Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

The GeoTief EXPLORE 3D Project – an Innovative Deep Geothermal Exploration for a Future Sustainable Heat Supply for the City of Vienna

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Keywords: 2D seismic, 3D seismic, Vienna Basin, geothermal heat, hydrothermal systems

ABSTRACT

The Southern Vienna Basin possesses up to 60 % of Austria's estimated resource of deep geothermal energy potential. In addition, the metropolitan area of Vienna has one of the largest district heating (DH) systems in Europe, which is highly applicable for the distribution of geothermal energy (hydrothermal systems) and thus may contribute to the reduction of greenhouse gas emissions in a large scale. Therefore, geothermal energy could play a key role in the future energy supply for Austria's largest city, the Vienna metropolitan area.

The potential geothermal reservoirs, underneath the city of Vienna and its surroundings, comprise Neogene basin sediments and the complex and steep dipping nappes of Triassic carbonates at depths of approximately 2,500 – 6,500 m. Although the Triassic basement of the Vienna Basin has been target of extensive exploration by the hydrocarbon industry, the knowledge about the geothermal reservoir properties is poor.

The future development of this renewable heat source depends on efficient exploration and implementation concepts and methods considering technical, economic and regulatory conditions. As a result, several experts from various Austrian universities, research institutions and companies are working together in the research project "GeoTief Wien". The project's aim is to develop and implement extensive concepts and methods for the exploration and utilization of deep geothermal energy in the Southern Vienna Basin resulting in a stepwise exploitation of all reservoirs. Furthermore, establishing the City of Vienna as a model region for a sustainable and economic heat supply based on geothermal energy should lead to an increasing use of geothermal energy even throughout Austria and neighbouring countries.

As a first step, the project aimed to expand the knowledge about the geothermal reservoirs by collecting, evaluating and preparing geological/geophysical and seismic data. The project team already carried out an innovative geophysical exploration concept, including 2D and 3D seismic acquisition, partly in the urban area of Vienna.

1. INTRODUCTION

There is a large technically usable potential for deep geothermal energy (hydrothermal systems) in Austria, which is up to 1,200 MW_{th} (Könighofer et al., 2014), but the resource is still very underdeveloped. There are currently 10 geothermal plants for heat production in operation, which have a total thermal capacity of 75 MW_{th}. This means that about 95% of the technical potential in Austria is still unused. In the long term, geothermal energy could provide up to 40% of heat demand (about 9 TWh) of Austrian district heating (DH) systems, and make a significant contribution to the reduction of greenhouse gas emissions.

The region of Vienna (see Figure 1) possesses up to 60% of the Austrian resource, which corresponds to an estimated economically usable amount of about 450 MWth. In addition, a part of the heat demand in the metropolitan area of Vienna is covered by one of the largest DH-systems in Europe, with about 1,300 km of pipe length. For this reason, the use of geothermal energy is able to play a key role in the future energy supply of the Vienna metropolitan area and is also mentioned in the most important city development plans.

By exploiting this potential, the aim is to cover a major part of future renewable energy share in the DH-network in Vienna based on deep geothermal energy. This local, renewable and baseload heat source will increase the heat supply security of the city of Vienna, reduce greenhouse gas emissions and at the same time greatly improve local air quality.

The potential geothermal reservoirs comprise Neogene basin sediments and the complex and steep dipping nappes of Triassic carbonates of the Northern Calcareous Alps in depths of 2,500 – 6,500 m. Although the hydrocarbon industry investigated both units, the knowledge about the geothermal reservoir properties is poor, especially for the carbonate basement that represents the more promising reservoir. However, drilling for hydrocarbons in the 1970's and 1980's discovered the Triassic hydrothermal reservoirs accidentally and was not pursued further, as geothermal use was not considered at that time. Based on these boreholes, the geothermal exploration well "Essling Th1", completed in 2012, was the first attempt to develop the geothermal potential in the Vienna Basin. The well was drilled solely based on a conceptual geological model without integration of seismic reflection data, and did not reach the targeted reservoir. Nevertheless, the well showed that present geological models do not agree with the encountered geological structures and brought a significant insight into the deep complex geological structures of the basement. For the exploitation of these reservoirs, an extensive knowledge about their structure is essential and requires the investigation of the whole area. Therefore, the research project "GeoTief Wien" was initiated in order to analyse those potential reservoirs. The innovative seismic approach of the project lays the foundation to develop a workflow for the assessment, exploration and exploitation of the geothermal potential.

