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Passive seismic investigation of Harrat Rahat

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Summary

Ambient noise correlation was applied to 18 months of continuous seismic data from 14 stations. The procedure of Bensen et al [2007] was followed with some changes to optimize signal-to-noise of the results. The 18 months of correlations (representing about 1 week of CPU time on a 12 core machine) were stacked and manually inspected to yield about 40 cross-correlations. These cross-correlations represent the Green's function between the station pairs and will be analyzed in part two of this project to yield velocity structure.

Overview. Initial studies and investigations [*Al-Dayel*, 1988; *Roobol*, 2007; *Rehman,* 2005; 2010; *Lashin et al*., 2014; 2015] suggested several major potential areas for geothermal production in Saudi Arabia: hot springs in the southwestern region (Jizan and Al-Lith), volcanic areas (harrats), granites in the northwest may be potentially productive as a site for Enhanced Geothermal Systems and deep aquifers in eastern Saudi Arabia [*Lashin et al*., 2015]. While the Kingdom of Saudi Arabia (KSA) possesses abundant hydrocarbon energy resources, an understanding the potential of renewable energy sources such as geothermal power is a topic of interest [*Hashem*, 2012; *Lashin et al*., 2015]. Possible uses are for power production or direct use.

However, despite the potential of significant high-temperature resources, little work has been conducted for geothermal exploration in the volcanic areas. In this work we propose a low-cost exploration strategy that relies on available geological and geophysical data to conduct a first-order reconnaissance survey to identify geothermal prospects within a harrat. The exploration will combine passive seismic data with regional and local geologic maps to detect and characterize anomalous zones in the shallow upper crust.

In the first part of this study, we conducted a regional geological survey of the region and identified areas of potential high value at Harrat Rahat (Figure 1 and 2). Our conceptual model is based on a geothermal field at Las Tres Virgenes in Baja California, which produces about 10 Mw from granitic fractured rocks below volcanic cover [*Hernandez et al.,* 1995]. The tectonic setting is very similar, as both Las Tres Virgines and the Saudi Harrats lie on the edges of an extension rift system. For Las Tres Virgines, it is the Gulf of California rift which is roughly analogous to the Red Sea rift. Tres Virgines is a Holocene set of volcanoes that occur at the intersection of faults in a granitic basement. Dor the potential Saudi resource we seek a shallow magma chamber that is near mapped faults and with active micro-seismicity.

The accompanying report [*Harris et al.,* 2016] demonstrates the use of advanced detection methods to identify local seismicity. In this report we demonstrate the use of passive ambient noise tomography to map out the 3D velocity structure.

Method. In this study we use ambient noise cross-correlation to estimate crustal velocity structure. We will derive Rayleigh wave group dispersion curves for surface waves between pairs of seismic stations within network and then estimate velocity profiles for each path. The advantage of this method is that, unlike event-based surface wave dispersion measurements, which require earthquakes in a specific geometry with respect to the seismic stations, dispersion curves from all pairs of stations can be constructed [*Shapiro and Campillo*, 2004; *Bensen et al*., 2007]. Ambient noise correlation has been widely used to create surface wave tomography maps in numerous regions including Europe [Y*ang et al.,* 2007], North America [*Sabra et al*., 2005; *Bensen et al*., 2009].

