Seismic reprocessing and attributes for geothermal exploration: a case study in Friesland, Netherlands

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ABSTRACT

Global development of sustainable energy is driving new methods of exploration and exploitation of geothermal energy. Reprocessing of vintage seismic data is shown to considerably enhance these data as well as derived seismic attributes for reservoir and fault characterisation. In this study, new reflection seismic processing and interpretation methodology is developed. Seismic attribute analysis performs substantially better on reprocessed data, particularly on Non Local Means filtered data. It enables interpretation by autotracking of horizons up to 6 km depth. Previous interpretations can be readily revised and geologic formations and faults that could not be interpreted before are now mapped in detail.

1. INTRODUCTION

This European ambitions in the development of sustainable energy are pushing innovations in exploitation of geothermal energy. Currently, a large number of coordinated research efforts in geothermal exploration and production (GE&P) are underway. Examples of geothermal exploration methods being considered are seismic imaging, magnetotelluric sounding, gravity modelling, INSAR measurements for geomechanical models and drilling campaigns. Seismic imaging is currently the method that provides the best possible trade-off between imaging detail and depth penetration. It profits from prior and parallel developments in both petroleum exploration and production (PE&P) and mineral exploration and production (ME&P). Advances and innovations in seismic imaging include reprocessing of vintage data, seismic attributes for reservoir and fault characterisation, amplitude-versus-offset (AVO) analysis, full waveform inversion, diffraction imaging, multicomponent/VSP imaging and others. Not only is there need for development of new methods, but also for case studies demonstrating the performance of these methods.

The Netherlands offers excellent grounds for a case study in advanced geothermal exploration using seismic methods. TNO, the Netherlands Organisation for Applied Scientific Research, manages a vast library of vintage 2D and 3D seismic data originating from the rich history of PE&P in the Dutch on- and offshore. This large collection of vintage data covers the majority of promising (ultra-deep) geothermal (UDG) provinces in the Netherlands. Hence, enhancing the quality of such vintage data and extracting new meta-information from these seismic data will unlock the potential of these geothermal targets. Most of them are sedimentary in nature and tend to be more shallow, but Dutch geothermal reservoirs are not limited to that. The UDG targets can either be sedimentary in nature, or can also resemble magmatic thermal systems in terms of high temperatures, high pressures, fracture/fault pathways and metamorphic mineralogy. A case study for UDG should demonstrate that it is not only possible to identify the reservoir and to create a reservoir model, but also to achieve these deliverables in a cost-effective way, leading to a viable business case. Budgets in GE&P are thinner than those in PE&P and ME&P, calling for less expensive resources. The ability to obtain large datasets, reprocessing and automatic interpretation will help this cause.

2. A DUTCH GEOTHERMAL CASE; THE FRIESLAND LOCATION

To get a first impression of the potential of Dutch UDG, the combination of seismic coverage and well control is essential. In the Netherlands there are three suitable wells which are drilled deeper than 5 km. These wells are located in the northern Dutch onshore, around the provinces of Friesland and Groningen. At a depth of 5 km and below, wells have encountered thick limestone formations, designated Dinantian carbonates. Particularly in Friesland, a thermal anomaly (~200° C at 4600 meter) is observed within the carbonates combined with increased fracture permeability (~60 mD) at depths of 4600-5200 meter. This makes both the provinces Friesland and Groningen suitable for a UDG case study. According to an internal TNO report (TNO, 2015), the province of Friesland makes for an optimal UDG case (Figure 1). With ultra-deep geothermal energy, which is locally available at depths of 5 to 7 km, there is a unique opportunity for industry there.

Figure 1: Overview map of research location (inset rectangle) in the Netherlands.

