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## Identifying Hidden Risk Elements For CO2 Storage From Reprocessed Seismic Data

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### Summary

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CO2 storage needs 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 exploration should identify risk elements for CO2 storage such as the risk of leakage, risk of pressure build-ups or drops, unexpected increase or decrease of storage capacity and spill points to name a few. These risks elements are often caused by hidden features such as a failing overburden seal, closed or open faults in either reservoir or seal and high- or low-permeability streaks in the reservoir. We have investigated a seismic reprocessing workflow for imaging and de-risking CO2 storage reservoirs and seals. The workflow includes statics, demultiple, velocity modeling, Prestack Time Migration, high resolution sparse spike deconvolution and Non Local Means filtering. 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 CO2 storage reservoirs and seals by identifying previously hidden faults, seal-reservoir contacts and thin reservoir streaks.

## Introduction

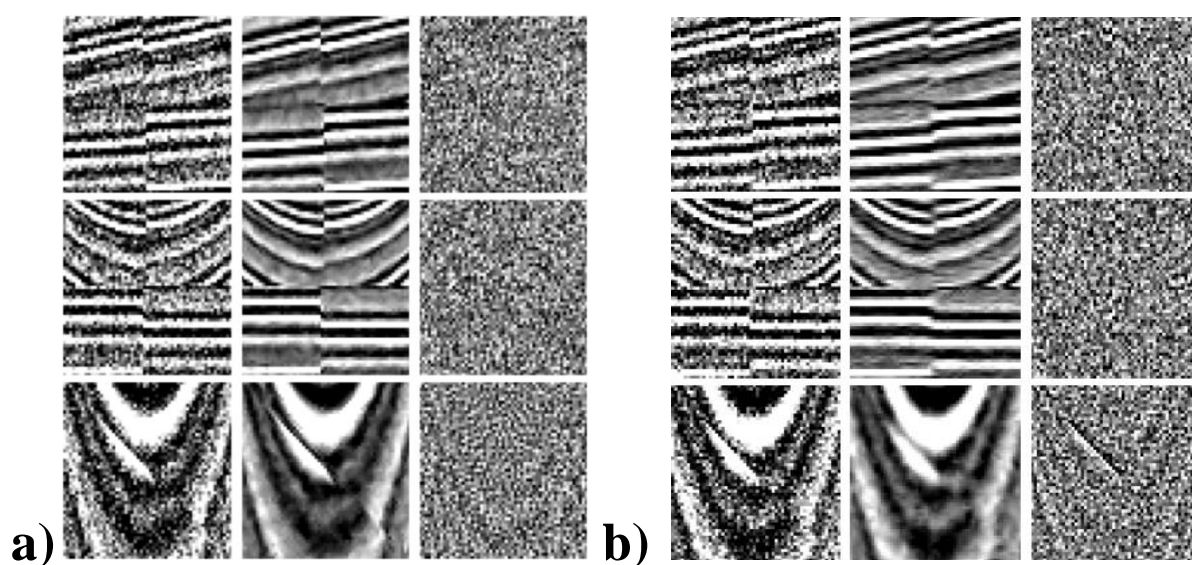
The CO<sub>2</sub> storage potential of reservoir and sealing formations in the Netherlands is being investigated in recent years as a result of the push for development of sustainable and unconventional energy resources in Europe. CO<sub>2</sub> storage needs economic business cases through cost-effective 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 accuracy for acquiring subsurface information at great depth. As such, seismic exploration offers the best chances of achieving both the cost-effective and the de-risking goals. More specifically it should identify risk elements for CO<sub>2</sub> storage such as the risk of leakage, risk of pressure build-ups or drops, unexpected increase or decrease of storage capacity and spill points to name a few. These risks elements are often caused by hidden features such as a failing overburden seal, closed or open faults in either reservoir or seal and high- or low-permeability streaks in the reservoir.

