

Supplementary material

Anti-repeating earthquakes and how to explain them

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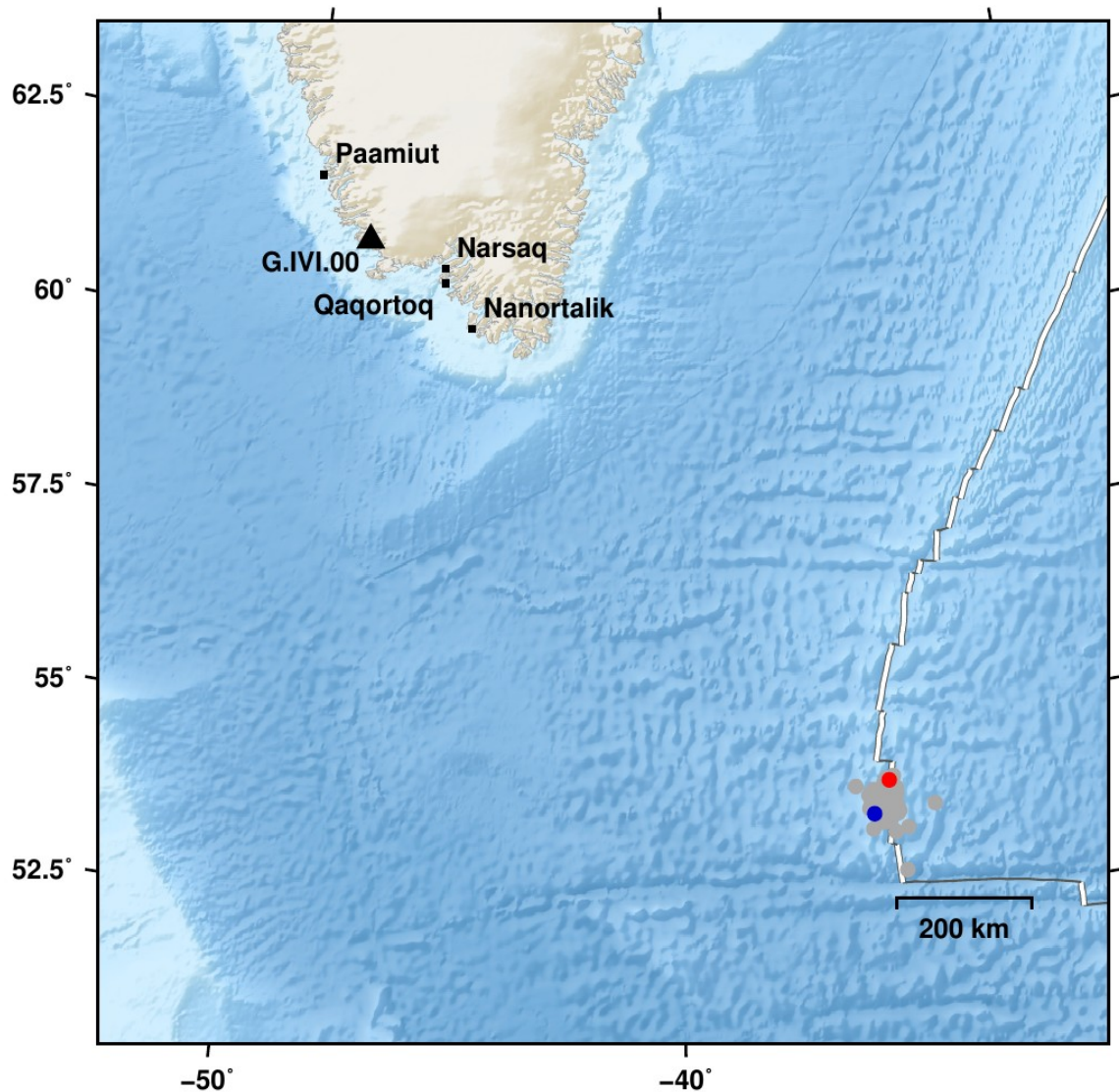
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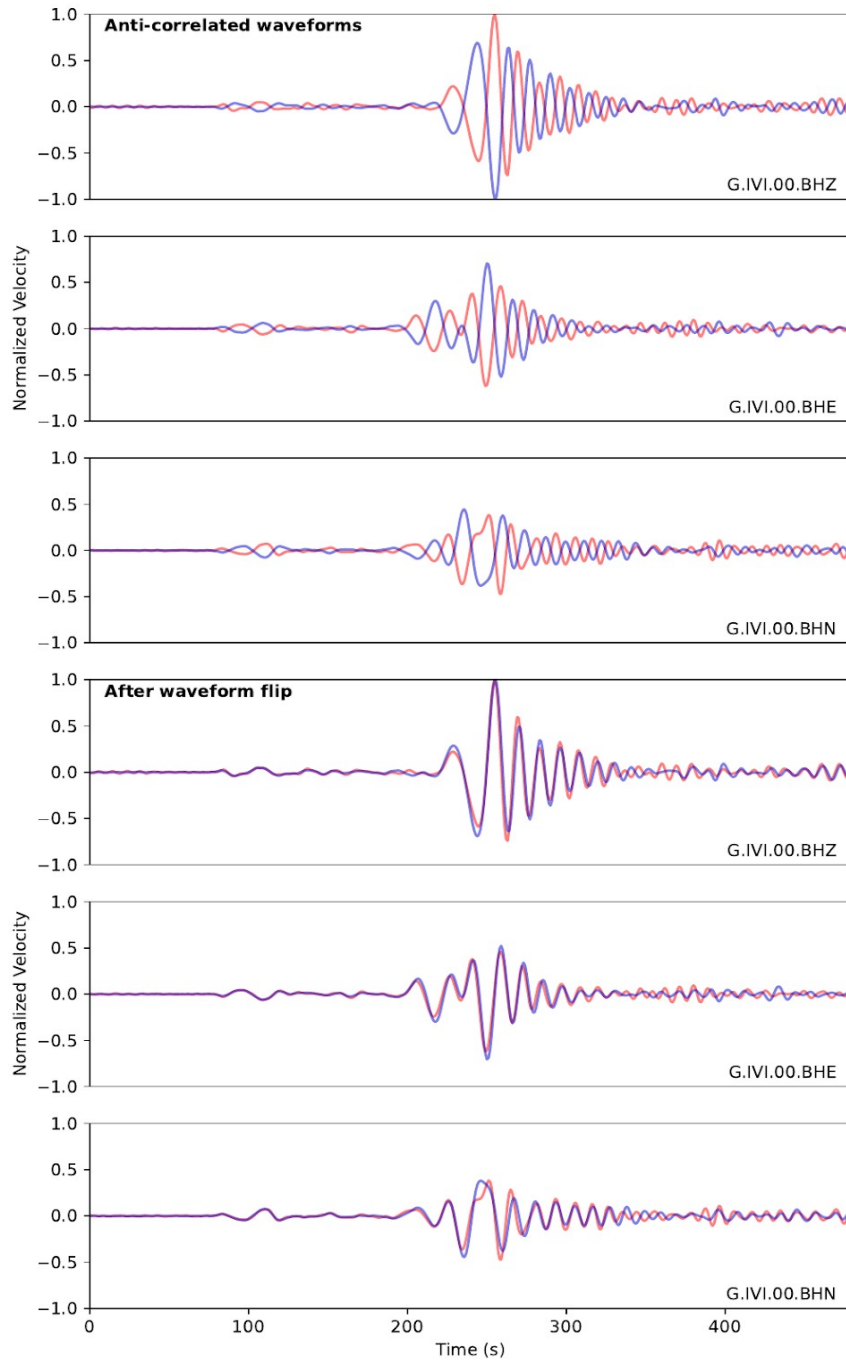