3. CASE METHODOLOGY

For the delineation of the UDG reservoirs on existing surface seismic data, a combination of existing and new seismic processing techniques has been developed at TNO in the context of the IMAGE programme (Greenhalgh et al., 2014). New generations of pre- and poststack noise-reduction and signal enhancement algorithms serve this purpose. Strong noise suppression together with edge preservation are necessary for revised reflection interpretation and fault delineation. Reprocessing will magnify the effect of subsequent attribute analysis and employing the combination of new data and attributes will enhance existing interpretations of the Dinantian geothermal reservoir and even allow new interpretations where previously there were none.

The workflow for getting to a revised and new Dinantian UDG seismic model is as follows:

1) Poststack reprocessing of 2D and 3D Friesland seismic data using Non Local Means filter

2) Generating Envelope, Instantaneous Phase and Coherence attributes

3) 2D and 3D autotracking of Top and Bottom Dinantian reflectors and faults

4) Production of gridded regional Dinantian Carbonate Top and Bottom surfaces

For the Friesland UDG case study reprocessing is done on poststack 2D and 3D active source surface seismic datasets (Figure 2). 3D data here consists of several merged 3D cubes of varying vintage, culminating in a 1500 square km 3D megacube. Added to this cube are 10 cross-secting 2D lines of on average +- 20 km length, effectively spanning a sparse pseudo 3D cube around the deep Luttelgeest (LTG-01) well. As the 3D pseudo cube and 3D megacube connect up, we create a consistent interpretation of the 5-6 km deep Dinantian Carbonate geothermal reservoir, which has not been done before as currently known to us.

The reprocessing methodology is based on existing and next-generation signal enhancement algorithms from the photo- and video processing industry. The fx-deconvolution and eigenvector filter algorithms are existing and established signal enhancement filters acting as noise suppressors in the fx- and eigenspace transform domains of seismic data respectively. For details on the algorithms we refer to Canales (1984) and Jones & Levy (2006). Essentially, fx-deconvolution spatially smooths seismic data based on predicted signal in overlapping fx-windows. Eigenvector filtering, also known as principle component filtering or Karhunen-Loeve Transform (KLT) filtering, correlates each seismic trace with all others, transforms the resulting correlation matrix to eigenspace, mutes specified eigenvalues/vectors and transforms back. Both filters have a global operator response throughout the whole data which, like most other multichannel filters, causes global spatial smoothing and artefacts. An often encountered limitation of these filters is the lack of edge preservation in seismic data while enhancing continuity.

The Non Local Means (NLM) algorithm (Buades et al., 2005; Bonar and Sacchi, 2015) acts as a multi-dimensional adaptive filter on seismic data in the spatio-temporal domain. It averages a central seismic sample exclusively with weighted contributions of neighbouring samples having similar Gaussian neighbourhoods as the central sample under consideration. The algorithm scores as one of the best denoising techniques on synthetic seismic data because of its superior random and coherent noise suppression, reflection continuity enhancement albeit with edge and amplitude preservation. It is because of this edge preservation ability that we apply NLM to our geothermal exploration case, where fault and fracture detection are of paramount importance.

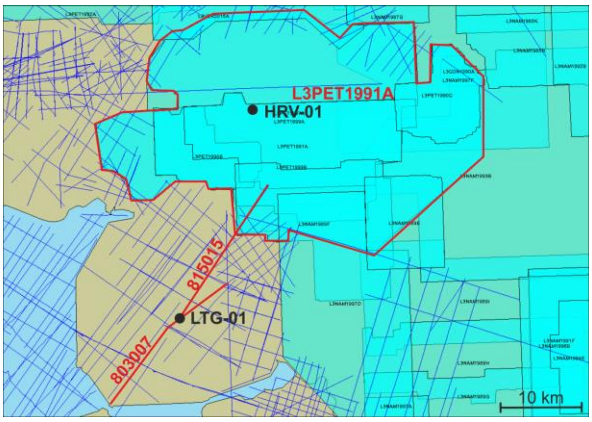

Figure 2: Map of investigation area Friesland with 3D seismic (polygon) and 2D seismic (lines).

