High-frequency hybrid modelling of near-source topographic effects at teleseismic distances: The Degelen mountain case study

Marta Pienkowska[1,2], Stuart Nippress[3], Tarje Nissen-Meyer[2] and David Bowers[3]

marta.pienkowska@erdw.ethz.ch

[1] ETH Zurich, [2] University of Oxford, [3] AWE Blacknest

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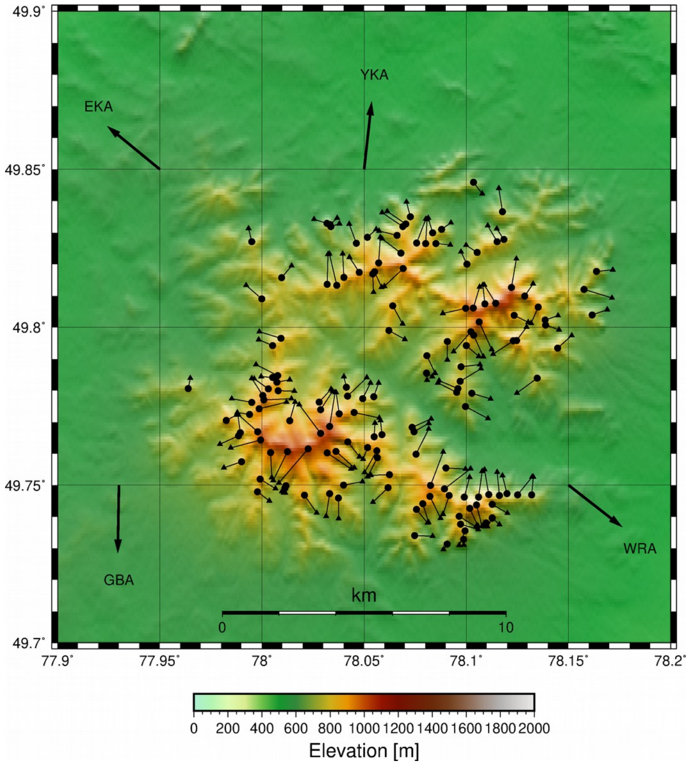
In brief:

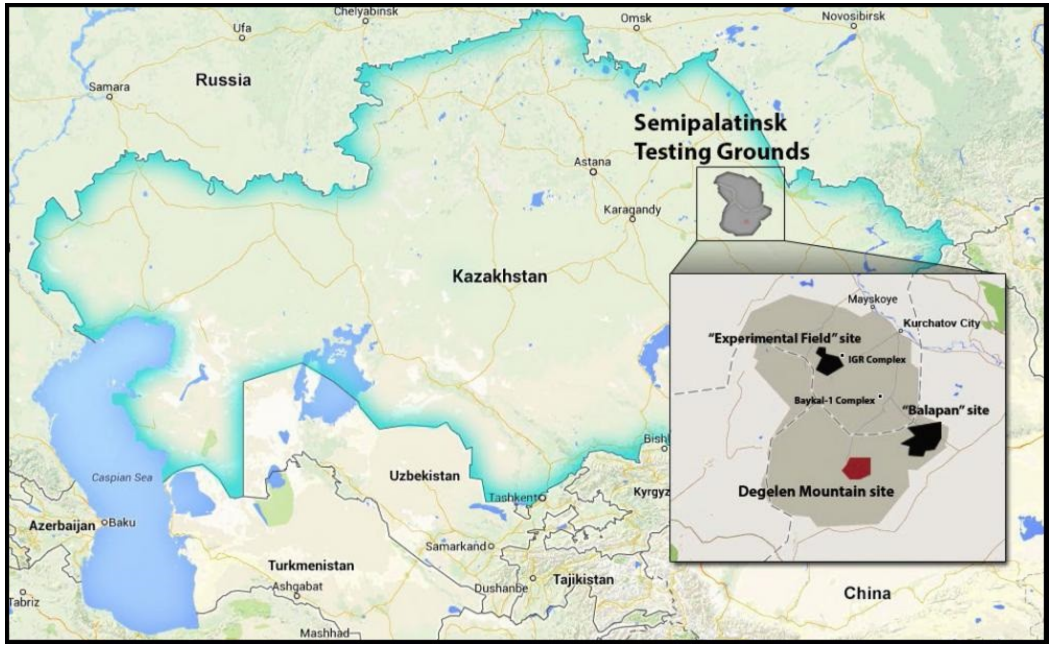
Teleseismic waveforms from underground nuclear tests often exhibit differences when the source location moves only a small distance (1-2 km). Observations suggest that such differences may be generated in the near-source region by emplacement and depth variations, scattering off topography and surrounding geology, or non-linear effects, yet the relative importance of contributing factors is not well understood.