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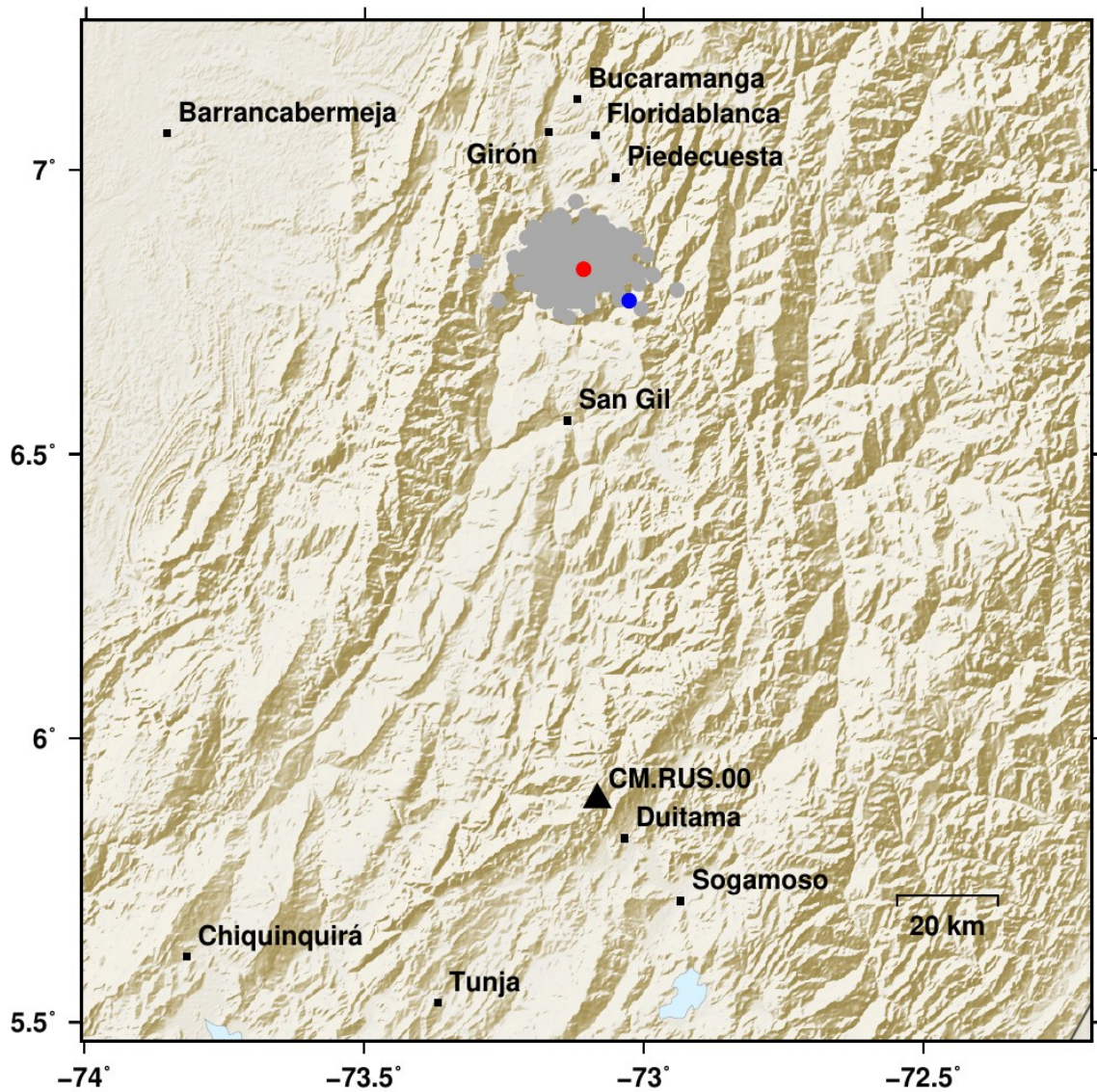
This document includes supplementary documentation, including 9 figures, which complement the main manuscript.



