Identifying risked potential of seals and flow in ultradeep and shallow geothermal reservoirs

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ABSTRACT

Geothermal production and storage is an increasingly mature energy sector thanks to the efforts of industrial operators, consultants and fundamental research in international projects such as IMAGE, HEATSTORE, MUSE, CAGE and LEAN in the research programmes Horizon 2020 and ACT. Like any serious energy project, geothermal projects need viable business cases. Major factors affecting these business cases are 1) cost-effective exploration, production and 2) license-to-operate through public support. A means to achieve firstly cost-effective exploration is the reprocessing and re-interpretation of existing vintage geophysical data. Learnings and best-practices from reprocessing vintage data in turn lead to smarter new seismic acquisition. The second factor, public support, requires de-risking and conformance control of production and storage operations. This study has evaluated the cost-effectiveness and de-risking capability of a workflow combining conventional and novel seismic reprocessing techniques. The workflow manages to identify hidden risk factors in two geothermal settings: ultradeep geothermal production and shallow geothermal storage, the former shallower than ~0.5 km deep and the latter deeper than ~4 km deep. The new workflow includes superior near-surface statics, demultiple, velocity modeling, Prestack Time Migration, high resolution sparse spike deconvolution, de-noising algorithms and a correlation based interferometric primary reflection imaging algorithm. This workflow managed at reduced cost to significantly de-risk onshore cases of ultra-deep geothermal production and shallow storage by identifying previously hidden risk factors like faults.

1. INTRODUCTION

The geothermal production and storage potential of reservoir and sealing formations in the Netherlands is being investigated in recent years as a result of the push for development of sustainable and unconventional energy resources in Europe. Geothermal systems need economic business cases through cost-effective exploration and production and needs license-to-operate through public support. Re-interpretation and reprocessing of vintage geophysical data is a means to achieve cost-effective exploration whereas de-risking and conformance control of storage operations is a means to obtain public support.

Seismic reflection imaging is currently the geophysical method with the highest resolution for acquiring subsurface information at both shallow and great depth. New seismic acquisition however is a relatively intense and expensive process which, if smartly done or replaced by reprocessing, enables much reduction in cost. As such, seismic exploration offers the best opportunities of achieving both the cost-effective and the de-risking goals. Seismic surveying should, with optimal efforts, identify risk factors.

This study addresses the cost-effectiveness and de-risking capability of a workflow combining conventional and novel seismic reprocessing techniques. We evaluate its ability to identify hidden risk factors in two geothermal settings: ultradeep geothermal production and shallow geothermal storage. Both settings pose a challenge to seismic imaging since exploration targets for vintage seismic data acquired for petroleum prospects are usually in mid-depth range: ~0.5 to ~4 km deep. Imaging shallower and deeper than that is necessary for geothermal exploration and requires a new tailored prestack seismic (re)processing approach. This workflow should manage at reduced cost to significantly de-risk the geothermal production and storage scenarios by identifying previously hidden risk factors. More specifically it should identify risk elements for geothermal production such as impeded flow due to low permeability, thin or low net-to-gross reservoir intervals, high skin and risk factors for geothermal storage such as leakage, heat conduction, pressure build-ups or drops, spill points and disappointing storage capacity. These risks factors are often caused by hidden structural geologic features such as a thin or failing overburden seal, closed or open faults in either reservoir or seal and high- or low-permeability streaks in the reservoir.

The new workflow includes superior near-surface statics, demultiple, velocity modeling, Prestack Time Migration, high resolution sparse spike deconvolution, de-noising algorithms and a cross-correlation based interferometric primary reflection imaging algorithm. A next step is to quantify the de-risking into reduced uncertainties and stochastic model realisations to be used as direct input into conformance monitoring workflows.

2. METHODOLOGY

Conventional seismic reprocessing of seismic pre-stack data combined with novel unconventional processing techniques are combined in one workflow to improve the seismic imaging for three onshore geothermal production and storage cases in the Netherlands: one production system in an ultra-deep Dinantian carbonate setting, one production system in a deep Rotliegendes sandstone setting and one storage system in a shallow sandstone aquifer setting. All systems are located in the center of the Netherlands.

