Optimizing the design of vertical seismic profiling (VSP) surveys for imaging of geothermal reservoirs

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Introduction

Seismic techniques are widely used in the oil and gas industry to image the subsurface but their use in geothermal exploration has been comparatively quite restricted. In recent years there has been a resurgence of interest in geothermal energy and so it is timely to investigate how seismic techniques need to be adapted and applied to geothermal sites, given the different nature of the targets and host rock. The primary focus of geothermal seismic imaging is to map dipping faults and fracture zones that control the permeability and the fluid flow. However, in hardrock basement the detailed seismic imaging of subsurface structures such as fracture zones is challenging for a number of reasons (e.g., Salisbury et al., 2003): (1) the large impedance contrast between the overlying sediments and the crystalline basement, (2) generally low signal-to-noise ratios due to weaker impedance contrasts between lithological units in the target crystalline rocks, (3) reflectors are either small or laterally discontinuous due to the complex morphology, lithology and deformation, (4) high velocities in crystalline basement that result in a loss of resolution due to the relatively longer wavelengths, (5) the often steeply dipping structures which are hard to image compared to usual sedimentary structures, especially for surface seismic where large offsets are required. Vertical seismic profiling (VSP) has a favourable geometry to map gently to steeply dipping interfaces (e.g., Cosma et al., 2003). Additionally, due to shorter travel-times compared to surface seismic surveys, and the fact that the waves only make one pass through the absorbing overburden, the signal amplitudes experience less attenuation and hence higher frequencies are preserved. The goal of this study was to optimize the survey design of vertical seismic profiling (VSP) surveying for imaging gently to steeply dipping fracture zones in the basement and to optimize the combination of migrated images for imaging a fracture zone of a certain dip.

Method

Acoustic synthetic modelling was performed with a 2D finite difference (FD) scheme (SOFI2D) (Bohlen et al., 2003). The geophysical model used for our survey design study is based on downhole sonic and other logging information from the geothermal site at Soultz-sous-Forêts (France). In this area, seismic velocities gradually increase with a high gradient within the sediments in the upper part (thickness ~1.4 km) and with a low gradient in the underlying basement (Figure 1a). To simulate a realistic degree of heterogeneity, stochastic fluctuations were superimposed on the 1D background velocity model. The simulated borehole is inclined at 30° and instrumented with 61 two-component receivers at 20 m spacing over the depth range of 3700-4900 m. A fracture zone of 40 m thickness characterized by a 15% reduction in both the velocity and density was inserted in the model at 4390 m depth. The dip of the fracture zone as well as the lateral distance from the borehole was varied for the tests. Ninety-one source positions placed every 100 m were simulated along the 9000 m wide model. Basic processing of the source gathers consisted of geometrical spreading correction, tau-p filtering to separate the direct wave from the reflected wave and two-component Kirchhoff depth migration (Figure 1b-d) (Yilmaz, 2001).

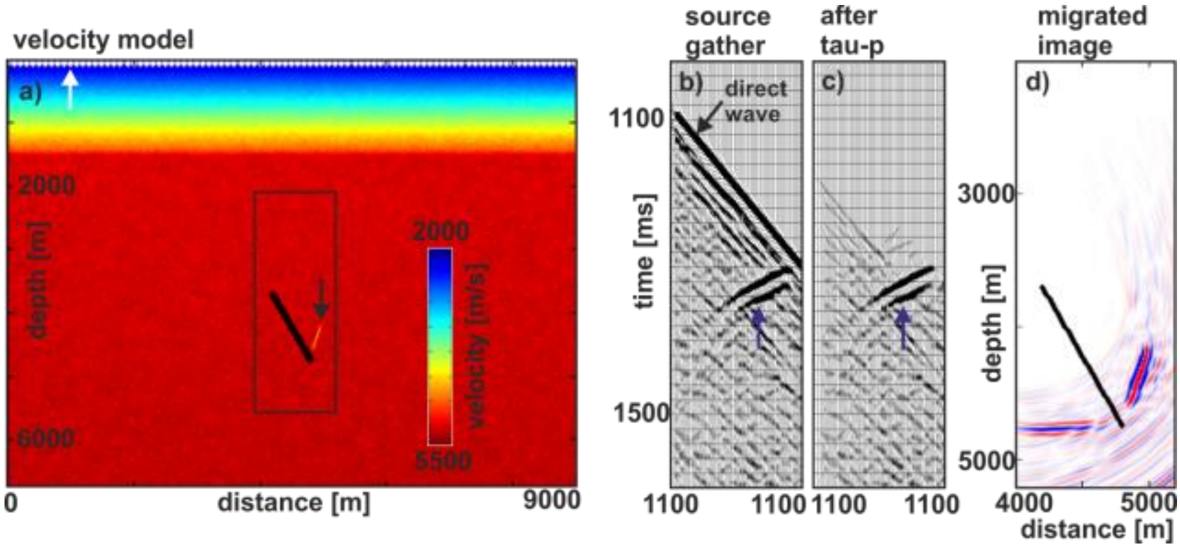


Figure 1: a) Velocity model with a 70° dipping fracture zone marked by the black arrow, receivers in black, source positions in white. b) Example source gather (x-component) of the source position marked by the white arrow in a). c) As b) but after tau-p filtering where the direct wave is removed. The blue arrow indicates the fracture zone reflection. d) Migrated image of the region marked by the black square in a) using the same source gather shown in c and d).