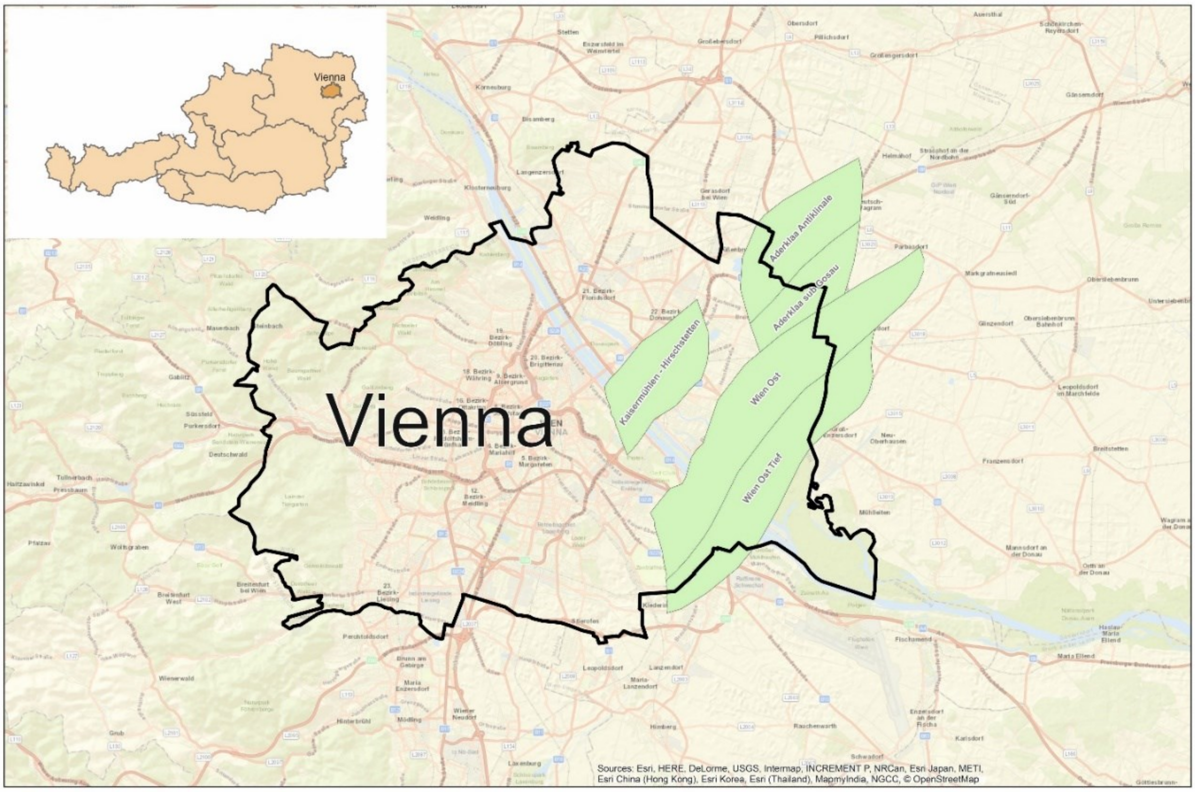

Figure 1: The region of Vienna possesses up to 60% of the Austrian resource in depths of 2,500 – 6,500 m beneath the ground level. The green areas represent the geothermal targets.

2. RESEARCH PROJECT "GEOTIEF WIEN" - METHODS

The "GeoTief Wien" research project is investigating the potential of deep geothermal energy in the form of a large-scale, comprehensive potential and feasibility study. An interdisciplinary team of experts from various Austrian universities, research institutions and companies in the fields of geology, geophysics, seismology, reservoir-, drilling- and production engineering, and energy provider are working together. In addition, the local oil and gas company, OMV Austria Exploration and Production GmbH, is providing data and their exploration knowledge to the project team. OMV has been active in the Vienna Basin for more than 60 years.

The main objective of the research project is the systematic development of deep geothermal energy in the Vienna region, making it a long-term heat source option for the existing DH-system. This requires a new development approach, which focuses on the efficiency-optimized and sustainable utilization of geothermal energy for the whole project area, instead of the merely cost-minimized and thus risky development of individual projects.

The first step of the project was to expand the knowledge about the structure and position of geothermal reservoirs in the Vienna area by collecting, evaluating and processing geophysical and seismic data. Therefore, an innovative geophysical exploration concept, including 2D and 3D seismic acquisition, has been developed and carried out (see also chapter 3). In addition, existing geological and geophysical data as well as data from existing wells (mainly from the hydrocarbon industry) were collected, analysed and compiled. In combination with further analyses (determination of geophysical rock parameters, geo-mechanical evaluation of fractures, etc.) a basis for the subsequent geological modelling and reservoir simulation (thermal-hydraulic combined with geo-mechanical simulation) is being created. Investigations and elaborations will also lead to a comprehensive 3D geo-mechanical model, which will provide essential insights for the estimation of associated seismicity.