Besides the conventional workflow that involves mainly Prestack Time Migration, novel processing techniques are used: the Non Local Means (NLM) filter (Buades, Coll, and Morel, 2005) and sparse spike deconvolution (SSD) (Chapman and Barrodale, 1983). The NLM filter aims to denoise the seismic images while preserving edges which are important for identifying risk elements such as faults and fractures. SSD using L1 norm regularization aims to increase the vertical and lateral resolution of seismic images thereby de-risking the seismic interpretation of geothermal reservoirs. The conventional seismic reprocessing improves the data by superior imaging with statics, demultiple, velocity modeling, Prestack Time Migration, whose improvements are then magnified by the novel techniques.

The NLM filter is a next-generation signal denoising algorithm which is originally proposed for image processing and has been used in medical imaging and seismic processing. It takes advantage of high redundancy in most natural images, which assumes for every small window in an image there are many other windows in the same image with similar structures. It takes the similarity between a neighborhood window of a main pixel with other neighborhood windows within the same image to calculate the averaged value of the main pixel. It is non local because the whole image contributes to the value of the denoised pixel in consideration, not just the neighborhood of the pixel. In practice, using the entire image for search window can became very computationally demanding and thus the process is restricted within a limited search window. Figure 1 shows the concept on synthetic data.

In SSD, the prior information is the assumption of earth reflectivity as a sparse sequence of spikes. This assumption is due to the fact that the bigger reflectivity coefficients are the main contributors of acoustic impedance, which can be seen as spatially spaced geological boundaries. By adding a sparsity constraint as prior information about reflectivity in the inversion, an approximation of the correct amplitude and location of the sparse reflectivity series can be obtained, and significant increase in bandwidth content can be achieved from band-limited seismic observations. In this research this is done by L1 norm regularized inversion, an estimated source wavelet and L2 norm smoothness derivative constraints in the cost function. Figure 2 shows the concept on synthetic data.

The application of seismic interferometry to reflection data allows to retrieve estimates of inter-receiver responses using the multiple reflections and reverberations caused by the strong contrast at the Earth's surface. The engine of the method is the cross-correlation of existing traces and summation over shots. The inter-receiver responses correspond to the responses from a virtual source at the position of the first receiver to a virtual-receiver at the position of the second receiver. In this project we have explored the potential of such interferometric approach to retrieve additional (shallow) reflection in the Dutch subsurface. This is identified as a promising method to improve shallow imaging of Dutch subsurface at lower cost by filling the illumination gaps in vintage, often incomplete, seismic data. For the application, we have used open-source C-codes developed at TU Delft that allows to cross-correlate large amount of data in Seismic Unix format. We deployed the codes on the TNO environment and adapted it to be suitable for a 2D-line pilot. The overall processing sequence to retrieve virtual reflection images from seismic exploration data involves in order:

- Acquire or collect the input seismic data
- Pre-process the data to enhance reflections while preserving the surface multiples (trace editing, muting, ground-roll removal, statics, etc)
- Cross-correlate the responses between pairs of receivers and sum the results from multiple shots (different normalizations are made possible, including the use of cross-coherence instead of cross-correlation)
- Sort the virtual data by CDP
- Optionally, use the cdp gathers to perform new or improve previous velocity analysis
- Apply NMO correction
- Produce a CDP stack or migrate the virtual data using a known velocity model

3. RESULTS

Figures 3-7 demonstrate how the workflow has enhanced the vintage seismic sections in the upper and left panels towards the reprocessed seismic sections in the lower and right panels. Overall, the temporal and spatial resolution of the new seismic sections identifies risk elements for geothermal production and storage such as overburden seal, faults in either reservoir or seal and high- or low-permeability streaks in the reservoir. Figure 3 features onshore ultra-deep Case 1, a comparison of an original 2D seismic line with a prestack reprocessed and NLM denoised version. In the upper panel a) with original section, only subtle hints of possible Dinantian reflections are noticeable below 3200 ms, whereas lower panel b) with reprocessed section shows interpretable reflections below target depth 3200 ms. Case 2, the onshore deep line, features a possibly suitable overburden seal for a geothermal production reservoir. From Figure 4 one can see that in the vintage data (left panels), the definition of the overburden above 800 ms is poor due to noise, lack of focus and unresolved contacts. The right panels indicate a much less complex fault regime, a more intact seal-reservoir contact and thinner intervals.

