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List of abbreviations and acronyms used in the text

AZU	Croatian Hydrocarbon Agency
BHP	Bottom Hole Pressure
BHT	Bottom Hole Temperature
CAPEX	Capital Expenditure
D#	Deliverable #
E&P	Exploration and Production
EB	Empordà Basin
EC	Electrical conductivity [µS m^{-1}]
EGDI	European Geological Data Infrastructure
ES-DMA	Ensemble Smoother – Multiple Data Assimilation
g	Gravitational acceleration [m s^{-2}]
GJ	Gigajoule
GLF	Girona Limestone Formation
H	Aquifer thickness [m]
HIP	Heat in Place [in HotLime commonly GJ/m^2]
K	Intrinsic permeability [m^2]
KBMZ	Clinical Hospital New Zagreb geothermal system
k_c	Hydraulic conductivity [m d^{-1}; m s^{-1}]
LCOE	Levelized Cost of Energy
M	Month (of GeoERA implementation)
Ma	Million years
masl	Meters above sea level
NAFB	North Alpine Molasse Basin
NN	Above sea level
NWECB	Northwest European Carboniferous Basin
OPEX	Operational Expenditure
PBS	Pannonian Basin System
PDF	Probability density function
Q	Discharge [l s^{-1}; m^3 s^{-1}]
S_c	Storativity [-]
SRP	(GeoERA) Scientific Research Project

SRTM	Shuttle Radar Topography Mission
s/t	Drawdown / time curves in well hydraulic tests
T	Transmissivity [m^2 d^{-1}; m^2 s^{-1}]
T#	Task number
TDS	Total Dissolved Solids [kg kg^{-1}]
TIN	Triangulated irregular network
UDG	Ultradeep Geothermal
UNFC	United Nations Framework Classification
URI	Uniform Resource Identifier
UTC	Unit Technical Cost
WHT	Wellhead temperature
WP	(HotLime) Work package
ZGF	Zagreb Geothermal Field
ρ	Fluid density [kg l^{-1} or g cm^{-3}]
µ	Fluid viscosity [centipoise, cp]

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1 Introduction

New and emerging geothermal plays such as deep carbonate bedrock provide promising yet challenging future targets to raise the share of sustainable and non-intermittent heat and power resources. Carbonate bedrock is widespread in many parts of Europe (Figure 1.1) and hydrothermal systems in such rocks, which commonly circulate in deep, permeable fault and fracture zones, are among the most promising low- and mid-enthalpy geothermal plays. However most deep carbonate bedrock has received relatively little attention from energy investors to date because such rocks are perceived as 'tight'. Exploration and development of these deep systems is a high-risk investment, often hampered by a lack of reliable information on the deep subsurface. It is therefore critical to improve our understanding of the geological conditions that determine the distribution and technical recoverability of the potential resources in these challenging geothermal plays.

This report examines the development of several deep geothermal projects from HotLime partner countries in order to compare and contrast application strategies and approaches to developments of carbonate geothermal projects. The purpose of this report is to provide learnings from these case studies to: 1) improve future development strategies; 2) identify and mitigate risks pertinent to carbonate targets; and 3) support policy-making.

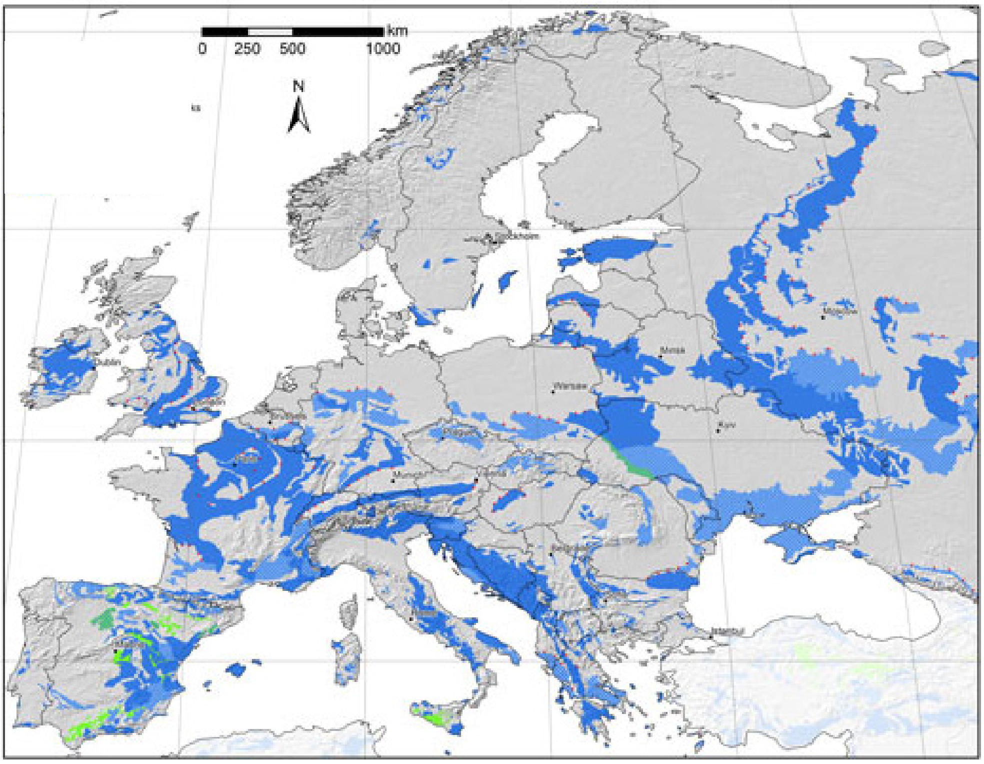

Figure 1.1. Map of near-surface carbonate rocks across Europe (in blue; evaporites shown in green). Reproduced from BGR et al. (2017).

1.1 The opportunities and challenges of deep geothermal energy in carbonate rocks

A revived interest in using renewable geothermal energy as a source of heat and power is the result of our current need to reduce greenhouse gas emissions to mitigate the Climate Emergency, driven by governmental commitments to the EU's 2030 Climate and Energy Framework and the EU goal of becoming climate-neutral by 2050.

Geothermal energy is defined as heat stored beneath the surface of the solid Earth, and can be used for heat or to generate electricity. It is proven in many different types of geological setting all over the world as a secure, sustainable and economical source of energy. Geothermal resources are commonly categorized as either "shallow" or "deep" in the literature. In general, shallow geothermal resources are used for heating and are located within a few hundred metres of the surface. Deep geothermal resources are found at depths in excess of 400 m. Very low-enthalpy shallow resources are almost always used in conjunction with a heat pump; deeper resources generally have higher temperatures and so can be used without a heat pump (direct use heating), or for electricity production. Deep geothermal resources require the drilling of expensive boreholes to access the heat; this high capital expenditure is one of the main barriers to development of these resources.

The high capital costs of deep geothermal heating projects mean that they only become economical at large scales, e.g., for district heating or for industries with high heat demand. Heat is difficult to transport without losses, so geothermal abstraction points must be located close to end-users. Figure 1.2 shows the heat demand density in Europe; a quick comparison of Figures 1.1 and 1.2 demonstrates the significant opportunities present for decarbonising our heat sector with geothermal energy from carbonate resources.

The environmental benefits of geothermal energy

Geothermal energy offers several environmental advantages relative to other energy sources. It is one of the cleanest energy generation technologies, and binary geothermal plants (for electricity generation with lower input temperatures) can produce zero emissions if managed properly. In the USA, geothermal electricity annually offsets the equivalent of 22 million tonnes of carbon dioxide, 200,000 tonnes of nitrogen oxide, and 110,000 tonnes of particulate matter from conventional coal-fired plants (USDoE, 2019). In the heat sector, replacing the need for individual homes to have fossil fuel or solid fuel burning systems also eliminates particulate matter and air pollution and improves air quality. Geothermal heating schemes usually use lower temperature resources than geothermal electricity projects, and are essentially zero-emission at source. The majority of carbon emissions for geothermal projects are generated through the construction and installation of the plant. Even so, deep geothermal district heating schemes can emit just 7% of the carbon emissions of an equivalent gas-fired boiler (see, e.g., McCaya et al., 2019). The land footprint required by geothermal projects is considerably smaller than other renewable energy technologies and the audiovisual impacts of operational geothermal systems are negligible. For 'open' systems (i.e., those extracting hot water from the ground and reinjecting cool water), good aquifer management is essential. For 'closed' systems, fluids are pumped through closed pipes in heated rock, therefore there is no direct contact between the fluids and the rocks or the surrounding ecosystems.

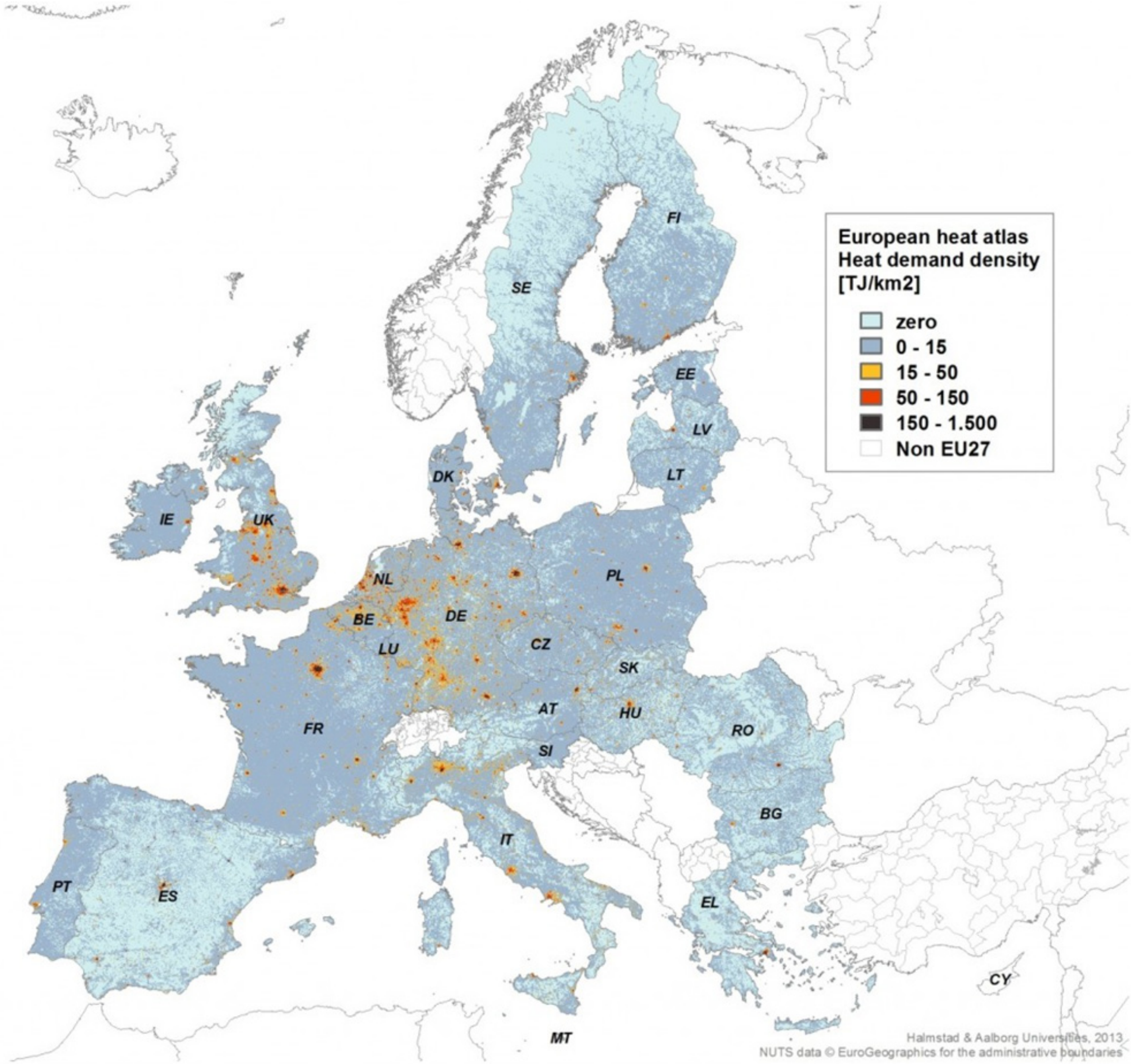

Figure 1.2. Map of heat demand density in EU. From Connolly et al., 2012.

1.2 The role of geological knowledge in the success or failure of deep geothermal projects in carbonate rocks

An objective of HotLime is to compare knowledge and experience of exploration for geothermal energy in carbonate basins and to seek those common geological factors that can inform exploration, reduce uncertainty (risk) and enhance the chance of success of a project. Geothermal resources occur in different configurations depending on the heat source and the geological controls on heat transport and thermal energy storage. Each configuration will require its own optimal exploration workflow in order to reduce costs and improve the robustness of exploration. This is why extensive preliminary site-specific studies are key to the success of any geothermal project.

Methodologies for providing a reliable estimate of geothermal potential and resource assessment in carbonate reservoirs, before site-specific exploratory drilling and flow testing, are needed for both regional resource assessment and for site development and bankability of projects. Cost-effective exploration methods contributing to improved imaging of geothermal reservoir structures (geometry and size) and rock and fluid properties (thermal, flow, chemical, mechanical) are critical to reducing exploration costs. Exploration risk remains high until the first exploratory well has been drilled and direct data can be obtained.

Exploration for deep geothermal energy has progressively targeted areas with limited surface manifestations (such as hot springs), and sedimentary basin structures with sparse subsurface data. In HotLime, carbonate basins of uncertain or unknown potential have been assessed by seeking commonalities with better-constrained examples. For areas where information is scarce, the aim is to develop and test methodological approaches to recognize and estimate geothermal potential by developing conceptual or predictive reservoir characterisation models using knowledge gained from successful and unsuccessful developments, their fracture network characterization, fluid-rock interaction features and catalogues of rock properties.

1.3 Characteristics of deep carbonate geothermal systems

Deep carbonate rocks have special characteristics, distinct from clastic reservoirs, and are frequently regarded as "tight", i.e., challenging or costly to exploit. The majority are characterised by low primary porosity, and hydrothermal circulation patterns in these rocks are dependent on secondary porosity and permeability controlled by faults, fractures and dissolution processes such as karstification. Targeting heterogeneous faulted or fractured reservoirs for geothermal prospecting can be challenging and requires a very site-specific understanding of the fracture network and groundwater regime. This geological uncertainty often makes projects very risky for would-be investors, so good-quality, publicly available, subsurface data is critical to encourage geothermal developments. In addition, general lessons learned from exploitation examples in other carbonate bedrock locations, such as those presented in this report, may be applicable.

The hydrochemistry of deep groundwater in carbonate geothermal systems is generally easier to manage than deep groundwater from other types of geothermal setting. The fluids from carbonate reservoirs are usually lower in total dissolved solids, and corrosion is rare as dissolved carbonate buffers the pH of the fluids. The main hydrochemical problem to expect is carbonate scaling; however this can be surmounted by periodic backflushing with acidified fluids.

The heterogeneous nature of carbonate geothermal reservoirs mean that they are more challenging to model than clastic reservoirs. Many tools for predicting outputs of geothermal wells depend on numerical models that are too simplistic to describe fluid and heat flow in fractured, and even potentially karstified, media. This means that the energy output of a well in a carbonate setting is harder to determine, and any estimates will have more inherent uncertainty.

The perceived threat of induced seismicity as a result of geothermal operations has been known to cause unease among regulators and the general public, and has resulted in many geothermal projects being suspended, including the Californië project in the Netherlands (see Chapter 5). As a result, developers should now recognise the importance of science communications and good public relations in determining the success of geothermal projects. The threat of induced seismicity is arguably of greater concern for developers in carbonate systems, as these projects generally involve pumping and injecting fluids in and out of a fault zone, which may also be open and active. It is of the utmost importance to develop a thorough understanding of the tectonic regime affecting the carbonate reservoir in order to adequately manage the reservoir pressure and prevent or limit induced seismicity. Carbonate reservoirs will respond differently to stress than clastic reservoirs, so designing a seismic monitoring network, or even forecasting induced seismicity in carbonate reservoirs may require different technological approaches.

1.4 Introduction to the case studies

The following chapters of this report present a series of deep geothermal project case studies from HotLime partners (Table 1.1). Some case studies refer to individual geothermal plants, while others describe whole geothermal fields, or clusters of projects governed by the same geological and legislative characteristics. Each study provides project details, describes the geological and geothermal characteristics of the study area and provides specific recommendations for future work (technical and non-technical).

From Table 1.1 it can be seen that where difficulties occurred, the major barriers to the success of these HotLime geothermal projects were non-technical, i.e., legal, political, financial or socio-economical. This in itself demonstrates that these carbonate geothermal resources are proven – the heat is there, and the technology is available to exploit it.

Project	Org.	Country	Intended use	Project status	Barriers to success?
1. Krško - Brežice field	GeoZS	Slovenia	Heat (balneology, space heating, agriculture)	In operation	
2. Zagreb Geothermal Field	HGI-CGS	Croatia	Heat	1 plant in production; 1 stalled	Non-technical: Legal, financial
3. Casaglia	SGSS	Italy	Heat (district heating)	In operation	
4. Californië	TNO	Netherlands	Heat (greenhouses)	Suspended	Technical and non-technical. Difficulties obtaining a permit after well became blocked. Perceived risk after seismic event.
5. Munich cluster	LFU	Bavaria, Germany	Power and heat (district heating)	17 plants in operation; 2 failed wells	Failures technical: insufficient flow rates
6. Jafre project	ICGC	Catalonia, Spain	Heat (horticulture, balneology)	Abandoned	Non-technical. 1988:legislative; 2000s:financial
7. Newcastle	GSI	Ireland	Power and heat (district heating)	Did not progress to completion	Non-technical: Policy, political

Table 1.1. Overview of case studies presented in this report.

1.5 References

BGR, IAH, KIT and UNESCO, 2017. World Karst Aquifer Map, 1:40,000,000. Berlin, Reading, Karlsruhe and Paris.

Connolly, D., Mathiesen, B. V., Østergaard, P. A., Möller, B., Nielsen, S., Lund, H., Trier, D., Persson, U., Nilsson, D., & Werner, S., 2012. Heat Roadmap Europe 1: First Pre-Study for the EU27. http://vbn.aau.dk/en/publications/heat-roadmap-europe-2050-second-prestudy-for-the-eu27%28306a5052-a882-4af9-a5da-87efa36efeaa%29.html

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2 Case study 01: The Krško – Brežice Basin, SLOVENIA

Authors: Dušan Rajver, Dejan Šram, Nina Rman, Andrej Lapanje, Miloš Markič, Simon Mozetič (GeoZS)

2.1 Overview

The Krško - Brežice Basin is geologically presented as a basin, more precisely as a syncline, filled with low permeability Tertiary and some Quaternary sediments. Their thickness reaches almost 3 km in its central eastern part (approx. between towns of Dobova and Krško and close to Globoko). In the syncline basement, especially in Triassic and Jurassic carbonate rocks, a convective thermal regime predominates, at least in its upper part. The syncline pattern and structure have been determined from the results of surface geological mapping and geophysical methods, carried out in several phases since 1959, and in a few limited areas considerably supported by medium deep drillings (< 800 m). The most important geothermal anomaly is found at the Čatež fault zone. There, the highest borehole temperatures have been reached between 50 and 64 °C. Geothermal anomalies at other localities have been less investigated and detected temperatures do not exceed 36 °C. Deep boreholes, available for geothermal measurements, are found mostly along the southern rim of the basin. Circulation of meteoric water into the kilometres-deep fissured and fractured fault zone is the only heating possibility for thermal water in the Čatež geothermal field. Based on information collected until now it is assumed that geothermal reservoir could extend at least 2 to 3 km deep beneath the surface.

2.2 Geology, hydrogeology and geothermal setting

A rather complex research treated the Krško basin in a period between 1973 and 1978 (Rajver & Ravnik, 2003). Later on, regional geophysical, hydrogeological and tectonic investigations were also performed (Verbovšek, 1990). In the late 1960s and in the 1970s, existent thermal springs were inventoried, the aquifer types were hydrogeologically classified, hydrogeochemical interpretation was done and the structure of the region was interpreted with geophysical methods and a geotectonic study (Rajver & Ravnik, 2003). Two localities, the Čatež Spa (Terme Čatež) and Topličnik near Kostanjevica were investigated in more detail and described in numerous reports (Rajver, 2001).

The Krško – Brežice basin with its thermal springs is a syncline, filled with low permeable Tertiary and some Quaternary sediments (Rajver & Ravnik, 2003). Geological knowledge is generally well constrained but less so in deeper parts. The lithostratigraphic column from the upper Paleozoic to Quaternary is well established. The broad structure is outlined, with the dominant Krško syncline and the Gorjanci antiform (Figure 2.1). The structure of the Krško syncline was well constrained by seismic reflection surveys of several phases. The Gorjanci antiform is also reasonably well constrained by geological mapping. The syncline pattern and structure have been determined from the results of geological surface mapping and geophysical methods such as gravimetric, seismic and geoelectrical measurements, which were performed already since 1959, together with drillings of medium deep boreholes.

The Čatež fault zone is fairly well outlined by geological mapping, particularly in areas where it is not covered by Quaternary sediments. The fault zone is presumably fairly steeply inclined (circa 70°) towards the southeast (Figure 2.2). The extent of this zone under Quaternary sediments is only assumed. Apart from the broader, general structure, there is a very significant uncertainty. The geometry of the fault zone at depth is to a large extent inferred from the surface trace, with a minor contribution from seismological data, and is considered to be rather poorly constrained. Any possible extension towards the northeast, east and southeast and its relationship with the Marija Gorica anticline to the northeast is so far unknown and requires acquisition of additional data. Smaller scale features, such as possible minor faulting intersecting with the main fault zone, the potential presence of any other significant fault zones buried beneath the Quaternary sediments, the internal structure and heterogeneity of the fault zone and variability in the fault zone geometry, particularly below the base of Neogene sediments, are unknown and require acquisition of additional data.

Geological data could be very significantly improved particularly by deep (5 to 10 km depth) 2D and potentially 3D geophysical investigations, combined with future deep boreholes. Smaller scale high-resolution seismic reflection profiles could additionally constrain the structure in the areas of the geothermal springs. In the area of the Krško nuclear power plant (NPP), geophysical and hydrogeological research was carried out mainly to determine the potential repository of low-to-medium level radioactive waste and to determine the stability of the power plant (Persoglia, 2000). The results of these studies were not used in this report because they are remote and do not influence the main geothermal anomaly in the Krško-Brežiško Basin.

Triassic dolomites, Jurassic limestones and dolomites, and few Cretaceous sediments represent abundant aquifers that are of regional importance due to their extension and mutual connection (Verbovšek, 1990). These aquifers are recharged from the surrounding areas by meteoric water circulating into deep fractured hot zones. Due to the forced and partly-free convection (especially in the Čatež fracture zone) this water appears at several thermal springs along the southern and southwestern rim of the basin. It is not expected that the Čatež geothermal field and the Zagreb geothermal field are hydrogeologically and geothermally connected as it is assumed that a certain anticline pre-Tertiary structure exists in between the two fields.

