Automatically detecting and locating induced and natural earthquakes using Multichannel Coherency Migration (MCM)

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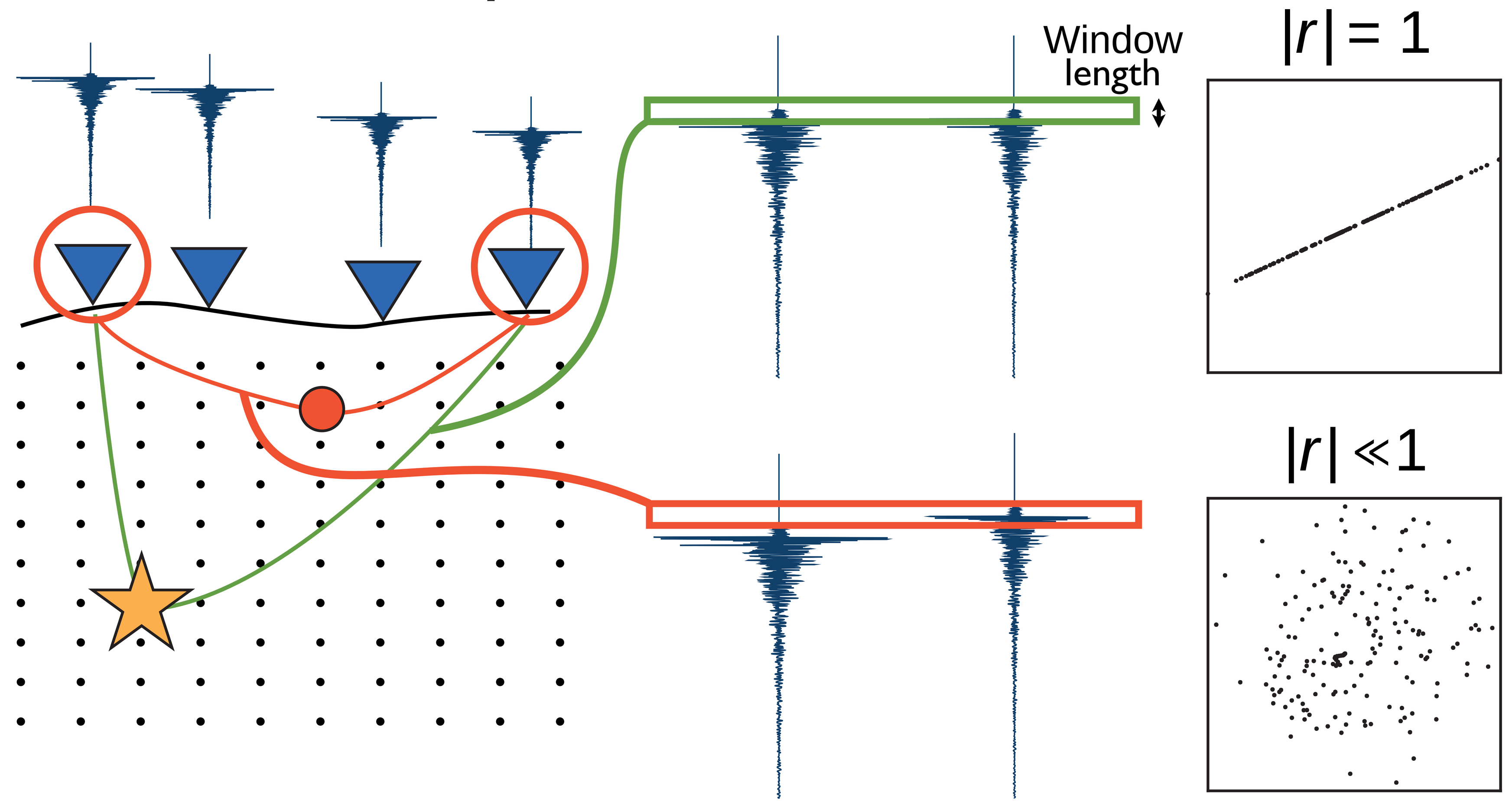
1. Theory

Multichannel Coherency Migration (MCM)

Our goal is to create a method to automatically detect and locate seismic events in noisy environments using sparse networks of passive seismic (broadband) sensors. We take pairs (or d-wise sets) of stations and migrate the absolute correlation coefficient $|r|$ (coherency) between each pair. Conventional migration approaches stack characteristic functions of individual stations, leading to a fold of N, where there are N stations. For the MCM, the fold is $N(N-1)/2$. Importantly, r does not depend on amplitude, so we do not need to deal with changes of polarity due to the event radiation pattern, and incoherent noise cannot affect the procedure.