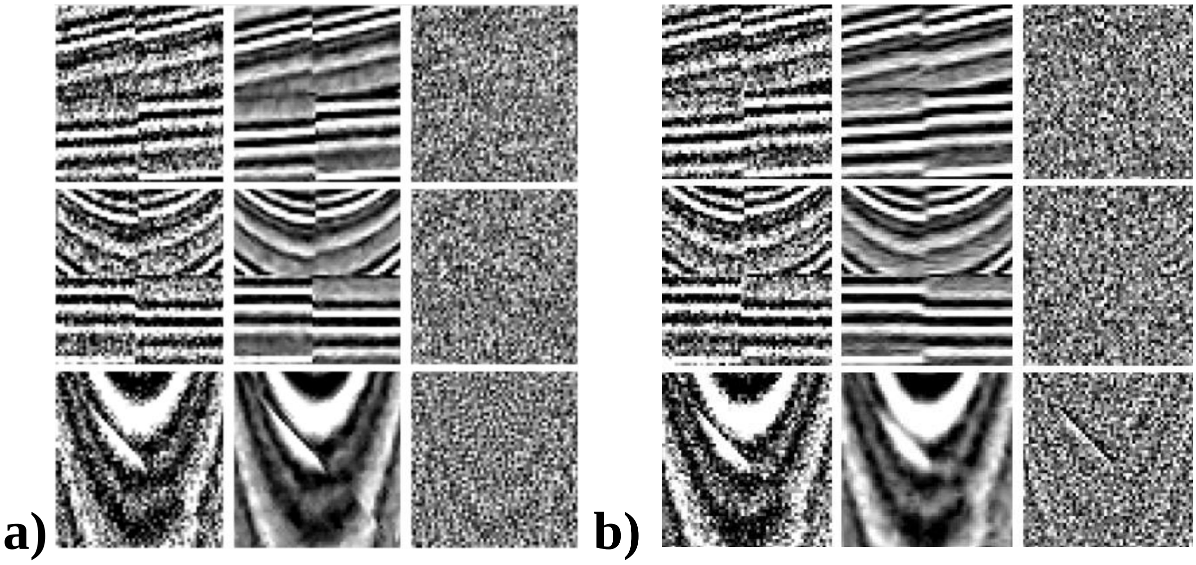


Figure 1: a) NLM as compared to b) Adaptive local slant stack, both applied to synthetic data. In both a) and b): Left column = original section, middle column = filtered section, right column = difference section.

