PhD Scholarship/Fellowship project:

APPLICATION OF SEISMIC INTERFEROMETRY TO WAVEFIELDS RECORDED OVER GEOTHERMAL SYSTEMS

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Seismic interferometry

Seismic interferometry (SI) refers to the principle of generating new seismic responses from existing recordings. In its simplest form, two receivers are used of which one receiver is turned into a so-called 'virtual source'. The Earth's response to this virtual source is then retrieved at the second receiver. Often, the new responses are obtained by simple crosscorrelation of the seismic observations at the two receiver locations (e.g., Campillo & Paul, 2003; Zhan et al., 2010). In case of controlled sources, the process involves an additional summation of crosscorrelations over the available controlled-source positions (e.g., Bakulin & Calvert, 2006; Schuster et al., 2004). When passive wavefields are exploited, this explicit summation is not required if the simultaneously acting sources are uncorrelated (e.g., Shapiro & Campillo, 2004; Wapenaar & Fokkema, 2006). Both interferometric body-wave responses and interferometric surface-wave responses have been retrieved from field data (e.g., Bakulin & Calvert, 2006; Draganov et al., 2009; Weemstra et al., 2013).

We propose the application of seismic interferometric techniques to seismic wave fields recorded over geothermal systems. In particular, we propose the application of transdimensional tomography to interferometric surface-wave responses. These virtual-source responses will be retrieved from recordings of ambient seismic noise that are collected in the context of the IMAGE (Integrated methods for advanced geothermal exploration) and GEMex (Joint European-Mexican geothermal energy research for development of Enhanced Geothermal Systems and Superhot Geothermal Systems) projects. In Figure 1, we present an example of the extraction of surface-wave phase velocity from a virtual-source response. The former project (IMAGE) resulted in an extensive seismic data set (e.g., Weemstra et al., 2016), whereas GEMex has its first seismic stations planned to be deployed by the end of 2017. The fact that geothermal systems are generally prone to high rates of (micro)seismicity can make them particularly well suited for the application of SI (e.g., Grechka & Zhao, 2012). At the same time, however, their relatively high temperature generally causes the seismic energy to dissipate at high rates, which may complicate the practical application of SI in a geothermal context.

Transdimensional tomography

As mentioned above, we propose to use the travel times derived from the interferometric surface-wave responses to retrieve the local surface-wave (phase) velocity structure (e.g., Weemstra et al., 2017). Phase velocity, in turn, may contain valuable information regarding subsurface temperature and/or geology. Most seismic arrays are characterized by non-uniform distributions of seismic stations: station coverage may be dense in one area, whereas the distribution of stations is sparse in other areas (For example the configuration of the Reykjanes array presented in Figure 1**b**). This implies that the achievable phase-velocity resolution can be expected to vary greatly across the region covered by the seismic array (higher in areas that are more densely covered by stations and decreasing where station density is low). To compensate for the variable station coverage, a model parametrisation that uses Voronoi cells can be used. In conjunction with a reversible-jump Markov chain Monte Carlo (rj-McMC) algorithm, this parametrisation allows the model to dynamically adapt itself to both data density and underlying velocity structure (Bodin & Sambridge, 2009). The rj-McMC algorithm computes the travel-time misfit with respect to a large number of velocity models. As such, an ensemble of solutions,