Above Cartoon of MCM procedure. The subsurface is discretised into imaging points, and we take each pair of stations, shift them according to the travel time predicted for the phase of interest at that point and calculate r within a time window. At the correct imaging point (yellow star) the traces correlate well and $|r|$ is large. Elsewhere (e.g., red point) the traces do not correlate. We sum the $N(N-1)/2$ values of $|r|$ to obtain our coherency value through space and time in a 4-D migration volume.

Sum over window of length t_w s — Time shift at imaging point k — Data for trace j

$$r_{ij} = \frac{\sum_{t=t_0}^{t_0+t_w}\left[d_i(t+t_{ki}) - \overline{d_i(t+t_{ki})}\right]\left[d_j(t+t_{kj}) - \overline{d_j(t+t_{kj})}\right]}{(N_t-1)\,\sigma_i\sigma_j}$$

Data for trace i — Mean of data in window — Number of samples in window — Standard deviations

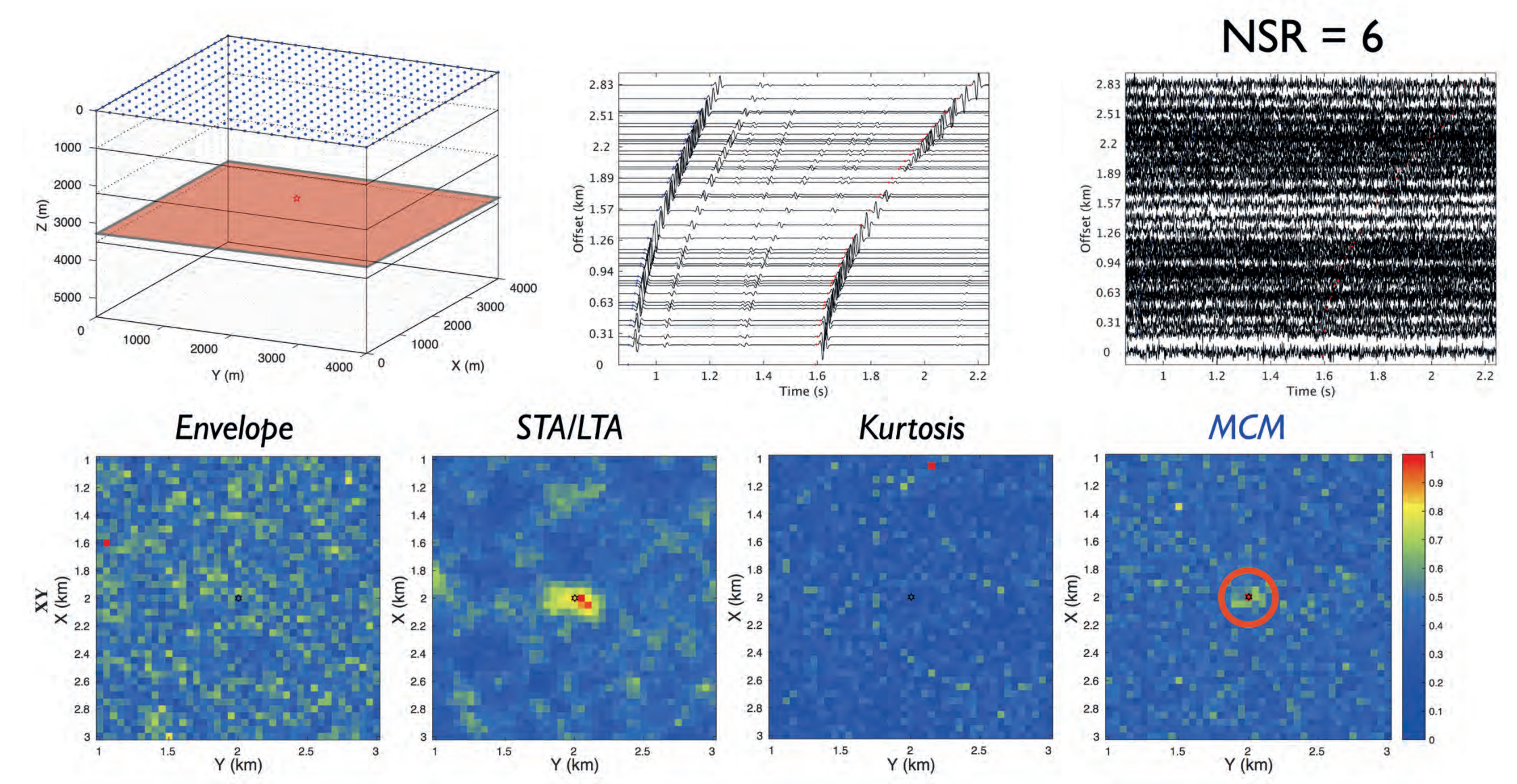
Above Expression for correlation coefficient.