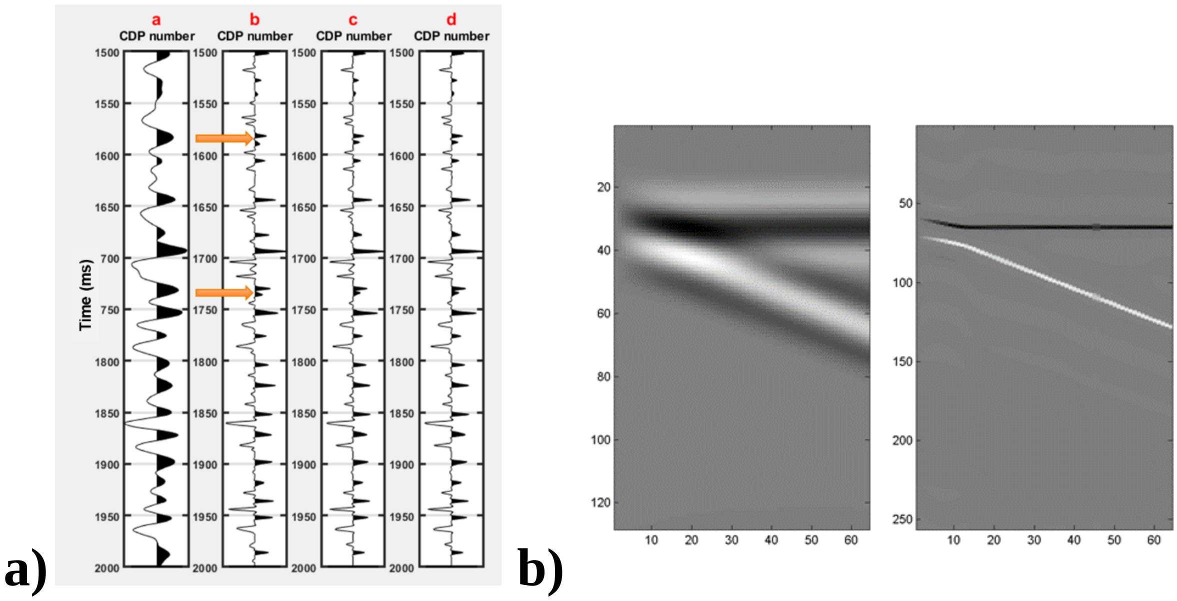
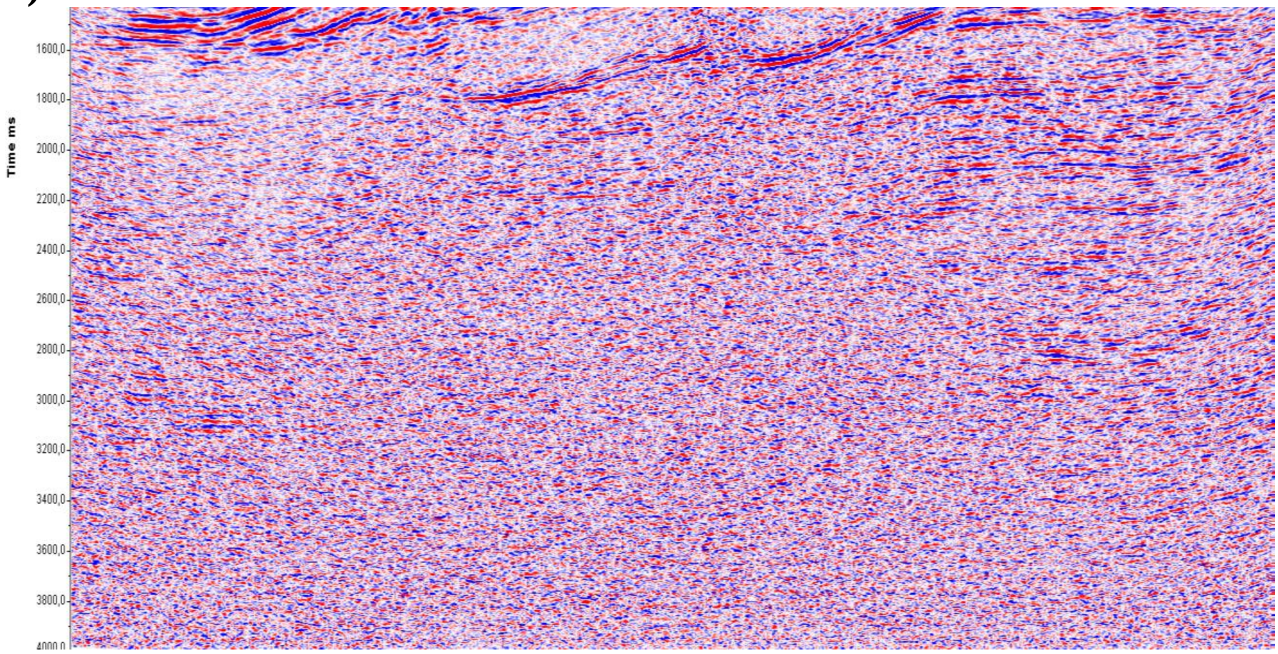


Figure 2: Demonstration of sparse spike deconvolution. a) A single stacked seismic trace in the first column a is deconvolved to sparse reflectivity traces with varying L1 sparsity constraints and L2 smoothness constraints in columns b, c and d. b) A synthetic seismogram imaging a wedge is deconvolved from left (original) to right (sparse).

a)



b)

