TRANSTHERMAL

Geothermal potential of the border region between Austria and Slovenia – Evaluation of the geothermal potential based on a bilateral database and GIS – maps for the regions of Carinthia, Styria and Northern Slovenia

INTERREG IIIA Austria – Slovenia

<u>Bilateral Final Report (Austria / Slovenia)</u>

Goetzl G., Lapanje A. (editors)

Authors:

Baek R., Budkovič T., Domberger G., Hribernik K., Lipiarski P., Poltnig W., Rajver D. & Rman N.

89 p., 47 Figs., 6 Tab., 15 Supplements

Vienna – Graz – Klagenfurt – Ljubljana, April 2008

TRANSTHERMAL: Geothermie der Ostalpen – Erfassung und zusammenfassende Darstellung des geothermischen Potenzials in Datenbanken, in einem Geothermieatlas und in GIS – basierten Kartenwerken im Bereich von Kärnten, Steiermark und Slowenien

TRANSTHERMAL: Geotermija Vzhodnih in Južnih Alp – evidentiranje geotermičnih podatkov in združen prikaz geotermalnih potencialov v podatkovni bazi, geotermalnem atlasu in Geografsko informacijskem sistemu na območju avstrijske Koroške in Štajerske ter severne Slovenije

TRANSTHERMAL: Geothermal potential of the border region between Austria and Slovenia – Evaluation of the geothermal potential based on a bilateral database and GIS – maps for the regions of Carinthia, Styria and Northern Slovenia

Project:

Community Initiative INTERREG IIIA AUSTRIA – SLOVENIA 2000 – 2006, common cross-border project TRANSTHERMAL

Executing Organization:

Amt der Kärntner Landesregierung, Abt. 15 Umwelt, DI Harald Tschabuschnig
Amt der Steiermärkischen Landesregierung, Abt. 19A Wasserwirtschaftliche Planung und Siedlungswasserwirtschaft, Dr. Gunther Suette
RRA Koroška d.o.o., Slovenia, Karmen Sonjak

Administrative Project Management

AKL, Abt. 15 Umwelt, Uabt. Geologie und Bodenschutz, Dr. Richard Bäk (Österreich)
Geological Survey of Slovenia, Mag. Andrej Lapanje (Slovenia)

Scientific Project Management

Geological Survey of Austria, Dr. G. Letouzé[1] (Austria)
Joanneum Research, Dr. W. Poltnig[2] (Austria)
Geological Survey of Slovenia, Mag. A. Lapanje[3] (Slovenia)

Editorial Staff:

G. Götzl[1], A. Lapanje[3]

Working Group:

T. Budkovič[3]	Geology
G. Domberger[2]	Hydrogeology, Cartography
G. Götzl[1]	Coordination, Geothermy, Database
K. Hribernik[3]	Database
S. Kumelj[3]	Database, Cartography
A. Lapanje[3]	Management, Hydrogeology
P. Lipiarski[1]	IT – ARC/INFO
P. Meglič[3]	Cartography

S. Mozetič[3] Cartography
A. Löwenstein[1] Database
W. Poltnig[2] Management, Geology, Cartography
D. Rajver[3] Geothermy
N. Rman[3] Database, Hydrochemistry

[1] Geologische Bundesanstalt, Neulinggasse 38, 1030 Wien

[2] Joanneum Research Forschungsgesellschaft mbH, Elisabethstrasse 16/11, 8010 Graz

[3] Geološki Zavod Slovenije, Dimičeva ulica 14, 1000 Ljubljana

Co-operation activities are part-financed by the EU in the framework of the Community Initiative INTERREG IIIA AUSTRIA - SLOVENIA for the period 2000 to 2006

CONTENTS

1 Project presentation

(Baek R., Lapanje A. & Rman N.)

This report is a result of the common cross-border project »TRANSTHERMAL – Geothermics of the Eastern and Southern Alps – collecting of geothermal data and common presentation of geothermal potentials in a database, in a geothermal atlas and in a Geographic information system in the area of Carinthia, Styria and Northern Slovenia«.

The project has been selected at European Union for funding in a frame of the second call »Initiative Programme of Community INTERREG IIIA AUSTRIA – SLOVENIA 2000 – 2006«. The project was running in Slovenia during July 2005 – October 2007, while in Austria from January 2006 to May 2008 with the aim to produce a common overview of the whole project area.

On the Slovenian side the partners in the project were **RRA Koroška, d.o.o., Regional development agency for Koroška** and **Geological Survey of Slovenia (GeoZS).** On the Austrian side the Carinthian government entered in the project, more precisely its department for the environmental, subdivision geology and soil protection (**Amt der Kärtner Landesregierung, Abteilung 15 Umweltschutz, Unterabteilung Geologie und Bodenschutz).** The Styrian government with its department for water management and water supply acted as coregistrant **(Amt der Steiermärkischen Landesregierung, Abteilung 19, Fachabteilung 19A, Wasserwirtschaftliche Plannung und Siedlungswasserwirtschaft).** The Project performers on the Austrian side were research staff of Geological Survey of Austria (**Geologische Bundesanstalt (GBA)** from Vienna and research institute **Joanneum Research (JR)** from Graz.

The project has been carried out as a joint project. Consequently the identical project activities have been performed on the Slovenian as well as on the Austrian side, whereas the financial liabilities between the countries have been separated. In Slovenia the project activities comprised the entire areas of Pomurje, Podravje and Koroška statistical regions and partly areas of Savinja, Central Slovenia and Gorenjska statistical regions. On the Austrian side they comprise the southern part of Carinthia (East of Bad Bleiberg) and the southern part of Styria.

During the last decades many geothermal studies have been carried out in both countries that have contributed a great quantity of heterogeneous data. The basic task of the project was to collect geological, hydrogeological, hydrochemical and geothermic data and to unify the different informations. Such an act helps in the interpretation of the geothermal potential of the cross-border area between Slovenia and Austria. The existent data are from archives and databases of GBA, Joanneum Research and GeoZS, as well as from published sources. All data have been collected in a database that made feasible the uniform judgement of geothermal potential of the cross-border area. The database is presented in a GIS application in form of different thematic maps, which can be used as a starting point for future economical exploitation of geothermal resources, and also for monitoring and protection of already exploited resources.

It had turned out that the task was pretentious because the level of the data handling and the accessibility, the extent of the data and the access to the geothermal investigation reports are very different in both countries. This can be seen at the elaboration of the general geological map in scale 1: 200.000, because there are many conceptual and technical imperfections despite a great extent of simplification and uniformity.

The project results should be understood as an attempt of unifying the existing geothermal knowledge, which enables an assessment of the potential and of the property in the cross-border area. However, the geothermal interpretation needs also an improvement by new research in the future. We must admit that in areas which have been now estimated as thermally non perspective some yet non recognized geothermal resources could exist, but due to the lack of data they can not be predicted at this time.

As we have improved knowledge on geothermal properties of the border area between Slovenia and Austria a better forecast of localities for future investigation on thermal water is possible. Today many communities strive for geothermal research in its area. With the common geothermal database produced by Transthermal with thematic maps it is possible to indicate the appropriate localities for future investigations.

2 Description of the project area

(Poltnig W. & Lapanje A.)

The investigated area covers the border region of Austria and Slovenia and includes the Northern and Northeastern part of Slovenia, and in Austria the Eastern part of Carinthia and the Southern part of Styria (see Fig.2-1).

Project activities in Slovenia cover the area of Pomurje, Podravje and Koroška statistic regions and partly the areas of Savinja, Central Slovenia and Gorenjska statistic regions. The border of the investigated area goes along the southern margin of the Sava valley from Rateče to Kranj and from there in a straight line towards the state border with the Republic of Croatia near Rogaška Slatina in the east. The western and central part of the investigated area is mountainous and includes the Karavanke Mountains, the Kamnik – Savinja Alps and a minor part of the Julian Alps. There are intramountainous basins like Ljubljana basin, Savinja and Šalek valley. The Eastern part is plain and belongs to the margins of the Panonnian basin.

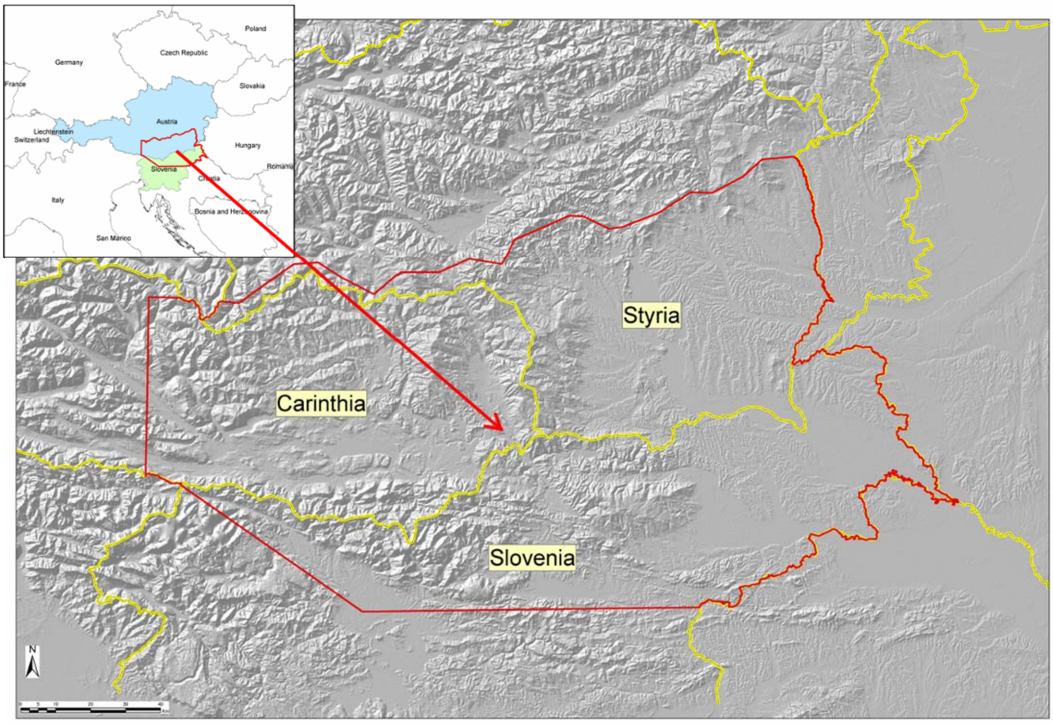


Fig. 2-1 Location of the investigation area in the border region of Austria and Slovenia

The state Carinthia is mainly mountainous, but intramountainous basins exist in the Eastern part. There are also known some natural thermal springs. Even in the state Styria the northern part of the investigated area is mountainous. An extensive plain of Miocene sedimentary basin, which is a part of the vast Pannonian basin, exists in the Southern and Eastern part of Styria and continues to Slovenia and Hungary.

The western border of the investigated area in Austria is a straight south-north extending line west of Villach, the northern border follows the border between Carinthia and Styria extending in the east to the border to Burgenland, whereas the eastern border of the investigation area follows the border between Styria and Burgenland.

3 Data sources

(Lapanje A., Goetzl G. & Domberger G.)

3.1 Introduction

A major goal of the study TRANSTHERMAL consists in building-up a bilateral data compilation, which allows evaluating the geothermal potential within the border region of Carinthia, Styria and Northern Slovenia.

The common database has to handle various kinds of data and information of quite heterogeneous origin. First of all it has to be distinguished between the following data sources:

- Deep wells containing relevant information about the actual geothermal regime
- Natural springs which show increased outflow temperatures (or at least show outflow temperatures, which do not correlate with annual temperature variations) and/or show increased mineral content
- Geothermal subsurface investigations (tunneling, mining)
- Literature sources (geological maps)
- Geophysical investigations (aero, surface, borehole), which have been used for structural analyses

Thematically it has to be distinguished between the following topics:

- Structural and lithostratigraphic conditions
- Thermal regime
- Hydrogeological conditions
- Hydraulic conditions
- Hydrochemical conditions
- Petrophysical conditions
- Thermal-water utilization aspects

In principle deep drillings and wells may contain measured significant values to all previously listed thematic topics and therefore represent the most crucial data sources.

3.2 Slovenian data sources

The Geological Survey of Slovenia (GeoZS) possesses an extensive archive of research reports, monographies and publications, which served as a fundamental source for geothermic, hydrogeological, hydrochemical and geological processing. Based on this archive the GeoZS has an excellent overview of the present geothermic situation within the Slovenian part of the project area TRANSTHERMAL.

Investigations were focused on:

- data sources regarding the exploitation of geothermal energy and
- data sources for determination of structural and depth relations, which have been used to determine the geothermal potential.

After a final overview, 300 relevant data sources, which linked to 283 individual objects, either boreholes or springs, have been identified for the Slovenian part of the common project area. Apart from archival data sources, cadastral datasets focused on Slovenian boreholes and other internal database of GeoZS have formed the fundament of project related interpretations.

The spatial distribution of the considered objects shows that within the Slovenian part of the project area the Pomurje region is by far the most investigated and exploited region for geothermal resources, comprising the main part of the present geothermal data sources. Drilled wells have been primarily aimed for hydrocarbons exploration, and later turned to geothermal. On the surrounding area of Radenci the existing boreholes are mostly drilled for the need of mineral water exploration.

Besides, two large areas with high density of exploration wells occur: Šaleška valley with predomination of exploration boreholes for coal and the area of Rogaška Slatina with predomination of boreholes for investigation of mineral water. At the western part the density of relevant data is clearly reduced. In this region thermal water utilization is connected to near-surface geothermal anomalies and outflow structures (thermal springs), which are locally confined and do not represent the regional geothermic conditions. For that reason only deep boreholes drilled for geothermal exploration purposes and which obtain clarified structural relations and measured geothermal parameters have been considered for processing of the subsurface temperature distribution maps. Moreover, temperature data from shallow boreholes inside the Karavanke tunnel have been used for interpretation also. However, it had to be kept in mind that these datasets show clearly reduced geothermal conditions due to strong surface water inflow.

3.3 Austrian data sources

In the Austrian part of the investigation area around 200 drillings and wells have been identified as at least partially useful for the objectives, which belong to TRANSTHERMAL. The drilling purposes cover hydrocarbon- and coal exploration, mining (ore exploration), thermal water use and water supply. Additionally some scientific drillings ("Naturraumpotential", scientific geothermal surveys in shallow wells) can be reported for the Austrian part of the investigation area. In a further step an additional evaluation of the preliminary selected drillings had to be done, so that the number of data-sources, which have been finally implemented to the common geothermal database, could have been reduced to around 100 objects.

The emphasis of available drillings is clearly situated at the Styrian Basin (primarily within the eastern and southern part), mainly executed for hydrocarbon, coal, thermal- and drinking-water exploitation. In contrast, within the area of Carinthia no hydrocarbon exploration wells can be reported due to shallow and under-maturated basins. Thermal water utilization is limited there to outflow structures nearby or within Preneogene basement.

Natural springs as well as shallow wells related to water supply often solely provide hydrological- (outflow rates, outflow temperatures) and hydrochemical data. According to the objectives of TRANSTHERMAL they have just been included at the common database in case of significant mineralization or outflow temperature, which in turn indicates hydraulic connection to deep-water systems. Subsurface thermal investigations have been implemented to the common geothermal database but are in general not used for thermal processing due to strong anomalous, locally confined geothermal conditions (see also chapter 7.2).

Geological and hydrological mapping results have been primarily stored in terms of literature notes in order to support future geothermal exploration.

In the course of TRANSTHERMAL a comprehensive geothermal data compilation had to be build up for the Austrian part of the common investigation area. Before, a comparable data compilation for the whole area has not existed, except for the area which has been studied in the course of the project NANUTIWA (q.v. DOMBERGER, 2007) for the eastern and southeastern part of the Styrian Basin. The operational activities started with a literature study at the library of the geological survey of Austria. After its accomplishment potential data sources with emphasis on deep wells had been identified for the Austrian part of the project area, focused on the acquirement of temperature data from hydrocarbon and geothermal wells.

Most of the acquired parameters did not have to be processed for database implementation. Processing and analyzing operations had been made only for the following derived values:

- Hochstein classification of geothermal aquifers (HOCHSTEIN, 1988)
- Derived hydrochemical values: D'Amore parameters (D'AMORE et al, 1983), geothermometric calculations (FOURNIER, 1977; FOURNIER & TRUESDELL, 1977; GIGGENBACH, 1988)
- Derived geothermal values: temperatures at a specific depth, geothermal gradients, heat-flow densities

4 Project database

(Lipiarski P., Götzl G. & Lapanje A.)

4.1 Introduction

The common geothermal database aims to afford a unified comprehensive interregional data platform in order to evaluate and visualize the currently known geothermal situation within the extended border region between Austria and Slovenia. By combination of Austrian and Slovenian geothermal results – remember, geological formations do not stop at the border – the elaborated database intends to act as a decision-support tool for the utilization of thermal aquifers.

Beyond, the common database should not just represent the actual geothermal knowledge at the time the current study has been executed in a static way. In fact a possible improved data situation in the future should be able to be implemented into the database and therefore lead to more accurate descriptions and predictions concerning the geothermal conditions. In short, the common database has to feature a dynamic and interactive configuration. Therefore, additional data and possible changes of geological allocations concerning characteristic values, as well as adding of new database tools later on should be executed in an incomplex and easy handling way.

4.2 Database structure

One major goal of the project TRANSTHERMAL consisted in the creation of a bilateral geothermal database (MS Access©, GIS-compatible), which would be able to store structural – geological information, measured and derived temperature information, hydrological data as well as information about aquifer conditions. Based on the results stored in the common database the geothermal potential focusing the exploitation of natural thermal water could be described for the common project area.

The common database has been designed three – lingual supporting the project languages English, Slovenian and German. Beyond, database filling has been executed individually by all three members of the project group. For this reason the database has been designed in 3 replicas (parts) which have been later merged to one database.

The common database has to handle various kinds of data and information of quite heterogeneous origin. First of all it has to be distinguished between the following data-sources:

- Literature sources with the quotation of report (allows determination of data origin)
- Metadata, which include the used research methods
- Significant (characteristic) values of the formation or geothermal object
- Evaluated or calculated data (calculations are not included in the database)

Information is distributed on following, for the project TRANSTHERMAL relevant topics (groups):

- Deep-drillings and wells containing relevant information about the actual geothermal regime
- Natural springs which show increased outflow temperatures (or at least show outflow temperatures, which do not correlate with annual temperature variations) and/or show increased mineral content
- Geothermic investigations in shallow temperature gradient boreholes as well as geothermal subsurface investigations in tunnels and mines)
- Published geological maps and
- Geophysical investigations (aero, surface, borehole) which have been used for structural analyses

In principle deep-drillings and wells may contain measured significant values to all previously listed thematic topics and therefore represent the most crucial data sources.

The concept of the common database provided the subdivision into 4 levels, commencing at a so called meta-database level and reaching up to a level of detailed information. Based on this theoretical background an MS Access© - based relational database structure has been developed.

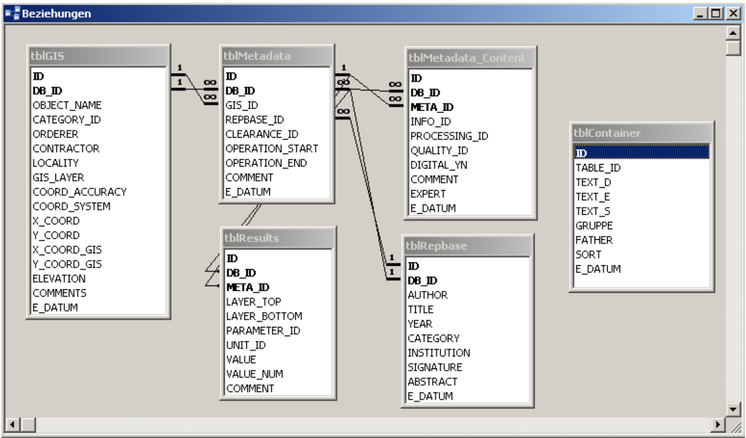


Fig. 4-1 Relationships of the database TRANSTHERMAL.

The database consists of 5 tables. Four of them are linked to the 4 levels of information (see Fig. 4-1), which have been defined above. The 5th table covers the so called multilingual thesaurus.

The so called „Thesaurus“ remarks the core piece of the database and comprises all parameters used in the database in 3 languages (German, English and Slovenian). It can also be easily linked to other languages. Inside of the thesaurus there are some internal relationships (father – son relations) which allow establishing a hierarchical structure.

Application TRANSTHERMAL

The application has been developed using MS-Access© and MS Jetset-Engine. The form “Start” offers the user the possibility of choosing the user („GBA“, „JR“, „SI“) and the working language. This feature is very important for data policy in order to assign database entries to the different project partners (Austria: GBA, JR; Slovenia: GeoZS).

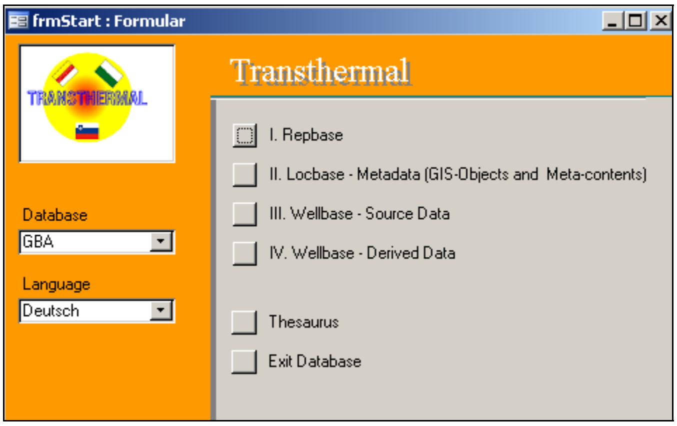


Fig. 4-2 Starting form of the database „Transthermal“.

The language can be modified also during the same working session. This is possible because the translation takes place in the thesaurus – level of the database.

In general the hierachical build-up of the application TRANSTHERMAL mainly follows the structure of the according database tables. It has been distinguished between input forms for the so called metainformation and input-forms for particular results and significant values.

In the following a short overview of the established input-forms will be presented:

Metainformation Level

- Form “REPBASE”: Input of literature notes (author, year, signatures and short abstract).

- Form “LOCBASE”: Input of metainformation concerning specific datasources (e.g. drillings, springs or thermal surveys) including location, orderer and contractor as well as general comments.

- Form “METADATA-SOURCE”: Allocation of literature sources (REPBASE) to specific data-objects (e.g. drilling).

- Form “METADATA-CONTENTS”: Input of metainformations concerning applied investigations and tests (e.g. drill stem tests, temperature measurements and borehole logging) including information about quality and state of processing of the applied methods. This form is linked to specific objects (LOCBASE) and literature sources (METADATA-SOURCE).

Result Level

- Form "RESULTS": Input of specific results and significant values. This form allows entries concerning the depth interval (interval of validation) of specific significant values, used physical units and short continuative comments. Data can be entered as numerical- or alphanumerical values.

To avoid redundant or non-linked entries all forms are linked hierarchically requiring the following datainput-sequence: *REPBASE* ➔ *LOCBASE* ➔ *METADATA - SOURCE* ➔ *METADATA - CONTENTS* ➔ *RESULTS*.

Examples of input forms are shown on the subsequent page (fig. 4.3 & fig. 4.4)

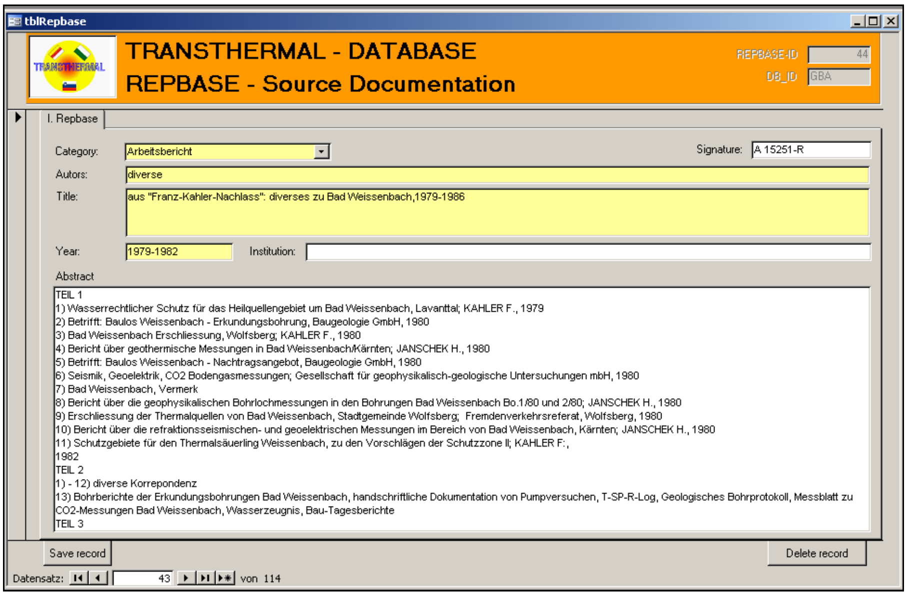


Fig. 4-3 Input-form „REPBASE"

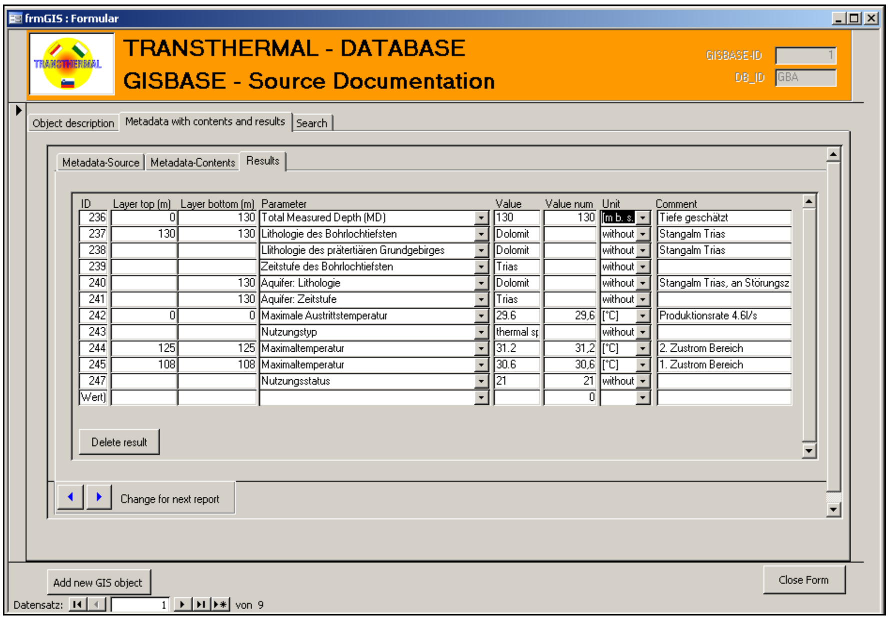


Fig. 4-4 Input-form "RESULTS"

Database-queries

It is possible to search for database entries in full-text mode. Behind this form there is a special database-query which combines all tables and parameters. Such queries have been established for each project language. The user can enter up to three search criteria joined with AND or OR keyword. The search string will be parsed and sent to the search query. Search keywords could be names, parameters, localities, coordinates, results and so on (see also Fig. 4-5).

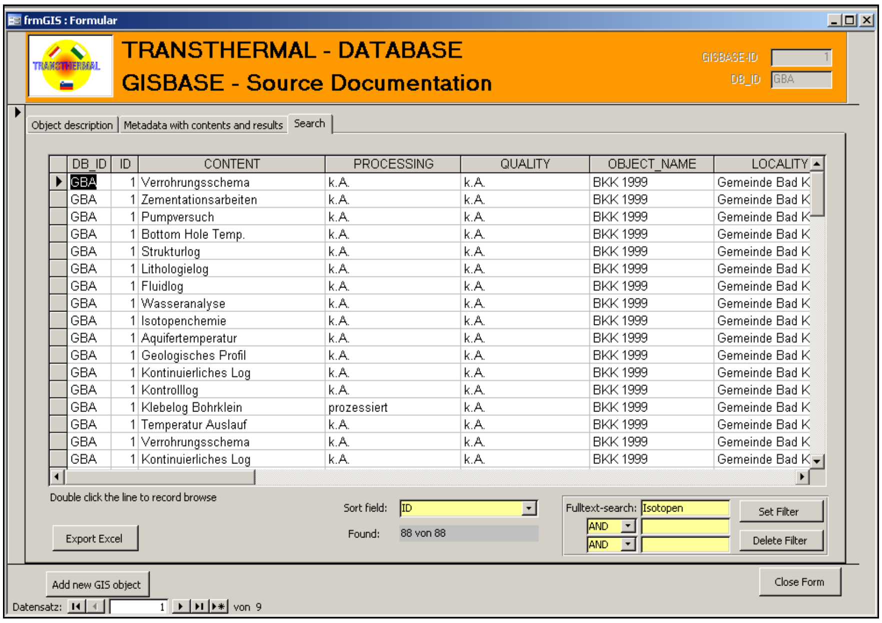


Fig. 4-5 Query-form of the application TRANSTHERMAL

4.3 Database content

In the following chapter the elaborated content of the common, bilateral database will be presented focusing on the following aspects:

- Acquisition of specific data sources (objects)
- Filling of the different database tables
- Acquisition of results

The data acquisition on the bilateral, Austrian and Slovenian border region led to the identification of 501 relevant object sources, which predominantly consist of deep drillings. For lucidity purposes deep drillings have been split to subcategories according to the different drilling purposes (e.g. geothermal well, hydrocarbon exploration well…). Within the Austrian part of the common project area 219 objects have been identified as relevant for the aims of TRANSTHERMAL. The emphasis of collected objects is clearly set on coal drillings, which have been considered for lithostructural interpretations. Besides, 38 geothermal wells and 4 geothermal surveys, which consist of temperature measurements in very shallow wells, as well as 13 natural springs, have been identified on the Austrian side. On Slovenian side 282 objects have been acquired, 8 among them is natural thermal and subthermal springs, 71 boreholes were drilled for geothermal prospection and 10 boreholes were made for determination of geothermal gradient only.