Right Stacking coherency is the sum of the values of $|r|$ for each phase.

$$p(x,y,z,t_0) = \frac{1}{N(N-1)}\left(\sum_{i<j}^{N}|r^P_{ij}| + \sum_{i<j}^{N}|r^S_{ij}|\right)$$

2. Synthetic tests

Comparison with other migration methods



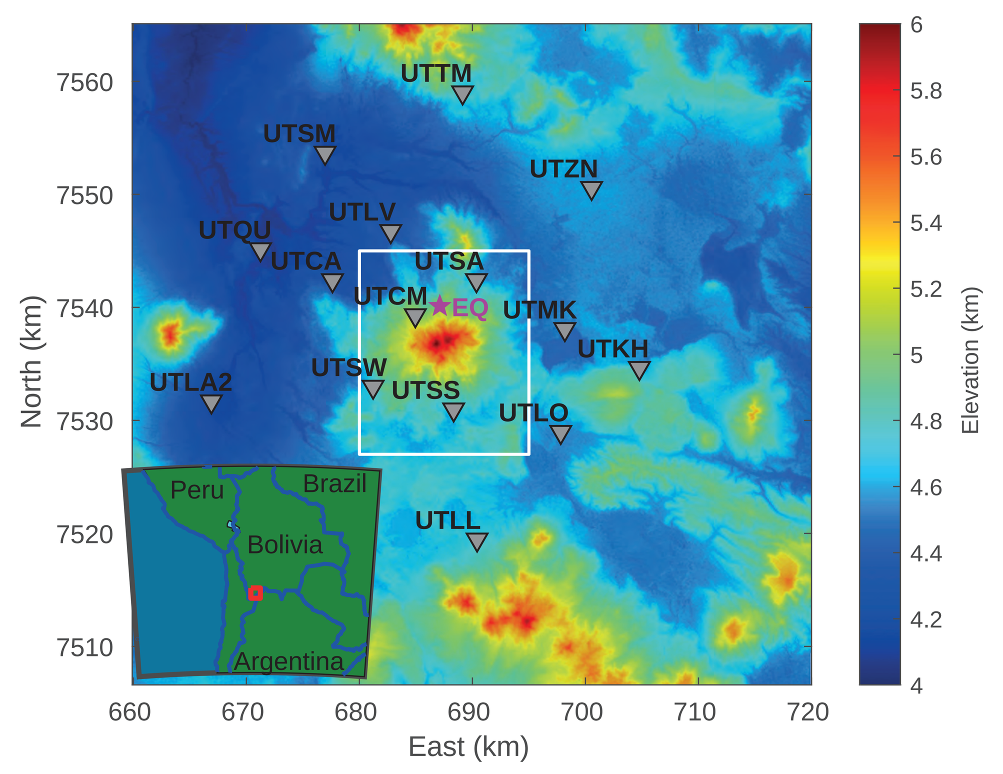
Above Comparison of MCM with other migration methods in synthetic tests. We migrate synthetics (top middle) for a 1D layered model (top left) after application of noise (top right). Migrating wavefrom envelopes, short-term- to long-term-average ratio or the forward derivative of waveform kurtosis sometimes produce acceptable results, though MCM maintains accuracy when noise-to-signal ratio (NSR) is high. Bottom row shows horizontal slices through migration volume.