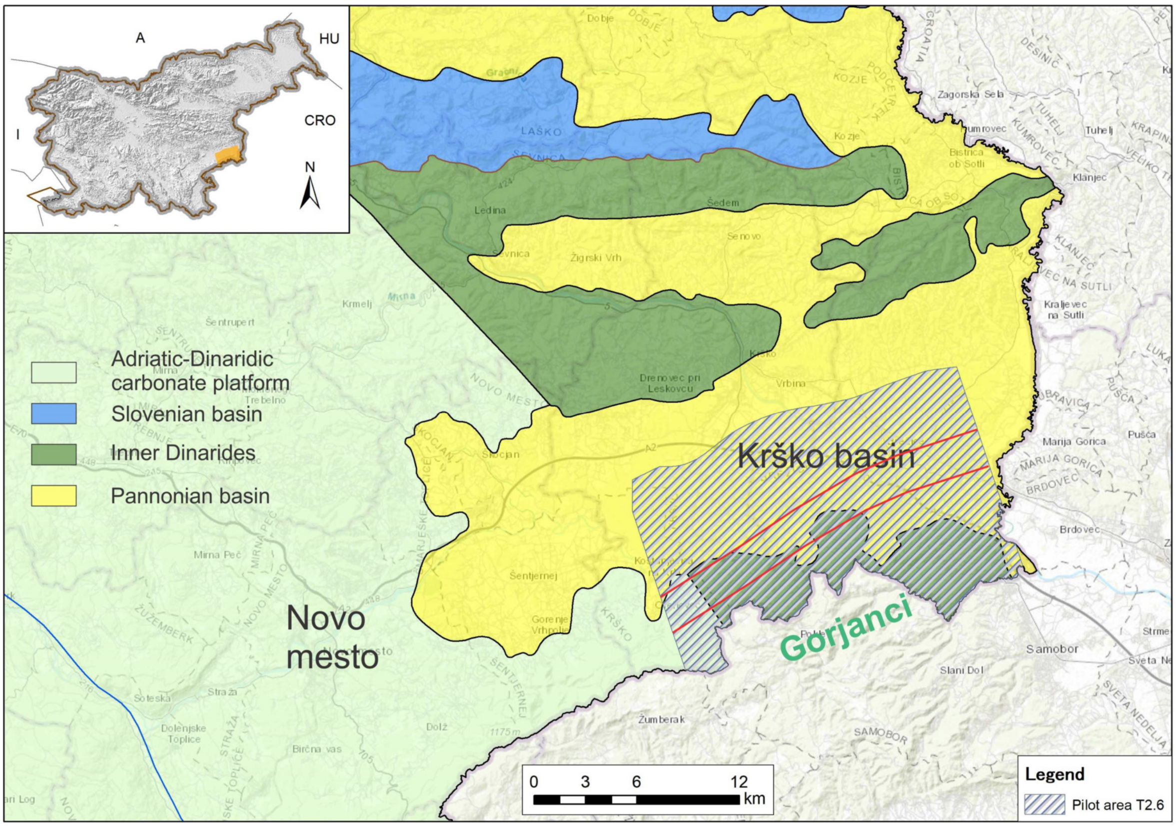

Figure 2.1. General overview of the Krško basin (a syncline) with Gorjanci Hill antiform in the south (Poljak, 2017).

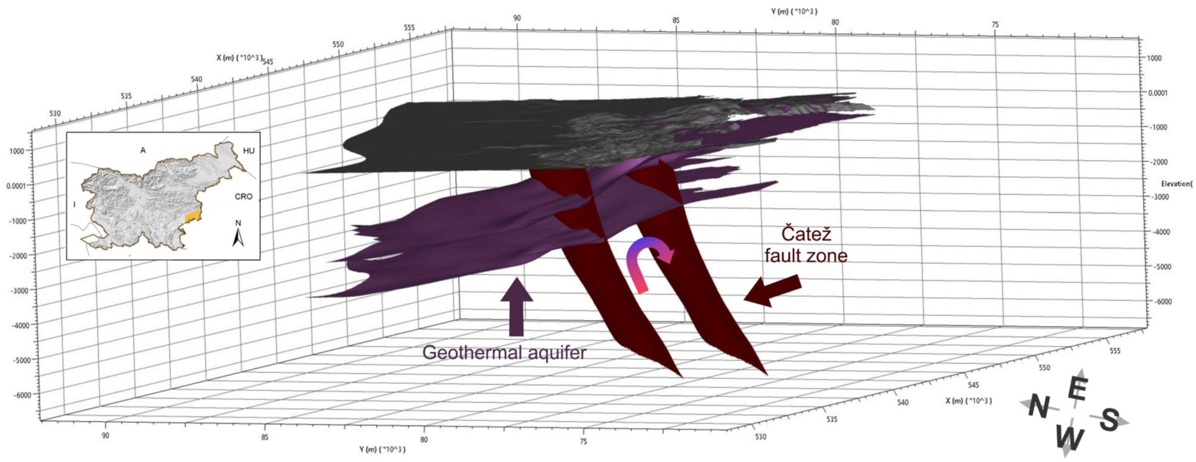

Figure 2.2. 3D geological model of the Čatež fault zone.

The most important geothermal anomaly is the Čatež geothermal field, developed within the Čatež fault zone, with the greatest concentration of geological, geophysical, and geothermal investigations and natural features (thermal springs). According to Moeck (2014), the Čatež geothermal field with a deep fault zone belongs to “(2) conduction dominated geothermal play type” with foredeep province and with fault and fracture zones (fault/fracture controlled). In the Čatež field, the highest borehole temperatures have been logged up to 64 °C in the well V-15/88 at a depth of 400 m soon after the well was completed and tested. Circulation of meteoric water into the sub-vertical, kilometres-deep, fractured Čatež fault zone is the only reasonable heating possibility for thermal waters in the Čatež field. Water circulation is probably deepest there than anywhere else in the Krško basin (Ivanković & Nosan, 1973; Verbovšek, 1990; Rajver & Ravnik, 2003).

The measured geotherms reflect a predominantly conductive thermal field. In the syncline basement, particularly in Triassic and Jurassic carbonates, but less so in Cretaceous rocks, a convective thermal field is predominant, at least in its upper part. In a much wider area of the basin geoelectrical soundings have been the only source of data for the construction of geotherms and applied to elaborate geothermal maps and cross-sections. This was enabled by a conversion from resistivity and borehole lithology into temperature data, using a one-dimensional simplified solution of Laplace’s equation. In such a way an approximative knowledge of geothermal conditions below the surface and beyond known geothermal anomalies has been extended (Rajver, 2001; Rajver & Ravnik, 2003).

The necessary circulation depth for meteoric water to reach temperatures of approximately 55 to 65 °C in the Čatež fault zone (Figure 2.3) may be estimated from the geothermal gradients in the conductive model of heat flow. In the boreholes in the Krško basin beyond the Čatež field anomaly, the gradients are determined in range of 17 to 27 mK m^{-1} and almost on the rim of geothermal anomaly they are circa 37 mK m^{-1}.

The structure is constrained from available data on the Krško syncline and a composite regional lithostratigraphic column. It includes the reservoir rock lithology and general geological structure, such as depth to top of the carbonate rocks which form the geothermal aquifer(s) (Figure 2.4) and thickness of the geothermal reservoir. The structure of the Krško syncline is reasonably well known down to a depth of approximately 3 km, to the base of the Neogene sediments. Deeper structure is assumed to be the same, without modifications by preceeding tectonic phases. These are major assumptions. However, no deep geophysical data and no deep borehole data are available to constrain the reservoir beyond these assumptions. The Čatež fault zone is constrained by geological mapping and seismicity (including fault plane solutions).

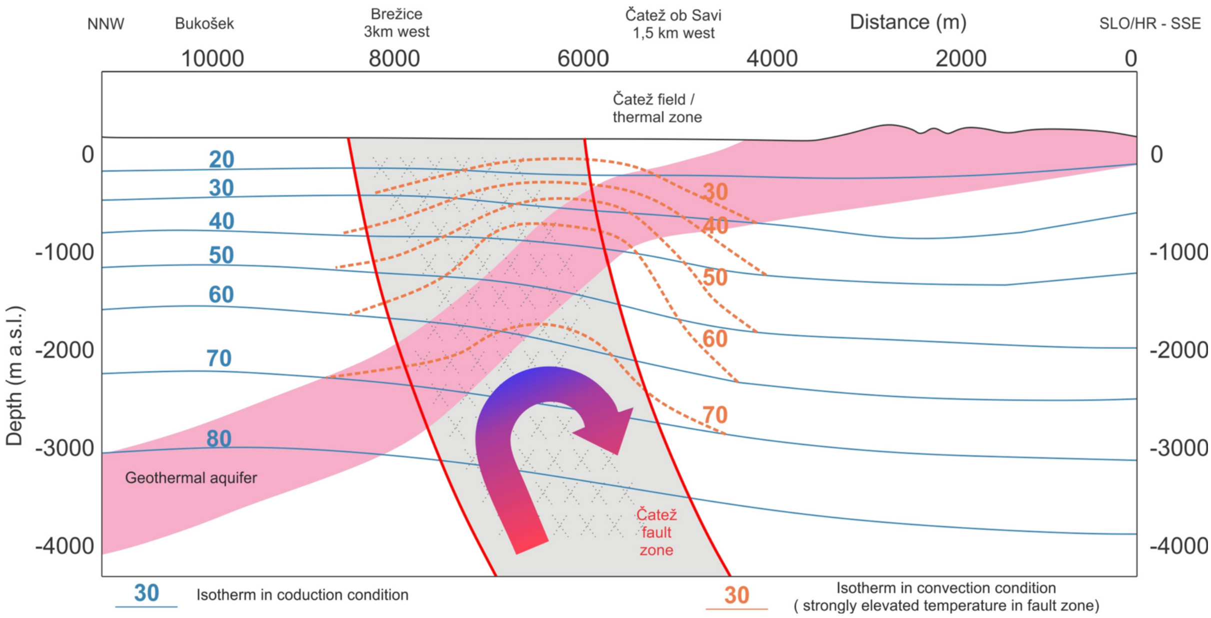

Figure 2.3. Typical cross-section with expected temperature and groundwater convection at the Čatež geothermal field.

Nevertheless, there are 11 boreholes which reached the geothermal aquifer and were drilled inside the Čatež fault zone, having a maximum depth of 706.5 m. They all finished with their bottom parts in the Triassic dolomite, limestone with dolomite and/or dolomite breccia rock type. The reservoir rock type is predominantly Late (and Middle) Triassic dolomite in deeper and shallower parts of the fault zone with possible late Triassic Dachstein limestone in shallower parts. In a wider area around the constrained Čatež fault zone, the top of the geothermal aquifer may be presented also with Jurassic carbonate rocks (limestone and dolomite).

With an assumed annual surface temperature T_0 of 11 °C, the mentioned geothermal gradients may place the circulation depth of the thermal water with at least 60 °C in a range of 2 to 3 km. Therefore, the Triassic geothermal reservoir could extend at least to these depths beneath the surface. On the other hand, the Čatež fault zone might extend to depths of at least 2 to 3 km beneath the surface, but not all the way within the Triassic carbonate rocks (dolomite, limestone), because it could also have formed within the other lithologies of presumably older age.

Temperature has been measured in almost 60 boreholes all over the Krško basin (GeoZS); among these 34 boreholes have thermally stable conditions. In the Čatež geothermal field (the most significant geothermal anomaly), temperature has been logged in 11 boreholes, up to a depth of 700 m in two of them (the L-1/86 borehole close to Čatež Spa and the AFP-1/95 borehole at Dobova). From these 11 temperature logs, maximum temperatures between 50 and 64°C have been recorded in the geothermal aquifer (Figure 2.5). In three boreholes the T-z geotherms clearly showed a very high temperature gradient in Tertiary sediments and isothermal character in the Triassic geothermal dolomite aquifer. Typical examples are the geotherms from the AFP-1/95 borehole at Dobova with 63 °C and L-1/86 borehole at Mostec near Čatež with 61 °C, both measured in the geothermal aquifer. These geotherms are a very probable sign that all 11 boreholes are situated on top of the fractured fault zone with predominantly free convection.

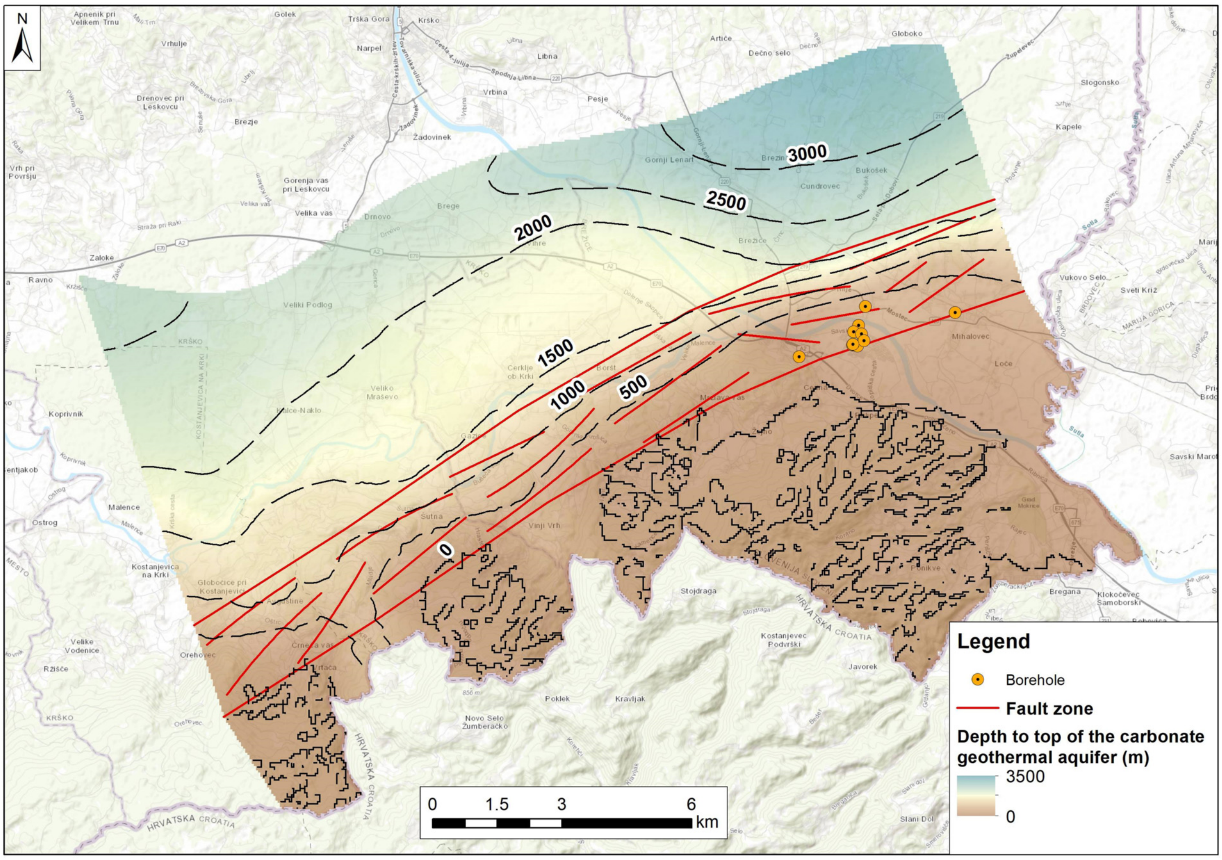

Figure 2.4. Depth to top of the carbonate geothermal aquifer(s) constrained also based on shown boreholes that reached the top of aquifer.

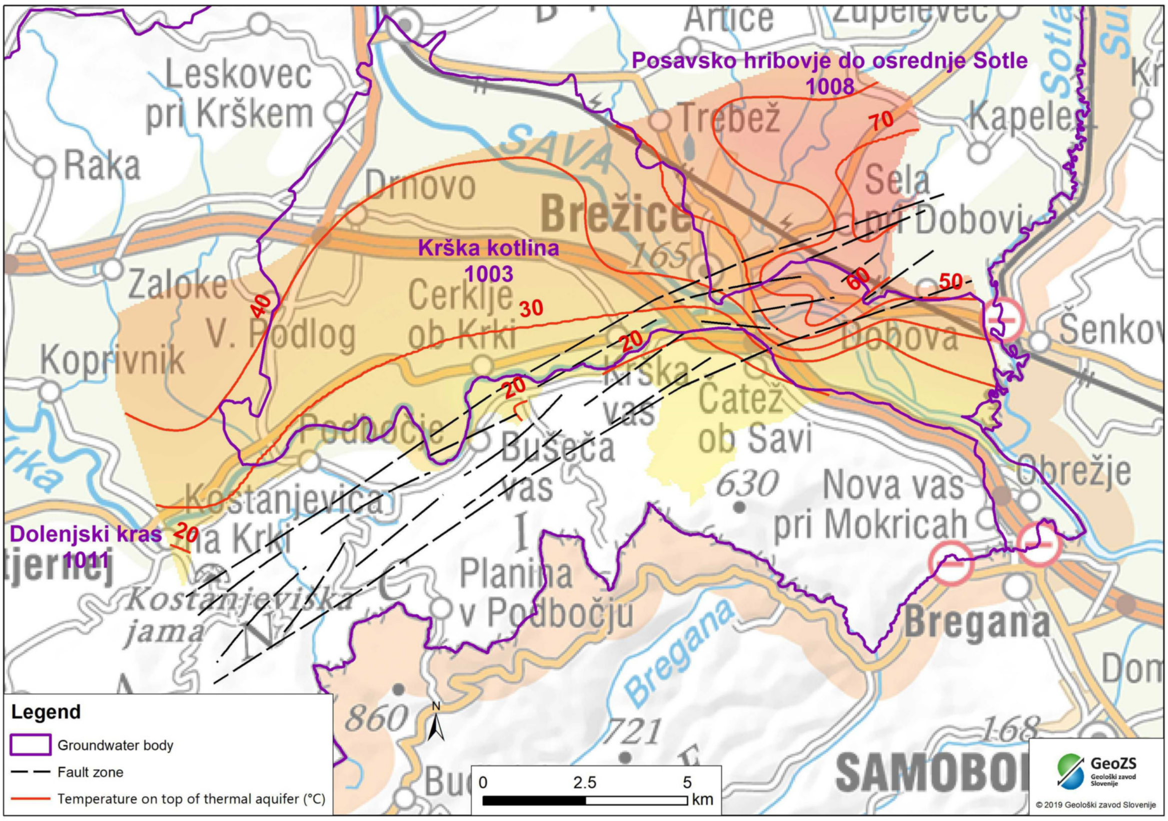

Figure 2.5. Temperature on top of the carbonate geothermal aquifer.

2.3 Resource assessment

The first attempt at a Heat in Place (HIP) calculation of the eastern part of the Krško basin was carried out by Rajver et al. (1996) for the purpose of the *Atlas of Geothermal Resources in Europe* (Rajver et al., 2002, in: Hurter & Haenel, 2002). Both of the resulting maps for Slovenia in that publication and the results of Hotlime HIP calculation (see Hotlime Deliverable 3.1 (Veldkamp & HotLime Team (2021)) suggest that there could also be other areas within the Čatež fault zone or in the immediate surroundings (perhaps more probable towards the north-east to east of this zone) where there is probability for new exploration and exploitation wells for thermal water of at least 50 to 60 °C at the wellhead. Within this fault zone there are possibilities for successful exploitation wells between the Terme Čatež and the small town of Dobova, and beyond Dobova to the east towards the Slovenian-Croatian border.

Total HIP (following the HotLime methodology) at the pilot area is estimated to 6.8 EJ. The average HIP is 54 GJ m^{-2}, with a maximum value of 128 GJ m^{-2} and a minimum value as low as 0.7 GJ m^{-2} per each modelling cell of 500 x 500 m (Figure 2.6). The methodology is described in Veldkamp & HotLime Team (2021).

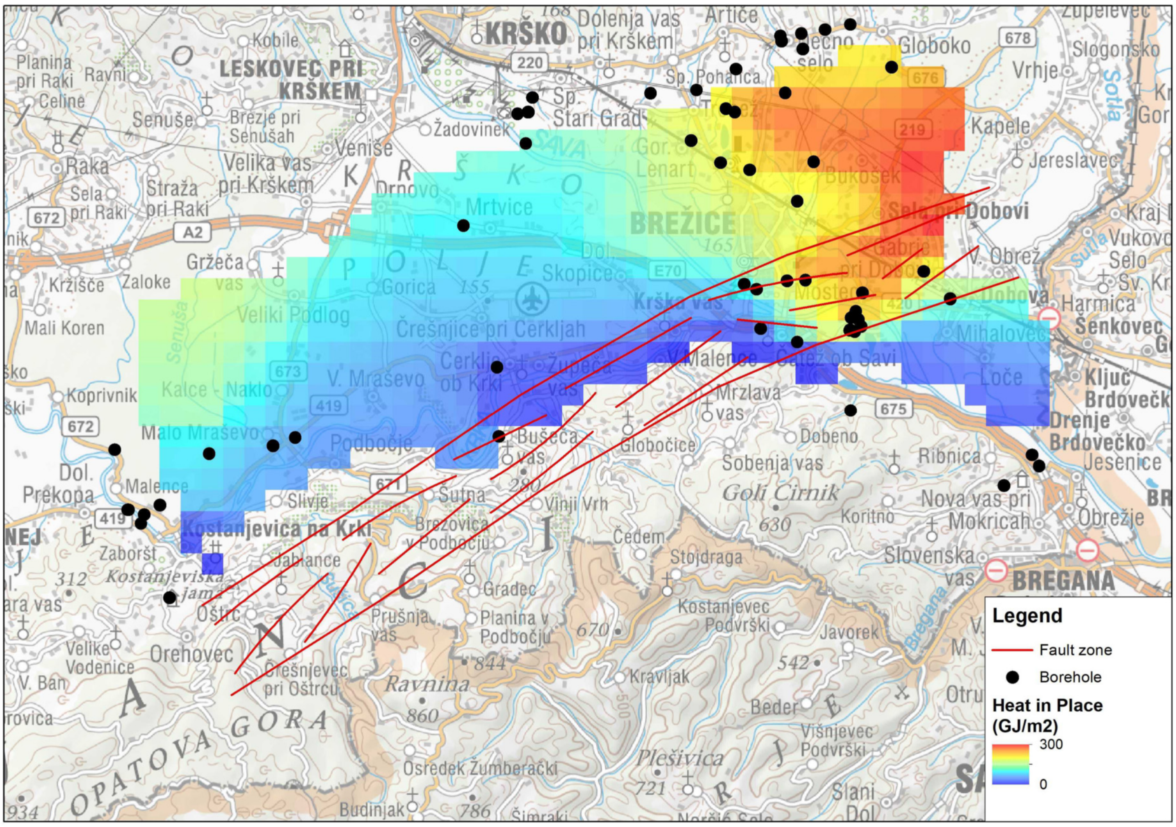

Figure 2.6. Estimated Heat in Place in the Krško basin. Grid cell size 500 m x 500 m.

2.4 Summary of the project

At the Krško - Brežice basin there are several operational geothermal wells (as of 2020 four wells at Terme Čatež, and two at Dobova - one for AFP Dobova and one for Terme Paradiso). These were developed as a consequence of the existing thermal springs in Čatež, which provoked the investors to explore in more detail in the vicinity of the Čatež area where there are significant signs of a shallow subsurface thermal anomaly. There, numerous exploration and exploitation wells were drilled for the Čatež Spa and the Agraria Company, the deepest one having 704 m. Later on, in the 1990s, two other investors appeared at Dobova where two production wells were drilled to a depth of 700 and 706.5 m, in 1996 and 2009, respectively. Thermal water is of Ca-Mg-HCO_3 type and has moderate mineralization (about 400 mg l^{-1}) and very low free gas content. It fulfills the requirements of drinking water. Almost no technological issues regarding its use are known to be reported, so regarding this aspect, this is the highest temperature of thermal water in Slovenia with such a favourable hydrogeochemical composition.

There are some technical barriers to geothermal development in the area such as lack of data and inaccessibility of the dolomite aquifer (depths to this geothermal aquifer may be greater outside the Čatež fault zone, and the drilling success is not guaranteed). Poor casing is noted in some wells, causing local intrusion of colder water in one well. It is anticipated that new wells should be better made in the future.

Non-technical barriers are, for example, the preference of some investors who prefer biomass, solar energy, and wood pellets for their heating plants, as such technologies receive more funding possibilities and have no geological risks. Concession conditions are quite demanding for some users, the concession fee is very high, and the administrative procedures can be very challenging. No one-stop-entrance-point for geothermal development and utilization yet exists in Slovenia.

There were no negative wells reported, all of them provided some thermal fluids with the expected temperature. Locally, the yield can be a greater challenge than the temperature to be reached. However, some wells were poorly executed in a technical sense, and the users had to drill extra compensatory wells.