TEXT_E	Number of Points
Geothermal	99
Coal	184
Geothermal Gradient	10
Hydrocarbon	122
Gas Storage	5
Mineral Water	49
Natural Spring	11
Structural Investigation	4
Water Supply	17
total	**501**

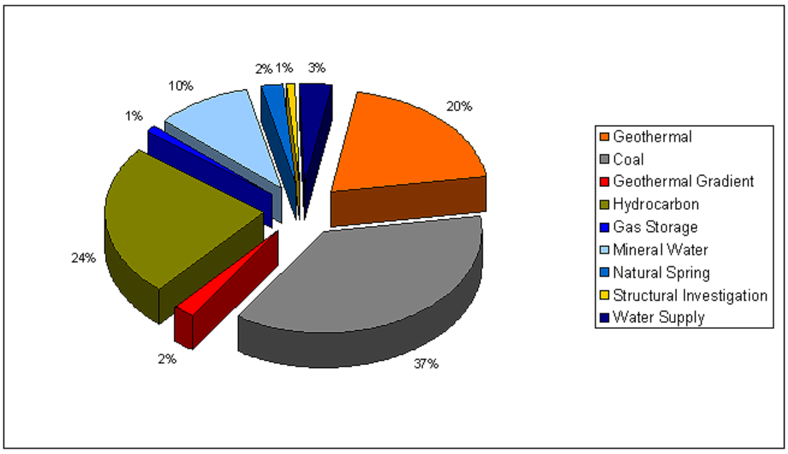


Fig. 4-6 Statistical overview concerning the identified data objects focusing on deep drillings and wells (Austrian and Slovenian datasets)

Table	Austria (GBA + JR)	Slovenia (GeoZS)	AUT + SLO
tblGIS	288	283	571
tblGISResults	282	261	543
tblMetadata	357	783	1140
tblMetadata_Content	460	1865	2325
tblRepbase	142	300	442
tblResults	2146	5862	8008
Total	**3675**	**9354**	**13029**

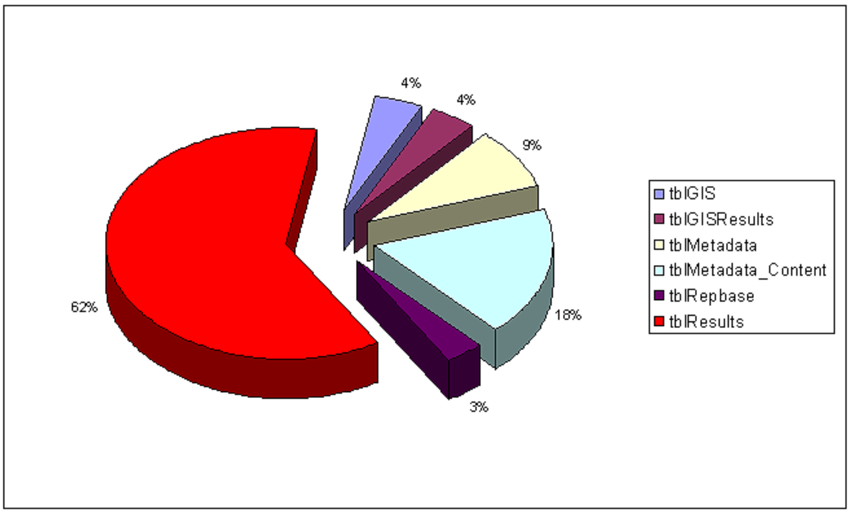


Fig. 4-7 Statistical overview concerning the filling of the different database tables (Austrian and Slovenian datasets)

Linked to the 501 objects in total 13029 database entries have been accomplished, which are split into 9354 entries of Slovenian- (~70%) and 3675 entries (~30%) of Austrian origin. Taking into account that the absolute number of identified objects (primarily deep wells) is more or less equal for both countries, Slovenian wells provide enhanced information about the geothermal regime and existing thermal water reservoirs. This assumption may be clarified by comparing the number of identified relevant literature notes, which is clearly enhanced on the Slovenian side (300 relevant literature notes in Slovenia compared to 142 literature notes in Austria). These statistical characteristics may lead to the conclusion that the state of geothermal exploration is clearly more improved in the Slovenian part of the common project area.

Taking a conclusive look at the acquired significant values as well as on the derived results stored in the common database the following statistical overview can be presented:

Table 4-1 Statistical overview concerning elaborated result values (1)
Geology, Hydrogeology & Tectonics

Parameter	N
Aquifer: Lithology	296
Lithology at Final Depth	133
Aquifer: Time Scale	123

Reservoir Type (Hochstein class.) - (derived)	63
Time Scale at Final Depth	55
Depth Pretertiary Basement	37
Lithology of Pretertiary Basement	34
Depth Crystalline Basement	28
Aquifer: Thickness (gross)	27
Used Aquifer: Lithology	9

Table 4-2 Statistical overview concerning elaborated result values (2) Hydraulic Regime & Hydrochemistry

Parameter	N
Production rate (consent)	274
Cl - Content	238
Ca - Content	230
Mg - Content	230
HCO_3 - Content	228
Total dissolved Solids (TDS)	225
Jäckli Watertype String	224
Na - Content	216
pH - Value	202
K - Content	201
SO_4 - Content	196
D'Amore A	156
D'Amore B	156
D'Amore C	156
D'Amore D	156
D'Amore E	156
D'Amore F	156
Used Aquifer: Permeability	155
Major Gas Component	152
SiO_2 - Content	105
Aquifer pressure: steady state condition	67
Further Substance of Content	63
Used Aquifer: Transmissivity	60
Depth of dynamic water table	48
Density of Thermal Water	40
Gas - Water ratio	5

Table 4-3 Statistical overview concerning elaborated result values (3) Geothermal Regime

Parameter	N
Maximum outflow temperature	276
Temperature in depth of 250 m b.s.	230
Temperature in depth of 500 m b.s.	218
Temperature in depth of 1000 m b.s.	205
Maximum observed Temperature	191
Temperature in depth of 1500 m b.s.	190
K-Mg - Temp.	182
Temperature in depth of 2000 m b.s.	177
Temperature in depth of 3000 m b.s.	148
Na-K-Ca - Temp.	137
Temperature in depth of 4000 m b.s.	133
Temperature in depth of 5000 m b.s.	130
Quartz - Temp.	99
Mean Temperature Gradient (Total drilling section)	47
Mean Temperature Gradient - Tertiary Sediments	44
Mean Annual Surface Temperature	38
Mean Temperature Gradient – preTertiary Basement	23
Temperature at Pretertiary Basement	22
Temperature in depth of 2500 m b.s.	13

Table 4-4 Statistical overview concerning elaborated result values (4) Petrophysical Parameters

Parameter	N
Used Aquifer: Effective Porosity	68
Used Aquifer: Total porosity	49

Table 4-5 Statistical overview concerning elaborated result values (5) General Technical Parameters (drilling-, utilization aspects)

Parameter	N
True Vertical Depth (TVD)	230
Perforated Section	142
Total Measured Depth (MD)	59
Minimum borehole diameter	32
State of Utilization	19
Maximum Inclination	3
Type of Utilization	2
Installed capacity: heating	1

5 GIS – Transthermal

(Domberger G. & Lapanje A.)

5.1 Coordinate systems

Spatial data used for the project originate from following different coordinate systems:

- Slovenian national system (D48, Gauss–Krüger)
- Austrian BMN
- Austrian GK

Therefore all important datasets had to be converted and projected to a common coordinate system (WGS_1994_UTM_Zone_33N). The transformation was made in ArcMap, which is a component of ESRI's ArcGIS Geographical Information System.

5.2 GeoDataBase

The GeoDataBase is used as base for the GIS-visualization of all wells and springs, as well as for several different GIS-vector datasets. This GeoDataBase (GDB) is standard MS-Access database based on GIS-functionality, therefore presents a combination of different datasets (points, lines, polygons).

Within the GDB different types of vector datasets are stored and organized. Several GIS-layers have their source in public available GIS-datasets and several additional datasets have been elaborated in the course of TRANSTHERMAL.

Information layers in the GDB cover the following contents:

- Wells (mapped out with well databases existing at the institutions JR, GeoZS, GBA)
- State and County borders (ESRI-data CD)
- City borders (ESRI-data CD)
- Rivers (ESRI-data CD)
- Borders of the sedimentary basins (mapped out within the TRANSTHERMAL-project)
- Geological map (compiled and mapped out within the TRANSTHERMAL-project)
- Tectonic elements (compiled and mapped out within the TRANSTHERMAL-project)
- Lithology (compiled and mapped out within the TRANSTHERMAL-project)

5.3 Grid data sets

DEM – Digital Elevation Model

The grid size of used DEM is 90 m x 90 m. The source of the used DHM is the CGIAR-CSI GeoPortal. The CGIAR-CSI GeoPortal provides SRTM 90m Digital Elevation Data for the entire world, which is originally produced by NASA. This data, provided on the site http://srtm.csi.cgiar.org/index.asp, has been processed to fill data voids. The SRTM 90m DEM's have a resolution of 90m at the equator and are provided in mosaic 5 deg x 5 deg tiles for download and use.

The used topographical map for the project area is the OeK500 map in scale 1:500.000.

6 Geology

(Poltnig W. & Budkovič T.)

6.1 Introduction

To be able to compare different geological maps of Slovenia, Carinthia and Styria the geological units were simplified and summarized within the project area.

The goal of the geological work within this project is to establish a general legend in the scale 1:200.000. With this general legend geological and tectonic cross border maps were made. On the basis of these maps it is possible to generate geological cross sections and interprete the geometry of Neogene and Paleogene basins and their basement lithology.

6.2 Origin of data and methodology

Origin of used geological data:

Bernhard ATZENHOFER, Rudolf BERKA, Maria HEINRICH, Johann HELLERSCHMID-ALBER, Gerhard LETOUZÉ-ZEZULA (Ltg), Irena LIPIARSKA, Piotr LIPIARSKI, Beatrix MOSHAMMER, Walter POLTNIG, Gerlinde POSCHTROZMÜLLER, Ralf SCHUSTER, Thomas UNTERSWEG: Digitale geologische Karte Kärnten.- GIS-Generierung einer geologischen Arbeitskarte von Kärnten als Basis weiterführender rohstoff- und angewandt-geologischer Bearbeitungen.- Endbericht zum Projekt KC-25 der Bund-/Bundesländerkooperation.- 29 Seiten, 17 Beilagen, 8 Abbildungen, 1 Anhang.- Wien, November 2005.

Basic geological map SFRJ 1:100.000, scale 1: 100.000, source date: 1967-1998, date of digitizing: 1998-2003, date accuracy: 2003. Used sheets: Beljak (Villach) in Ponteba, Celovec (Klagenfurt), Celje, Čakovec, Goričko, Kranj, Ljubljana, Maribor in Leibnitz, Nadjkaniža, Ravne na Koroškem, Rogatec, Slovenj Gradec and Varaždin. Digitalisation in frame of the project: Vzpostavitev geološkega informacijskega sistema, Investor. RS MOP ARSO, Beginning in 1996 – still in progress. Geological Survey of Slovenia.

BRENČIČ, M., KUMELJ, Š., ŠINIGOJ, J., BUDKOVIČ, T. (2005): Program raziskav obmejnih vodonosnikov področja Karavank : (priprava dosedanjih rezultatov raziskav za predstavitev javnosti) : mejnik 1 : mejnik 2. Ljubljana: Geološki zavod Slovenije.

BUSER, S.: Geološka karta Slovenije 1:250 000 (v tisku – in print).

POLJAK, M. (2007): Strukturno-tektonska karta Slovenije 1 : 200 000.-GeoZS., Ljubljana.

POLJAK, M. (2007): Strukturno-tektonska karta Slovenije 1 : 200 000. Tolmač. (52. str.) -GeoZS., Ljubljana.

POLTNIG, W.: Ergänzungen zur digitalen geologischen Karte Blätter 200, 201, 202, 204, 210, 211, 212, 213 (auf ANDERLE, 1977, 1977; auf BAUER [Bearb., 1981, 1985]; nach BRENČIČ et al., 1995 und eigenen Quellen). – Unveröff. Digitale Korrekturen, JR – Geol. Bundesanst. / FA Rohstoffgeologie, Graz, 2005.

SCHUSTER R. (2007): Manuskriptkarte der tektonischen Einheiten von Kärnten.- Geol.B-A., Wien.

SCHWENDT, A. (1998): Digitale geologische Karte der Steiermark 1:200.000.- Joanneum Research, Graz.

6.3 Attributes of geological polygons

The national digital data of geological polygons were merged together without changing the original attributes. To create the general legend and to construct a geological and tectonic map new attributes were added to the polygons. The new attributes are a harmonised synopsis of the original attributes, which further admit to generate a common cross border geological and tectonic map. An additional new attribute (Leg_sort) enables to allocate similar legend items (f. e. micaschist) to different tectonic units.

6.4 Compilation of geological and tectonic overview map

The used digital geological maps of the investigation area are in different scales. Styria has a digital map in scale 1:200.000, Slovenia in scale 1:100.000 and from Carinthia 20 digital maps in scale 1:50.000 were used. The Carinthian maps are digitised data from maps of different ages and authors, therefore the maps do not fit at the map borders (see fig. 6-1).

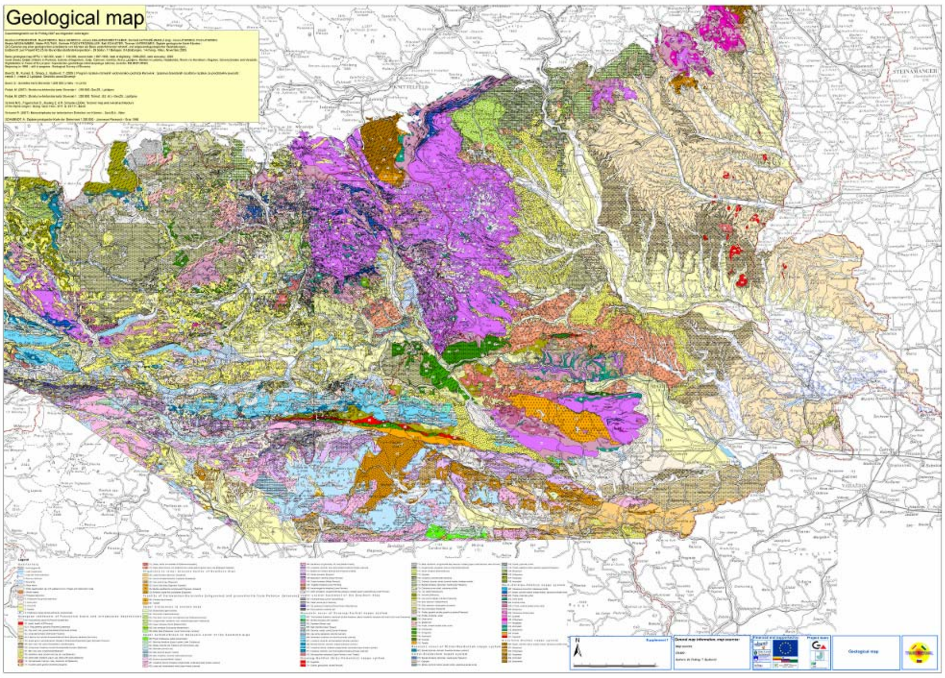


Fig. 6-1 Geological map of the investigation area

In a first step the legend items of the sheets from Carinthia were unified and merged to a new attribute column to reduce the existing 1385 different legend items. Original attributes remain unchanged. In a second step the aggregated legend items from Carinthia have been merged and unified with the legend items from Styria and Slovenia.
In the third step all polygons were allocated to tectonic units similar to the existing classification for tectonic from Carinthia. These tectonic units have been aggregated to enable a general legend of tectonic units for Carinthia, Slovenia and Styria. The basis for this unification is the tectonic classification described in SCHUSTER R. (2003) and SCHMID M.S. et al. (2004).

Subsequent main classification has been used for the geological and tectonic map (see fig. 6-2):
Silvretta-Seckau nappe system – This tectonic unit is only presented in the north of the investigation area and comprises mainly of paragneiss and orthogneiss with embeddings of micaschists, amphybolites, serpentinites and marbles.
Wölz-Koralpe-Pohorje nappe system – This tectonic unit is found in the central part of the investigation area (in the area of Saualpe, Koralpe and Pohorje and also in the most western part of the investigation area north of the Drau valley). The nappe system consists of several nappes with different metamorphosis ranging from phyllitic rocks in the lower nappes to eclogite bearing units in the higher nappes. A great part of this nappe system in the investigation area comprises of paragneisses and micaschists with embedded amphybolites, eclogites, marbles and quartzites.
Ötztal-Bundschuh nappe system and Mesozoic cover of the Ötztal-Bundschuh nappe system – This tectonic unit is presented in the northwest of the investigation area. Paragneisses and micaschists are common, Mesozoic carbonate rocks are found in the uppermost part of the nappe in the transition zone to the overlaying Drauzug-Gurktal (Grazer Paläozoikum) nappe system.
Drauzug-Gurktal (Grazer Paläozoikum) nappe system – Several nappes of this nappe system overlay the crystalline units. The nappes are built up of crystalline rocks with variscian metamorphosis or of Palaeozoic metasediments. Permomesozoic cover is present.
Mesozoic cover of the Drauzug-Gurktal (Grazer Paläozoikum) nappe system –Thick Triassic carbonate rocks are present in the area of the Northern Karavanke, where rocks within a stratigraphic range from Permo-Scythian to Lower Cretaceous age are proven. The Permo-Mesozoic cover in the Northern Karavanke (Krappfeld, Granitztal-Lavanttal) has a different facies and stratigraphic range than the latter one. Jurassic rocks are absent, but we can find here rocks from Upper Cretaceous to Eocene above the Triassic beds.
Upper crustal basement of the Southern Alps – South of the Periadriatic lineament low- or non metamorphic clastic and volcanic influenced rocks from old Paleozoic age with embeddings of limestones are present. In the west of the investigation area these rocks belong to the Karnian Alps and in the area of Karavanke to the Seeberg Paleozoic.
Postvariscian and Mesozoic cover of the Southern Alps – Postvariscian and Mesozoic cover comprises of young Paleozoic molasse sediments of Upper Carboniferous to Lower Permian age, marine Permian beds, thick Triassic carbonate rocks, Jurassic to Lower Cretaceous carbonates and flysch of Lower Cretaceous age.
Upper Cretaceous to Eocene deposits – They are found in the Gosau basins of the Drauzug-Gurktal (Grazer Paläozoikum) nappe system (Krappfeld, Kainach, Lavanttal) and as tectonic remnants within the Southern Karavanke. It is possible that they also exist in the Preneogene basement of the Mura-Zala basin in Slovenia.

Oligocene to Lower Miocene basins of the Southern Alps – Oligocene basins with sediment fill and andesitic volcanism are only present south of the Periadriatic lineament, respectively the Donat-zone. The stratigraphic range comprises of Oligocene to Lower Miocene. North of the Periadriatic lineament Oligocene tonalites of the Karavanke and Pohorje appear.

Neogene sediments of the Pannonian basin and intramontane depressions – Neogene sedimentation in the Pannonian basin and intramontane depressions start with fluviatile coarse sediments of Ottnangian and Carpathian age. The outskirts of the Pannonian basin in the investigation area caused limnic-fluviatile and marine deposition from Badenian age upward.

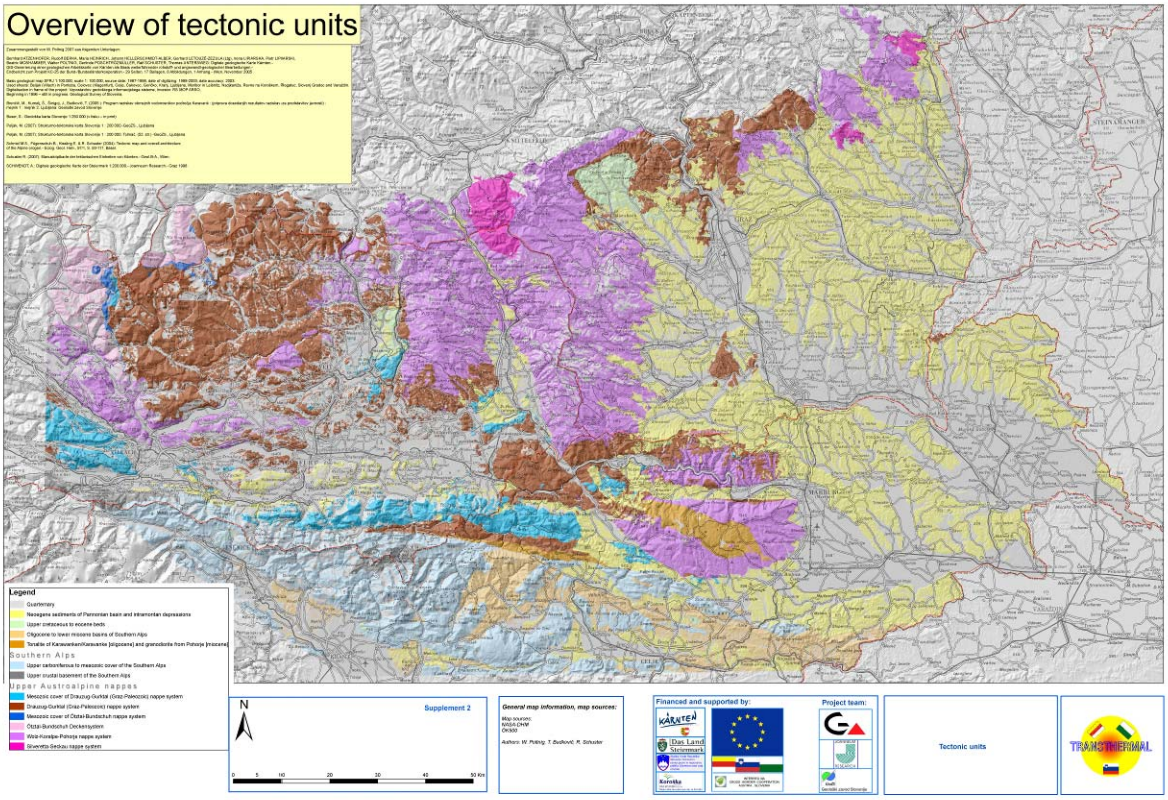


Fig. 6-2: Tectonic units of the investigation area

6.5 Lithology of Preneogene basement in Carinthia, Styria and in the Mura-Zala basin in Slovenia

In the Neogene basins of Carinthia (Lavanttal, Karawankenvorland) no borehole reached the Preneogene basement. Interpretation of these rocks is deduced from the tectonic map. The extent of the different lithologies in the basement can not be given exactly, because tectonic units are built up of many different lithological units.

In Styria and Slovenia some deep boreholes reached the Preneogene basement, but the exact extent of the different lithologies in the basement is not known, nonetheless it is possible to allocate the

basement to tectonic units largely. The classification follows the existing lithology maps of FLÜGEL H., (1988), RAJVER D. et al. (1994) and JELEN B. et al. (2006).
Subsequent units of Preneogene basement were classified:

⇒ **Crystalline of the Wölz-Koralpe-Pohorje nappe system** – Within this unit mainly gneisses, micaschists and amphibolites (eclogites) with minor appearence of marbles are found. Extension: Northern and eastern part of the Lavanttal basin, the Styrian basin and the Murska-Sobota high east of Maribor.

⇒ **Drauzug-Gurktal (Grazer Paläozoikum) nappe system** – Lithology of the Drauzug-Gurktal (Grazer Paläozoikum) nappe system in the Neogene basins of Carinthia and in the Mura-Zala basin is built up mainly of old Palaeozoic phyllites, schists and tuffitic schists. In the Styrian basin within this unit also old Palaeozoic limestones and dolomites from the "Grazer Paläozoikum" nappe are present.

⇒ **Mesozoic cover of the Drauzug-Gurktal (Grazer Paläozoikum) nappe system** – The bedrock of the Villach basin can be interpreted as the continuation of the Gailtal Alps and should therefore be mainly built up of Triassic carbonate rocks. In the Granitztal and adjacent Lavanttal basin the development of Mesozoic rocks is different from the "Drauzug". Carbonate rocks are not as thick as there, Permo-Scythian sandstones and Triassic schists are widespread and some Cretaceous deposits overlay the Triassic rocks. The Lavant fault displaces these west – east striking rocks to the south. The continuation of these rocks could be probably found in the basement area around Radkersburg. Also bedrocks, mainly interpreted as clastic rocks, in the area of Ptuj – Ljutomer (conglomerates, sandstones, marls, limestones) could belong to this Mesozoic unit or to the unit of Upper Cretaceous to Eocene deposits.

⇒ **Postvariscian and Mesozoic cover of the Southern Alps** – Between Periadriatic lineament and Sava fault mainly south alpine Triassic carbonate rocks and molasse sediments of Upper Paleozoic are developed. These rocks are tectonically dragged into the fault zone south of Pohorje (Donat-zone) and probably build the bedrock of Neogene sediments in the southern part of the Haloze – Ljutomer synform south of the Ljutomer fault.

⇒ **Upper Cretaceous to Eocene deposits** – Sandstones and marls (Kainacher Gosau) form the Preneogene basement rocks in the Stallhofen basin west of Graz. Similar rocks could also occur locally in the Preneogene of the Mura-Zala basin.

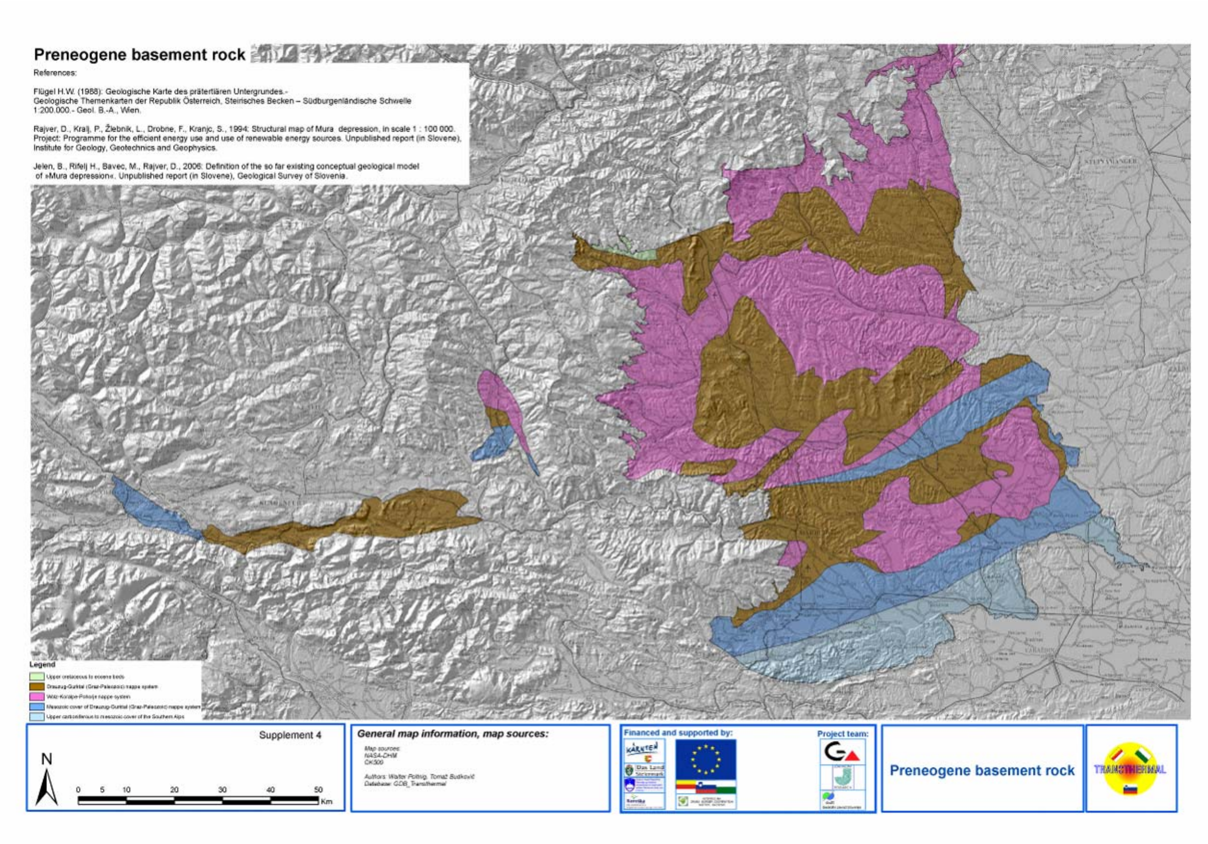


Fig. 6-3: Map of Preneogene basement rocks

<u>Used maps</u>:

FLÜGEL H.W. (1988): Geologische Karte des prätertiären Untergrundes.- Geologische Themenkarten der Republik Österreich, Steirisches Becken – Südburgenländische Schwelle 1:200.000.- Geol. B.-A., Wien

JELEN, B., RIFELJ, H., BAVEC, M., RAJVER, D., 2006: Opredelitev dosedanjega konceptualnega geološkega modela »Murske depresije«. Interno poročilo, Arhiv Geološkega zavoda Slovenije.