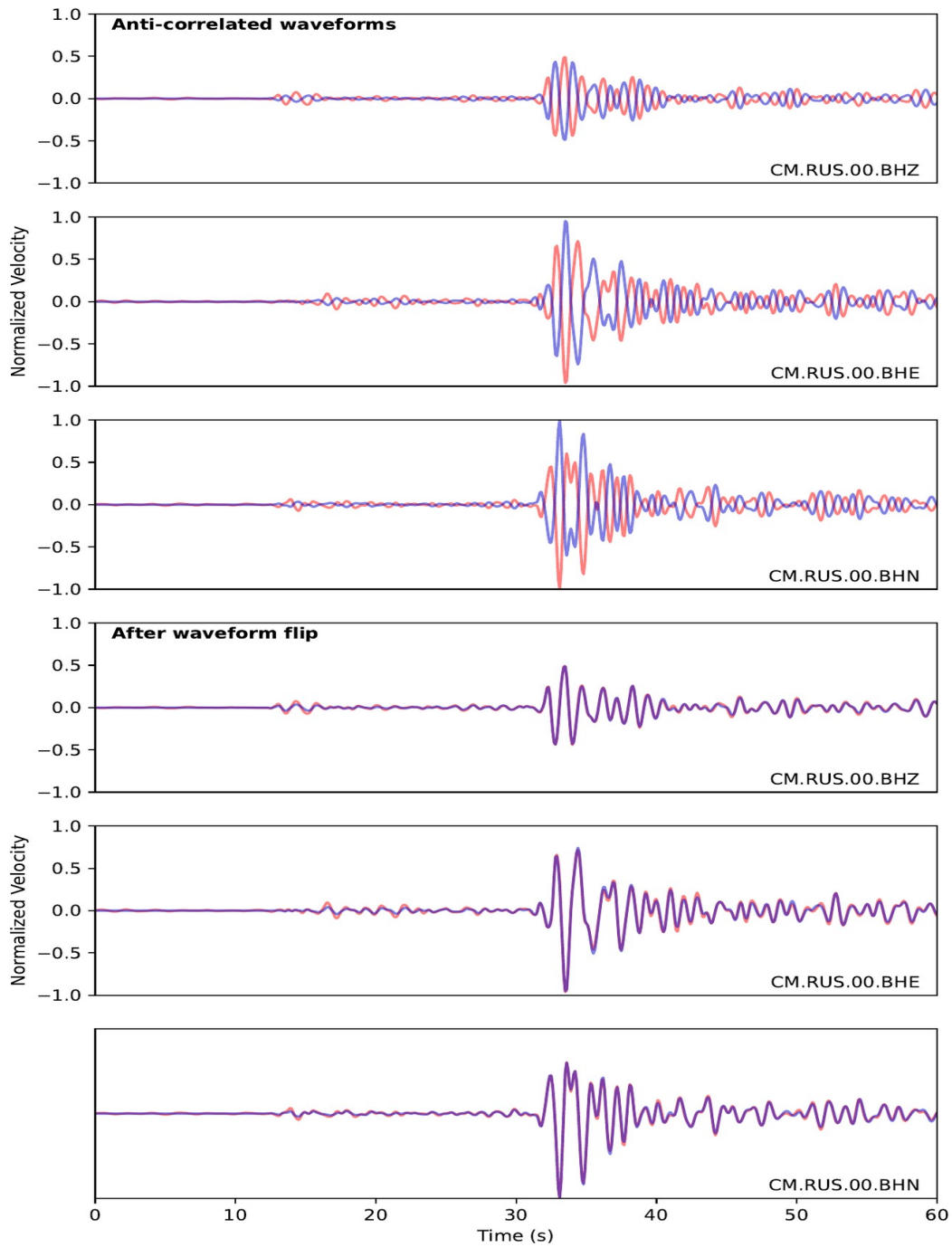
Suppl. Fig. 1. Source-receiver locations for observed anti-repeaters at the Nord Mid-Atlantic Ridge. Recordings are discussed for station G.IVI.00 (black triangle) for two earthquakes (red and blue circles) occurring during a seismic swarm (dark grey circles) in September-October 2022¹.



