Interreg North-West Europe DGE-ROLLOUT

Exploration Toolbox

Take the optimal steps to find opportunities in the subsurface to develop a DGE project

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Date 17 August 2022

Introduction

This exploration toolbox serves to help Deep Geothermal Energy project developers and local governments to find suitable exploration steps and decrease uncertainty about the subsurface in a cost-effective and time-effective way. It is part of a suite of deliverables from the DGE-Rollout programme. Some of the relevant related deliverables are described below.

Table 1: Related DGE Rollout Deliverables

Deliverable	Description
WP T1 D 1.3 Transnational harmonized depth and thickness map of deep geothermal potential in project area	Construction of a harmonized depth and thickness map (methodology and nomenclature), showing deep geothermal reservoirs in the project area. Level of knowledge and uncertainty will be taken into account.
WP T1 D 4.1 - Decision making tool	Online map tool to create a decision support system. This tool will be applied to identify investment hotspots, considering regional specificities & heterogeneities in parallel to investor profiles.
WP T2 D 2.1 - Decisions support chart and standardized decision support workflow checklist for the Upper Rhine Graben	Based on the advanced exploration toolbox a decision support chart and workflow check list for the Upper Rhine graben will be developed including the newest results of ongoing industrial and R&D projects in the area
WP T1 D 2.3 - Socio-economic potential mapping for DGE	Demand, infrastructure and land access are the main socio-economic factors influencing geothermal project assessment at surface and are presented through maps covering the target regions of NW-Europe.
WP T2 D 2.3 ThermoGIS Doublet Calculation – adaptation and application	Construction of a harmonized map (methodology and nomenclature) showing deep geothermal reservoirs in the project area (merging the results of D1.1.1, D 1.1.2 and D. 1.1.3). Level of knowledge and uncertainty will be taken into account.

Preparation

Some of the steps described in this document are cost, time and resource intensive. Before embarking on these they should be made part of an overall development plan. This should preferably be a plan supported by all public and private stakeholders and at local, regional and national level.

Scope

This document focuses on the exploration of the subsurface. It provides steps and tools to increase knowledge about the subsurface and decrease the risks of a geothermal project – financially as well as operationally.

Additional considerations

While it is not within the scope of this document, for development of a DGE-project the surface situation is at least as important. Within the DGE-Rollout project there is ample attention for this. In short, relating to the surface, it is important to get, in parallel with exploration, insight in at least the following things:

- **Demand for low emission heat –** Is there an expectation that consistent demand can be found to provide a steady basis for a DGE-project?
- **Public acceptance for geothermal energy –** To what extent will the local community positively perceive a geothermal energy project?
- **Support from local and regional governments –** Are local governments supportive of DGE, is it part of their policy, and are they willing to support a DGE-project, if not financially then at least politically?
- **Considerations and concerns around seismicity –** Seismicity risk can be a real and often a perceived risk for DGE-projects. It is important to know about the risk categorization for seismicity at an early stage and engage with local stakeholders on this topic.

While we have provided links to existing knowledge and data, local knowledge and interaction is always required to ensure local support. The general rule is that early engagement helps in the long run. Ideally this is at least a year before the final choice for the project location.

Main questions

As you will see, the exploration flow is focused on three main questions about a potential reservoir: thickness, depth, and permeability. These factors are important determinants for the expected power that can be produced from a reservoir.