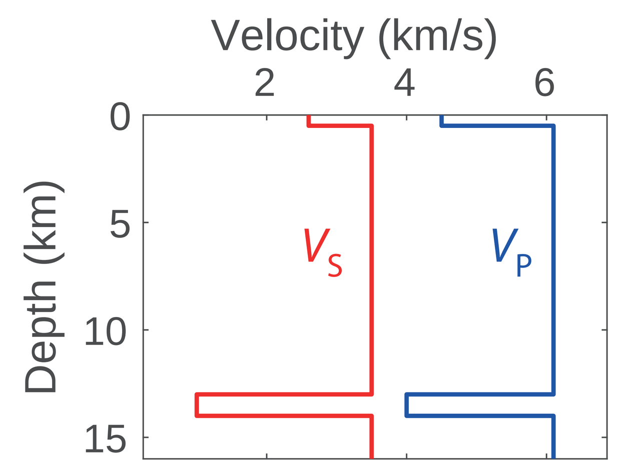
4. Conclusions

- We propose the Multichannel Coherency Migration, which uses the correlation coefficient between pairs of channels (or combinations with greater numbers) of continuously-recorded seismic data to automatically detect and locate seismic events.
- The method is robust to noise and often performs better than existing migrations, especially in noisy settings.
- We automatically detect ~320 volcano-tectonic earthquakes beneath Uturuncu volcano, triggered by the passage of surface waves.
- The MCM is computationally expensive but suitable for real-time monitoring.

3. Volcano-tectonic seismicity

Uturuncu, Bolivia



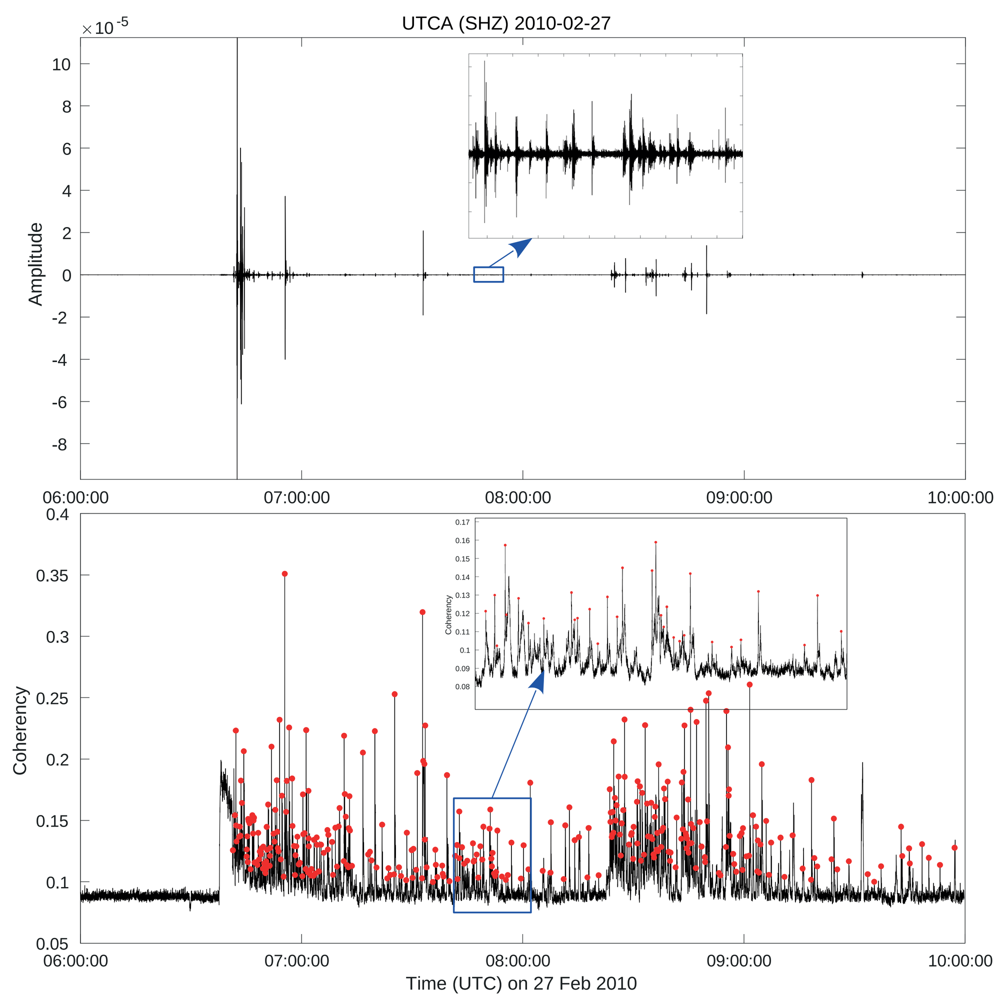


Above Velocity model used in the migration for events.