RAJVER, D., KRALJ, P., ŽLEBNIK, L., DROBNE, K., KRANJC, S.,1994: Strukturna karta Murske depresije v merilu 1 : 100.000. Program za učinkovito rabo energije in obnovljivih virov energije. Pridobivanje energije iz obnovljivih virov. Geotermalni viri Slovenije in njihova izraba, I. faza. Interno poročilo, Geološki zavod Slovenije.

6.6 Geological cross sections

To show the geological structure seven geological cross sections were made, five of them in N-S direction and two in E-W direction. The horizontal scale is the same as in the map – 1 : 200.000, vertical scale is 1 : 50.000 (for better presentation of geological units). Surface data was taken from the geological map, Pretertiary basement data for the Styrian basin and the Südburgenländische Schwelle from the 1:200.000 map (FLÜGEL, H. W. 1988 : STEIRISCHES BECKEN – SÜDBURGENLÄNDISCHE

SCHWELLE. Geologische Karte des prätertiären Untergrundes. GBA, Wien 1988). For the Slovenian part of the Pannonian basin we used RAJVER, D., KRALJ, P., ŽLEBNIK, L., DROBNE, F., KRANJC, S., 1994: Structural map of Mura depression, in scale 1: 100 000. Project: Programme for the efficient energy use and use of renewable energy sources. Unpublished report (in Slovene), Institute for Geology, Geotechnics and Geophysics.

We also used deep boreholes geology, where they are situated at cross sections. Tectonic lines for the Slovenian side were taken from POLJAK, M. 2007: Strukturno – tektonska karta Slovenije 1: 250.000. (map and explanation book) Geološki zavod Slovenije, Ljubljana.

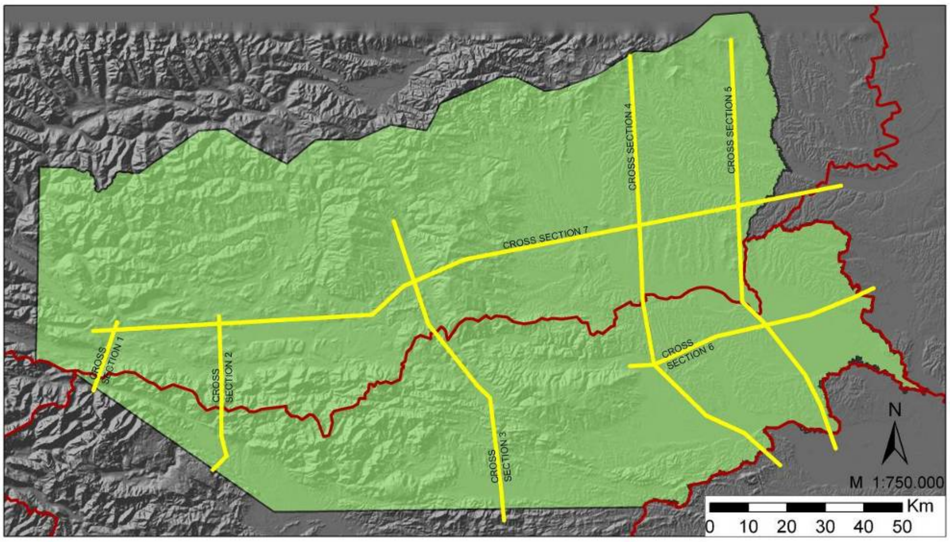


Fig. 6-4: **Location of the cross sections 1 – 7**

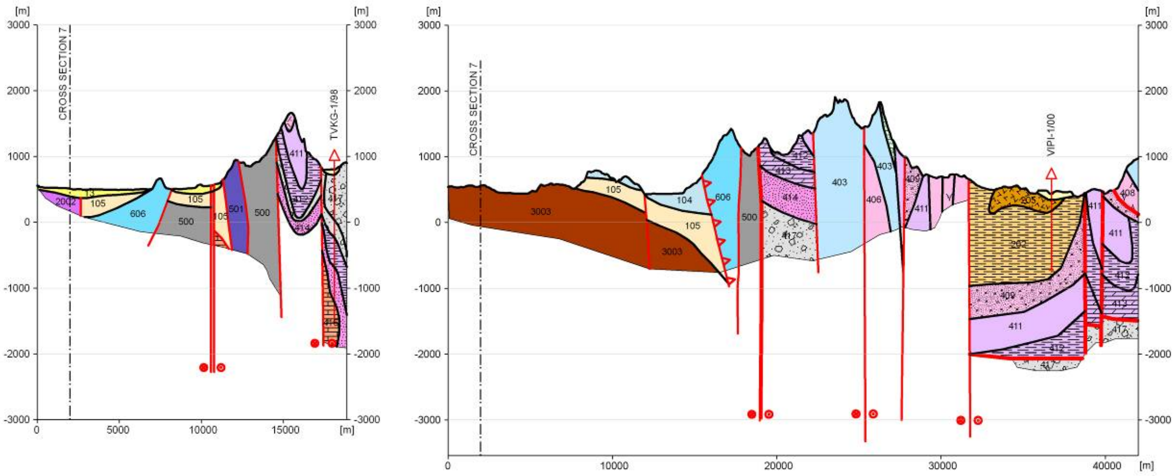


Fig. 6-5: Cross section 1 and 2 (north to south = left to right)

Cross section 1 is situated at the western part of the Karavanke Mountains and their vicinity. Looking from N to S it crosses the Mölltal fault, the Mesozoic cover of the Drauzug-Gurktal overthrust system, the Periadriatic lineament, the Postvaristic and Mesozoic cover of the Southern Alps (Southern Karavanke) and the Sava fault, ending at the deep borehole TVKG–1 in Kranjska Gora.

Cross section 2 starts north in the metamorphic rocks of the Drauzug-Gurktal overthrust system, crosses the Mesozoic cover of the Drauzug-Gurktal overthrust system, the Periadriatic lineament, the Southern Karavanke, the Radovljica depression (filled with Paleogene sediments underlain with Triassic sediments) and the NE wedge of Jelovica plateau (the last three belong to Postvaristic and Mesozoic cover of the Southern Alps).

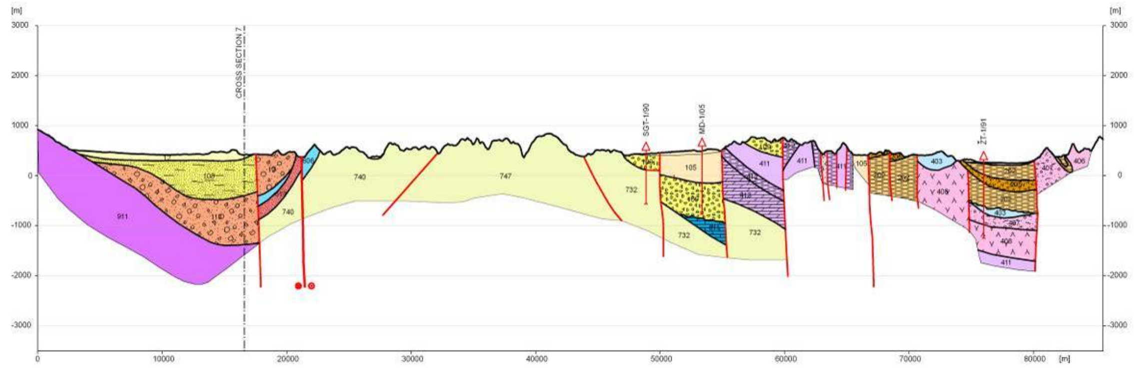


Fig. 6-6: Cross section 3 (north to south = left to right)

The northern part of cross section 3 begins in the metamorphic rocks of the Wölz – Koralpe – Pohorje overthrust system, dipping under the Wolfsberg depression, filled with thick sequence of Neogene sediments. The middle part of the section consists of metamorfic rocks of the Drauzug-Gurktal overthrust system, dipping under the Slovenj Gradec depression to the south. The southern part of the cross section intersects the Celje depression, filled mostly by Paleogene sediments deposited on Postvaristic and Mesozoic cover of the Southern Alps.

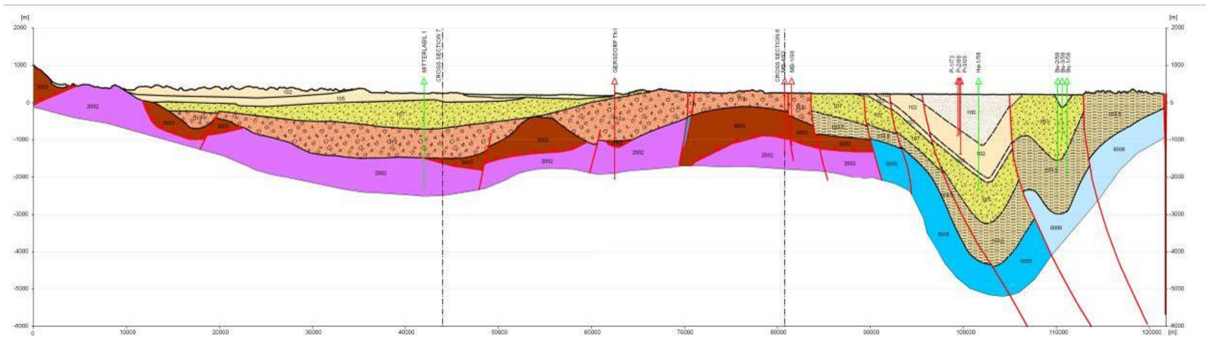


Fig. 6-7: Cross section 4 (north to south = left to right)

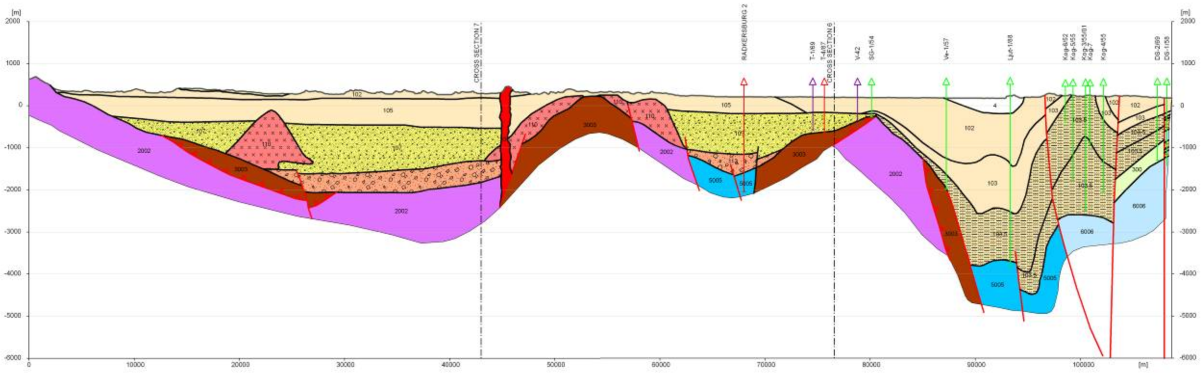


Fig. 6-8: Cross section 5 (north to south = left to right)

Both geological cross sections (4 and 5) begin north in the metamorphic rocks of the Wölz – Koralpe – Pohorje and Drauzug-Gurktal overthrust systems, dipping under the Neogene sedimentary and volcanic cover of the Styrian basin which is divided from the Mura – Zala basin by the Burgenland high. The Mura – Zala basin (marine sediments dominating) is deeper than the Styrian basin (with terrestrial and marine sediments). The most important faults are the Raba fault (NE – SW oriented) in the central part of both cross sections, and the Ljutomer and Donačka gora faults (mainly E-W oriented) in the southern part. The Ljutomer fault divides the Eastern from the Southern Alps.

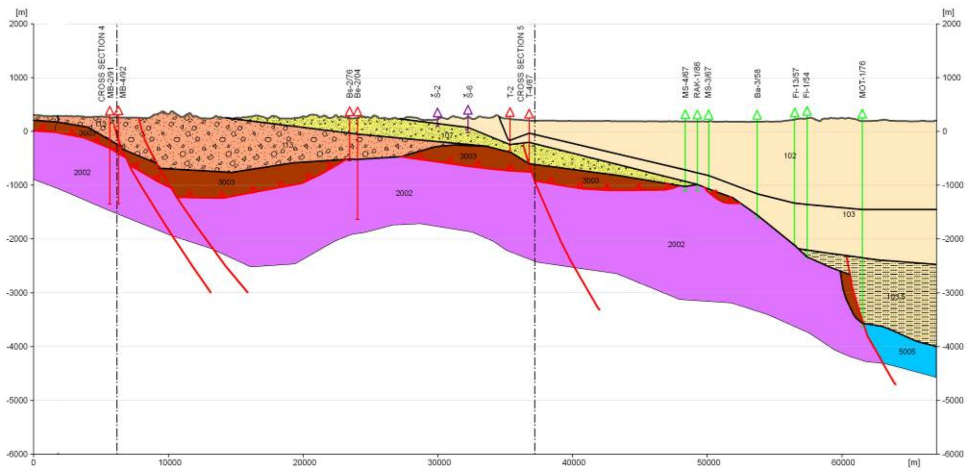


Fig. 6-9: Cross section 6 (west to east = left to right)

Cross section 6 is situated in the Slovenian part of the Mura – Zala basin and is oriented in W – E direction, parallel to the main geological structures. In the eastern part of the cross section the Pretertiary basement subsides along the NW – SE striking fault.

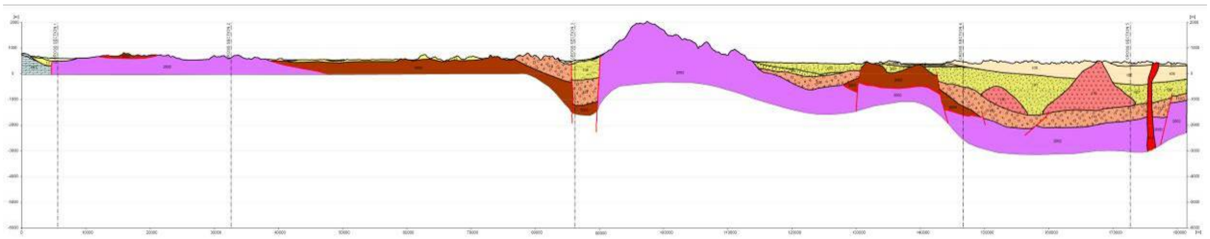


Fig. 6-10: Cross section 7 (west to east = left to right)

Cross section 7 is situated in W-E direction on the Austrian territory. In the west it begins in the Mesozoic cover of the Drauzug – Gurktal overthrust system, separated from metamorphic rocks of the Wolz – Koralpe – Pohorje and Drauzug-Gurktal overthrust systems by the NW-SE oriented Mölltal fault. Metamorphic rocks of both overthrust systems form the western part of the cross section. In the middle, the cross section intersects the Wolfsberg depression filled with Neogene sediments. The depression has two different parts: to the west a shallower synform with Mesozoic sediments in the basement and Karpatian sediment filling. This structure was cut by the Lavanttal fault and probably has its eastern continuation on Slovenian territory. The other part, formed along the Lavanttal fault, is deeper. To the east metamorphic rocks of the Wölz – Koralpe – Pohorje and Drauzug-Gurktal overthrust systems, building Koralpe, dip to the east under the Neogene cover of the Styrian basin. In Neogene sediments bodies of vulcanites are situated.
A legend of the lithological units is given in the Geological Map (supplement 1).

7 Geothermal conditions

(Götzl G. & Rajver D.)

7.1 Introduction

The area treated in the project Transthermal is geothermally characterised by average geothermal gradients and surface heat flow density (HFD). Only in the very eastern part (eastern Austria, northeastern Slovenia) the gradients and surface HFD values are elevated.

The project area covers the existent regional geothermal maps that were processed more than 8 years ago for elaboration of the two atlases. The elaboration of the older one started 20 years ago. Therefore, somewhere the isotherm and HFD isoline patterns are somewhat obsolete or out-of-date or not accurate, somewhere else, namely in southern Austria, these isolines are partly missing or established by interpolation of the adjacent areas, above all in the area of Carinthia. So the present project focused on an improvement of the geothermal picture of both countries with new data, to fill in some blank areas if possible and moreover to make the temperature depth maps more thorough.

The regional geothermal picture that encompasses the common project Transthermal was already presented in different geothermal atlases such as the "Geothermal Atlas of Europe" (HURTIG et al.,

1992) and the "Terrestrial Heat Flow in Europe" (ČERMAK & HURTIG, 1979). The sheet from the first named atlas, titled *Rome – Surface Heat Flow Density*, shows the surface HFD distribution for southern Austria, and the whole Slovenia (as a part of the former Yugoslavia at the time of elaborating and producing the atlas). The surface HFD isolines in Slovenia have a simple pattern with weak anomaly in the Ljubljana basin and higher values towards the northeast of the Pannonian basin region, and partly to the east where they attain somewhere above 80 or even 90 mW/m^2.

Low heat flux values are spread over the regions of the Southern and partly Eastern Alps, the Internal Dinarides and all over in the south where the karstic geomorphology is developed. For southern Austria the same map shows elevated values in Carinthia, even over 100 mW/m^2, which are quite uncertain according to the recent data in the eastern part of Styria and in Burgenland (between 80 and 90 mW/m^2). Despite, some regions of Carinthia have been left totally blank.

In the "Atlas of Geothermal Resources in Europe" (HURTER & HAENEL, 2002, editors) three geothermal maps for the whole region of Europe are presented: heat-flow density, temperature distribution at 1000 m and at 2000 m depth. All three maps are the result of the compilation of different data density and data quality from many countries. For some countries data from the atlas after HURTIG et al. (1992) were just used. Besides, for the HFD map drawing the software program "Geographic Mapping Tools" (WESSEL & SMITH, 1998) was used. For the grid drawing the algorithm by SMITH and WESSEL (1990) was applied while no geological criteria were used. In this way, the HFD isolines in the map of Europe follow the main tectonic elements only in regions where the data set is dense enough. After this sort of processing the isolines do not exhibit this much real pattern for Slovenia since the HFD anomaly in eastern Slovenia is too large, and in the northeastern part only partly real. In Austria the elevated HFD values are visible in southeastern part, which is in southeastern Styria and in Burgenland, about over 100 mW/m^2. Towards west the HFD values decrease, and in Carinthia they attain only 30 to 40 mW/m^2. These values for Carinthia have to be considered as too low for the area north of the Karawanke Mts. since HAENEL & ZOTH (1973) estimated the HFD values between 60 and 80 mW/m² from the sea floor measurements in Carinthian lakes (e.g. Woerther See).

In temperature maps at 1000 m and 2000 m depth from the before mentioned atlas the isoline pattern is pretty realistic for Slovenia and roughly suits the detailed maps. At 1000 m depth high temperature anomalies are discernible from Lenart to Murska Sobota, about 60 to 70°C, elsewhere in northeastern Slovenia temperatures are just little above average, about 40 to 50°C. In the western part of northern Slovenia temperatures decrease down to 15 to 20°C. In Austria there are few anomalies in southeastern Styria, with 50 to 60°C. At 2000 m depth the pattern is similar. Temperature values attain 90 to 100°C in northeastern Slovenia, between Lenart and Murska Sobota even 100 to 120°C, elsewhere there above 80°C. Few anomalies are noticeable in southeastern Austria, with up to 90 to 100°C. Towards west, however, temperatures get lower in northern Slovenia as well as in southern Austria, and attain some 25 to 30°C. North of the Pohorje Mountain isotherms are not drawn in southern Austria due to a lack of data or very low quality of data, as most temperature data there derive from oil wells.

Taking a concluding look at the geothermal regime within the project area the recent geothermal regime is mainly governed by lithostructural conditions. Decreased Moho depths (associated with decreased lithospheric thickness) plead to elevated geothermal conditions within the eastern part of the project area (southeastern Styria, northeastern Slovenia), while increased lithospheric thickness due to orogenic activities significantly reduces them in the western part of the common project area. In regions with strong surface-water inflow (e.g. Karavanke Mountains) the present thermal conditions get even more decreased due to advective influence.

7.2 Data Background Slovenia

The project area belonging to Slovenia has already been fully covered with geothermal maps, temperature maps at different depths as well as with an HFD map. They were made in the framework of the former Yugoslavia for the Geothermal Atlas of Europe (RAVNIK et al., 1987; RAVNIK et al., 1992a). Later on, the geothermal maps for Slovenia were drawn as internal reports within research projects until 1994. Of course, these maps have been gradually improved with the new data from existing and new wells. These new maps have been drawn mostly to depth of 2000 m (RAVNIK et al., 1995; RAJVER & RAVNIK, 2002; RAJVER et al., 2002). It is worth noticing that isolines on these maps are reliable in northeastern Slovenia where numerous oil and geothermal wells occur, and most of central Slovenia. But in many other places, especially in the mountaineous (Alps, Karavanke) regions and in northern Slovenia west from Maribor they are less reliable. However, in the western part there are a few deep wells with good temperature measurements (for example in Kranjska Gora, Slovenj Gradec, Snovik) but the number of the wells with geothermal data is generally low and consequently the contour pattern there is less reliable. Examples of the earlier maps are shown in Figs. 7.1 and 7.2.

Within the Slovenian part of the Transthermal project area geothermal data from 302 wells are available. For almost all wells temperature measurements and for 56 wells among them petrophysical data, such as thermal conductivity or radioactive heat production based on in-situ or laboratory measurements on drilling cores, are available.

Thermal conductivity and radioactive (radiogenic) heat production rates

The thermal conductivity was measured in a laboratory of the Geological Survey of Slovenia by using a transient line source (LS) method called a "generalised hot wire method" (PRELOVŠEK and URAN, 1984). The imprecision of the conductivity data can be quantified as ~ 3%, whereas inaccuracy is estimated to be not more than 10% (RAVNIK et al., 1995). Besides, data on the radioactive heat production of cored rocks are available from 23 wells. The concentrations of the radioisotopes U, Th and K^{40} have been determined at the Institute Jožef Stefan by a gamma-ray spectrometer with a Ge/Li detector. The heat production rates were calculated using the equation given by RYBACH (1988). The depth of the samples for thermal conductivity and radioactive heat production ranges down to 4016 m. The rock density was measured in a geomechanical laboratory of the Geological Survey of Slovenia (RAVNIK, 1991; RAVNIK et al., 1995).

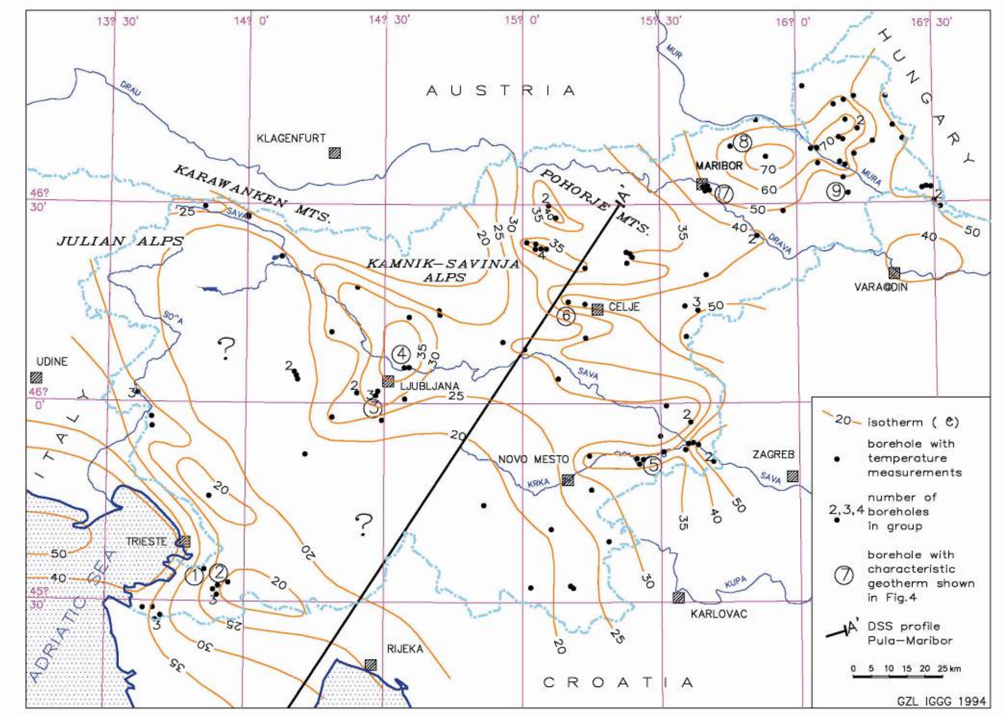


Fig. 7-1 Temperature distribution at a depth of 1000 m (RAVNIK et al., 1995)

Temperature data

Borehole temperatures were measured at 299 wells applying different methods. The temperatures were measured in five different manners where the final scope was to acquire the formation temperature known as the *virgin rock temperature* (VRT). Thermal information was mainly determined using electrical resistance thermometers with Pt sensors, but also by integrated sensors from Analog Devices and thermistors. In deep oil wells the data were obtained by using either Hg-maximum thermometers or Amerada devices (RAVNIK et al., 1995).

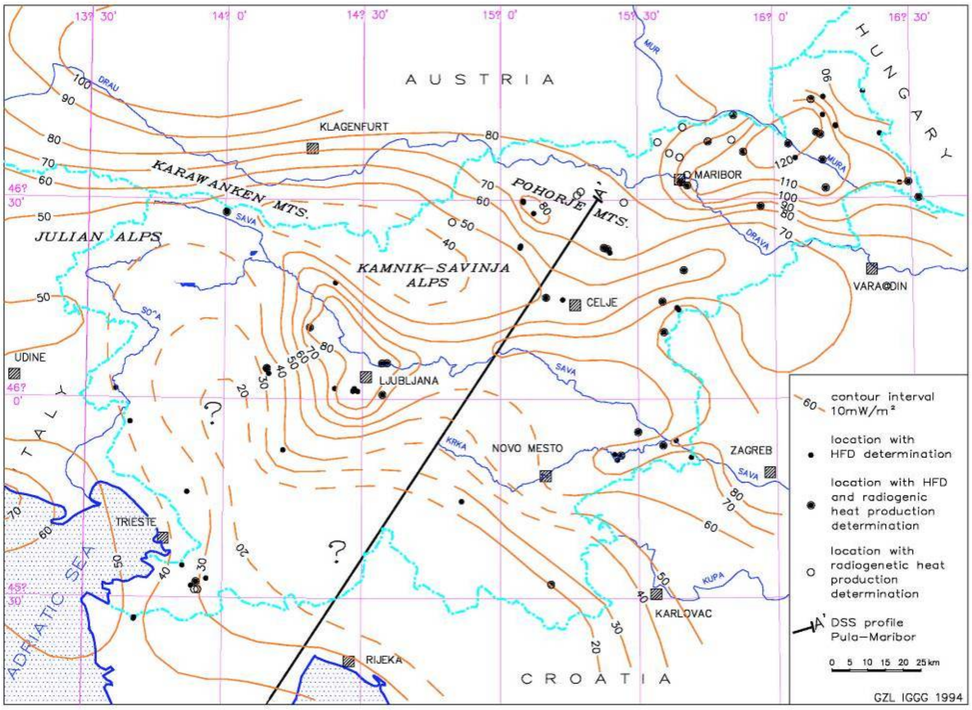


Fig. 7-2 Heat flow density map of Slovenia (RAVNIK et al., 1995)

In the following text a short overview concerning the different origins of available temperature information is presented:

<u>a) Bottom Hole Temperature</u>

Bottom hole temperature (BHT), available at 112 wells, has been measured during drilling or immediately after the end of drilling. Since it has been gained during thermally unstabilized conditions, corrections for the influence of circulating drilling mud (BHT – correction) have to be applied. Unfortunately no BHT – processing is possible at Slovenian wells. The reason is that the logging experts of these mostly older measurements have not provided additional data necessary for correction. Only in a few wells VRTs were determined by using BHT data, which have been processed applying the Horner plot technique (RAVNIK et al., 1995). Later, especially in the last eight years, the experts from the Nafta Geoterm Company have measured temperature and pressure in a steady state condition in the same oil wells, thus these better temperatures were used for this project.