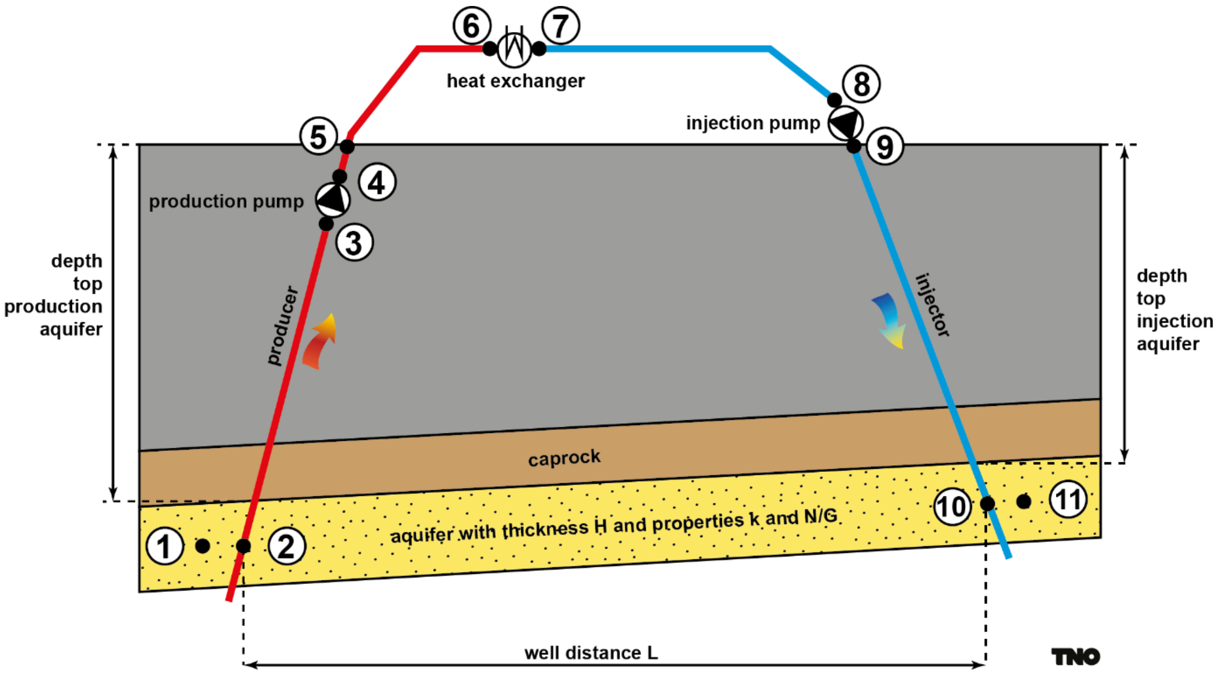


Figure 1: Deep Geothermal Doublet (Source: https://www.thermogis.nl/sites/default/files/2018-10/VanWees-NJG-91-4-13.pdf)

Figure 1 shows a schematic doublet. For detailed explanation we refer to the Thermogis manual.[1] For the purposes of this introduction we will focus on three elements that together are the most important determinants for the potential for DGE:

Thickness of the aquifer – The thickness of the aquifer is important because a thick aquifer allows for more flow of water. More flow of water means higher power.

Depth of the aquifer – Depth of the aquifer is important because temperature increases with depth. A higher temperature also means higher power, and more application possibilities.

Permeability of the aquifer – This is the extent to which water can flow through the rock that constitutes the aquifer. Together with thickness, this improves the flow of water and therefore the potential power output. It is important to be aware that there are distinct types of permeability:

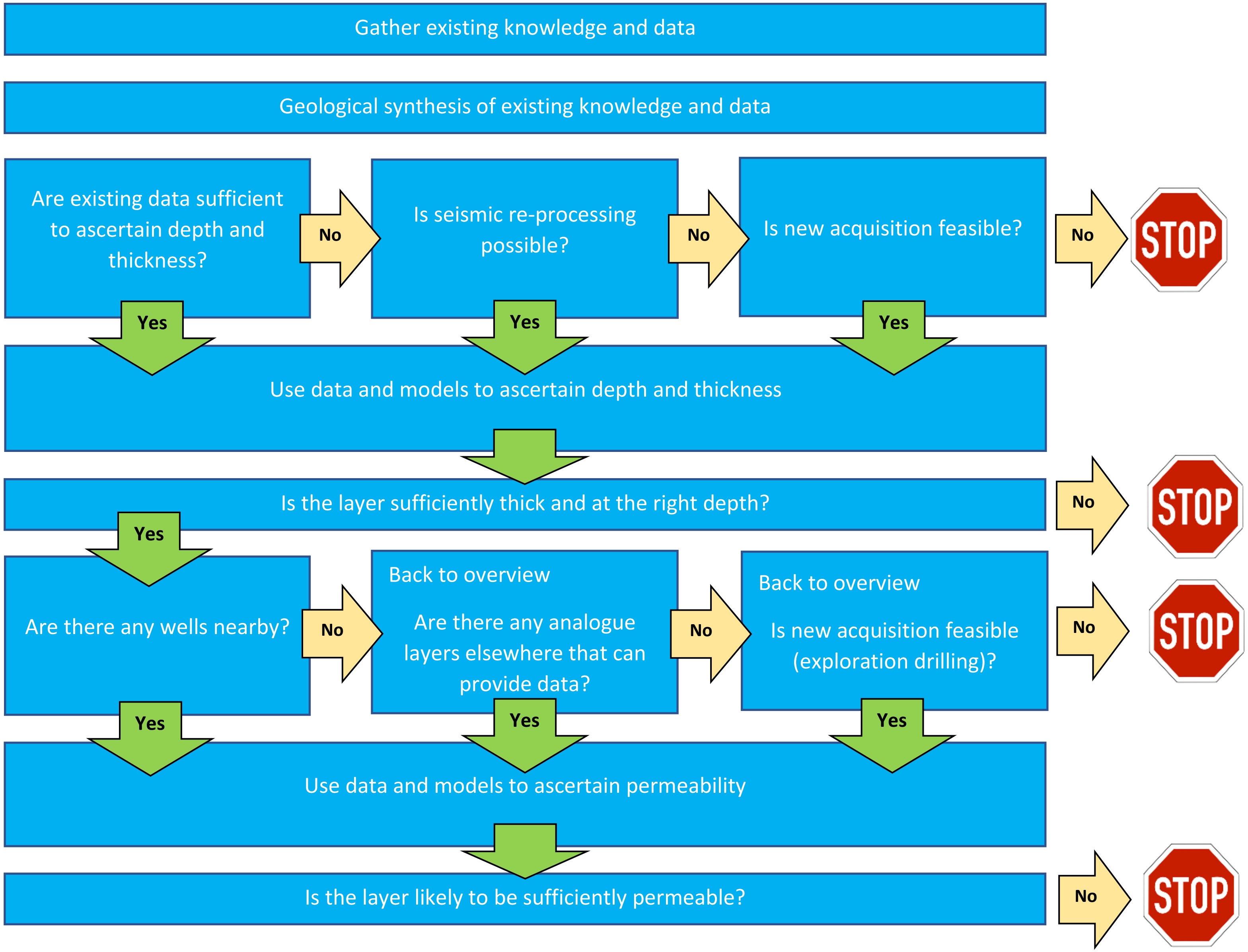
1) ***(Primary or) Matrix-permeability*** means the rock itself is permeable. This works in for example sandstone, where small pockets between the grains of sand - and connections between these pockets – allow water to flow through the rock.
2) ***Secondary permeability*** means that permeability is based on fractures or karst (rock that is partially dissolved), while the rock itself is not permeable.[2]