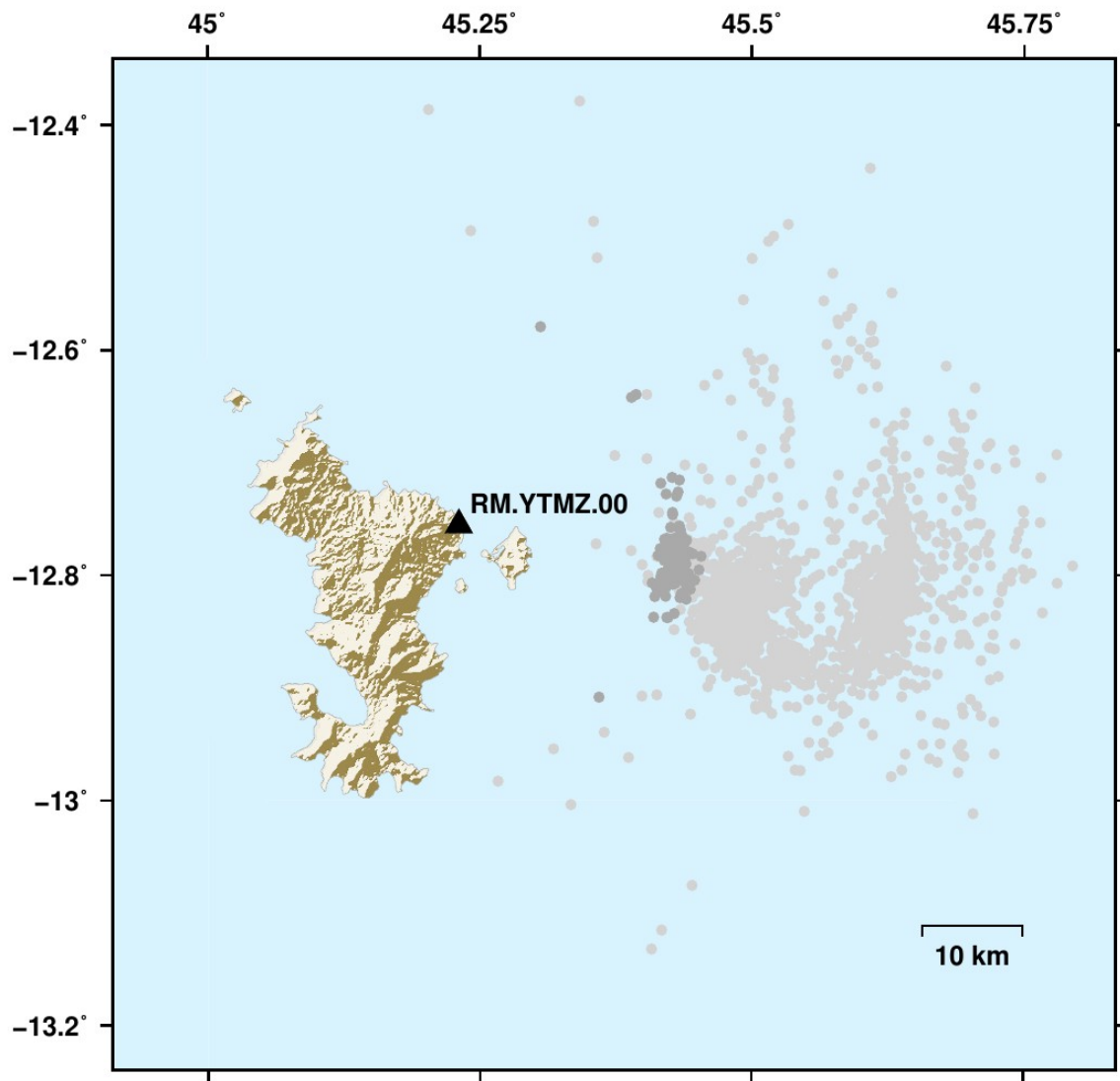
Suppl. Fig. 2. Example of anti-repeaters at the Nord Mid-Atlantic Ridge. The signal is shown for three components at broadband seismic station G.IVI.00 for channel BH. Normalised velocity data are bandpass filtered between in the band 0.02-0.10 Hz, using a 4th-order Butterworth filter. Top three rows show the original anti-correlated set of signals (red, blue), while bottom three rows show the similarity of the same signal, after flipping red traces.