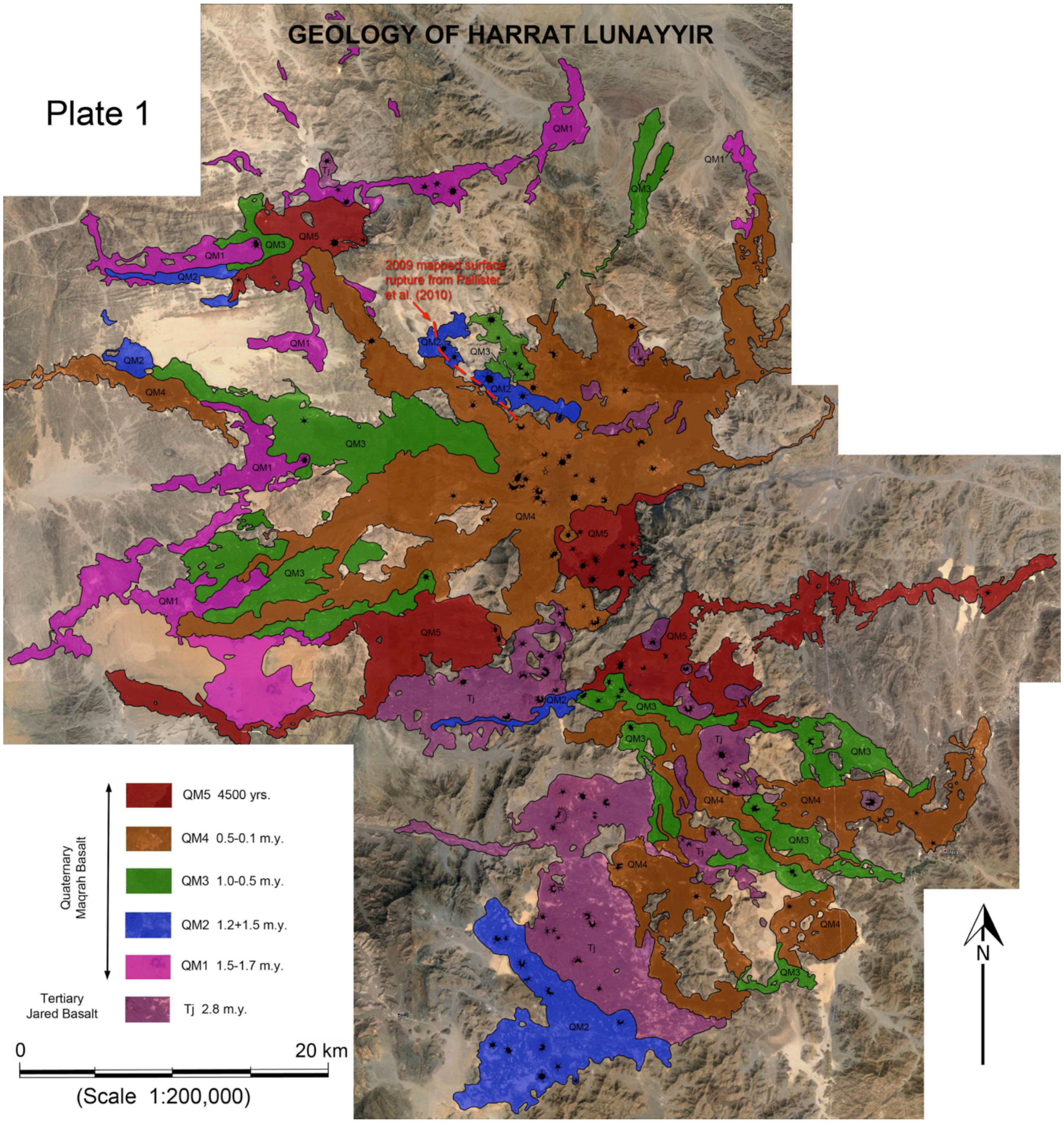

Figure 1. *Geological map of Harrat Rahat overlain on a Google Earth image. Colors refer to lava flows of different ages. Dots indicate volcanic cones.*

Correlation of long time periods of seismic noise recorded at a pair of stations will yield the Green's function response of the path between the two stations. If vertical components are correlated then the Green's function will primarily represent Rayleigh waves. Once Green's functions have been calculated for each station, the next step is to convert them into representations of the velocity structure. One approach is to apply multiple filter analysis to measure the group velocity at different frequencies. Another technique inverts the dispersion curves for 1D structure along the path [e.g. *Lawrence and Wiens*, 2004]. We expect that the area directly under Harrat Rahat will show anomalous velocity structure due to high temperatures and zones of magma when compared with the surrounding crust.