For both exploration as for seismicity these two types require different approaches. Therefore, it is important to be clear early in the exploration process what type of permeability is explored. The steps that are described in this Exploration Tool revolve around these three main factors: Thickness, depth, and permeability.

[1] https://www.thermogis.nl/sites/default/files/2018-10/VanWees-NJG-91-4-13.pdf

[2] ThermoGIS is mainly based on matrix permeability. For this type of permeability it is easier to predict the permeability of a layer based on a single data point – these layers are relatively homogeneous across larger areas. Karst and fractures are more dependent on local geological events, like earthquakes and inflow of rainwater during geological history.

Step approach



Reading Guide

How to read this document
This toolbox provides steps to move towards de-risking the subsurface. These steps are as follows:

1) Gathering existing knowledge and data
2) Geological synthesis of existing knowledge and data
3) Seismic acquisition
4) Borehole acquisition

Gather existing knowledge and data

The first step in the exploration for geothermal energy is to ensure that you are aware of all existing data about the subsurface. This can be data that was specifically gathered for the purpose of exploring for geothermal energy. In many cases however data have been gathered for other reasons, for example for oil or gas exploration or scientific reasons.

A good starting point are the national or regional Geological Surveys. They often have a legal obligation to collect data and make it publicly accessible. Also, it is recommendable to engage a geological consultant. They can also help with the next step, the geological synthesis of existing knowledge and data.

Geological synthesis of existing knowledge and data

A good and low-cost step is to first bring together the existing knowledge and data to ascertain the geothermal potential. This is best done on a broad, regional level, to ensure that it has value for a broad range of stakeholders, and that areas of interest and therefore further exploration can be identified in a larger area. A good synthesis will also help identify which questions remain unanswered, and what further steps – for example data-acquisition – can help answer these questions.

For a report like this it is recommended to engage a geological consultant.

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Are existing data sufficient to ascertain depth and thickness?

The first step to take is to find out what subsurface information is available in the area of interest. Exploration might have taken place before, either for geothermal energy or for other resources, like oil and gas. This information might exist in the form of:

- **Seismic data –** To gain insight in the position of subsurface layers, seismic data interprets how sound waves are reflected by the layer boundaries in the subsurface. This provides an intersecting two-dimensional profile of the subsurface. Geologists use this to ascertain whether certain layers are present, and if they are likely to be the kind of layers that are suitable for producing geothermal energy. This work would result in a geological model.
- **Well data –** There might be existing data from wells in the area. These give an indication about the type of rocks that are present at that location, at what depths and what thickness. The advantage of data from wells compared to seismic data is that the depth and thickness of layers can be determined quite precisely. The disadvantage is that it only provides data about a single point, not a line.
- **Geological models –** Often, seismic data have been consolidated into a geological model. This is an interpretation of the existing seismic data and well data. A geological model gives an estimation of the depth, thickness and a rough expectation of the characteristics of the layers present.

Existing information is not always easily located or easily accessible. In many cases it can be proprietary information. It requires careful searching and sometimes negotiating to get access. It is helpful to have a geologist who has a contact network to gather this information.

In an appendix you will find sources for this type of information.

Box 1: Seismic data

Gathering seismic data consists of two main steps:

Field data gathering – The first step is acquiring the primary data. This means that in the field 1) a 'source' will generate sound waves that are sent down into the subsurface, and 2) 'geophones' (microphones buried superficially in the topsoil) record the exact time at which these (scattered) reflections return to the surface.