Subsequently, the risk analysis rests on a holistic approach to determine factors that influence the future successful development and utilization of geothermal energy in the Vienna Basin. This analysis contains the determination and evaluation of geological, technical and economic potential risks, starting with the assessment of associated seismicity, the probability of success, effects of the chemical composition of the thermal water on plant components and operation, up to the integration of the geothermal heat through a multitude of plants into the district heating network of Vienna.

An important aspect in this context is that the studies are carried out not only for a single project area, but also for the entire potential area with several different reservoirs. The ultimate goal of this concept is to develop a large number of possible drilling projects respectively geothermal plants, evaluated and ranked in terms of their geological, technical and economic feasibility. Putting all these aspects together will lead to a roadmap for the best possible development and use of deep geothermal energy for the entire region.

Accompanying this, comprehensive data management is carried out to transparently and clearly manage the enormous amount of diverse (existing and newly generated) data. The centralized data storage and visualization tools provide easy access to the geological information and data for the project partners. This will become public domain in the future.

Furthermore, the combination of geothermal exploration and established hydrocarbon industry workflows will lead to new scientific concepts as well as to the development of workflows and methods transferable to other geothermal potential areas in Austria.

An additional project goal is the improvement of the framework conditions for deep geothermal energy in Austria by interacting with stakeholders and decision-makers. Concepts for improving the general environment for the exploration and use of deep geothermal energy in Austria will be developed. These measures will lead to risk reductions for companies and energy suppliers with the aim to enable a significant expansion of geothermal energy in Austria in the long term.

Overall ”GeoTief Wien” will establish the city of Vienna as a model region for a sustainable and economically viable heat supply based on geothermal energy. The research results will also enable the expansion of geothermal energy in the Southern Vienna basin surrounding Vienna and enhance further geothermal investigations and implementations in Austria and neighbouring countries.

3. GEOPHYSICAL EXPLORATION

In general, the "GeoTief Wien" exploration strategy includes the reprocessing of existing 2D seismic sections from the oil industry and acquisition of new 2D and 3D seismic data in the project area. The main geothermal targets within the Vienna Basin are Triassic carbonate rocks comprising the pre-Neogene basement in depths of 3,000 – 6,500 m. Although the seismic data were collected to focus on the Triassic carbonates, the deep Neogen basin fill, including the geothermally very promising Aderklaaer Conglomerate (2,500 – 3,000 m), was imaged as well.

There are two challenges when imaging the Triassic targets with the seismic to develop drilling targets. First, the carbonates are very deep between 3,000 m to 6,500 m meters. Second is the complex geological structure due to deformations during the Alpine orogeny. The geological profile in Figure 2 represents the state of the art concerning the basement of the Vienna basin.

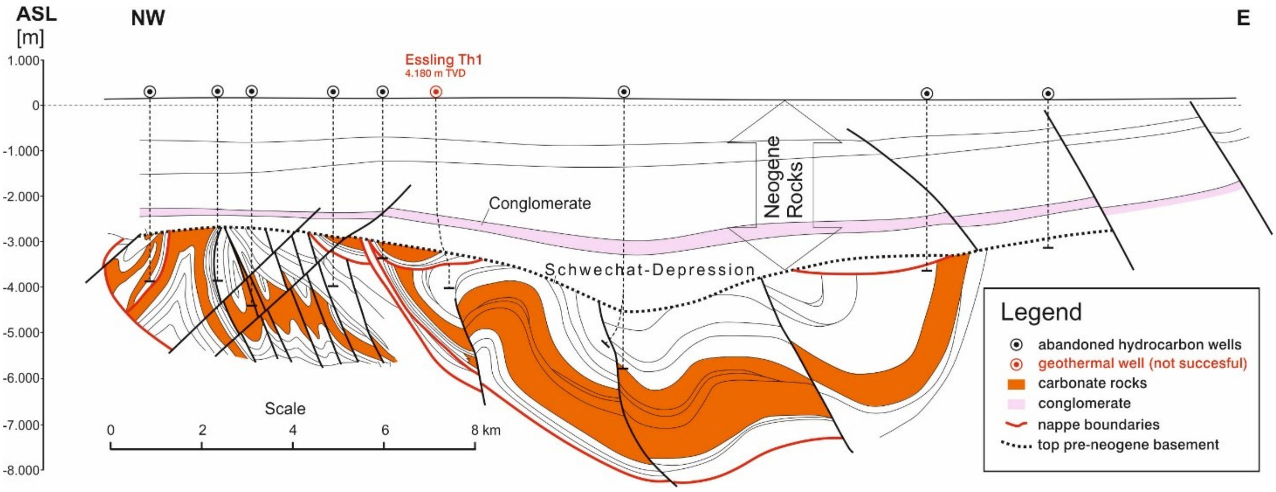

Figure 2: The geological profile shows the main geothermal targets with the very complexly deformed sediments in orange. These targets are Triassic carbonate rocks at depths of 3,000 m to 6,500 m. A second target – Neogene conglomerates - at a shallower depth of about 2500 m to 3000 m are indicated in pink colour (modified after Elster et al., 2016).