<u>b) Continuous temperature logging</u>

In 105 wells continuous logging has been applied. These wells also cover some geothermal production wells where such logging was only partially performed at distinctive depth intervals at longer shut down periods (no mud circulation). The measurements were performed especially during the last two years based on state of the art logging equipment.

<u>c) Temperatures measured during drill stem tests (DST)</u>

Thermal DST-data have been collected at 10 oil wells within potential hydrocarbon reservoirs. In case of adequate performance the measured DST temperatures provide better VRT-information than processed BHT values (RAVNIK, 1991).

d) Point to point temperature measurements

In 110 wells the temperature was measured at uniform depth intervals of 1 to 10 m, usually of 5 or 10 m (point by point method). These measurements are of the best quality since the temperature was usually measured after longer relaxation or stand still time.

e) Single point temperatures

In 96 wells the temperature was measured in single points (intervals of 25 to 100 m or even more meters). These measurements also mostly provide good data quality and plausibility.

In general the quality of available BHT values is at a low level since they have to be corrected due to transient temperature condition at the borehole. Usually background information concerning the duration of drilling, shutdown time and the duration of circulation is missing. In contrast, temperature readings from the DST measurements generally obtain higher data-quality and plausibility. Moreover, the continuous logging temperature is of good quality at some wells, especially from the recent measurements carried out with the new (Robertson Geologging) equipment.

The bulk of measurements were performed by geophysicists and hydrogeologists of Geological Survey of Slovenia (GeoZS) and predecessors of GeoZS. These data are stored at a related geothermal database at the Geological Survey of Slovenia. The initial period of the data collection and interpretation was described by RAVNIK (1991), while an enlarged database was described by RAJVER & RAVNIK (2002). However, data from three wells at Okonina were extracted from a report of the Geoko Company (SADNIKAR et al., 1996). Eight years ago the Nafta-Geoterm company (Lendava) started with a systematic redevelopment of old hydrocarbon production-wells, executing a comprehensive program of hydrodynamic as well as pressure and temperature measurements in steady-state condition. Consequently better temperature data (NAFTA GEOTERM, 1998-2007) could be gained from this campaign. These temperature measurements pointed out increased temperature gradients in practically all the wells measured, also in those that were transformed into the geothermal wells in the meantime.

The collected geothermal data confirm a good and trustworthy data basis for several deep oil wells in northeastern Slovenia, in the Pannonian basin and also for some wells in other areas of northern Slovenia (Maribor, Slovenj Gradec, Celje valley, partly Vaseno-Snovik). Besides, processed heat flow density values (HFD) gained at shallow wells complete the actual data fundamentally in Slovenia. Recently measured temperature data have been generally gained after a sufficient shutdown period to obtain high-quality data. Exceptions had to be made at some wells in the Velenje basin and some geothermal production wells. In many oil wells the originally gained low-quality BHT measurements have been added with recently repeated, thermal steady-state measurements at even more depth points than before.

Borehole measurements in strongly advection influenced wells (thermal water inflow) have not been included into the elaboration of geothermal maps for the Slovenian part of the investigation area. Another example of aberrant thermal conditions has been observed in a well in Vaseno in the Tuhinj valley as a consequence of a shallow geothermal anomaly zone. It is remarked by a slightly decrease of borehole temperatures below the initial elevated temperature section. Such thermograms can not be considered for extrapolation of geothermal conditions with depth.

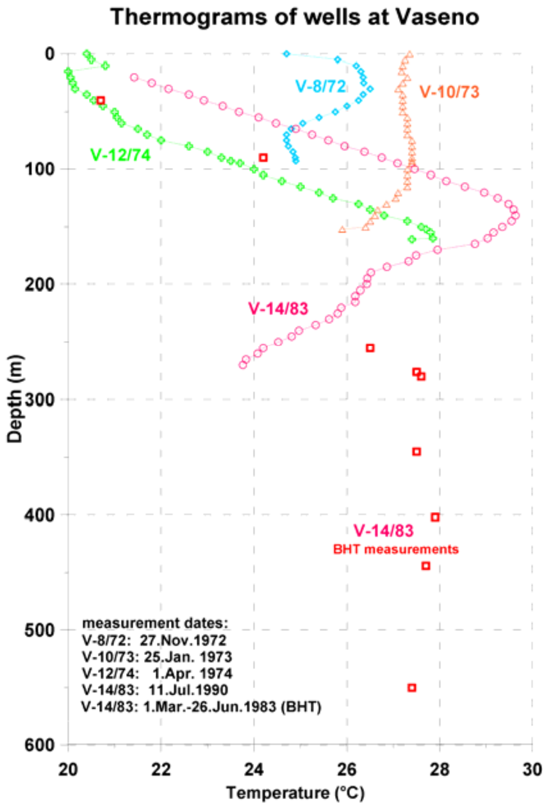


Fig. 7-3 Example of measured temperatures in few wells in Vaseno, northern Slovenia.

7.3 Data Background Austria

The initial situation concerning detailed temperature or heat flow maps in the Austrian part of the investigation area is quite ambivalent. While maps showing geothermal information already exist for the eastern and south-eastern part of the Styrian Basin (Figure 7-4), the western part of the Styrian Basin as well as the Carinthian basins still remain more or less undescribed (see also chapter 7.1). In Carinthia thermal studies have only been executed in connection with existing thermal spas (e.g. Bad Bleiberg, Warmbad Villach, Bad Kleinkirchheim…), which are strongly related to locally confined thermal-water outflow structures. Recent investigations cover the vicinity of the planned “Koralm Tunnel”, where a two-dimensional coupled hydraulic-thermal modelling is currently carried out (GRAF et al 2001).

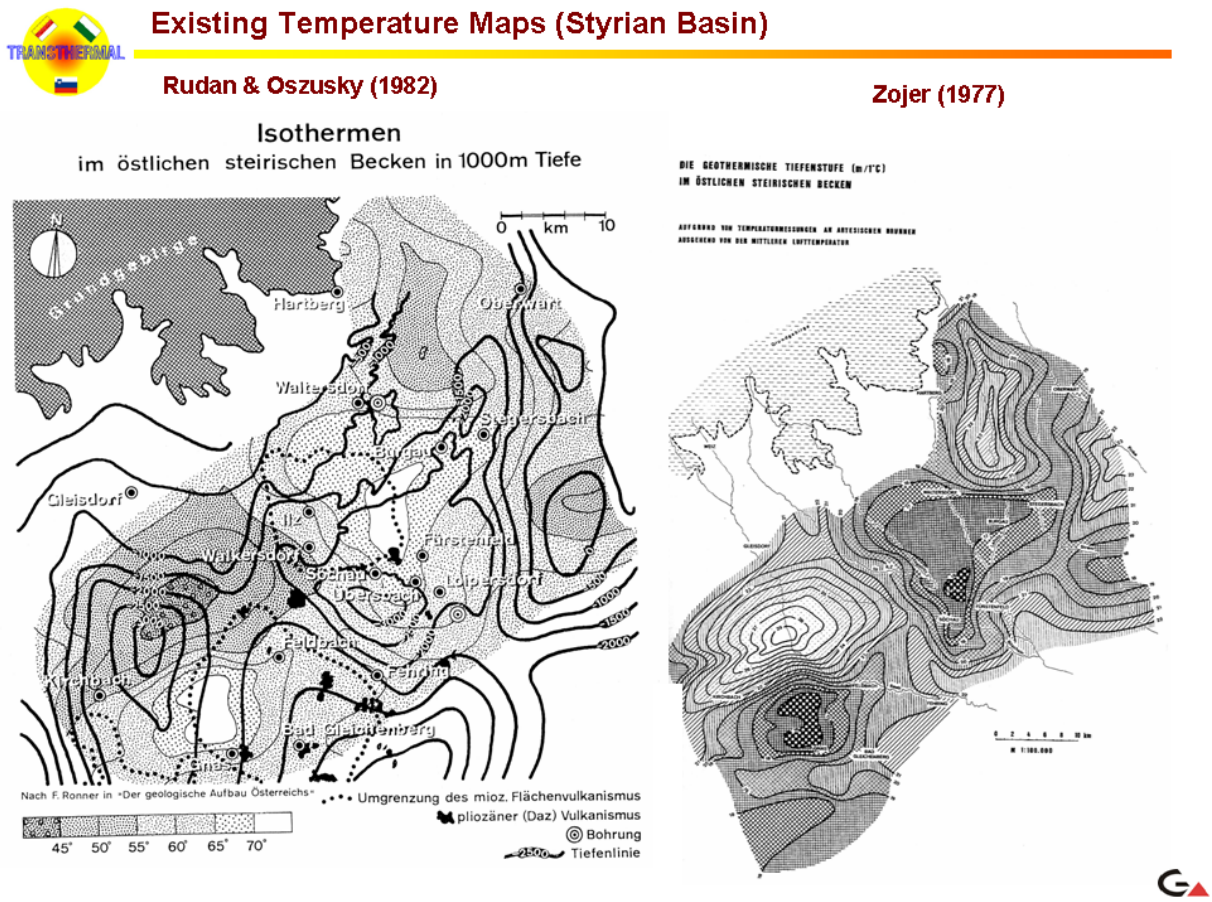


Fig. 7-4 **Existing geothermal maps for the eastern part of the Styrian Basin**

Figure 7-4 shows existing geothermal maps for the eastern part of the Styrian Basin. The underlying database of these maps mainly consists of temperature measurements at artesian wells in Eastern Styria and Southern Burgenland (ZOJER 1977, ZÖTL & ZOJER 1979). The investigated aquifers are limited to depths of approximately 200 meters below surface. Therefore it can be supposed that the extrapolated geothermal conditions shown in these maps are significantly influenced by the conditions at the uppermost part of the underground.

According to the aims of TRANSTHERMAL deep drillings represent the most crucial thermal data-source. During the course of the project it became evident that hydrocarbon exploration wells in general contain the highest content of thermal information in the Austrian part of the project area.
In general, the following thermal datasets may potentially be available at specific drillings:

a) Measured Bottom Hole Temperatures (BHT)

BHT – data are gained during the course of geophysical borehole logging and represent the maximum drilling - mud temperature at the bottom of the borehole. BHT data generally do not represent the true formation temperature due to thermal perturbation of mud-circulation and therefore have to be corrected.

b) Temperature logging

Temperature-logs represent continuously gained data and are carried out for thermal investigations or for thermal checkup of the borehole cementation (ZKB – Log). Significant data can only be gained after sufficient shut down time of the circulating drilling mud (at least 3 days). In many cases, above all at hydrocarbon exploration, the shut-down times are very low at typical ranges of 2 to 24 hours. In such cases the measured logs are influenced by mud circulation. Unfortunately no data correction is possible for temperature logs.

c) Temperature data gained at the course of drill-stem tests (DST)

These temperatures are generally gained directly above hydraulically investigated borehole-sections during the course of water-pressure measurements. In the case of significant formation-water inflow DST-data represent reliable temperature information. In the case of gas inflow DST – data have to be considered as non-reliable due to adiabatic cooling effects by gas expansion.

Geothermal and water supply wells have lower thermal information-density compared to hydrocarbon exploration wells in general. In many cases available thermal data is limited to outflow temperatures, measured at the surface. Outflow temperatures are generally lower than true formation-temperatures due to cooling effects in the course of water uplift in the borehole.

For the Austrian part of the common project area the emphasis of available thermal data is clearly situated in the Eastern Styrian Basin. This area is well explored for hydrocarbon- and thermal water use. In turn hardly any thermal information is available for the western part of the Styrian Basin. In Carinthia the actual thermal data situation also differs distinctly from the Eastern Styrian Basin. Due to exploitation of near-surface thermal water (Bad Kleinkirchheim, Villach, Bad Weißenbach) the depths of existing drillings are low (< 200 m b.s.) and measured temperature logs are often influenced by inflowing thermal water. Beyond there also some scientific drillings exist (Naturraumpotential Jaunfeld, Naturraumpotential Krappfeld), which provide temperature profiles that are not influenced by thermal water-inflow. Subsequent figure 7-2 offers a general overview of data-sources which have been used for thermal processing and analyses in TRANSTHERMAL.

In addition some explorative and scientific geothermal surveys could be included especially for the Carinthian area (e.g. Bad Kleinkirchheim, Warmbad Villach). Those surveys have been carried out by the use of very shallow drillings (drilling length less than 10 meters) at sites nearby known or estimated thermal-water exfiltration areas or at the floor of Carinthian lakes (e.g. Wörther See, Längsee). The firstly listed surveys have been conducted for thermal-water exploration and are in general not suitable for region-scale thermal analyses. Scientific measurements at Austrian lake-floors (HAENEL & ZOTH 1973) in turn offered reasonable heat-flow density values, which have been used for thermal processing.

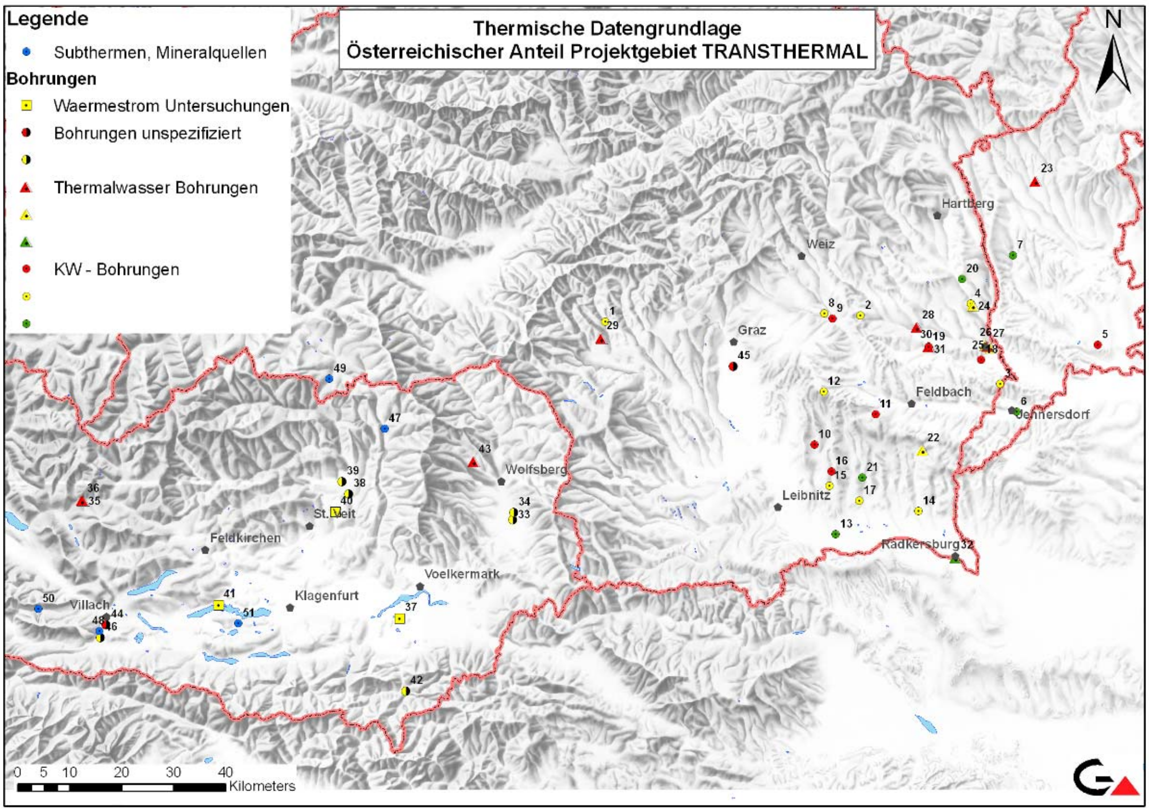


Fig. 7-5 **Overview of thermal data-sources, which have been used for the study TRANSTHERMAL**

Red colored datum points represent data sources with a generally low content of thermal information. Green datum points represent data sources, which contain high-quality information.

It has to be mentioned that for the Austrian part of the project area the measured thermal data-logs have been accomplished after a non-sufficient shutdown period in most cases and therefore have not been considered in thermal analyses. Moreover the general logging documentation for hydrocarbon wells is quite poor, so that lots of assumptions had to be done for BHT-data corrections.

Unfortunately, no thermophysical rock-parameters, such as “heat conductivity” or “radiogenic heat production”, could be investigated for the Austrian part of the project area. As those parameters are needed for heat-flow calculations, Slovenian datasets from more or less equivalent geological units had to be used for data processing.

7.4 Data processing and modelling in Slovenia

Systematic gathering of the geothermal data from 1986 onwards has made a solid database for the entire Slovenia. In the investigated area measured temperatures and other parameters have been acquired from 302 wells. The qualitatively quite different temperature-depth profiles have afterwards been critically checked keeping the following goals in mind:

- Acquisition and extrapolation of formation temperatures at the following depths: 250, 500, 1000, 1500, 2000, 3000 and 4000 m below surface,

- Determination of surface HFD values applying thermal conductivity measurements of the cored rocks from numerous wells,

- Derivation of geothermal gradients for the upper 500 m and/or for the Tertiary sedimentary basins section for additional thermal maps in future.

Data suitable for extrapolation of measured temperatures into depth have been identified taking the measurement conditions into account. Due to actual high-quality temperature measurements in oil wells there was no need to execute BHT-corrections for these values. Based on the geothermal database of the Geological Survey of Slovenia thermograms combined with other geothermal parameters such as thermal conductivity and radiogenic heat production have been drawn. Afterwards HFD values have been calculated for specific borehole sections as well as overall HFD values for the entire drilling section. An example of this database geothermal processing is shown in Fig. 7.6.

It was often necessary to interpolate temperature values to a certain depth, for example into 500 m depth from reliable measured temperatures at greater depths. Greater uncertainties than in this case were noticed in extrapolation of measured temperature values into greater depths. Here the anticipated geological structure and probable permeable layers have also been considered as much as possible, although the latter are not to be expected in greater depths of sedimentary basins. At some localities simple extrapolation was not possible. Therefore, we resorted to theoretical calculation of temperatures in depth with the following equation (RYBACH, 1981):

$$T(z) = T_0 + q_0 \frac{z}{K} - \frac{H \cdot z^2}{2 \cdot K} \qquad (7\text{-}1)$$

T_0 = mean annual surface temperature (°C)
q_0 = surface heat flow density (mW/m^2)
z = depth (m)
K = thermal conductivity (W/m·K)
H = radiogenic heat production (μW/m^3)

The last term on the right side of the equation (7-1), describing the radiogenic heat production, was considered only in some cases (e.g. for extrapolations at greater depths of more than 3000 meter below surface) since it provokes only a slight decrease of the calculated temperature. For deep buried sections at Northeastern Slovenia, where formation temperatures exceeding 100°C and more have to be expected, a temperature depending function of the thermal conductivity was considered at thermal modelling (which provokes a slight decrease of the calculated geothermal gradient) in order to obtain more realistic temperature predictions for greater depths.

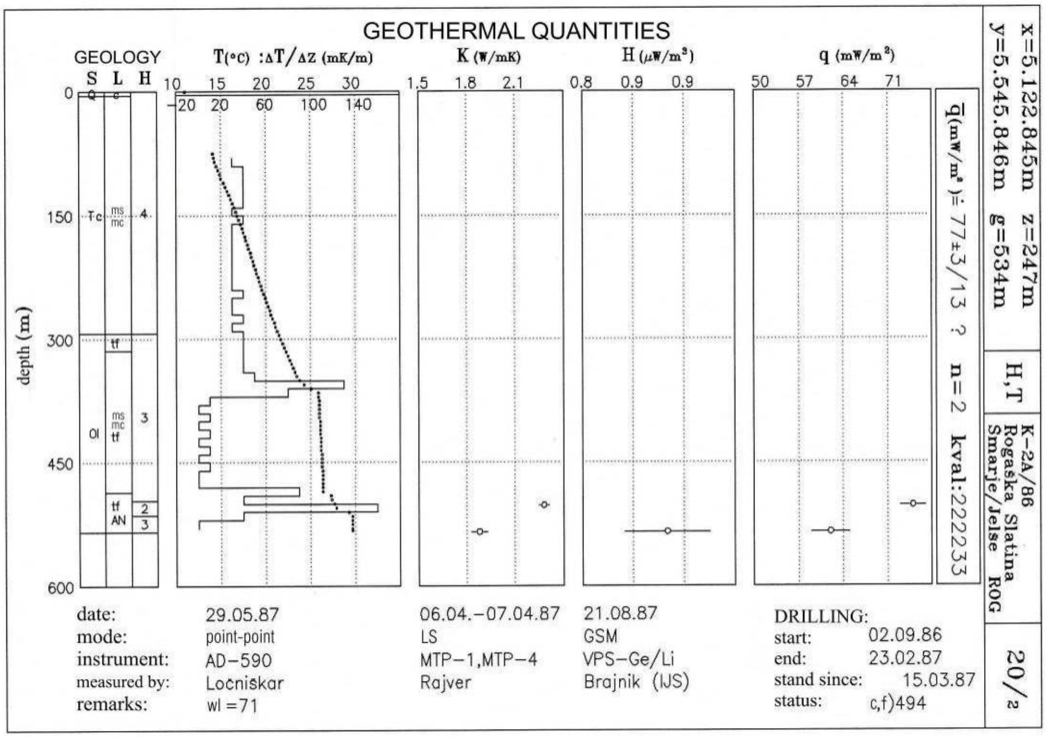


Fig. 7-6 **Example of a database extract for the well K-2A/86 near Rogaška Slatina (translated into English).**

Using the equation (7-1) for a conductive regime the anticipated temperatures were calculated in depths mentioned before at selected sites in regions without any wells with geothermal data. For this purpose the geology structure was necessary, so geological cross sections from the General Geological Map Sheets (scale 1:100.000) of former Yugoslavia were used, while for deeper geological levels additional informations were supplied by regional geologists. For northern Slovenia, covered by the Transthermal project, there are 50 such points. In the bulk Earth's crust formation temperature *T* is determined by conductive heat flow *q* by the first Fourier equation (CARSLAW & JAEGER, 1959; KAPPELMEYER & HAENEL, 1974):

$$q = -K \cdot \nabla T = -K \cdot gradT$$ or in 1-D form

$$q = -K \cdot \frac{dT}{dz} \qquad (7\text{-}2)$$

Considering equation (7-2) HFD values have been calculated for all wells, which obtain sufficient thermal data-quality and petrophysical information. At some wells lacking petrophysical data, significant rock parameters have been adopted from the neighbouring wells with similar geology. Calculations have been executed applying the interval method, which pays regard to individual lithological segments. In some cases the Bullard method (POWELL et al., 1988) has been additionally applied.

7.5 Data processing and modelling in Austria

For the Austrian part of the project area non-comprehensive geothermal data compilation had existed before. Therefore the available, quite heterogenic thermal datasets (BHT, DST-temperatures, logged data…) had to be gathered, digitized and implemented to local databases for later processing.
Thermal processing has been carried out in order to derive the following geothermal parameters:

- Formation temperatures at the following depths: 250, 500, 1000, 1500, 2000, 2500, 3000, 4000 [m b.s.],
- Temperature gradients (geothermal gradient) for the following sections: total drilling section, tertiary deposits, pre-tertiary basement and
- Surface heat flow density.

To reach this goal the following processing steps had to be carried out:

- BHT – corrections (elimination of thermal perturbations due to mud circulation),
- Elaboration of thermal profiles for drillings based on processed data and
- Temperature and heat flow modeling based on pure conductive heat transfer.

BHT – corrections

As mentioned in chapter 7.3 only BHT – data can be corrected for the perturbing influence of circulating drilling mud. All other types of thermal information (e.g. DST datasets) have only been checked for plausibility. Topographic and paleoclimatic data corrections have not been carried out in order to obtain real existing formation temperatures. In a first step borehole deviations from a straight vertical axis have been corrected to obtain true vertical depths. In this context a tolerance level of 2% of the total drilling length has been accepted. The BHT – corrections itself have been carried out based on two different approaches

1) Methods based on line source approach regarding mud circulation (HORNER 1951, LACHENBRUCH & BREWER 1959) and
2) Methods based on cylindrical source approach regarding finite borehole radii and bulk thermal diffusivities according to a two-component system *borehole (mud) – surrounding rock* (LEBLANC et al. 1982).

Both approaches base on the assumption of pure conductive heat balance between the drilling mud (heat sink) and the surrounding soil. This asymptotic approximation leads to equilibrium temperatures, which are set identical to true formation temperatures.

Ad 1) Methods based on the line source approach

Both used methods (HORNER 1951, LACHENBRUCH & BREWER 1959) represent graphical methods, at which measured BHT values are plotted against shut-down times (LACHENBRUCH & BREWER 1959) or combined terms of shut-down time and mud circulation time (HORNER 1951) using a logarithmic scale. Therefore at least 2 different BHT values have to be available at a specific depth. Both methods can be easily carried out, but may lead to inaccurate results if either the shut-down time or the mud circulating time is not known in detail.

The fundamental heat exchange equation can be expressed by

$$T_{\infty} = BHT(t) - \frac{q}{4\pi\lambda} \ln[\frac{t+s}{t}] \tag{7-3}$$

With: q = source term,
λ = thermal conductivity of the drilling mud,
T_{∞} = true formation temperature,
t = shut down time and
s = circulating time of the drilling mud.

The subsequent figure 7-7 shows data examples for graphical BHT – corrections:

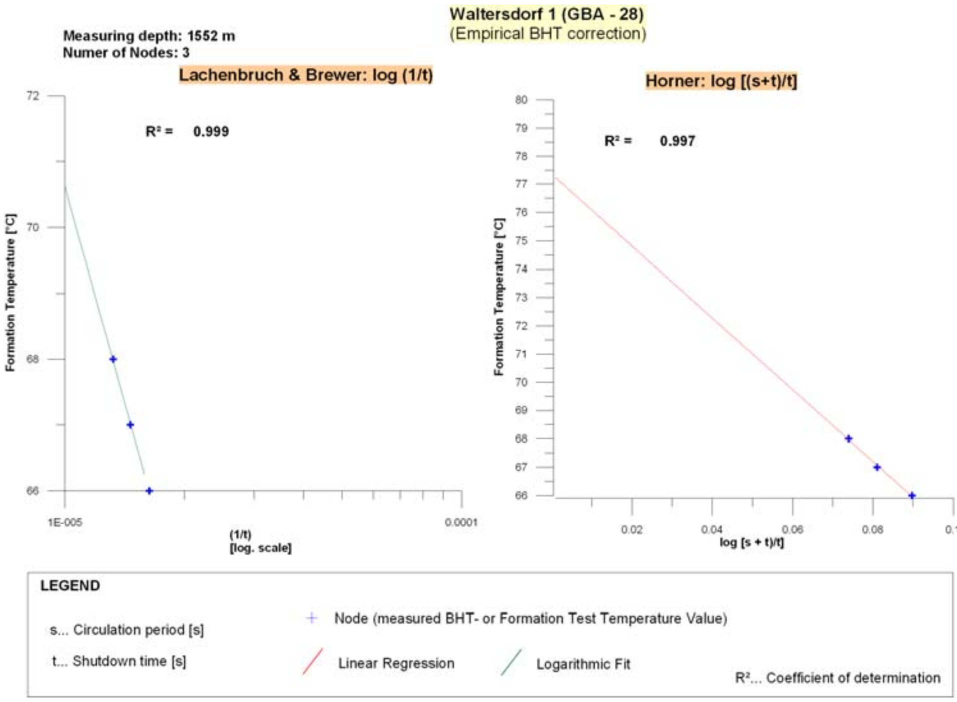


Fig. 7-7 Graphical BHT – corrections applied on an original dataset of the hydrocarbon drilling Waltersdorf 1

The drilling Waltersdorf 1 has been carried out originally for hydrocarbon exploration, but was later turned into the first geothermal well for heat production in Austria.

Ad 2) Methods based on the cylindrical source approach

The fundamental concept for this approach was presented at LEBLANC et al. (1982). These methods consider cylindrical boreholes (finite radius) and a bulk thermal diffusivity for both drilling mud and surrounding rock. For the execution of BHT – corrections at TRANSTHERMAL a simplified numerical method based on LEBLANC et al (1982) was applied if at least 3 different BHT values existed at a specific depth. The fundamental heat balance equation is:

$$T_{\infty} = BHT(t) - \Delta T' \left[\exp\left(-\frac{a^2}{4\kappa t} \right) - 1 \right] \tag{7-4}$$

With: a… radius of the borehole, κ…bulk thermal diffusivity, ΔT …initial temperature distortion (equal to T_{∞} - T_M, with T_M… initial temperature of the drilling mud).

The utilized modified method bases on equation 7-4 in order to derive a numerical inverse algorithm, which uses residuals between measured and modeled BHT values at different shut down times for optimization of predicted true formation temperatures.

In a first processing step an estimation of the initial mud temperature has been carried out by using an empirical formulary. After an accomplishment of graphical- and numerical data corrections (at least 2 different BHT values at a specific depth) the calculated true formation temperatures were plotted against the estimated initial mud temperatures for the TRANSTHERMAL dataset, which mainly consists of data from the Eastern Styrian Basin. The derived regression line allows estimating true formation temperatures based on mud temperatures. At a final processing step numerical BHT – corrections based on LEBLANC et al (1982) have been carried out for datasets which only consist of one or at most two different BHT values at a specific depth. The previously derived regression line was therefore used to estimate the range of error of BHT corrections, which only base on one BHT value per specific depth. Beyond error estimations for datasets of at least two BHT values have been carried out by calculating standard deviations for datasets of calculated true formation temperatures based on graphical and numerical methods. The average, relative error of the applied data corrections is in the range of 4% of the calculated true formation temperature for the Austrian datasets.

