2D & cross-spread mini-3D surveys for geothermal doublet planning in The Netherlands.

E. Kleiss[1], A. Vondrak[2], E. Van der Voet[2], B. Turner[3], R. De Kunder[4]

[1] Kleisseis; [2] Ennatuurlijk Aardwarmte; [3] Dayboro Geophysical; [4] Faraday Geophysics

Summary

We present the results of two small target-oriented sparse seismic surveys for planning and optimising geothermal doublets. These surveys combine short conventional 2D seismic lines with 3D cross-spreads formed by orthogonal 2D lines, to obtain a reliable areal image of the subsurface in a limited area-of-interest. Data were acquired using low-power electromagnetic vibrators and nodal sensors which made seismic acquisition in this mixed urban-industrial-agricultural area possible. Despite the high ambient noise levels, low source energy and restricted access, the data successfully imaged subsurface targets at 2000m-2500m bmsl and provided the operator with useful additional subsurface information, particularly on small faults and fault patterns in the development blocks.

Introduction.
In densely populated and highly regulated regions like The Netherlands, acquisition of high-resolution seismic data for geothermal development often faces practical and environmental constraints that limit the use of conventional large-scale 3D seismic surveys. Small-scale, high-density seismic campaigns, combining 2D and cross-spread mini-3D acquisition geometries, offer a flexible and cost-effective alternative for de-risking geothermal doublets, particularly in urban and industrial environments.

In autumn 2024, Ennatuurlijk Aardwarmte acquired two small-scale seismic surveys for geothermal projects. The first one was to gain better subsurface understanding for optimisation and possible remedial action for an existing doublet, where existing seismic data did not offer sufficient insight. Taking the opportunity, a second 'exploration' survey was conducted in another concession area to check out favourable subsurface structures at a prospective doublet location and to avoid surprises in a possible development there.
Objective for both areas are the Rotliegendes sandstones, below the Base Zechstein which is a strong regional seismic reflection at 1500-1700ms TWT (i.e. 2000-2500m bmsl).

Each of these two surveys consisted of a base 2D survey of two 2D seismic lines of approximately 7km each, complemented by two or three receiver-only lines. All receivers were deployed at the same time on all lines to record all shots. Such configurations enable the acquisition of two proper 2D lines plus some 'offset lines', which combine a source (S) line with receivers (R) on another more-or-less parallel line to get an additional 2D image along their CMP trajectory. By combining data from intersecting S- and R-lines also 3D 'cross-spread' volumes are acquired, which were hoped to provide a better-focussed 3D image of potential fault blocks than just the 2D images. Such cross-spread acquisition has earlier been successfully tested for similar objectives by EBN as part of their SCAN project (Rehling et al. 2024).

Data were acquired using Stryde autonomous recording nodes at nominally 10m receiver point spacing (locally refined to 5m spacing in the central part of survey 1) with a 10kN Storm e-vibe electromagnetic vibrator as seismic source at 5m source point distance using a single 2-75Hz linear sweep.

A usable S-R offset range of roughly 2km at TD was expected, yielding nominally 100-fold 2D data and 2-fold 3D data (for each individual cross-spread combination) in 5m bins It achieves an imaged subsurface area of roughly 4km (2D) and 2-3km^2 (3D), targeting a really limited but specific AOI. Given the low source energy and locally noisy operating environment the final data quality depends on careful processing and exploiting the fine point spacing (5m) and high 2D stack fold, and for the cross-spreads the high 3D migration multiplicity.

Survey 1 (Middenmeer - MDM)
Figure 1 shows the planned and the achieved geometry for this survey.