Suppl. Fig. 3. Source-receiver layout for anti-repeaters at the Bucaramanga nest, Colombia. The pair of anti-repeaters signals at the Bucaramanga nest, Colombia, were identified based on recordings at the seismic station CM.RUS.00. Their epicentral locations (Tab. 1) are shown in red and blue. Epicentral locations of events spatially clustered² in the nest, according to the revised ISC catalogue³⁻⁴ during the time period 2018-2020 are shown as grey circles.



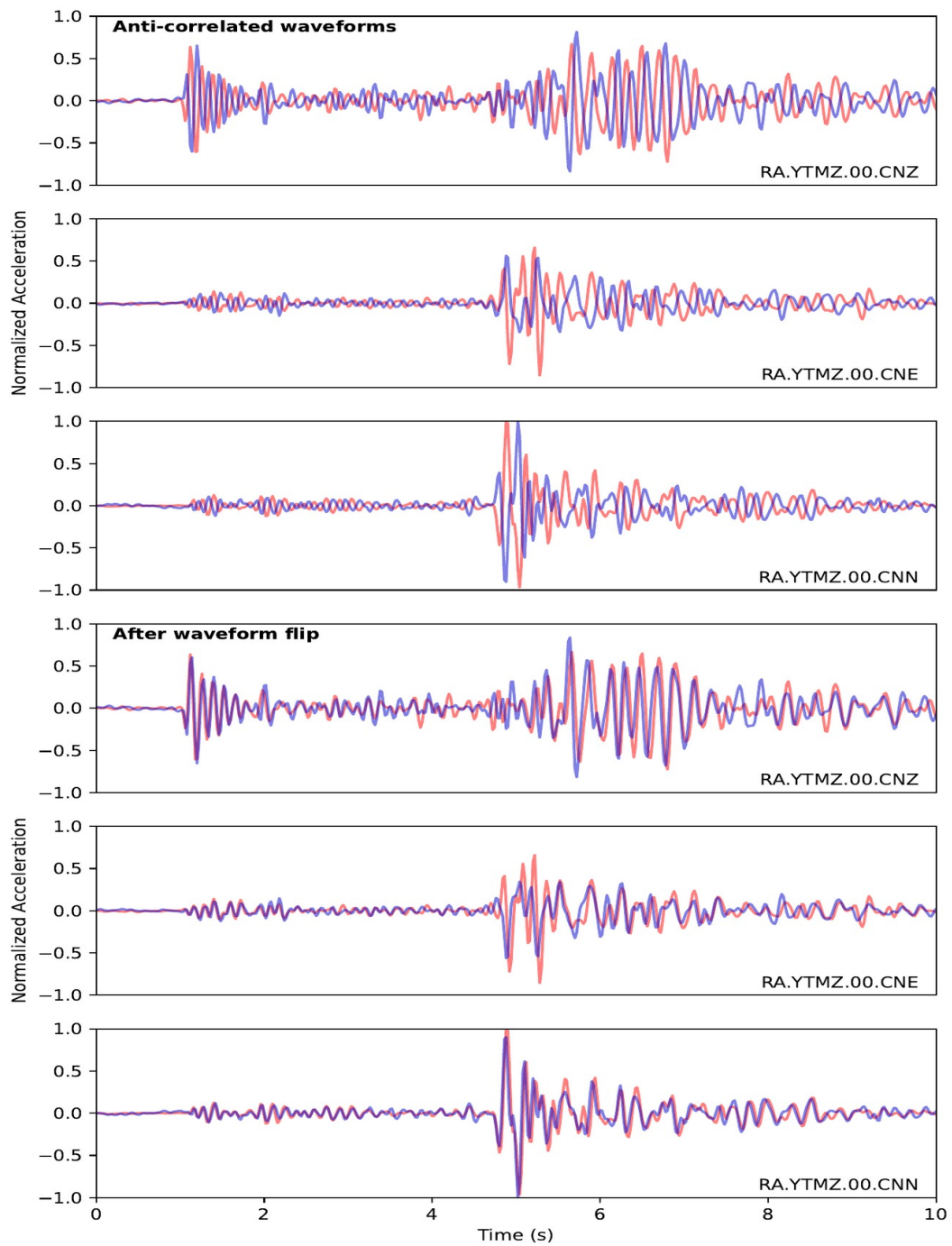
Suppl. Fig. 4. Example of anti-repeaters at the Bucaramanga nest, Colombia. The signal is shown for three components at broadband seismic station CM.RUS.00 for channel BH. Normalised velocity data are bandpass filtered between in the band 0.375-4.0 Hz, using a 4th-order Butterworth filter. Top three rows show the original anti-correlated set of signals (red, blue), while bottom three rows show the similarity of the same signal, after flipping red traces.