3. RESULTS - REPROCESSING

The fx-decon and eigenvector filter are applied sequentially to the Friesland deep seismic datasets, since they reinforce each other's noise suppression effect. This combined result is then compared to the NLM filter result for a one-to-one assessment of the filter performances. A successful filter application with additional edge-preserving on the Friesland deep seismic datasets has groundbreaking implications. Given the dense seismic data coverage in the Netherlands, it will unlock a new class of national deep geothermal reservoir potential and most likely for Europe as well.

First, the NLM filter has been put to work on a vintage 2D line, designated 803007 (Figure 2). Filter parameters used were 9 x 9 x 0.0015 (S x N x h). Results are promising: Figure 3 shows the difference (3c) between original 2D poststack data (3a) and the NLM reprocessed data (3b). Indeed the reprocessed data have greatly reduced noise levels and retained the edges of the faults (yellow ellipses). The overall image of the carbonate platform at 5 km depth (between green arrows) displays much more clarity. What is striking as well is how the noise was successfully removed locally from the original image (3c, within yellow ellipses and green arrows). Areas with low signal-to-noise-ratio S/N were filtered stronger than areas with high S/N. This is how a multichannel filter preferrably works: attack the noise where it resides, let intact the healthy signal and structure and prevent smearing.

It appears that the NLM algorithm is capable of enhancing, or rather preserving signal and edges/structure in vintage 2D data. This is good news for the geothermal case, where reflector continuity and fault sharpness are required for delineation of the reservoir. However, application on 3D data and subsequent automatic tracking of the Top and Bottom Dinantian horizons is mandatory for successful exploration of the geothermal reservoir and cost-effective exploitation later on. A 3D version of the NLM algorithm is implemented by TNO as well and applied to the vintage 3D survey L3PET1991A (Figure 2). Filter parameters were 3 x 3 x 0.001 (S x N x h); smaller S and N are possible due to the larger redundancy of the 3D data. Figure 4 shows an inline section through the 3D cube, connecting up with 2D lines 803007 and 815015 along the Luttelgeest well (Figure 2). 4a displays the inline through the original data, 4b the NLM reprocessed data and 4c the fx-decon + eigenvector (FXEV) reprocessed data. Overall the noise suppression and continuity enhancement is evident in 4b and 4c. The difference between NLM and FXEV filtered results is subtle, yet profound in the derived attribute coherence. Coherence is a trace-by-trace correlation based attribute, also known as similarity, variance and semblance. It gives low correlation (red-to-black colour) at high impedance contrasts and structural discontinuities like faults and unconformities, and high correlation (grey-to-white) along reflectors and smooth transitions. In Figure 5, one can see the coherence response of the seismic inlines from Figure 4. Here, the differences between the 3D NLM filtered data (5b) and the 3D FXEV filtered data (5c) are much more pronounced. As expected, the FXEV data suffer from the global operator response throughout the data, smearing edges and other structure. Many faults that run through the Dinantian at 5-6 km depth (black stripes in yellow ellipses) get wiped out. The NLM data manages to preserve reflection continuity and most of the faults at minor impact and actually retrieves new faults at the expense of noise clouds (left side of the images). Edge preservation and reflector continuity appear successful with the NLM filter as opposed to the FXEV data.