Along a line of 10s to sometimes 100s of kms, sound waves are generated repeatedly. This can be done by a truck with a vibrating platform ('vibroseis') or by the detonation of small charges in a 10-40-meter-deep borehole.

While the sound waves are generated, geo-phones, which have been put in place along the same line prior to this, record the reflection exact time at which the reflections return at the surface.

These recordings are the so-called 'field data'.

Processing – The field data consists of many recordings of many geo-phones. Combining these recordings to compose an image of the subsurface layers is called 'processing'. This results in a best explanation of how the sounds waves reflected on layers in the subsurface. This requires significant computing power because of the large amount of data and computations that are required, and the enormous number of possible explanations that need to be analysed by the algorithms. With the increase in computing power, the quality of the seismic processing has also improved over the years.

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Is seismic re-processing possible?

If existing data is not sufficient to ascertain depth and thickness of layers that might be feasible for production of geothermal energy, it might be possible to use existing field data from earlier seismic acquisition, and 're-process' that data. This means that the original processing is repeated to enhance the quality of the seismic image. With the increased computing capacity of modern computers, this can result in considerable improvements compared to earlier results.

Advantages of re-processing (compared to acquiring new seismic data) are:

- **Costs –** Re-processing does not require new field data to be gathered. The work is mostly desk based. The costs are therefore up to thirty-five times lower than for the acquisition of new seismic data. In absolute terms the cost of re-processing is between 450 and 600 euro/km at the time of writing.[3]
- **Practicalities and speed –** Not having to acquire field data considerably reduces the amount of interaction with stakeholders and the commensurate run-time of a project. Re-processing can be carried out by contractors without local knowledge and without having to be on site. They are therefore easier to find.
- **Timeline –** Depending on the accessibility and the data quality, re-processing can be carried out within 1-2 years.

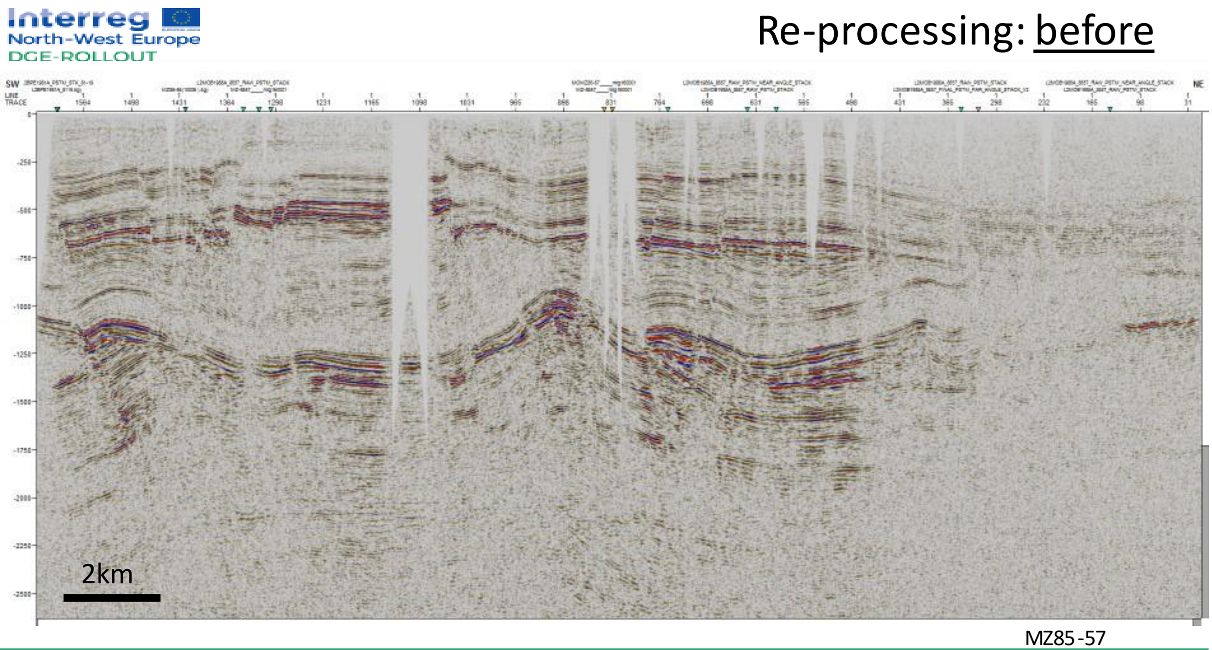

Figure 2: Re-processing image - before

[3] This does not include potential acquisition costs for non-public data. This can add a cost of up to €1000 euro per kilometre.