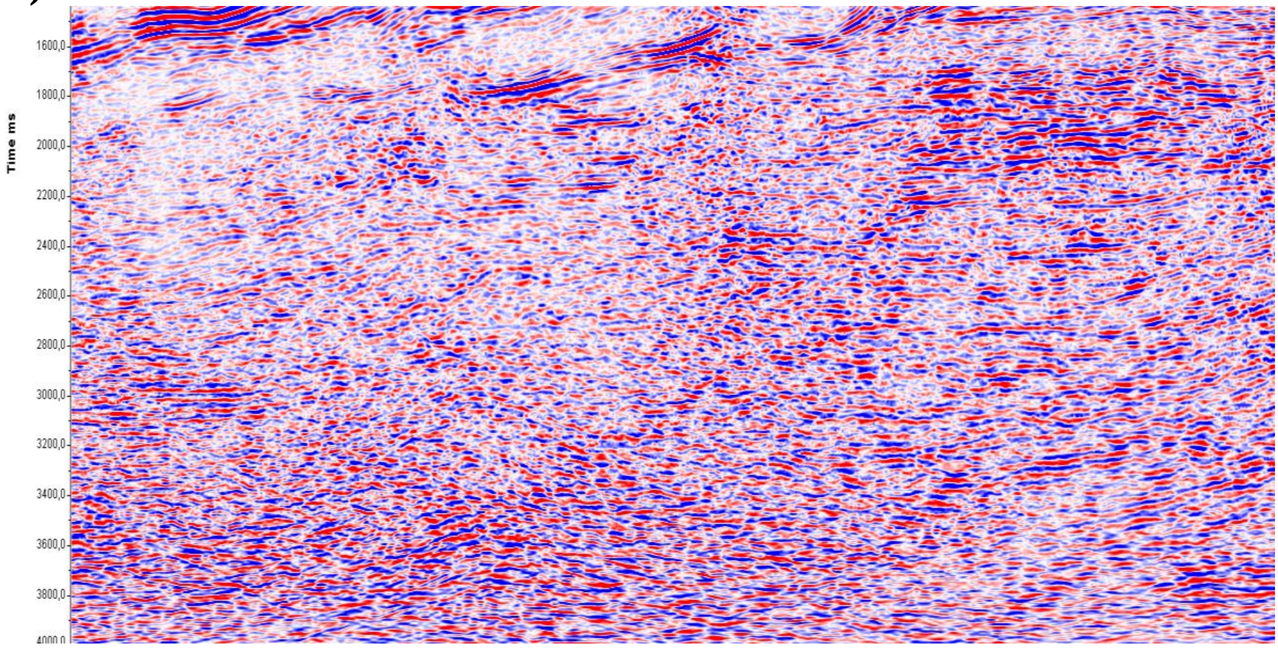


Figure 3: The comparison between zoomed section of onshore dataset MZ85-15 on the deep sections a) old section b) PSTM migrated section after NLM application. Note how possible Dinantian reflectors appear below 3200 ms.