Existing 2D seismic sections from the 1970s and 80s are generally of poor quality because of a low seismic fold and low vertical resolution. On the other hand, the target depths of these seismic sections were designed for reservoirs within the Neogen sediments (approximately 2,000 – 3,000 m), whereas in the current geothermal project, the target reservoirs are located at depths of 2,500 – 6,500 m. However, the reprocessed seismic sections can be used for building simplified geological models of the Neogene sediments and later on for planning of new seismic campaigns.

The first "GeoTief Wien" seismic campaign included two 2D seismic sections. One was collected along the geological section of figure 2. The second section was collected perpendicular to the first, which represents the strike direction of the Alpine compressional tectonic regime. The experimental design of this survey was focused on the basement of the Vienna Basin using P-wave imaging. Additionally, shear waves were recorded in order to estimate the Vp/Vs ratio of the Neogene sediments as a basis for geomechanical modelling. As currently no shear wave vibrators are available in Europe, standard vertical vibrators were used as sources. In order to generate S-waves directly a special short-term experiment (SHOVER method, Edelmann, 1981, Dankbaar, 1982) was included. Single-receiver recording was made using small group intervals of 10 m with 3-component MEMS. This was supported by using a conventional recording with larger group intervals of 30-50 m. The use of MEMS sensors in the exploration is increasing and presently may account for about 10-15% of land surveys. Single MEMS receivers, which are easier to handle by a field crew, yield similar data quality as analogue geophone groups (Tellier and Laine, 2017). MEMS receivers are very broadband sensitive, down to 0 Hz. Full use of these low frequencies would be possible with impulsive sources. However, in urban settings this may not be possible, even with very low frequency sweeps, because of the risk of damage to buildings.

Raw records clearly show that standard sources such as vertical vibrators emit not only P-waves but also S-waves at substantial energy levels. In contrast to strong refracted S-waves (first breaks), the raw records yielded no clear reflections. Only stacking by CDP processing enhanced some reflections within the upper 2 km of the layered basin. For this depth, reasonable Vp/Vs ratios could be obtained.