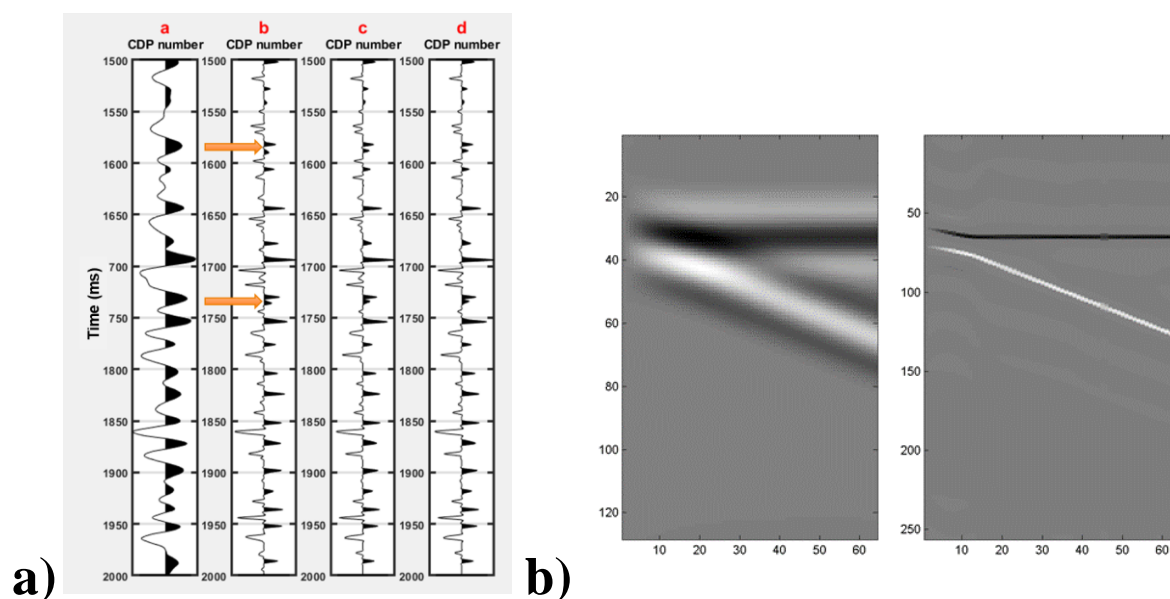
This study addresses the cost-effectiveness and de-risking capability of a workflow combining conventional and novel seismic reprocessing techniques by evaluating its ability to identify hidden risk elements in two prospect CO<sub>2</sub> storage case studies. One case study considers the sealing capacity of an on-shore overburden and one case study considers the storage capacity of an off-shore reservoir.

## 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 two CO<sub>2</sub> storage prospects in the Netherlands: an on-shore line with potentially suitable overburden seal and an off-shore line targeting potentially suitable reservoir. The novel processing techniques used are 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 CO<sub>2</sub> storage systems. The conventional seismic reprocessing improves the data by superior imaging with statics, demultiple, velocity modeling, Prestack Time Migration, which improvements are then magnified by the novel techniques.



**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).

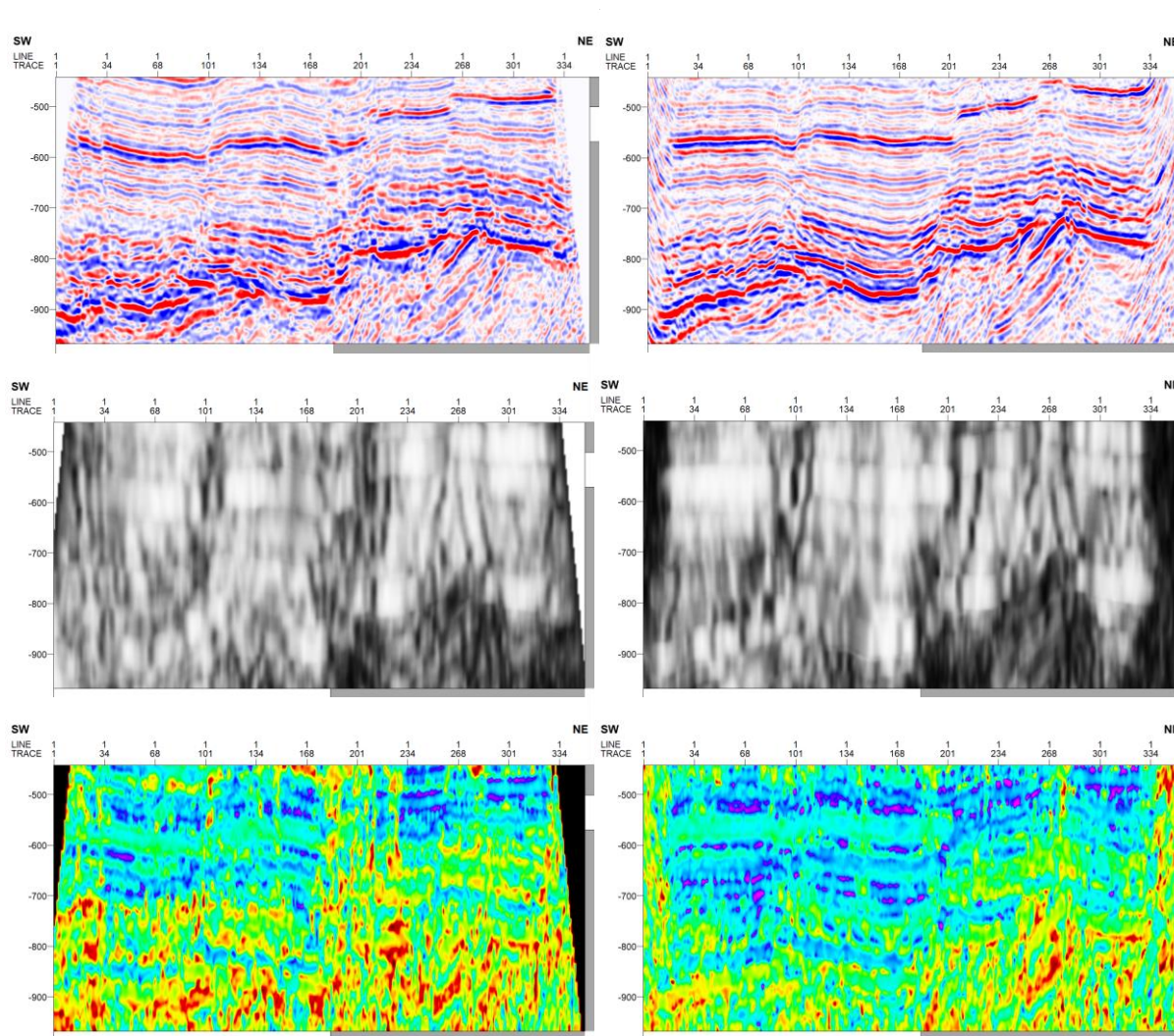
The NLM filter is a next-generation signal denoising algorithm which is originally proposed for image processing and has been used in medical imaging and seismic processing. It takes advantage of high redundancy in most natural images, which assumes for every small window in an image there are many other 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 become 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.