3. RESULTS – SEISMIC INTERPRETATION

As a result of the NLM reprocessing, a revised interpretation is done on the top of the Dinantian Carbonate platform and the platform bottom can now be picked as well. A 2D and 3D autotracker is used for reflector picking. A useful aid for the autotracking is the option of introducing a 3D co-volume, whereby either the primary seismic volume (cube) is used, the co-volume or a mix of both. In this way, tracking can continue onto the other volume in spite of missing or disrupted reflections in one volume. Further constraints on the autotracking are the connection of the 2D lines to the 3D cube, where the 2D horizons function as seed points for the 3D autotracker. The combination of using the NLM reprocessed 3D cube as a primary volume and an Instantaneous Phase attribute NLM cube as a co-volume turns out to be a successful combination. With minimal user interaction both the Top and Bottom Dinantian were successfully tracked. After the generation of these two horizons, they were gridded onto the extent of all combined 2D and 3D seismic data into surfaces using a minimum curvature interpolation algorithm. The overall result of the autotracked and gridded Top and Bottom Dinantian surfaces based on the NLM reprocessed vintage 2D/3D data and attributes is presented in Figure 6. A comparison is made between 6a) the original interpretation of Top Dinantian by Kombrink (2010) and Van Hulten & Poty (2008), 6b) the revised Top Dinantian, and 6c) the new Bottom Dinantian.

Indeed the level of detail due to the new information is evident, and uncertainties in the picked interpretation of the Top Dinantian are greatly reduced. The addition of the Bottom Dinantian horizon allows for thickness maps for the potential geothermal reservoir. Newly determined depths of top and bottom reservoir deliver more accurate temperature maps and net-to-gross estimates for the reservoir interval are now possible. Due to the preserved amplitude character of the original data and the greatly reduced noise levels, poststack seismic P-impedance inversion is now feasible as well, further reducing uncertainties.