2.5 Future work and recommendations

The characteristics of geothermal anomalies will be more thoroughly established only with more comprehensive future subsurface investigations. In particular, deeper boreholes need to be drilled into Triassic and Jurassic rocks with all necessary measurements and tests. However, it would be interesting to know how far the Čatež hydrogeothermal system spreads towards the northeast and east, and also perhaps towards the west-southwest. To answer this, it would be interesting to drill some temperature gradient boreholes in these directions to build a picture of the elevated gradients due to the geothermal zone. Deep geophysical investigations and subsequent deep drilling is also needed between Kostanjevica and Šmarjeta Spa to the west, and perhaps around Krška vas.

However, both of these investigation plans require high investment, which is currently unavailable.

In the future, encouragement of investment in deep geothermal energy is required, along with communication of the benefits of using the heat from thermal waters from these carbonate aquifers. Perhaps some new potential investors for developing thermal waters from the Čatež geothermal aquifer can be found in Brežice town and its surroundings. Of course, it is not entirely clear whether the Čatež fault zone and the geothermal anomaly extends into this area; it may only extend to the southern part of the town. This could be demonstrated by measuring the geothermal gradient in shallow boreholes.

Increased geological exploration and research of this geothermal resource, as per the suggestions above, is necessary to improve the overview of geothermal potential for the local energy plans of the municipalities and local communities in this area. The cascade utilization of geothermal water is successfully practised at Čatež Spa, however it needs to be celebrated and promoted for other users in the future.

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3 Case study 02: Zagreb Geothermal Field, CROATIA

Author: Staša Borović (HGI-CGS)

3.1 Overview

Zagreb geothermal field (ZGF) was chosen as a case study for Croatia. It is a defined geothermal field situated in the Croatian capital (Figure 3.1), with active permits for geothermal water utilization. However, out of 15 positive geothermal wells, only one doublet is in successful, decade-long operation (Mladost-3 as production well and Mladost-1 as reinjection well since 1987). The utilization of other fully equipped wells (KBNZ technical system) with equally favourable water temperatures is stalled.

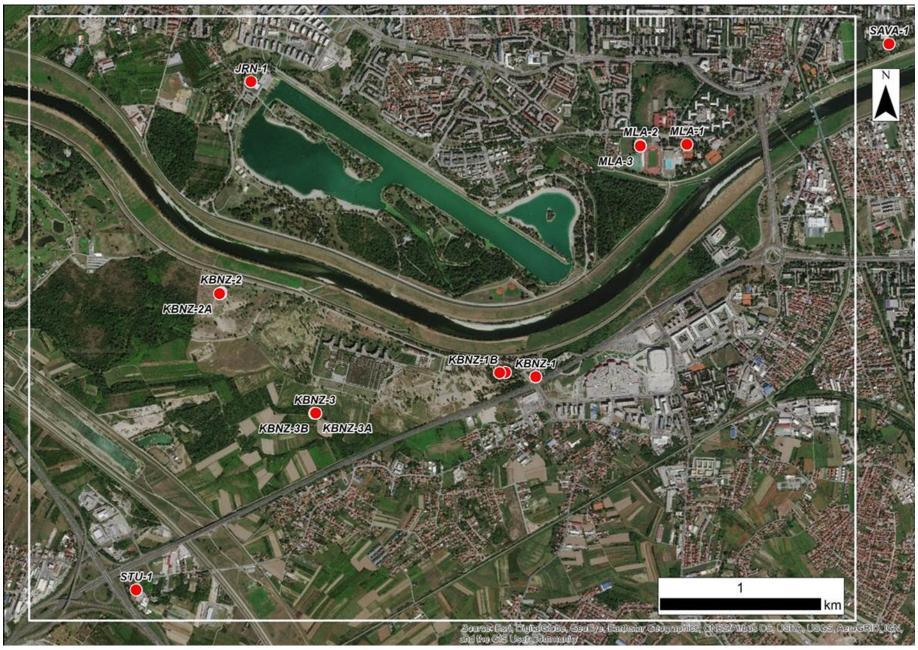

Figure 3.1. Zagreb geothermal field in the Croatian capital. Red points indicate existing geothermal wells (satellite imagery in the background by Google Earth).

3.2 Geology, hydrogeology and geothermal setting

Geological knowledge is moderately constrained. The Zagreb area, due to the fact that it is a national capital and the majority of research institutions are situated there, has been investigated in much detail. On the other hand, the structure of the area is quite complex and would require a multidisciplinary holistic interpretation and (possibly) 3D geological reconstruction. Works on that track are currently being undertaken at the Croatian Geological Survey in the scope of the H2020 project GeoTwinn, as well as in the scope of HotLime in collaboration with the Faculty of Mining, Geology and Petroleum Engineering (their professors and students). The works are progressing more slowly than desired due to a need for digitisation of old data, only available in the form of scanned reports.

ZGF includes two distinctive but connected carbonate thermal aquifers: Triassic dolostones, limestones and dolomitic limestones and Lower and Middle Miocene bioclastic (*Lithotamnium*) limestones. The Triassic aquifer is very fractured and can predominantly be classified as dolomite breccias with high secondary porosity and good permeability. The thickness of the aquifer varies from 5 to 357 m. The Miocene aquifer has good primary porosity due to bioclastic composition, but also good secondary porosity, appearing as breccia or breccia-conglomerate in some boreholes. Owing to that, it has excellent permeability.

The whole formation has a thickness of between 35 and 1,016 m, however, it also includes marly sections of lower permeability and cannot be considered an aquifer over its total thickness.

Although drilling operations have proven that the water resides in the dolostone and limestone aquifers, the water chemistry does not immediately reflect it; the waters display Na-HCO_3 hydrochemical facies, and adding to that, also high chloride anion content.

Temperatures range from 27 to 52 °C at 500 m, and from 38 to 81 °C at 1,000 m depths. The highest temperatures were recorded at the locations where two geothermal technological systems are established; Mladost (active) and KBNZ (inactive – stalled).

More details on data availability and obstacles, as well as on the geological, hydrogeological and geothermal characteristics of the ZGF can be found in the HotLime D2.0 report on resource mapping and characterisation.

3.3 Resource assessment

Resource assessment and classification according to UNFC for geothermal projects have been done in the scope of HotLime Deliverable 3.1 (Veldkamp & HotLime Team, 2021). This was possible due to the fact described in the introduction: ZGF is a developed geothermal field so it is fully tested and the data were made available by the Croatian Hydrocarbon Agency (AZU).

The Mladost system classifies as 7.09 PJ E1.1; F1.1; G1 + 5.43 PJ E1.1; F1.1; G2 + 3.25 PJ E1.1; F1.1; G3. This system is in successful continuous operation since 1987, so it is clearly feasible and socio-economically accepted. The neighbouring system KBNZ of the same geothermal field must be classified as 7.25 PJ E3; F1.3; G1 + 7.08 PJ E3; F1.3; G2 + 7.32 PJ E3; F1.3; G3 because – although all the wells are in place since 1987, they have been tested, concession was granted, etc. – the system never became operational. The KBNZ case is a typical example of legislative, administrative and political barriers to project implementation, leading to E3 classification of a project which could be in operation for decades already.

3.4 Summary of the project

Mladost technical system (Figure 3.2) of ZGF has been operational for 34 years, so its thermal output can be compared to the theoretical output (as planned by the main mining design) (Zelić et al., 1994). According to the most recent published data (Cazin & Jurilj, 2019), the annual utilization is 3 MW in capacity. In comparison to the P90 estimate, this is only 60% of the possible energy load, i.e., the exploitation should be organized in a much more efficient fashion.

Figure 3.2. Water and gas sampling at the Mladost-3 active production well of the ZGF (photo by V. Cazin).

KBNZ system is not in operation, so none of the available energy is put into useful function.

Figure 3.3. Water and gas sampling at the KBNZ-1b inactive production well of the ZGF (photo by V. Cazin).

Considering that the field is situated in the national capital with a number of possible users, it can be considered as an example of a resource abandoned for decades due to socio-economic circumstances. Barriers to resource utilization in the Zagreb geothermal field are obviously non-technical.

3.5 Future work and recommendations

There are a number of barriers which can be categorised as one of the following:

1. Inappropriate legal framework;
2. Non-existent feed-in tariffs in the past years.

Utilization of geothermal waters using boreholes (from blind geothermal systems) is regulated by the Hydrocarbon Act. It is clear that regulating renewable resource utilization in the same way as the utilization of fossil fuels cannot be an optimal solution. The procedures are therefore long and complicated, so the potential investor into renewables in Croatia will rather turn to solar or wind power. More on the legal framework is presented in HotLime Deliverable D5.1.1.

Regulation on feed-in tariffs has not been proclaimed since the governing law changed in 2017 so it is impossible for a potential investor to calculate the return period and, consequentially, to obtain funding from financial entities.

If one main deterrent to public funding of geothermal development should be named, it would be geological risk and the non-existence of insurance against geological risk.

Local, municipal and regional governments commence investigations of geothermal potential from time to time, they finance the studies of geothermal potentiality of their area based on existing data including recommendations for future research, and some even invest into new surface geophysical research. However, none have been actually willing to invest in an exploration-exploitation well, without which it is not possible to really assess project feasibility. This is understandable, considering that this phase includes much higher costs, the highest risk of failure, and there is no possibility to become insured against geological risk. Even if they are not extremely conscientious about using the public funds, it is clear that a failure of millions of Euro worth of an investment would be their undoing in a political sense, so such decisions cannot be expected from public- funded entities until there is a way to get some kind of insurance.

An exploitation concession for geothermal waters in Croatia can only be granted after some prerequisites are met. One of these prerequisites is the environmental impact assessment (EIA) report. This is not a barrier in the case of ZGF (it has been given the exploitation concession), but has an impact on the public acceptance of geothermal projects. An EIA report has to be conducted by a company which has the permit to conduct such studies, and involves the following assessments: influences on water and water bodies; protected areas and their flora and fauna; ecology; landscape; population; transportation; historical and cultural heritage; forest and game management; soil and agricultural land; air quality; ambient noise; waste management; and possibility of accidents. Public debate on the document is obligatory and the EIA report has to be made available to the interested public for 30 days prior to the debate. Everyone is entitled to give opinions and suggestions for amendments in written form. After the public debate a report on the debate is compiled, containing all the received feedbacks and whether the suggestions were accepted, partially accepted or rejected. The report on the debate must be submitted for further steps in permitting.

Practical considerations:

1. From the required contents of the EIA report it is clear that they are not technology-specific, and in no way specific for geothermal exploration and exploitation;
2. Insight into the public debate reports shows that public debates frequently take place around August 15, with insight into documentation granted from Jul 15 to Aug 15. In the Croatian system and organization of year-round workflows, this can be considered as the least favourable period for communication with the interested public.

In this manner, the public that should be engaged and pacified by the reports made by experts from different research fields, instead find themselves feeling outmanoeuvred after returning from summer holidays and finding out that the time for presentation and debate about something impacting their environment has run out. It would be much better for the communication of geothermal installations development if the EIA reports would consider relevant parameters and if the debates would be announced in time and held in better timeframe.

Projects (especially those which received EU funding) researching geothermal potential have usually organized awareness-raising meetings, presentations and workshops. However, the general impression is that the knowledge on geothermal resources is quite low. A certain degree of understanding (clearly depending on the personal interest of the employee in charge) is usually present in the communities of sectoral experts (energy /water /spatial planning /tourism) in the authorities who take part in permitting in one or more phases of geothermal project development, and in research and higher education institutions.

As a public research institution, Croatian Geological Survey has undertaken many awareness-raising events among professionals, students of different age groups and the general public. However, progress in awareness about geothermal potential in the City of Zagreb, or in Croatia, is not observed on a significant level from one event to another (again, it is observed on an individual basis). Periodic organization of events could be the answer, as well as informing the public via dedicated web sites, media, social networks and mobile apps. However, all such endeavours would require additional funding and personnel trained (or experienced) in public relations in geoscience.

Public opinion has not presented an issue during any geothermal project implementation in Croatia so it is possible to conclude that the public is, depending on the location, either well-educated; absolutely uninformed; or, not interested. To the best of our knowledge, there were no polling campaigns which could indicate the dominant reason.

No single biggest barrier to geothermal development can be (or has been) identified in the presented pilot area. However, it is visible that:

1. there is no adequate national or regional strategy which would favour and promote the utilization of this resource;
2. economic feasibility of the projects is not optimal due to a lack of feed-in tariffs, regulations and the strong competition posed by relatively cheap natural gas, which is mostly readily available in the Pannonian part of Croatia that also displays favourable geothermal potential;

3. it has been brought to public attention on multiple occasions that the projects have been part of political manoeuvres, instead of serious geoscientific, engineering and economic analyses.

Currently the utilization of geothermal waters in Croatia is regulated by three different acts:

- Water Act;
- Mining Act; and
- Hydrocarbon Act.

The governing act is determined on the basis of the proposed utilization plans (water for bottling, recreation or therapy; extraction of minerals from geothermal water; energy from water for heating or electricity generation purposes). Obviously, these acts regulate many areas which are not inherently connected with geothermal operations, and that complicates the procedure on many instances (e.g., many requested data are irrelevant while many relevant data are not requested).

The most favourable solution would be to exclude geothermal waters from those acts and devise a legislative framework which considers only geothermal waters from different reservoirs (play types) and for different purposes. A significant policy change could be to enable some supporting mechanisms to geothermal development. Currently it is only possible to get a subsidy from the Environmental Protection and Energy Efficiency Fund. However, this subsidy is only available to Croatian investors and the maximum amount of the subsidy is €27,000. With such a low intensity subsidy it is hard to expect significant results.

Furthermore, it would be good if legislative framework would consider creating provisions introducing the possibility of insurance against geological risk for renewable energy developers. Adding to that, reliable feed in tariffs and good heat purchase agreements for geothermal operators would be beneficial (these should be tailored to fit geothermal by the existing energy regulatory agency).

3.6 References

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4 Case study 03: Casaglia, ITALY

Author: Fabio Carlo Molinari (SGSS Regione Emilia Romagna)

4.1 Overview

The Casaglia geothermal reservoir was discovered through the "Casaglia 1" exploration well drilled in 1955. Only later in the 1980s was it decided to characterize the geothermal reservoir for possible use for city district heating purposes. In 1981 the "Casaglia 2" well was also drilled. The first concession, which dates back to 1984, was awarded by the Ministry of Industry, of Commerce and Crafts to AGIP and Enel for the cultivation of two wells, Casaglia 1 and Casaglia 2. In 1995 the concession for the cultivation of the Casaglia 3 well was issued, from use as a production well.

The Casaglia geothermal plant is located about 7 km north-west from the town of Ferrara, in the locality of Casaglia. The plant is located in an agricultural area, and is bordered by a metal fence. It is spread over two areas:

- Casaglia 1 station, about 6,500 square meters, where the reinjection well is located; and
- Casaglia 2 and 3 station, about 11,700 square meters, where the two production wells are located.

Figure 4.1 shows the perimeter of the mining concession, and includes the "Casaglia 1" and "Casaglia 2" / "Casaglia 3" stations, and the connection between the two stations, which carries the geothermal fluid taken from the production wells to the reinjection well.

By means of heat exchangers, the geothermal fluid helps to heat the water used in the district heating system of the Municipality of Ferrara through a direct use of the geothermal resource. The heat exchange takes place downstream of a filtration system, when the fluid passes through a battery of three titanium plate heat exchangers, to which it transfers part of its caloric content (the inlet temperature of the fluid is about 100 - 102 °C, and the output is 65 °C). Once the heat exchange has taken place, the fluid is brought back through an underground pipe, to the location where the "Casaglia 1" reinjection well is located, where it is reinjected into the deposit.

Over the course of over 20 years, the flow of geothermal fluids produced and reinjected over has always operated between a maximum of 400 $m^3 h^{-1}$ in winter – during the time of maximum energy demand by users - and a minimum of 200 $m^3 h^{-1}$ in summer. The inlet and outlet temperature to the exchanger are basically kept constant; seasonal modulation of thermal power is obtained by reducing the flow rate extracted from one of the two wells, which in times of lesser demand can cause a temporary shutdown of the pump.

Operational experience has confirmed the capacity of the Casaglia 1 well to absorb 400 $m^3 h^{-1}$ with a head-to-head pressure of about 11-12 bar. The re-injection capacity is itself kept constant over time, ensuring full and continuous efficiency of the system. As regards the Casaglia Wells 2 and 3, both have maintained the levels of production, a symptom of the fact that the submersible pumps are located well below the current dynamic level, and this allows avoidance of cavitation whilst at the same time maintaining a margin of productivity increase through the increase of the pump flow.

Figure 4.2 shows the main data and features relating to the use of the geothermal reservoir and heating plant (2004).

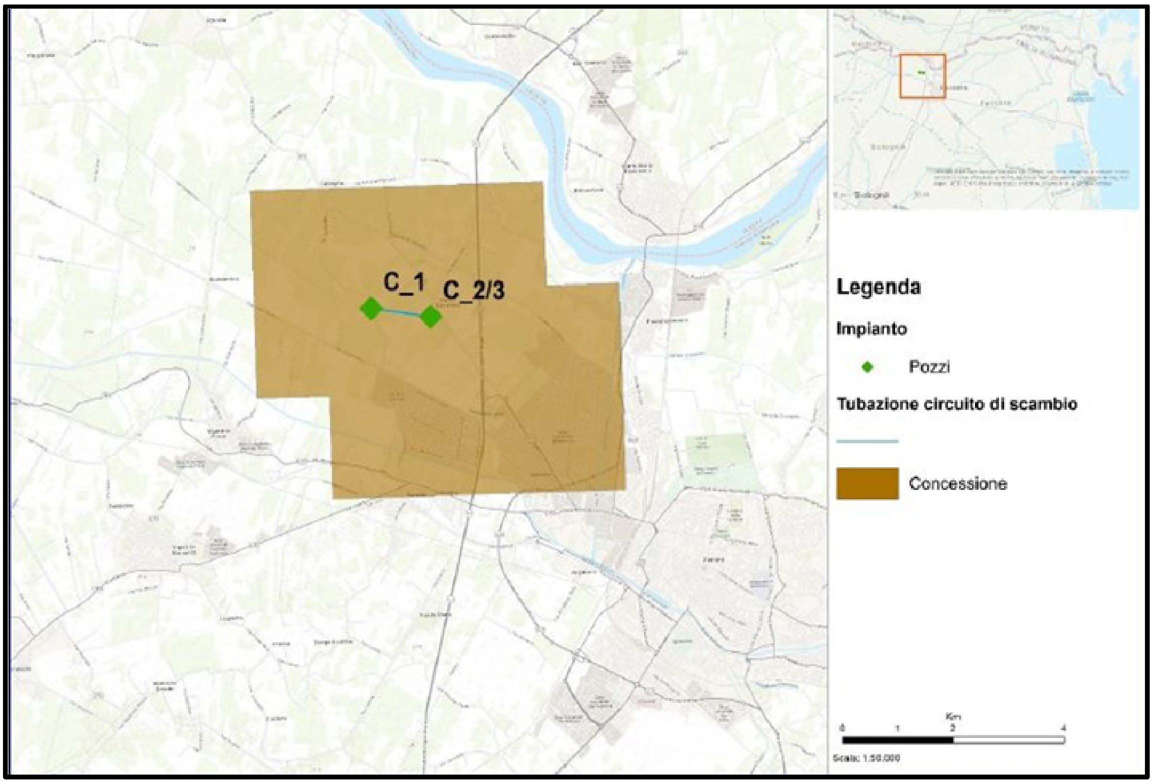
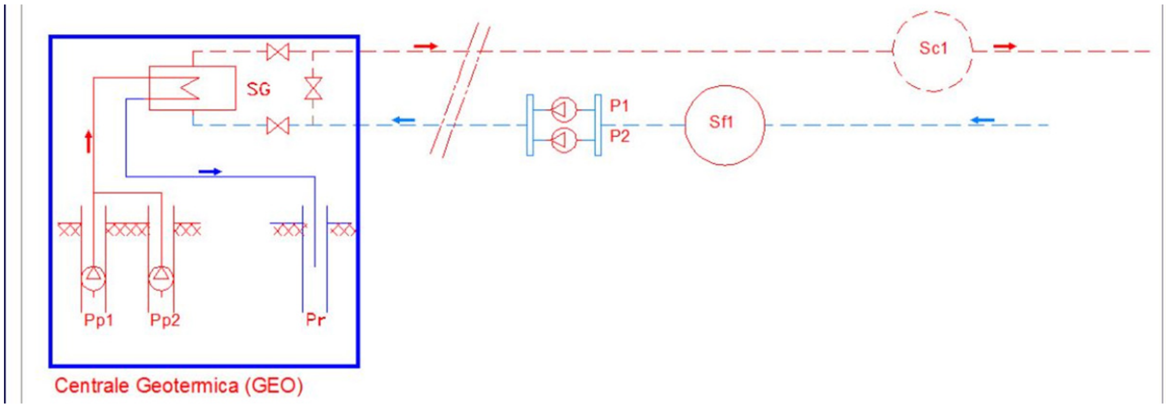


Figure 4.1. Map of the Casaglia geothermal concession (brown area). Geothermal wells are indicated by green diamonds (C_1 is the injection well, C_2/3 are the production wells).

Overall flow rate: 400 m^3 h^{-1}
Geothermal fluid temperature: 100 -105 °C
District heating fluid supply temperature: 90 – 95 °C
District heating fluid return temperature: 60 -65 °C
Nominal thermal output: 14 MW_{th}
Supports continuous use
Thermal energy supplied: 80 GWh per annum (for 2004)
Salinity of the fluid : about 65 g l^{-1}



Pp1 Withdrawal well n° 1 Qmax= 200 m^3 h^{-1} tp = 102 °C
Pp2 Withdrawal well n° 2 Qmax= 200 m^3 h^{-1} tp = 102 °C
Pr Reinjection well n° 1 Qmax= 400 m^3 h^{-1} tr = 70 °C
SG battery of 3 titanium plate exchangers
P1 Delivery pump Qmax = 400 m^3 h^{-1}
P2 Delivery pump Qmax = 400 m^3 h^{-1}
Sf1-2 Cold storage tanks tf = 60 °C
Sc1-2Hot storage tanks tf = 90 °C

Figure 4.2. Reference data from the Casaglia geothermal plant.

4.2 Geology, hydrogeology and geothermal setting

Tectonic setting

The present-day structural architecture of the Po Basin area is the result of Mesozoic rifting, acting on the Adria continental paleomargin, and subsequent Alpine/Apennines compressional phases. In the study area the convergence between the European and Adria plates since the Late Cretaceous is responsible for the thrusting. Several thrust systems of the Northern Apennines are mapped, buried and even blind, related to the Apennine compressional phases (Late Oligocene-Pleistocene), both acting on the previously deformed continental margin (Figure 4.3). One of the main Northern Apennines thrust systems is the Ferrara-Romagna Arc (Figure 4.3 Section C).