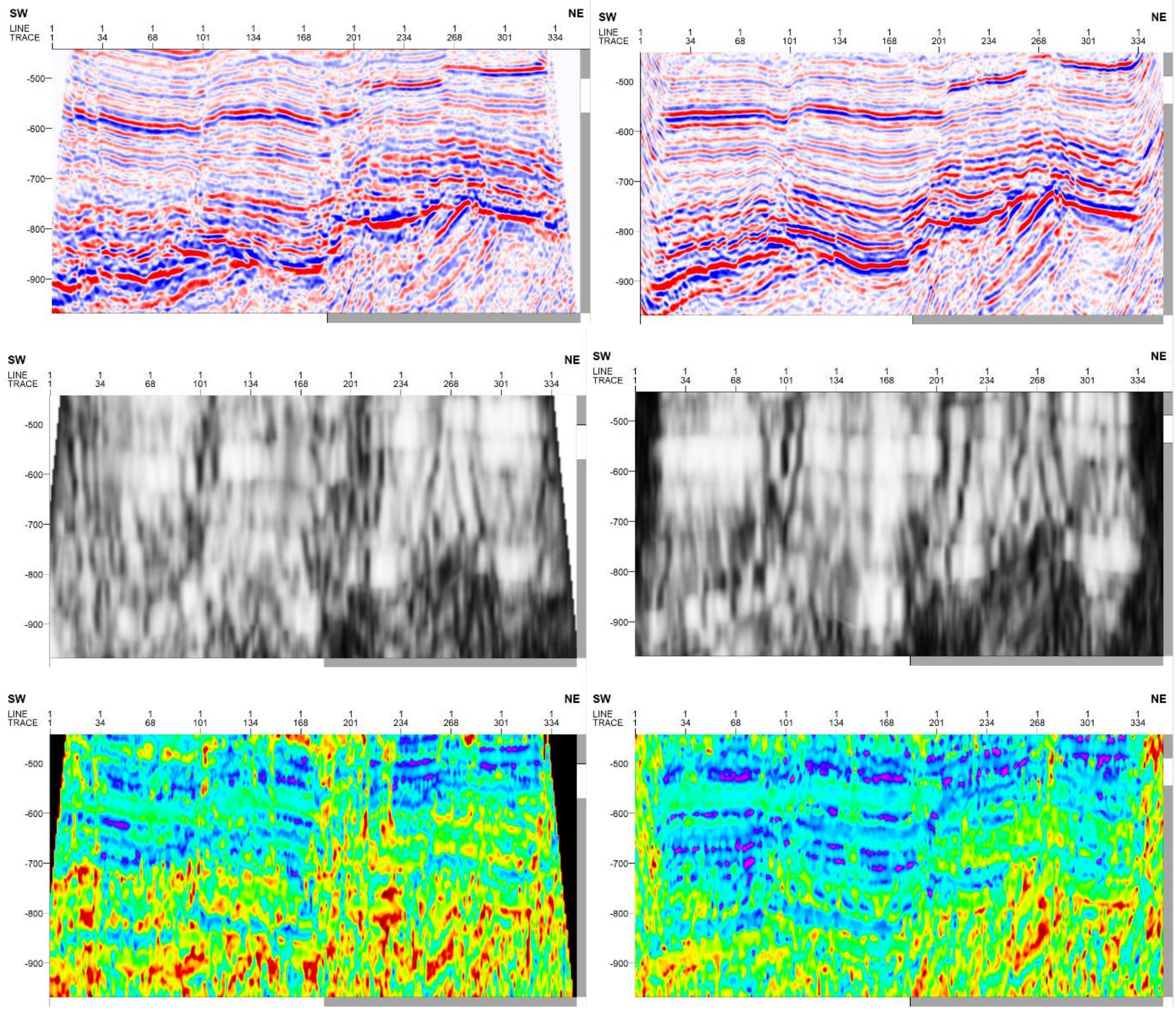


Figure 4: Application of the novel reprocessing workflow on the second geothermal case: the on-shore seismic line. The left column of panels depicts the original vintage seismic section, whereas the right column of panels depicts the reprocessed seismic section. The first row of panels shows the normal amplitude section, the second row shows a 'coherency' attribute applied to the top row seismic section and the third row shows an 'instantaneous frequency' attribute applied to the top row seismic section. Note how the definition of the overburden seal and its risk elements like faults (above 800 ms) and seal-reservoir contact (800-900 ms) is greatly improved from the left to right panels.