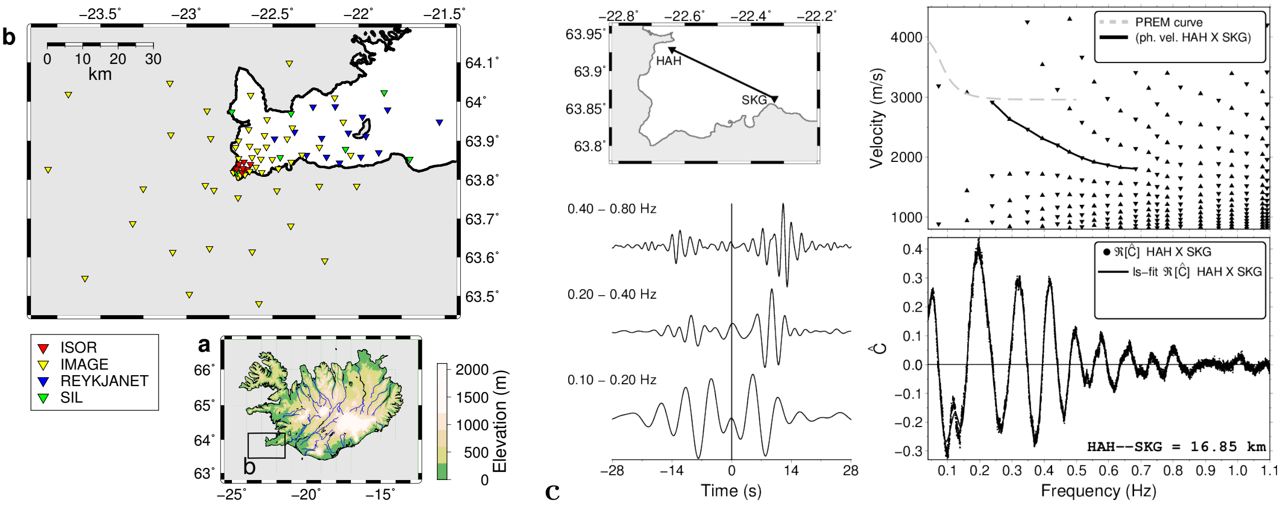

Figure 1: *Extraction of surface-wave phase velocity from the virtual-source response between a pair of seismic stations of the Reykjanes Array (RARR). The location of the RARR is shown in* ***a*** *and its station configuration is depicted in* ***b****. In* **c***, the extraction of phase velocity from seismic interferometric responses is demonstrated for station couple HAH-SKG (separated by 16.85 km). Station locations and ray paths are depicted at the top left. At the bottom left, the time averaged crosscorrelation is shown for three different frequency bands. At the bottom right, the real part of the cross-spectrum is shown (dots) with the linear combination of third-order polynomials that best fits their behavior overlain (solid lines). The top right plot presents the velocity values (triangles) for which the zeros of a zeroth order Bessel function of the first kind coincide with the zeros of these least-square fits (the underlying theory is explained in Boschi et al. (2013)). Rayleigh wave fundamental-mode phase velocities for the preliminary reference Earth model (PREM, but with the oceanic layer removed; Dziewonski & Anderson, 1981) are given by the gray dashed curve. The PREM dispersion curve is used to determine the seismologically most plausible dispersion curves (black solid curve). For details regarding the picking of these phase velocity curves we refer to Kästle et al. (2016).*

which forms an estimate of the posterior probability density function (PDF), is obtained. Because the number of parameters itself is one of the quantities that is estimated, the method is referred to as ‘transdimensional’. This implies that the method is purely data driven and requires minimal assumptions regarding the model. Compared to more traditional inversion methods that keep the model parametrisation fixed, the method is particularly flexible: it dynamically adapts to non-uniform data coverage without requiring the use of any arbitrary regularization (e.g., damping or smoothing). The method was used successfully by Bodin & Sambridge (2009) to obtain Rayleigh-wave velocity models of Australia from ambient-noise interferometry. Galetti et al. (2015) further generalized the method by making it fully non-linear: they showed that if both model parametrisation and raypaths are allowed to vary freely simultaneously, then the method also defines loop-like uncertainty structures around isolated low-and high-velocity anomalies which define the spatial resolution of those structures. The method has recently been applied successfully to the British Isles (Galetti et al., 2016).

Time-lapse transdimensional tomography

The ultimate goal is to apply the method described above in a time-lapse manner. Time-lapse imaging is of immediate interest for geothermal systems. In particular, this is the case if geothermal energy is produced from the geothermal system: it has been shown that geothermal production may causes drastic changes in reservoir conditions (Axelsson et al., 2015; Obermann et al., 2015). Time-lapse application of transdimensional tomography using interferometric surface-wave phase velocities extracted from time-lapse crosscorrelations of ambient seismic noise may enable us to localize changes in surface-wave phase velocities and hence localize changes in reservoir conditions.

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