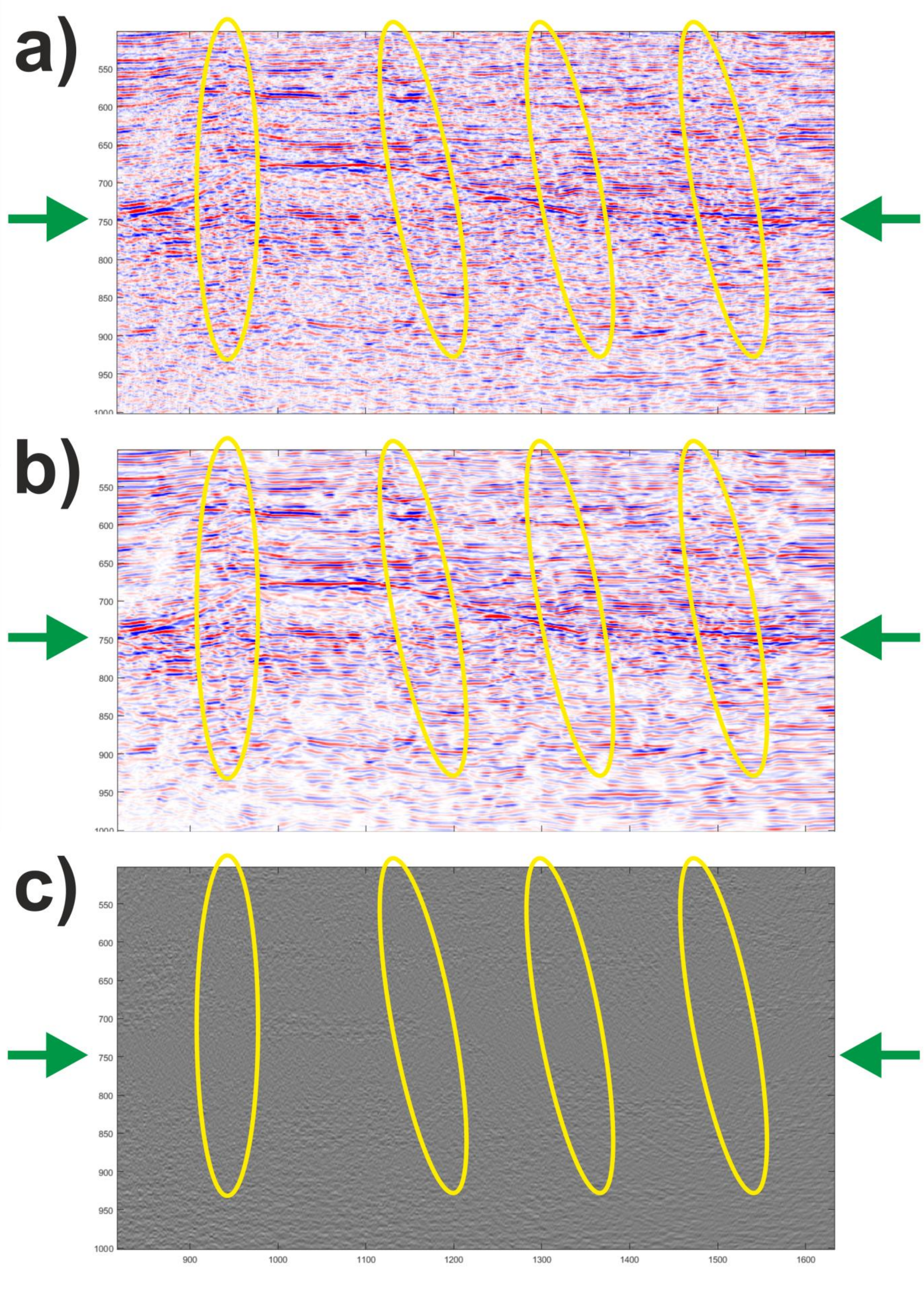

Figure 3: NLM application to vintage 2D seismic data in Friesland. a) original data, b) NLM data, c) difference. Note the selective, local suppression of noise within the yellow ellipses and green arrows.