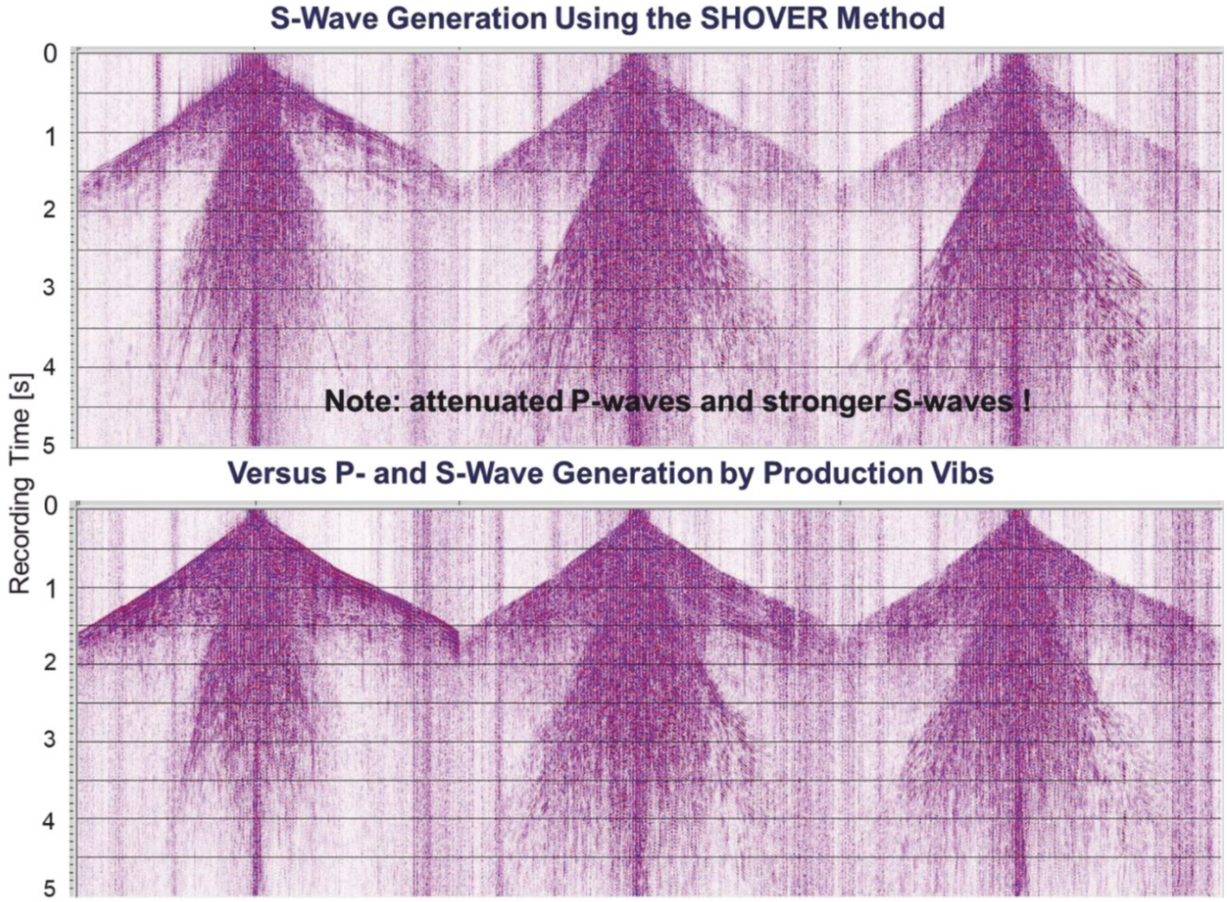

Figure 3: Top: Typical SHOVER record (components Z, HII, Hcrossline, from left to right) Bottom: Comparison with a production record from the same position. Note that P-wave first arrivals of SHOVER record are attenuated and S-waves are strengthened, particularly on the Hcrossline-component (right side). Amplitudes are true observed (no scaling).

Care is necessary to distinguish between directly generated vertically polarized S-waves (SV) and (incident P-wave to SV-wave) waves converted at target horizons. The lack of clear deeper reflections may be due to the particular radiation pattern for SV-waves, which shows maximum radiation at about 30-40°, or to the lack of impedance contrasts at fluid-saturated layers.

The SHOVER method was applied with promising results. It produced strong horizontally polarized S-waves. However, the interaction of sweeps with opposite polarity required difficult manoeuvring of the side-by-side vibrators. Often there was not enough space on roads or tracks for this necessary movement. In this experiment, the only available section was on a ploughed agricultural field. In the sense of seismic energy, coupling this area was not the best choice. A complete survey using this method, in addition to a conventional survey would be expensive. It is recommended to use this method only for focusing on specific targets at depth. Then it could be advantageously applied for vertical seismic profiling (VSP), since only one source location would be necessary.

Based on the 2D seismic sections and seismic forward modelling with the focus on the complex structure of the basement units, the acquisition pattern for a new a 3D seismic was designed by OMV. The challenge of the 3D seismic was to image the steep tectonic boundaries dipping southeast in a depth of 3,000 – 6,500 m. The main result of the seismic forward modelling was a minimum offset of 6,000 m in both strike and dip direction of the target rocks. Due to the steeply dipping reservoir rocks in southeastern direction source offsets up to 14 km were recommended, whereas in northwestern direction only a short offset is needed. Because of the modelled large offsets in southeastern direction needed for the illumination of the complex tectonic situation at depth, the acquisition area increased from the originally planned 90 km² to more than 125 km².

The acquisition design study had to fulfil certain requirements. Due to the complexity and depth of the target horizons, it was clear from the beginning, that conventional approaches (using standard formulas and rules of thumb in combination with standard seismic planning tools) would not be sufficient to optimize the acquisition parameters. At the same time a synthetic modelling and processing of full waveform data was also not feasible from a computational point of view. Therefore, a sophisticated seismic forward modelling was deemed necessary.

The NORSAR modelling package was identified as a suitable compromise. It features a powerful seismic modelling tool that allows for complex overturned structures and allows for the derivation of imaging and coverage attributes in a three-dimensional way along the target horizons of the model. Offset dependent hit density maps and simulated time migration amplitude maps were generated for several geometry options. A possible option to derive a simplified PSDM response was not used due to very high computer-time requirements.

The first step was the creation of a 3D structural model, which is a reasonable approximation to reality (see Figure 4). Interpreted surfaces from the software PETREL were imported and additional features of the model were generated directly in the NORSAR package. Then different acquisition designs were generated using the software OMNI and exported into NORSAR. The third step was to calculate several imaging attributes for different survey designs, different azimuths and offset classes. Hit density maps, simulated migration amplitudes and other attributes were calculated as functions of azimuth and offset. Thereby it was possible to identify the strong and weak points of each design and evaluate the optimum value for the maximum offset required to illuminate properly the deep target horizons. It was also possible to evaluate the sensitivity of any specific design properly to model variations. The final step was the suggestion of the most ideal design parameters and optimal acquisition directions.