This study focuses on the 1960s-1980s nuclear explosions from the USSR test site in the Degelen mountains, where the recorded waveforms up to 2 Hz seem to bear a strong signature of such near-source effects. An analysis of the dataset suggests that waveform features are dependent on the source location in the Degelen mountain range, and we propose that the change in signal characteristics on all arrays is related to the mountainous topography of Degelen. Simple measures, however, do not indicate a straightforward relationship with topography, and the hypothesis cannot be validated from data alone.

We therefore turn to deterministic hybrid modelling to evaluate waveform variations stemming from topographic interactions in the vicinity of the source. Despite the simplistic modelling assumptions and uncertainties in real source locations, features from observed recordings are present in the synthetics, suggesting a significant effect of the Degelen topography on teleseismic P waves. We found a very good overall qualitative fit of shape pulses and amplitudes at each station were well reproduced by synthetic seismograms at 2 Hz, showing that topography significantly contributes to waveform complexity at teleseismic distances.

Degelen test site: 1961-1989





- 224 underground nuclear tests, largest at 124 kt
- Blacknest archive:
  153 @ EKA,
  128 @ GBA,
  112 @ WRA,
  150 @ YKA
- 68 absolute event locations and origin times are available (Bocharov et al., 1989)

We choose the Degelen mountain range, as the large and unique Blacknest dataset provides an ideal starting point for a systematic analysis that can be related to synthetic data – the source locations, site topography and site geology are well known, and waveforms have been extensively processed. Such prior knowledge reduces the level of uncertainty in the subsequent numerical set-up and allows for more straightforward comparisons between the observed data and synthetics.

Waveform variations in the Degelen dataset appear:

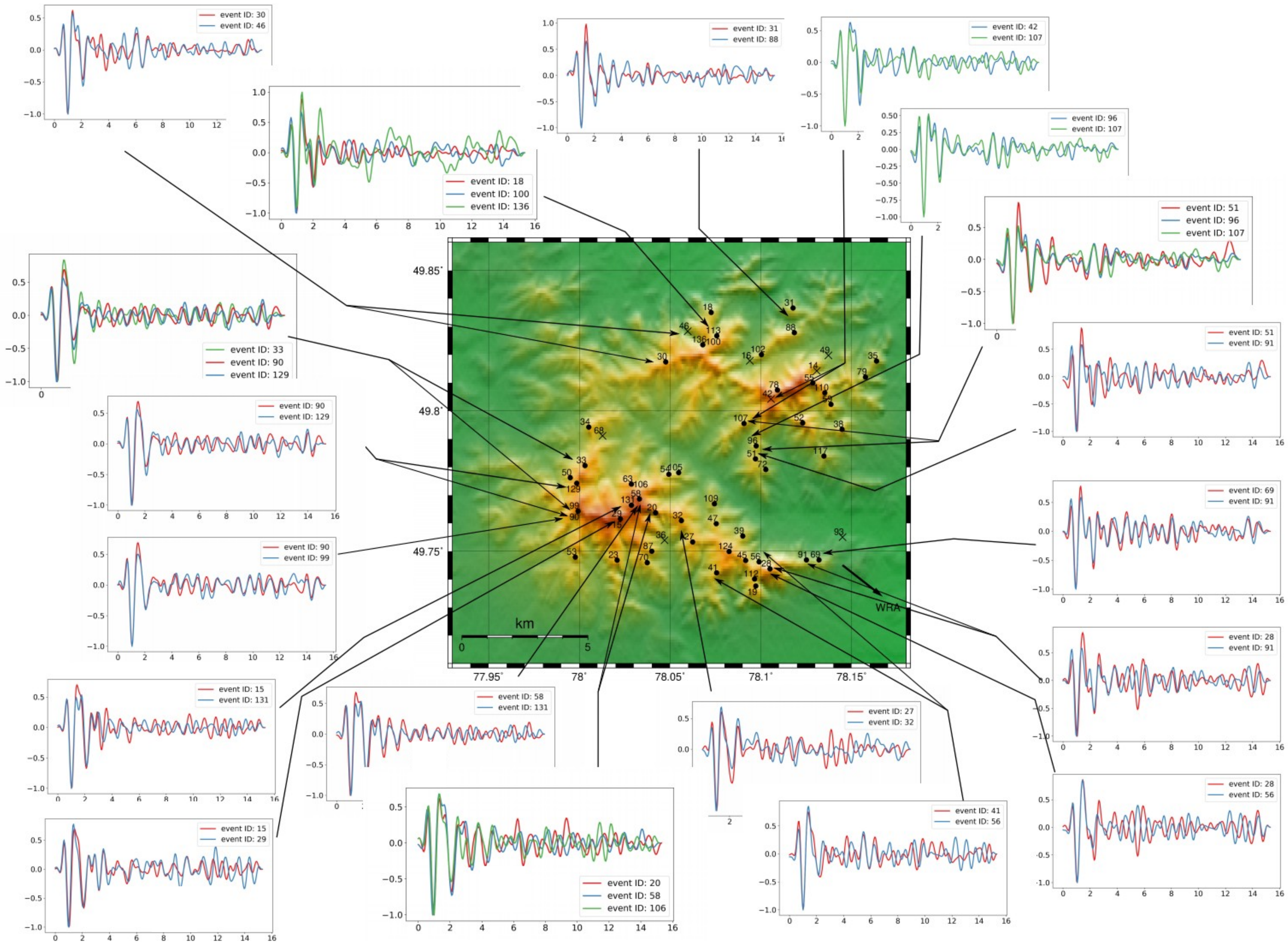
1. Independent of depth.
2. Independent of yield.
3. Dependent on location.