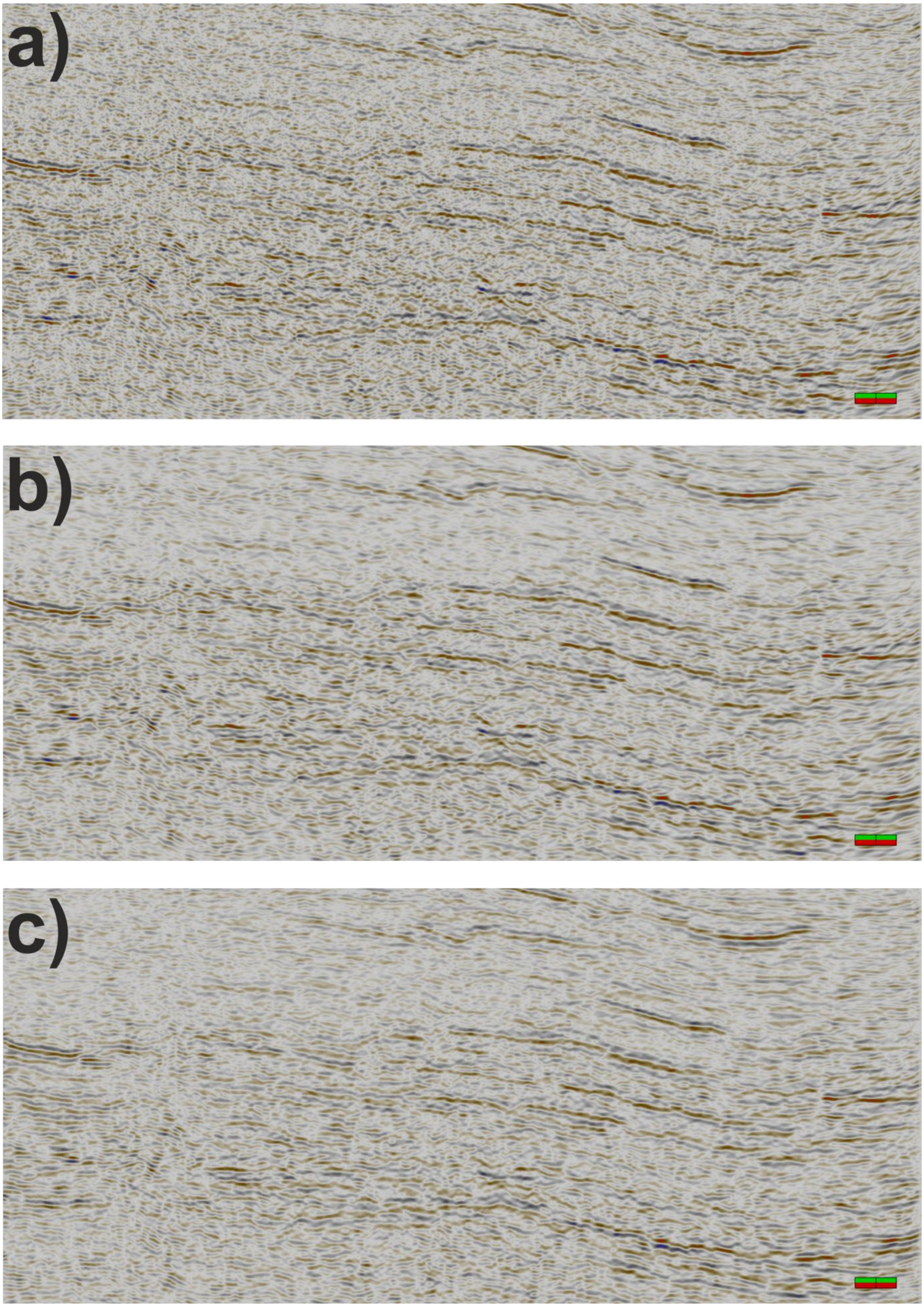

Figure 4: NLM application to vintage 3D seismic data in Friesland and comparison. Inline with a) original data, b) NLM data, c) FX-decon + Eigenvector (FXEV) filtered data.

