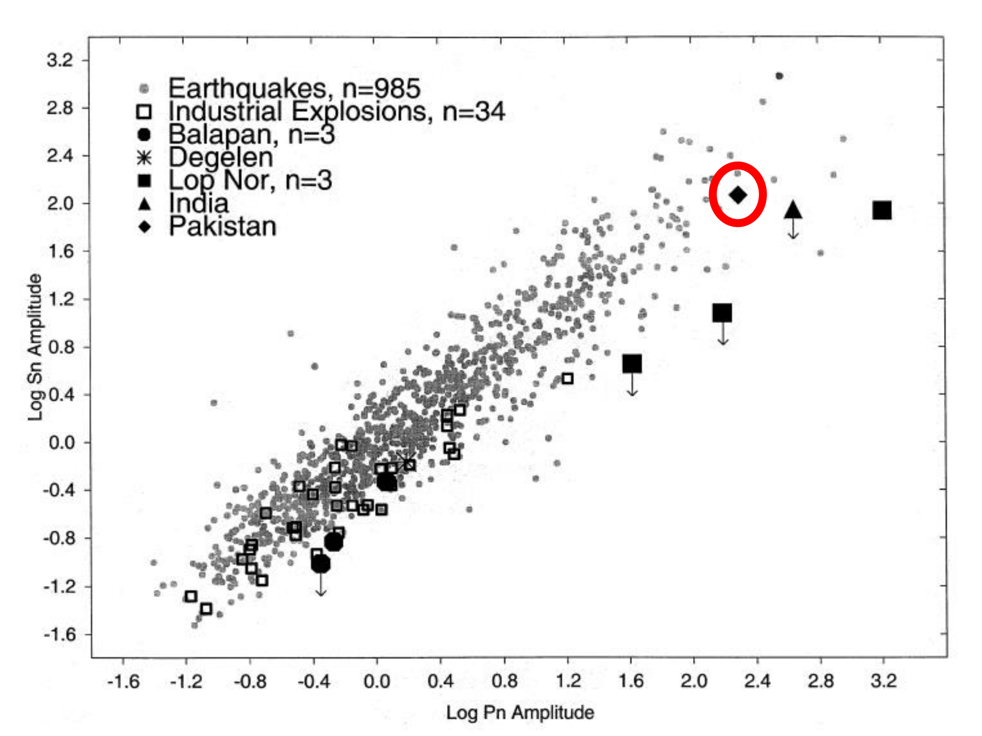
Challenges with Characterising Events

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

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Dataset

Six DPRK announced nuclear tests and one "collapse" event (Myers et al., 2018).

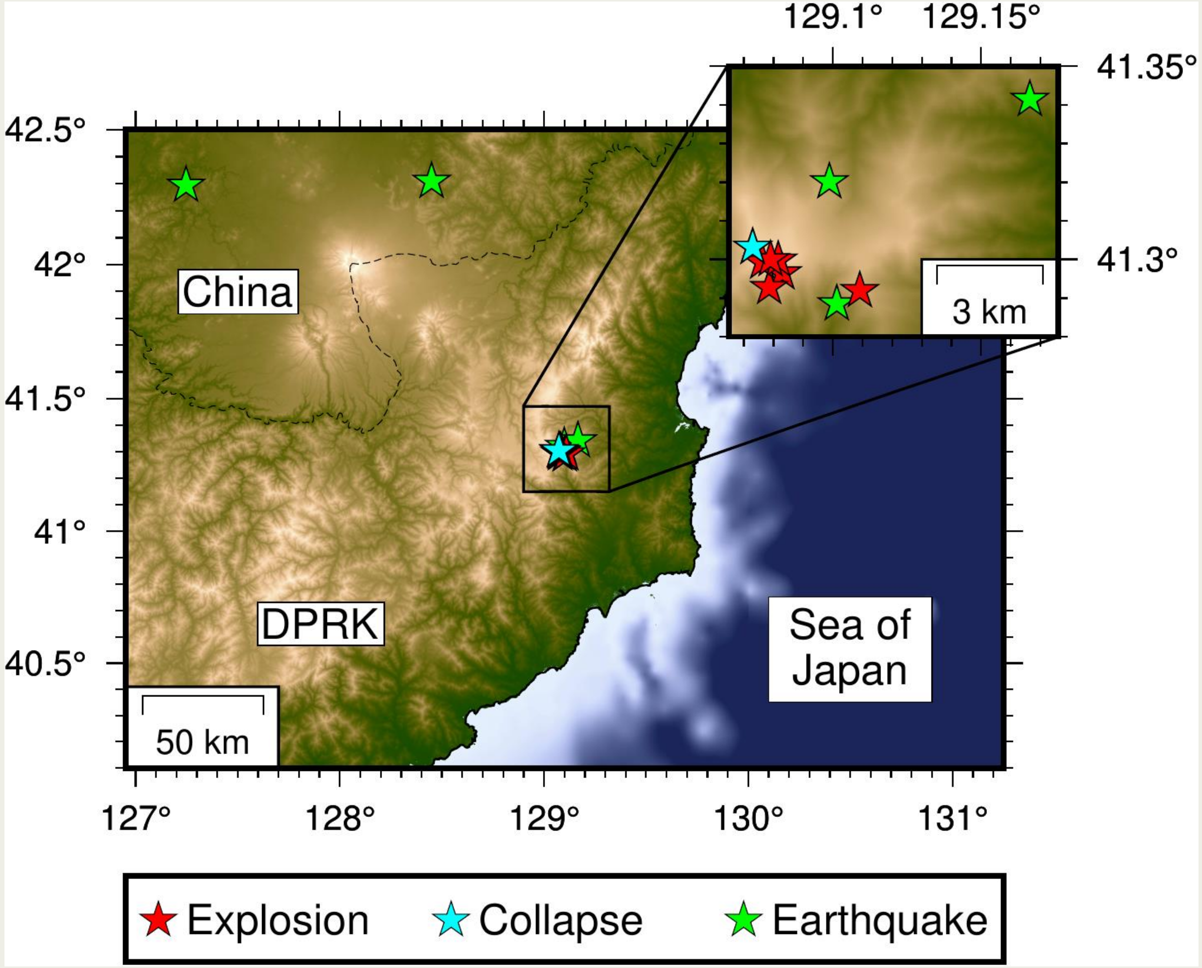
Five earthquakes from the International Monitoring System (IMS) Late Event Bulletin (LEB).