On the next two slides you can see a map of the Degelen topography, with adit (tunnel) ends indicated by numbered black circles. The numbers are the event IDs we have assigned to the explosions.

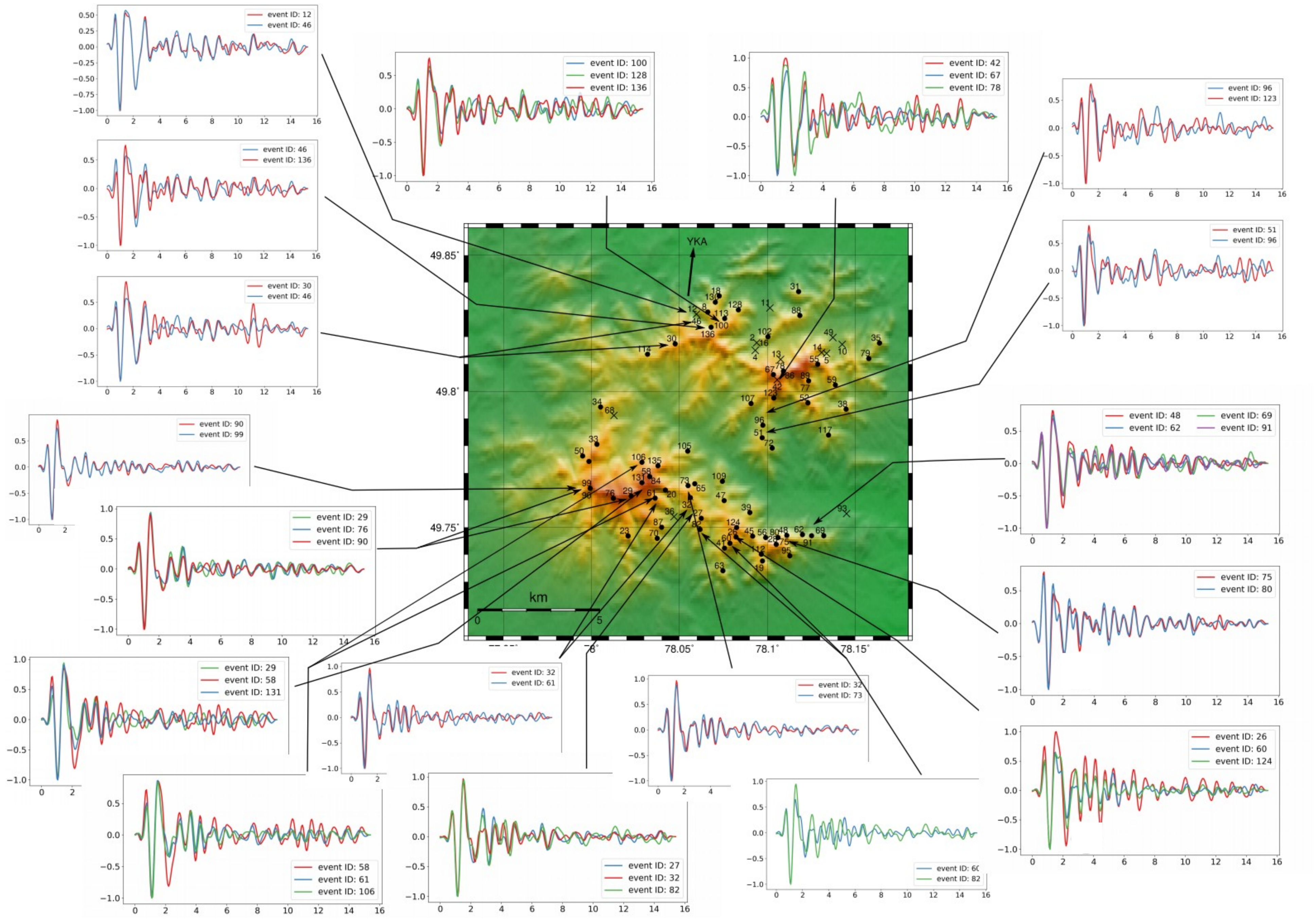
Z-component seismograms at WRA (85.3 degrees epicentral distance) and YKA (67.0 degrees epicentral distance) stations are plotted for many of the explosions, showing a progressive location-dependent change in waveform characteristics. I will not discuss this in detail here, but given this year's EGU format I will let you enjoy and explore the 'wiggles' in your own time. The waveforms are low-pass filtered at 2 Hz.