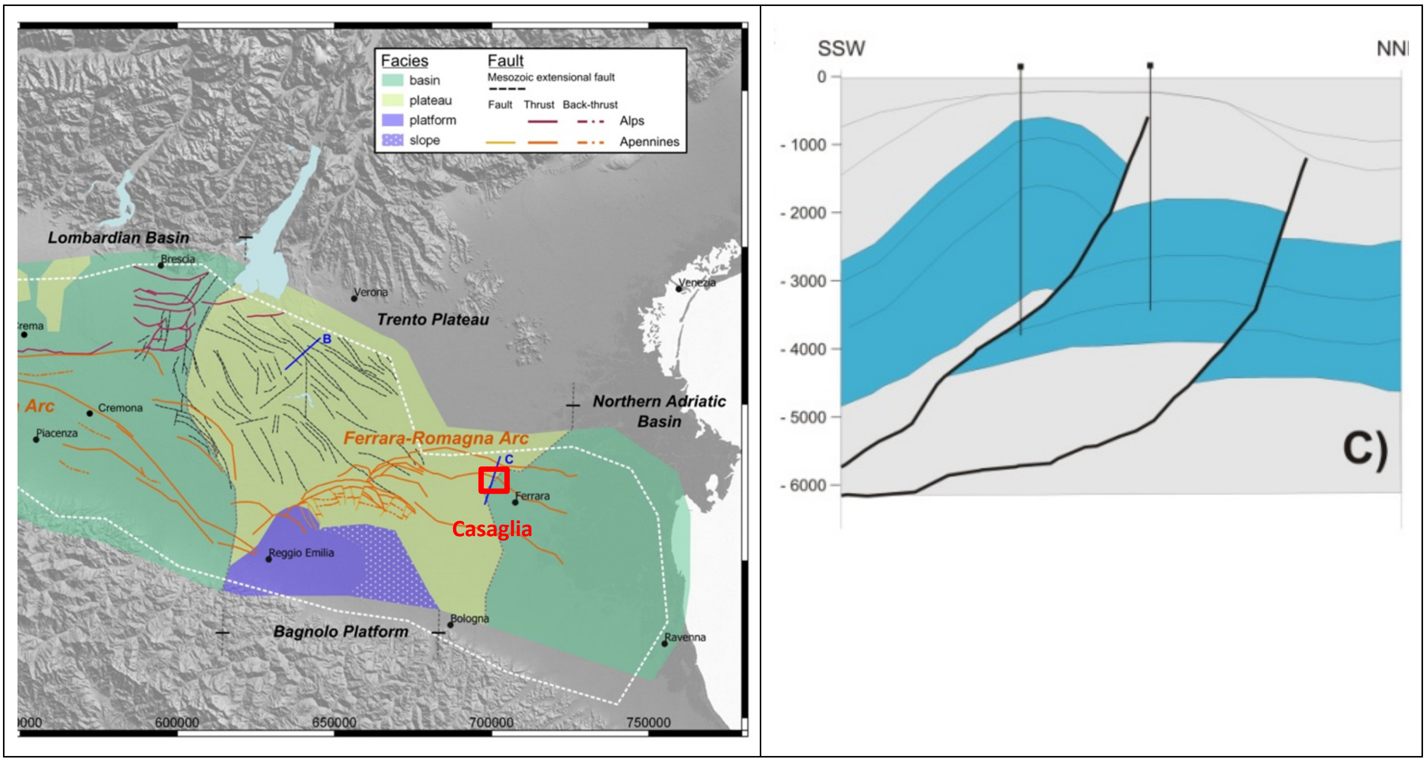


Figure 4.3. Paleogeographic domains and carbonate facies of the Po Basin; the mapped faults include Mesozoic extensional faults, and Alpine and Apennines thrusts with associated structures. The white dashed line is the boundary of the HotLime case study area. The blue lines are the cross-sections; see the Section C passing through the Casaglia sector. The blue color represents the carbonate reservoir units.

Geology

The geothermal reservoir of "Casaglia" consists of Unit TR-J (Late Triassic-Early Jurassic) that includes: i) Norian-Raethian dolostone and calcareous dolostone, dolomitized mudstone, and wackestone; and ii) Lower Jurassic intraclastic, oolitic, onkolitic, and fossiliferous grainstone-to-mudstone, sometimes dolomitized (mainly at the base), calcareous dolostone, dolomitic limestone, dolostone, stromatolitic grain-to-wackestone and mudstone, with local paleokarst. The deposits sedimented in shallow-water carbonate platform environments: the Trento Plateau that evolved from a carbonate platform (Late Triassic-Early Jurassic) to a pelagic plateau. The maximum thickness of the carbonate units is up to 2,000 m. In Casaglia sector, the top of the reservoir is very shallow (less than 1,000 m; Figure 4.3).

Geothermal Setting

In the Ferrara Folds sector the geothermal gradient range is between 32 and 80 °C km^{-1}. The positive geothermal anomalies are located in the Ferrara folds sector, probably due to recent structural evolution, and controlled by the position of the top of carbonate succession. The geothermal setting is determined by orogenic belt/foreland basin, i.e., a sedimentary basin within a wedge-shaped foreland basin adjacent to an orogenic mountain belt.

In the Casaglia sector the geothermal resource is classified, according to Muffler and Cataldi (1978), as intermediate-temperature resources (90 - 150 °C), as the maximum temperatures recorded were around 113 °C to the depth of 2,422 m (“Casaglia 1” well). Given the geological and structural setting and the temperatures present in the reservoir (< 120 °C), it is believed that the heat transport is mainly of the conductive type (Fourier's law) and only secondarily due to the convective component. The “Casaglia” reservoir can be classified as a “warm water system” or “low-temperature system” (Kaya et al., 2011; Diaz et al., 2016). This is the most commonly encountered geothermal system in nature (< 120 °C, i.e., h < 504 kJ kg^{-1}). “Low-temperature systems” in sedimentary basins are simply warm water systems. In these systems, deep ground water is heated by the local natural thermal gradient, mainly through conductive heating.

The geothermal fluid is composed of fossil high salinity waters (65 g l^{-1}) as the reservoir is confined by a powerful thickness of “cap rock” (siliciclastic Oligo-Miocene succession) and laterally limited by the main thrusts of the Ferrara Folds System.

The SGSS developed a temperature model of the Casaglia sector using FeFlow 6.1 based on the elaboration of a 3D geological model (Figure 4.4 (a)) and on the hydrogeological and petrophysical parameters present in the documentation of the Casaglia research permit from 1983. From the processing the heat rate budget was calculated, which made it possible to estimate the heat flow present for certain sectors. A first very interesting fact is how the heat flux present in the sectors of maximum structural high is about 80 - 85 mW m^{-2} while that in the low structural sectors is comparable to the heat flux which is also found in bibliographic studies relating to the Po basin, i.e., about 40 - 35 mW m^{-2} (Figure 4.4 (b)).

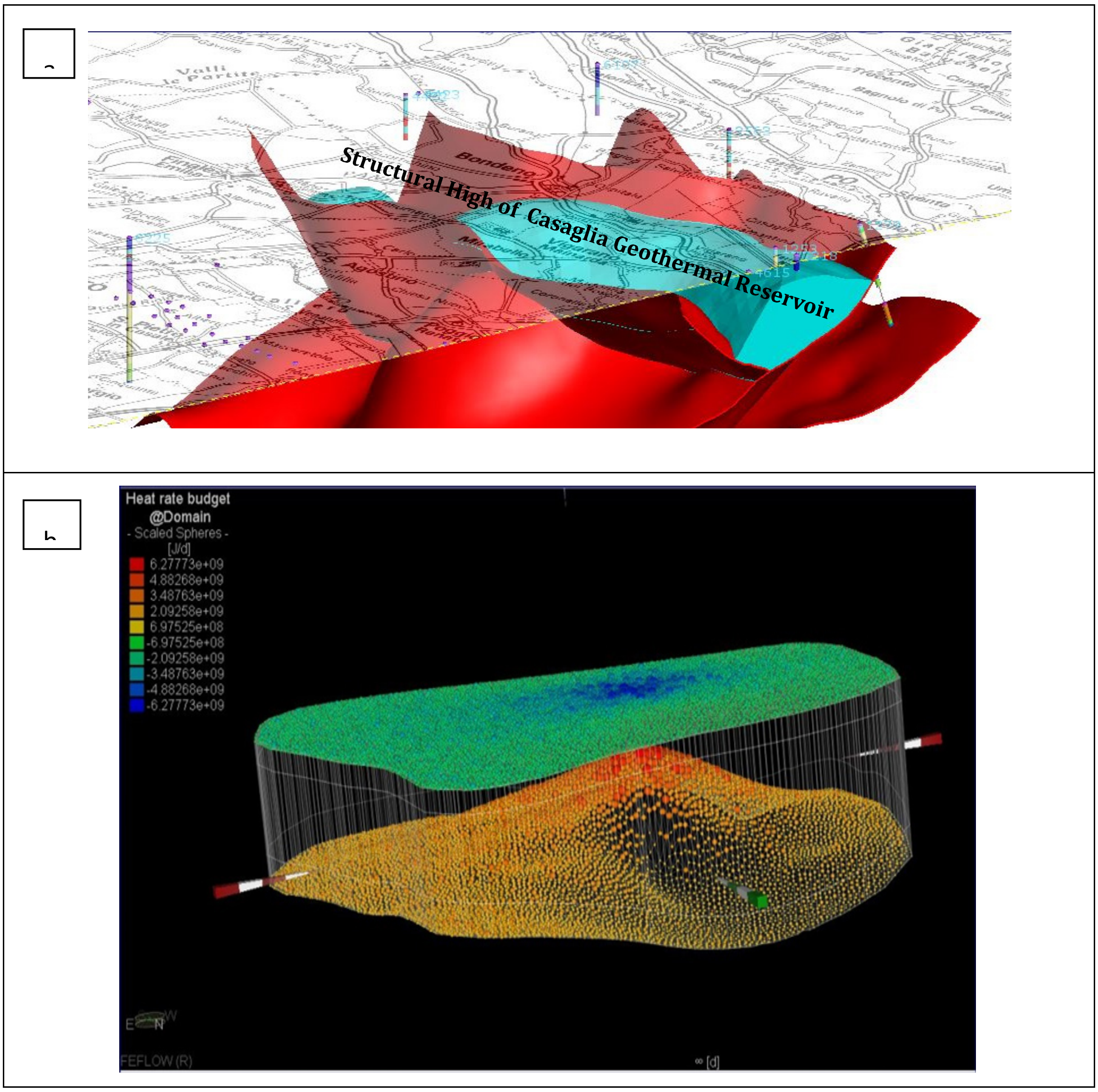


Figure 4.4. a) Geological model of Casaglia sector (SGSS, 2019). b) Heat rate budget from SGSS temperature model, FeFlow 6.1.

4.3 Resource assessment

The productivity tests offered high values as shown by the P.I. (Productivity Index) of the "Casaglia 1" well, calculated as 16 m^3 h^{-1} bar^{-1} and for the "Casaglia 2" in 60 m^3 h^{-1} bar^{-1}. The geothermal fluid at well head has a temperature of 102 – 105 °C and salinity more than 66 g l^{-1}. In the research permit documents it is reported that “starting from an aquifer surface of about 14 km^2, maximum usable area for the Ferrara project, geothermal project with wells pushed up to 2,000 m, and calculating an average thickness of the carbonate/dolomite aquifer, evaluated around 900 m, it has been calculated that in the subsurface Ferrara sector there is a reserve of 885 x 10^{12} kcal”.

The permeability of the "reservoir" is provided by the presence of secondary porosity due both to the micro-fracturing within the carbonate succession and to the fracturing in the vicinity of the main fracture systems. Based on the exploration results derived from the Casaglia wells, a series of parallel fractures with strong permeability with an east-west direction and inclined by about 70° was highlighted.

It should be noted that the pumping system has also been optimized with the replacement of the submersible pump. On the basis of the new monitoring data, it has been seen that the P.I of the intake wells is approximately 138 $m^3\ h^{-1}\ bar^{-1}$, which confirms the high hydraulic transmissivity of the carbonate reservoir.

Figure 4.5 shows the map of the Heat in Place (HIP) ($Gj\ m^{-2}$) in the Ferrara sector, using the volumetric method, developed by the United States Geological survey (USGS) and reported by Muffler & Cataldi (1978) and considering a T_{ref} of 18 °C. The distribution of the thicknesses and the depth of the top of the carbonate succession explain the strong variability (range) of values in the HIP maps. The factor that therefore most influences the distribution of HIP is mainly the highly heterogeneous geological setting especially in the "Ferrara Folds" sector.

4.4 Summary of the project

In April 2017, the tender was launched for the reassignment of the concession, which is now entrusted by ARPAE to the Temporary Business Grouping (RTI) between Enel Green Power Spa and HERA Spa (which together constitute the proponent of this project). The concession was subject to the launch of an Environmental Impact Assessment (VIA) procedure. At the end of the VIA procedures in 2019 the new concession for the exploitation of the geothermal resource was awarded. In the new concession the entire part of the heat exchange on the surface has been optimized; in this way, with the same volumes and flows drawn from the geothermal source, the annual energy production has risen to about 115,000 – 120,000 MWh.

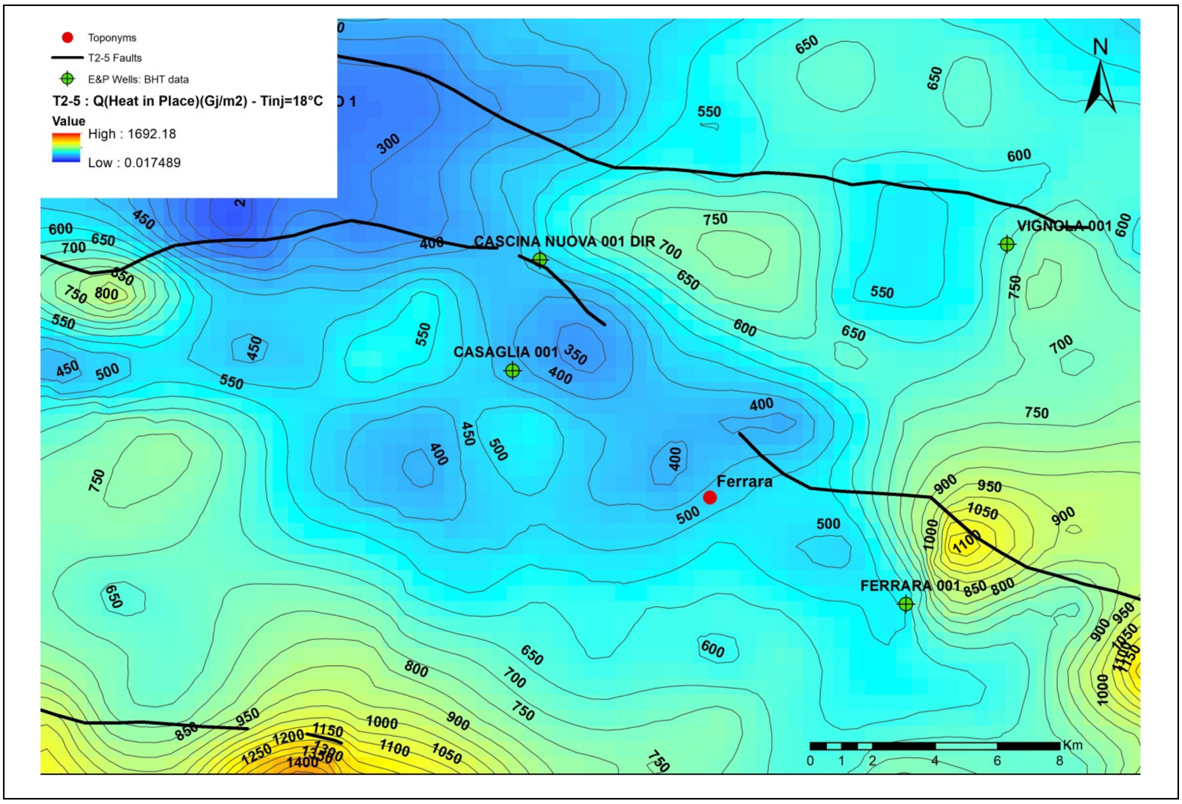


Figure 4.5. Portion of the HIP map (Gj m^{-2}; T_{inj}=18 °C) in the Ferrara sector

The plant is currently being evaluated for reinjection at a temperature of 30 °C with the same flow rates, which would represent an increase in thermal production of 40%; in actuality the reinjection temperature is 60 °C. A further increase in production could be obtained, keeping the current mineral assets unchanged, if it were possible to exceed the limit currently existing on the re-injectable flow. In fact both the production wells and the reinjection well still maintain a margin of hydraulic capacity. Of course, the achievable technical limit should be verified experimentally and, depending on the maximum extractable flow rates, any adjustments should be made to the existing systems (submersible pumps, filters, coil of exchangers, piping). Once the maximum achievable production has been identified, it would be necessary to predictively evaluate the sustainability of the cultivation, and verify it experimentally with an adequate observation period.

The renewal of the geothermal concession has shown how the cultivation of the resource has been sustainable over time and has not caused critical issues and/or significant environmental impacts. In general for the private sector the main deterrent in the development of private geothermal plants is the distrust of citizenship regarding the impact these can have on the subsurface. In particular, the main problems causing concern, first of all, the induced seismicity and secondly the subsidence. In recent years, after the 2012 seismic event in the Emilia-Romagna region, important studies have been launched regarding induced seismicity such as the ICHESE Commission (International Commission on Hydrocarbon Exploration and Seismicity in the Emilia Region) and Laboratorio Cavone (a project aimed at developing monitoring and research activities in the "Mirandola" hydrocarbon cultivation concession and possible correlations with induced seismicity).

Furthermore, in general, the length of the authorization procedures and the uncertainty about the economic incentives to geothermal energy can also represent deterrents. For local authorities the deterrents coincide with those listed for the private sector in addition to the fact of being afraid of public opinion. It should be emphasized that in general and especially for public bodies there is little knowledge on the potential of the geothermal resource and on its possible uses.

4.5 Future work and recommendations

To favour the development of geothermal energy and to improve the public knowledge it is necessary to implement specialized studies (geological and geothermal) both at the regional and at the local scale that allow to better estimate any possible negative effects both in the medium and long term. Another important aspect is improving how to transfer the acquired knowledge to inform public opinion and to the local population whose territory is affected by geothermal research permits.

Due to the considerable density of geophysical data and exploration wells, mining risk is usually relatively low in this area (good knowledge and estimation of temperature data and total thickness/gross pay of the geothermal reservoir). The location of the data is relatively homogeneous throughout the Po Valley and therefore within the T2.5 pilot area.

An aspect that can be highlighted is how in the eastern sector (Emilia-Romagna and Veneto Regions) the total thicknesses of the geothermal reservoir (carbonate/dolomite) are considerable and of the order of several hundred metres with a relatively regular distribution, especially in the Lombard-Venetian monocline.

Overall, the example of the Casaglia geothermal heating plant demonstrates the high geothermal potential of the area, along with its sustainability over time and low environmental impact. The main future developments required, in order to accelerate and encourage the acquisition of new research permits and concessions, are:

1) an incentive plan (feed-in tariff) with security and relatively long duration (at least 10 years); and

2) a regulatory simplification that allows the authorization of exploration wells to be concluded in a relatively short timeframe (e.g., no more than 2 - 3 years). Currently in Italy for medium enthalpy geothermal plants it takes at least 3 - 4 years to obtain authorization for the exploration well/s.

4.6 References

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5 Case study 04: Californië, NETHERLANDS

Author: J.G. Veldkamp (TNO)

5.1 Overview

Since the start of exploration for geothermal energy around 2006 (drilling of the Vandenbosch-GT-01 well), its focus has mainly been on reservoirs that had previously been targeted by the oil and gas industry: sandstone reservoirs of Permian, Jurassic and Cretaceous age in the western and northern parts of the Netherlands (figure 5.1). Apart from various coal exploration wells which encountered carbonate rocks belonging to the Dinantian age Zeeland Formation at shallow depth in the southernmost part of the country, the Dinantian had received relatively little attention. The oil and gas industry had drilled various exploration wells which targeted the Dinantian (from Winterswijk-01, in the east in 1977, through Uithuizermeeden-02 in 2001 and Luttelgeest-01 in 2004, in the north, and also various wells in the southeast between the late 70s and early 90s), but they were all dry. Most encountered a tight reservoir with the exception of the Thermae2000 wells, located east of the town of Maastricht, which found the reservoir at depths between appr. 100 and 400m, and have sufficient flow for balnaeological purposes. The drilling of the first Californië geothermal triplet which targeted the Dinantian limestones in 2012 (CWG: wells Californië-GT-01, -02 and -03) was therefore an innovative step forward. The success of CWG triggered the drilling of a second doublet nearby in 2016 (CLG: wells Californië-GT-04 and -05). Both geothermal systems produced heat for greenhouses.

Figure 5.1. Doublets in the Netherlands showing the reservoir age. Heerlen Minewater produces from abandoned mine shafts.

5.2 Geology, hydrogeology and geothermal setting

The development of the Dinantian reservoir flanking the London Brabant massive was outlined in Hotlime deliverable D2.0 (Case Study T2.4). The reservoir consists of rocks formed on carbonate ramps flanking the London Brabant Massive in the Southern part of the Netherlands (figure 5.2), and isolated carbonate build-ups further north (Mozafari et al., 2019). In between the ramps and build-ups, in the deeper parts of the basin, shales were deposited. The carbonate rocks were exposed subaerially various times between the Carboniferous and the Cenozoic, resulting in multiple phases of karstification (Bouroullec et al., 2019; Mozafari et al., 2019). The most intense phase of karstification is thought to have occurred prior to the deposition of the Chalk limestones of Cretaceous age.

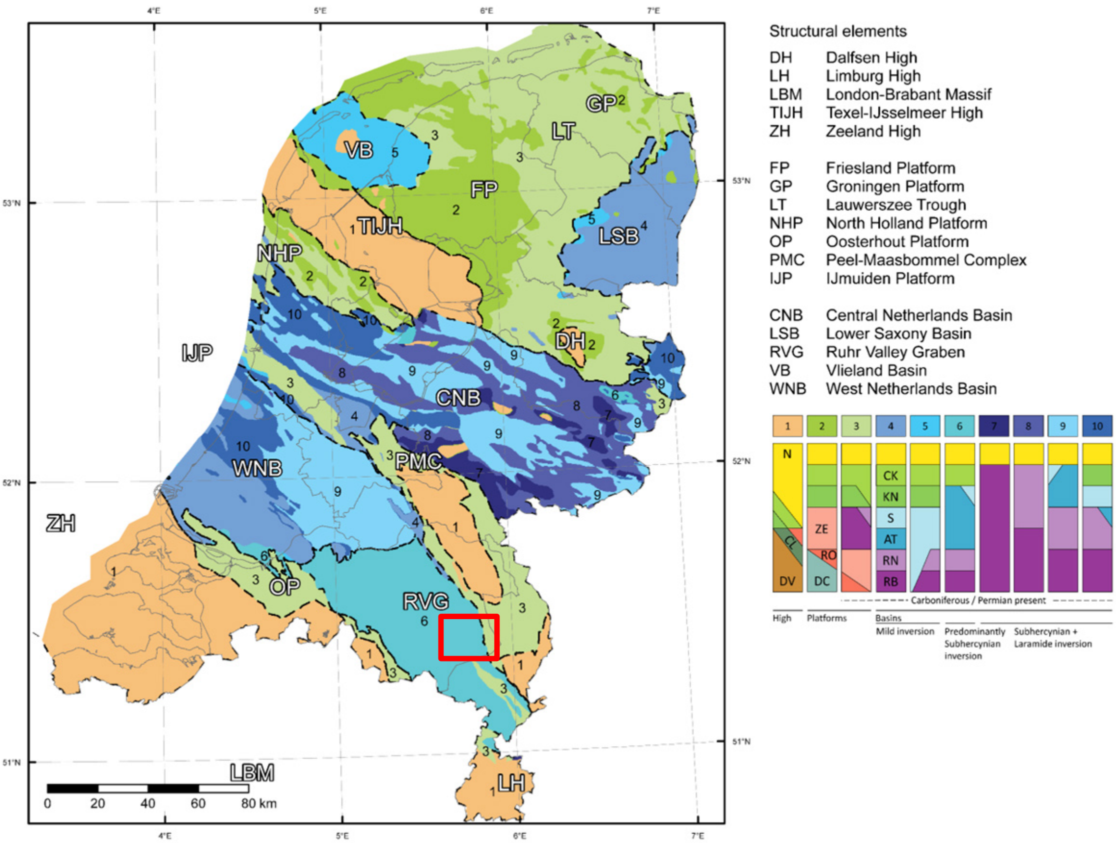

Figure 5.2. Structural elements of the Netherlands (Békési et al., 2020; modified after Kombrink et al., 2012).