## Results

The combined reprocessing workflow was applied on two CO<sub>2</sub> storage cases: a vintage on-shore line and an off-shore line. The details of these lines are anonymized, but both lines are available at no cost. Figures 3, 4 and 5 demonstrate how the workflow has enhanced the vintage seismic sections in the left panels towards the reprocessed seismic sections in the right panels. Overall, the temporal and spatial resolution of the new seismic sections identifies risk elements for CO<sub>2</sub> storage such as overburden seal, faults in either reservoir or seal and high-permeability streaks in the reservoir. Case 1, the on-shore line, features a possibly suitable overburden seal for a CO<sub>2</sub> storage reservoir. From Figure 3 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. The same goes for the off-shore case in Figure 4, where the vintage data in the left panels missed out on several fault-bounded pop-up structures and several wedges with terminating reservoir intervals at 1575 ms. On top of that, Figure 5 reveals thin reservoir intervals that are high-perm streaks as confirmed in an adjacent well.





**Figure 3** Application of the novel reprocessing workflow on the first CO<sub>2</sub> storage 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.

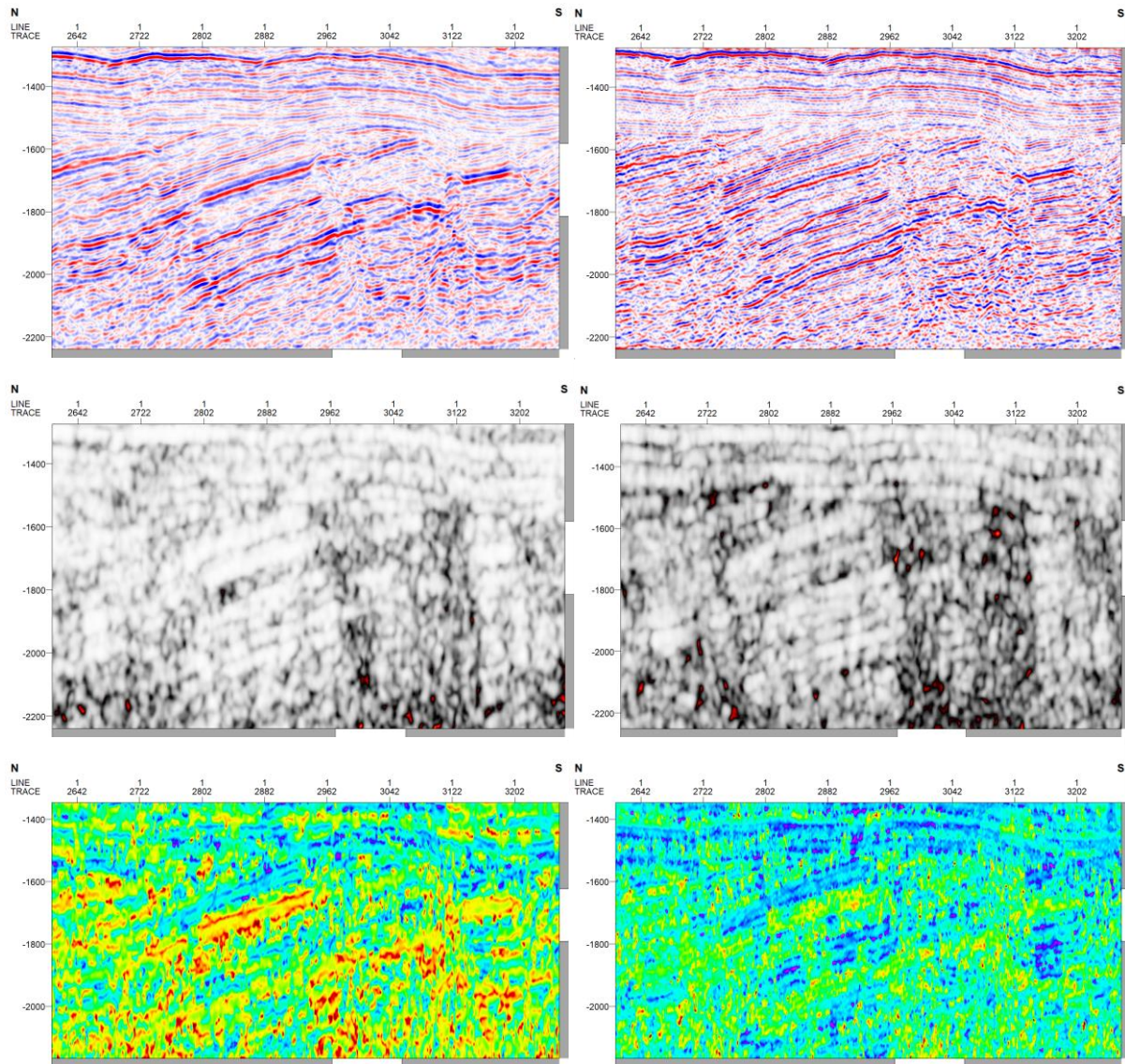