The question we want to address with modelling is whether we can attribute any of this variation to the mountainous topography of Degelen?

location-dependent pattern @ WRA

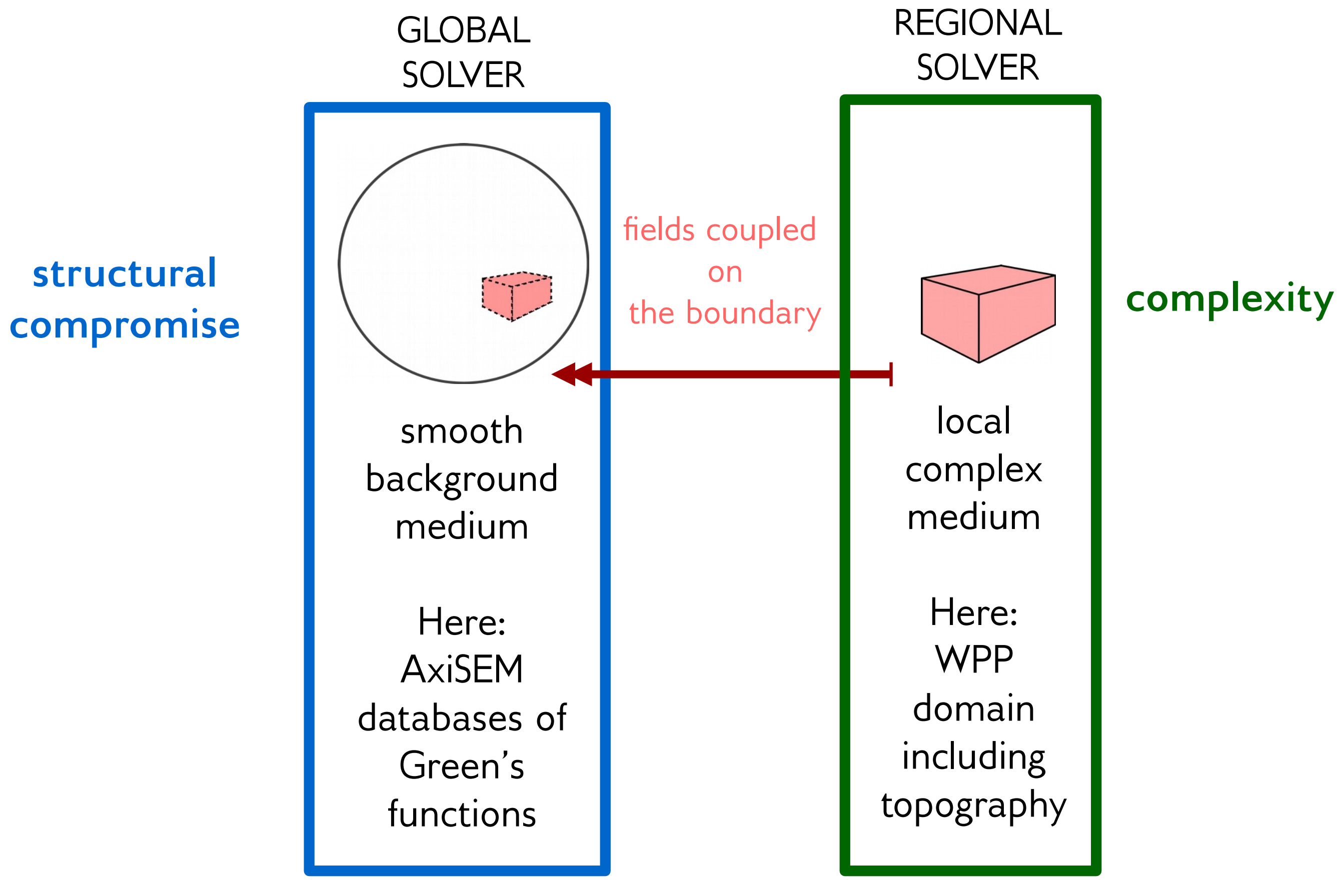


location-dependent pattern @ YKA



Hybrid modelling

Pienkowska et al., submitted to GJI.