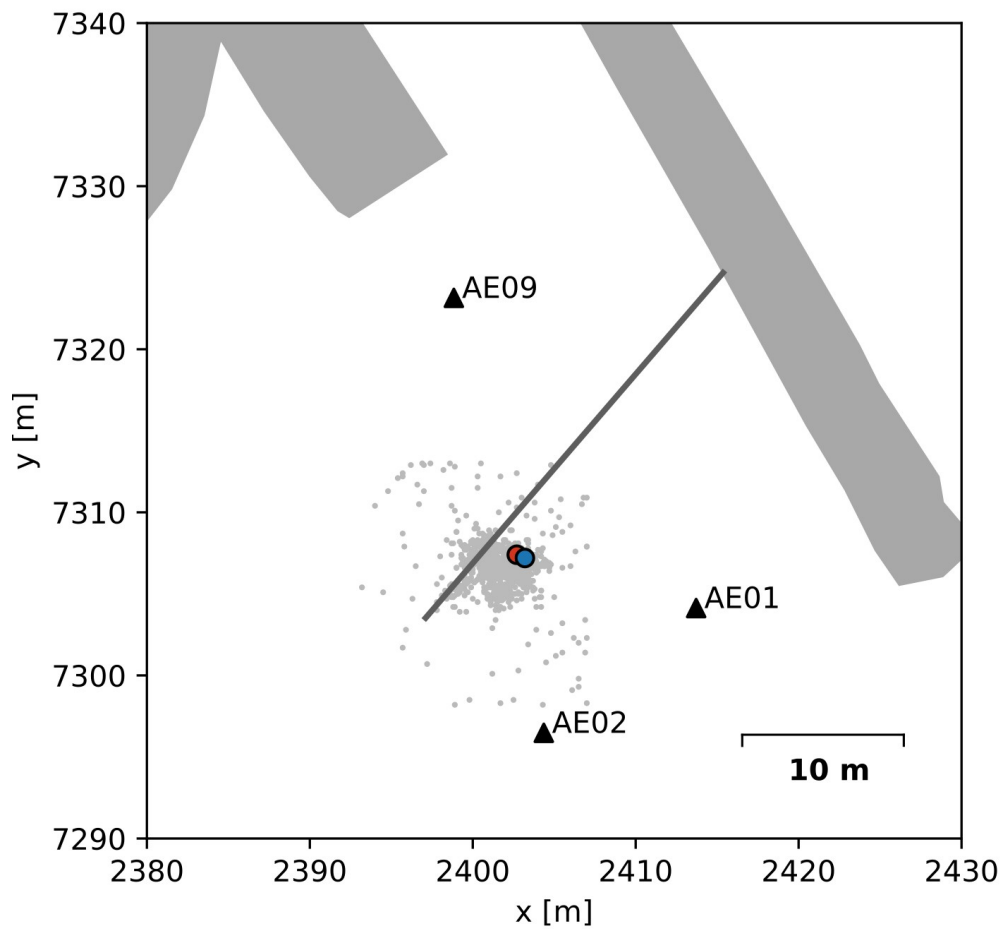
Suppl. Fig. S5. Source-receiver layout for anti-repeaters at Mayotte, Comoro Islands.

The sources of anti-repeaters signals at Mayotte Islands, identified by anti-correlating waveforms at the seismic station RA.YTMZ.00 (black triangle), could not be located.