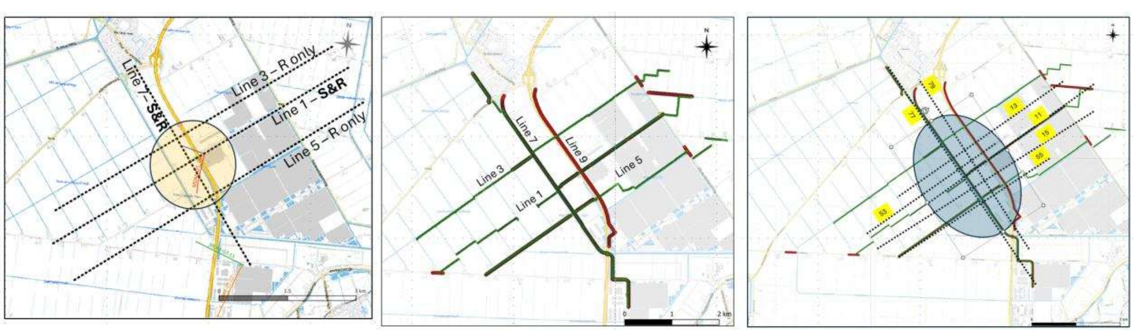

Figure 1. *Geometry for MDM survey; from left to right:*
a) *Originally plan with 2 full 2D lines and 2 receiver-only lines; AOI around doublet indicated;*
b) *Actual achieved S (red) and R (green) locations (receivers are partly obscured by shots);*
c) *Approximate achieved 2D CMP combinations and 3D (Cross-spread) image area (blue oval).*

The original plan was to acquire two orthogonal 2D lines (line 1 and 7), complemented by two receiver-only lines 3 and 5; in addition to proper 2D lines 1 and 7 this produces 'offset lines' 1-3 and 1-5 combining shots on line 1 with receivers on lines 3 and 5, respectively. It also enabled recording

of 4 partly overlapping single-fold 3D cross-spreads by combining S-line 7 with R-lines 1, 3 and 5 resp. and S-line 1 with R-line 7 which can all combine to a single 3D volume.
Sources were positioned mostly along existing roads and accessible pastures; receivers along roads or canals and in accessible farmlands. Some extra shots at the far ends of 2D lines 1, 3 and 5 helped in data processing to stabilise the statics solution. Due to access restrictions in the farmlands on the SW of line 1, sources had to move from the SW part of line 1 to line 5, and some to line 3. This truncated the imaged area of key line 1 but added a few more, shorter offset 2D lines in-between and some partial cross-spreads. To further mitigate a 'data hole' in the cross-spreads from a receiver gap in line 1 an ad-hoc source-only line 9 was added. Unfortunately, the disturbed offset distribution would locally detriment the final imaged data quality.
A total of 2897 shots were recorded into a total of 2943 receivers, taking about 3 weeks in total.