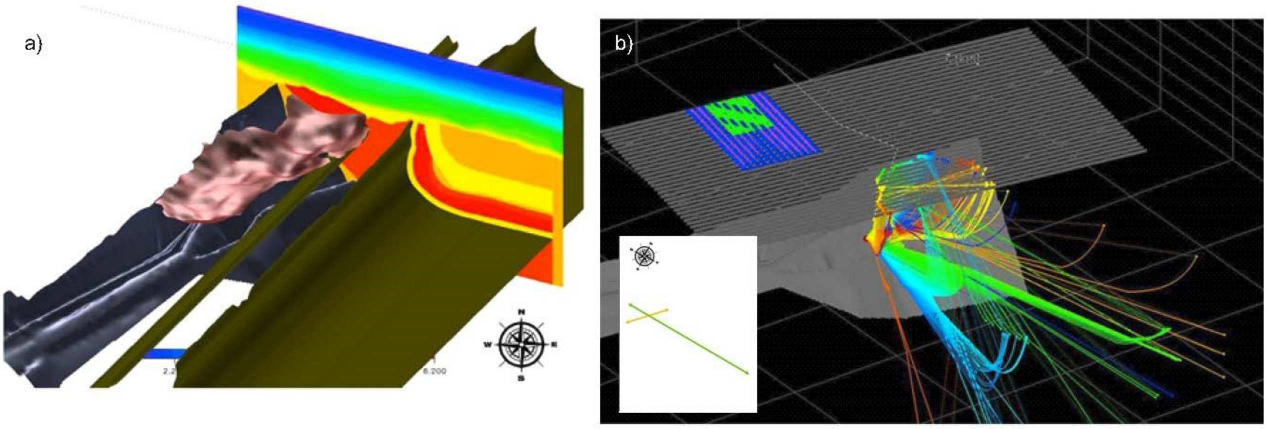

Figure 4: a) Structural model of the Vienna Basin with the key horizons and the pre-Neogene target rocks (red and yellow colour). Notice the steep dipping rocks and nappe boundaries at the lower positions in depth of about 6,000 m. b) Ray tracing for the target zones were modelled on the structural model. Significantly shorter offsets needed along strike (orange arrow) compared to across strike (green arrow) direction.

As a result of the seismic forward modelling process an area of about 125 km² should be recorded. In a first project phase, after the unsuccessful well Essling Th1 an old 3D seismic survey (Seyring 3D) was additionally used to build the initial structural model. This seismic survey covers the northern part of the area of interest only. The unsuccessful geothermal well Essling Th1 is situated at the boundary of Seyring 3D and therefore it was not possible to integrate this well information reliably (see Figure 5).

The “GeoTief Wien” geothermal seismic survey „3D-Donaustadt” was part of Europe´s largest onshore seismic campaign (total area more than 1500 km²) “3D-Schönkirchen-Donaustadt”, carried out together with OMV in the winter season 2018/2019. Approximately 25% of the GeoTief Wien seismic layout covers densely built areas. Additionally, areas with big nature reserves (e.g. Danube Floodplains National Park) with strict time limitations were part of the survey. This would have made the survey very time-consuming and cost-intensive with conventional seismic methods. Therefore, an advanced seismic acquisition technique with a modern wireless recording system together with slip-sweep mode was used. The seismic contractor DMT used a wireless recording system with 9,000 live channels per patch and more than 30,000 active channels per swath. Working hours were programmed to start at 5:45 am and stop at 7:00 pm UTC time. The receiver and source distance were designed with 40 m at 400 m line distance. At the far offset, receiver stations with 24 geophones per string were used at each position. In the centre part of the seismic survey, 12 geophones per string were used. This resulted in more than 100,000 installed receiver stations for the entire seismic survey and 22,329 stations of it for the part “3D-Donaustadt”.

A source of up to 4 fleets of 3 vibrators, each with a peak force 61,800 lbs, were used parallel in a slip-sweep mode with a signal band width of 2 – 90 Hz, 64 sec. In denser residential areas, the sweep was changed to 8 – 90 Hz, 64 sec. On narrow tracks one fleet of three small vibrators, each peak force 36,000 lbs with a signal bandwidth of 5-90 Hz, 64 sec. was used. In total, 105,703 VPs (vibration points) have been recorded within 5 months. 15,766 of those were part of the geothermal survey (125 km² source area related) and have been recorded over a period of 38 days in the 3D project averaging 414 VPs per day, whereas the average over the whole project was 800 VPs per day. The theoretical source and receiver lines of “3D-Donaustadt” are shown in Figure 6.