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).



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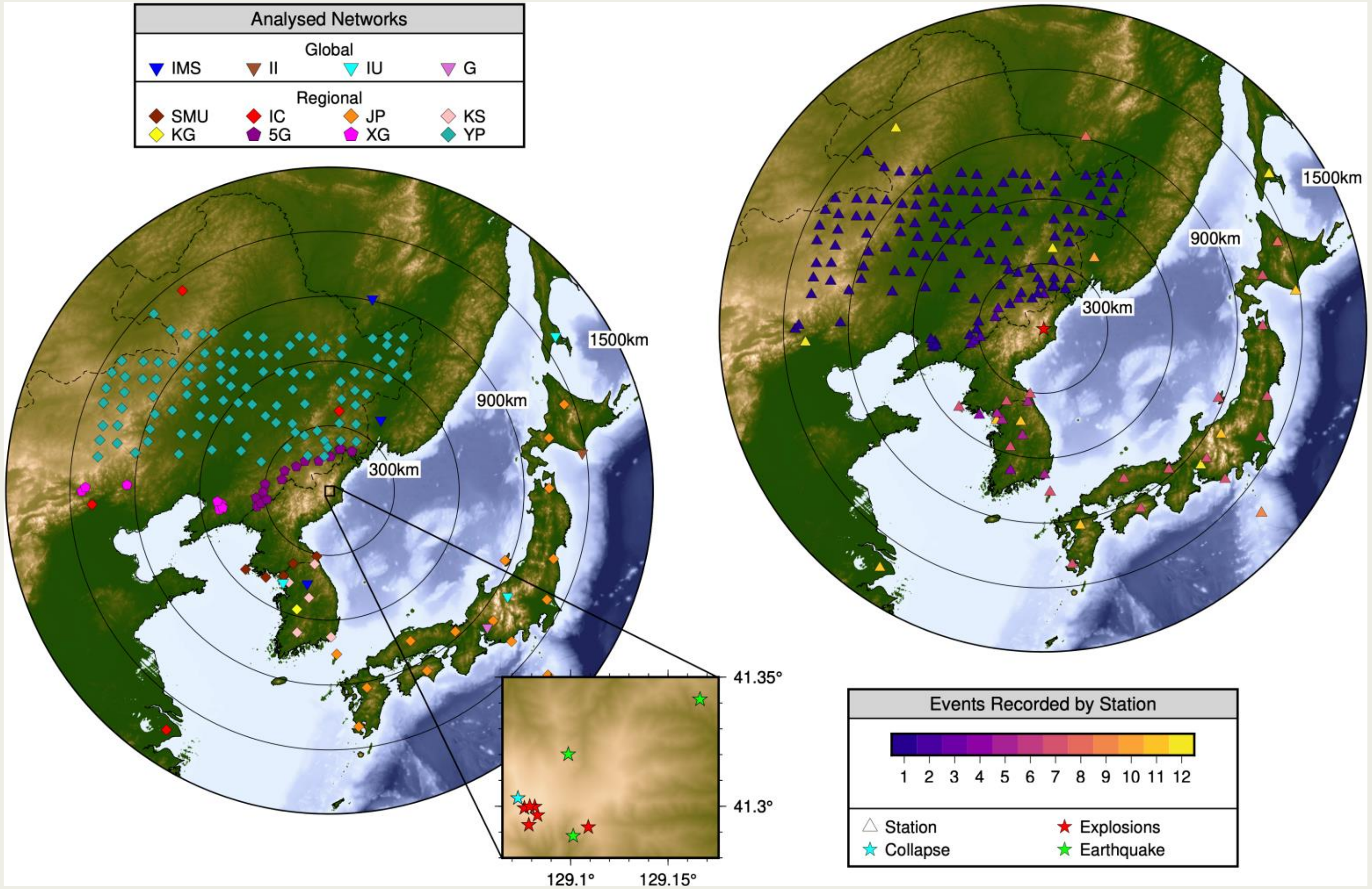
Dataset

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.



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Methods - MTTime

Time Domain Moment Tensor Inversion in Python (MTTime) is a well-documented and computationally cheap method to produce full MTSs (Chiang et al., 2021).