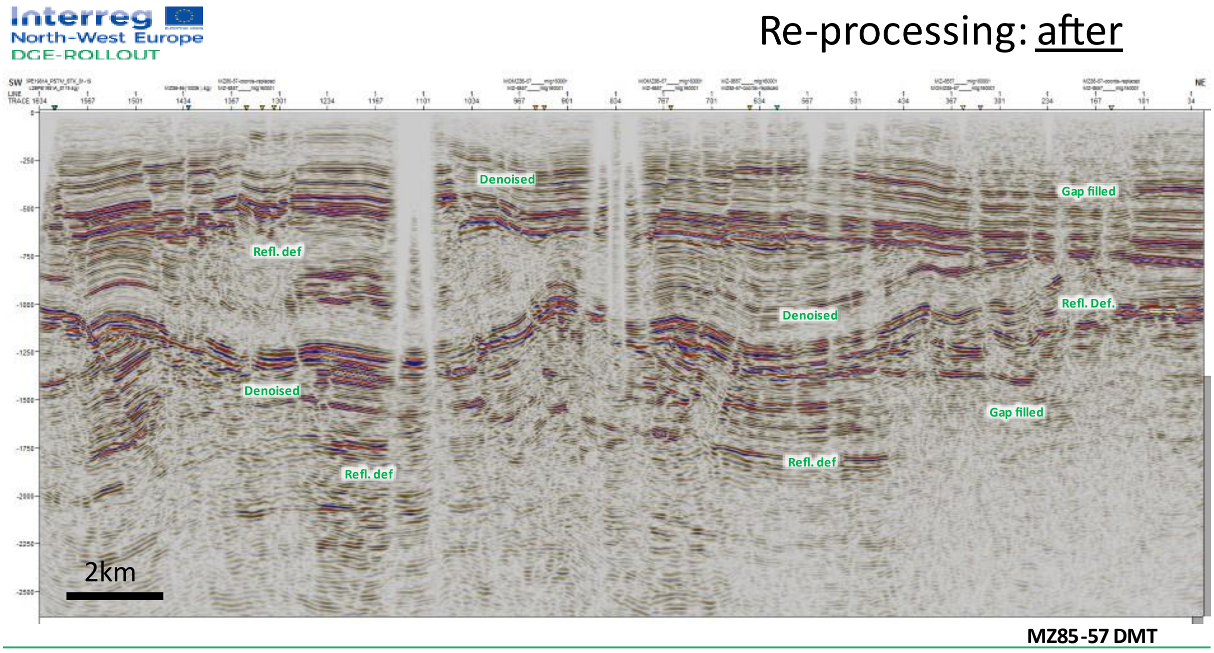

Figure 3: Re-processing image - after

Considerations around re-processing

The following must be considered related to re-processing activities.

- **Data must be legally accessible –** Seismic data is often owned by the companies that acquired them originally and is often not publicly available for use. To use these data, it might be required to reach an agreement with such companies. This might involve a payment.
- **Data must be available and complete –** If data is legally available, this does not mean it is available and complete. For a data set to be fit for re-processing, it needs to be complete and consistent. This might include different complementary data sets. In many cases the data is not complete and therefore does not qualify for re-processing.
- **Data sometimes needs to be digitalized or physically obtained from storage –** In some cases data is only available in specific physical locations. This means a physical search needs to be done, and sometimes the retrieved data first needs to be digitalized. This requires time and money.
- **Quality is not as good as new acquisition –** Even the best re-processing is not as good as acquiring new seismic data. This is because also the field equipment has improved through the years.

Who can help?

To make the right decisions the following resources might be needed:

- **Geophysicist –** A geophysicist can help to design a seismic survey in a way that will maximize the amount of information for the geologists. This relates amongst other things to the choice for the exact positioning of the lines to maximize the quality of the imaging. Also determining the best parameters (for example choice of geophones and source depth) are for a large part to be determined by geophysicists.
- **Contractor –** Generally, seismic acquisition needs to be outsourced to a specialized contractor. This contractor carries out the work in the field, like placing the geophones and sources and

possibly the work that is required for getting permits and permission to access land. Hiring a contractor often requires tendering procedures which can be time consuming.

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Is new acquisition feasible?

If re-processing is not possible, or does not provide the insights that are required, new acquisition can be considered. This requires more time, effort and financial resources, but allows for specific targets to be investigated based on the requirements of the project. Generally, it takes about 2-4 years to complete a campaign from the moment of inception.

Two potential sources

As discussed in Box 1, seismic data can be acquired with two main types of sources, 'vibroseis' and 'shothole'. These are further explained below.

Vibroseis

Vibroseis is a technology that uses heavy vibrating plates carried by trucks to create subsurface vibrations. In the picture below the vehicles are shown with the vibrating plates underneath.