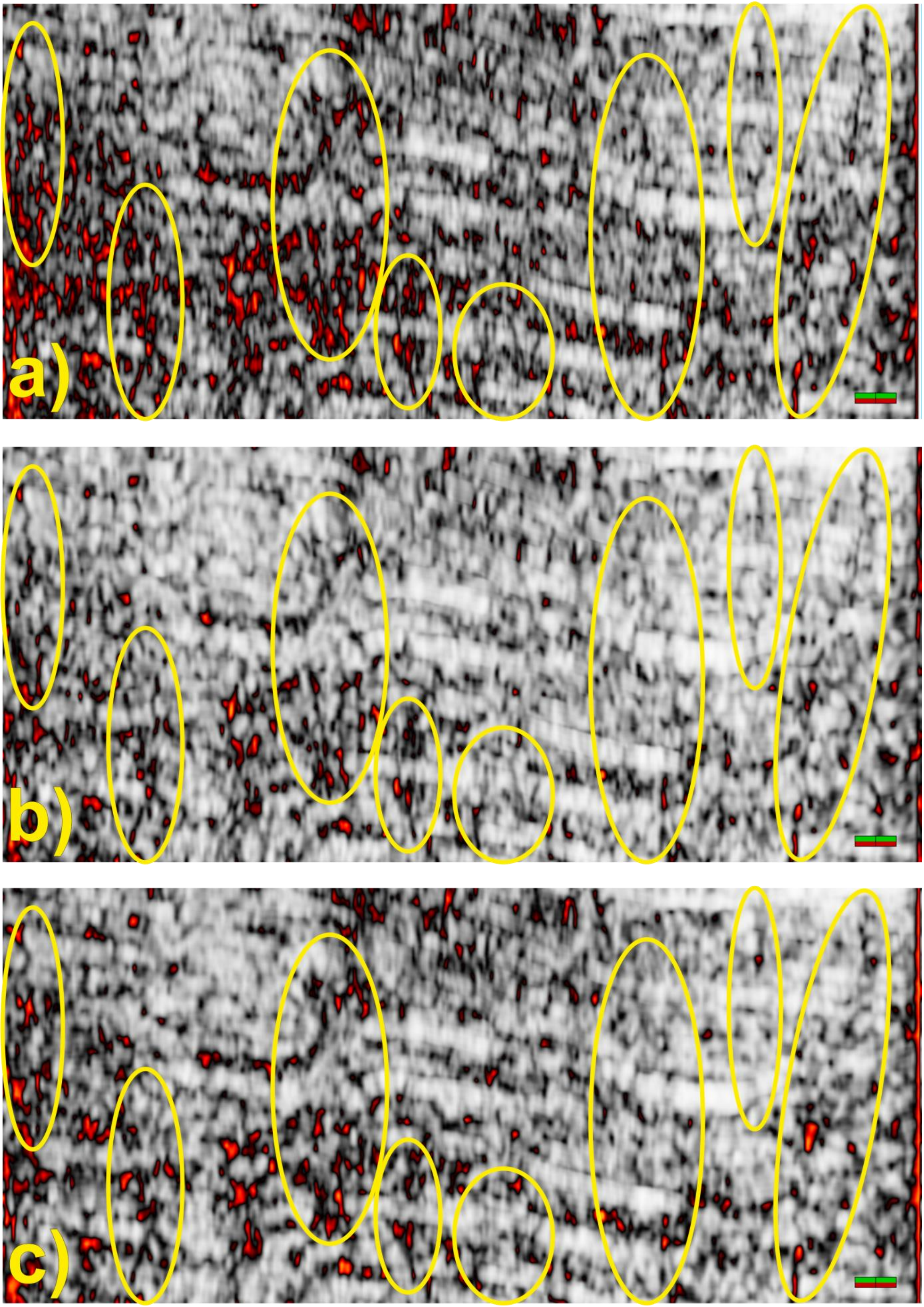

Figure 5: NLM application to vintage 3D seismic data in Friesland and comparison. Inline with a) original data, b) NLM data, c) FX-decon + Eigenvector (FXEV) filtered data.