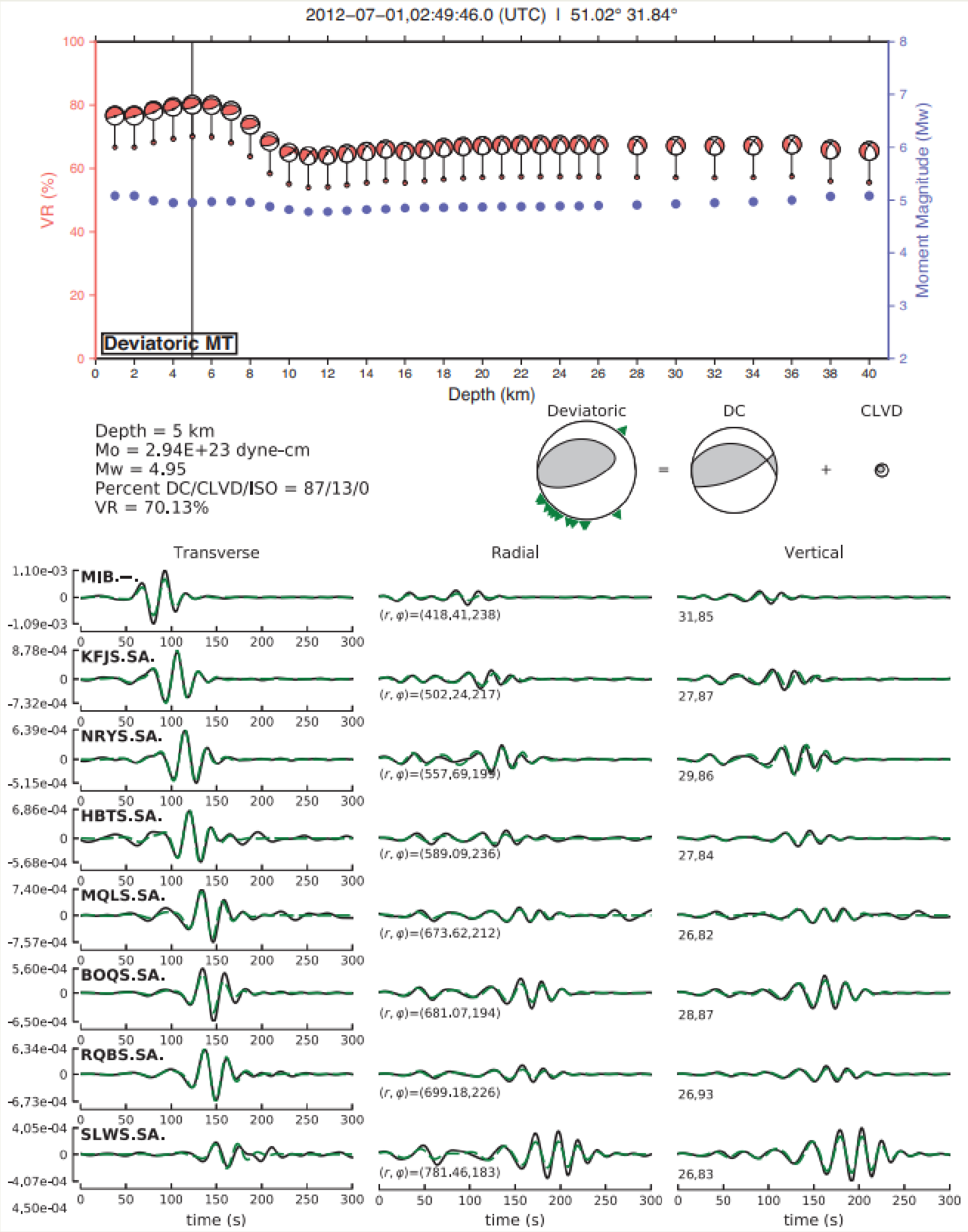
Synthetic displacement seismograms are calculated as a linear combination of the basis Green's functions weighted by the MT.

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)

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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).

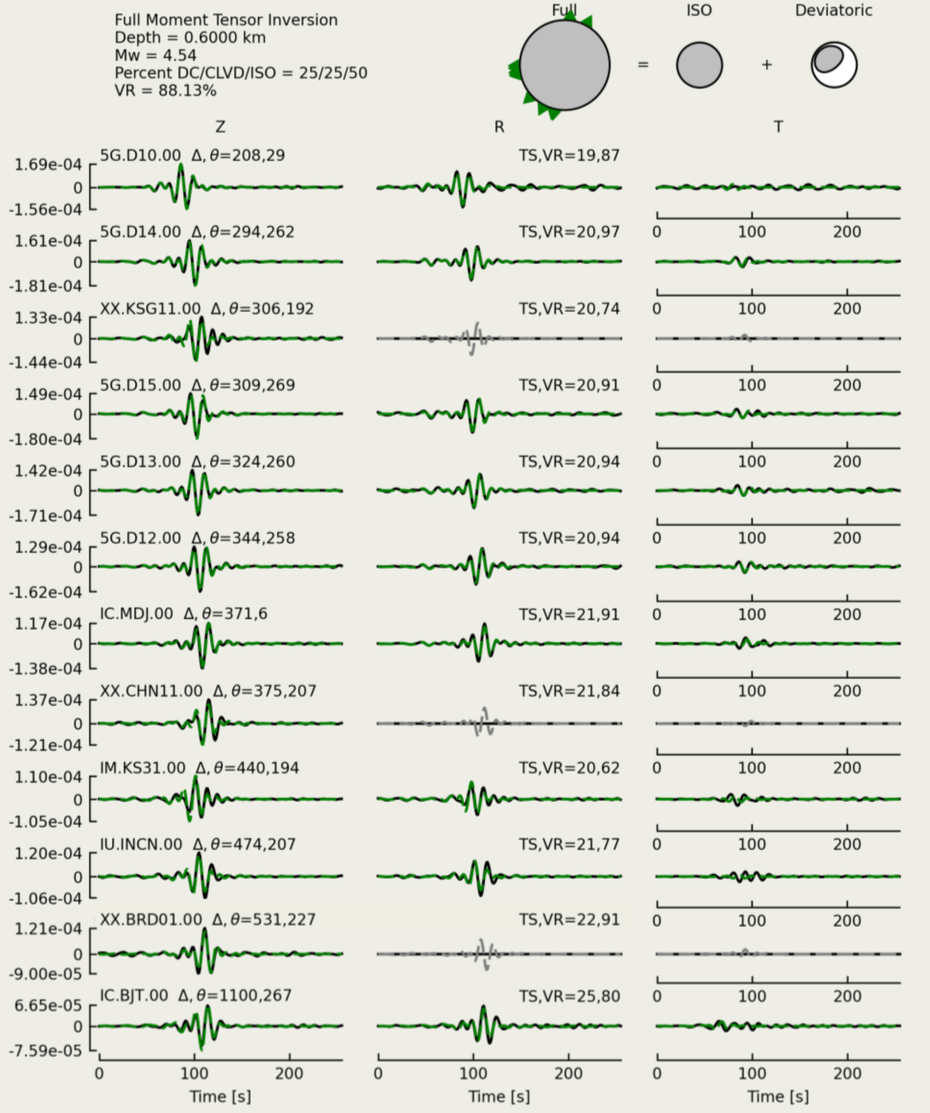
Bandpass filter 0.04 - 0.1Hz (DPRK 1 – 2), 0.02 - 0.1Hz (DPRK 3 – 6).