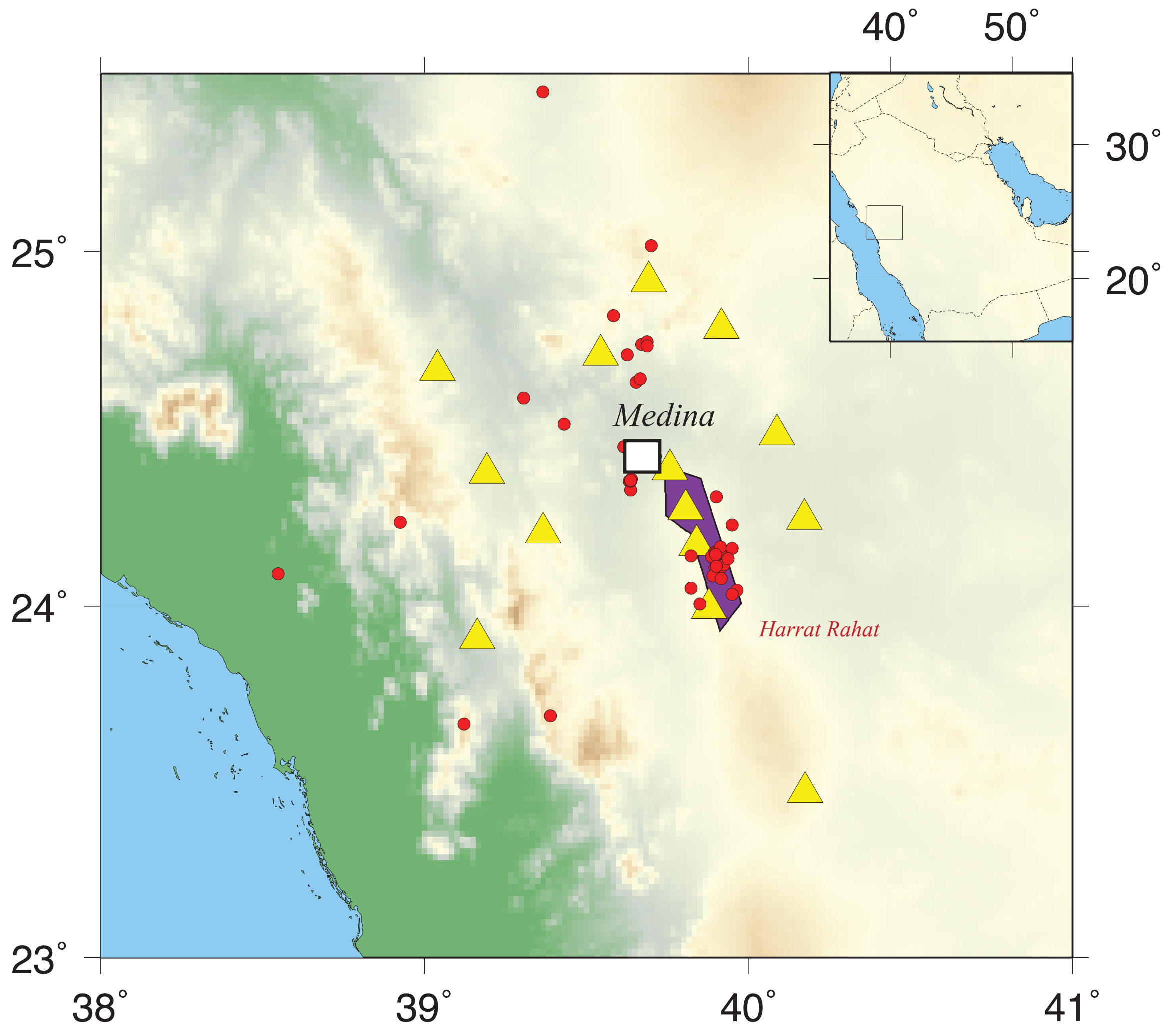

Figure 2. *Map of seismic stations (yellow triangles), earthquakes (red circles), the central area of Harrat Rahat deemed most prospective (purple), and the city of Medina*