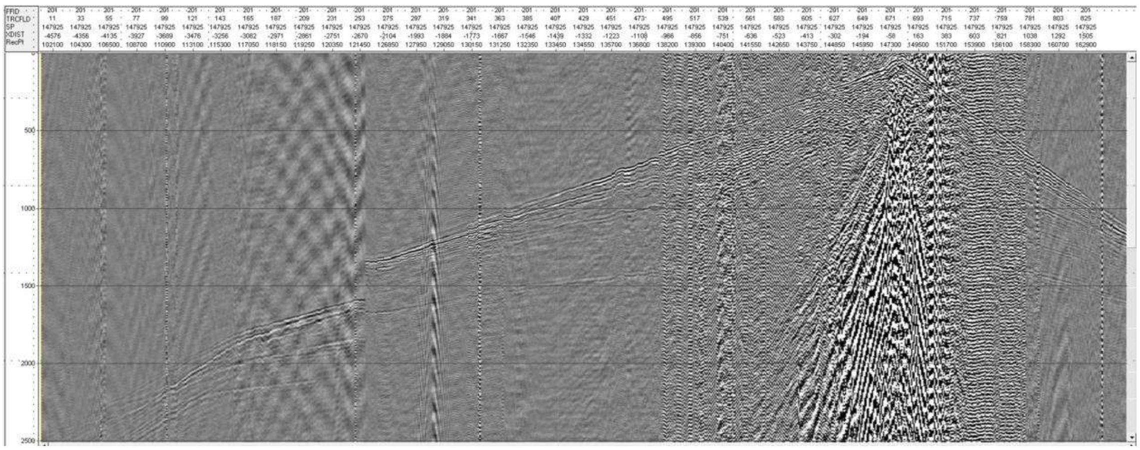

Figure 2. *Typical 2D shot record survey 1*

Figure 2 shows an example 'good' shot record along 2D line 1. Visible are faint first-breaks and some reflections, but overwhelmed by shot-generated low-velocity groundroll, traffic noise, and ambient noise from a/o agro-industrial greenhouses, data centres and wind turbines. The full data set was taken through a robust, full 3D surface-consistent processing sequence with refraction statics, LNA, FX denoise, s.c. decon, TVSW, s.c. residual statics, AGC. A satisfactory refraction statics solution was obtained by virtue of the smooth refractor velocity in this part of the Netherlands. The various 2D subsets were used for velocity analysis and residual statics and 2D Kirchhoff PreSTM. From the cross-spreads, after additional residual statics and 3DRNA, using the combined 2D velocity fields a 3D Kirchhoff PreSTM volume was obtained.

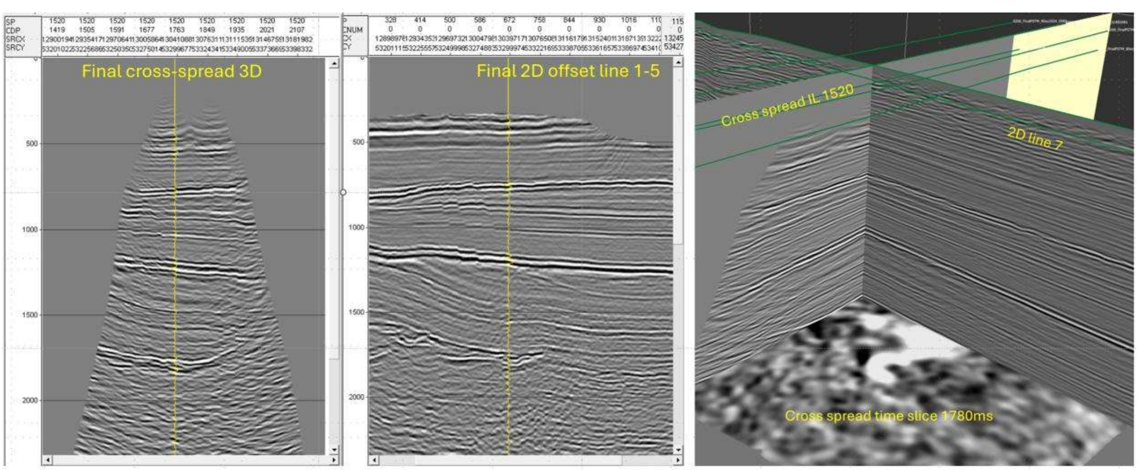

Figure 3. *(a) comparison of final PreSTM of cross-spread 3D volume and of 2D offset line 1-5*
(b) 'Chair' display of cross-spread 3D, 2D line 7 and time slice from cross-spread.

Figure 3 shows some 2D and 3D results which were surprisingly good, given the poor signal to noise ratio (S/N) of the raw data and the numerous acquisition irregularities. Obviously, the full lateral extent of the cross-spread is limited by the achievable S-R offset and migration aperture.
The acquired data provided a good insight into the top of the Rotliegendes and the extent of the presence of the Zechstein (which erodes to the east toward the Texel-IJsselmeer High (Duin et al. 2006). The Zechstein hardkick is clearly present in the data and can be used as a marker for the top Rotliegendes, however where it is not present interpretation gets hard. These new data also provide a better grasp on the presence of (small) faults (figure 4) and the 3D proved valuable to pinpoint the fault propagation. More faults appear than originally interpreted from the sparse vintage data. The operator now has a better understanding of the area and is looking for optimisation of the doublet.