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?).



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Results – DPRK “Collapse”

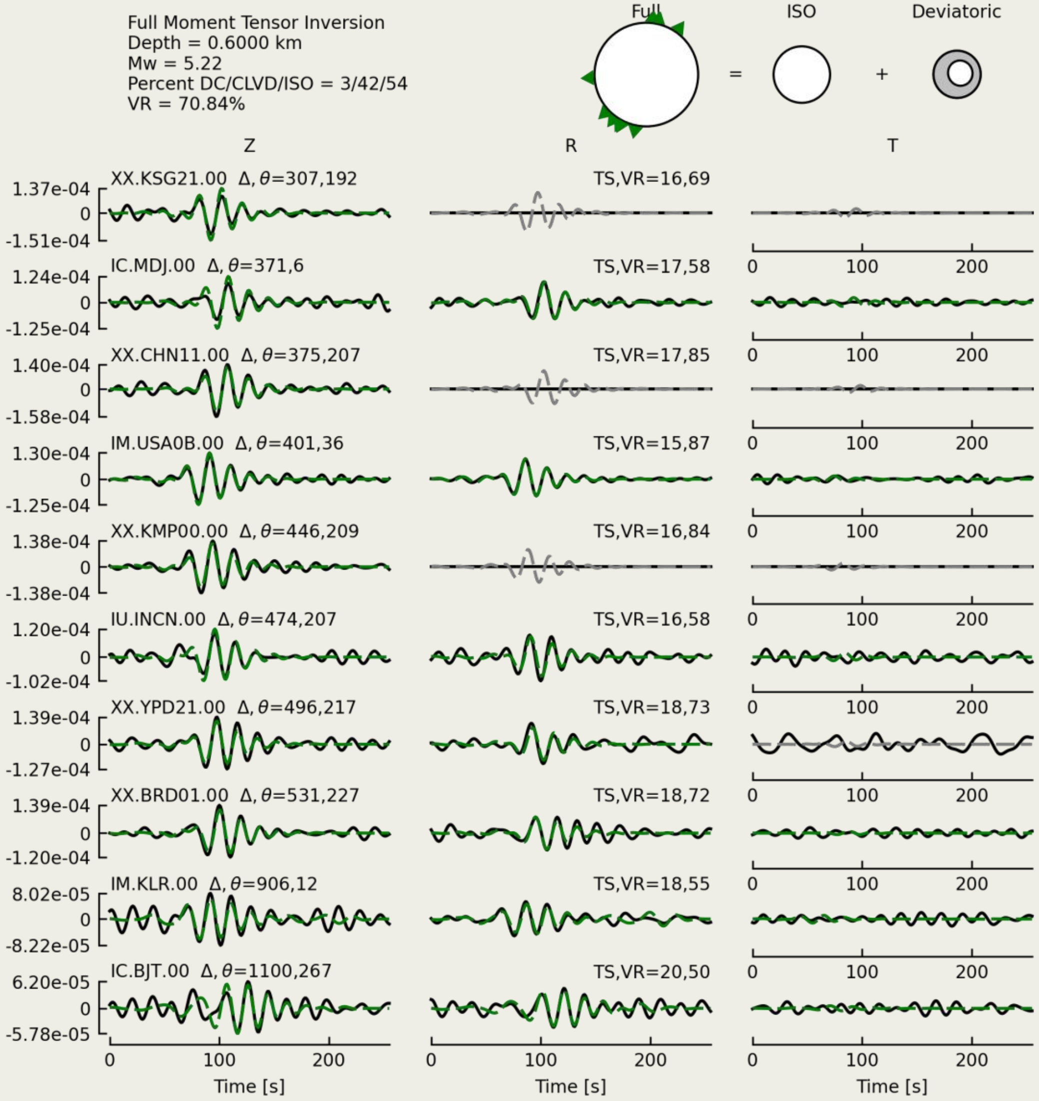
Fixed depth of 0.6km (Chiang et al., 2018).

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?