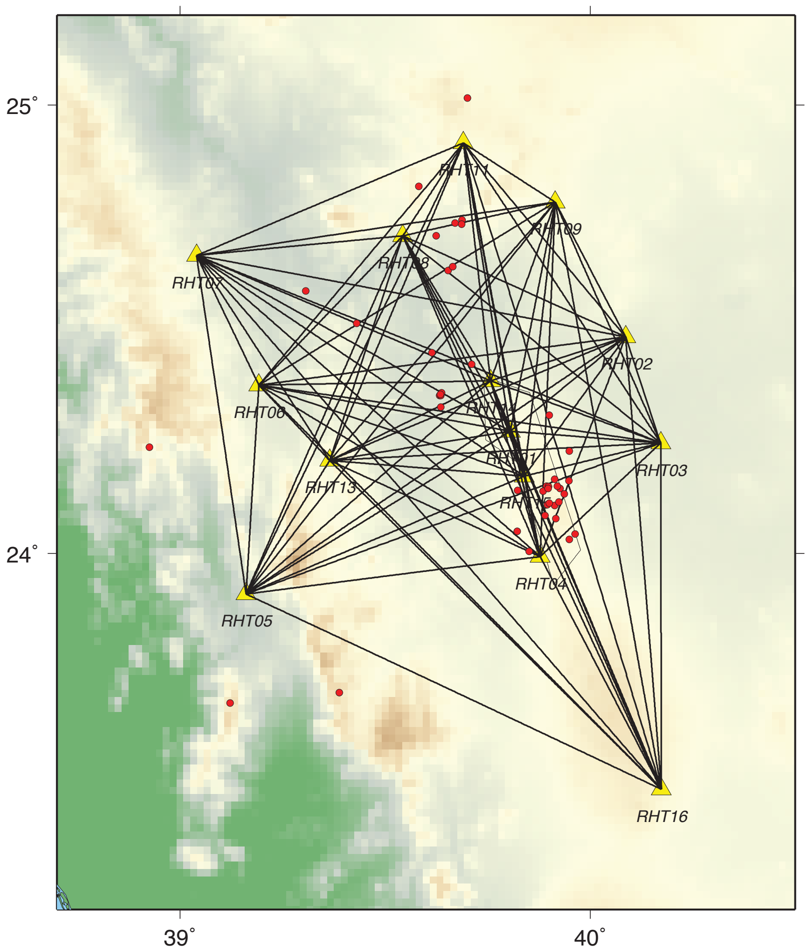

Figure 3. *Map showing paths connecting all pairs of stations. The noise correlation technique allows Green's functions and individual velocity models to be calculated for each path. We will compare paths through the Harrat with paths outside of the Harrat. Not all pairs yielded good results in this study.*

Data. The available data is from 14 stations that comprise a local network in the region around the Harrat Rahat (Figures 2 and 3). 18 months of continuous data is available from August 2013 to September 2014. In general it is best to use a year or more of data as the technique is sensitive to seismic noise, which varies in amplitude seasonally [Al-Amri et al., 1999]. The data was converted to seismic analysis format (SAC), the instrument response was removed, and then divided up into day-long files, one for each station (Z component) and decimatedto 5 Hz.

Processing followed the general procedure of *Bensen et al.,* [2007] although a running average was used rather than a signbit to normalize outliers. Cross-correlations for each day/station pair were calculated and then stacked by months. These stacks were then manually examined for artifacts due to instrument problems or large signals. All month stacks were then stacked for each station pair. 67 stations pairs were calculated. Processing the entire dataset required approximately 700 Gb of disk space and one week of CPU time on a 12 core Linuz machine. Several runs were made to test different normalization routines (e.g. signbit) and filter parameters (Figure 4). Auto-correlations were also calculated to validate processing.