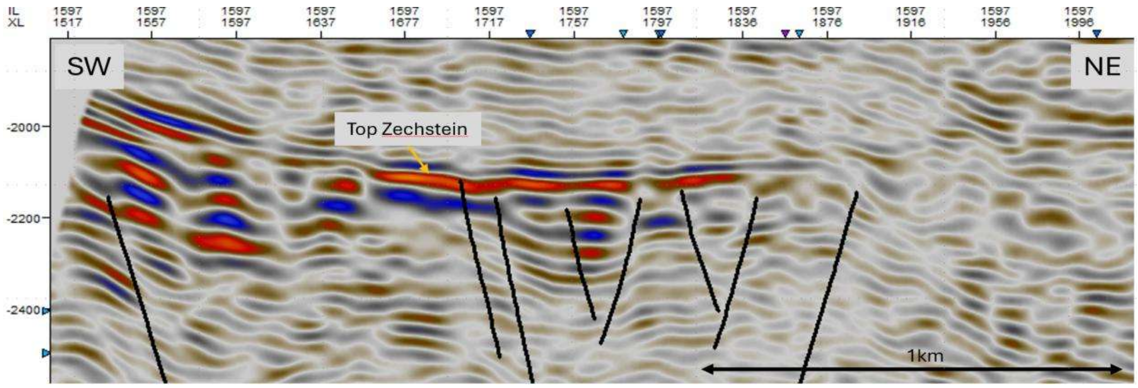

Figure 4. *Illustration of new fault interpretations on the MDM 3D volume (time-to-depth converted).*

Survey 2 (Andijk - ADK).

This survey (figure 5) comprised 2 parallel 2D lines with sources and receivers, plus 3 more or less orthogonal receiver-only lines, plus some shots at the ends of the R-only lines. The lines followed mainly existing roads and 'weaved' through the village and around obstacles. This layout resulted in two proper 2D lines 1 and 2, one 'offset 2D line' 1-2, and six partly overlapping cross-spreads. The key AOI is around the intersection of lines 1 and 4 where a doublet might be developed; furthermore, a tie to vintage 2D lines at the West was desired. A total of 2927 shots were recorded into 2708 receivers during a period of three weeks.

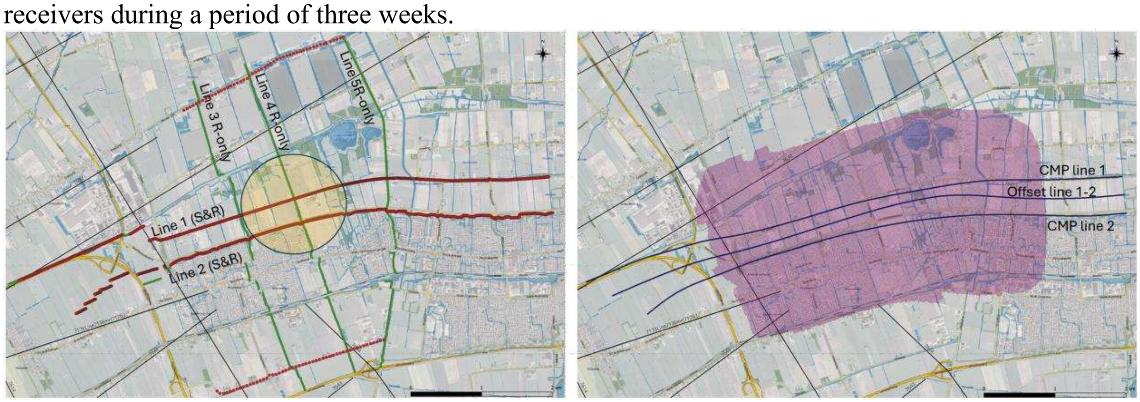

Figure 5 *– outline of survey 2 (ADK). Black lines are vintage 2D lines*

a) *Left: surface map of shots (red) and receivers (green, partly visible); AOI is indicated yellow*
b) *Right: subsurface coverage by three 2D CMP lines and combined 3D cross-spreads (pink).*

The data quality and processing challenges and flow were similar to that of survey 1 and will not be discussed here further.
The final PreSTM of 2D line 1 and 'offset 2D' line 1-2 are shown in figure 6 below. Note the adequate imaging of the Zechstein at 1500ms and of some Rotliegendes fault blocks underneath. Also note that the better S/N of the 'offset line' 1-2 with respect to the 'proper' 2D line 1, from its double multiplicity from two source lines and two receiver lines combined. The 3D shown in figure 7 below is somewhat noisier than the 2Ds but still provides a good time slice (indicating structural trends at 45^{o} angles to the 2D lines, helping to better assess the structure) and has perhaps a better focussing of

some faults. Some irregularities can be seen at the intersections of S-R lines (from near-offset groundroll) and at local receiver gaps. This 3D would have benefitted from partly denser R spacing (as in part of survey 1) and perhaps closer or extra receiver-only lines to improve overlap.