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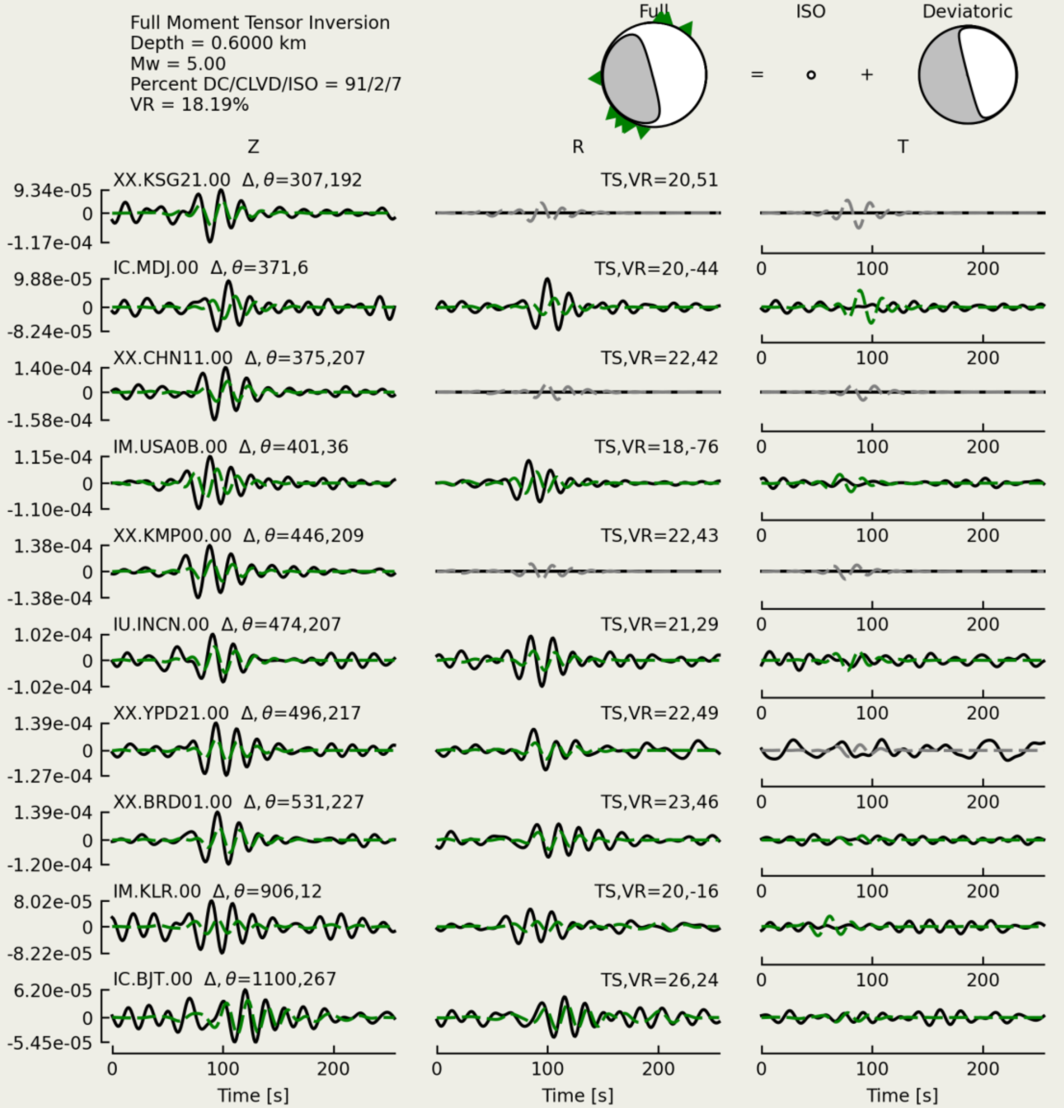
Alternative "Collapse" MTSs

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>



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Alternative “Collapse” MTSs

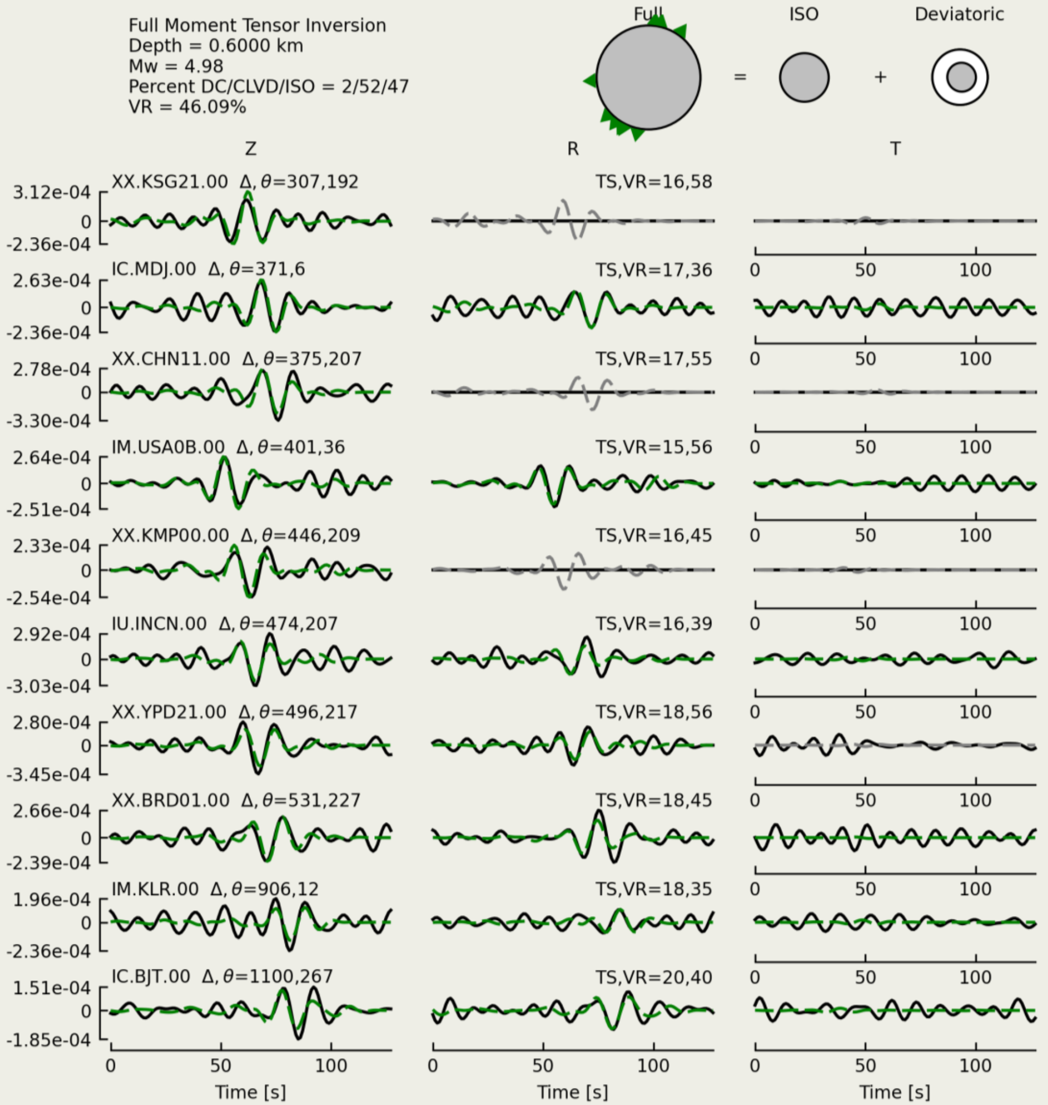
Higher frequency Butterworth bandpass filter 0.04-0.1Hz.