Elaboration of temperature profiles for drillings

In the subsequent processing step corrected BHT values have been combined with uncorrected DST- and continuous logging temperatures to compile overall temperature profiles. This had to be done qualitatively so that the final data plausibility check-up could be applied (see also figure 7-4).

Thermal data modelling

Thermal modelling had been carried out because of heat flow densities (HFD) calculation and temperature extrapolation with depth. In the first step HFD values have been calculated for drillings assuming a pure conductive heat transfer following Fourier´s law (see also equation 7-2).

In the first step specific HFD values have been calculated for different geological sections of a specific drilling by using Slovenian datasets of thermal conductivities (λ). To obtain a mean HFD value for the total drilling section each individual HFD value has been averaged by using formation thickness as weights. In a subsequent working step temperature extrapolation with depth has been applied by using the following progression algorithm:

$$T_{i+1} = T_i + \frac{\overline{q}}{\lambda_j}\left(z_{i+1} - z_i\right) \qquad (7\text{-}4)$$

For this reason the previously calculated averaged HFD values and hypothetic thermal conductivities, according to estimated extrapolated lithological profiles, have been applied.
In the course of geothermometrical temperature calculations the extrapolated temperature profiles have been used for an estimation of hypothetic maximum advective circulation depths of the investigated aquifer systems.

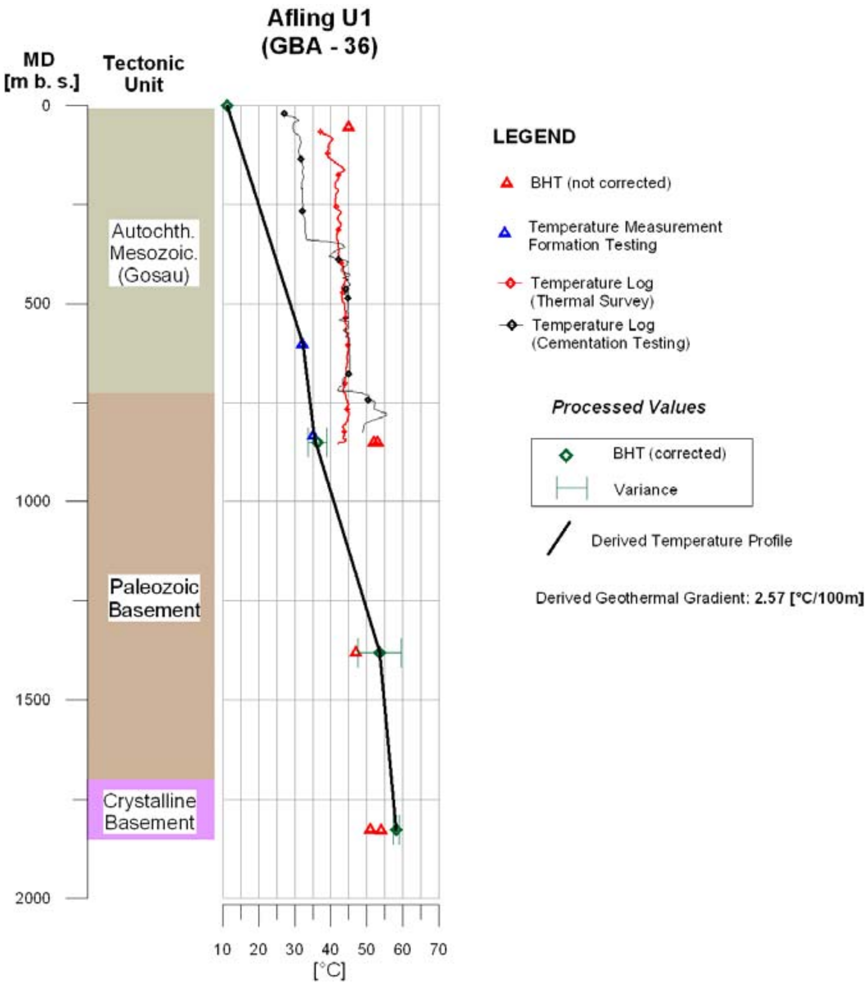


Fig. 7-8 **Data example for the compilation of temperature profiles (hydrocarbon drilling Afling U1, situated at the north – western margin of the Styrian Basin)**
The temperature profile has been compiled qualitatively by using corrected BHT data (green colored datum points) and DST temperatures (blue colored datum points). Existing continuous temperature logs (colored lines) have not been used for the compilation of the overall profile due to insufficient shut down time.

7.6 Results

In the following, the derived results concerning the present geothermal conditons within the project area of TRANSTHERMAL will be presented according to the following aspects:

- Temperature profiles (thermograms)
- Geothermal gradients
- Heat flow densitiy (HFD)
- Geothermometric modeling

Temperature profiles (thermograms) and derived geothermal gradients

From measurements in the shallow depths temperatures have been extrapolated to greater depths considering the extrapolation criteria of the IHFC (international heat flow commission), which allows to extrapolate only 50% deeper from the deepest measured temperature point in a borehole on the condition that the subsequent geological structures are known. Extrapolation has only been applied on good quality thermal profiles, which show a continuative temperature increase with depth and, furthermore, allow reliable forecast of deep geological structures. Extrapolation into greater depths has been done because otherwise temperature maps for depths greater than 2000 m would be in many places too vacant for gridding with the computer program Surfer (Golden Software).

The temperature maps were drawn for different depths below the surface: 250 m, 500 m, 1000 m, 1500 m, 2000 m, 3000 m and 4000 m.

Slovenia

Geothermal data from 302 wells in the project area have been analyzed. Combined profiles of all temperature measurements are shown separately for the Pannonian basin (Fig 7-9) and for the rest of northern Slovenia (Fig 7-10).

The subsequent table 7-1 shows the individual numbers of processed thermal datum points (wells), which vary between different depths:

Table 7-1: Total number of wells from which geothermal data were used for the elaboration of specific temperature maps

Map at depth (m)	Number of wells
250	225
500	215
1000	186
1500	172
2000	170
3000	155
4000	143
Heat Flow Density	Calculated on the sites of 50 wells

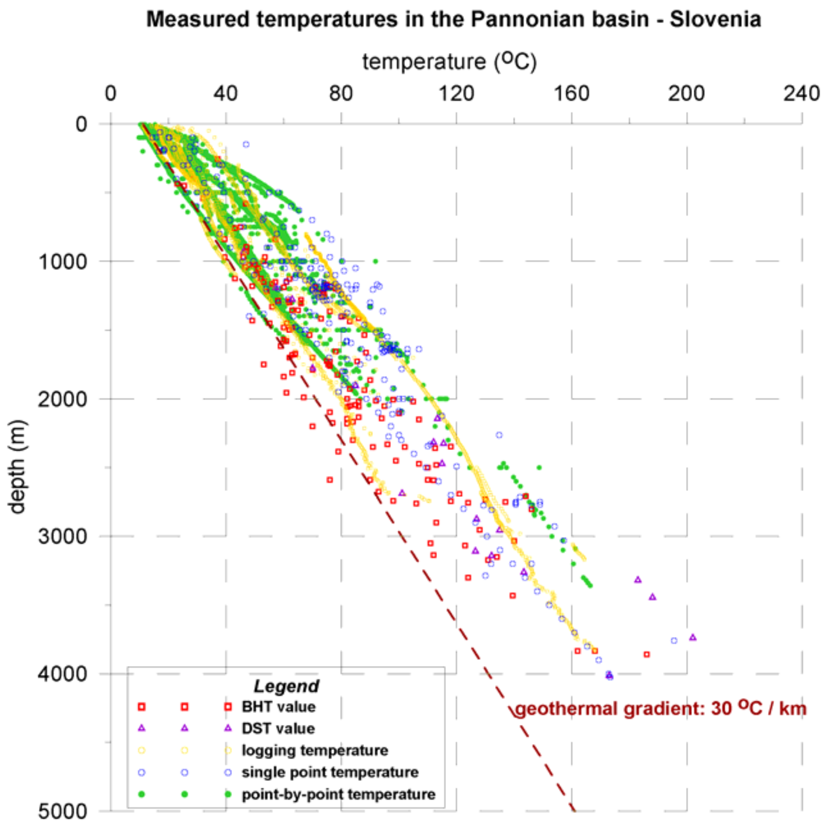


Fig. 7-9 **Combined review of the measured temperatures in wells of the Pannonian basin and its margin in Slovenia.**
Qualitatively the best ones are the temperatures measured in a point by point manner (tipically every 5 or 10 m) and also single point measurements, while the logging temperatures were measured mostly too soon after the drilling had stopped. In the upper kilometer of the sedimentary package the geothermal gradients are about 65°C/km or even higher, especially in the Murska Sobota high. Deeper down to the pretertiary basement the measured gradients are lower, yet still higher than the global continental average (30°C/km). The highest values were measured near Lendava.

The highest geothermal gradients have been observed within the upper few hundred meters thick sedimentary package at the wells of Benedikt and Radenci. A bit lower but still elevated geothermal gradients have been ascertained in the area of Murska Sobota and Moravske Toplice. In Benedikt such a gradient has been measured in the Miocene layers above a convective thermal zone in the metamorphic rocks, while in Radenci in the Pliocene layers, and in Moravske Toplice and Murska Sobota partly in the Pliocene, partly in the Miocene layers.

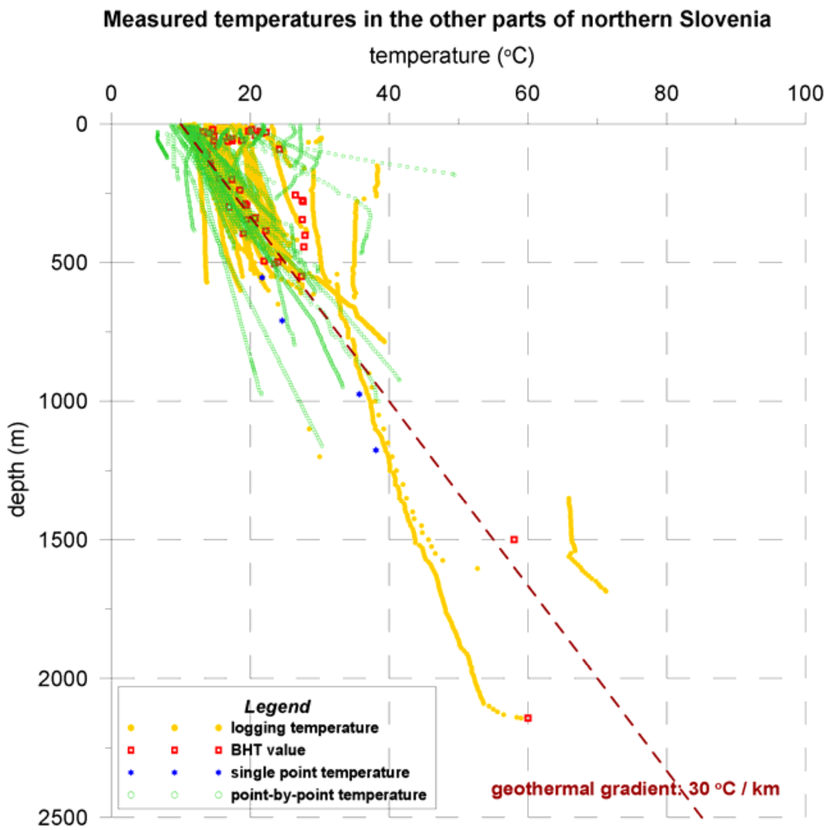


Fig. 7-10 Combined review of the measured temperatures in wells in the other parts of northern Slovenia.

In some wells in the known geothermal areas increased geothermal gradients were ascertained in the upper sedimentary cover or above the zone of thermal convection, but in many places elsewhere measured temperatures are of average or even lower than average (indicated here with geothermal gradient 30°C/km) due to advection of cooler subsurface water in the hilly and mountainous regions.

The geothermal gradients in the Tertiary sediments (see fig 7-11 & fig 7-12) are elevated practically everywhere in the Slovenian part of the Pannonian basin. The only exception is the area in the southwest near Slovenske Konjice where the geothermal anomaly of the Pannonian basin does not appear anymore. East of Maribor towards Gornja Radgona the geothermal gradient is the highest in Benedikt, where temperature was measured in two wells that were finished in the metamorphic rocks. In the areas of Murska Sobota, Moravske Toplice and partly Veržej the gradients are still high, about 52°C/km or more. In the area from Ptuj via Ljutomer to the northeast they don't exceed 44°C/km. The Tertiary sedimentary package is the thickest in the Haloze-Ljutomer sub-basin. Around Lendava and particularly towards Murski gozd in the southeast the gradients are above 44°C/km.

AGE		LITHOSTRATIGRAPHIC UNITS Lithology		Thermal Conductivity W/(mK) from – to (mean)	Geothermal Gradient °C / 100 m from – to (mean)
PLIOCENE	DACIAN	sand	MURA formation	1.48 – 2.9 (2.1)	7.7 - 3.9 (5.4)
MIOCENE	UPPER PONTIAN	clay, sandy clay, some coal with clay	MURA formation	1.1 – 2.3 (1.7)	10.3 – 4.9 (6.7)
MIOCENE	LOWER PONTIAN	**Peklenica** member to **Siget** sandstone: sandstones, marls	LENDAVA formation	1.23 – 2.4 (1.8)	9.2 – 4.7 (6.3)
MIOCENE	UPPER PANNONIAN	**Lenti** marl	LENDAVA formation	1.23 – 1.8 (1.52)	9.2 – 6.3 (7.5)
MIOCENE	LOWER PANNONIAN	**Petišovci** sandstone	ŠPILJE (MURSKA SOBOTA) formation	1.7 – 2.4 (2.05)	6.7 – 4.7 (5.5)
MIOCENE	LOWER PANNONIAN	**Benica** marl	ŠPILJE (MURSKA SOBOTA) formation	1.3 – 1.9 (1.6)	8.7 – 6.0 (7.1)
MIOCENE	SARMATIAN	**Selnica** member: silty sandy marl, sandstone	ŠPILJE (MURSKA SOBOTA) formation	1.45 – 2.41 (1.96)	7.8 – 4.7 (5.8)
MIOCENE	BADENIAN	**Šentilj** member: sandstone, silty sandy marl	ŠPILJE (MURSKA SOBOTA) formation	1.94 – 3.07 (2.5)	5.9 – 3.7 (4.5)
MIOCENE	KARPATIAN	sandstone, marl		2.46 – 4.0 (3.2)	4.6 – 2.8 (3.6)
MIOCENE	EGGENBURG.-OTTNANGIAN	silty-calcitic marl		2.0 – 2.53 (2.27)	5.7 – 4.5 (5.0)
PRE-TERTIARY	MESOZOIC	dolomite, brecciated dolomite		3.3 – 5.2 (4.25)	3.4 – 2.2 (2.7)
PRE-TERTIARY	PALEOZOIC-PROTEROZOIC	gneiss, greenschist,amphibolitic schist, mica schist tuff, eclogite, phyllonite		2.35 – 3.75 (3.05)	4.8 – 3.0 (3.7)

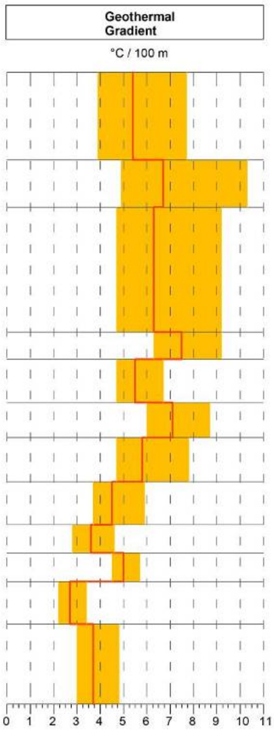


Fig. 7-11 Distribution of the geothermal gradients for the Mura depression (the Mura-Zala basin with the Ormož-Selnica antiform).

Fig. 7-11 is based on a simplified approach considering pure conductive heat transfer and ignoring the radiogenic heat production. The modelled distribution of the geothermal gradients with increasing depth relies on lithostratigraphic conditions for the Mura depression in Slovenia (simplified and altered from KISOVAR, 1977, in: JELEN et al., 2006) assuming a constant background HFD of 113.6 mW/m^2 (calculated mean value for this area). The rock thermal conductivities represent the geological units drilled by the Slovenian wells in the Pannonian basin.

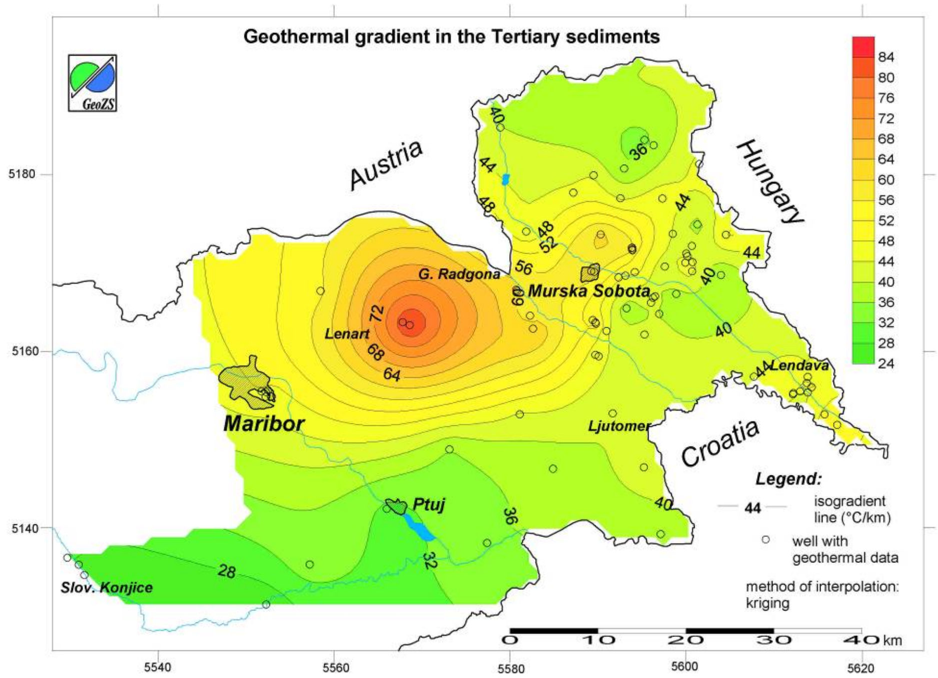


Fig. 7-12 The pattern of geothermal gradients in the Tertiary sediments of the Pannonian basin in Slovenia

Austria

For the Austrian part of the project area geothermic data processing has been applied on around 30 drillings. In total, around 200 significant geothermic values have been calculated. The subsequent Fig. 7-13 shows a combined profile of all derived temperature profiles for the Austrian part of the project area with emphasis on the Eastern Styrian Basin:

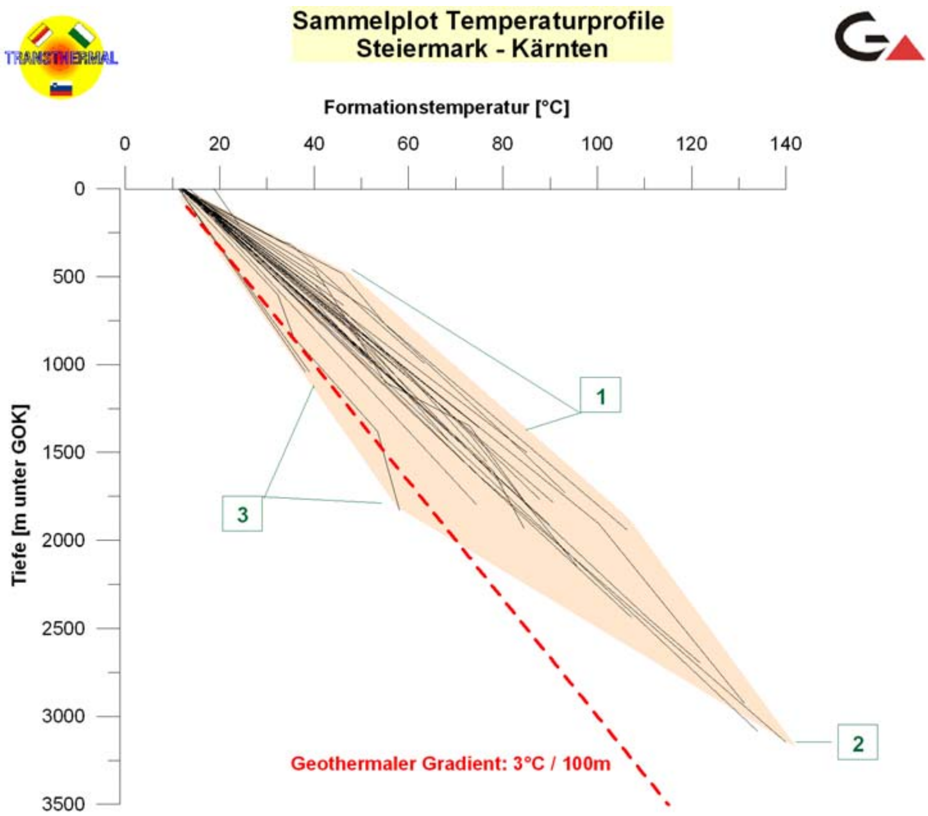


Fig. 7-13 **Combined plot of derived temperature profiles within the Austrian part of the project area**

Figure 7-13 shows a hypothetic temperature trend assuming a mean global geothermal gradient of 3°C per 100 Meter progression with depth. The combined plot exhibits three typical geothermal conditions: Range 1) contains elevated geothermal conditions in shallow depth ranges as well as in areas with positive advective influence within the Styrian Basin. In these regions geothermal gradients up to more than 5.5°C per 100 Meter have been observed. Area 2) shows the deep sections of the Styrian Basin, where geothermal gradients have significantly decreased. The course of the temperature curves are in this section more focused than in the shallower sections. Area 3) shows significantly lowered geothermal conditions at the western margin of the Styrian Basin and the Carinthian basins (e.g. Lavanttal) with geothermal gradients at global average or slightly below.

The following figure 7-14 shows a modelling example based on pure conductive heat transfer for the regional lithostratigraphic conditions in the Styrian Basin in order to gain an interval of confidence of expectable geothermal gradients.

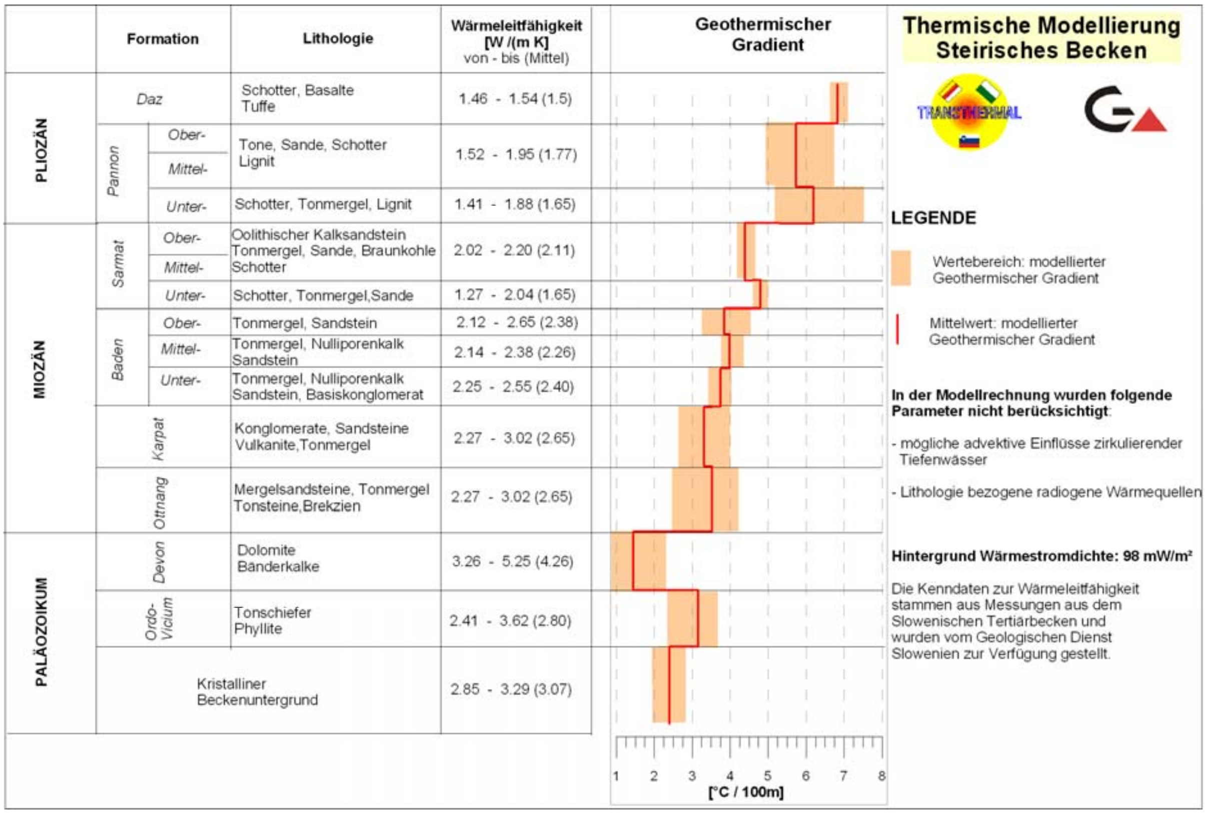


Fig. 7-14 Distribution of geothermal gradients for the Styrian Basin based on simplified pure conductive heat transfer modelling ignoring radiogenic heat production

The modelled distribution of geothermal gradients with increasing depth relies on generalized lithostratigraphic conditions at the Styrian Basin (taken from KOLLMANN 1980, simplified) assuming a constant background heat flow density of 98 mW/m² (calculated mean value for this region). The model calculation is based on petrophysical parameters from comparable geological units within the Slovenian Basin, which have been provided by the Geological Survey of Slovenia. Red colored areas represent the data-range of calculated geothermal gradients according to the variance of the thermal conductivity.

The modelled geothermal gradient pattern is very similar to the processed datasets for the Styrian Basin. A continuous decay of geothermal gradients can be caused by compaction of deposits and lithological changes at basement layers. According to this model high geothermal gradients can be expected in poorly consolidated or clay dominated deposits, which primarily appear in uppermost part of the subsurface in many areas of the Styrian Basin. Generally reduced gradients, which have been observed at the Pretertiary basement, can be explained by this model.

Surface heat flow density (HFD)

The interval HFD is the product of the temperature gradient and the thermal conductivity of rocks in a depth section for which the temperature gradient is calculated. In most cases it is calculated by the interval method along the borehole (POWELL et al., 1988). The surface HFD is calculated as an overall average of all interval HFD values.

The surface HFD map was also elaborated without topographic and paleoclimatic corrections in order to obtain present existent surface HFD values.

Slovenia

The subsequent Fig. 7-15 shows a statistical distribution of calculated HFD values from the Slovenian part of the project area. Together with the values elsewhere in Slovenia they were the basis for drawing the recent surface HFD maps for Slovenia (e.g. RAJVER & RAVNIK, 2002) that were necessary for temperature calculations in greater depths. For the entire Slovenian part of the Transthermal project area the average HFD value (± s.d.) equals 87 ± 34 mW/m^2 from data of 50 wells. However, for the part belonging to the Pannonian basin the average of 26 boreholes is higher, about 114 ± 22 mW/m^2, and for the other parts of northern Slovenia it is 58 ± 16 mW/m^2 from data of 24 boreholes.