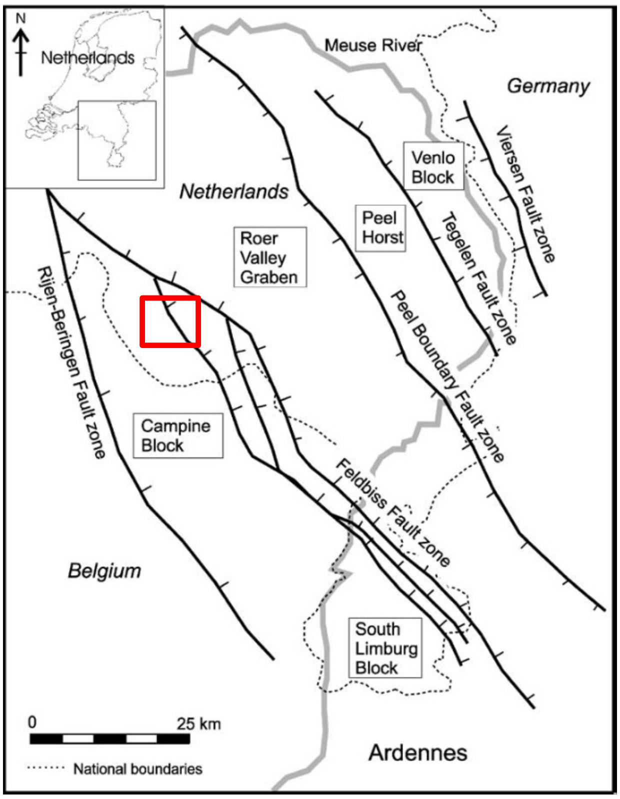

Figure 5.3. Tectonic features of the Roer Valley Rift System, the Netherlands (Houtgast et al., 2002). Box indicates location of geothermal operations.

In the study area, rocks of the Zeeland Formation overlie those of the Devonian Condroz Group and the Bosscheveld (mostly quartz cemented sandstones) and Pont d'Arcole (shale) Formations. The rocks belong to the platform facies; the basinal shales have not been targeted for geothermal production. They are covered by Namurian shales towards the southwest, and by Permian, Triassic, and Cretaceous sandstones and marls, as well as unconsolidated siliciclastic sediments belonging to the Cenozoic towards the northeast (figure 5.2, figure 5.5).

From a structural geological point of view, the target area is located on the Peel-Maasbommel High Complex (PMC, figure 5.2, 5.3). The Peel-Maasbommel Complex is situated to the Northeast of the Ruhr Valley Graben (RVG, figure 5.2, 5.3). In this graben continuous subsidence resulted in the deposition of thick successions of rocks of Triassic and Jurassic age. After a period of inversion and erosion, deposition continued, resulting in a thick succession of sediments of Cenozoic age. The PMC is separated from the RVG by a number of faults, the most important one being the Peel Boundary Fault Zone. The Peelhorst and Venlo blocks are both located on the PMC, and are separated from each other by the Tegelen Fault Zone. The faults in the area are still active nowadays, which is emphasized by the observation of thickness variations of recent deposits over the various faults (Houtgast et al., 2002). On April 13 1992 an earthquake occurred near the city of Roermond, situated about 40 kilometers to the Southwest from Californië in the Ruhr Valley Graben. It had a moment magnitude of 5.8. It is the strongest known earthquake which occurred in the Netherlands since the Royal Meteorological Institute of the Netherlands (KNMI) started registering. As can be seen from figure 5.6, the Ruhr Valley Graben area is tectonically very active. The location of the Californië doublets is further to the north, but here also tectonically induced seismic events have taken place in the past.

5.3 Resource assessment

For the resource assessment, the determining factors are the net thickness of the reservoir, the permeability and the depth / temperature. All were reported for the application for the SDE+ subsidy (‘Stimulering duurzame energieproductie’ or Stimulation Renewable Energy Production) for the CLG doublet (Broothaers, 2013), and were checked, when possible, against the data of the five wells which are all in the public domain.

The gross thickness of the reservoir was initially determined on the basis of the two seismic lines that were shot prior to drilling the CWG triplet. For the CLG doublet, the well results of the first three wells were used for updating the reservoir model. Figure 5.5a shows the (gross) thickness of the reservoir, which significantly thins towards the Venlo Block, from about 900 meters in the Tegelen Fault Zone, to about 100 meters on the Venlo Block. The cross section suggests that the thickness variation is in part due to erosion, given the absence of nearly the complete Namurian through Triassic sequence over the Venlo block, but possibly thickness variations were already initiated during deposition. This thickness variation, in combination with the sparse available seismic data, introduces considerable uncertainty about the thickness at locations that are not on or directly adjacent to the seismic lines.

Porosity and permeability in may exist either in the matrix of the rock, or in fractures. Analysis of available core material and petrophysical logs shows that the matrix porosity and permeability is very low (Carlson, 2019). Therefore, geothermal production should come from fractures and/or karstified zones (the former is often accompanied by the latter), which is the case for the Californië doublets. The net-to-gross ratio of the reservoir is usually defined by a porosity cutoff. Because the largest part of the Zeeland Formation has very low porosity and permeability, it could be considered very low net-to-gross. (Broothaers, 2013) defined the net-to-gross as 5%, which would result in a net thickness of 0.05 * 900m = 45 m (for CAL-GT-01 and -03). If the porosity cutoff is set very low, on the other hand, the net thickness will be higher, but as a result, the average permeability lower.

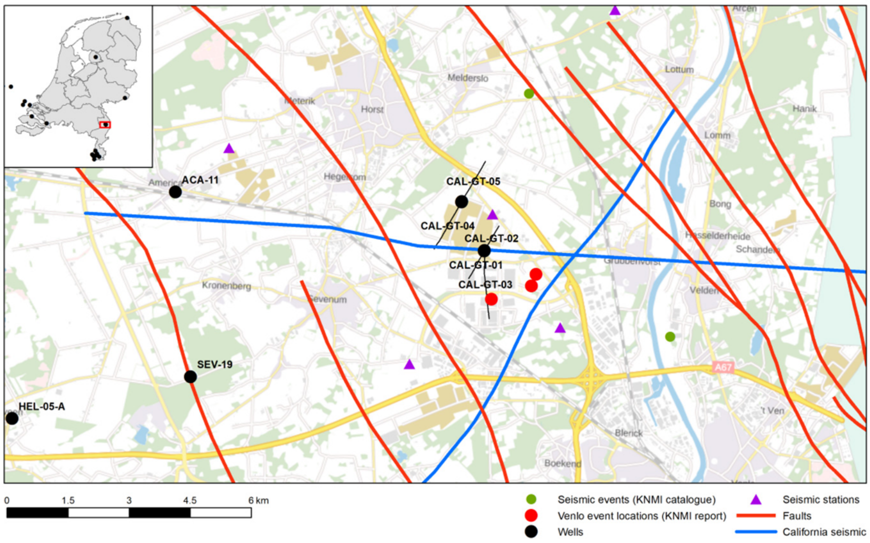

Figure 5.4. Overview map of the area around the Californië geothermal systems. The inset map shows the locations where the Dinantian was drilled. The fault southwest of the wells is the Tegelen fault. Wells 1, 2 and 3 constitute the CWG triplet, wells 4 and 5 the CLG doublet.

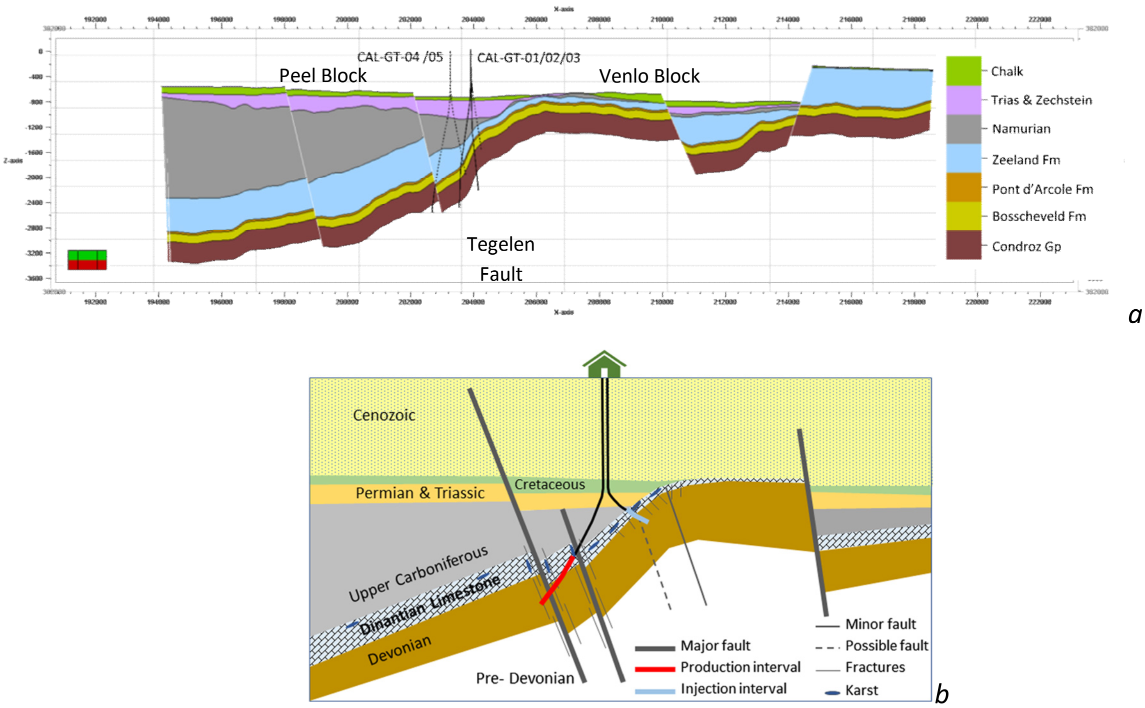

Figure 5.5. *a* Cross section along the West-East seismic line shown in Figure 5.4 (Cenozoic units not shown). *b* Sketch of the CWG and CLG geothermal systems showing the targeted fractured Dinantian limestones and Devonian sandstones ((Mijnlieff, 2020) modified after (Califonië Lipzig Gielen BV & VITO, 2013).

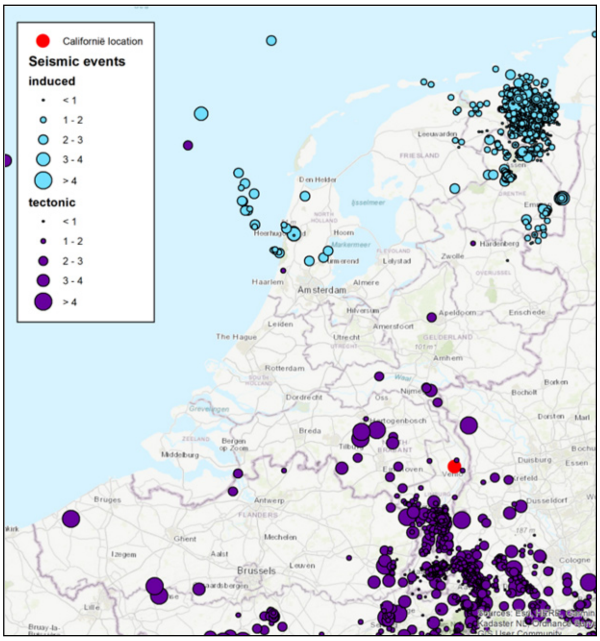

Figure 5.6. Tectonic and induced seismic events in the Netherlands since 1911. Source: KNMI data center (www.knmi.nl), data downloaded 2021/05/21.

A complicating factor is that, although the porosity and permeability of the *reservoir* is very low, the porosity and permeability within the Tegelen fault zone is high (fracture and/or karst permeability). Therefore it is more relevant to define the transmissivity (product of thickness and permeability) than net thickness. The transmissivity is in fact what is measured by the well test. For the production test of CAL-GT-01 a permeability of 6100 mD was derived when the productive interval was assumed to be 50m (@218 m^3 hr^{-1}). For the injection test on CAL-GT-02, the derived permeability was 260 mD (@240 m^3 hr^{-1}) (Broothaers, 2013). What complicates the matter of permeability further is the fact that part of the rocks in the fault zone do not belong to the Dinantian Zeeland Formation, but to older units of Devonian age, which have a low primary permeability, but which probably contribute to the production from faults and fractures.

The temperature of the produced water during the well tests exceeded 80 °C (measured @ESP (Broothaers, 2013)), so the reservoir temperature is slightly higher. It is difficult to calculate a temperature gradient, based on the recorded temperature and the depth of the reservoir; because it is unknown which depths of the reservoir contribute which amounts. The CLG doublet found even warmer water of 87 °C at slightly larger depth (Burghout et al., 2019).

The CWG doublet has produced an average rate of 234 m^3 hr^{-1} (based on reported monthly averages), the CLG doublet 132 m^3 hr^{-1}.

5.4 Summary of the projects

After the CWG system had been in operation for five years, and CLG for two years, two events caused the suspension of both.

The target of the wells had been twofold: production from fractured rocks, induced by the presence of the Tegelen fault (wells CAL-GT-01, -03 and -04), and injection in a direction away from the Tegelen Fault, aiming at karstified rocks, induced by pre-Chalk exposure events (wells CAL-GT-02 and CAL-GT-05).

The CWG system was designed to produce from two wells drilled in the Tegelen fault zone, and inject in a single well drilled away from the fault zone, in karstified horizons. Shortly after the completion of this triplet, the uncased part of the CAL-GT-02 well became blocked. Several attempts to clean this well were unsuccessful, thereby effectively reducing the triplet to a doublet. The lower part of well CAL-GT-03, ending in the Tegelen fault zone, had also become blocked. It was therefore decided to use well GT-03 as an injector because injection was now expected not to take place directly into the fault zone, but in a karstified zone higher up in the well. A temporary permit was then issued by the State Supervision on the Mines (SodM) to CWG, allowing the injection in CAL-GT-03 for a limited duration. The reason not to issue a permanent license for injection in CAL-GT-03 was the risk that injection near the Tegelen fault might induce a seismic event by increasing the pressure in the fault zone. Initially, the pressure in the fault zone was only expected to become lower, because production would be from this zone, while injection would be away from it, thereby reducing the risk of induced seismicity. Apart from safety issues, this setup also enhanced the risk of early breakthrough of the cold water from CAL-GT-03 to CAL-GT-01. Because multiple attempts to clean CAL-GT-02 failed, making injection away from the fault zone impossible, the criteria described in the permit were not met, and the system was suspended as of May 2018 by order of the State Supervision of the Mines (SODM, 2018).

The suspension of the CWG triplet did not affect CLG, which was initially allowed to continue production. On August 25, 2018, however, a small seismic event occurred in the area, with a peak ground velocity (PGV) of 0.03 mm s^{-1}. As a matter of precaution, the system was then suspended on August 28, 2018. On September 3rd, another seismic event took place, this time with a PGV of 1.1 mm s^{-1}, and a magnitude of 1.7. The events were monitored by the network of 5 geophones that had been installed around the operations (figure 5.4). An attempt was made to determine where the event came from, and whether it was a tectonic or induced event. Various potential locations for the hypocenter were calculated (red dots in figure 5.4), all close to the Tegelen fault (known to be tectonically active). Although the events appeared to occur several kilometers below the geothermal reservoir (Burghout et al., 2019; Spetzler et al., 2018), they are temporally correlated to production stops in the CWG doublet (Baisch & Vörös, 2019; Buijze et al., 2019). More recent evaluations using alternative seismic velocity models have resulted in hypocenter locations close to the injection location. The lack of sufficient control on the subsurface layer and fault geometry and seismic velocity information results in siginificant uncertainty about the exact location of the hypocenter.

The Seismic Hazard Assessment report (Baisch & Vörös, 2019) states that it is likely that the recorded seismic events can be correlated to the geothermal production, but also that ‘the seismic hazard assessment conducted in the current study concludes that resuming geothermal production with the CLG doublet (with production rate of 200 m^3 h^{-1}) will most likely not cause seismicity on the known faults'. The State Supervision on the Mines had the SHA report reviewed by an independent reviewer of the Swiss Federal Office of Energy. The State Supervision concluded that 'despite the extensive investigation by the geothermal company CLG, State Supervision of Mines has established that ultimately there is insufficient scientific data about the specific underground situation to be able to produce geothermal energy responsibly. As a result, the uncertainty about the risk of injuries and tremors causing damage for [CLG] staff and local residents remains too large' (SODM 2019).

5.5 Future work and recommendations

Whereas the problem of CWG can be viewed as a technical problem which could be overcome in principle, by drilling a sidetrack or a new well, the problem of CLG is more severe, and comes down to the question of whether a geothermal operation in this area may induce seismic events, and if so, if they are acceptable or not. The subsurface of the Californië area is not very well understood, among other reasons due to the limited amount of seismic data available. The importance of the nearby Tegelen fault is acclaimed by all authors, but it is yet impossible to attribute the recorded seismic activity to either the tectonic regime, or the geothermal production. It is likely to be a combination of both. Burghout et al. (2019) proposed a traffic light system (TLS, figure 5.7), which was not acceptable by the State Supervision on the Mines.

TLS Status			
Definition	PGV < 0.1 mm/s	PGV ≥ 0.1 mm/s	PGV ≥ 0.3 mm/s
Actions	none	1. investigate likely cause and potential mit-igation measures 2. report to regulator	1. stop operations 2. report immediately to regulator

Figure 5.7. Traffic light system (TLS) proposed by Burghout et al. (2019) for the CLG system.

Currently, both geothermal systems, CWG and CLG do not have permission to restart their operations. It is very unlikely that, in the current situation, other exploration permits will be issued in the area, unless safe production can be proven. This has its bearing on the entire play, especially that part which lies in the tectonically active area indicated by the events in , whether the operation may be close to active faults or not. A better understanding of the geological structure may help in determining whether operations can be allowed.

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6 Case study 05: Munich cluster, GERMANY

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6.1 Overview

The North Alpine Foreland Basin, also known as the Molasse Basin, despite lacking any surface geomanifestations related to geothermal potential, over the last decades turned out one of the most prolific geothermal targets in Central Europe. Early indications of thermal water aquifer systems emerged since the hydrocarbon exploration campaigns starting in the 1930s. Encountering thermal water at a depth of about 1,000 m the Füssing (Lower Bavaria) oil exploration drilling in 1938 first furnished evidence. Initially, since the 1960s, the utilization of thermal waters was confined to balneological purposes. The 65°C thermal water tapped at 2,350 m depth during a 1983 oil exploration near Erding northeast of Munich (#1 in Figure 6.1) was developed the first district heating utility of the Molasse Basin. Operating since 1999, it triggered further geothermal projects in the north and northeast of Munich in the early 2000s.

Secured by a first of its kind exploration risk insurance, Unterhaching municipality project south of Munich (#2 in Figure 6.2), starting in 2004, was the first geothermal energy project aimed at power production in addition to district heating. Drilled to 3,580 m TVD, thermal water of about 120°C was encountered allowing a flow rate of 150 $l\ s^{-1}$ for continuous operation. District heat supply commencing in 2007 and 3.36 MW_e power generation from 2009 on made Unterhaching a highly successful geothermal installation overachieving expectations and, already during its construction phase, stimulated further heat and/or power projects in the southeast of Munich.

At present, the Greater Munich area features 17 geothermal installation plants in operation, one triple doublet under construction (pale red in Figure 6.1), but also two failed projects due to insufficient flow rates (marked **X** in Figure 6.1).

6.2 Geology, hydrogeology and geothermal setting

The North Alpine Foreland Basin developed along the northern margins of the emerging European Alpine chain some 35 million years ago. As part of the Alpine-Carpathian Orogen the Alps have resulted from the collision of the of the Adriatic and European plates during Cretaceous and Tertiary, culminating in a continent-continent collision between Africa and Europe when the northward thrusting nappes emerged as a mountain range and the weight of the orogenic wedge made the European Plate bend downward. As a result a deep elongated depression along the forefront of the emerging orogenic belt developed, a foreland basin progressively infilled with 'Molasse' sediments eroded off the northward thrusting Alps during Tertiary and the southern parts deformed and incorporated into the Alpine orogenic wedge. The large-scale downwarping of the European plate and its overburden resulted in tilting of the shallow marine shelf deposits such as the Upper Jurassic carbonates, which now form the south dipping footwall of the Molasse Basin extending beneath the Alpine Orogen.

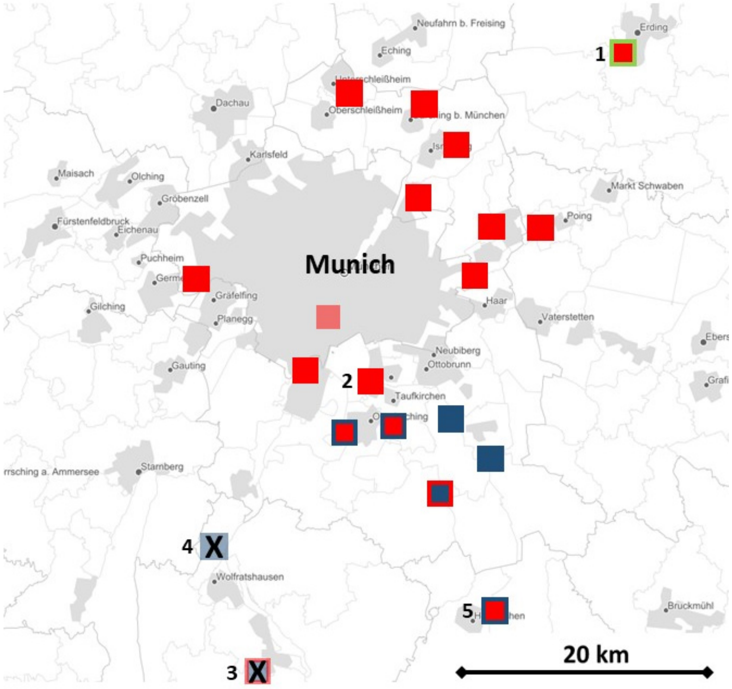

Figure 6.1. Geothermal installations of the Greater Munich area as of 2020. The color of the squares indicate the present main use, square rims indicate the secondary use: Red - district heating; Blue - power generation; Green - balneology / spa; Pale red - under construction; X – failed. Numbers refer to the projects mentioned in the text.

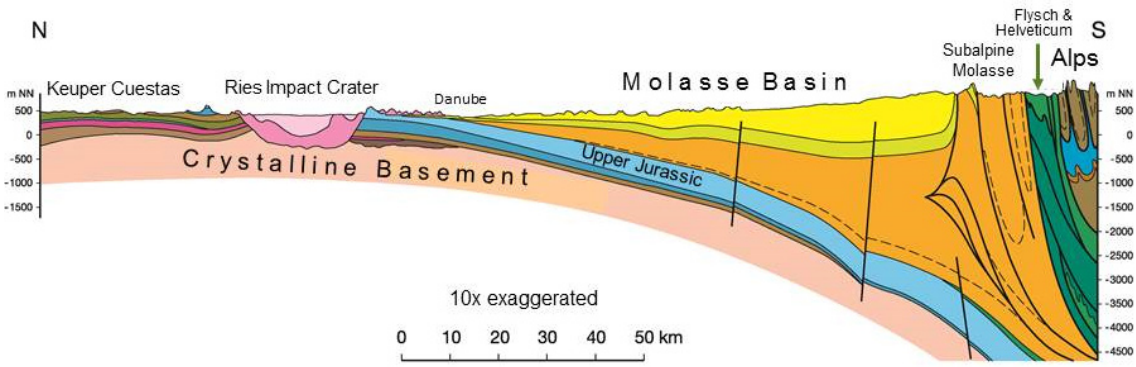

Figure 6.2. Geological section across the southern Cuesta Region, the Alpine Foreland and the Pre-Alps in western Bavaria (from Diepolder et al. 2019b after Doppler et al. 2004, modified). The south-dipping Upper Jurassic karstified carbonate rocks forming the footwall of the Molasse Basin feature the most prolific geothermal aquifer in Central Europe.

Even though foreland basins are considered hypothermal (cooler than normal) with a low geothermal gradient and heat flow (Allen & Allen 2005) the North Alpine Foreland Basin, particularly the South German Molasse Basin, features the highest geothermal potential in Central Europe. Due to the highly productive Upper Jurassic carbonate aquifer at great depths an average geothermal gradient of about 30 °C km^{-1}, but varying considerably on a regional scale, allows for viable geothermal installations.

Wide areas of exposed Upper Jurassic carbonate rocks in the Franconian Alb (almost completely replaced by the Ries Impact Crater in Figure 6.2) contribute to the sufficient recharge of the buried aquifer. However, carbonate plays are highly anisotropic and heterogeneous with the groundwater yield of the hydrothermal aquifer being all but equally distributed. Therefore the principal challenge for geothermal projects is to identify and tap suitable structures that enduringly ensure a sufficient flow rate. It is generally acknowledged that the groundwater yield in carbonate reservoirs is principally controlled by fault, fracture and karst conduits. The quality of carbonate reservoirs with respect to the hydrothermal potential thus is governed by the fracture and fault network and the degree of dolomitization and karstification widely controlled by the facies type. As all realms of the Upper Jurassic aquifer featuring an adequate temperature for viable geothermal utilization are at a depth of least 2,000 m, buried under a thick succession of younger undeformed sediments, all faults are blind faults that cannot be detected and traced from surface exploration.