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>



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Results – DPRK Earthquakes

Hypocentres of five earthquakes from IDC LEB catalogue.

Bandpass filter 0.04 - 0.1Hz.

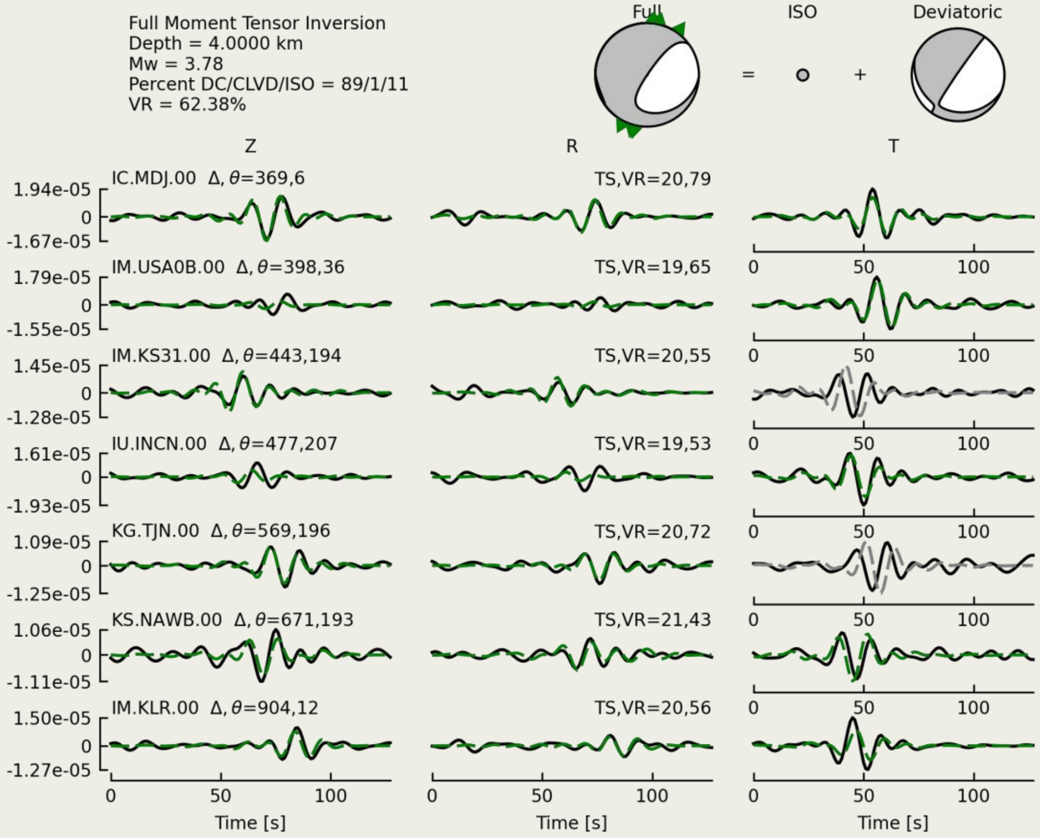
Earthquakes are dominantly DC MTSs.

Event 24271315 (right) has 89% DC, and 62% waveform fit, with dominantly vertical dip-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).