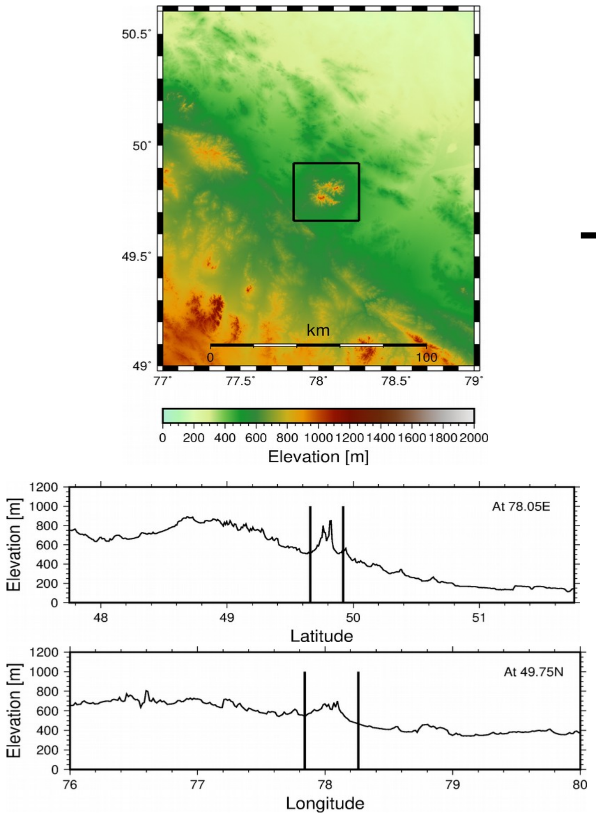


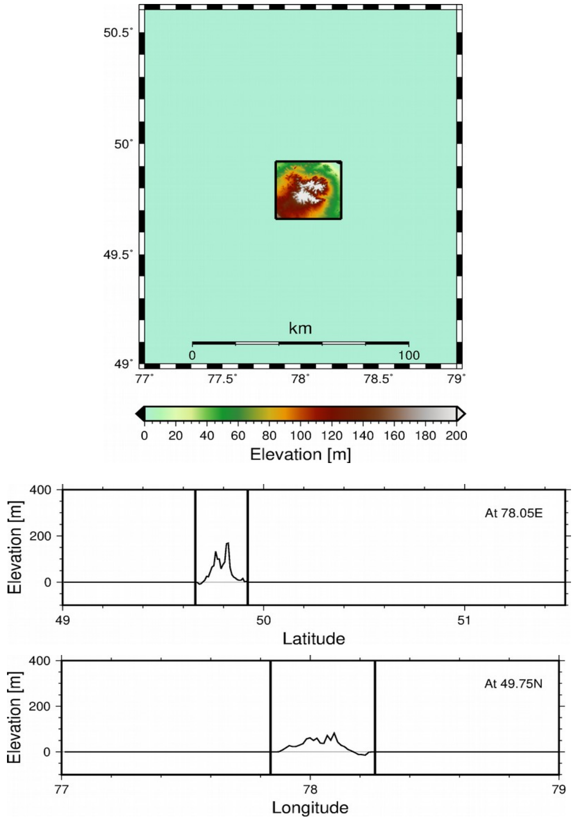
We have generated synthetic seismograms up to 2 Hz for Degelen using a hybrid methodology.

The hybrid code couples global databases of Green's functions (generated with AxiSEM (Nissen-Meyer et al, 2014) for Instaseis (van Driel et al., 2015)) in a 1-D Earth model with a local 3-D wave propagation code that accounts for small scale scattering. We therefore compromise on complexity in the 'background' medium, but thus can account for high frequencies and local small-scale scattering at teleseismic distances.

You can imagine a local "3-D box" – where complexities of interest are represented – embedded in a global 1-D model. The box is on the surface and includes the Degelen test site with topography, while the receivers are in the smooth 1-D background. We have used WPP (Nilsson et al., 2007) as the 3-D domain in this study.