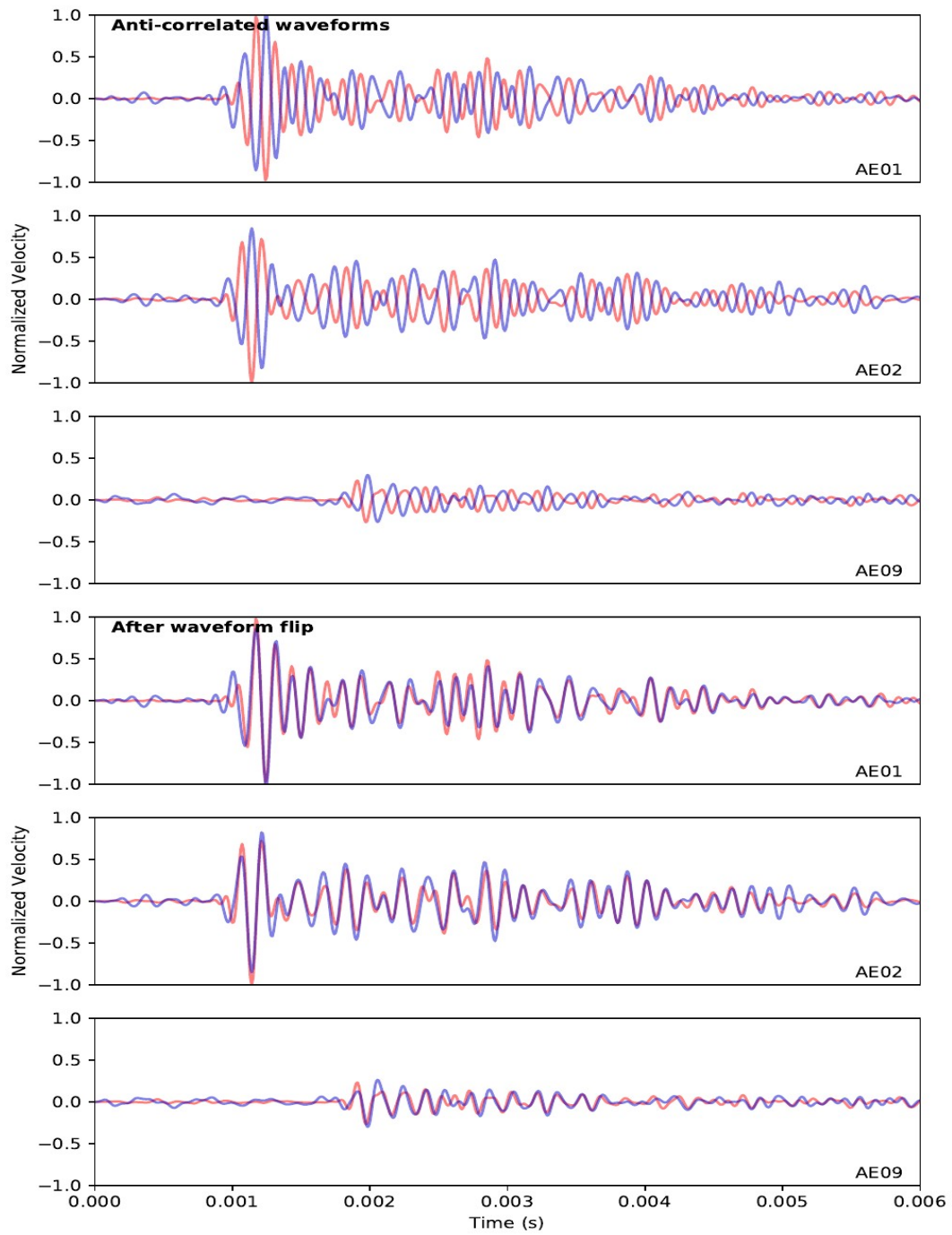
However, they were most likely located in the cluster (dark grey circles) of events occurring during the same unrest phase⁵ and having similar S-P differential times (~3.5-3.9 s). Light grey circles denote the locations of the other events in the unrest.