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Results – Event Characterisation

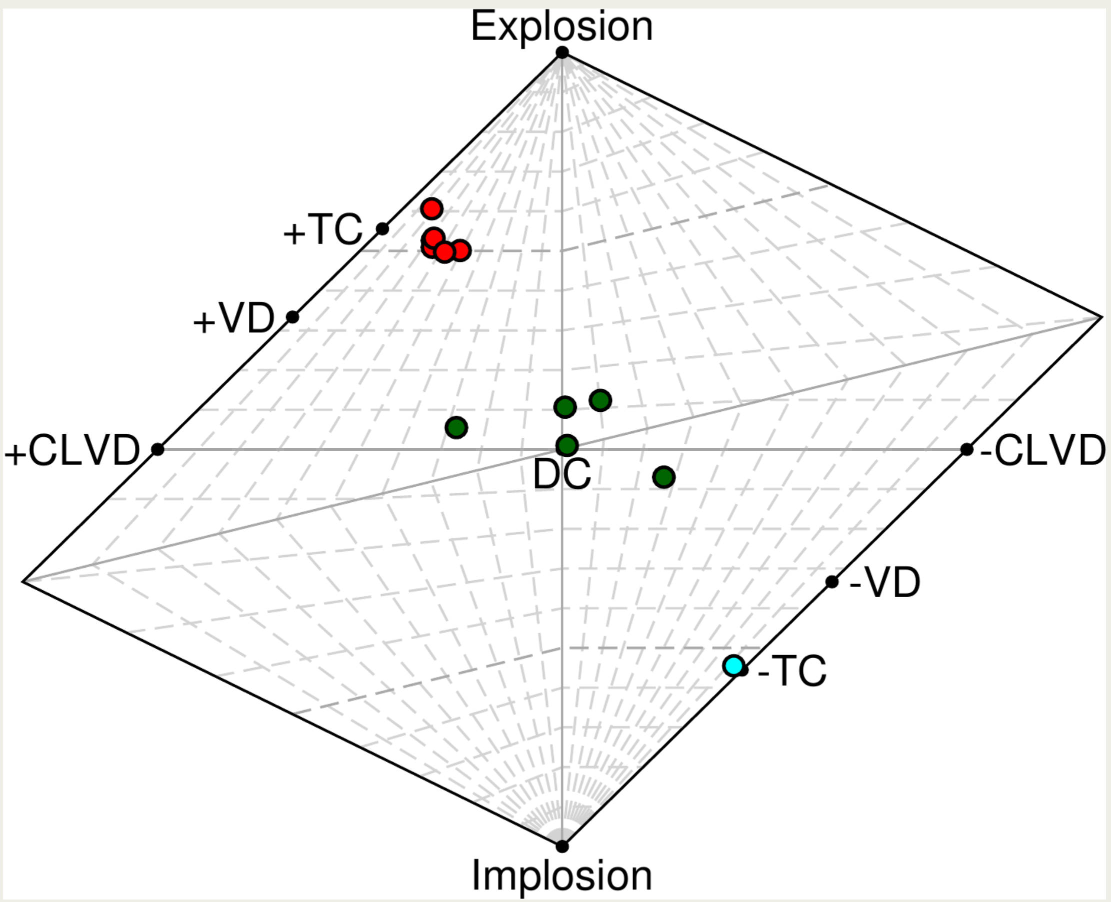
Source-type of the MTSs can be plotted on a Hudson plot.

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).



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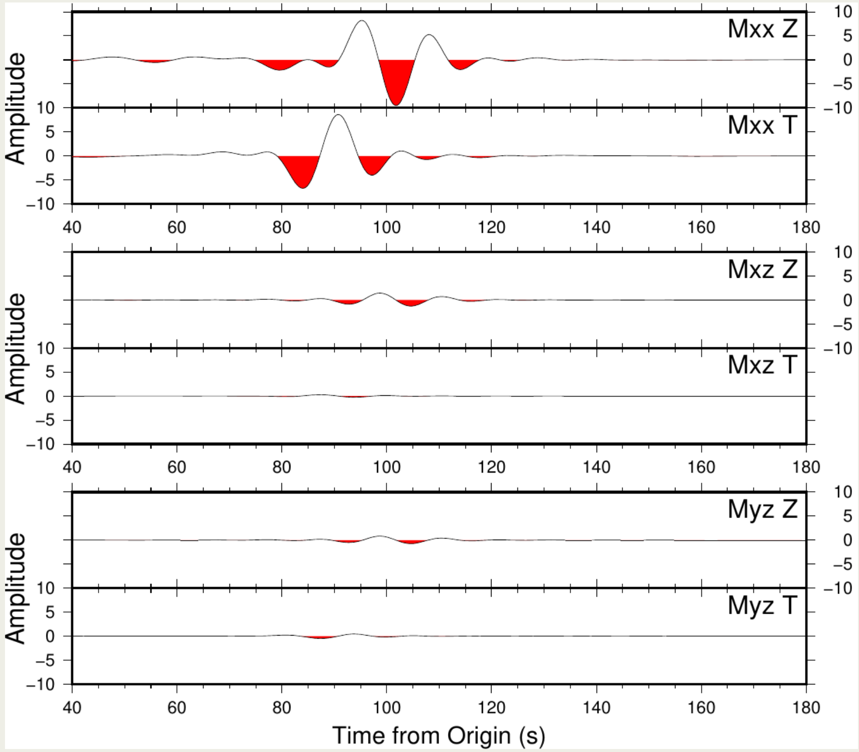
Difficulties with Using Surface Waves for MTSs