Combinations of different migrated common-source gathers were analysed to determine ideal survey layouts. Optimal source positions were determined by the maximum crosscorrelation value of a single or progressive combination of migrated images compared with a reference image (full survey migrated image involving all sources, but windowed around the reflection to exclude any remaining processing artifacts; Figure 2e). Starting with the optimum single image, the image that yielded the highest increase in correlation of the sum compared to the reference was added iteratively. Benefit-cost curves (number of images vs. correlation coefficient) as well as the quality of the final migrated images were analysed to define the optimal survey layout in the sense of the best source-positions. An example is shown in Figure 2a, where a 70° dipping fracture zone was modelled 300 m away from the borehole. After stacking a certain number of migrated images, the crosscorrelation value does not increase

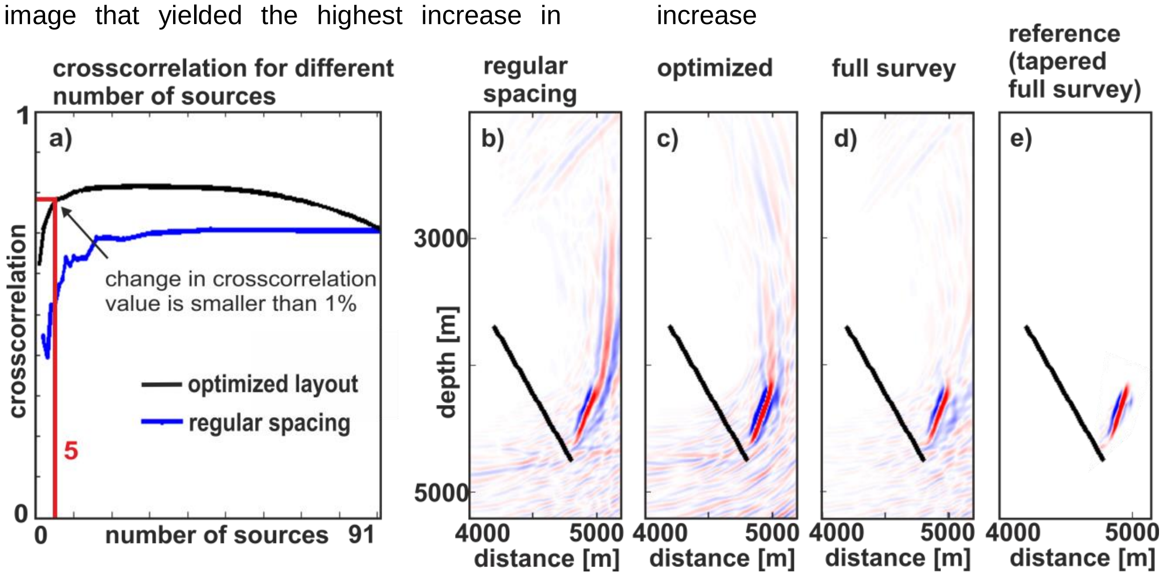


Figure 2: a) Crosscorrelation value for different numbers of stacked migrated images with the reference image e) for a regular source spacing and the optimal survey layout. Five source positions lead to a favorable survey layout as indicated in red. b) Migrated image using 5 regularly spaced sources. c) Migrated image using the optimized survey layout of the 5 optimum source positions. d) Migrated image using all 91 source positions. e) Reference image that corresponds to d) but windowed and tapered around the fracture zone. Note that the optimized migrated image shows fewer artifacts compared to the regular spaced image and is comparable to the full survey migrated image.

substantially or even decreases for some source positions. When the increase in crosscorrelation value is smaller than 1%, adding another source position to the sum of migrated optimal images does not improve the image remarkably. Therefore this point was chosen as the number of optimal source positions; for the case in Figure 2 this corresponds to 5 source positions. The final migrated images for 5 regularly spaced sources, 5 optimum source positions, 91 sources (full survey) and the reference image are shown in Figure 2b-e. The optimized layout shows fewer artifacts compared to the regular spacing and is of similar quality as the full survey (all sources) image.

Results

We examined cases of various fracture zone dips (30°, 50°, 70° and 90°) as well as different closest lateral distances from the borehole (fracture zone crossing the borehole (zero distance) and lateral distance of 300 m). In addition to stochastic velocity variations, random noise was added to the seismic data to simulate real data with a signal-to-noise ratio (S/N) of 4. The different geophysical models that were tested are displayed in Figure 3, along with the spreads of the optimal source positions.