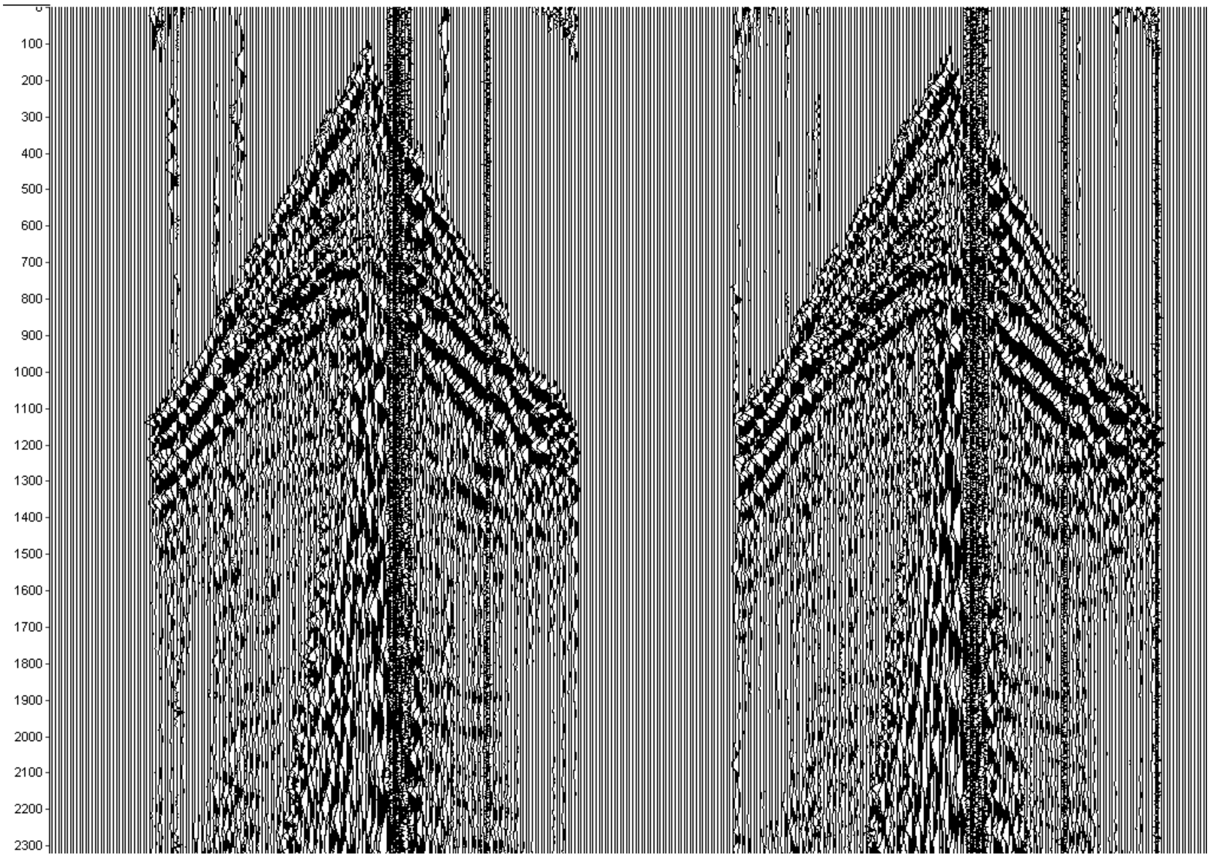


Figure 5: Example of shots in line 812054 (L2NAM1981P) (NW-SE).

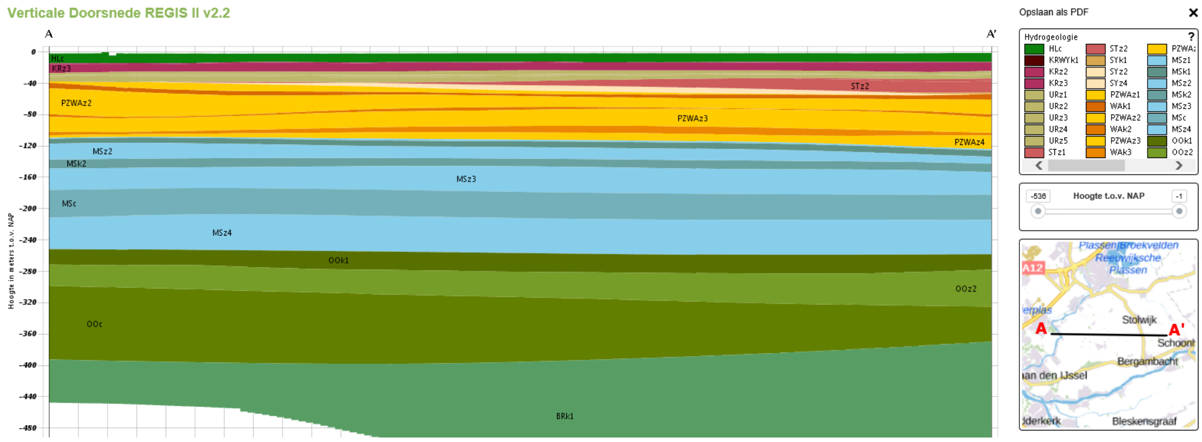


Figure 6: Cross-section of REGIS-II model along line 812054 (L2NAM1981P) (NW-SE).

