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Modelling complex P-wave seismograms from the 28th May 1998 Pakistan explosion

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INTRODUCTION AND MAIN RESULTS

- Teleseismic P-waves from the 28th May 1998 Pakistan nuclear explosion are complex compared to those typically observed from underground explosions.
- We observe a spatial correlation between waveform complexity and take-off angle; with the most simple seismograms being recorded at small take-off angles and at seismic stations to the south of the explosion.
- Waveform simulations suggest that the observed complexity can be explained by near-source geology

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28th May 1998 Pakistan Nuclear test

- On 28th May 1998 Pakistan announced that it had fired five nuclear explosions, with a combined yield in the range of 30–35 kilotons
- The explosions were fired simultaneously so that individual explosions are indistinguishable
- Using satellite imagery and media sources Albright *et al.* (1999) identified the entrance to the tunnel and inferred the location of the detonation point (Fig 1.)
- The Reviewed Event Bulletin (REB) of the prototype International Data Centre (pIDC) reported P-times for 63 stations within the International Monitoring System [IMS] (Fig 1.)

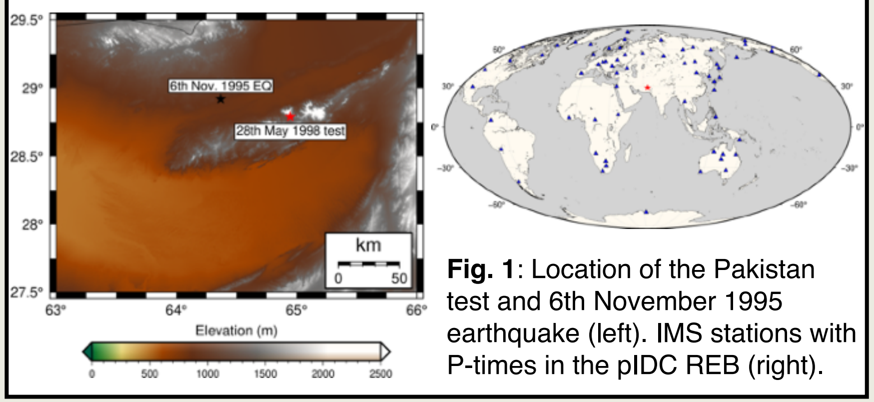

Fig. 1: Location of the Pakistan test and 6th November 1995 earthquake (left). IMS stations with P-times in the pIDC REB (right).

Waveform Complexity

- The P-waves from the the Pakistan nuclear test are among the most complex ever observed for an underground nuclear test (Fig. 2)

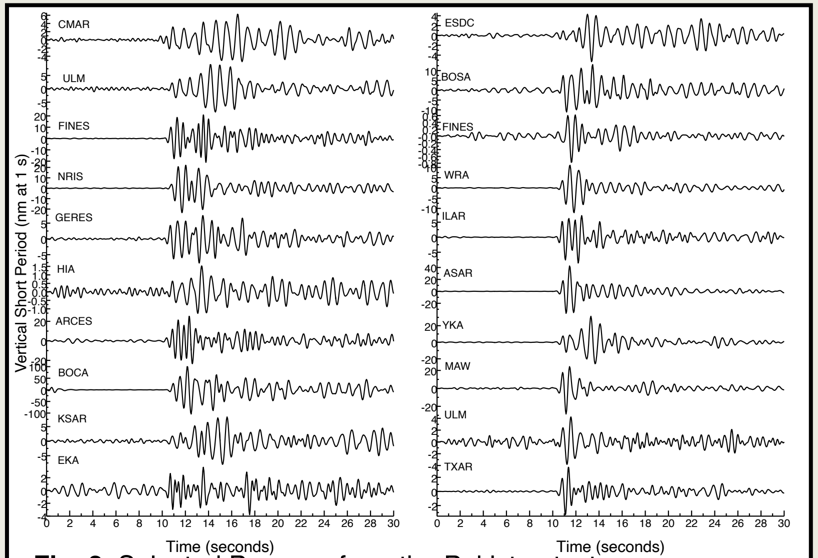

Fig. 2: Selected P-waves from the Pakistan test.

- Numerous measures of waveform complexity of been previously defined (e.g., Douglas, 1967)
- We define complexity as the root-mean-squared (RMS) amplitude between 2.5 - 5.0 s following the P onset divided by the RMS amplitude within 2.5 s of the P onset
- Before measuring RMS the waveforms are filtered between 1.0 - 2.5 Hz

- Waveform complexity (Fig. 3) appears to be:
  - smaller to the south, but generally there is no clear azimuthal relationship
  - correlated to take-off angle

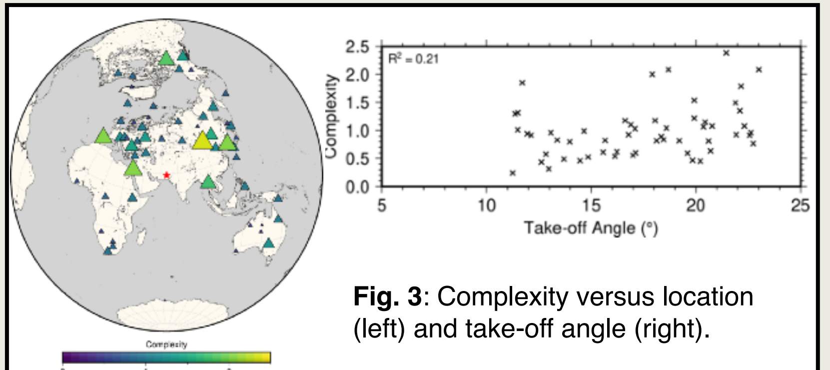

Fig. 3: Complexity versus location (left) and take-off angle (right).