The advantage of this technology is that progress can be relatively quick along a line, and the effort of creating the vibrations is low once the truck is available. This makes it a cost-efficient option. Costs are roughly 10-14k€ per kilometre.

A disadvantage of this technology is that the trucks are heavy. This means that – especially in wet conditions - they cannot go off-road as they will damage fields and might get stuck. This means they are road-bound. As buildings and infrastructure tend to be road-bound too, vibrating trucks are more often restricted in the strength of the vibrations they are allowed to create.

Figure 4: Vibration trucks in the field in Flanders – masks are related to COVID-19 measures in place at the time

Shothole

Shothole technology involves drilling a 10- to 40-meter-deep hole, in which a small explosive is placed. This explosive is subsequently detonated to act as a source for the sound waves needed for the seismic acquisition.

The advantage of shothole acquisition is that it does not require access by road. The hole is drilled by a tractor with a small drilling rig mounted to it. The geophones can be placed on foot. Another advantage is that the vibrations are initiated below any soft soil that might be near the surface. This makes that the vibrations can travel further down to the layers of interest providing a better insight in deeper layers as well.

A disadvantage of shothole acquisition is that the sound of explosions can cause local concerns. Also, as it does not follow roads, more access to private land is needed which requires effort, coordination and can endanger the continuity of the line if a land-user does not give, or worse, retracts their permission. Also, shothole acquisition is more expensive, between 18-22k€ per kilometre.

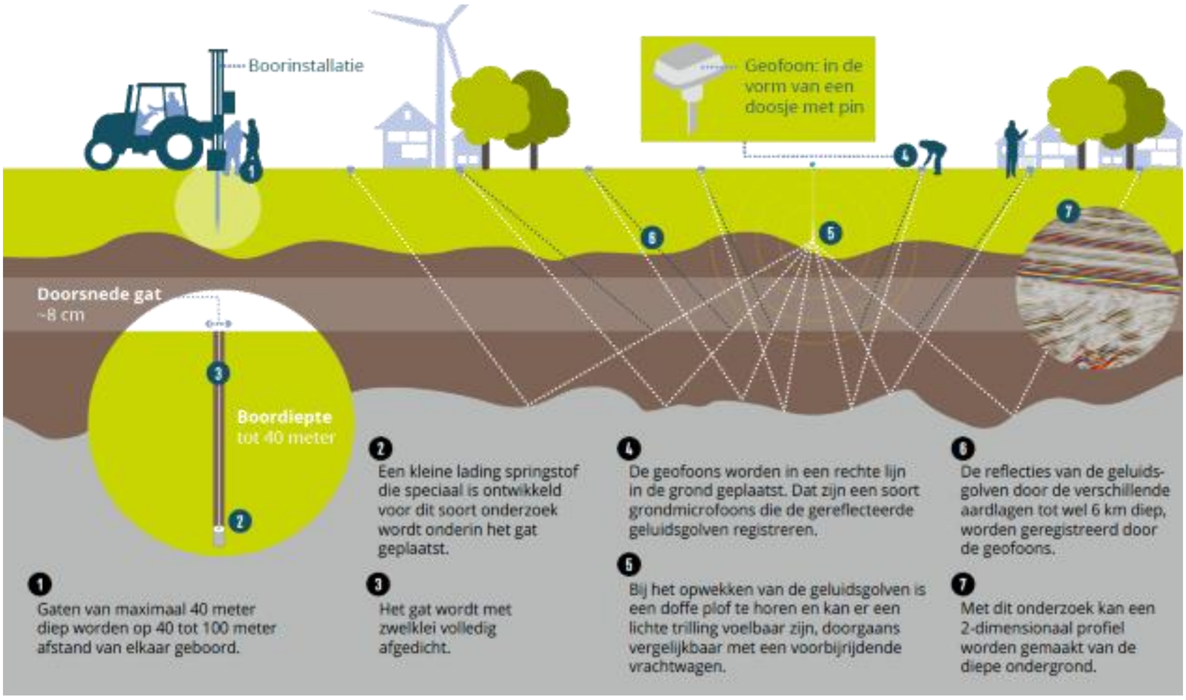

Figure 5: Shothole seismic acquisition

Survey design

Before considering a seismic survey, it is important to have a geological report summarizing what is known and what the remaining geological questions are that would need to be answered with a seismic survey. This is required to design a survey that is fit for purpose, choose the most appropriate technology and choose the exact parameters for the seismic survey. Examples of parameters are the distance between the geophones and the sources, and the frequency and strength of the vibrations.

This means engaging:

- An exploration geologist
- A geophysicist
- An advisor on the practicalities around seismic acquisition

Once the requirements are clear, a seismic contractor will be needed. Examples are:

DMT - https://www.dmt-group.com/services/exploration/geophysics.html

Rossingh - https://rossinghgeophysics.nl/

Geofyzika Torun https://www.geofizyka.pl/services/seismic-data-acquisition/

2D or 3D?