Figure 4 (right): a-d) Migrated images for a fracture zone 300 m away from the borehole and e-h) for a fracture zone crossing the borehole. In each case different dips were used (30°, 50°, 70° and 90°). Benefit-cost curves (crosscorrelation value vs. number of sources) for each example are shown below. The point where the crosscorrelation increases by less than 1% defines the optimal number of sources. The location of the source positions defines the spread and hence the optimal survey layout shown in Figure 3a). Note that for a fracture zone 300m away from the borehole the fracture is imaged quite accurately for all the dips. For fracture zones crossing the borehole, larger offsets are required and the steep fractures (70° and 90°) are only imaged crudely.

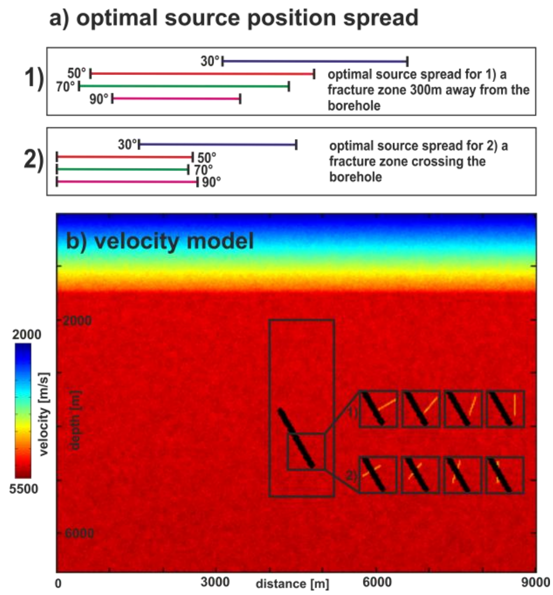
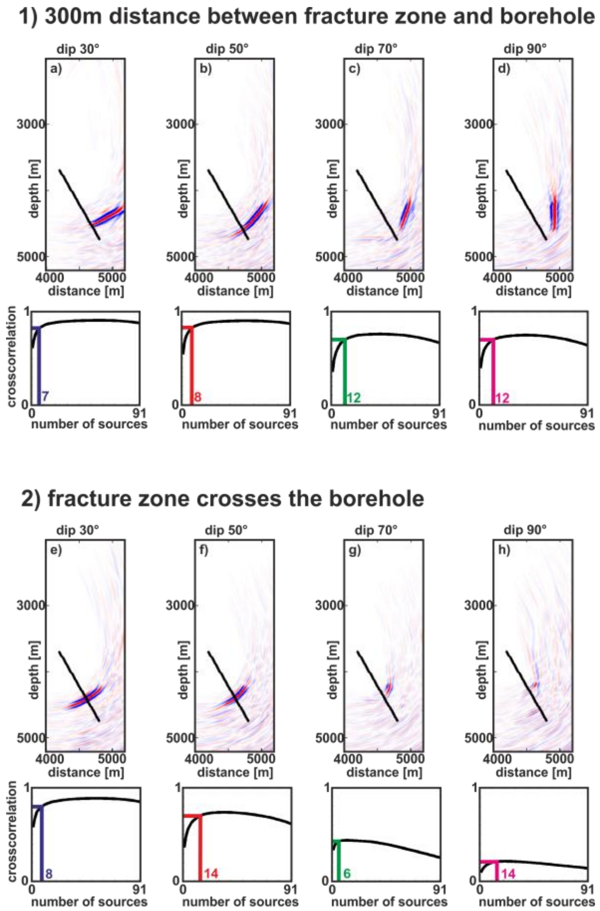


Figure 3: a) Optimal source spread for a fracture zone 1) 300 m away from the borehole and 2) crossing the borehole considering different dips. b) Velocity model with receivers indicated in black. The large black rectangle indicates the area of the migrated images in Figure 4. To illuminate the fracture zone crossing the borehole, larger source offsets are required.



The migrated images resulting from the stack of optimal source positions and the resulting benefit-cost curves for the four examined cases are shown in Figure 4. Large source offsets (distance between the source and the borehole) are required for steeply dipping interfaces, especially for fracture zones crossing the borehole. Fracture zones with a lateral distance from the borehole of 300 m can be imaged more accurately than fracture zones crossing the borehole. Limitations of the VSP experiment are observed for steeply dipping interfaces crossing the borehole which can only be imaged in the most rudimentary manner.

Conclusion

Synthetic seismic modelling and numerical data migration were undertaken to optimize the VSP survey layout for imaging fracture zones over a simulated geothermal area. From the benefit-cost curves the optimal number of sources and their positions can be determined to plan an ideal seismic survey, based on a known or assumed approximate fracture direction and location in the subsurface. The optimal source positions strongly depend on the fracture direction and its lateral distance from the borehole. Large source offsets are required for steeply dipping interfaces, especially for fracture zones crossing the borehole.

If no *a priori* information is available, or different dip directions are present, the method can be used to optimize the seismic processing specifically for a certain fracture zone dip. From the benefit-cost curves it was observed that adding some source positions results in a decrease of crosscorrelation value. Hence, the presented method can be used to find those source positions that lead to an optimal migrated image for a certain dip.

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