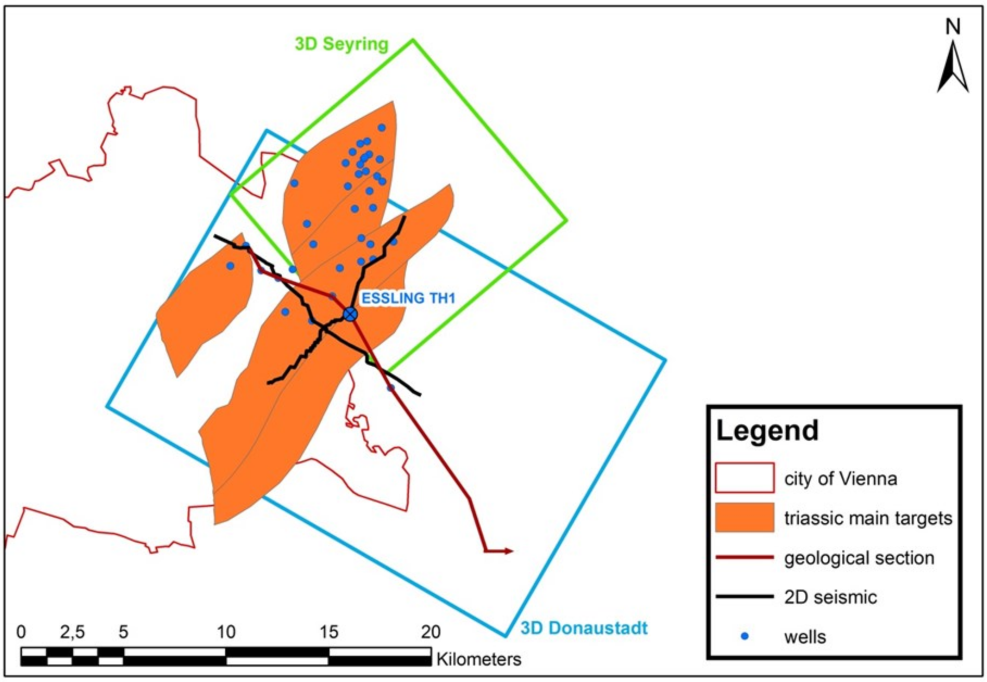

Figure 5: The 3D seismic survey covers about 125 km² source area of which 25 % located in densely built areas within Vienna. The red polygon shows the city boundary. Notice that the unsuccessful geothermal well is situated at the boundary of the existing seismic survey "3D Seyring" (green colour). The geological section of Figure 2 is indicated as red line from northwest to southeast.

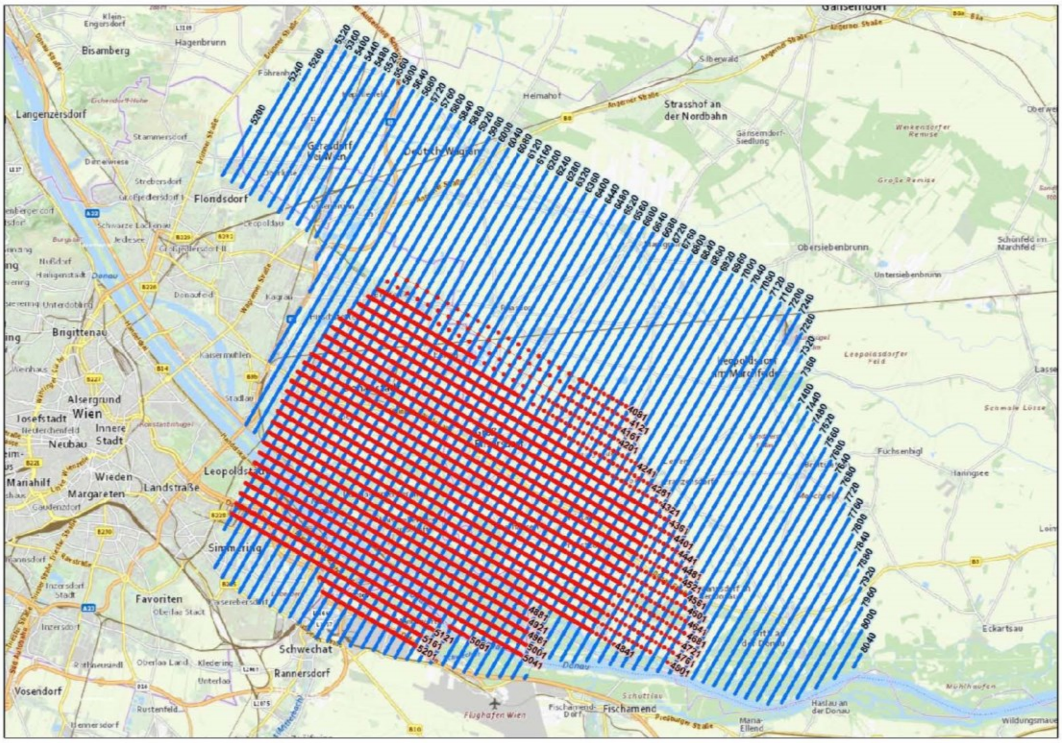

Figure 6: Theoretical base map with source and receiver lines.