6.3 Resource assessment

Geothermal resource assessment of low enthalpy systems, thus, by nature, at great depths, faces the problem of high degrees of uncertainties for both subsurface geometries and petro-physical property data. Characterizing the highly anisotropic and heterogeneous carbonate plays at depths is particularly challenging because borehole information coverage, imperative for petro-physical property assessment, increasingly dwindles with increasing depth. Even though the Molasse Basin features an unusual high number of deep downhole data, originating especially from the 1950's to 1990's hydrocarbon exploration campaigns, this subsurface information is scattered and clustered with large scale voids in between, hence good for characterizing only a few focal areas of hydrocarbon prospectivity and for deriving characteristics deemed generic.

The only crucial factor that can be reliably assessed on a larger scale and at the forefront of geothermal exploration before drillings are carried out is the fracture density. Generally, the highest density of discontinuities is found in the vicinity of faults which can be clearly identified in reflection seismic.

Accordingly, legacy seismic surveys for hydrocarbon exploration, acquired by the concessionaire, have been the starting point for early geothermal resource assessments in the Greater Munich area (and elsewhere), often supplemented by additional, more focused surveys commissioned by the concessionaire. With the improvement of the tools and novel methods for seismic surveying, reprocessing and interpretation, specifically the implementation of 3D seismic surveys, the knowledge of the structural set-up of the Greater Munich area incrementally improved. Formerly subseismic, i.e. undetectable features, specifically soft links between faults such as relay ramps and horsetail splay structures became apparent and incrementally improved the overall picture of the geological situation.

However, it must be emphasized that this gain of knowledge is in the aftermath of explorations, quasi a retrocognition of the geological situation in license areas where a geothermal installation is already well underway: Until 2020, as a rule, site-specific surveys of the concessionaire were treated as company secret and the disclosure of findings (interpretations) was due for the operation plan approval procedure only. The Geological Survey Organization of Bavaria, as the competent authority supporting the Mining

Authority and Energy Regulator, is entitled to store and process that geoscientific data and to synthesize it for an incrementally evolving conceptual framework. However, beyond purely scientific communication, this conceptual framework cannot be used for any site-specific advice or predictions, because the GSO as the neutral advisor of the approval authority and arbitration-board is not entitled to accept private commissions or to compete otherwise with consultants and planners of the private sector (cf. Diepolder et al., 2019). The collation and synthesis of all that site-specific data and its alignment with large-scale findings improves the overall picture of the geological situation and evolution and allows for an incremental amendment and refinement of the conceptual model as the basis for larger scale predictions, an improved exploration strategy and the targeted focusing of future geothermal projects.

Use restrictions and setbacks

The success story of geothermal exploration and exploitation in the Greater Munich area proved the prospection strategy of focusing on discontinuities (faults and fractures) rather than on facies distribution. However, this targeting of ruptures, known to be tectonic movement planes relieving stress and strain in the subsurface, hence prone to seismicity, involves the danger to trigger or induce earthquakes. Furthermore, recent failures of ultra-deep (> 5,000 m TVD) explorations (marked **X** in Figure 6.1), due to insufficient flow rates, show that targeting discontinuities is not inherently propitious as seismic surveys rarely reveal evidence of the permeability of the faults.

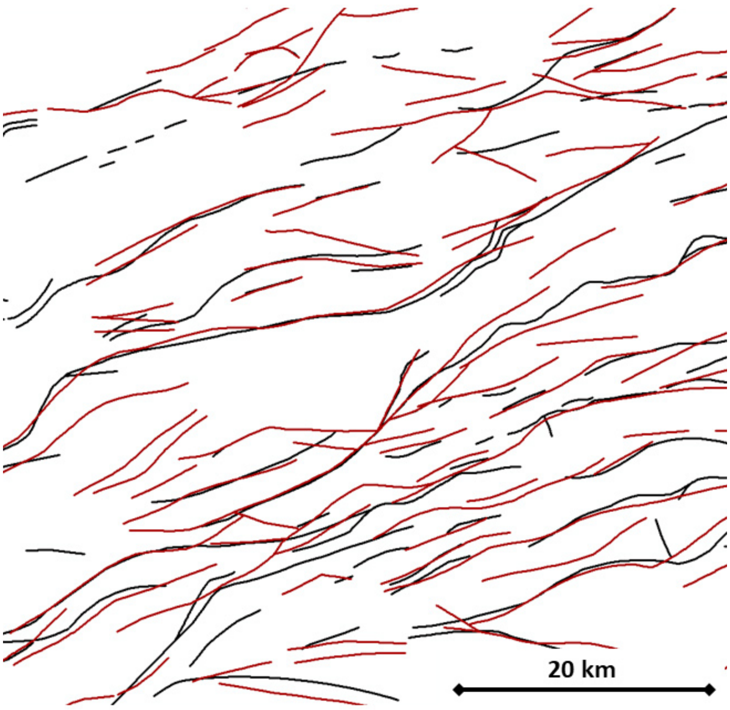

Figure 6.3. Principal faults at the top of the Upper Jurassic hydrothermal aquifer in the Greater Munich area (approx. same area as in Figure 6.1). Black lines are the traces of faults as in Bayerischer Geothermieatlas (Bay. StMWIVT, 2010), red lines are the revision and amendment as identified in the projects GeoMol (GeoMol Team, 2015) and HotLime (e.g., Diepolder et al., 2019a; Diepolder & HotLime Team, 2020), largely based on the interpretation of recent 3D seismic surveys provided by the concessionaires.

Seismicity: Even though under horizontal stress due to the close proximity of the Alpine orogenic front, the Central Molasse Basin is considered fairly aseismic. Seismicity reported over the last century is scarce and weak, rarely reaching a magnitude Ml of 2.0 on the Richter scale. Since the 2000s geothermal boom, specifically in the east and southeast of the Munich Cluster, some minor earthquakes have been detected, rarely felt, suspected to be triggered by geothermal installations, pursuant to Dahm et al. (2010): “Earthquakes occurring in spatial and temporal proximity to such (human) operations are immediately under suspicion to be triggered or induced”. To better monitor the relationship of geothermal installations and seismic events, a monitoring system (Figure 6.4) was set up and progressively densified. As a result, some events, turned out to likely have been induced, e.g.: Sauerlach 02-2010, Ml 2.1; Poing 11-2016 and 09-2017, Ml 2.4; and Ottobrunn 03-2020, Ml 1.9.

Figure 6.4. Seismic monitoring network in the Larger Munich area, “Subnetz München” https://www.erdbeben-in-bayern.de/erdbebendienst/stationen/subnetz-muenchen/ **progressively densified over the last decade with an increasing number of geothermal installations. The circle next to Vaterstetten indicates the 2020-12-03 06:43 ML 1.8 seismic event, with a focal depth of 21 km clearly not induced or triggered by one of the nearby geothermal installations (from** https://www.erdbeben-in-bayern.de/ **).**

Combined thermal/stress modelling (e.g., Seithel et al., 2019), most commissioned by the concessionaire of the involved geothermal installations, made probable that high reinjection pressures, when the reinjection is performed close to an (assumed) fault, and/or a large temperature difference between the thermal water at depth and the reinjected water are the main reasons for that induced or triggered seismicity. By slightly lowering the reinjection pressure and raising T_{inj} to about 50 °C the proneness to seismicity could be lowered considerably, thereby only negligibly reducing the energy yield.

Insufficient flow rates: Due to the heterogeneity of karstified carbonate rock suites and their fault inventory, flow rates or reinjection rates falling short of expectations/prognoses are not uncommon. Acidification, switch of production and reinjection wells, or augmenting the doublet by a third well remedied this deficiency in most cases. However, two recent ultra-deep (> 5,000 m TVD) drilling campaigns in the Greater Munich Area did yield such low flow rates that they were abandoned before venturing another drilling (#3 and #4 in Figure 6.1). These two drillings, featuring temperatures of up to 155 °C, despite intersecting several large-scale faults, turned out to be virtually dry. Also hydraulic stimulation by "conventional" means (e.g., acidification – by statutory provisions fracking is not an option in Germany) did not bring the expected success. In contrast, a concurrent drilling, Holzkirchen (#5 in Figure 6.1) only 20 km away from the failed projects in a geological setting deemed comparable, and overachieved the expectations/ prognosis with respect to the groundwater yield.

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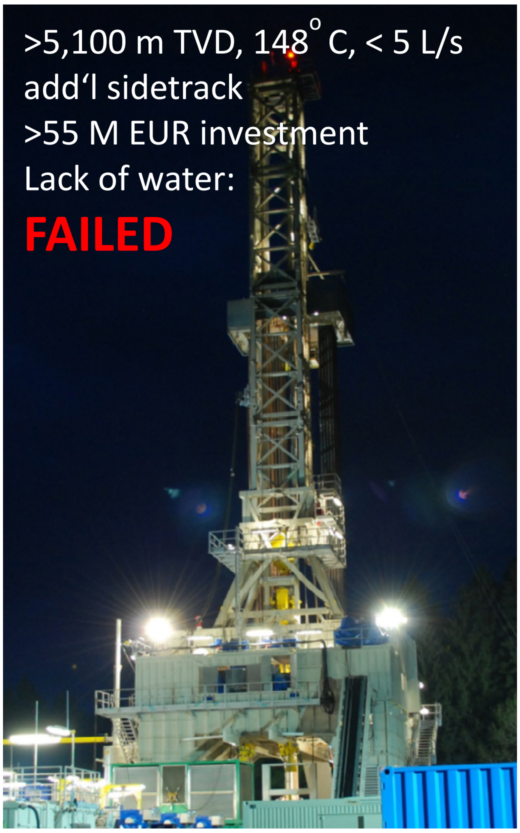

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Figure 6.5. Unlike the Geretsried project (right, #3 in Figure 6.1), Holzkirchen project (left, #5) overachieved the prognosis for maximum water withdrawal. (From Diepolder et al., 2021, WGC2020+1 #16040 video presentation.)

Icking Geothermal Project (#4 in Figure 6.1) was abandoned immediately, while Geretsried became a research site on the optimal trajectory of a sidetrack (Figure 6.6). However, also the sidetrack, intersecting a different fault did not bring forth the desired results. Rather, coring sections across the target faults (red rimmed sections of GEN-1ST-A1 in Figure 6.6) within the frame of the accompanying research measures, clearly revealed that the faults at great depths are completely closed and sealed.

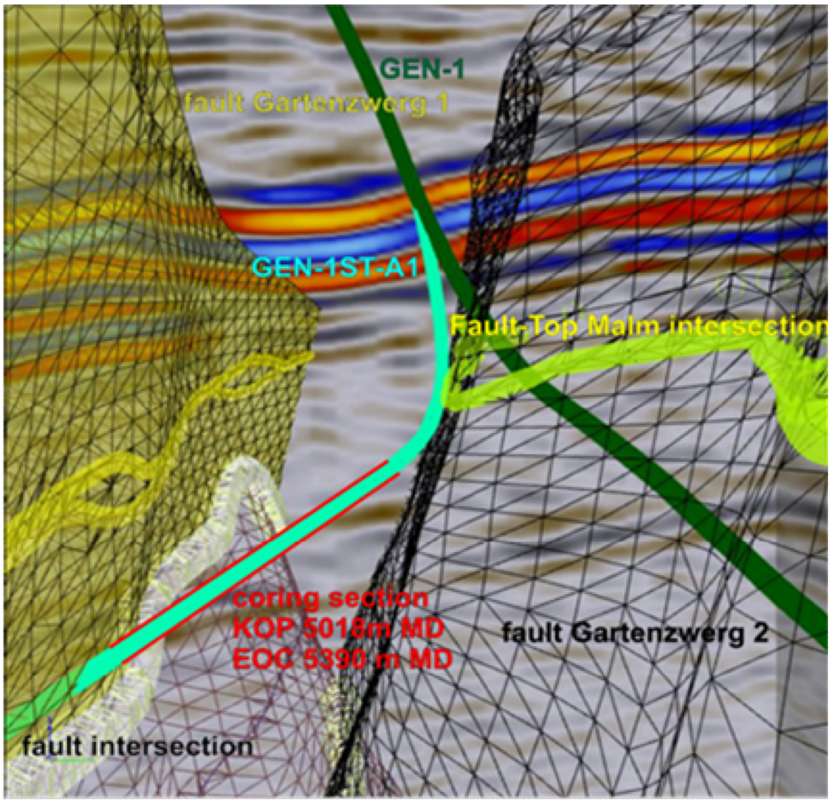

Figure 6.6. 3D geological model of the target area of Geretsried geothermal project featuring a bottom hole temperature of 155° ± 3°C but very low flow rates only. The first drilling GEN-1 pierced the top of Upper Jurassic (Malm) at its intersection with fault Gartenzwerg 2. The sidetrack GEN-1ST was deflected to fault Gartenzwerg 1 and included a coring section between 5018 and 5390 m MD. (From the 2018-09-18 HotLime Kick-off Field Trip Guide, courtesy of LIAG.)

Mitigation and salvage measures

Ultra-deep exploration campaigns are acknowledged to be an expensive enterprise. Once the target horizon has been reached and viability tests (pumping tests, etc.) and subsequent hydraulic stimulation have been carried out, tens of millions of Euro might be used up and, in case of the project's failure, few concessionaires are willing to write off these costs by immediately abandoning the project. However, finding an investor for open-ended mitigation and salvage measures, is a difficult endeavor**.**

Two of the overall four failed geothermal projects (e.g. #4 in Figure 6.1) were abandoned after hydraulic stimulation by "conventional" means did not bring the expected success and no investor could be found for the additional costs of mitigation or salvage.

On the other hand, Mauerstetten Project, west of the Munich cluster, at present a research project, is geared towards converting the borehole into a deep ground source heat pump.

For the failed Geretsried Project of the Munich cluster (#3 in Figure 6.1), a feasibility study was carried out on creating artificial conduits through one or more horizontal drillings at great depth from sufficiently distant locations to ensure a suitable dwell time for heating-up. In 2020, the concessionaire and Eavor Technologies Inc. entered a letter of intent to form a geothermal project development company to construct an Eavor-Loop™ heat and power project. Front end engineering and design (FEED) of the project are in progress (Eavor, 2020) and a second drill site has been acquired.

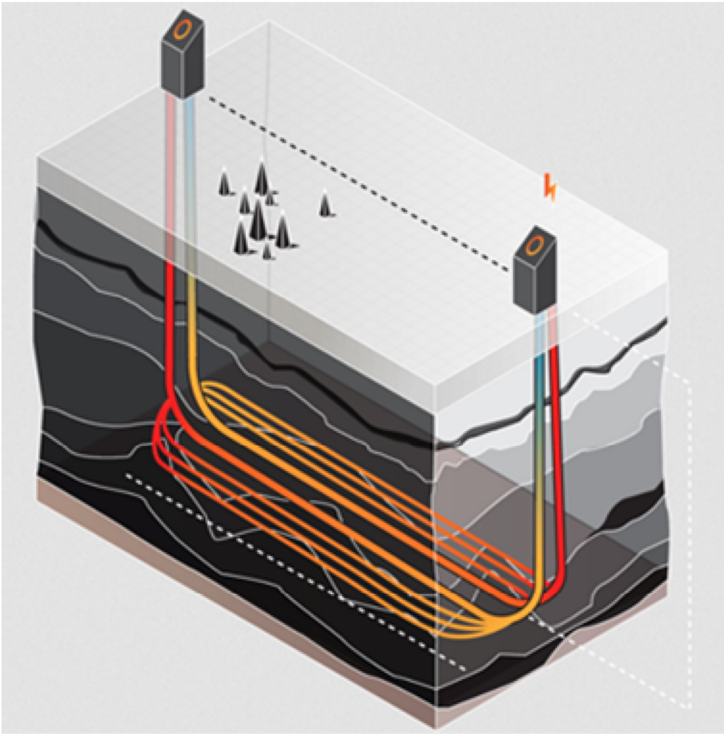

Figure 6.7. Eavor-Loop™ (Eavor Technologies Inc., www.eavor. com) as planned for implementation at the Geretsried Project drill site at about 2,600 m depth using the existing drill hole of GEN-1 and a new one at a sufficiently distant location.

6.4 Summary of the Munich Cluster projects

At present, Greater Munich area features 17 geothermal plants in operation, one triple doublet with drilling operations successfully completed and two more projects in the stage of feasibility analysis and front end engineering.

Based on the geological knowledge from hydrocarbon E&P in the 1960's to 90's and kicked off by the rather incidental discovery of a promising geothermal reservoir, geothermal E&P in the Molasse Basin, even though featuring a normal to subnormal geothermal gradient, turned out a true success story, driven by the combination of high demand of district heating in a densely populated area, risk propensity of some communal utilities inline with the politics of energy transition and lately government-funded under the German 2017 Renewable Energies Act (a Feed-In-Tariff under which the government augments the electricity price for a period of 20 years). Favourable geological characteristics such as low mineralized water and low proneness to seismicity further promoted the boom and progressively improved the knowledge of the Molasse Basin's deep subsurface, helping to incrementally focus the target structures more precisely.

On the other hand, the failure of overall four geothermal projects (two outside the Munich cluster but in similar geological settings, cf. Figure 6.8), not only led to the abandonment of the projects but also triggered varied research. Presently three basic reasons are discussed as generic for the insufficient flow rates and are thus subject to further research.

- High stress of the surcharge of > 5000 m overburden may cause the closure of voids and enhance secondary mineralization.
- Horizontal stress due to the close proximity of the drillings to the Alpine orogenic front may enhance this process and may be the main reason for the lack of conduits.
- The occurrence of the Helvetic facies of Upper Jurassic at depth, a basinal, dense, bituminous, marly limestone (Quintener Kalk https://data.geoscience.earth/ncl/geoera/hotLime/units/7199), known to be less prone to karstification and less faulted and fractured due to more ductile characteristics, extends further to the east than previously assumed. (Figure 6.8).

6.5 Future work in the Munich Cluster projects

Numerical modelling and balancing of the Greater Munich Area subsurface, including geothermal operations simulation and forecast modelling (Wenderoth, Chapter 5 in Schulz & Thomas, 2012) showed that there is no mutual interference of the operating geothermal installations and the reservoir's exploitation is considered not yet mature. Despite this remaining potential, at present, the realization of schemes in the Greater Munich realm is somewhat dragging. Some projects in Munich's exurbs have been stopped by public campaigns; other undertakings, specifically in the south of Munich are on hold, awaiting the further development of the Geretsried Project and the associated research outcomes. However, some operators of running geothermal installations are considering extensions by a new doublet and plant.

The present focus of investigations and front end engineering of heat and power projects in the Molasse Basin has moved eastwards to the southern west-flank of the Landshut-Neuötting Crystalline Rise (Figure 6.8) and beyond, the Lower Bavaria Molasse Basin.

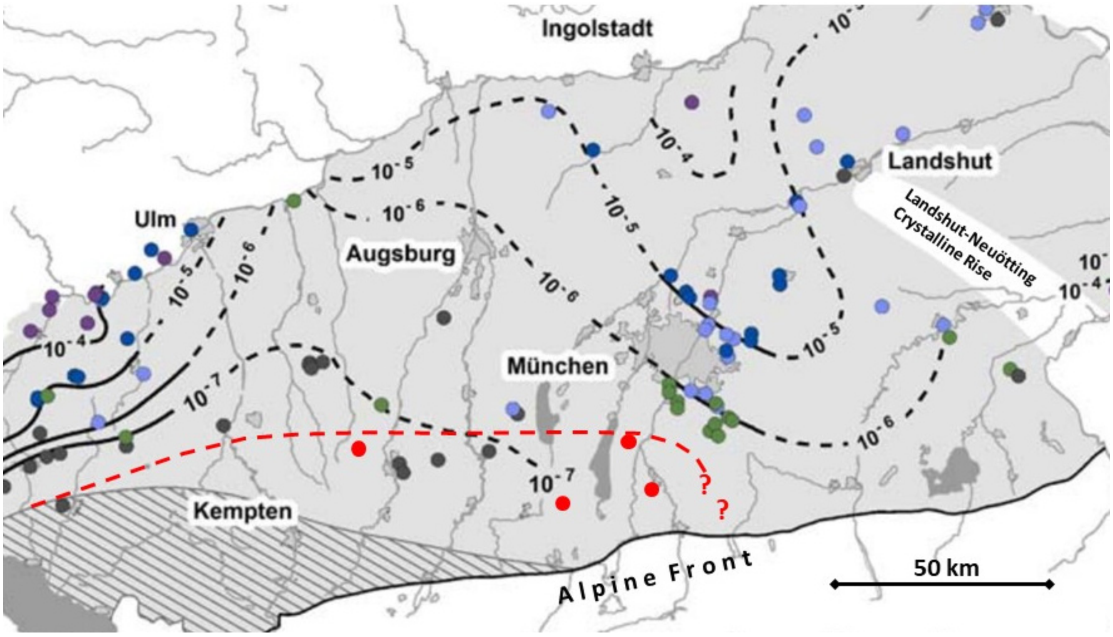

Figure 6.8. Formation permeability distribution in the Central Molasse Basin (from Birner 2013, modified) and the location of the 4 recently failed geothermal projects (red dots) indicating that the low permeability Helvetic facies (hatched area, cf. https://data.geoscience.earth/ncl/geoera/hotLime/units/7199) extends considerably further to the east (dashed red line) than previously assumed.

Due to its specific starting conditions (good geological knowledge from Hydrocarbon E&P, dense population thus high heat demand, partly pre-existing district heating grids, political intent for energy change) the success story of the Munich Cluster cannot be considered usual.

To trigger the high and risky investment of a sound geothermal reservoir development, a promising first geothermal base assessment (like HotLime's deliverables) must be on hand, first project(s) must be encouraged and supported by public funds and exploration risks must be mitigated by collateralization. As long as no skilled local consultants are available, concomitant research must be carried out by the State Geological Survey in charge and/or academia, and all that must be flanked by investor friendly statutory provisions. Once a first showpiece is completed and the best practice for success is defined, follow-up actions might become a no-brainer.

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7 Case study 06: The Jafre project, Empordà Basin, CATALONIA

Authors: Montse Colomer, Ignasi Herms and Georgina Arnó (ICGC)

7.1 Overview

The geothermal "Jafre well" is located in the NE of Catalonia within the well-known Empordà Basin, near the town of Jafre. Figure 7.1 shows the situation of the well within the scope of the fractured limestone aquifer under study, the 'Girona Limestone Formation' (GLF).

In the 1960s and 1970s, several oil and gas exploration wells were drilled in Catalonia. One of the wells drilled within the Empordà basin was called 'Girona-2' (1962-1965; Figure 7.1) with a depth of 3319 m. During the drilling campaign, it was observed that the fractured limestone aquifer located at a depth of 964m could have geothermal interest. The well showed artesian behavior, with almost constant flowrate of 3-4 L s^{-1}, WHT of 48 °C and with a fluid supersaturated in CO_2. Today, this well is clogged and unusable.

The first attempt to tap the geothermal potential: 1988

Years later, in 1987, it was proposed to recover the old Girona-2 well for a geothermal project designed to produce spirulina algae. The idea was abandoned due to technical difficulties in the attempt to reopen it. The following year, it was decided to execute a new well, called the 'Jafre' well, 970 m deep, by a public company named IMPROGESA. This new well drilled the same fractured limestone aquifer attributed to the base of the Tertiary GLF. It confirmed the geothermal potential observed within the old Girona-2 well from 915m to 968 m deep. The new Jafre well also showed the same artesian behavior and a geothermal fluid with WHT of 51°C with a constant artesian regime, and BHT of 53.5 °C.

However, energy policy changed, and it was decided to focus on fossil fuels instead of geothermal resources, and a decision was made to abandon geothermal exploration and therefore this specific project.