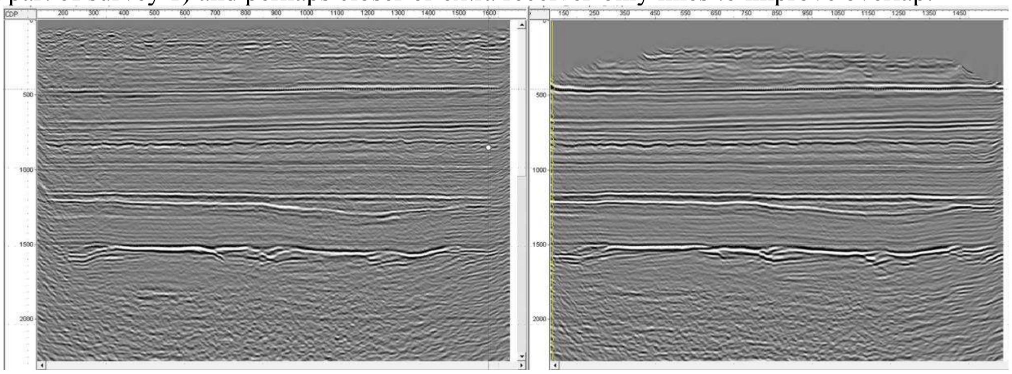

Figure 6. *Final PreSTM images for 2D line1 (left) and offset 2D line 1-2 (right). Objective is below the strong regional reflector at 1500ms.*

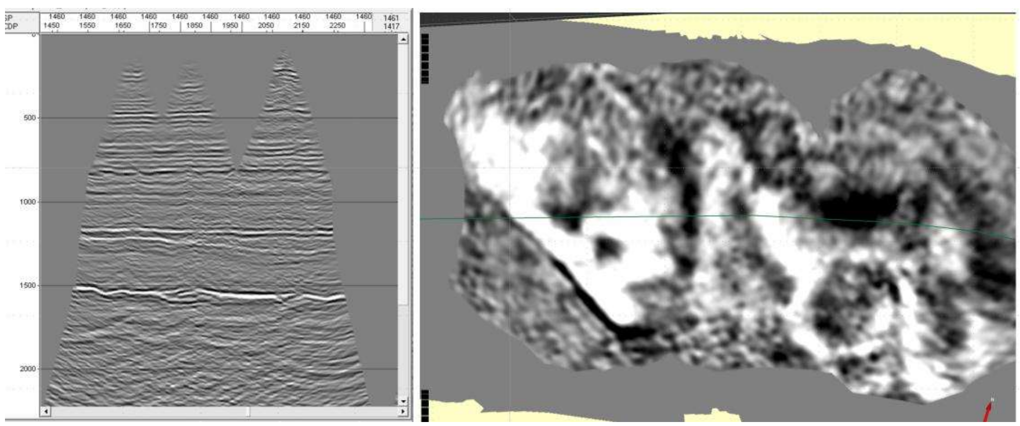

Figure 7. *3D cross-spread PreSTM results: inline (close to offset 2D line 1-2) and time slice at 1544ms showing the fault trends at 45 degrees to the 2D lines.*

The new data provide a better grasp on the propagation of faults which were already interpreted on the vintage 2D data. In Andijk, the reservoir is a bit shallower than in Middenmeer which does have a positive effect on the data, containing less noise and being easier to interpret. This resulted in better insight in the AIO subsurface, ensuring the operator is now able to properly assess if and where a new geothermal project can be started.

Conclusions. These two surveys have served their purpose of providing subsurface information that was not earlier available to the operator, in an affordable manner. More importantly, it demonstrated that for typical geothermal targets in the Netherlands down to about 2km depth small-scale seismic campaigns, combining 2D and cross-spread data, focussed on specific local target areas, can image relevant subsurface structures with light vibroseis. In urban and industrial settings where large-scale surveys with explosive sources are difficult, expensive or impossible the use of small vibratory sources allows a flexible and high-density acquisition at only a small percentage of development costs, with 2D and even low-fold 3D cross-spreads giving meaningful subsurface information.

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