The wireless recording system does not allow to QC the data on a daily basis. The recorded data were harvested only when it was necessary to change the position during the roll-along technique. Therefore, it was not possible to check the noise level. To overcome this problem, an additional noise monitor recording with up to 4,000 live channels was installed. Additionally, an LVL (low velocity layer) survey was carried out in the survey area. The objective was to get an image of the low velocity layers in the near subsurface and to determine velocity and depth information for the calculation of static corrections. In total 34 LVL´s have been surveyed within the geothermal area. To avoid damages to residential buildings or sensitive industrial units the seismic survey included vibration velocity measurements at the buildings, pipelines or objects most at risk. All measurements were conducted according to the Austrian standard “ONORM S 9020”. The standard states that the resultant guidance value V R-max should not exceed 6.8 mm/s. Due to this, 341 VPs were skipped.

The seismic processing will be provided by OMV within 24 months after receiving all field data. The complete survey including the part of OMV and the geothermal part of 125 km² covers more than 1,500 km². The still ongoing seismic processing includes all data from both areas to avoid an internal boundary. This enables the examination of the geothermal portion separated from the total seismic cube without having low fold areas and migration fringes at the northeast and northwest boundaries. Both time and depth migration are planned. First reliable processing results of “3D Donaustadt” will be available by end of 2019 and therefore the interpretation of the complex structure of the pre-Neogene sediments of the Vienna Basin will be shown in the first half of 2020.

In June 2019 first interim fast track processing results were used to interpret the Neogene sediment rocks and the top of the pre-Neogene basement. One of the main targets, the conglomerate layer within the Neogene sedimentary rocks, can be interpreted in the fast track processing results very clearly. These interim interpretation results are used as a basis for planned pre-stack depth migration.

The big challenge after the seismic processing will be the interpretation on the pre-Neogene target rocks. Generally, a seismically differentiation between different carbonate rocks (dolomite and limestone) is not easy due to low density and velocity constraints. Therefore, the interpretation has to be orientated on geological models, which are derived from outcrop analogies and available geological well information. In order to avoid unrealistic models, it is planned that several different geological models will be built and discussed. A ranking of the different geological models will help to reduce the number of models for the fully coupled thermal-hydraulic-geo-mechanical (THM) scenarios simulation. The THM simulation is furthermore necessary to estimate the risk of associate seismicity during production of a geothermal doublet.

4. CONCLUSION

The earlier unsuccessful exploration for geothermal energy in the greater Vienna area has shown that a new, innovative approach in the geothermal exploration is necessary in order to be able to exploit the geothermal potential successfully for the city of Vienna in the future. For this reason the “GeoTief Wien“ research project was developed through the cooperation of several experts from various Austrian universities, research institutions and energy suppliers.

The seismic surveys carried out as part of “GeoTief Wien” form the central element of the concept. The planning of the geophysical measurements was coordinated with experts of the individual disciplines with regard to the aspects of the subsequent analyses. In the 2D seismic, for example, Vp/Vs ratios, specifically for the issue of induced seismicity were estimated for the first time in the Vienna Basin.

Due to the innovative planning of the seismic acquisition, the project team developed a tailor-made survey program (asymmetric design of the survey and specially adapted acquisition parameters) for visualizing the very complex geology in the whole area of interest. The challenges with the very large survey area including densely populated urban area and nature reserves during the 3D seismic acquisition were overcome with the help of the innovative wireless measuring systems and slip sweep method.

The preliminary results from the seismic data processing show that this innovative approach in the planning and acquisition of the 2D and 3D seismic will deliver promising results in terms of the upcoming analyses. Thus, with the successful implementation of this seismic campaign, the “GeoTief Wien” project reaches the first major milestone for a possible future development of geothermal energy in Vienna and the Southern Vienna Basin.

REFERENCES

Dankbaar, J. W. M.: Comment on “SHOVER shear-wave generation by vibration orthogonal to the polarization” by Edelmann, Geophysical Prospecting, 30, (1982), 519-520.

Edelmann, H. A. K.: SHOVER shear-wave generation by vibration orthogonal to the polarization, Geophysical Prospecting, 29, no. 4, (1981), 541-549.

Elster, D., Goldbrunner, J., Wessely, G., Niederbacher, P., Schubert, G., Berka, R., Philippitsch, R. and Hörmann, T.: Thermalwässer in Österreich. 1:50.000. Geologische Themenkarten der Republik Österreich, Geologische Bundesanstalt, (2006).

Könighofer, K. et al.: GeoEnergie 2050 Potenzial der Tiefengeothermie für die Fernwärme- und Stromproduktion in Österreich, FFG Projektnummer 834451, (2014).

Tatham, R. H. and McCormack, M. D.: Multicomponent seismology in petroleum exploration, Investigations in Geophysics, Series 6, SEG, (1991).

Tellier, N. and Laine, J.: Understanding MEMS-based digital seismic sensors, First Break, 35, no. 1, (2017), 93-100.