The second attempt to tap the geothermal potential: 2000s

Interest in the 'Jafre' well was launched again in the 2000s, thanks to a private investment with the aim of promoting a new hotel-spa. The project was called 'Prestige Hotel' or Jafre Hotel-spa project (PH, S.A. 2003). The well was reopened, and new hydraulic tests were carried out. However, this project was also abandoned for economic reasons a few years later.

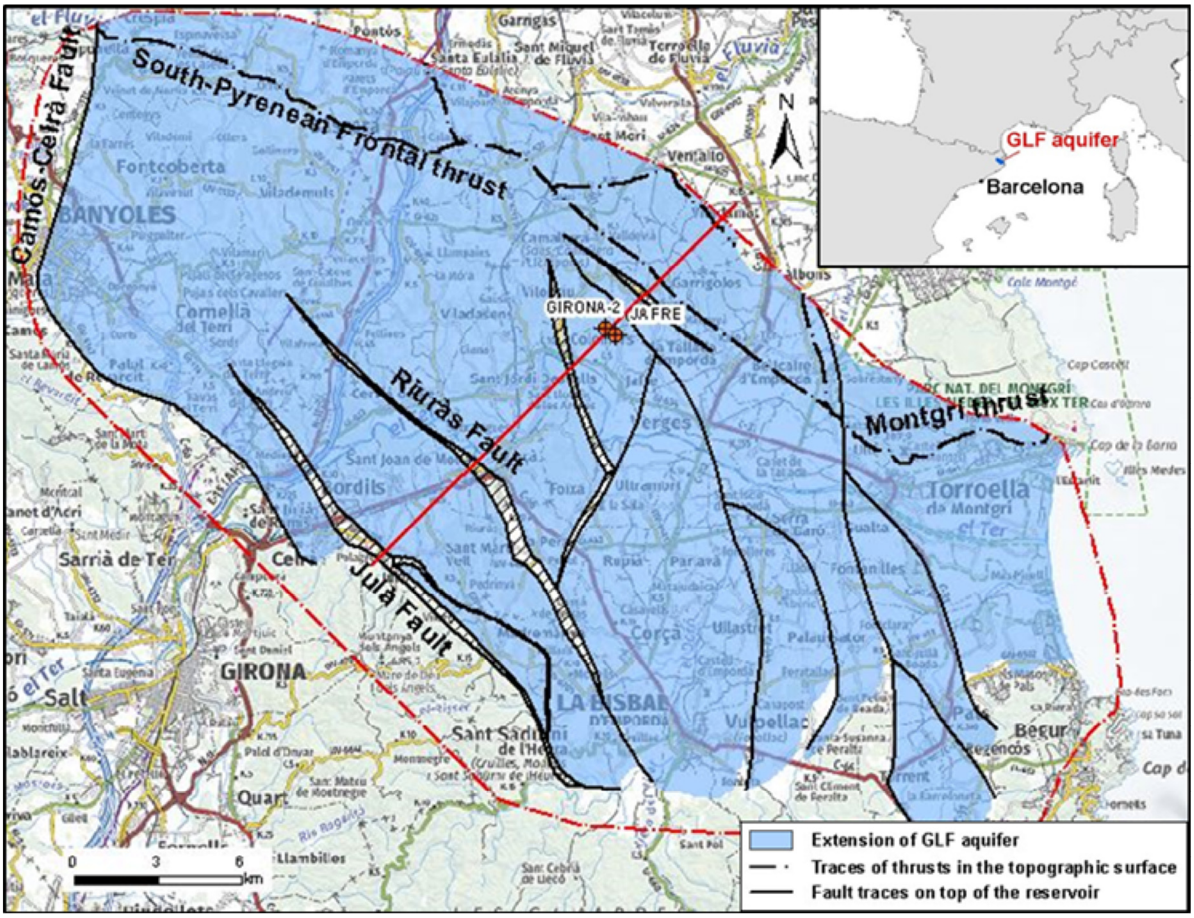

Figure 7.1. Extension of GLF aquifer and its structural boundaries (continuous black lines are fault traces on top of the reservoir; dashed black lines are traces of thrusts in the surface) in the study area of Empordà Basin (dash red line).

Recent activities:

So far, there have not been any other initiatives to tap the geothermal potential of the well, or to carry out new exploration in the same aquifer or in other areas of the same basin.

The 'Jafre' well remained closed until August 2017, when, due to the well-head pressure and the corrosive characteristics of the fluid, the well-head suffered a burst causing uncontrolled artesian flow at 50 °C and almost 3-5 L s^{-1}, and consequently some environmental effects in the surroundings (Figure 7.2).

That year, the mining authorities decided to order the definitive sealing of the 'Jafre' well with a concrete block. But the inadequate design of the final seal to deal with the corrosive nature of the water and the artesian pressure led to new water leaks appearing through the block at the beginning of 2018. The remedial measures taken in the well make it unlikely that it could be recovered for a possible new project in the future. The key fact is that the geothermal potential of the GLF aquifer remains untapped.

Figure 7.2. Uncontrolled hot water flow leakage @50ºC from the 'Jafre' well head (photo: August 2017).

7.2 Geology, hydrogeology and geothermal setting

Geological setting

The Empordà Basin (EB) is a Neogene basin located in the NE of Catalonia, close to the Pyrenees ranges. It was generated during the opening of the 'Valencia Trough' (Late Oligocene – Middle Miocene) as the prolongation of the European Cenozoic Rift System. Due to extensional tectonics, EB was formed as a tectonic graben by a NW-SE-trending fault system, which overlaps the contractional structures of Alpine period (Saula et al., 1996). EB is internally cut by normal faults with listric geometry and measured dip slips of about 1,000 m in the main ones. This faulting caused a blocky structure in the pre-Neogene bedrock, which presents a general deepening towards the north (Figure 7.3).

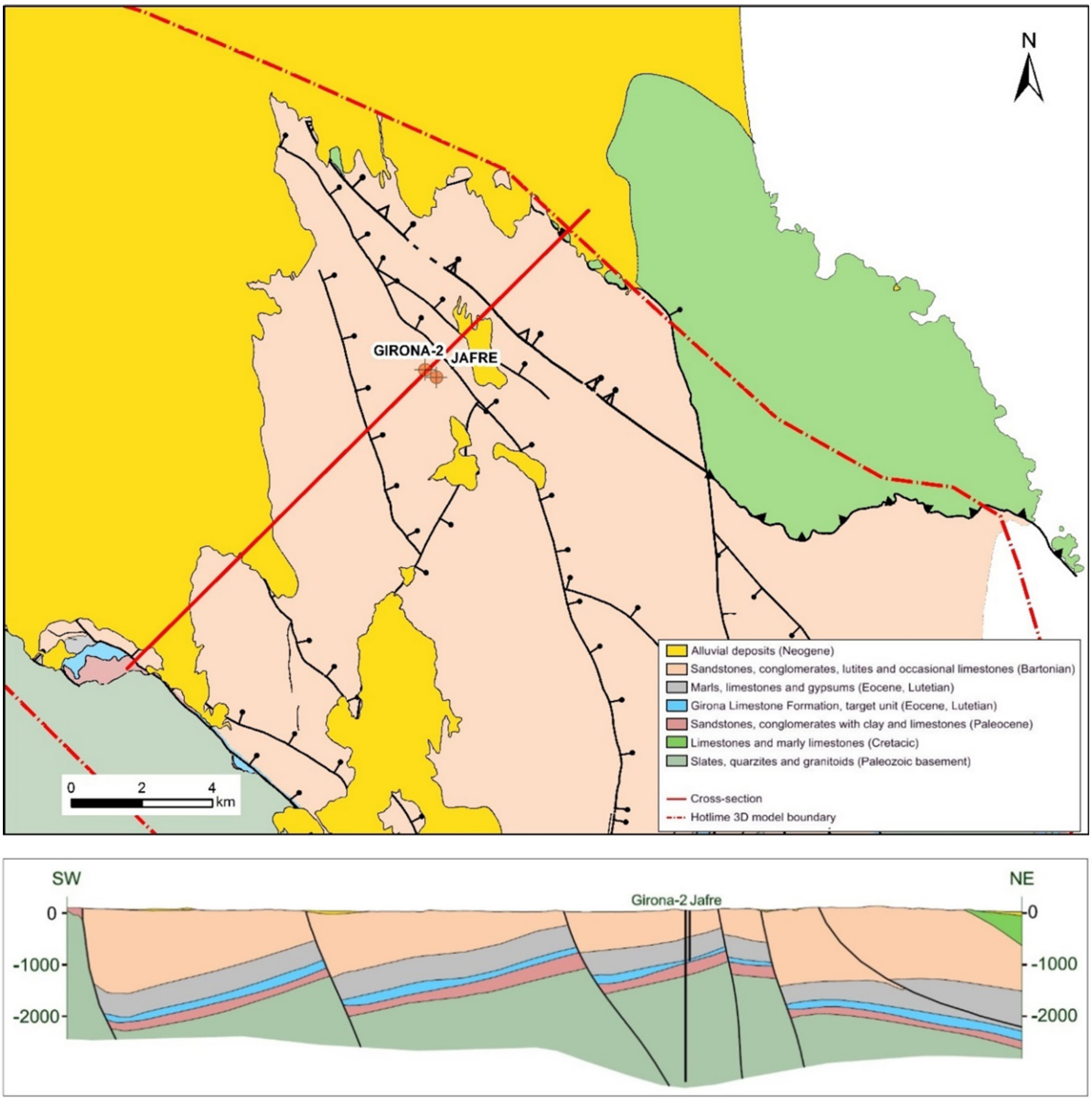

Figure 7.3. A) Geological map and B) geological profile.

Within the lithostratigraphic succession from the Paleozoic to the Paleocene, a potential hot limestone aquifer was detected. It corresponds to the well-known GLF, located in the Lower Eocene part of the sequence. Its aquifer thickness (H) values range between 22m to 170m with an average of 75m. The H shows an increase from E to the W (Pallí, 1972). Towards the N and in depth, the H value increases to 270 m, according to interpreted cross-sections. The maximum depth reaches 2,650 m in the study area. The aquifer covers an area of more than 400 km^2.

Hydrogeology

The hydraulic parameters of the reservoir were interpreted in the 'Jafre well' by means of a well pumping test done over 14 days in March 2003 for the reopening project (PH, S.A. 2003). Two flow rate steps were used: 25 L s^{-1} (8.04 days) @ 51.6 °C and 50 L s^{-1} (1.5 days) @ 51.7 °C with the corresponding recovery periods. The aquifer behaved as a confined aquifer with an estimated BHP of 90 bar at steady state.

Considering a H of 25 m in Jafre well, and an isotropic and homogeneous aquifer, the short-term analysis of the pumping test suggested the T, k_c and S reservoir values of 100 m^2 d^{-1} (1.7e-3 m^2 s^{-1}), 4m d^{-1} (4.6e-5 m s^{-1}) and $3e^{-04}$, respectively. Considering values of ρ = 987.62 kg m^{-3} @ 51 °C and μ = 0.54 cp (or 5,4 Kg $m^{-1}s^{-1}$), the estimated K would be around 2,6E-12 m^2 or 2,62E+03 mD. More recently, laboratory results obtained by ICGC-UB (2019) from rock samples suggest that matrix K is very low in between 0.2 to 0.01 mD. However, the analysis of the outcrops shows that the rock has a relatively high fracture density, likely allowing the GLF behaving as a fractured reservoir.

Despite the hopeful permeability values obtained in the short-term analysis (PH, S.A. 2003), the interpretation of the s/t curves at long-term also showed that, at least in this part of the basin (as can be observed in Figures 7.1 and 7.3), the aquifer is compartmentalized due to the presence of faults that can act as very low permeable geological boundaries. Considering those boundaries into the model, the well test interpretation revealed T, k_c and K equivalent values of 4 m^2 d^{-1} (1.7e-3 m^2 s^{-1}), 0.18 m d^{-1} (2.08e-6 m s^{-1}) and 1,16E-13 m^2 or 1,18E+02 mD, respectively, which would correspond to a medium to low permeability fractured rock reservoir. In this context, the aquifer capacity in the Jafre well study area should be considered moderate to low. On the contrary, it is estimated that towards the west of the basin, the compartmentalization in the deeper parts of the aquifer could be less according to the current geological knowledge, and the transmissivity higher due to a higher aquifer thickness.

Regarding the reservoir porosity, the new data obtained by ICGC-UB (2019) indicates the rock matrix values are between 1 to 15%. In the other hand (PH, S.A. 2003) reported a value of 7.6% estimated from density-neutron logs. In this context, the fractures must play and important role increasing the secondary porosity.

Regarding hydrogeochemistry, the fluid in the reservoir presented slightly acidic average pH values around 6.4, EC of 4575 μS cm^{-1}, SO_4 of 2.185 mg L^{-1}, Cl of 100 mg L^{-1}, HCO_3 of 1340 mg L^{-1}, SiO_2 of 27.5 mg L^{-1}, Ca of 618 mg L^{-1}, Mg of 98 mg L^{-1}, K of 94.5 mg L^{-1}, and Na of 681 mg L^{-1}. The water would be saturated with respect to calcite, dolomite and anhydrite. According to these values, it presented calcium-sodium sulphate facies (PH, S.A. 2003).

Geothermal setting of the aquifer at the Jafre location

Considering the BHT corrected values, for the Girona-2 well it was estimated the temperature gradient of the aquifer is 47 °C km^{-1}. According to the BHT Jafre values, a geothermal gradient of 42 °C km^{-1} measured from the top of the aquifer could also be considered, considering a mean annual surface temperature of 15 °C.

7.3 Resource assessment

The Jafre Hotel-spa project (PH, S.A. 2003) evaluated the geothermal potential of the aquifer at a local scale through numerical modeling using the finite difference approach. The model was calibrated with the transient drawdown data observed in the well itself during the pumping test carried out in March 2002.

After the calibration, some simulations were run. The objective was to estimate the most favorable pumping regime to exploit the resource in the long term. The model used implemented a simplistic approach considering a horizontal, homogeneous and isotropic captive aquifer of constant H, despite the huge observed heterogeneity. The overlying and underlying strata were considered as impervious.

No other geothermal resource assessment of the aquifer has been carried out, either at local or regional scale.

Within the framework of the Hotlime project, a new map of deep geothermal potential at regional scale using the classical Heat-in-Place method has been prepared using a probabilistic approach. It is estimated that a new 3D flow and heat transport model that explicitly implements the geometry of the aquifer obtained from the 3D geological model elaborated within the GeoERA HotLime project, could allow better re-interpretation of the tests and provide a new more accurate evaluation of the resource at the Jafre location.

Nevertheless, according to all available data, it seems that the geothermal conditions of the aquifer towards the west and in the deeper parts of the basin could be better than in the Jafre location, from the following interpretations:

- the degree of aquifer compartmentalization due to regional faults (according to the structural map of the Figure 7.1) could be less;
- the reservoir temperature, at the same gradient, could be higher;
- the aquifer thickness is greater reaching values of 140-170m in some outcrops, increasing the transmissivity of the aquifer; and
- probably, the Jafre well, due to the attempted sealing work carried out in 2017, could no longer be recovered.

Consequently, the Jafre location, at the moment, does not appear to be the most interesting and promising area of the aquifer for a possible geothermal exploitation project, even though it is the only location in the aquifer where, to date, a deep well has been drilled for exploration.

7.4 Future work and recommendations

So far, no deep geothermal development project for the industrial or domestic sector (DH urban areas, greenhouses, industrial processes) has been carried out in Catalonia, except for balneology purposes in some fault-controlled shallow hydrothermal systems located at the boundaries of some Neogene basins. In this respect, Catalonia has an almost 50 years lack of activity since hydrocarbon exploration ended in the 1970s. In recent years, with the help of environmental policies on climate change, the new energy transition and the need for the decarbonization of the heating sector, geothermal energy interest, fortunately, is coming back.

In this context, recent actions were:

- In 2012, the Institut Cartogràfic i Geològic de Catalunya (ICGC) published the digital Geothermal Atlas of Catalonia (AGC), which incorporated the first maps of inferred estimations of deep temperatures, surface heat flow and shallow geothermal gradients. The main task of this project was to collect the old available information and to synthetize it into different geo-thematic GIS layers. The Atlas also presents the most promising areas for deep geothermal energy in Catalonia.

- More recently, in 2014 ICGC launched a new project called GeoEnergy Resources with the objective to advance towards the quantification of the deep geothermal potential in terms of the available and recoverable base energy resource in those specific areas identified in the AGC. The works combine new data acquisition (i.e. geophysics, rock sampling and petrophysical analysis) and 3D modelling techniques using a probabilistic approach to carry out an assessment of the geothermal resources. The project delivers models and 2D maps in order to contribute to the knowledge improvement of this energy resource as a renewable energy source in Catalonia.
- In 2019, a new Geothermal Working Group was created within the Catalan Efficient Energy Cluster (CEEC), including engineering companies, manufacturers, academia, R+D organisations and public entities promoting renewable energies. This group has the aim to make actions to disseminate, promote and raise public awareness of geothermal energy, from shallow to deep. ICGC is a co-founder and is co-leading this group.

In order to promote deep geothermal projects, after almost 50 years of lack of exploration, it would be necessary to launch a new and modern Regional Exploration Plan. In this plan, at least, new reflection 2D seismic campaigns should be executed to replace the old uninterpretable profiles of the 60s, in order to confirm and refine the 3D distribution of the carbonate aquifer and the faults. Afterwards, it would be also necessary to drill new deep exploratory slim-holes geothermal wells and to do new hydraulic tests, logging and sampling.

At the same time, it would be necessary to obtain explicit support from the national government (following the actions of other EU countries) in terms of boosting geothermal feed-in tariffs, fixed payments to ensure the bankability of the private investments and/or establish risk mitigation and insurance schemes, like the GEODEEP SAS risk insurance fund (Boissavy, 2020) for electricity and /or heat generation in France, which focuses on deep geothermal energy.

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8 Case study 07: Newcastle, Dublin, IRELAND

Authors: Sarah Blake and Brian McConnell (GSI)

8.1 Overview

The faulted southern margin of the Carboniferous limestone Dublin Basin has been explored for geothermal energy potential at Newcastle, Co. Dublin. Two boreholes were drilled to depths of 1,340 and 1,400 m by GT Energy in 2008. Borehole data and geophysical models have suggested the presence of geothermal resources in fractured carbonate rocks and sandstones in the lower part of the Dublin basin succession close to the faulted basin margin.

Despite positive exploration results, and a favourable planning decision for a 4,000 m geothermal doublet and a 4 MW_e binary geothermal power plant, the Newcastle project was suspended in 2011 for non-technical reasons; the lack of legislation, planning guidelines, clear policy signal, or financial incentives made it an unattractive risk for the developers.

In recent years, the Climate Emergency has revived interest in Irish geothermal energy resources and their potential for decarbonisation. Using data from the Newcastle boreholes, Geological Survey Ireland (GSI) estimated that between 80 and 400 MW_{th} of heat could be provided from deep geothermal energy in the southern part of the Dublin basin (Codema, 2019). As an action under the Irish Government's Climate Action Plan 2019, GSI published *An Assessment of Geothermal Energy for District Heating in Ireland* (2020); simultaneously the Department for the Environment, Climate and Communications published *Geothermal Energy in Ireland: A Roadmap for a Policy and Regulatory Framework* (2020). These two documents set out the next steps required to develop the geothermal energy sector in Ireland and initiate a period of public consultation. As the most significant deep geothermal venture in Ireland to date, experiences from the suspended Newcastle project will help to inform the development of fit-for-purpose geothermal energy policy.

8.2 Geology, hydrogeology and geothermal setting

The geology of the Dublin basin is described in detail in HotLime D2.0, Case Study T2.3b, (Rupf et al., 2020, https://repository.europe-geology.eu/egdidocs/hotlime/hotlime_deliverable_20.pdf). The geological target at Newcastle was the fracture zone associated with the Blackrock Newcastle Fault (BNF; see Figure 8.1). This normal fault bounds the southern side of the Carboniferous Dublin Basin, with syn-sedimentary and subsequent throw of at least 1,500 m. Viséan turbiditic argillaceous limestones blanket the lower strata of the basin fill, which includes carbonate grainstones, 'Waulsortian' mudmounds and basal siliciclastic rocks (McConnell & Philcox, 1994; see Figure 8.2). Lateral displacement of the BNF during Variscan shortening may have created dilational fractures (Phillips et al., 1988), thus developing potential pathways for geothermal fluid circulation.

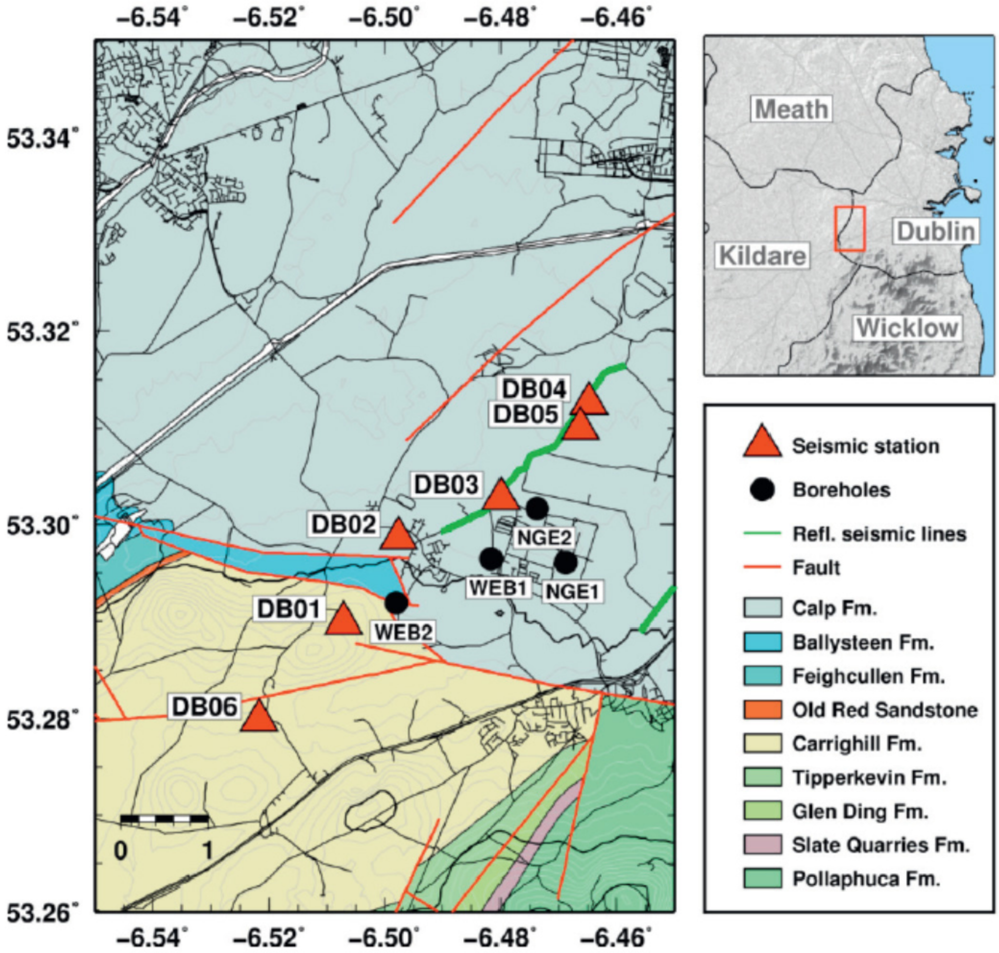

Figure 8.1. Geological map of the Newcastle area showing locations of previous geophysical surveys and the basin-bounding Blackrock Newcastle Fault (BNF) (from Licciardi et al., 2014). Boreholes NGE1 and NGE2 were drilled to depths of 1,340 and 1,400 m.