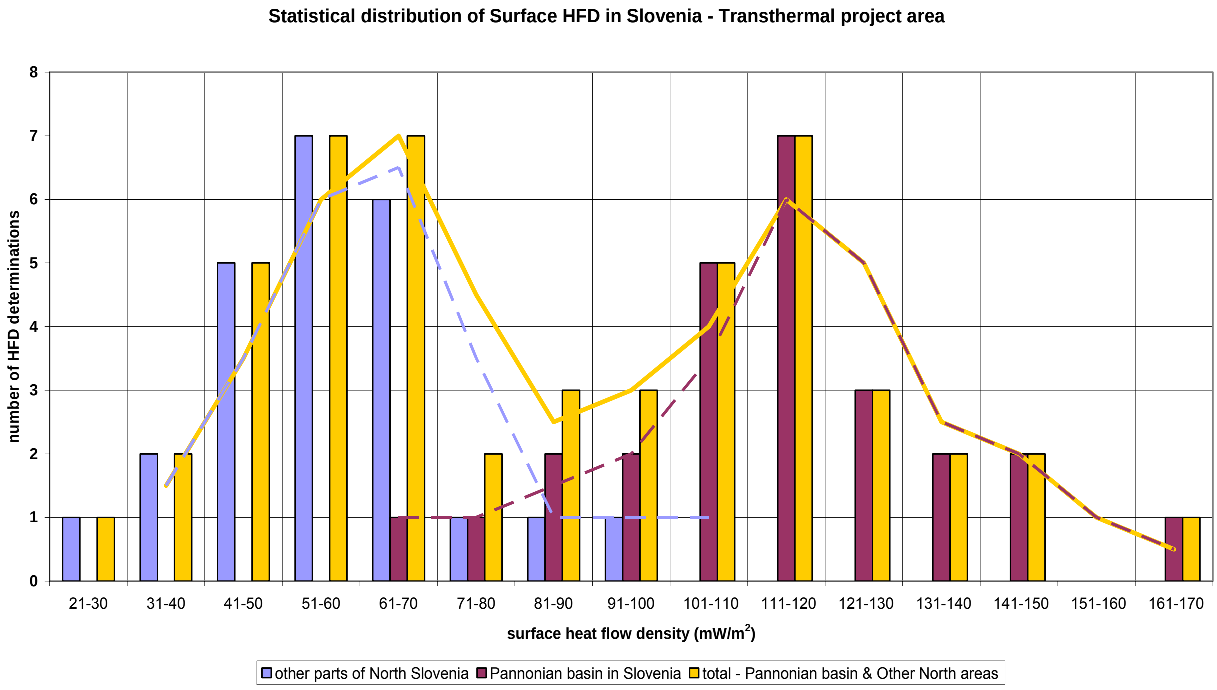


Fig. 7-15 Statistical distribution of surface HFD for Transthermal project area in Slovenia

Austria

The following figure 7-16 shows the statistical distributions of the calculated heat flow densities at the Austrian part of the project area:

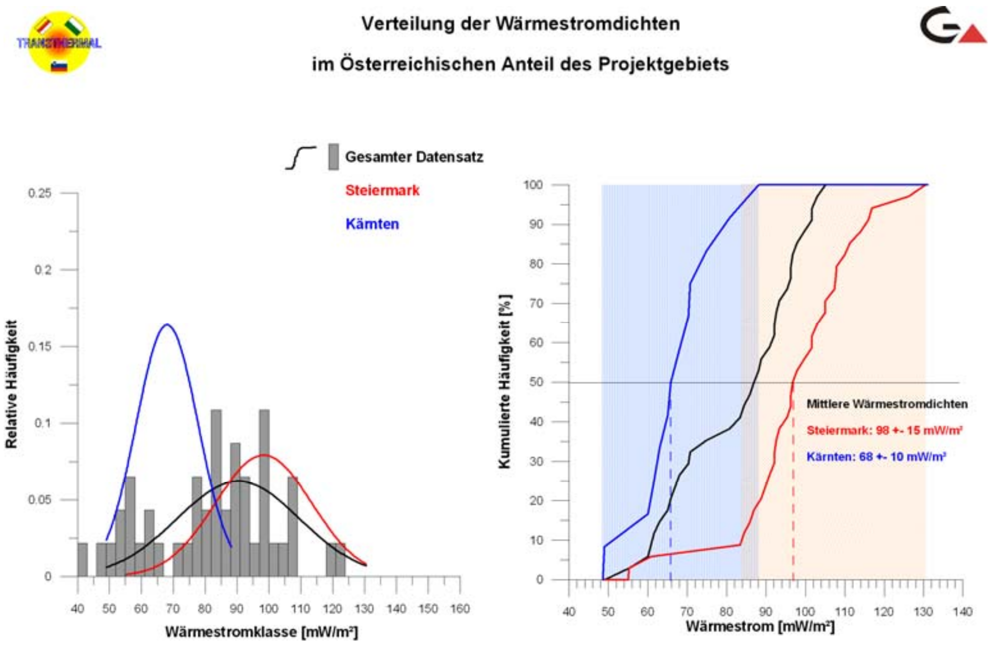


Fig. 7-16 **Statistical distribution of the heat flow densities (HFD) at the Austrian part of the project area**

The Austrian thermal datasets have been split into the Syrian Basin and the Carinthian region. For the Styrian Basin (with emphasis on its eastern part) average HFD values of 98 mW/m² have been calculated. In contrast, the Carinthian region shows average HFD values of 68 mW/m². Colored areas represent the different ranges of calculated HFD values according to the Styrian (red-) and Carinthian (blue-) datasets.

The calculated HFD values which are shown in figure 7-16 have been used for temperature progression with depth. Based on these modelled temperature sets mean geothermal gradients have been calculated for different depth intervals. The subsequent figure 7-17 shows the partly observed and partly modelled temperature sets for Styria and Carinthia.

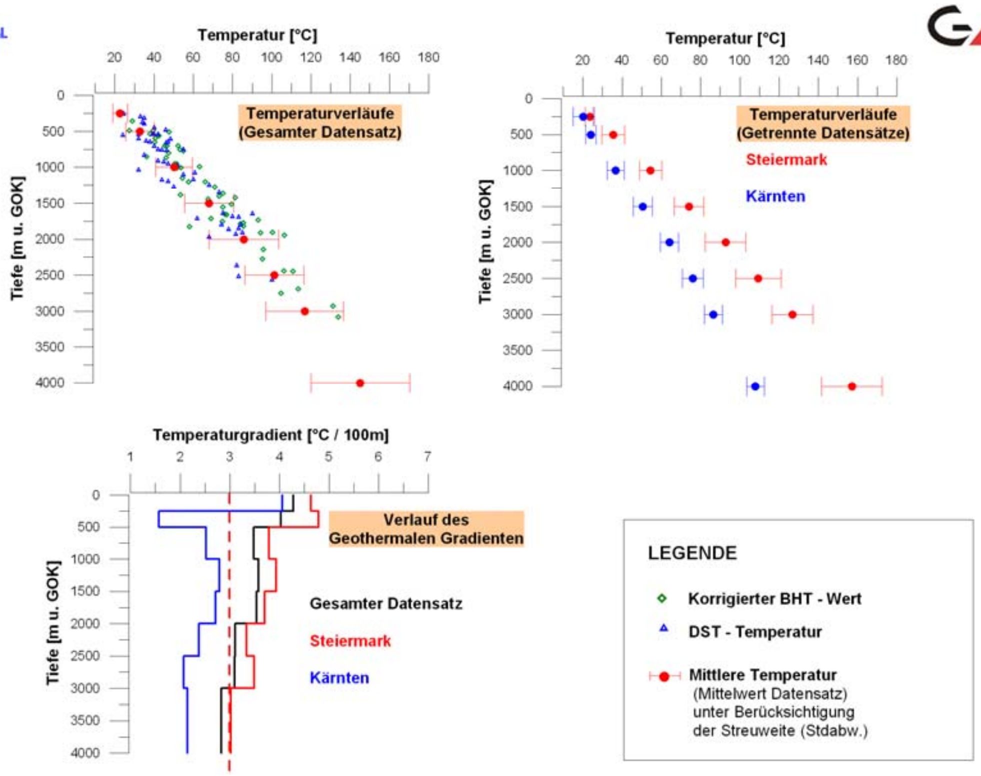


Fig. 7-17 **Combined Temperature profiles for Styria and Carinthia based on observed and modelled datasets**

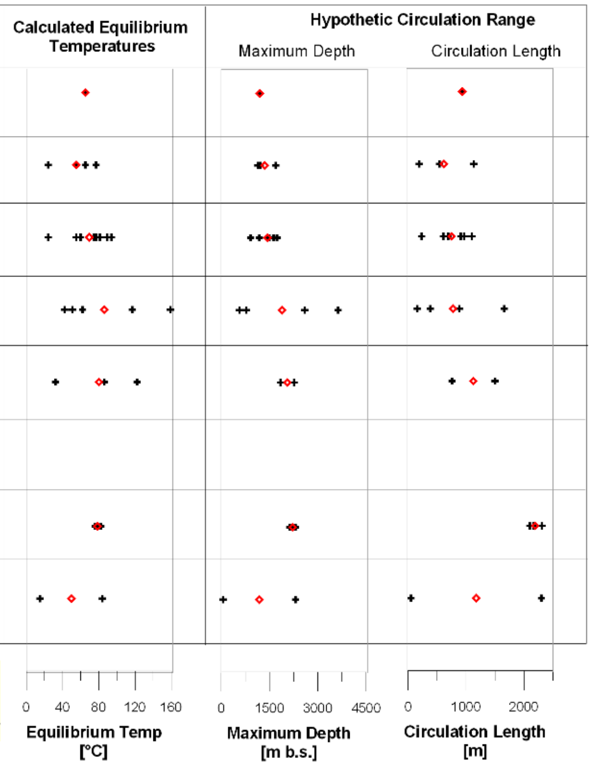
Top-left: Combination of measured DST- and processed BHT values with modelled temperature distribution with depth
Top right: Comparison of modelled temperatures profiles for the Styrian- and Carinthian datasets
Bottom: Comparison of averaged geothermal gradients at different depth intervals for the Styrian- and Carinthian datasets

Geothermometric modelling

Austria

Geothermometrical calculations have been applied to estimate the influence of advective heat transport mechanisms on the thermal regime within the Austrian part of the investigation area. The calculated equilibrium temperatures based on Quartz- and K/Mg- Geothermometers have been combined with the previously modelled temperature profiles to estimate maximum depths of the circulation. Taking the observed depths of aquifers into account hypothetical advective circulation ranges (difference between aquifer-vertex and calculated maximum circulation depth) have been calculated in a final analyzing step. The subsequent figures 7-18 and 7-19 show the results of the combined hydrochemical (geothermometrical) - thermal modelling:

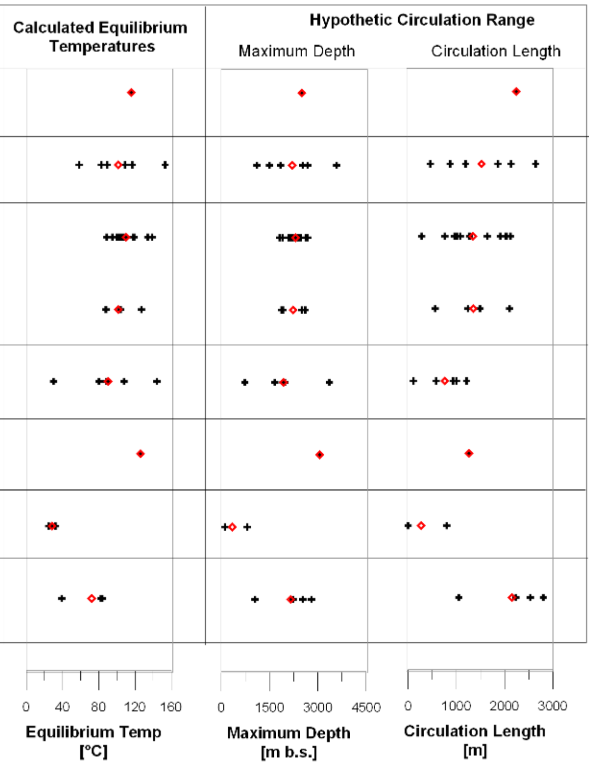
Aquifer System	Stratigraphic Unit	N	Aquifer depths [m b.s.] (from - to)	TDS [g / l] (from - to)
Sedimentary Basin Systems (Hochstein Type 1)	*Pannonium*	1	255 - 270	0.43
	Sarmatium	6	555 - 964	1.23 - 2.76
	Badenium	12	310 - 1909	2.57 - 57.61
	Karpatium	6	766 - 2020	8.05 - 68.68
Basement Systems (Hochstein Type 2)	*Paleozoic Basement (in general)*	5	619 - 2843	0.38 - 23.33
	Triassic Carbonates (Styrian Basin)	1	1791 - 1857	8.92
Warm Spring Systems (Hochstein Type 3)	*Triassic Carbonates (Carinthia)*	4	0* - 644	0.28 - 0.32
	Crystalline Bedrocks (in general)	4	0* - 50*	1.66 - 2.35



Hydrogeothermic Calculations
Quartz - Geothermometer

Fig. 7-18 **Results of combined hydrochemical (geothermometrical) – thermal modelling for the Austrian datasets based on the Quartz – Geothermometer**

Aquifer System	Stratigraphic Unit	N	Aquifer depths [m b.s.] (from - to)	TDS [g / l] (from - to)
Sedimentary Basin Systems (Hochstein Type 1)	*Pannonium*	1	255 - 270	0.43
	Sarmatium	6	555 - 964	1.23 - 2.76
	Badenium	12	310 - 1909	2.57 - 57.61
	Karpatium	6	766 - 2020	8.05 - 68.68
Basement Systems (Hochstein Type 2)	*Paleozoic Basement (in general)*	5	619 - 2843	0.38 - 23.33
	Triassic Carbonates (Styrian Basin)	1	1791 - 1857	8.92
Warm Spring Systems (Hochstein Type 3)	*Triassic Carbonates (Carinthia)*	4	0* - 644	0.28 - 0.32
	Crystalline Bedrocks (in general)	4	0* - 50*	1.66 - 2.35



Hydrogeothermic Calculations
K / Mg - Geothermometer

Fig. 7-19 **Results of combined hydrochemical (geothermometrical) – thermal modelling for the Austrian datasets based on the K/Mg – Geothermometer**

Summary

Slovenia
For the Slovenian part of the project area the following conclusive observations can be made:

1) For the north-eastern Slovenia, that is the Mura-Zala basin as part of the Pannonian basin, the average HFD values in the range of 114 ± 22 mW/m² were calculated. In contrast, lower geothermal conditions were observed for the other parts of northern Slovenia with the calculated HFD average values in the range of 58 ± 16 mW/m².

2) According to 1) the Mura-Zala basin region shows clearly higher geothermal gradients than the global average of 30°C per kilometer with top values up to 80°C per kilometer on the Murska Sobota high (Benedikt to Radenci). Heading westwards to the Celje and Slovenj Gradec basins, and further westwards towards the Ljubljana basin lower geothermal gradients in the range of the global average or slightly below it can be observed. At the westernmost area of northern Slovenia (e.g. borehole KGTV-1 in Kranjska Gora) the geothermal gradient around 20°C/km is observed.

3) In both regions the geothermal gradients successively decrease with increasing depth below the surface showing the highest gradients within the uppermost 700 to 1000 meters below the surface in the Pannonian basin region, whereas locally variable in the remaining northern Slovenia, but mainly within the uppermost 300 to 1100 meters below the surface, depending on the thickness of the sedimentary layers.

4) According to 1) and 2) the range of the modelled formation temperatures at a depth interval of 4000 meters below the surface varies between 80 ± 25°C for the western parts of North-Slovenia and 160 ± 40°C for the Mura-Zala basin. Using this derived geothermal parameter the difference between geothermal conditions in the Mura-Zala basin and the western area of northern Slovenia can be clearly pointed out.

Austria
Taking a conclusive look at the elaborated results the following observations concerning the geothermal regime can be made for the Austrian part of the common project area:

5) For the Eastern Styrian Basin average HFD – values in the range of 98 ± 15 mW/m² have been calculated. In contrast, lowered geothermal conditions have been observed for Carinthia with calculated HFD values in the range of 68 ± 10 mW/m².

6) According to 1) the region of the Eastern Styrian Basin shows geothermal gradients clearly higher than the global average of 3°C per 100 meter with top values up to 5.5°C per 100 meter. Heading westwards towards the Carinthian area, lowered geothermal gradients in the range of the global average or slightly beyond can already be observed at the westernmost margin of the Styrian Basin (e.g. drillings Afling U1, Koeflach TH1).

7) In both regions geothermal gradients successively decrease with increasing depth showing the highest gradients within the uppermost 500 meters below surface.

8) According to 1) and 2) the range of modelled formation temperatures at a depth interval of 4000 meters below surface varies between 108 ± 5°C for the Carinthian area and

157 ± 15 °C for the Eastern Styrian Basin. Using this derived geothermal parameter the difference between geothermal conditions in the Eastern Styrian Basin and the area of Carinthia can be clearly pointed out.

9) The utilization of the K/Mg - Geothermometer led to more plausible results for porous aquifers within the Tertiary deposits of the Styrian basin (Hochstein Reservoir Type 1). The Quartz – Geothermometer instead led to better results for geothermal warm spring systems (Hochstein Reservoir Type 3), which have dominantly been observed in the Carinthian area. For basement aquifers (Hochstein Type 2) both methods led to more or less convenient results.

10) The combined hydrochemical – thermal calculations show more or less homogenous equilibrium temperatures for the different aquifer systems of the Eastern Styrian Basin in the range of 104 ± 25 °C corresponding with maximum circulation depths of 2207 ± 584 meter below surface for both basin- and basement aquifer systems.

11) For investigated warm spring systems within the Carinthian area equilibrium temperatures in the range of 80 ± 3 °C have been calculated, which in turn correspond with hypothetical maximum circulations depths of 2233 ± 74 meters below surface.

7.7 Description of elaborated geothermal maps

Temperature at 250 m depth

For temperature distribution over Slovenia at 250 m depth a continuative passage from low values in west towards high values in the northeast is observed. In the Karavanke and Kamnik-Savinja Alps area for example, only 11°C or even less can be detected which is a consequence of deep meteoric water leaking through fractured rocks. Such water does not warm down to this depth because this happens at higher altitudes where the meteoric water is pretty cold throughout the year. In the northern edge of the Ljubljana basin the temperatures are somewhere higher than 14°C, the same in the Velenje basin, and in the Celje basin higher than 17°C. On the Pohorje Mts and generally on the Eastern Alps massifs the temperatures should be rather low, yet isolines there are pretty doubtful. East of Maribor there are higher temperatures on the Murska Sobota high, that is over 26°C, and higher than elsewhere in Pomurje and Podravje regions. Elevated temperatures occur also in Lendava and Murski gozd area, over 23°C, and in Rogatec, over 20°C. In the Austrian part the highest temperatures reach 23 to 26°C in the Styrian sedimentary basin, above all in its southeastern part, elsewhere they are lower, especially in the central and western part. Temperatures are much lower towards the west and in Carinthia they are even lower in the Klagenfurt basin than north from there where low permeable rocks of the cristalline complex prevail.

Temperature at 500 m depth

Low temperatures are expected to be found in the Karavanke and Kamnik-Savinja Alps area, below 14°C, at higher altitudes even below 11°C. Below the massifs of the Eastern Alps such as Pohorje and Kozjak the temperatures usually don't exceed 23°C. In the Celje and Velenje basins they are in some places higher than 26°C. The highest values are on the Murska Sobota high from Lenart in the west to Moravske Toplice in the east, reaching there mostly over 38°C, and in Benedikt and Radenci they are even higher than 46°C. A slight increase to regional surrounding values can be noticed only in Lendava and Murski gozd. In Austria the temperatures reach about 35°C in the southeastern part of the Styrian basin, while in the northern part of it they are a bit lower. Towards the west values get lower and in Carinthia they are roughly between 20 and 29°C, except close to the Karavanke Mts with values even lower due to possible advection in deep groundwater circulation.

Temperature at 1000 m depth

The pattern of the isotherms is similar to that for 500 m. In the west temperatures are the lowest, below 23°C, in the higher altitudes they remain also below 17°C. Only in Kranjska Gora we measured slightly higher temperature at this depth, namely 27°C. Somewhat higher temperatures are expected in the northern part of the Ljubljana basin, which is above 30°C, but only beneath lowland. Towards the east they increase and are mostly higher than 34°C. Only on the Pohorje Mts and its environs, for example on the Paški Kozjak massif, they could be a bit lower due to topography and possible circulation of meteoric water through fractures, but practically we don't have measured values there at all. In the Velenje and Celje basins they are higher than 38°C and in Rogatec they reach above 42°C. Temperatures above 46°C are expected northeast from the Maribor-Ptuj line, roughly east of the Drava river. The greatest anomaly covers the Benedikt and Murska Sobota - Moravske Toplice area. Otherwise, it is not clear how extended this anomaly in Benedikt is, since it is perhaps an outcome of some deeper fracturing in the metamorphic rocks. This fracturing makes the convective heat transfer through fractures from depths of over 1.8 km upwards into Tertiary layers feasible. The heat probably emerges in greater depths due to slight cooling of a certain intrusive (gabbro ? or other) volcanism in a basement of the metamorphic rock complex. This may be a cause for an enhanced geothermal anomaly appearing also in the north in the Styrian basin, where the geothermal gradient is increased, especially in its southern part, a bit less towards the northeast. Elsewhere in Styria somewhat lower temperatures exist, particularly to the west, as well as in Carinthia where they do not exceed 42°C and are comparable to those in the Velenje and Celje basins.

Temperature at 1500 m depth

The course of the isotherms shows similar pattern as those for the shallower levels. The temperatures are the lowest in the west, mostly below 34°C, in areas of higher altitudes they are below 29°C. In the northern part of the Ljubljana basin above 42°C may be expected, and towards the east values still increase. In the Celje basin the temperatures above 50°C are possible; in the neighbourhood of Slovenj Gradec they are similar. Everywhere east of the Maribor-Rogaška Slatina line they are higher than 54°C. Even higher values exist east of Lenart on the Murska Sobota high, above 70°C, where the anomaly in Benedikt is still visible yet not so strong anymore. The highest values, above 80°C, exist in the area of Moravske Toplice, Murska Sobota, Veržej and Lendava with Murski gozd. The thickness of the Earth's crust there is the thinnest, what contributes to a higher conductive heat flow from the Earth's mantle towards the surface. As a consequence rather high temperatures are found in the southern part of the Styrian basin, between 58 and 70°C. Towards the north temperatures slightly decrease, and towards the west even more, where in Carinthia in the mountainous region they are similar as those beneath Pohorje and Kozjak. Only in the central Carinthia they are slightly higher, likely to around 50°C, first of all due to absence of completely carbonatic massifs as low permeable crystalline rocks prevail there.

Temperature at 2000 m depth

In the west temperatures are the lowest, mostly below 38°C, and in the areas of higher altitude somewhere also below 29°C. In the northern part of the Ljubljana basin above 50°C may be expected, and towards the east values increase. East of the Dravograd – Velenje – Polzela line they are mainly higher than 54°C, except in the Paški Kozjak area where they are supposingly a bit lower as to the anticipated geological structure. Between Žalec and Celje they can be above 64°C. On the Pohorje and Kozjak massifs they are somewhere higher than 58°C, but there we do not have any boreholes logged in temperature. East of the Maribor – Ptuj line practically everywhere temperatures are higher than 84°C. The Benedikt anomaly is not discernible anymore, as the thermal circulation obviously causes high geothermal gradient in the subsurface sedimentary cover there. The highest temperatures in Slovenia, above 100°C, exist in Veržej, across Murska Sobota towards Moravske Toplice and northeast from there, and in a wider Lendava area. The highest temperatures in the Styrian basin, above 90°C, occur in its southern part and along the southern border with Burgenland. In some places they are also higher than 100°C. In the northern part of this basin the temperatures decrease slightly, and even more towards the mountaineous west, therefore in Carinthia they mainly do not exceed 64°C. Temperatures are especially low along the Karawanke edge.

Temperature at 3000 m depth

In the west temperatures are the lowest, mainly below 58°C, and in the areas with higher altitude also below 54°C. In the northern part of the Ljubljana basin somewhere above 70°C may be expected. Towards the east values progressively increase, as from the approximate Slovenj Gradec – Polzela line values are already mainly higher than 77°C, except below the Paški Kozjak massif where they are a bit lower. Therefore, approximately east of the Maribor – Rogaška Slatina line we may anticipate temperatures mostly higher than 100°C, in Pomurje and in some places in Podravje they are higher than 125°C, for example between Veržej and Bukovci. The highest temperatures occur in the eastern part of Pomurje, roughly in the area between Hodoš and Motvarjevci, as well as in the Lendava area temperatures above 135°C are expected at this depth. In Murski gozd close to Lendava even temperatures above 145°C are expected. The geothermal anomalies, observable in this part of Pomurje, practically at all greater depth levels, are caused by thinner crust, but the fracturing of the preTertiary basement along several fault systems is also possible as it permits leakage and rising of hot fluids from greater depths and/or more intensive conductive heat transfer. In the Styrian basin the highest temperatures occur, above 107°C, likely in its southern part and along the border with Burgenland, and even above 115°C in the southern part in Bad Gleichenberg and Wiersdorf. Towards the west temperatures are lower, above all below the mountainous massifs of Saualpe and Koralpe. In Carinthia, in its central part temperatures are likely to be above 84°C, but at the edges of the Klagenfurt basin, such as Karavanke, they are much lower due to advection of subsurface water in carbonatic rocks.

Temperature at 4000 m depth

In mountainous regions in the west temperatures are the lowest, mainly below 77°C, and in the higher altitude areas also below 70°C. In the northern part of the Ljubljana basin somewhere above 90°C may be expected, and towards the east values gradually increase. East of the Dravograd – Velenje – Polzela line temperatures are mainly higher than 100°C, except probably below the Paški Kozjak massif. Between Žalec and Celje they can be above 107°C. Below the massifs of Pohorje and Kozjak temperatures are somewhere higher than 107°C, in the eastern part of both hilly massifs also above 115°C, but we don't have any measured temperature in boreholes there. East of the Maribor – Rogaška Slatina line temperatures are higher than 125-130°C, and approximately east of the Maribor – Ptuj line they are above 140°C. In areas of Murska Sobota, Moravske Toplice, Veržej and more to the south around Ljutomer they reach above 155°C. In the eastern part of Pomurje temperatures exceed 170°C, while somewhere in the wider Lendava area and particularly towards Murski gozd they are even above 185°C. High temperature has been measured slightly deeper than 4 km only in Slovenian deepest well Ljut-1 near Ljutomer, to be exact, 173,4°C were measured at the depth of 4026 m. In addition, temperatures have been measured in Pomurje in a series of wells with depths between 3 and 4 km. The highest temperature (a bit questionable) of 202°C has been measured in Murski gozd area (well Mg-6). In the Styrian basin the isotherm pattern is similar to the shallower one, so that the highest values, above 170°C, are expected in the southern part, and elsewhere in this basin just a bit lower. In the western part of Styria and Carinthia the temperatures are much lower, yet mainly above 100°C, except along the southern edge with the Karavanke and Kamnik-Savinja Alps Mts range, where they can be lower than 77°C.

Surface heat flow density

The surface heat flow density (HFD) map of the Transthermal project area has been namely made without the corrections for toporaphy and paleoclimate. A cause for heterogeneous distribution of the thermal field lies in the geological and tectonical appurtenance to different units of the Karpathian-Pannonian system of sedimentary basins and of the Dinarides. Several thousand square kilometers of large geothermal anomalies, whose linear extensions are of scale of the lithosphere thickness in this part of Europe (50 to 70 km) show that the cause for great differences lies deep in the Crust or in the Upper Mantle (RAVNIK, 1991). Such large geothermal anomaly occurs also in the northeastern Slovenia in a part of the Pannonian basin. Due to the Pannonian basin extension the sinking of the thinned crust and the inertly lifted hot astenosphere below its bottom are characteristic for this basin. Direct consequences of this are regionally enhanced temperatures and surface HFD (RAVNIK, 1991 and literature therein).

In the Alpine area in the west the HFD values are lower than 50 mW/m^2, and below higher mountains also below 40 mW/m^2. In Kranjska Gora 54 mW/m^2 (topographic correction included) has been determined, while values higher than 60 mW/m^2 are recorded in places in the northern part of the Ljubljana basin. Towards the east the HFD gradually increases, so from the Ravne – Velenje - Zreče – Celje line it is higher than 60 mW/m^2. For drawing the HFD isolines we have resorted 50 additional auxiliary points, however, at such points there is always an anxiety present that they are not correctly calculated due to doubtfulness of the input data. A weak anomaly, above 80 mW/m^2 is indicated in Rogaška Slatina, while strongly enhanced HFD values, above 110 mW/m^2, are trailed along the Murska Sobota high, which leads from Maribor to Moravske Toplice and Pečarovci. A smaller anomaly with the HFD values above 110 mW/m^2 occures in the Ljutomer area and a bit larger in Lendava. On the Austrian side two strong anomalies are perceivable, in the southern and in the western part of the Styrian basin, with surface HFD above 110 mW/m^2. Elsewhere in this basin the HFD values are also higher than the continental average. However, they decrease towards the west where in Carinthia average values occur, yet a bit lower are values on the Koralpe and Saualpe massifs.