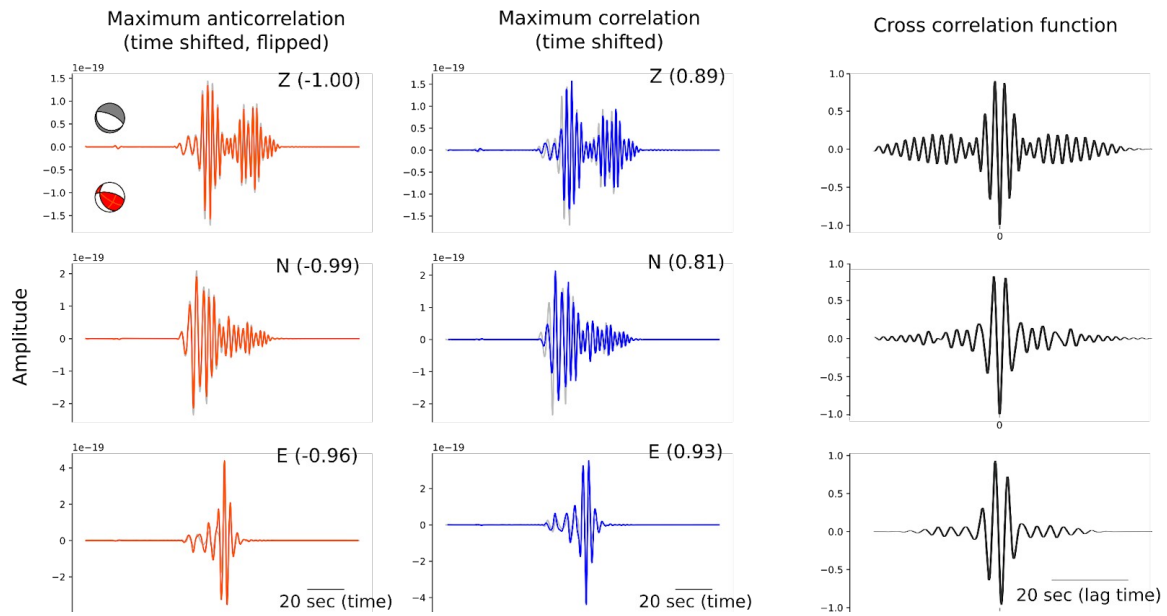
Suppl. Fig. 6. Example of anti-repeaters at Mayotte, Comoro Islands. The signal is shown for three components at the strong motion station RA.YTMZ.00. Normalised acceleration data are bandpass filtered between in the band 0.4-4.0 Hz, using a 4th-order Butterworth filter. Top three rows show the original anti-correlated set of signals (red, blue), while bottom three rows show the similarity of the same signal, after flipping red traces.



Suppl. Fig. 7. Source-receiver layout for anti-repeaters at the Äspö Hard Rock Laboratory, Sweden. Anti-correlating recordings for the anti-repeaters at the Äspö Hard Rock Laboratory are reported for three piezometers: AE01, AE02, AE09. The two acoustic emissions sources (red and blue circles) were located within the epicentral cloud of those sources (grey), accompanying the stimulation stage HF2⁶. The tunnel system of the mine laboratory is shown in grey. The black line marks the injection borehole.



Suppl. Fig. 8. Example of acoustic emission anti-repeaters at the Äspö Hard Rock Laboratory, Sweden. The signal is shown for three piezometers (AE01, AE02, AE09). Data are bandpass filtered between 3 and 7 kHz, using a 4th-order Butterworth filter. The top three rows show the original anti-correlated set of signals (red, blue), while bottom three rows show the similarity of the same signal after flipping red traces.



Suppl. Fig. 9. Example waveforms of two synthetic anti-correlated events with nearly perfectly flipped focal mechanisms. When only considering the positive part of the cross-correlation function, a pair of anti-correlated events (grey and orange traces in the first column) could be missed in favour of a pair of apparently very similar events. The cross-correlation function on the right shows an isolated negative peak but two similar peaks in the positive domain, indicating cycle-skipping issues.

Supplementary References

1. Cesca, S., Metz, M., Büyükakpınar, P., Dahm, T. (2023). The energetic 2022 seismic unrest related to magma intrusion at the North Mid-Atlantic Ridge. *Geophys. Res. Lett.*, <https://doi.org/10.1029/2023GL102782>
2. Cesca, S. (2020). Seiscloud, a tool for density-based seismicity clustering and visualization. *Journal of Seismology* **24**, 3, 443-457.
3. International Seismological Centre (2023), ISC-GEM Earthquake Catalogue, <https://doi.org/10.31905/d808b825>
4. Bondár, I., E.R. Engdahl, A. Villaseñor, J. Harris and D.A. Storchak (2015). ISC-GEM: Global Instrumental Earthquake Catalogue (1900-2009): II. Location and seismicity patterns, *Phys. Earth Planet. Int.* **239**, 2-13, doi: 10.1016/j.pepi.2014.06.002.
5. Cesca, S. et al. (2020) Drainage of a deep magma reservoir near Mayotte inferred from seismicity and deformation. *Nature Geoscience* **13**, 1, 87-93.
6. Niemz, P., Cesca, S., Heimann, S., Grigoli, F., von Specht, S., Hammer, C., Zang, A., & Dahm, T. (2020). Full-Waveform-Based Characterization of Acoustic Emission Activity in a Mine-Scale Experiment: A Comparison of Conventional and Advanced Hydraulic Fracturing Schemes. *Geophys. J. Int.* **222**, 1, 189–206. <https://doi.org/10.1093/gji/ggaa127>