Topography





+ IASP91

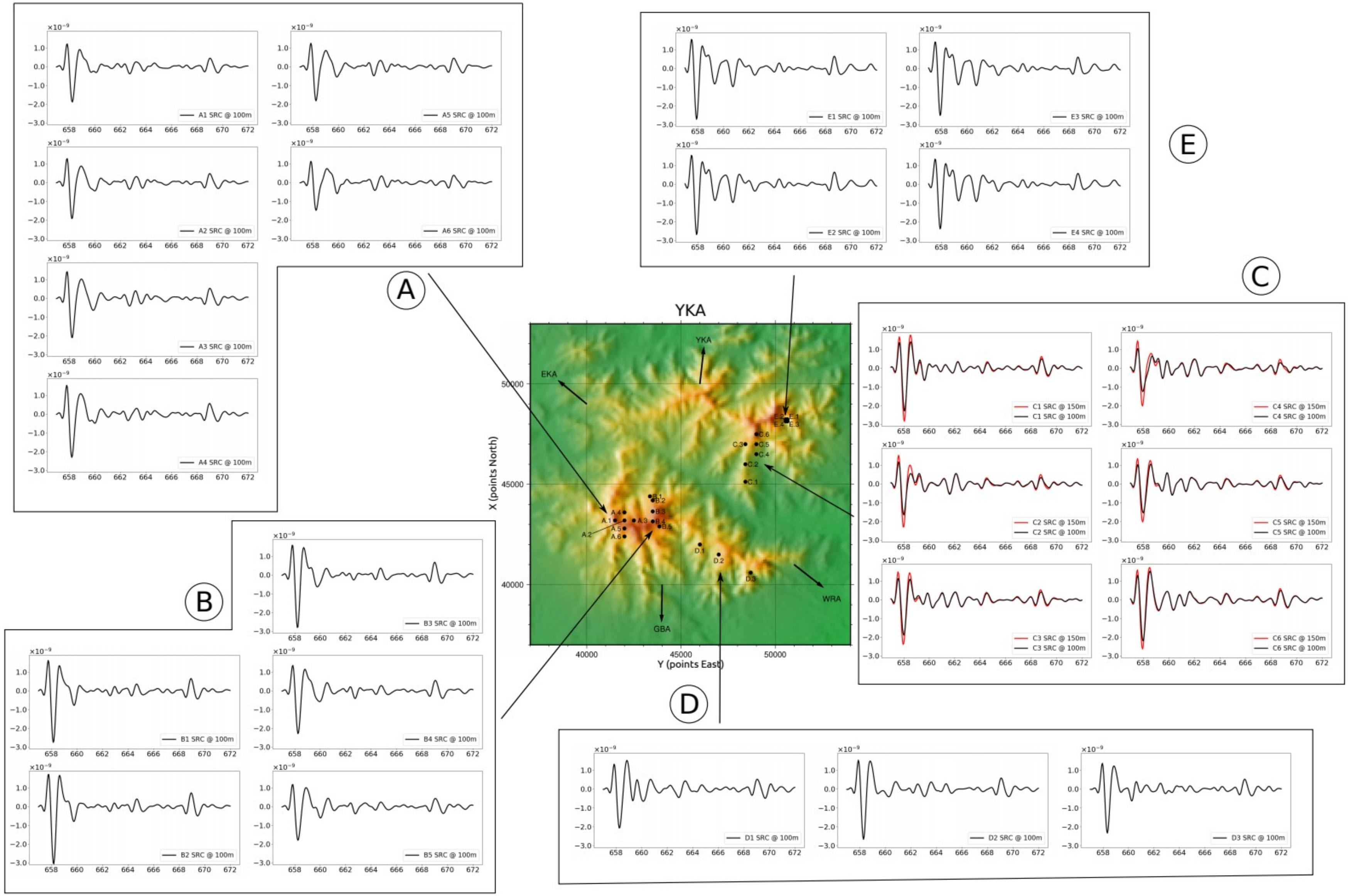
We have used the SRTM topography, cropped and detrended, isolating the mountain range and thus tapering it to the background 1-D model: IASP91 in this case. This is a requirement for hybrid coupling.

The local domain was 30x30x15 km in size, and we have used Gaussian source time functions to simulate explosions.

Saving the three-component velocities and six-component strains on the boundary of the local domain, we then repropagate the wavefields to receivers at distance via the IASP91 global database.

The database generated for this study captures interactions up to 2 Hz at teleseismic distances!

Exact source locations were not considered, and the same approximate source model was used for all simulations regardless of the yield and depth.