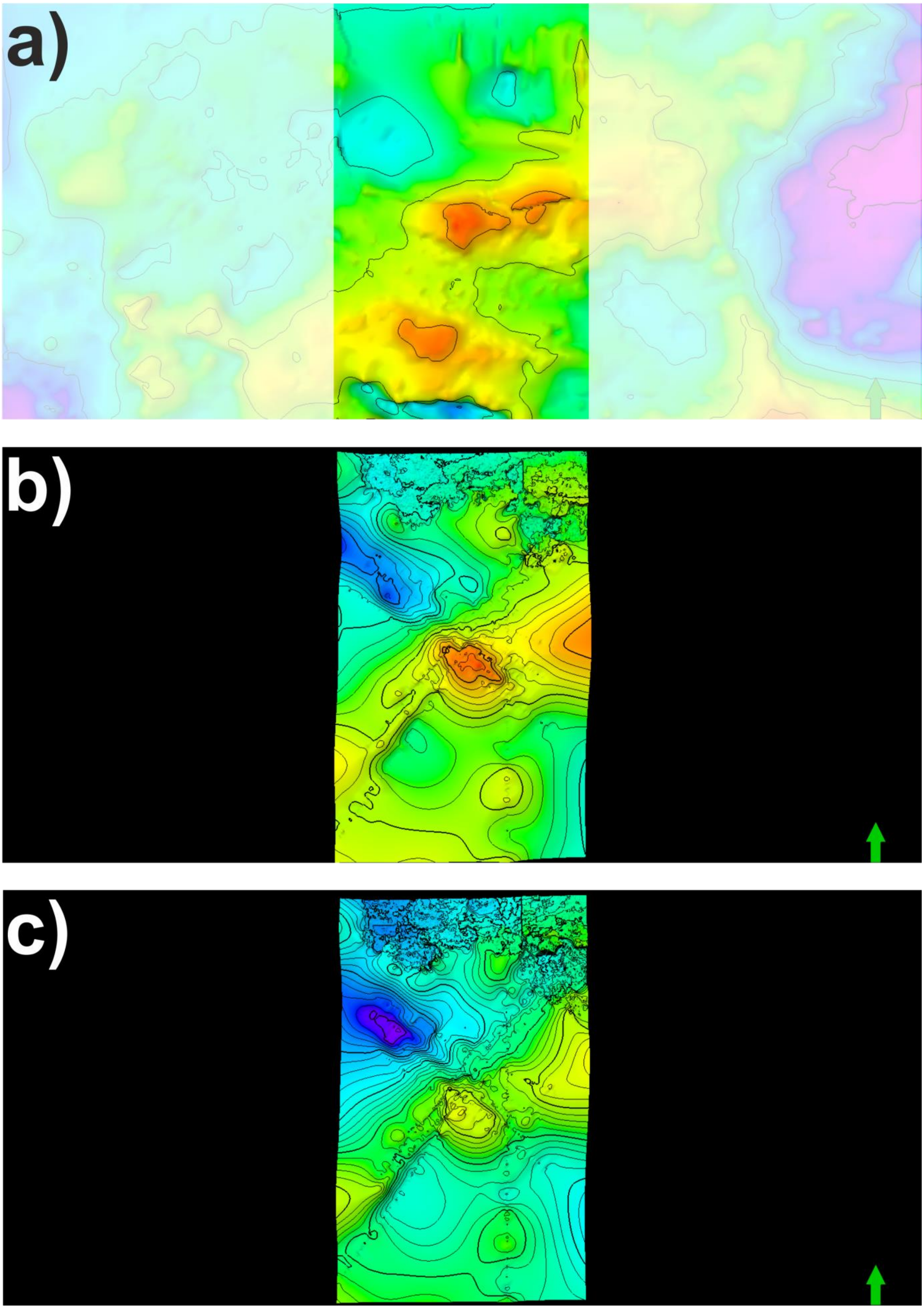

Figure 6: Dinantian horizons: a) old interpretation of Top Dinantian (Kombrink, 2010; Van Hulten & Poty, 2008), b) revised interpretation of Top Dinantian tracked in NLM data, c) new interpretation of Bottom Dinantian tracked in NLM data.

3. CONCLUSIONS

In this study, new active seismic acquisition, processing and interpretation methodology is developed. A next-generation reprocessing algorithm from video- and photo processing industry is put to the test on synthetic data and real data for an actual ultra-deep geothermal exploration case in the Netherlands. The Non Local Means multichannel filter is applied to vintage 2D and 3D seismic data from the Friesland province, with the goal of demonstrating the feasibility of ultra-deep geothermal exploration and production. If feasible, potentially viable business cases can be constructed for deep geothermal reservoirs in the Dutch subsurface and in the rest of Europe as well.

The NLM filter outperforms several state-of-the-art multichannel filters such as the fx-decon and eigenvector filter in terms of reflection continuity enhancement and fault preservation. For this reason, NLM is preferred above other algorithms for reprocessing vintage 2D and 3D poststack seismic data. At a relatively low cost, large amounts of seismic data can be reprocessed in this way delivering interpretable signal up to 6 km depth. Given the seismic coverage of the Netherlands in terms of 2D and 3D poststack data, this unlocks a vast geothermal potential at national and possible international scale.

Seismic attributes perform substantially better on NLM reprocessed data and enable interpretation by autotracking of horizons up to 6 km depth. Former interpretations can be readily revised and geologic formations previously inaccessible in seismic data are now open to interpretation. The characterisation of (ultra-)deep geothermal reservoirs is improved together with greatly reduced uncertainties. New and existing meta-analyses of geothermal reservoirs can benefit from the improved seismic delineation, for example seismic inversion, log analyses, heat and convection modeling, fault and tectonic modeling and others.

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