- PcP waveforms, with small take-off angles, also appear simple (smaller complexity) compared with P waveforms recorded at the same station (Fig. 4)

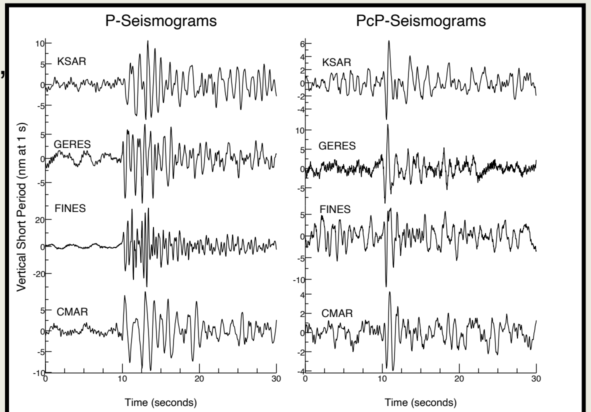

Fig. 4: Comparison of P and PcP seismograms.

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What could be the Source of the Waveform Complexity?

1. Spalling of the free-surface:
   - Usually confined to within 2 s of the P-wave onset (Patton, 1990)
2. Near-source topography:
   - Pienkowska *et al.* (2025) show that waveform complexity due to near-source topography is confined to a few seconds after the P-wave onset
3. Upper mantle structure or receiver crustal structure:
   - 6th November 1995 deep earthquake close to the test site (Fig. 1) displays simple P-waves compared to the explosion (Fig. 5) - suggests observed complexity seen for the explosion is not due to path or receiver-side effects
4. Variable near-source geology at Pakistan test site:
   - Could this explain the waveform complexity?

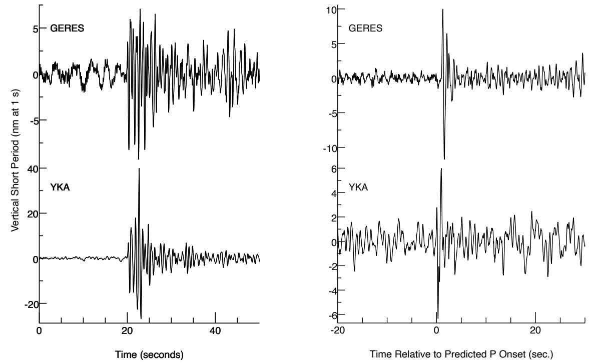

Fig. 5: P-seismograms from the Pakistan test (left) and the 6th November 1995 earthquake (right) at GERES and YKA.

Waveform Modelling

- To model the influence of near-source geology on seismic wavefields we use SW4 (Petersson and Sjogreen, 2012)
- Topography is taken from the Shuttle Radar Topography Mission (Farr *et al.*, 2007)
- The source, located in the Cretaceous volcanics (tuff), sits between syenodiorite basement to the north and a ultrabasic intrusion to the south (Fig. 6)
- Synthetic seismic stations 32km equidistant from the source with take-off angles of 0° - 25° (Fig. 6)

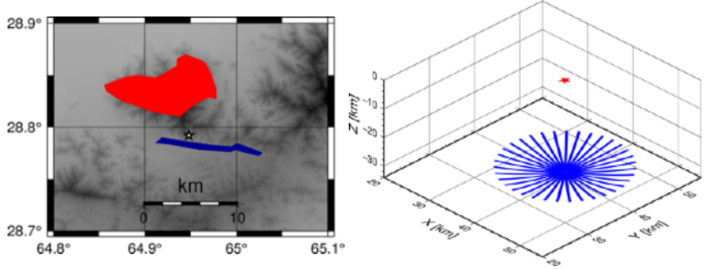

Fig. 6: Simulation setup. Left: simplified geology. Right: hemisphere of stations (blue circles) 32 km from the shot.

- Run simulations for an explosion source using AK135 with topography and AK135 with topography and near-surface geology variations
- Calculate RMS amplitude and complexity of the filtered [1 - 2.5 Hz] waveforms decomposed into P-, SV- and SH- ray coordinates (Fig. 7)
- Near-source geology significantly alters the wavefield and complexity

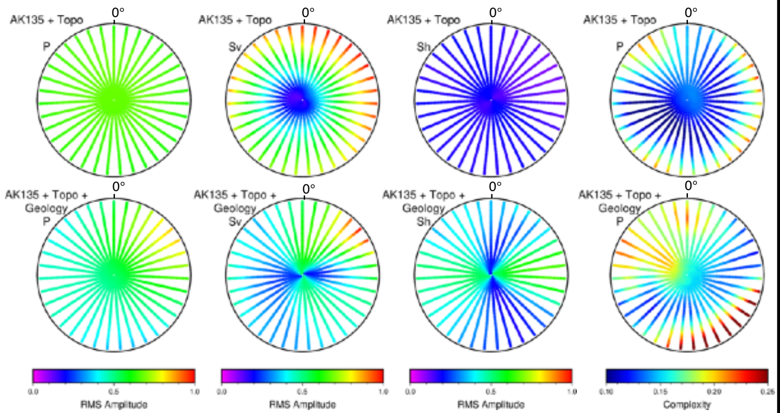

Fig. 7: Right: RMS amplitudes of the P-, SV-,and SH-polarized waveforms. Left: Complexity of the P-polarized waveforms.

- Future work: use technique of Pienkowska *et al.* (2025) to propagate these wave fields to teleseismic distances - are they still complex?

Summary

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