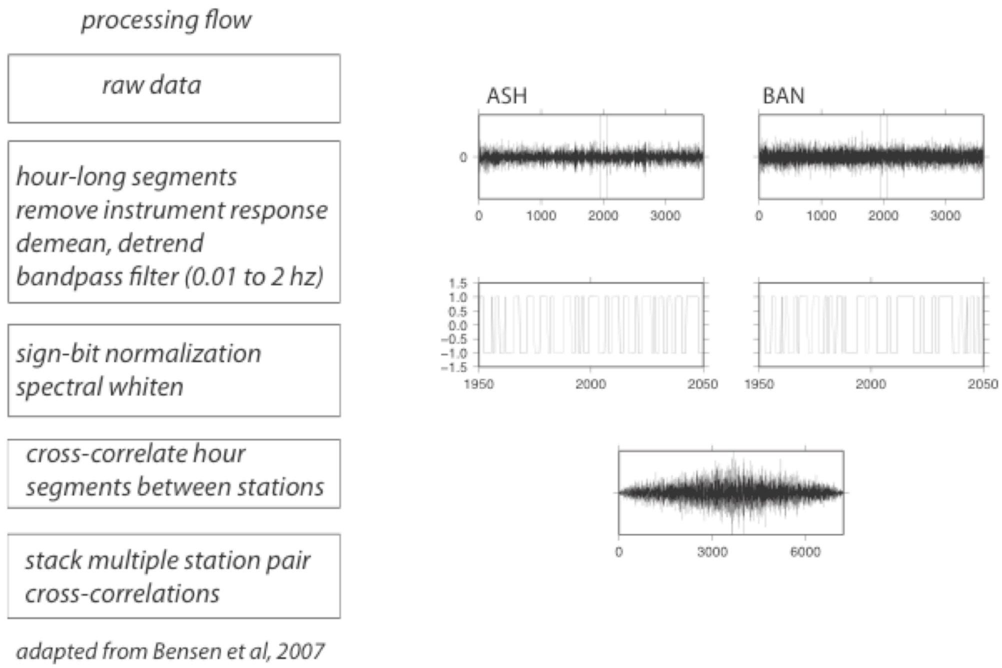

Figure 4. *Ambient noise processing showing example from stations ASH and BAN in Oman. For the Harrat Rahat data the sign-bit normalization was replaced by a running average as that showed better signal-to-noise, possibly due to lower overall seismic noise in the interior. From Mellors et al., 2014.*

Results. Figures 5 through 8 show the Green's functions. Creation of the Green's function represents about 70% of the computational effort. These will be analyzed using multiple filters to generate surface wave dispersion curves, which will then be used to generate velocity models.

Only a preliminary examination of the result have been conducted but the Green's functions show clear differences between station pairs indicating substantial differences in velocity stricture and possibly attenuation. A drawback is that several show clear asymmetry, which indicates that the noise is not azimuthally balanced, which will bias results.

The next steps are to generate velocity models from these Green's functions. We expect good results.