## Conclusions

We have investigated a seismic reprocessing workflow for imaging and de-risking CO<sub>2</sub> storage reservoirs and seals. The workflow includes statics, demultiple, velocity modeling, Prestack Time Migration, high resolution sparse spike deconvolution and Non Local Means filtering. 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 CO<sub>2</sub> storage 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.

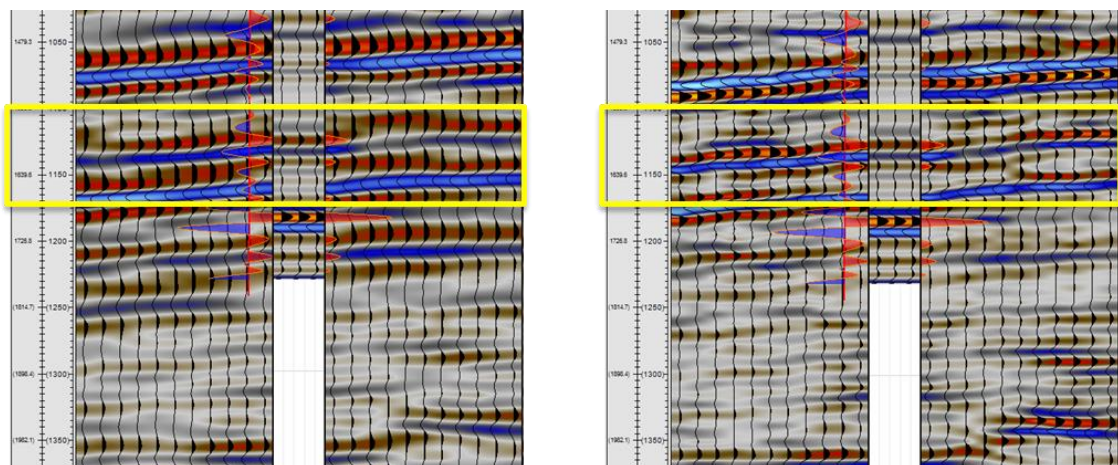
## References

1. Buades, A., Coll, B., and Morel, J.M. (2005). A review of image denoising algorithms with a new one. *Multiscale Modeling and Simulation*, Vol. 4, No. 2, pp. 490–530.
2. Chapman, N.R. and Barrodale, I. (1983). Deconvolution of marine seismic data using the L1 norm. *Geophysical Journal International* 72.1, pp. 93-100.





**Figure 4** As in Figure 3, but now for the second CO<sub>2</sub> storage case: the off-shore seismic line. The definition of the reservoir and its risk elements like seal and faults (below 1575 ms) is greatly improved from the left to right panels.



**Figure 5** As in Figure 4, but now for a well-tie on the off-shore seismic line. The seismic sections are split by a well-synthetic in the middle. The definition of the reservoir reflectivity fits better to the well from the left to right panel.