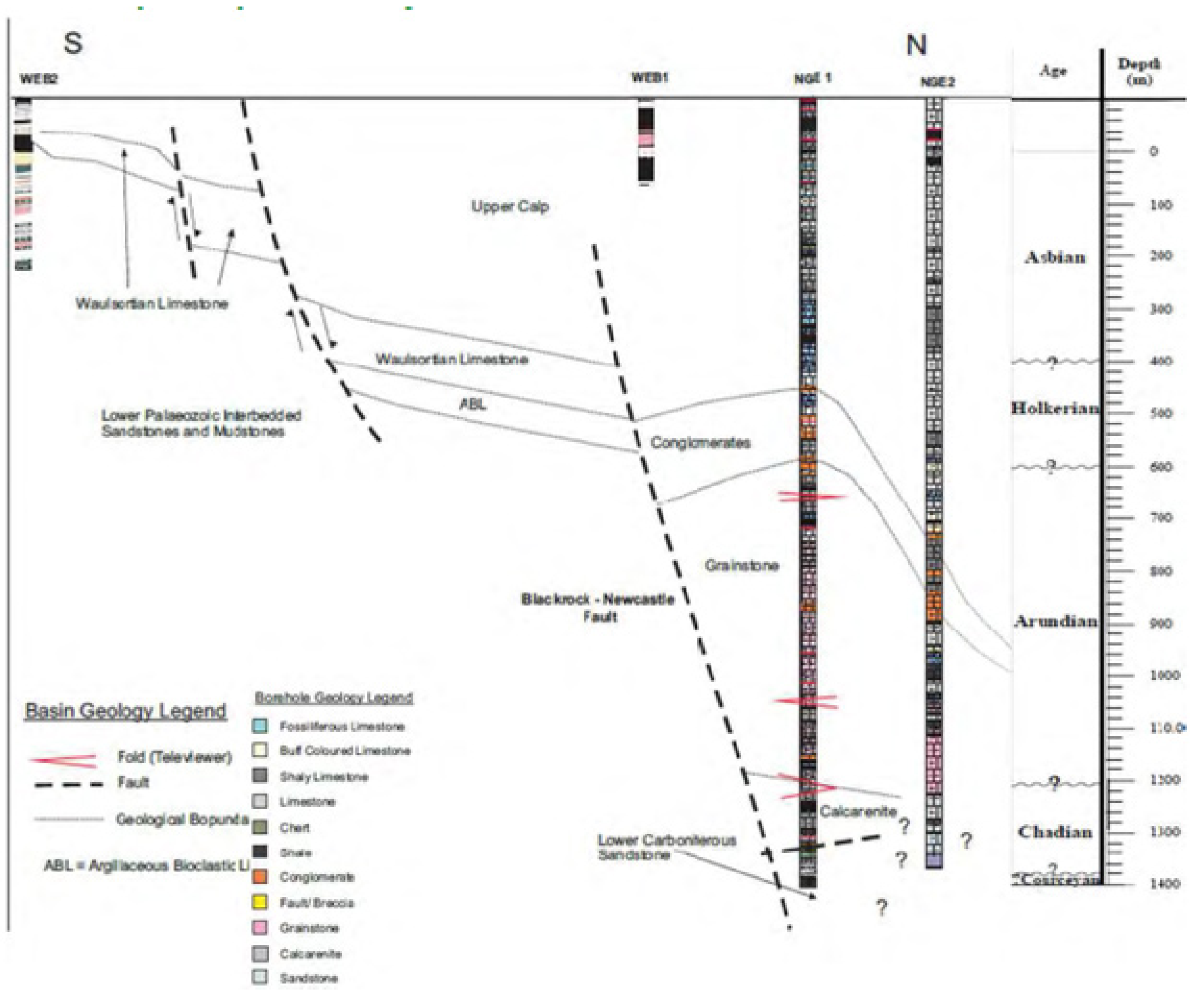

Figure 8.2. Interpreted cross-section through Newcastle target zone showing locations of deep boreholes (from Pasquali, 2018).

GT Energy undertook a geothermal exploration programme on the Blackrock - Newcastle fault between 2007 and 2010. Several shallow boreholes and two deep boreholes, NGE1 (1,340 m) and NGE2 (1,400 m), were drilled in the Carboniferous sedimentary succession just north of the fault at Newcastle, Co. Dublin. Seismic reflection profiles were acquired across the fault structure. The deep boreholes intersected argillaceous limestone and shale above carbonate and silicate grainstone successions, without reaching basement (Figure 8.2).

A temperature of 46.2 °C was measured at the bottom of borehole NGE1 (1,340 m depth). The highest geothermal gradient recorded was 32 °C km^{-1}. A significant fault and water strike was encountered at the bottom of NGE1 and fracture permeability was evident throughout the bottom section of the borehole (SLR, 2008). The local geothermal gradient was observed to decrease beneath the encountered fault zone, and downhole conductivity measurements suggest upwelling of brines along the fracture zones. The findings of the investigation suggest that the fractured carbonates and porous sandstone in the lower part of the Carboniferous sedimentary sequence close to the fault have good reservoir potential to deliver heat through a geothermal well doublet. It is likely that geothermal energy exploitation along the margin of the Dublin Basin will require the stimulation and development of fracture permeability reservoirs associated with large fault structures in the lower parts of the basin (SLR, 2008).

Recent magnetotelluric modelling (Vozar et al., 2020) has imaged a dextral shear zone with the BNF as a highly fractured and partly conductive zone. A shallower zone, up to 1–2 km deep, features NE–SW oriented conductors that cross the surface trace of the BNF and are interpreted as fractures filled with saline waters. A deeper zone, 2–4 km deep, of conductors along the BNF is interpreted to be a highly fractured fault system infilled by saline waters.

The Newcastle geothermal project was stopped for non-technical reasons before any detailed resource assessment was carried out. Apart from academic geophysical research, no work has taken place to develop the geothermal potential of the Newcastle site since 2011.

8.3 Summary of the project

The geothermal exploration programme undertaken at Newcastle was part-funded by the Sustainable Energy Authority of Ireland, and demonstrated favourable geothermal reservoir potential for both heat and electricity production. District heating schemes for a local hospital and business park were the anticipated uses for the heat produced. Planning permission for a 4,000 m geothermal doublet and a 4 MWe binary geothermal power plant was obtained from South Dublin County Council by GT Energy in 2011, with an expected investment of over €35 M (Pasquali, 2018). No developments have taken place to date. The developer cited the lack of legislation and licencing process for geothermal energy in Ireland as the reason for pulling out of any development. The timing coincided with a period of economic recession and general decrease in construction in the area, so it is likely that a lack of a secure market for the geothermal heat was also a contributing factor to the suspension of the project.

There have been several geophysical academic studies since 2011 highlighting the geothermal potential of the area; the existing deep boreholes have been used to groundtruth the geophysical models. In 2019 Codema (the energy agency for Dublin local authorities) and Geological Survey Ireland used data from Newcastle to analyse the potential for geothermal district heating in South County Dublin as part of the Interreg HeatNet project. This analysis was carried out using techniques and knowledge transfer from Hotlime project partners. It was estimated that between 80 and 400 MW_{th} of heat could be provided by deep geothermal energy from the limestone reservoir of the Dublin Basin, giving carbon savings (when compared to natural gas) of between 80,000 and 400,000 tonnes of CO_2 per annum.

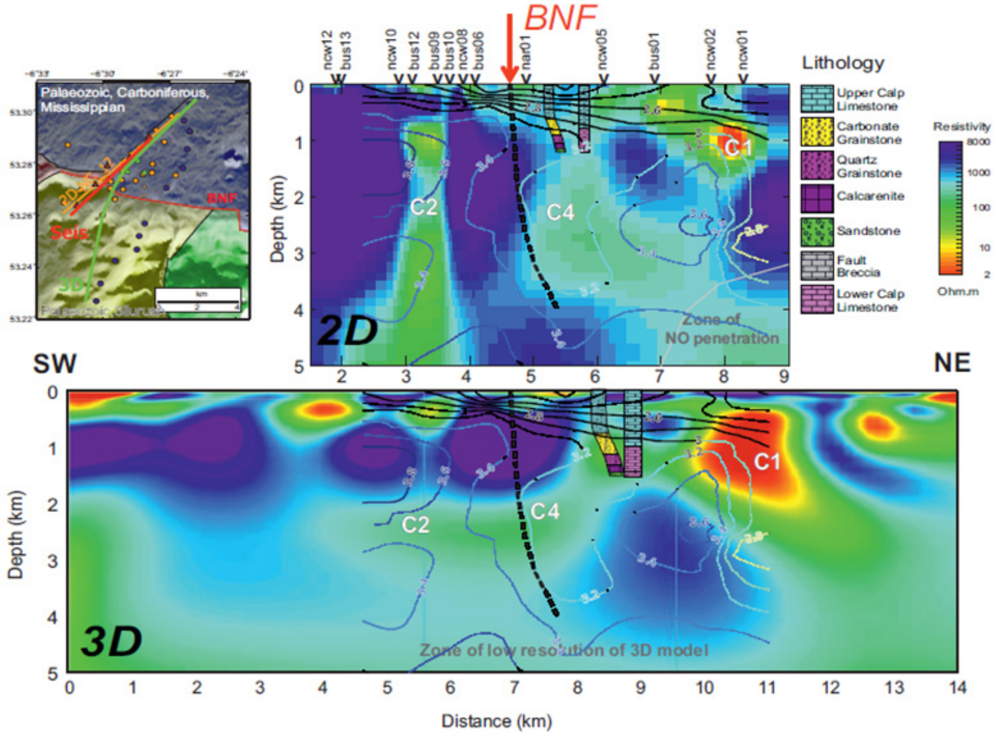

Figure 8.3. Electrical resistivity model of the subsurface beneath Newcastle from Vozar et al. (2020). BNF: Blackrock–Newcastle Fault (cf. https://data.geoscience.earth/ncl/geoera/hotLime/faults/6828)

8.4 Future work and recommendations

The Newcastle geothermal project failed for non-technical reasons, but succeeded in demonstrating the geothermal potential of the Dublin Basin. For further development of the Newcastle geothermal prospect was to occur, there would probably need to be specific geothermal legislation and some financial incentives in place.

The government has developed policy documents to guide Ireland's implementation of EU policy packages in decarbonisation and emissions reduction. Increasing renewable energy production and reducing greenhouse gases are constant themes to which geothermal energy can contribute, particularly where district heating and/or heat pumps are proposed for decarbonising the heat sector. The following recent all-of-government papers consistently refer to geothermal energy:

- The Climate Action Plan 2019 (Action Item 70) directs Geological Survey Ireland to examine the potential of geothermal to contribute to district heating and to develop a Roadmap;
- The National Mitigation Plan 2017 lists geothermal energy as a possible source for renewable heat and electricity generation and Geological Survey Ireland is tasked with assessing Ireland's geothermal potential; and
- The 2015 White Paper, Ireland's Transition to a Low Carbon Energy Future 2015-2030, notes the potential contribution of geothermal energy to the residential heating sector.

Despite these clear policy signals, Ireland has no specific legislation covering geothermal energy, apart from a definition of "geothermal energy" as "energy stored in the form of heat beneath the surface of solid earth" in Statutory Instrument No. 147 of 2011, which gives effect to some provisions of EU Directive 2009/28/EC, and the classification of geothermal energy as a renewable energy source in regulations that implement the EU Energy Performance of Buildings Directive (recast) (Directive EU 2018/844). A draft Geothermal Energy Development Bill was submitted to the government in July 2010, but has not been enacted and the text is not yet publicly available.

Legal ownership of geothermal energy has not been clarified. There is no process for licencing the exploration for, or development and production of, geothermal energy resources. There is no mandatory national or local reporting on geothermal projects beyond requirements under existing environmental and planning regulations.

While the lack of geothermal legislation does not necessarily preclude exploration for or development of geothermal energy, it does increase the level of risk and uncertainty for projects and potential investors. Having a regulatory framework for geothermal energy should help to attract interest in developing geothermal energy for all uses, including district heating.

Arising from actions outlined in the Climate Action Plan of 2019, GSI published *An Assessment of Geothermal Energy for District Heating in Ireland* (2020); simultaneously the Department of the Environment, Climate and Communications (DECC) published *Geothermal Energy in Ireland: A Roadmap for a Policy and Regulatory Framework* (2020). The Roadmap sets out the next steps in the development of the legislation and regulation required to support geothermal energy projects in Ireland, and initiate a period of public consultation. It aims for a policy statement on geothermal energy by the end of 2021 and approval of a regulatory framework by Government, and preparation of the necessary supporting legislation, by 2022. The preparation of the policy documents are being undertaken by DECC with technical support from GSI.

To conclude, approximately 40 % of the island of Ireland is underlain by carbonate bedrock, including the capital city and its hinterland, and it is highly likely that these carbonate basins represent usable geothermal resources for a large proportion of the population. It is therefore key that our legislative framework takes into account the unique technical conditions of exploration and exploitation of carbonate-hosted geothermal resources. It is also important to minimise geological uncertainty insofar as possible, through publicly-funded subsurface investigation (deep seismics and exploratory boreholes are particularly lacking at present). It is anticipated that the learned experiences from the Newcastle project, alongside the outputs from international collaborative projects such as Hotlime, will assist Irish policy makers to develop a geothermal legislative and regulatory framework that is fit-for-purpose and fully supportive of an emerging geothermal sector.

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9 Discussion

Synthesis of the case studies presented in Chapters 2 through 8 above has been used to develop a list of risks and mitigation measures pertinent to carbonate targets, and a series of technical and non-technical recommendations to support these types of project. The main geothermal characteristics of the case studies are summarised in Table 9.1.

Project	Installation type	Geology	Major structures	Depth of abstraction	Reservoir temperatures
1. Krško – Brežice	Extraction wells	Krško basin	Čatež fault zone https://data.geoscience.earth/ncl/geoera/hotLime/faults/4513	up to 706.5 m	up to 64 °C (reservoir)
2. Zagreb	Open loop doublets	Pannonian Basin System - Sava Basin	Sava fault	800 - 1100 m, depending on the borehole	70 - 80 °C (production)
3. Casaglia	Open loop triplet	Po Basin, Triassic / Jurassic carbonates	Ferrara-Romagna Arc thrust system https://data.geoscience.earth/ncl/geoera/hotLime/faults/4374	Circa 2,000 m, based on research permit	100 – 105 °C (production)
4. Californië	Triplet (CWG) and doublet (CLG)	Dinantian carbonates (karstified)	Tegelen Fault Zone https://data.geoscience.earth/ncl/geoera/hike/faults/7822	Between 1,450 and 2,560 m depth	80 °C (production)
5. Munich cluster	Doublet or triplet closed loop	Upper Jurassic carbonates beneath Molasse Basin	Munich Fault https://data.geoscience.earth/ncl/geoera/hotLime/faults/3487 Unterhaching Fault System https://data.geoscience.earth/ncl/geoera/hotLime/faults/3459	Between 2,350 m in the north and 5,000 m in the south	Between 65 °C in the north and 148 °C in the south (production)
6. Jafre	Not yet planned	Empordà basin	NW-SE Emporda Large-Scale Fault System https://data.geoscience.earth/ncl/geoera/hotLime/faults/6989	Exploration detected target reservoir around 1 km but planned installation could be 1.5 - 2 km	Jafre well: 53.5 °C at 0.97 km depth
7. Newcastle	Planned open loop doublet	Dublin basin	Blackrock Newcastle Fault, aka https://data.geoscience.earth/ncl/geoera/hotLime/faults/6828	Exploration boreholes 1.4 km, planned installation 4 - 5 km	46 °C at 1.4 km depth

Table 9.1. Main geothermal characteristics of the HotLime WP4 case studies.

9.1 Environmental and technical issues related to deep geothermal projects in carbonate rocks

One of the principal objectives of HotLime is to de-risk deep geothermal exploration and production by providing the best possible geological information for the case study areas (see, e.g., HotLime Deliverable 2.0). This includes the collation of mitigation and corrective measures that should be applied to underachieving and failed projects (this report).

The *Online Risk Register* of the GeoRisk Project (https://www.georisk-project.eu/) lists a wide variety of possible reasons for underachievement or failure of geothermal projects and suggests corrective measures. This comprehensive and general risk register (i.e., not focused on a specific geological setting or environment) was used as a basis for allocating HotLime's appraisal of potential issues, and to specify and adapt GeoRisk's itemizations to carbonate rock geothermal reservoirs as considered in HotLime. The following list focuses only on those GeoRisk categories where specification or adaptations for carbonate rock reservoirs apply; original text from GeoRisk is written in grey, and HotLime additions are in black. (The full listing of each topic in the GeoRisk *Online Risk Register* can be accessed through the hyperlinks *in italics*.)

GeoRisk topic: *Flow rate lower than expected (reservoir)*

Corrective measures:

- Adaptation of the drillpath to reach multiple targets
- Try to drill long enough production section for securing the expected yield
- In low-enthalpy systems such as most carbonate reservoirs, the target formations are at great depth. Side-tracks thus, are very costly and should be considered only as a last resort to avoid a total loss.
- Prime targets in carbonate reservoirs are usually faults and fractures and their damage zones. Extending the drill path beyond the fracture zone might protrude into competent country rock, and have a negative effect on yield.
- Acidification is an effective common practice in carbonate rocks to improve the flow rate, but should be applied before routine production starts (Schumacher and Schulz, 2013).

GeoRisk topic: *Flow rate degrades over time*

Prevention:

- Thorough reservoir management plan
- Select suitable production rates, consistent with reservoir hydraulic parameters
- Avoid over-exploitation, or situating the landing points of the production and reinjection wells too close together; this can be avoided through proper planning and hydraulic tests.
- Avoid scaling and/or sanding by regular flush scouring of boreholes.

Corrective measures:

- Perform stimulation (thermal, chemical, hydraulic)
- Hydraulic stimulation by acidification is an effective common practice in carbonate rocks.

- Decrease of production rate (temporary)
- Drill additional production well or drain
- As stated above, in low-enthalpy systems such as most carbonate reservoirs, the target formations are at great depth. Drilling of additional production wells or drains, thus, are very costly and should be considered only as a last resort.

GeoRisk topic: *Temperature lower than expected (reservoir)*

Prevention:

- Use of cement with increased heat insulation properties
- Additional investigation early in the project
- Sound preliminary investigation will avoid a lack of knowledge of the geology or physico-chemical characteristics.

Corrective measures:

- Increase of the flow rate
- The prime target in carbonate reservoirs is usually to intersect faults and fractures and their damage zones. Increasing the flow rate might trigger seismic events, specifically when the reinjection of cooled water is performed in / close to fault zones.
- Adaptation of the drillpath to reach multiple targets - drill further
- As stated above, prime targets in carbonate reservoirs are usually faults and fractures and their damage zones. Extending the drill path might have a negative effect on the yield when protruding into competent rock.

GeoRisk topics: *Target formation is missing in the well*; *Target formation has no/insufficient fluid for commercial production*

Prevention:

- Sound preliminary investigations to avoid a lack of geological knowledge, or uncertainty in the physico-chemical characteristics.

GeoRisk topic: *Extensive scaling in the geothermal loop*

Corrective measures:

- Installation of inhibitor dosing station
- Temperature Maintenance
- Regular maintenance of the equipment, replacement or patch if needed
- Adapt the material selection to the chemical/physical properties of the fluid
- The principal scaling threat to carbonate reservoirs, which usually feature low to moderate total dissolved solids, is carbonate scaling. Periodic backflushish and the application of acidified fluids is common practice to avoid performance-reducing scaling.

GeoRisk topics: *Excessive corrosion in the geothermal loop*; *Particle production ("sanding")*

General:

- Corrosion is rare with the fluids found in carbonate reservoirs. Dissolved (hydro-) carbonate load normally buffers the pH of the fluids; other dissolved corrosives that are not buffered by carbonates are limited to (rare) specific geological settings.
- To avoid sanding, marly and/or sandy carbonate sections within the reservoir should be sealed by casing off the respective sections of the production well.

GeoRisk topics: *Hydraulic connectivity between wells is insufficient for commercial use*; *Re-injection of the fluids is more difficult than expected*

Corrective measures:

- Stimulation (thermal, chemical or hydraulic)
- Drill another well in same hydrogeological unit
- Adaptation of the drillpath to reach multiple targets
- In low-enthalpy systems such as most carbonate reservoirs, the target formations are at great depth. Side-tracks thus, are very costly and should only be considered as a last resort.
- Prime targets in carbonate reservoirs are usually faults and fractures and their damage zones. As discussed above, extending the drill path beyond the fracture zone might have a negative effect on the yield.
- Acidification is an effective common practice in carbonate rocks to improve the flow rate, but should be applied before routine production starts (Schumacher and Schulz, 2013).
- Swapping the functions of the production and re-injection wells has turned out to be a successful correction measure in some instances.

To conclude, most topics listed in the GeoRisk *Online Risk Register*, at least those referring to geological issues, can be avoided with sound preliminary investigations for site selection followed by detailed site-specific studies. The outputs of HotLime are appropriate to support preliminary investigations, at least in the HotLime study areas, and provide reliable area delimitations for selecting sites worthy of further investigation.

9.2 Recommendations

The HotLime case studies in Tables 1.1 and 9.1 demonstrate the wide range of applicability of low-enthalpy geothermal resources found in deep carbonate bedrock across Europe; applications range from balneology, agriculture and horticulture, to district heating, and even electricity production (Germany, Ireland although project did not progress to completion). The projects have a wide range of depths, geothermal gradients and production temperatures, but are all exploiting fracture zones associated with major fault structures.

It is clear that the major barriers to the development of these resources are non-technical, ranging from a lack of any legislative framework at all (Ireland), to a legislative framework that is not fit for purpose causing prohibitive delays to the project (Slovenia), to a lack of polictical support (Croatia, Catalonia) and perceived risk of seismicity (Netherlands). Lack of financial support (access to funds, or feed-in tariffs) was cited often as a major barrier to geothermal development in the case studies.

In the cases where the projects failed for technical reasons (e.g., two of the wells in the Munich cluster), this can be attributed to a lack of geological knowledge of fracture networks (e.g., location, or whether the fractures were closed or open) resulting in dry wells or inadequately designed installations.

In the cases where geothermal projects were deemed successful, a critical factor was the developer having access to adequate funding/insurance for the project; the bankability of geothermal projects is inextricably linked to the presence of a robust legal framework (e.g., Germany, Netherlands). In several cases (Slovenia, Croatia, Italy) these projects were established decades ago and have been operating over long time scales.

The following steps are recommended in order to increase the uptake of deep geothermal developments in carbonate bedrock reservoirs (these recommendations also apply for large-scale geothermal projects in general):

- Decrease risk for developers by increasing the amount of good-quality deep subsurface data.

By de-risking the preliminary stages of exploration through the provision of high-quality geological maps and models, particularly around strategic deep fault zones, Geological Survey Organisations can promote and publicise these geothermal resources and provide a secure footing for the planning and financing of geothermal developments. The existence of trusted maps and models in the public sphere has been the basis of the geothermal boom of the last decade in the Netherlands and Germany.

- Develop financial instruments to make geothermal energy attractive for investors.

Some case studies (e.g., Slovenia, Croatia) cited the competition from “cheaper“ alternative renewable energy resources as a deterrent for would-be investors. As the capital costs are high for geothermal projects, appropriate financial supports (insurance and feed-in tarriffs) are needed to justify the investment and make it competitive. However, financial institutions will not lend or insure unless the geothermal resource is well-characterised and the developer can be relatively sure of the amount of energy available.

- Develop or streamline the permitting process for geothermal projects.

A functional legislative framework for geothermal energy abstraction must exist if deep geothermal energy projects are to be encouraged. The legislation must establish, at a minimum, ownership of the abstracted heat, and the government bodies responsible for regulation of the licensing process. It is important to streamline the permitting and licensing process as much as possible, to avoid costly delays to project development.

A comparison of the governing regulatory bodies different jurisdictions may be of interest for policy makers; this information is available for most of the case study areas in HotLime Deliverable 5.1.1 (Borović

& Hotlime Team, 2021: Synopsis outlining the regulations for licensing the exploitation of geothermal energy in the HotLime partner countries, https://repository.europe-geology.eu/egdidocs/hotlime/hotlime_deliverable_511.pdf).

- Focus on science communication to alleviate public concerns.

It is clear that a lack of public awareness of geothermal resources in general persists across many of the study areas. On the other hand, the perceived risk of induced seismicity can cause geothermal projects to be shut down and suspended indefinitely (as in the example of the Californië project, Netherlands). Geological Survey Organisations are a trusted source of impartial advice and geoscience information, and so have an important role to play in the interpretation and dissemination of geothermal research and geological information.Transparency and proactive communication are key to keeping the public engaged and informed.