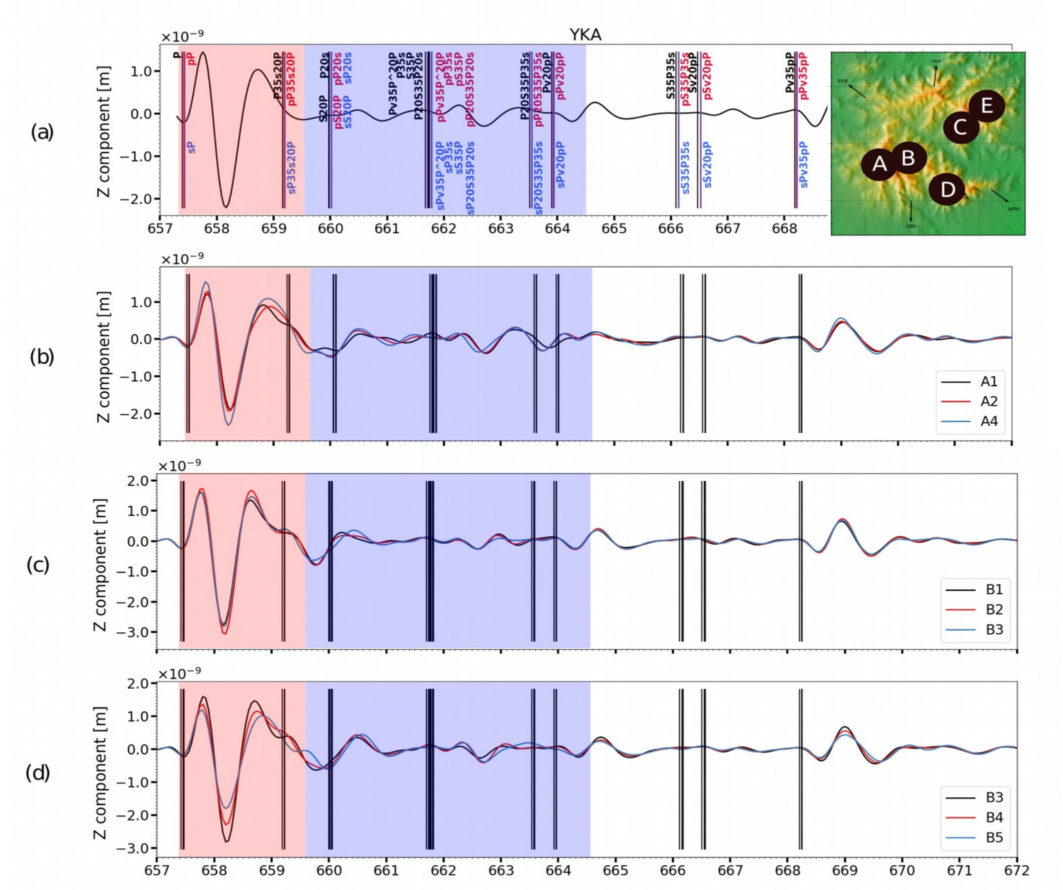


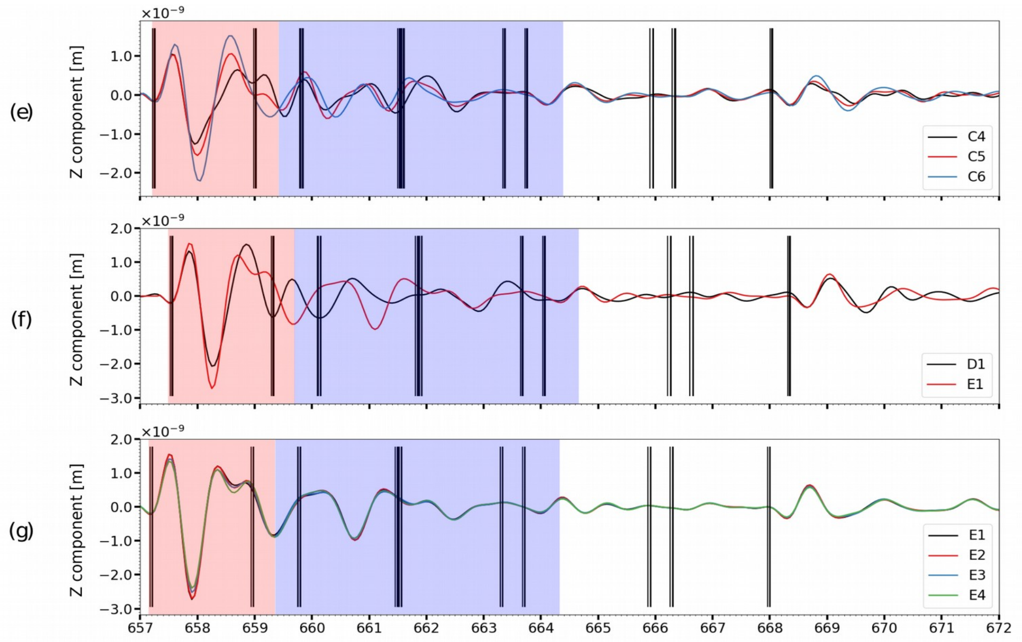
Simulations reproduce some waveform characteristics from the data, and amplitudes are in good agreement.