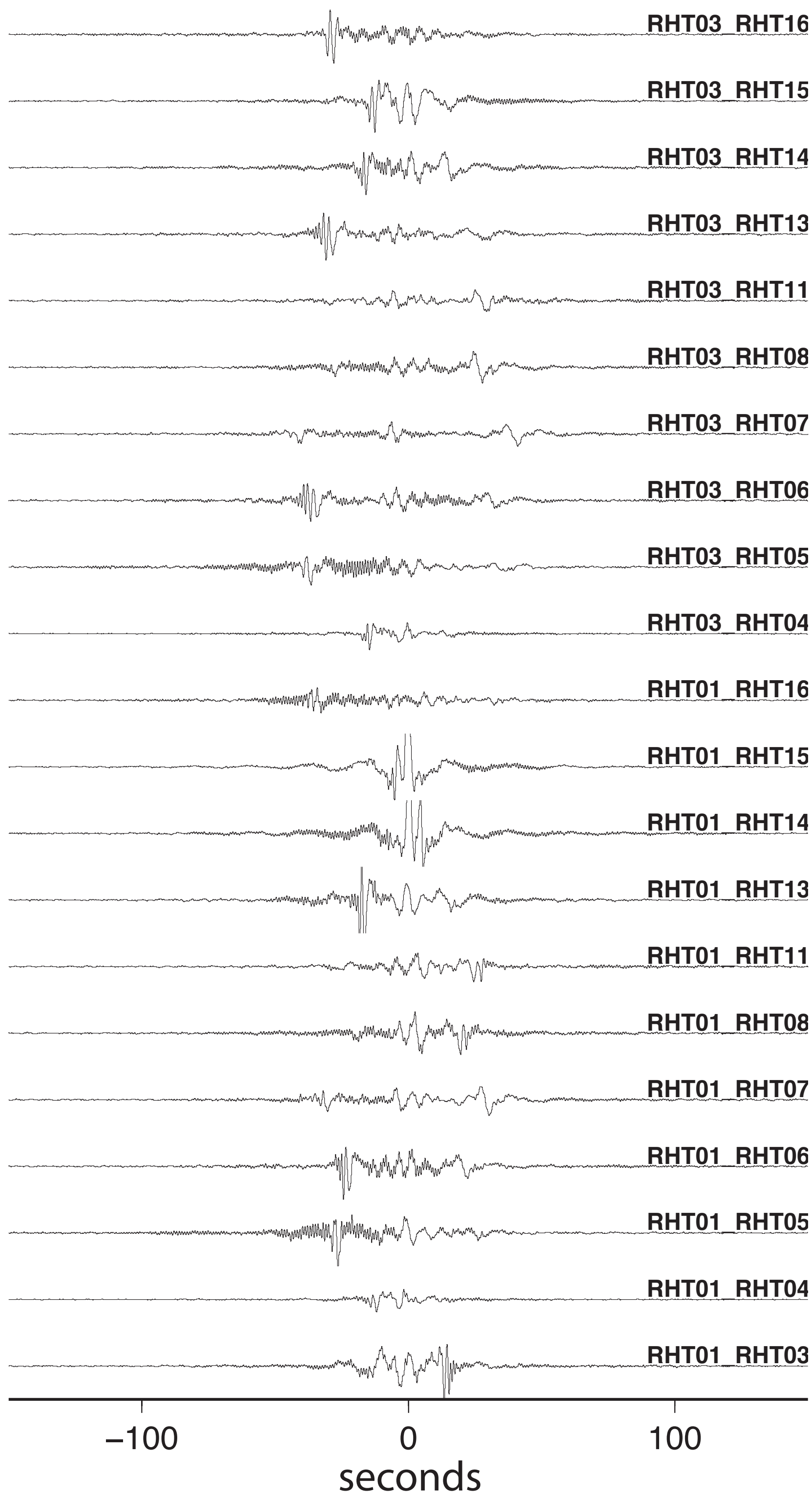

Figure 5. *Cross-correlations 1-21.*

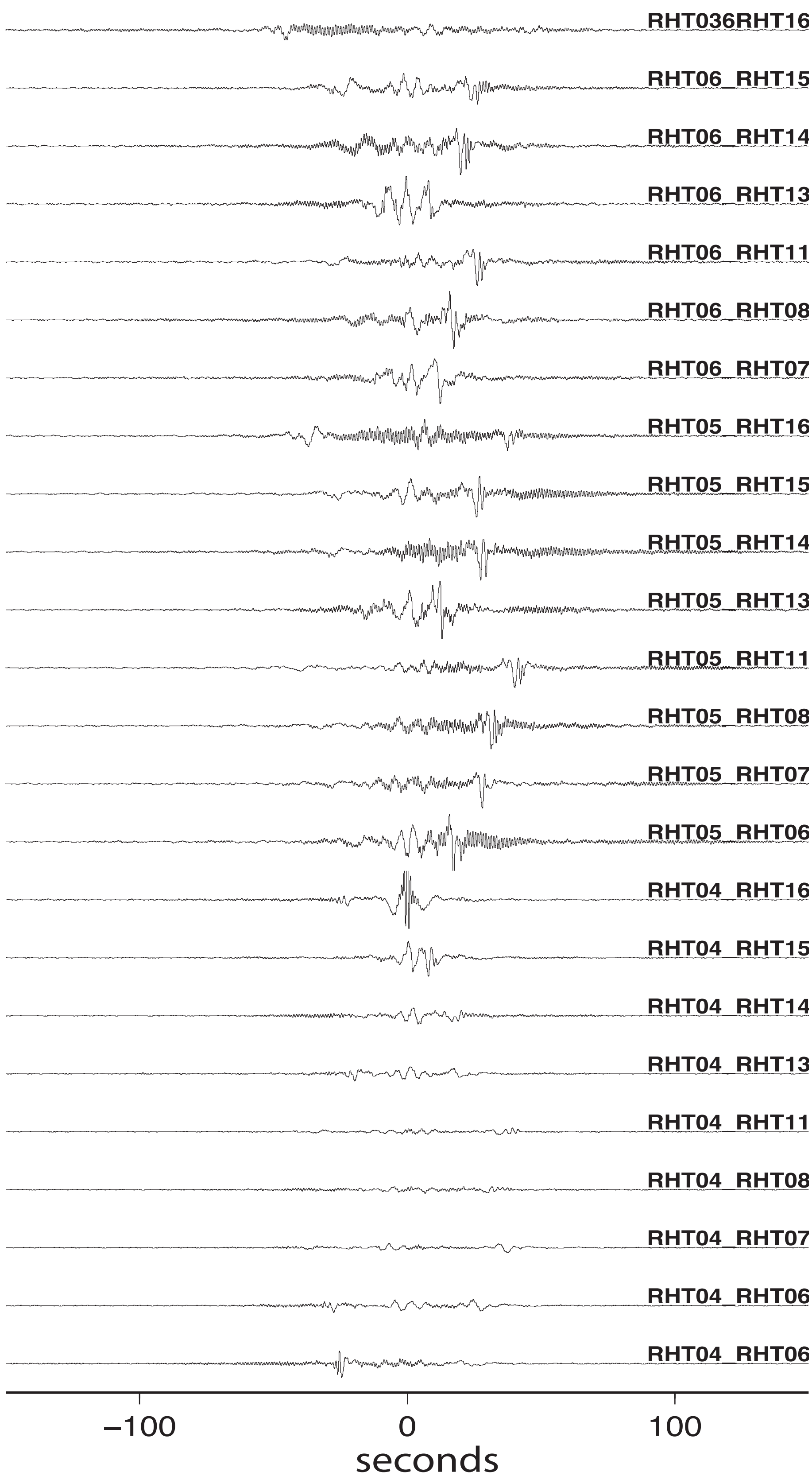

Figure 6. Cross-correlations 22-45