7.8 Discussion and conclusion

Slovenia

A great geothermal anomaly of the Pannonian basin and its margins is clearly noticeable apart for the remaining western part of the northern Slovenia. This is a consequence of different lithospheric conditions in both areas. The elevated geothermal values in the Pannonian basin and its environs, that is in the Pomurje and Podravje regions of Slovenia as well as in the eastern part of the Austrian Styrian Basin, coincide with decreased thickness of the Earth's crust there, also below 30 km. Towards the west the Crustal thickness increases to about 46 km in the Julian Alps and the Dinarides (GOSAR, 2005), which causes lower surface HFD and depth temperature values. From the wells on Slovene side of the Pannonian basin increased geothermal gradient is very clearly revealed, also up to 60°C/km, but only in the first upper kilometer of the sediments. The geothermal gradient can locally be even higher (Radenci and environs), but only in a shorter depth section below the surface. According to this model high geothermal gradients can be expected in poorly consolidated or clay dominated deposits, which primarily appear in the uppermost part of the subsurface in many areas of the Mura-Zala basin. This can be explained with lithological differences and consecutively differences in thermal conductivity and with increased geothermal values on the Murska Sobota high in the Pretertiary basement. Elsewhere in northeastern Slovenia elevated gradients appear also in the areas of Lendava, Murska Sobota with Moravske Toplice and between Maribor and Radenci. This does not mean that a certain anomaly zone is not hidden somewhere else too, yet at the moment there are just no wells to touch a concealed one with. However, the geothermal gradients in Slovenia and Austria continuously decrease with depth due to a compaction of the Tertiary sediments, but nevertheless the temperatures measured in the Slovenian wells have indicated that decreasing does not continue so strongly from depths of about 800 to 1000 m down to the Pretertiary basement. Perhaps slightly decreased geothermal gradients can occur in deep sections of the Tertiary layers within the sub-basin with great depths of the Mura-Zala basin in its deepest part, but there are no deep wells to prove this. The geothermal gradient is, however, more reduced in the pretertiary bedrock, carbonatic as well as metamorphic.

Significant synclinal structures with great Pretertiary basement depths, as existent at the Haloze-Ljutomer sub-basin, and the Martjanci sinform, coincide with slightly lowered temperature gradients at deep sections within the Tertiary deposits as observed, for example, in the deep wells in Petišovci (Pg-1 and Pg-2), but interestingly, not in the deepest well in Ljutomer (Ljut-1).

In principle the cooling effects can also take place in the synclinal structures due to lateral inflow of water, but this was not noticed by any of the measured geotherms in the Slovenian wells belonging to the Pannonian basin. Besides, transient geothermal effects may be taken into consideration as a cause of the basin subsidence along with fast depositions of "cold" sediments. On the other hand, the Ljut-1 present geotherm shows in its upper part a distinct signature of the last ice age (Wűrm) temperature minimum push (ŠAFANDA & RAJVER, 2001) due to the diffusive character of the process.

An advective heat transfer due to deep water circulation is capable of provoking locally confined influence on the geothermal regime down to depths of 1.5 to 3 kilometers below the surface, depending on the existence of the hydraulically conductive layers or fault-systems within crystalline bedrocks, as evident from wells in Benedikt and perhaps Maribor in northeastern Slovenia, and in the

Slovenj Gradec basin in northern Slovenia. The overall geothermal regime is in turn mainly governed by the conductive heat exchange depending on the regional crustal thickness variation, which leads to significant changes in the geothermal conditions between the eastern Pannonian region and the western part of northern Slovenia.

Austria

According to the gained observations listed in the chapter before, it is obviously for the Austrian part of the investigation area, that geothermal conditions are clearly more favorable at the Styrian Basin than in the area of Carinthia. The different overall geothermal regime is in both regions mainly governed by lithospherical conditions. While reduced crustal thickness which coincides with reduced depths of the Moho discontinuity leads to elevated thermal conditions within the Eastern part of the Styrian Basin, alpine orogeny along with crustal stacking clearly reduces the overall geothermal heat flow density (HFD) in the western regions of the Austrian part of the investigation area (see also chapter 7.6).

The pattern of the processed geothermal parameters indicates for the Eastern Styrian Basin slightly reduced geothermal conditions in its southern most part (area around Bad Radkersburg) as well as for its north – eastern margin (area around Litzelsdorf – Fürstenfeld). For both areas reduced conditions due to advective influence (water circulation systems) may be assumed. Clearly elevated conditions have in turn been observed in the area around Wiersdorf – St. Peter – St. Nikolai, situated in the southwestern part of the Eastern Styrian Basin. For this area positive advective influence (exfiltration towards the "Sausal Schwelle") may be conceivable. Similar effects have been observed at some drillings situated in the north – western margin of the Eastern Styrian Basin (e.g. the water supply well Puntigam TB3 situated south of Graz or the hydrocarbon drilling Ludersdorf 1).

For the Western Styrian Basin there is hardly any thermal information available, except for the western margin at the area around Köflach – Afling. Two drillings situated there already exhibit clearly reduced thermal conditions at geothermal gradients below 3°C / 100 m. Similar conditions have been observed at drillings within the area of Carinthia. It has to be pointed out once again, that the actual geothermal data situation is very sparse in the region of Carinthia (see also chapter 7.2). Although there are a number of known and utilized thermal springs within this area, most of the available data are not valid for regional interpretation. Deep drillings situated at the Lavanttal (eastern part of Carinthia) indicate thermal conditions, which are very close to the global average of 3°C / 100 m (equivalent to a HFD value of 70 mW/m²). Other drillings containing thermal information, which unfortunately did not exceed penetration depths of more than 200 meters below surface, generally show HFD values of 60 mW/m² to maximum values of 80 mW/m². Clearly elevated thermal conditions are confined to local thermal water ascend and exfiltration paths, which are in turn linked to local fault- or karst- systems (e.g. Bad Kleinkirchheim, Bad Weißenbach, Warmbad Villach).

As mentioned before, most derived temperature profiles within the Austrian part of the investigation area exhibit elevated geothermal gradients at the topmost 500 meters below surface along with continuously reduced conditions towards greater depths (q.v. figure 7-16). This can be interpreted as a lithological phenomenon, although advective heat transportation plays an important role at some sections, but is mainly limited to local scales.

Significant synclinal structures with great basement depths, as existent in the Fuerstenfeld- or Gnas-Basins coincide with slightly lowered temperature gradients at deep sections within Tertiary deposits, as for example observed at the drillings Petersdorf 1 and Fuerstenfeld TH1. In principle cooling effects due to inflowing water can be assumed at synclinal structures. Beyond, transient geothermal effects may be taken into consideration as a cause of basin subsidence along with fast depositions of “cold” sediments. Similar phenomena have been observed at deposition-centers within the Neogene Vienna Basin.

Concerning the advective influence of hydraulic circulation systems on the geothermal regime, the applied geothermometrical analyses indicate mean advective circulation depths of approximately 2200 meter below surface for the Eastern Styrian Basin. According to this water exchange between basement and basin aquifers has to be taken into consideration. Similar maximum circulation depths of approximately 2200 meters below surface have been calculated for some fault-system related thermal water systems at the region of the intra-alpine regions of Carinthia and Styria (e.g. Wildbad Einöd). In contrast maximum advective circulation depths of investigated carbonate aquifer systems in Carinthia (e.g. Warmbad Villach, Bad Kleinkirchheim, Bad Bleiberg) are clearly reduced and seem to coincide with the maximum subsidence of the specific carbonate reservoir.

It can be concluded that advective heat transport due to deep-water circulation is able to have a distinctive but locally confined influence on the geothermal regime down to depths of 2 to 3 kilometers below surface, depending on the existence of hydraulic-conductive basement layers (e.g. Paleozoic dolomite in the Styrian Basin, Mesozoic carbonate rocks in the Carinthian region) or fault-systems within crystalline bedrocks (e.g. Wildbad Einöd, Bad Eisenkappel). The overall geothermal regime is in turn mainly governed by conductive heat exchange depending on the regionally changing crustal thickness, which leads to significant changes in the geothermal conditions between the eastern and the western part of the Austrian investigation area.

8 Geothermal potential

(Domberger G., Rman N. & Lapanje A.)

8.1 Introduction

One of the primary goals of the project is the identification of the areas with not yet exploited geothermal potential. Potential areas are assumed as areas where geothermal reservoirs with significant amount of thermal water with temperatures above 40-50°C are expected. Beside that it has to be remarked that the water temperature of thermal water by definition is above 20°C, but in most cases 20-40°C is too low to use thermal water without a heat pump in an economic way.

Geothermal potential is determined indirectly with knowledge of structural geology relationship, temperature profiles in depth and estimation of the Earth’s heat flow. This is qualitative job and represents synthesis of the geological, hydrogeological and geothermal conceptual model. Of course, spatial information is essential, too.

The subsequent chapter gives a description of the geothermal potential of subsurface layers focused on the area of the existing sediment basins in the TRANSTHERMAL project area.

It is possible to describe the geothermal potential by the following requirements:

- Permeable, water bearing layers
- Depth of specific layers
- Possibility for an economic use of thermal water
- Already known hydrochemical condition of the thermal water

In the TRANSTHERMAL area three main hydrothermal reservoir types occur:

- Low to intermediate temperature geothermal systems in sedimentary basins – water-bearing clastic sediment layers (sand, gravel, sandstone)
- Low to intermediate temperature geothermal systems in the Pretertiary basement of the sedimentary basins – carbonate rocks, karstified or fissured rocks
- Low temperature geothermal systems with warm springs and fracture porosity – mostly carbonate rocks

According to the high degree of investigation of geothermal systems with warm springs, which are used mainly for balneology, geothermal potential is reduced to areas of existence of carbonatic or fissured rocks within the basement rocks or permeable layers in the Neogene or Paleogene clastic sediments.

Therefore a possible approach for description of the given geothermal potential in the whole investigation area may base on the following aspects:

- Topography of the Pretertiary basement (see supplement 05)
- Lithology of the Pretertiary basement (see supplement 04)
- Thickness of the sediment layers (see supplement 06)
- Lithology of the sediment layers:
  Considering the fact that the lithology of the sediment layers is very heterogeneous the description of the geothermal potential in these layers is very hard to do and therefore focused on existing wells and the calculated geothermal conditions (HFD, rock temperatures).

In Slovenia an extensive geothermal low temperature aquifer is developed in the Mura-Zala sedimentary basin. It is already exploited in great extent on a regional scale. Thus a risk of overexploitation exists. We noted this aquifer as potentially geothermal area with high degree of use (see Supplement 13). Although proven potential exists, intensivation of further utilization would cause problems for all users.

8.2 Topography of the Pretertiary basement

The elaborated topography is a result of combination of different existing maps and accomplished studies (e.g. project NANUTIWA) concerning this topic. In addition to the existing maps and studies all wells which have reached the Pretertiary basement have been taken into account for interpretation. Therefore, the map of the topography of the basement is the first and newest transboundary compilation of all existing information concerning the sedimentary basins and tectonic framework within the TRANSTHERMAL area.

In some sedimentary basins in the TRANSTHERMAL area sufficient information about the depth of the basement already exist together with good knowledge about subsurface- and tectonic structures. In other basins or parts of the basins calculation and visualization of the basement is yet not possible due to lack of structural data. As a consequence, no precise predictions about the expectable geothermal potential can be made for those basin areas (for detailed location see Fig. 8-1).

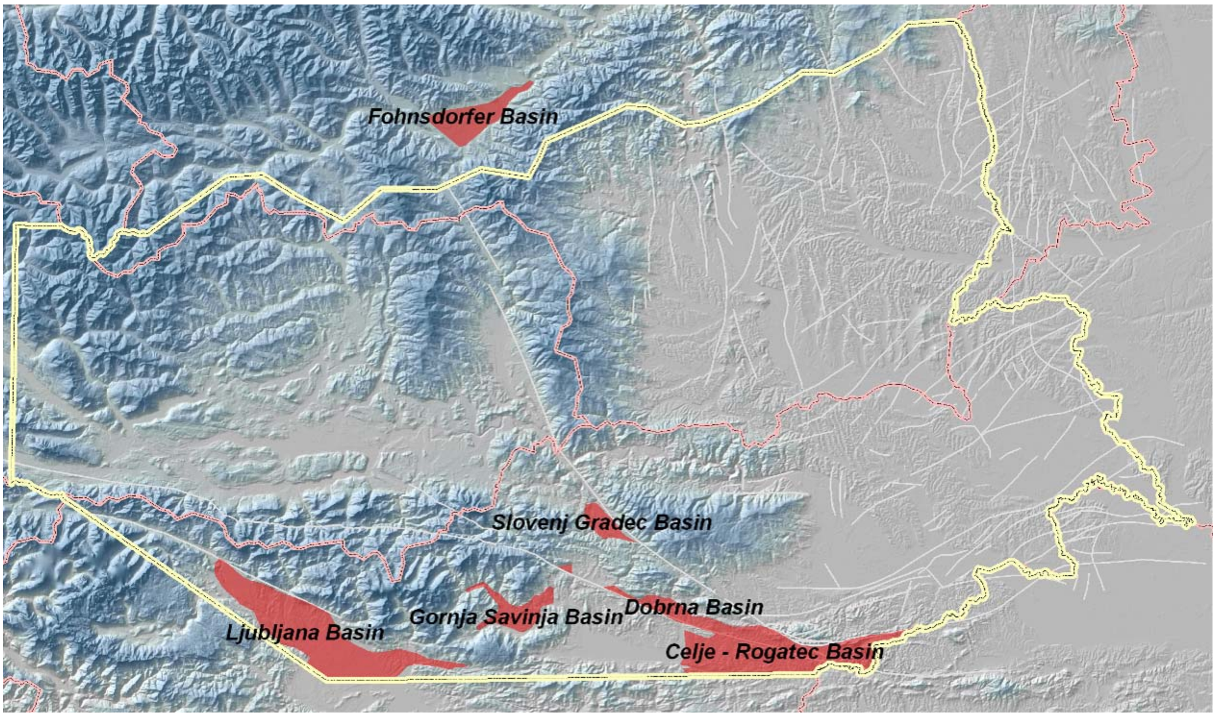


Fig. 8-1 Basins without detailed depth information

8.3 Lithology of the Pretertiary basement

The description of the lithological situation concerning the geothermal potential in the basement, covered by sediment layers, is mainly focused on the existence of thermal water-bearing hard rock formations in the subsurface. Hence, the most important information is the existence of permeable hard rocks in the basement that are fissured or carstified carbonatic rocks (see also Fig. 8-2 - blue zones), or fissured crystalline rock.

Supplement 04 gives an overview of main lithological classes of the Pretertiary basement of the investigation area (see also Fig. 8-2).

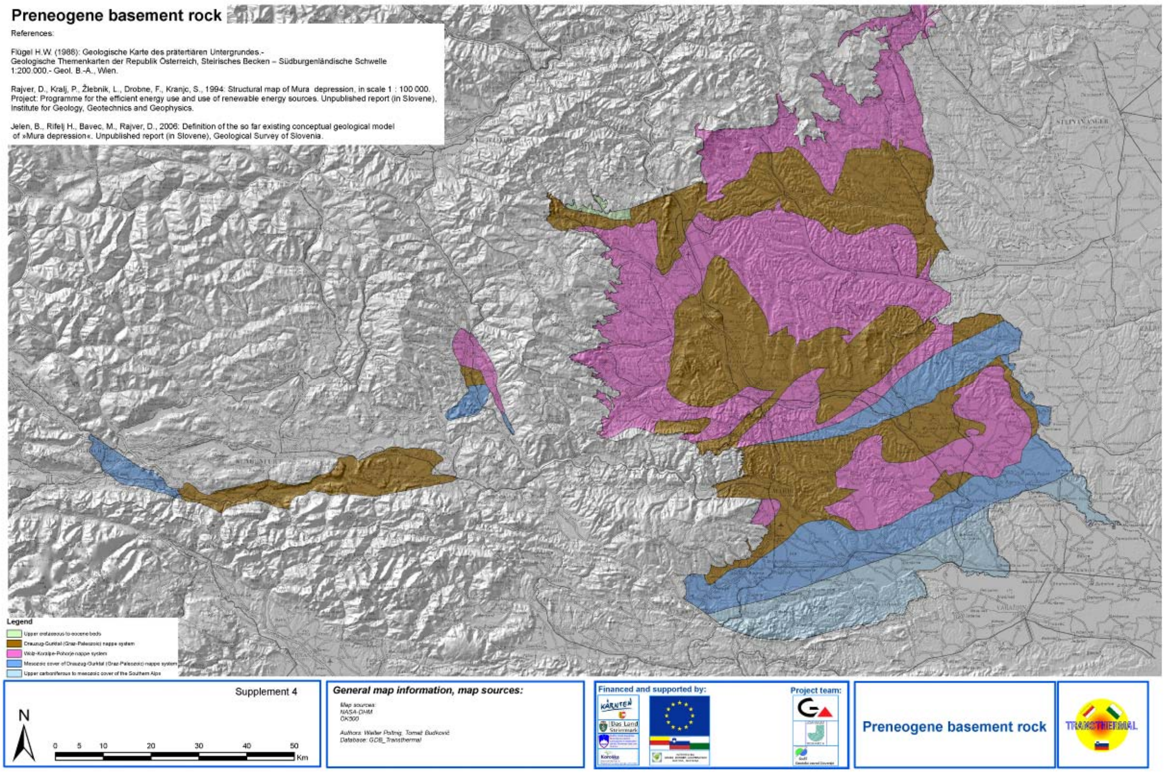


Fig. 8-2: Lithology of Pretertiary basement rocks

8.4 Thickness of the sediment layers

The thickness of the Neogene and Paleogene sediment layers outlines the geothermal potential and the risk of a geothermal exploration well, planned to use aquifers in the sediment layers. Beside this parameter, their permeability is important, too, as it determines their transmissivity and yield capacity.

In areas with great thickness of the sediment layers the chance of making a successful well is clearly enhanced because the chance to reach permeable zones increases. Layer thickness is one crucial factor determining the transmissivity of a specific aquifer. Besides, the heterogeneous sedimentation and changes in facies lead to variation of aquifer permeability, the other crucial factor determining the transmissivity. In many parts of the project area the latter factor is not well known. Furthermore, the maximum vertex of a sediment layer as well as its thickness limits utilizable water temperatures according to the local geothermal gradient.

Supplement 6 shows the calculated sediment thickness derived from the vertical distance between elaborated topography maps of the hardrock basement and existing surface terrain models (see also Fig. 8-3).

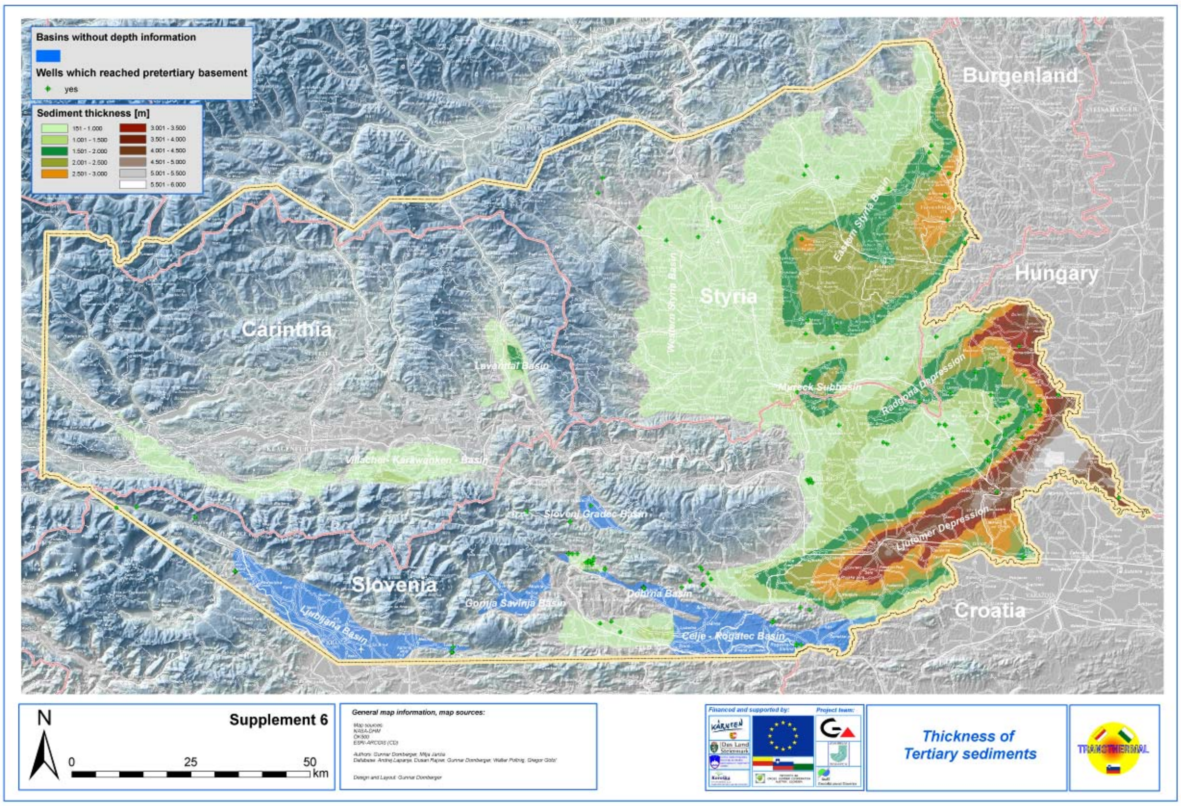


Fig. 8-3 Thickness of Tertiary sediments

8.5 Geothermal potential in the sediment layers

Based on the calculated sediment thickness it was possible to generate different thickness zones which describe the geothermal potential in the sediments.

If the sediment thickness is below 500 m the geothermal potential decreases. Supposing a geothermal gradient of 3°C /100 m down to a depth of 500 m the water temperatures have to be expected in the range of 15°C (western part) to 25°C (eastern part of the Pannonian Basin). These temperatures are too low for an economic use in spas or for direct heating and, consequently, geothermal utilization requires the interposition of heat pumps. In this context, it has to be stated that heat pump systems (shallow geothermal use) have not been a target of the TRANSTHERMAL project objects.

Therefore, in the map for the geothermal potential in the sediment layers (Supplement 13 see Fig 8-4) sediment thickness below 500 meters have been marked as non-profitable.

The thickness interval 500-1000 m is expected to have water temperature of up to 40°C to 50°C. In areas with higher temperature gradients the expected temperature is even higher, up to 60°C.

Zones with sediment thickness over 1000 m and existence of permeable layers are expected to have the elevated geothermal utilization potential.

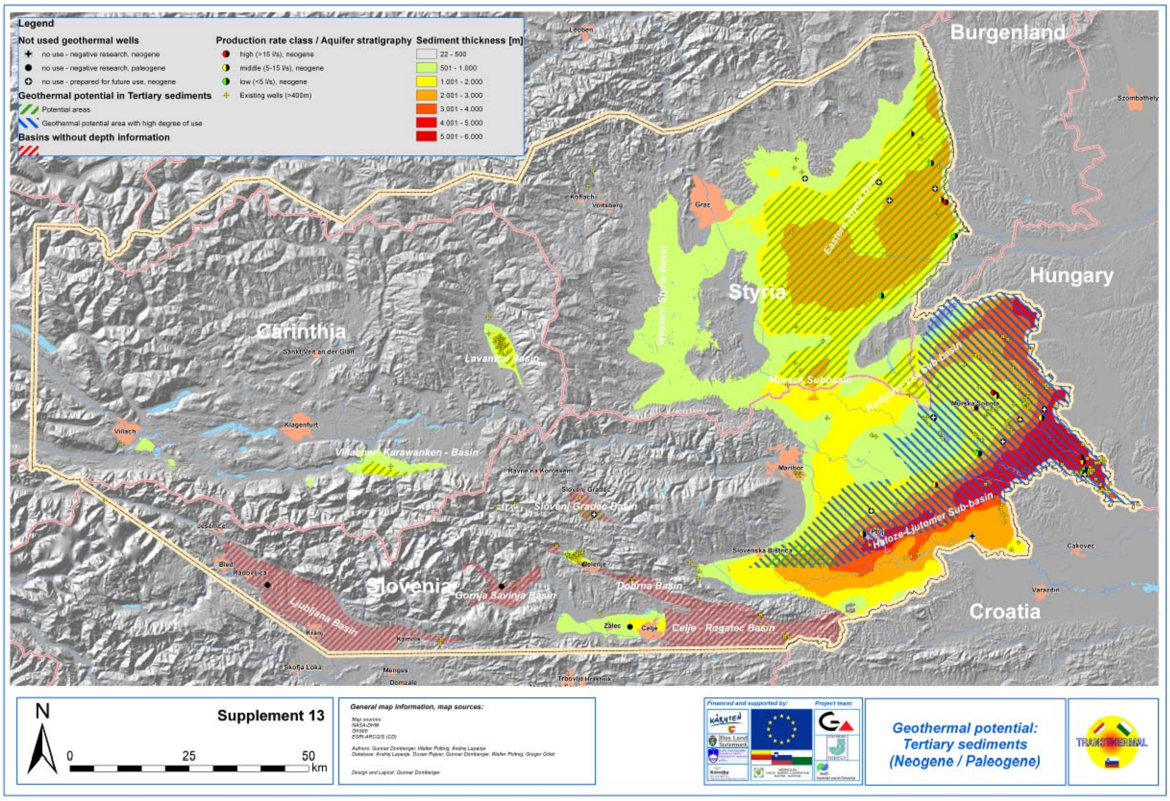


Fig. 8-4 Geothermal potential in the sediment layers

Due to the fact that in some areas there is yet no reliable information about the sediment lithology available, it is not possible to sufficiently take the sediment conditions into an account. Predictions are limited to areas where wells exist and also indicate thermal water-bearing layers. Considering the complicated and heterogeneous sedimentation it is not possible to make correlations between the wells across longer distance.

In Slovenia geothermal aquifers in the sedimentary basins are expected only in sediments of Upper Miocene and Pliocene age in the Mura-Zala sedimentary basin. However, in the Slovenj Gradec basin and, perhaps, in the southwest part of the Drava field perspective permeable sediments of the

Karpatian age are developed. All older Neogene rocks, with exception of the former, are generally low permeable, so significant accumulation of the thermal water is not expected despite high temperatures. On the supplement 13 this potential area in the northeastern Slovenia is specially marked. Practically anywhere in this area, if a well is deep enough, the thermal water can be captured. Unfortunately, density of the thermal water users is high and some influence of overexploitation is already observed. This means that the usage now is greater than the natural recharge of thermal aquifers. Regional trends of the pressure drawdown in the aquifers were already noticed by KRALJ & RAJVER (2000) and KRALJ (2007). The reinjection of thermally exploited thermal water and sustainable use of the thermal water will be a main concern in the following years, especially within the transborder region of the Pannonian Basin (eastern part of the project area).

In the Southern Alps Paleogene sediments and volcano-sedimentary rocks with low permeability prevails. This is also the reason why geothermal aquifers in the sedimentary basins are not developed there.

8.6 Geothermal potential in the basement rocks

The geothermal potential in the basement rocks is mainly defined by the lithology and the depth of the top of the basement. In some areas the lithology of the Pretertiary basement is well known due to the existence of a great number of hydrocarbon wells. In other areas no direct information about lithology, stratigraphy and aquifer conditions at the hard rock basement exists.

Basically it is known that carbonate rocks which can be fissured and/or karstified have the best geothermal potential of the basement rocks. But karstified aquifers change their conditions often in a small scale. Therefore, it is very hard to plan and realise a successful well. In this context, one of the main geothermal targets are faults accompanied by fissured and/or karstified zones within carbonate rocks. Further it is possible to explore fissured zones in the crystalline rocks. The risk of success in this lithological framework is clearly elevated.

In Slovenia potential geothermal areas in the basement of sedimentary basins are expected beneath the Mura – Zala sedimentary basin, between Gornja Radgona and Hodoš in the Radgona – Vaš tectonic half-graben, in the wider area of the Raba tectonic fault (JELEN, 2006), southwest of Maribor and in the Haloze region (supplement 14). The Paleozoic and Mesozoic carbonate rocks are foreseen there. In the transitional zone between the Eastern and Southern Alps (in the junction of the Šoštanj, Periadriatic, Donat, Velenje and Lavantal faults) the geothermal aquifer in Mesozoic carbonate rocks is expected in Črna na Koroškem, Mežica, beneath Slovenj Gradec basin, in Vitanje, Šalek valley and Rogatec. Opposite to the aquifers in the sedimentary basins where the porosity is a primary characteristic of the sediment, here, the porous zones of the aquifer are expected only near fissures and fractures which are spatially limited.

In the area south of the town Lendava the highest aquifer temperatures within the project area are expected at a range exceeding 200°C at a depth of 4000 m in the Pretertiary basement rocks.