Again, given the “presentation format” I will let you explore the waveforms yourselves. In particular, have a look back at slide 6, and notice the similarities – the most notable being the occasional “splitting” of the second positive arrival.

As before, you can see here the Z-component low-pass filtered at 2 Hz.

YKA synthetics in detail:



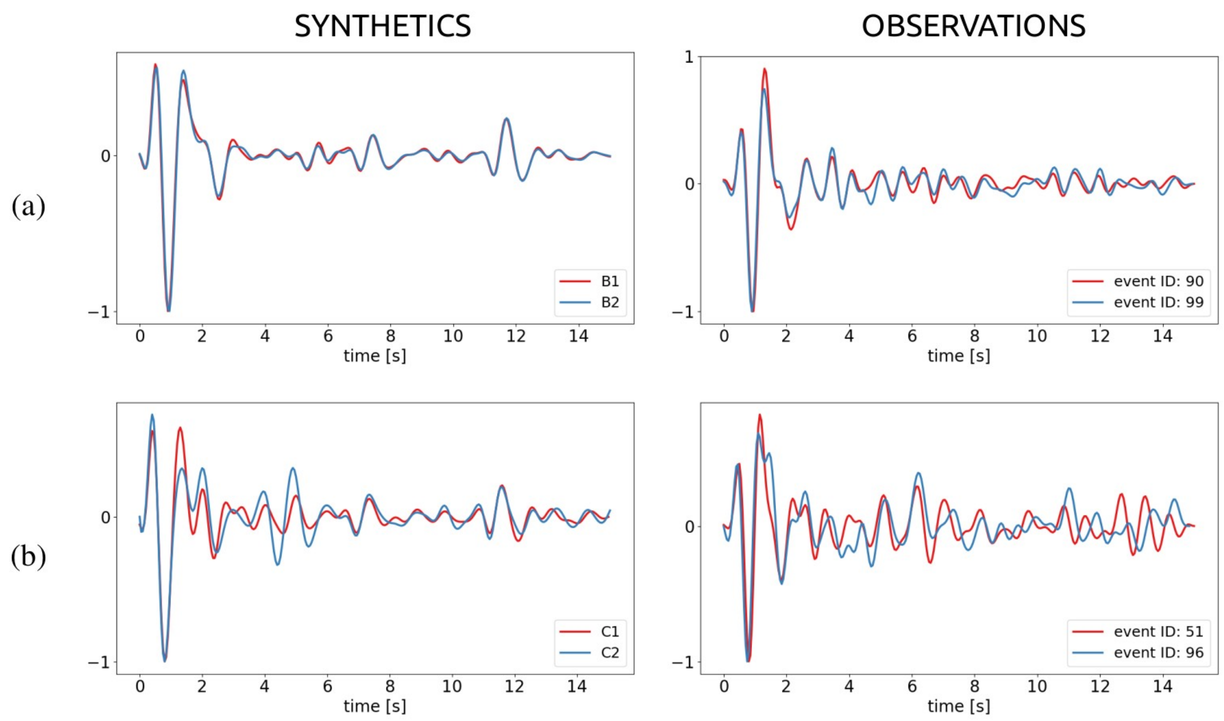


Here we can look at the YKA synthetics in a bit more detail.

(a) illustrates the 1D phases, while (b)-(g) show simulation results from different areas indicated on the map in (a) and how the 1D arrivals are perturbed.

The red shade highlights the P and pP interaction, while the blue shade highlights differences in subsequent reverberations within the mountain range.

Synthetics vs data:



Source proximity influences the similarity of waveforms both in the synthetics and in the data, suggesting that topography plays an important role in contributing to the observed differences. In (a), events are close by (<200 m), while in (b) they are further apart (>500 m).

Note the difference in corner frequency between the data and the synthetics. The simulated seismograms have been generated to contain most of the energy up to 2 Hz with a minimal computational effort ('dominant frequency' of 2 Hz, i.e. corner frequency of 1 Hz), and thus have a lower corner frequency than the data.

The amplitudes also show an excellent fit (figures not included here).

More data analysis and simulation results will be presented in upcoming papers, currently in preparation!

Wrapping up:

data:

suggests dependence of features on the location in the mountain range

modelling parameters:

did not account for realistic source models, geological heterogeneities, non-linear effects

modelling results:

good overall qualitative waveform fit despite modelling simplifications

next:

1. match the corner frequency of the data (i.e. dominant frequency of 3-4 Hz)
2. include more accurate source models
3. reproduce actual instances of source locations to replicate the full dataset with syntheitcs