The above descriptions are about '2-Dimensional' (2D) seismic acquisition. That means it creates an image along a line, resulting in a two-dimensional image of the subsurface. It is also possible to carry out 3-Dimensional (3D) seismic acquisition. This will result in an image of a cube of the subsurface.

For a first step in regional exploration, 2D is the preferred choice. It allows a first insight in the depth and thickness of potential reservoirs. If a likely reservoir is identified, a 3D seismic survey helps to get a better view of the shape of the reservoir in all directions (not just in a plane). This will help to confirm the expected potential and is helpful and often even necessary for the well-design of an actual drilling. Furthermore, 3D seismic surveys are important for tracing fault zones at reservoir depths with high confidence.

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Use data and models to ascertain depth and thickness

Once all new data is gathered a geologist will be able to better indicate the depth and thickness of the target reservoirs. Also, it might be possible to link the reservoirs more accurately to any existing wells in the area. This might give a better indication of porosity and permeability.

To provide information about the deep subsurface of a specific project site the preparation of a 3D structural model may be necessary. Such a model (Fig. 1) usually includes all available data from deep wells and seismic measurements and relies on the extrapolation of surface geological and structural data (e.g., exposed fault boundaries and measurements for the strike and dip of geological formations). Besides the depth and thickness, geological structures such as salt domes, folds or faults are aimed to be illustrated as realistically as possible.

Geological models naturally contain several sources of uncertainty. These include the imprecision and quality of the data, the variety of possible interpretations (also due to incomplete knowledge), as well as inherited uncertainties from underlying source data (e.g., previous interpretations).

The 3D structural model is the base for the preparation of a reservoir model, which intends to evaluate the long-term productivity (e.g. production rates), distancing and dimensioning of geothermal wells in the aquifer, and will be a basis for mining law approval processes.

