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Detection of fractures within the Soultz-sous-Forêts EGS geothermal reservoir by processing of Vertical Seismic Profile data

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The 4 component multi-source/multi-offset VSP (Vertical Seismic Profile) conducted at the Soultz-sous-Forêts EGS (Enhanced Geothermal System) site in 2007 provides records of seismic waves recorded in the fractured granite basement within wells GPK3 and GPK4. Waves generated at 26 surface positions, located at distances between 500m and 5km from the well head in different azimuths, are recorded by 3 component geophones at depths between 5000m and 3000m with a 20m depth interval.
The seismic source is a vibrator emitting a 16s long sweep with frequencies varying linearly between 8 and 88 Hz. Two shot locations were simultaneously recorded, one with an upsweep [8 to 88Hz], the other with a downsweep [88 to 8Hz]. Successive correlation with the two sweeps allows retrieving distinct seismograms for each shot from the mixed raw uncorrelated records. Most records show clear downgoing P and S waves. Detecting waves reflected or diffracted by fractures intersecting the wells requires extracting low amplitude upgoing waves from the dominant downgoing wavefield. However, the up to 30° inclination of the well relative to the vertical and the 60 to 90° dips of the fracture zones make the separation of the different waves complex.
The wavefield separation of the vertical geophone component is done in the frequency-wavenumber Fourier domain which separates waves according to their apparent velocity across the receiver antenna. Picking of the first arrival times and shifting times allows aligning predominant P wave downgoing wavefield at constant times, or infinite apparent velocity in Fourier domain. Filtering the infinite apparent velocity attenuates all the waves having the same apparent velocity as the first arrivals. A second filtering at the downgoing S waves velocities is then applied, providing two downgoing wavefields, one for the P waves and the other for the S waves. The residuals correspond to the upgoing wavefield. To reduce the reverberations in the upgoing wavefield, we apply a Wiener deconvolution. Faint coherent waves that may originate from fractures are observed in restricted depth intervals.
In order to model the arrival times of the extracted reflections/diffractions at the different shot positions, we need a velocity model of the 1400m thick sedimentary cover. P velocities from VSP data of one shot recorded in well GPK4 in sediments and structural information from geological logs and interpreted surface seismic profiles are used to build an initial 3D model with 3 layers separated by dipping plane interfaces. 3D ray tracing is used to compute first arrival times and adjust our model to the data, by modifying the dip of the interfaces. It is then possible to adjust the upgoing waves arrival times to reflections or diffractions on fractures in the reservoir.