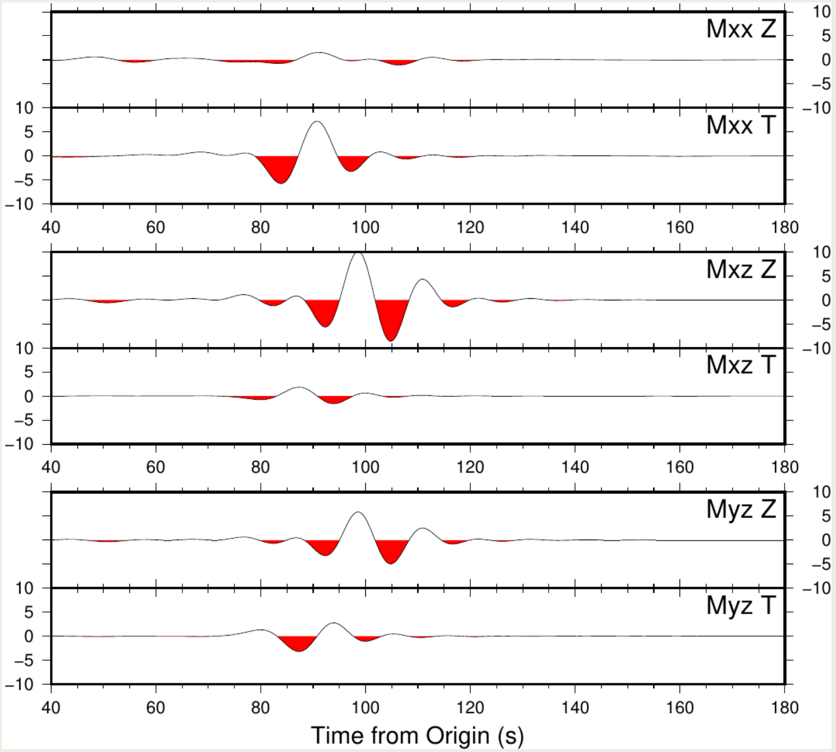
Several fundamental challenges posed by using surface waves (0.02-0.1Hz) to calculate full MTSs for shallow (<5km) sources.

M_{xz} and M_{yz} components have near-zero amplitudes and therefore cannot be resolved in the inversion process.

<u>*0.6km source*</u>



<u>*20km source*</u>



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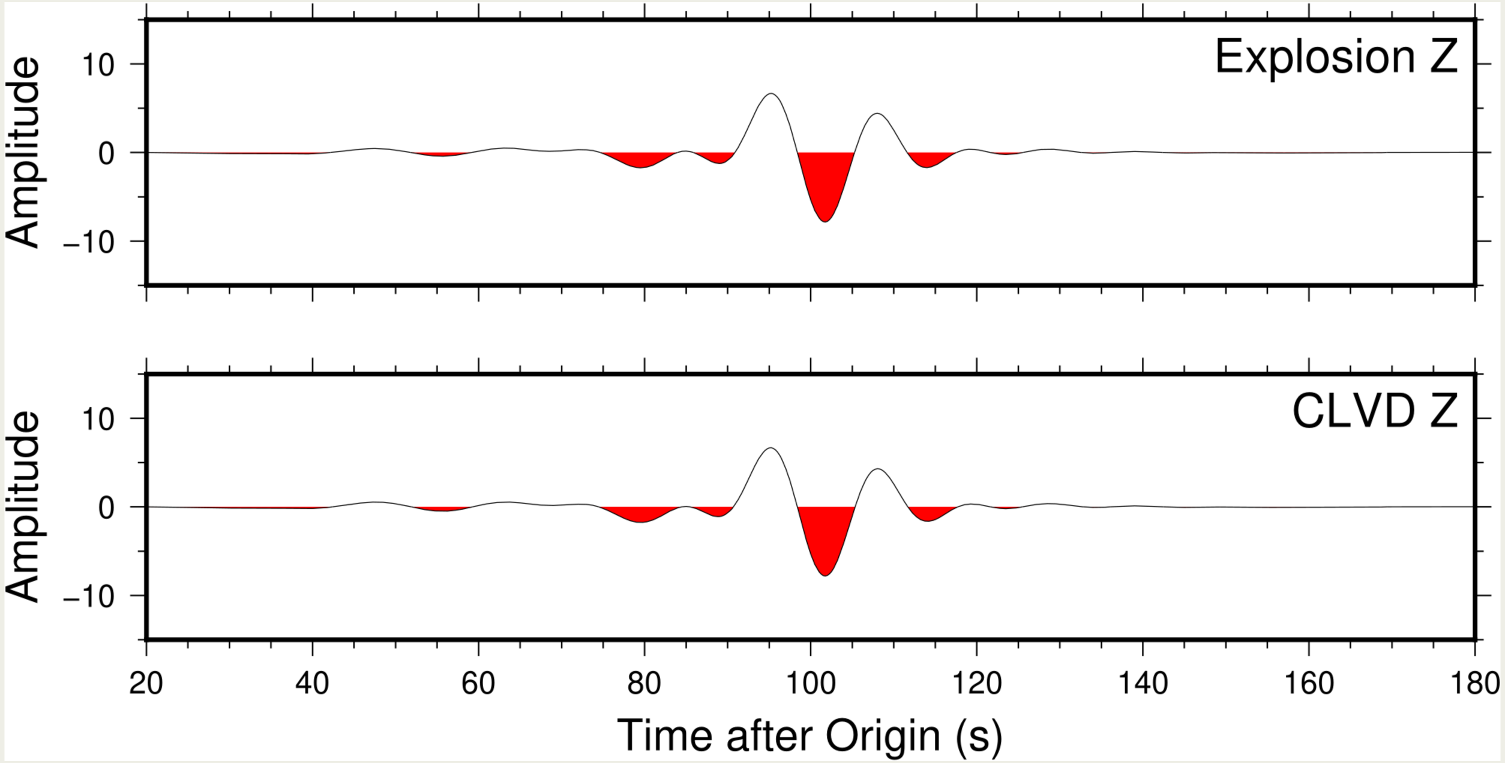
Difficulties with Using Surface Waves for MTSs

The M_{zz} and (M_{xx} + M_{yy}) 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.



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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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