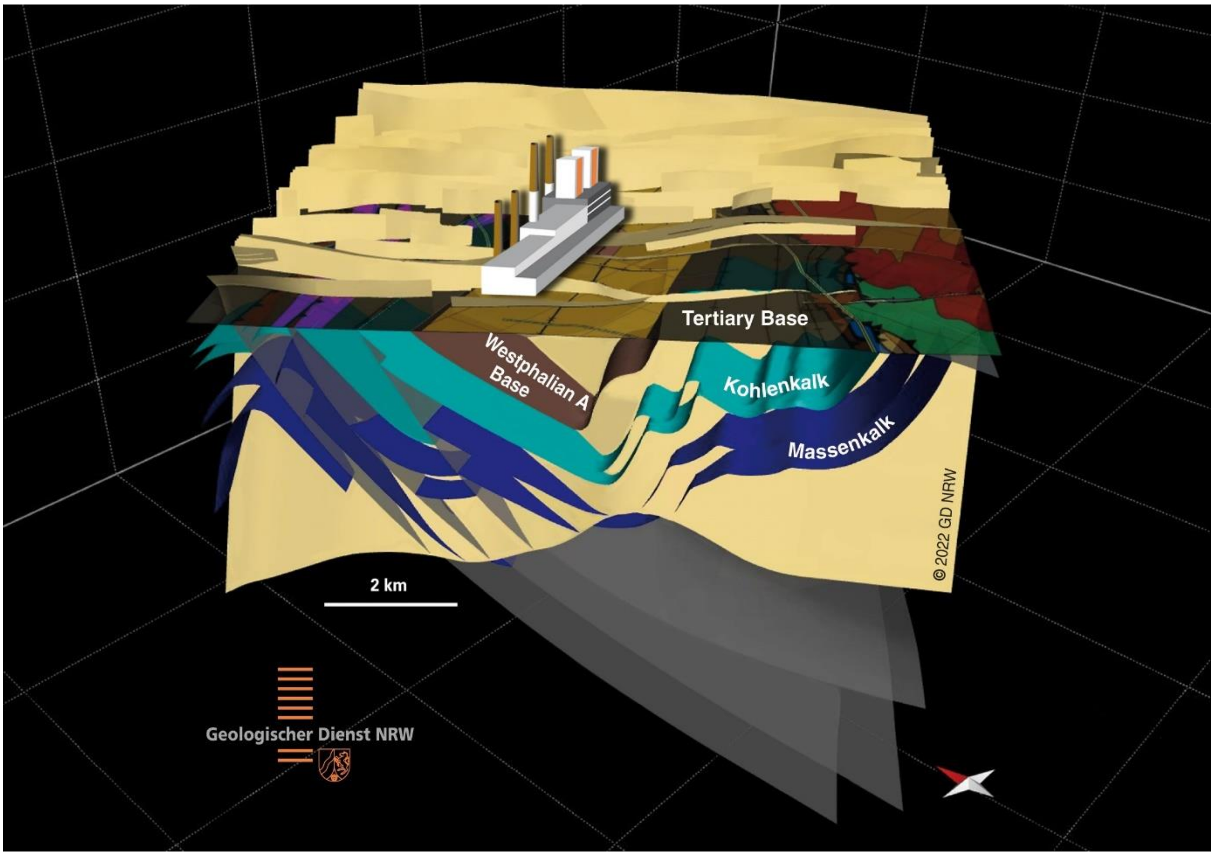

Figure 6: 3D structural model of the subsurface of the Weisweiler power plant, including the tops and bases of the Kohlenkalk and Massenkalk potential geothermal reservoirs. Tertiary faults in yellow, Variscan thrust faults in grey.

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Is the layer sufficiently thick and at the right depth?

If the layer is deemed to be sufficiently thick and deep, and there is sufficient expectation of permeability, the next step of exploration can be embarked on.

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Are there any wells nearby?

If it seems likely there is a layer of sufficient depth and thickness, it is necessary to find out whether that layer consists of rock that is sufficiently permeable to allow the necessary flow and commensurate geothermal power.

The first step in this search is to find out whether any data from wells in the same or a similar layer are available. These data can help to determine the expected permeability of the layer. Like with seismic data, this data is not always publicly available.

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Are there any analogue layers elsewhere that can provide data?

If data from the same layer is not available, it might help to find data from a similar layer. These 'analogues can provide general information about the layer in question. The advantage is that there is no need for geographical proximity and therefore the likeliness of finding data is higher. The disadvantage is that the prediction value of the data is lower.

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Is new acquisition feasible (exploration drilling)?

If insufficient data is available, the only way to find out about permeability is to drill a new well. This way it can be determined without question that the reservoir is there, it is located at the expected depth and that it has the required permeability.

Drilling a new well is a significant investment. Particularly in areas where wells are scarce, there is uncertainty that a feasible reservoir will be found. However, if placed strategically, such a first well can have exploration value for a much larger area of tens of kilometres from the site itself. If a good reservoir is found, the subsequent wells carry a far lower risk, accelerating the roll-out of geothermal energy.

Box 2: Exploration and production wells

There are several types of wells. Without suggesting that there is a strict definition, these are some of them:

Exploration well – Strictly speaking, an exploration well is only drilled to gather data about the subsurface. It intends to prove or disprove the occurrence of a reservoir at a certain location. Typically, an exploration well is drilled in an area where little is known about the subsurface. An exploration well is designed to be abandoned within about a year from drilling. It is not intended to be used for production, and often this is technically and legally not possible.

Production well – A production well is drilled to produce geothermal energy. A geothermal doublet consists of two (sometimes three) of these wells. The wells are designed to last up to 30 years. It should be noted that often the first well of a doublet also has some elements of an exploration drilling. While the expectation of finding an economically feasible reservoir is high, this can only be fully confirmed with the first drilling completed.

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Other technologies

There are other studies and assessments that might be helpful for ascertaining the potential and planning for DGE. These are:

- **Geothermal gradient –** While the general rule is that deeper is hotter, regional differences in the relation between depth and temperature exist. It can be worth investigating whether locally these may deviate from the standard gradient.

- **Check hydrocarbons –** It is important to be aware of the likeliness of any hydrocarbons in the targeted reservoir or above them. Hydrocarbons are a risk for operations – both for safety and environmental reasons. When drilling, these hazards must be taken into account.
- **Seismicity check –** Any issues around induced or natural seismicity must be identified and flagged early. For safety reasons and public support these risks must be known to the developer and the public, and any necessary measures must be taken to ensure the chance of seismicity and the possible impact of it is minimized.
- **Gravimetric-Magnetic methods –** With these methods the subsurface structure is modelled using gravimetric and magnetic data. This has limited added value, as the outcome of such a modelling is highly circular – it depends heavily on the input, which in its turn is dependent on the expected outcome. These techniques only add value if no (good) seismic data is available.

Use data and models to ascertain permeability

The available data needs to be combined in a geological model that results in an assessment of the permeability of a reservoir and – by combining it with depth and thickness – the expected production capacity of a reservoir. This can be the basis for a business case.

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Is the layer likely to be sufficiently permeable?

Whether a layer is sufficiently permeable is a question that can only be answered based on the business case. The outcome of the business case depends on many aspects not related to the subsurface, such as: willingness to pay for sustainable heat, subsidies, required return on investment, and design of the well.

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Information sources

Dutch Geological Survey - https://www.nlog.nl/en/welcome-nlog

Geologischer Dienst NRW - https://www.gd.nrw.de/ge_dk.htm

Geological Survey of Belgium - https://gsb.naturalsciences.be/

French Geological Survey - https://www.brgm.fr/en/challenges/geology-knowledge-subsurface

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