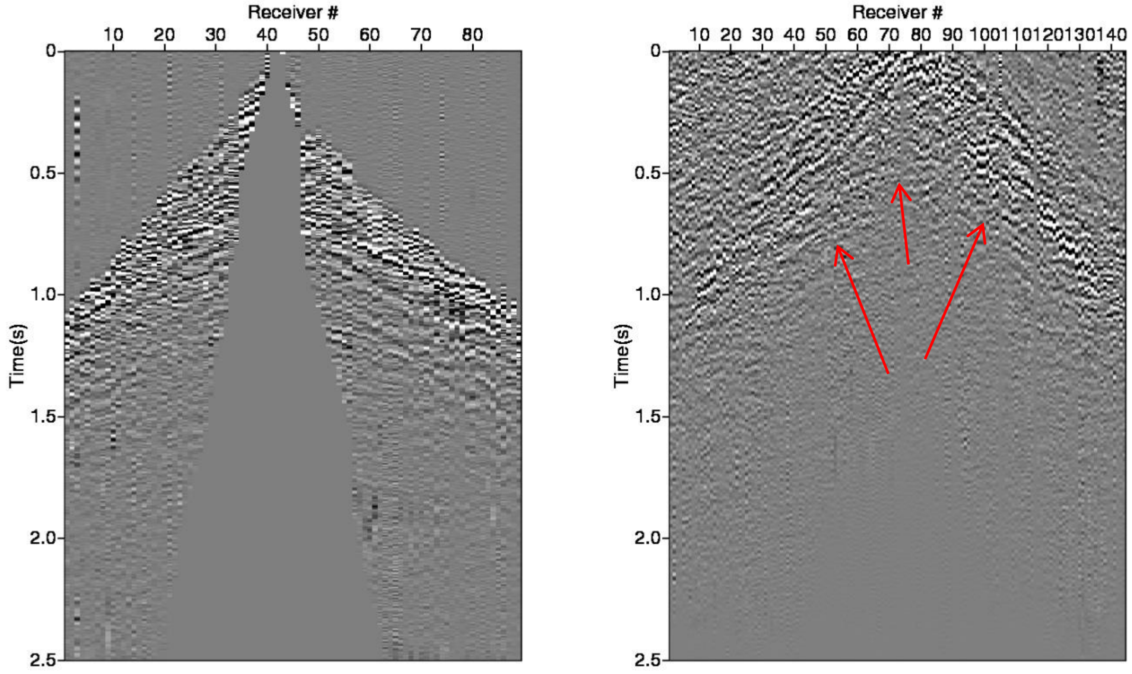


Figure 7: Left panel shows an active shot from the input data after a center mute was applied. Right panel shows a reconstructed virtual-shot at the same position as the actual active shot on the left.

The novel method for reconstructing and reprocessing vintage shallow 2D seismic data with seismic interferometry was applied in shallow Case 3. To this end, we first gathered a desired test dataset comprised of two lines in a seismic survey representative for the pilot site areas. These two lines contain shallow seismic data of sufficient signal quality to input in a correlation-based interferometric reconstruction method followed by subsequent seismic reprocessing. The following 2D line was selected: Line 812054 (L2NAM1981P) (NW-SE). Figures 5 illustrates two typical shot gathers of this line. Figure 6 displays a cross section along Line 812054 through the best know subsurface model of REGIS-II, a hydro-geological model developed and maintained by the Geological Survey of the Netherlands, housed within TNO.

A challenge for this line 812054 was that no observer logs and no navigation from archives were available, only navigation every 10th shot point. In first instance this was deemed not suitable for reprocessing, but after careful inspection and manual work, we could derive a geometry with spread layouts per shot from the scanned top labels of the two lines, and with that relative shot positions. Individual station intervals were reconstructed. The top label had (shot) statics, which allowed to identify station numbers for each individual shot. The top label also had a coverage diagram from which the spread layout could be inferred. For the split spread, the station number for the first left channel, last left channel, first right channel and last right channel was derived from the plot.

We retrieved virtual data from a seismic dataset containing 70 shots and 198 active geophones in total. The left panel in Figure 7 shows an active shot from the input data after a mute was applied to eliminate the strong air and surface waves. The removal of such undesired signals is an essential pre-processing step to avoid their interference in the cross-correlation process. After such mute is applied to the 70 shots, the pre-processed data is cross-correlated and summed using the dedicated code. The right panel in Figure 7 shows the virtual-shot at the same position as the actual active shot on the left. The red arrows indicate retrieved reflection events that present large similarities with the ones on the left at around 0.7 s and producing major new reflectors in the shallow (0.5 s) part of the active images. Note that these events on the right are also retrieved in a part of the panel that was previously muted in the data due to ground roll, thus illustrating the potential to retrieve valuable but missing data. This missing data can help to further constrain the REGIS-II model with reconstructed seismic data.

3. CONCLUSIONS

We have investigated a seismic reprocessing workflow for imaging and de-risking geothermal production and storage reservoirs and seals. The workflow includes statics, demultiple, velocity modeling, Prestack Time Migration, high resolution sparse spike deconvolution, Non Local Means filtering and a correlation-based seismic interferometry method for reconstructing shallow primary reflections. Non Local Means filtering increases signal to noise ratio while preserving edges and the sparse spike deconvolution produces results with superior vertical and lateral resolution. This workflow manages at low cost to considerably de-risk the geothermal reservoirs and seals by identifying previously hidden faults, seal-reservoir contacts and thin reservoir streaks. A next step is to quantify the de-risking into reduced uncertainties/scenarios and input these into conformance monitoring workflows.

In this study, we have also made significant steps forward in the development and application of a workflow that reconstructs and reprocesses shallow seismic data for achieving advanced characterization of geothermal storage systems. To this end, we assessed seismic and well data quality and determine gaps in these data with respect to the 3D subsurface models. With success we tested an experimental processing routines concerning correlation-based seismic interferometry, effectively doing shallow seismic imaging with multiples. This method managed to reconstruct an important shallow primary reflection.

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