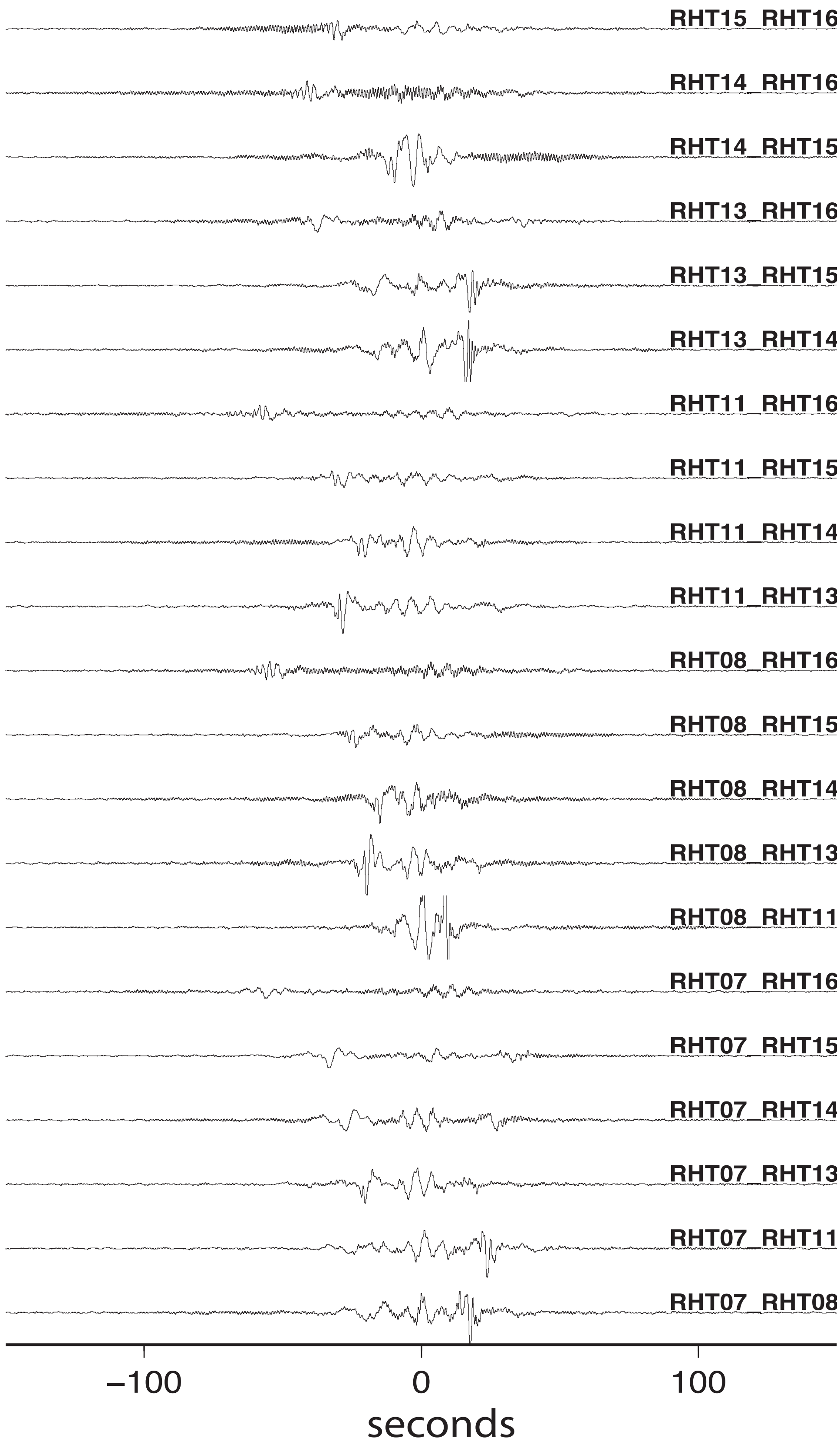

Figure 7. Cross-correlation 46-67

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