Left Map of region around Uturuncu volcano showing stations (triangles). White box is extent of migration volume.

Seismicity triggered by 2010 Maule M8.8 earthquake

The passage of the surface waves from the 27 February 2010 Maule earthquake nearby triggered hundred of detectable events beneath the volcano. These were detected by Jay *et al.* (*Bull. Volc.*, 2012) by manual inspection.

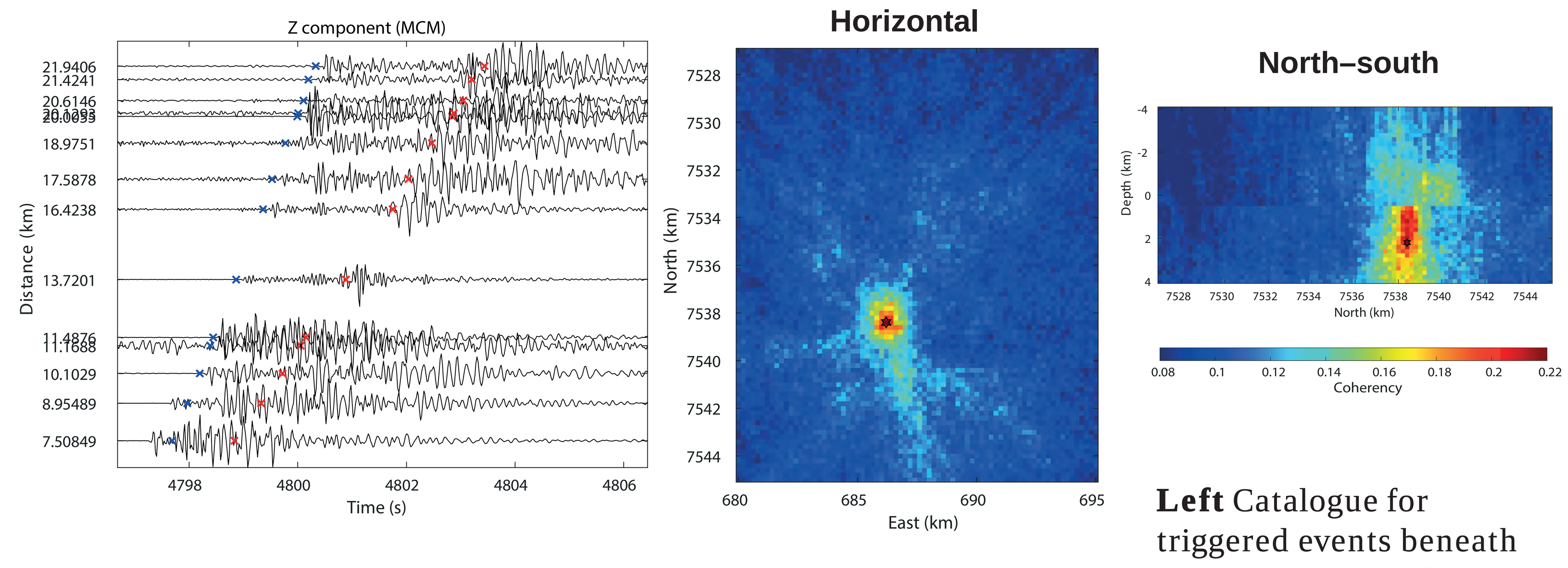


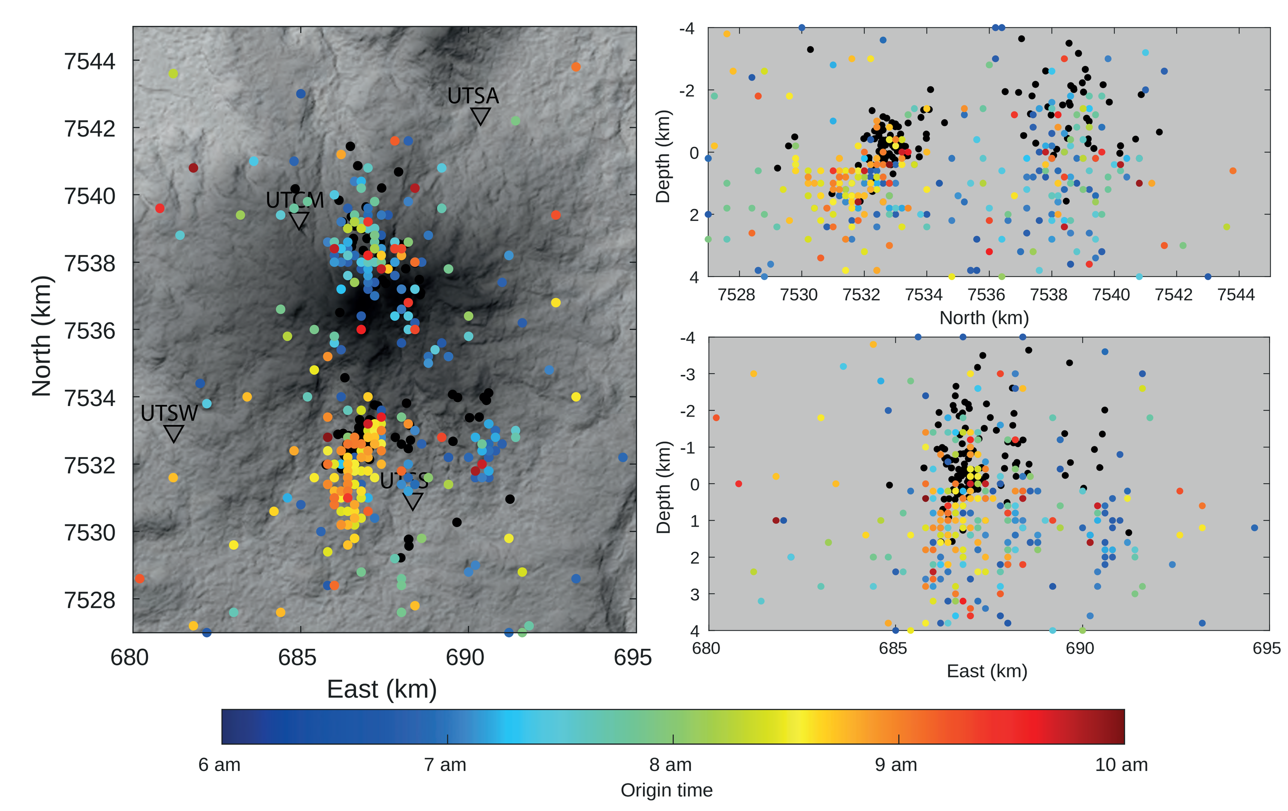
Upper left Example data for station UTCA (vertical component, bandpass filtered between 4.2 and 21.6 Hz) after instrument response removal, showing multiple events throughout the period after the arrival of the Rayleigh wave at ~06:40 UTC.

Left Maximum coherency of MCM throughout imaging volume through time (time sampling 0.08 s). Red dots show maxima associated with manually verified seismic events.

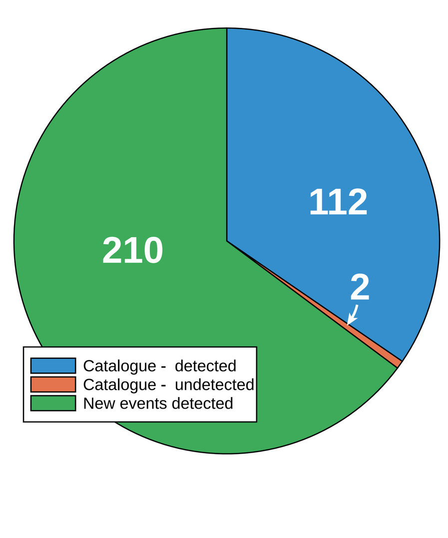
Bottom left Record section for event marked EQ on map, above. Blue and red marks are MCM arrival picks for P- and S-wave respectively.

Below Slices through migration volume for event marked EQ, an example of one not in the Jay *et al.* catalogue from manual picking.





Left Catalogue for triggered events beneath Uturuncu obtained via MCM (coloured dots, showing origin time) and the catalogue from Jay *et al.* obtained by manual inspection and arrival time picking, then location inversion using *genloc* Pavlis *et al.*, 2014). Note that the MCM locates events deeper despite using the same velocity model. MCM predicted arrival times better match seismograms than predictions from existing catalogue locations.



Left Proportion of events detected in existing manually-picked catalogue of Jay *et al.* (2012) versus those not detected, and additional events found using the MCM.

Right Histogram of events detected with surface wave arrivals marked.