In Austria there are some areas with Paleozoic carbonate rocks which are used at the locations Blumau and Bad Waltersdorf. Additional in the transboundary region of Bad Radkersburg Mesozoic carbonate rocks exist which supply the spa of Bad Radkersburg,

Supplement 14 gives an overview of the geothermal potential in the basement rocks (see also Fig. 8-4):

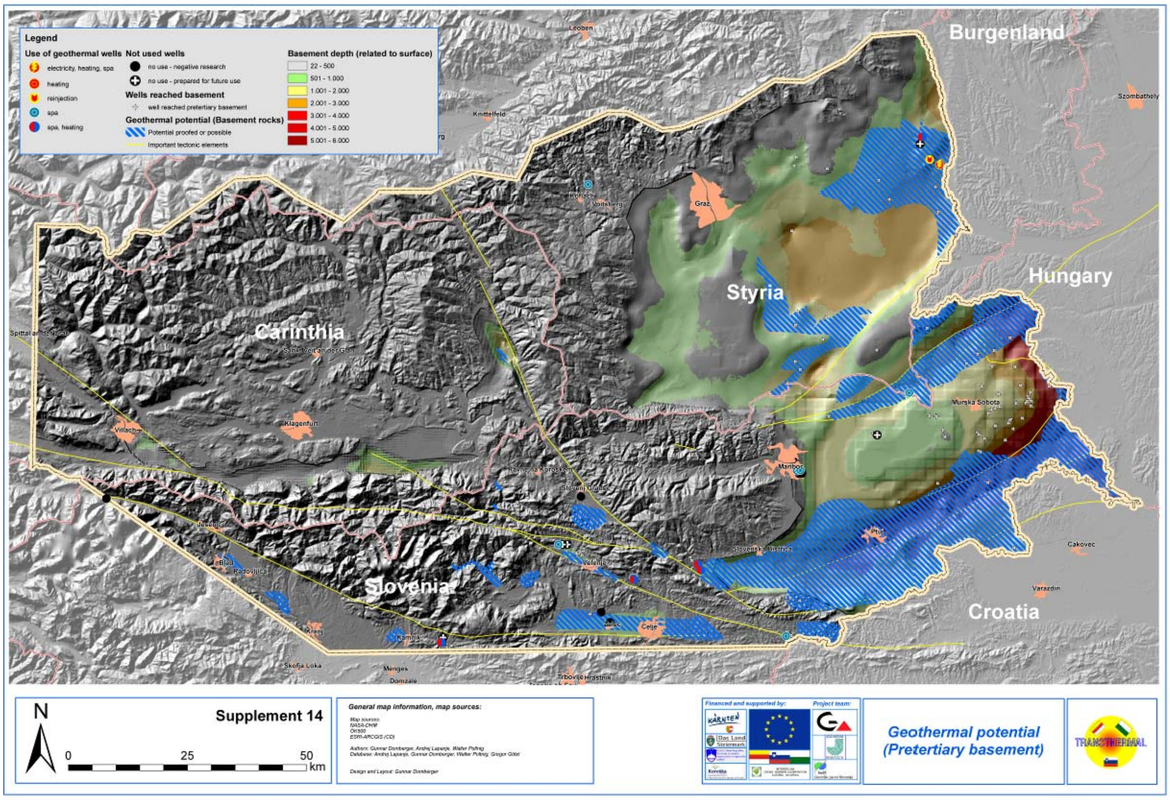


Fig. 8-5: Geothermal potential of the Pretertiary basement layers

Basis for the geothermal potential in the basement is the lithology of the basement and the depth of the top of the basement, considering the geothermal gradient and the required temperatures. So if the top of the basement is shallower than 500 meter below surface, the geothermal potential has to be marked as very low and in most cases without any economic relevance. Therefore these areas have been ignored in the geothermal potential map.

A detailed description of the geothermal potential in the basement requires intense and special geophysical and hydrogeological investigations. Only a detailed prefeasibility study allows estimating the risks and chances of a thermal well.

8.7 Total geothermal potential

The best conditions for geothermal exploitation can be found in areas with geothermal potential in the sediment layers in addition with geothermal exploitation potential in basement layers and beyond, in combination with high basement depths. At those regions, the risk of catching thermal water with a new well is relatively low compared to remaining areas.

In the Austrian part of the project area a known “combined” geothermal potential exists in the area of Bad Waltersdorf and Blumau. For example, both, a geothermal potential in the Neogene sediment layers and in the Paleozoic basement carbonates, exist there.

Supplement 15 shows the derived “total utilization potential” based on the previous described individual potentials of the sediment and bedrock layers.

Used potential classes are:

Potential class 1 (hatched blue zones): Geothermal potential exists in the basement

Potential class 2 (hatched red zones): Geothermal potential exists in the sediment layers

Potential class 1+2 (hatched blue-red zones): Combined geothermal potential in the basement and in the sediment layers

Supplement 15 (see also Fig. 8-6) shows an overlap of the spatial distribution of potential areas in the Tertiary sediments and the Pretertiary basement. The overlap is very obvious in the Styrian basin and the region of Radgona / Bad Radkersburg. In the lower extend both types of aquifers are foreseen in the Lavantal and Slovenj Gradec basin. However, transboundary aquifers are developed only in the border region between Styria and Pomurje. The aquifer which is exploited in Bad Radkersburg spreads in a narrow wedge from Austrian to the Slovenian side and further against northeast, over Goričko region to Hungary.

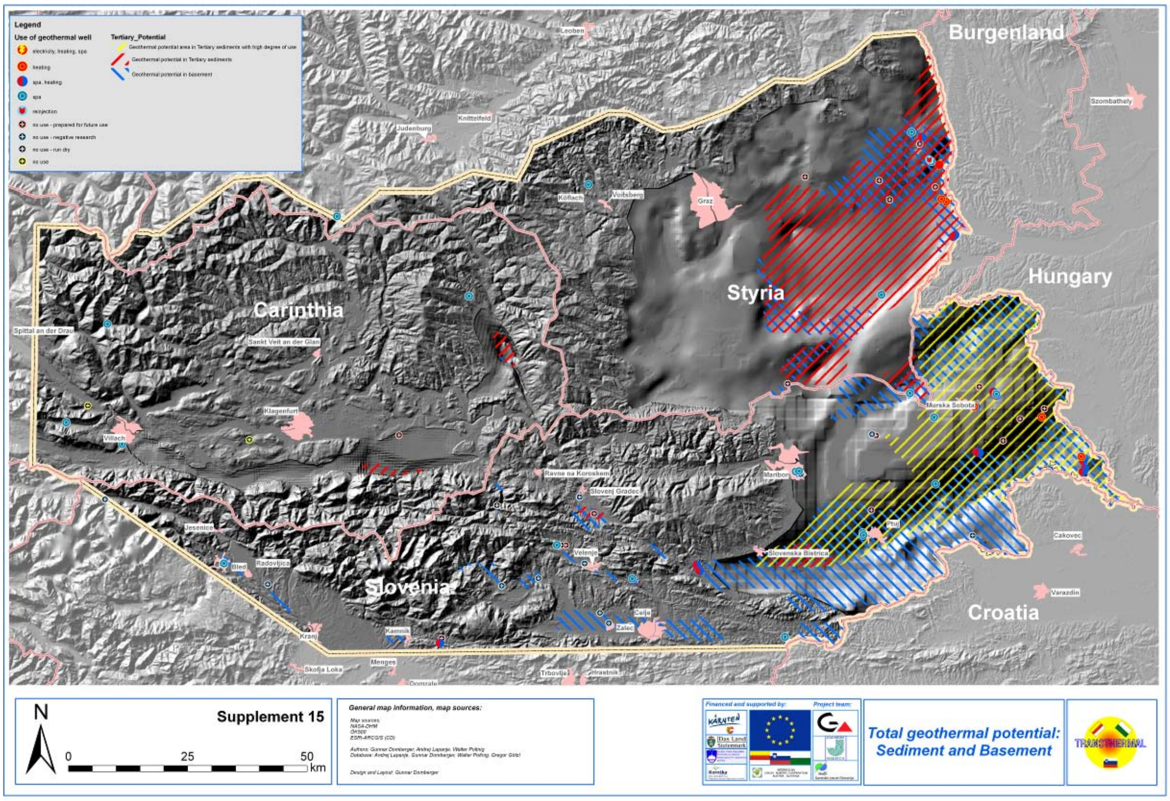


Fig. 8-6: **Total geothermal potential (sediment and basement rocks)**

Generally speaking, the potential increases with the thickness of the sediment layers and according to the depth of top of the basement. Therefore in the combined geothermal potential map classes strongly follow the isolines of the sediment thickness.

9 Actual use of thermal water

(Domberger G. & Lapanje A.)

9.1 Utilisation of thermal water resources

Recent use of hydrothermal resources is the best and most reliable indicator of the geothermal potential in the project area. In areas where spas or geothermal energy plants exist, a longtime proofed geothermal potential is indicated. Therefore, long time used wells are the best quantifier for available geothermal exploitation at a specific aquifer.

At the moment thermal water is used in spas, for heating and combined use. At one site (Bad Blumau) elevated water temperatures (100-120°C) enable production of electric power based on the ORC process. Beside this, deep buried, partly thermal or sub-thermal aquifers within the project area are used for mineral- and drinking water supply.

Supplement 8 shows an overview of the recent situation of use (see also Fig. 9-1). Beside active geothermal objects, negative boreholes and boreholes which are prepared for future use are also shown.

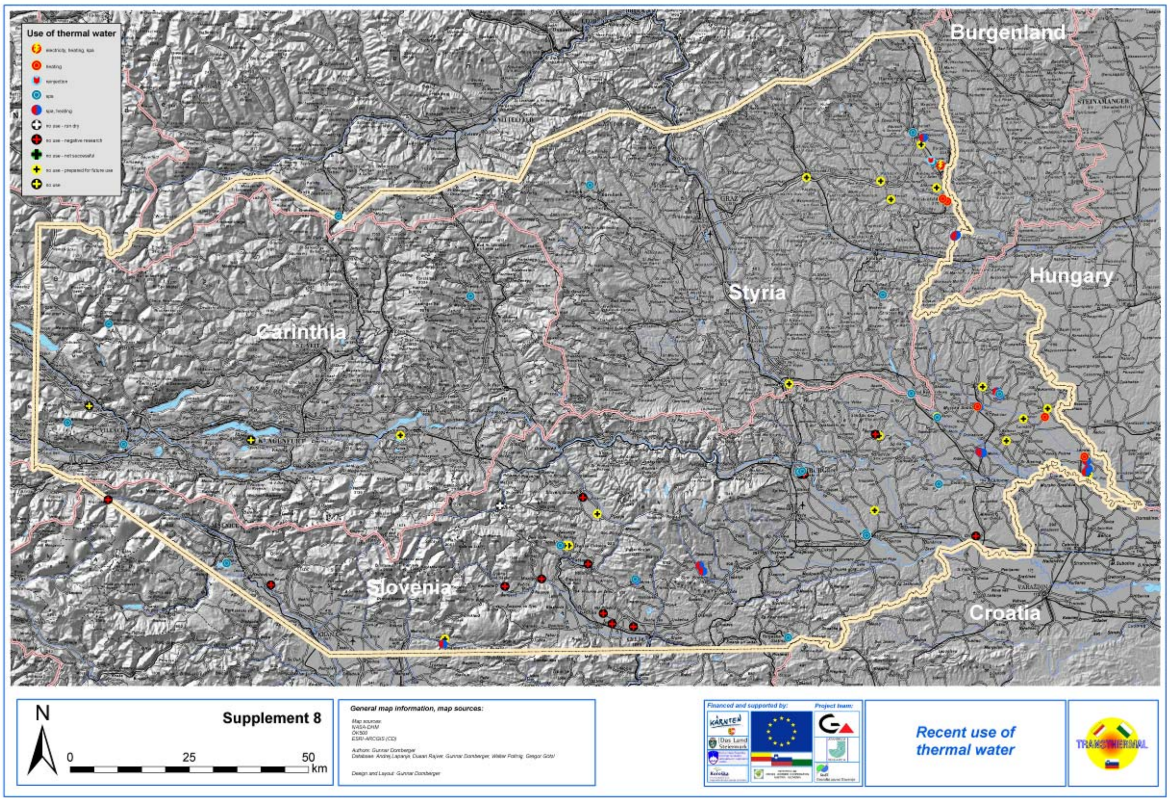


Fig. 9-1: Recent use of thermal water

Present state of direct utilization of geothermal energy in Slovenia according to the purpose as well as estimation of the installed thermal power has been systematically monitored since 1995 according to the methodology of the International Geothermal Association (RAJVER et al. 1995; KRALJ & RAJVER, 2000; RAJVER & LAPANJE, 2005).

9.2 Water temperatures

The water temperature at the wellhead and outflow temperature of natural springs (either thermal or sub-thermal) are suitable for an estimation of the thermal conditions at potential reservoirs. The temperature of thermal water on surface depends on several factors such as reservoir temperature, yield and cooling factors. In the case of natural thermal springs mixing proportion with shallow and cooler aquifers influences the temperature.

In this context supplement 9 (see also Fig. 9-2) shows classified borehole and spring temperatures.

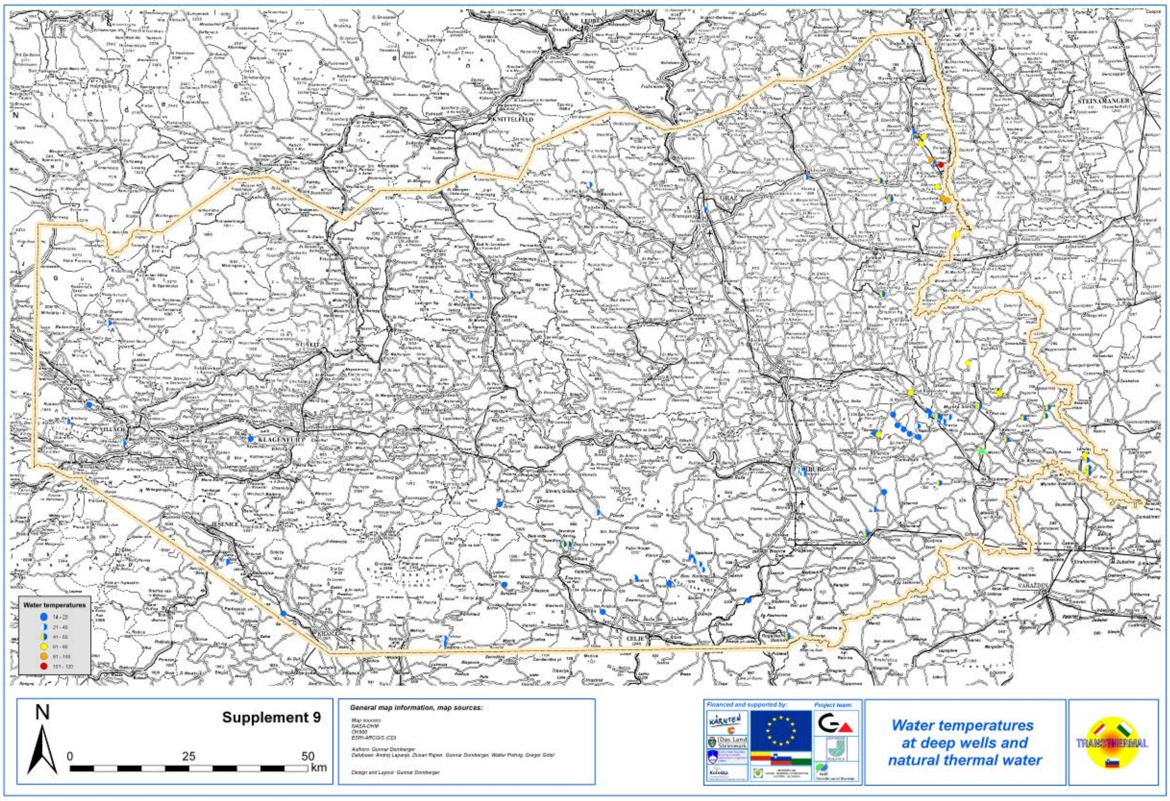


Fig. 9-2: Water temperatures at deep wells and natural thermal water

The highest verified production temperature within the TRANSTHERMAL area is about 110°C at the well Blumau 2 in the Styrian Basin, which is used for production of electricity, heating and spa.

On Slovenian side the maximum produced temperature is 80°C on the wellhead of Be-2/04 (KRALJ, 2007). Temperatures between 61 and 80°C are recorded in the wells Le-2g/94 in Lendava, Ve-1/57 and Ve-2/57 in Banovci, Mt-1/60, Mt-4/74 and Mt-5/82 in Moravske Toplice and Dan-3/90 in Dankovci in the Goričko region.

The used temperature values are single measurements and therefore represent single production situations. Variations of the water temperatures are expected, but reliable time series of the water temperatures are yet not available. The implementation and acquisition of reliable time series of different parameters should therefore be a main future task for a common transboundary monitoring as a base for sustainable use of geothermal resources.

9.3 Water types – Hydrochemical conditions

Supplement 10 shows hydrochemical conditions of the water types within the TRANSTHERMAL project area. The classification has been made according to the contents of the main ions in the water which are Na, K, Ca, Mg and HCO_3, Cl and SO_4. The defined hydrochemical classes shown in supplement 10 follow standardized water types characterised by equal mass contents [unit: mequ%] with emphasise on contents above 20%. In addition, total dissolved solids in water [unit: g/l] are also listed (see also Fig. 9-3).

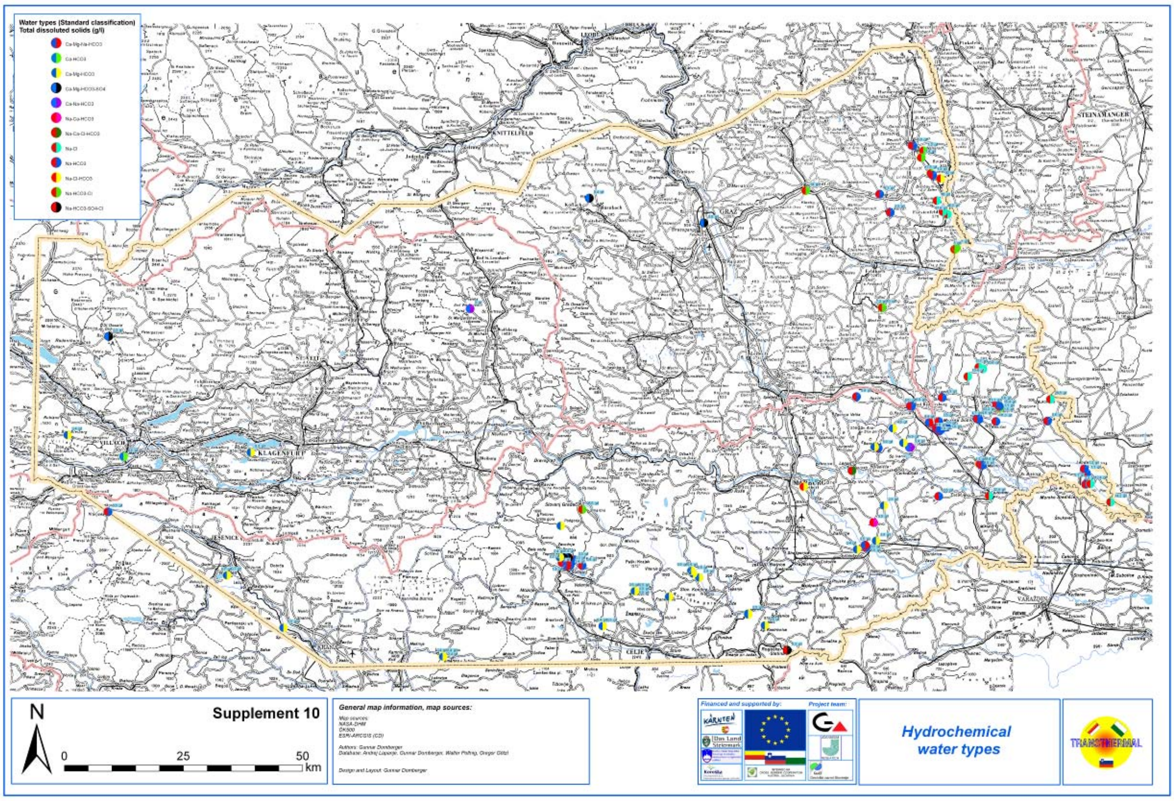


Fig. 9-3: Hydrochemical water types

This supplement acts as an overview at a large scale and therefore a detailed interpretation of this map is not advisable.

In the western part of the Slovenian project area thermal water of Ca-Mg-HCO_3 type significant for the carbonate aquifers in the basement of sedimentary basins and warm spring systems prevails. Near Topolšica Ca-Mg-HCO_3-SO_4 type of water was determined. Rare water type is exhibited at borehole MD-1/05 in Mislinjska Dobrava (Na-Ca-Mg-HCO_3) and RT-1/92 in Rogaška Slatina (Na-HCO_3-SO_4).

In the Northeastern Slovenia Na-HCO_3 type is predominant. Chemistry of the thermal water changes according to the distance from feeding zones and with depth. In shallow depth the water is mainly Ca-Mg-HCO_3, and changes with depth through transitional water types Ca-Mg-Na-HCO_3 and Na-Ca-HCO_3 into Na-HCO_3. Chemical composition changes because of interaction between water and host rock. In the Upper Pontian and Pliocene aquifers the water is low-mineralized (below 1 g/l total dissolved solids), on the contrary, in older sediments the water is thermomineral (more than 1 g/l total dissolved solids).

In the Pretertiary basement of the Mura-Zala and Styrian basin highly mineralized thermomineral water of Na-Cl type exists. This water includes traces of natural gas and oil. Waters from Pretertiary basement and from Tertiary sedimentary basin aquifers are conjoined at some locations and therefore produce water of Na-HCO_3-Cl or Na-Cl-HCO_3 type. The warmest thermomineral water in Slovenia (Be-2/04 in Benedikt) is of Na-HCO_3 type (KRALJIĆ et al, 2005).

9.4 Yield classes

Supplement 11 gives an overview concerning the water pump and water flow rates. Due to the fact that no reliable water production data are yet available, it was necessary to define classes of the flow and pump rates called yield classes. According to known production rates 3 classes (<5 l/s, 5-15 l/s, >15 l/s) have been defined, however, at some places no reliable information is available. For more detailed interpretation of sustainable use of thermal water, time series of pressures and production rates will be essential (see also Fig. 9-4).

In Slovenia geothermal objects with intermediate yield predominate as only four exhibit flow higher than 15 l/s: captured spring Toplica in Topolšica, borehole TVD-10/86 in Lajše, borehole Le-2g/94 in Lendava and borehole Mt-8g/05 in Moravske Toplice.

Yield of boreholes depends on different factors which can be natural, linked to permeability of the geothermal reservoirs or technological. The efficiency of boreholes is almost always higher than the natural capacity of geothermal aquifers and, consecuently, negative influence of thermal water pumping should be avoided with sustainable use and/or reinjection of exploited thermal water back to the reservoir.

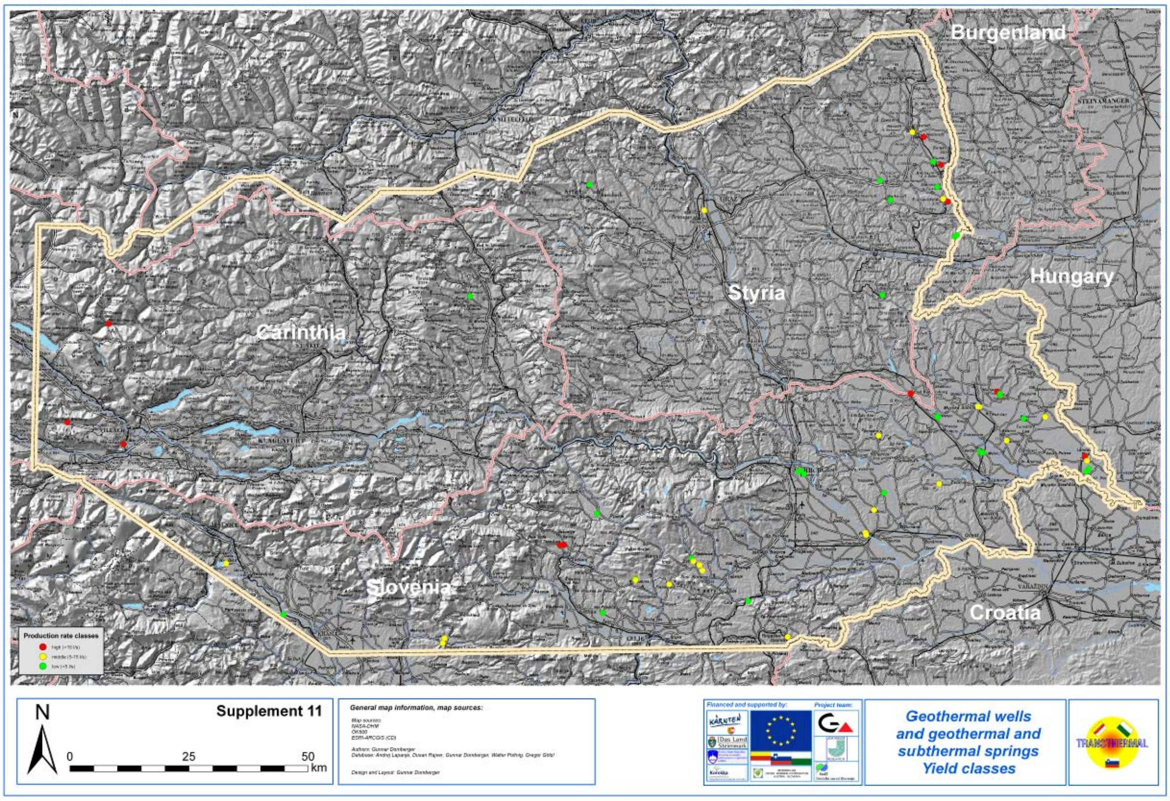


Fig. 9-4: **Geothermal wells and natural thermal and subthermal springs - Yield classes**

10 Abstracts

10.1 Summary

Lapanje A., Götzl G., Poltnig W., Rajver D. & Domberger G.

The hydrogeothermal utilization potential (exploitation of naturally occurring thermal water) has been investigated within the TRANSTHERMAL project area. The TRANSTHERMAL region covers the border region of Austria and Slovenia and includes the northern and northeastern part of Slovenia and the eastern part of Carinthia and the southern part of Styria.

Emphasis has been set on natural hydrogeothermal reservoirs. Geothermal potential that could be exploited from greater depths using the HDR (Hot Dry Rock) technology is not yet economically applicable and was therefore treated only marginally. The future economy of such facilities depends first of all on the expectable depths of needed reservoir temperatures. For example electric power generation based on ORC (Organic Rankine Cycle) methods requires rock temperatures exceeding 90°C. The map of temperature distribution at 4000 m depth (supplement 12) is useful for pondering on where the exploitation of possible HDR reservoirs is prosperous in the future. Shallow geothermal

utilization based on heat pump technology and exploitation is realized by subsurface horizontal collectors, vertical heat exchangers and ground water geothermal heat pumps down to approximate depth of 250 m and has also been treated marginally at the presented study.

In order to provide a basis for geothermal interpretation already existing geological datasets within the investigation area have been collected and new transboundary geological and tectonic maps have been created. The goal of geological activities during the presented project was to establish a general transboundary legend for a scale of 1:200.000. By the help of this generalized legend cross border geological and tectonic maps have been established. Based on the achieved transboundary maps and geological cross sections future structural interpretation of Neogene and Paleogene basins and their related basement lithology will be possible.

Already existing temperature datasets, predominately gained at drillings, enabled elaboration of transboundary maps showing the distribution of heat flux and rock temperatures at different depths (supplement 12).

Geothermal potential analyses in the TRANSTHERMAL area have been made by compiling knowledge on transboundary geological conditions and previously elaborated geological maps and cross-sections. The investigation of geothermal potential indicates the future possibilities of use and consequently, the analyses of present geothermal conditions and use are also important (spas, heating, electric energy). The central processing tool of the TRANSTHERMAL project consists of an extra designed database, connected to a ARCGIS 9.2 program. A geothermal atlas, the main result of the project, is set up from the database with combination of different geological information, geothermal characteristics of the area, existing boreholes, as well as thermal water utilization. The atlas is presented as 15 printed supplements.

The geothermal potential has been distinguished according to general geological conditions in two sets:

- Potential of the Pretertiary basement rocks and bedrock inside narrow fault zones
- Potential of the Tertiary sediments.

Joint geothermal potential has been achieved by superposition of previously elaborated polygons showing sub-potentials related to Tertiary sediments and bedrock sections. Areas showing the best geothermal conditions are characterized by increased geothermal gradient or favorable hydrogeological conditions (occurrence of water-bearing zones). In the areas of uncovered carbonate massifs geothermal potential is generally insufficient due to significant fresh water inflow. It has to be mentioned that the statement is based on rare deep boreholes, but these conditions are generally observed in high permeable karstic regions. However, possibility of thermal water utilization cannot be excluded there. As successful examples spas in Snovik and in Bled can be mentioned. In comparison with the sedimentary basins in the east of the investigated area the risk is greater as geothermal potential decreases due to increased thickness of the Earth's crust and lower HFD. In contrast, areas with increased HFD can be found in the northeastern Slovenia and southeastern Styria.

Even in the area with increased geothermal potential the exploration boreholes must be drilled first to confirm or disprove the predicted conditions. The forecast obscurities that stem from the generally heterogeneous geological data can be reduced only by increased exploration activities. Irrespective of geological risk assessment also the restricted economical factor of thermal water capture exists. The drilling costs increase with depth and represent a substantial part of investment. The present study is in the first place a surveying study, and can not replace the needs for further, more detailed geothermal investigations.

10.2 Zusammenfassung

Götzl G., Poltnig W. & Domberger G.

Die bilaterale Interreg IIIA-Studie TRANSTHERMAL hatte zum Ziel, geothermie-relevante Meta- und Kenndaten aus der Grenzregion Österreich – Slowenien zu erheben und in einer grenzüberschreitenden Datenbank zu sammeln. Darauf aufbauend wurden themenspezifische geothermische Karten des Untersuchungsgebiets erarbeitet und als GIS–Applikationen bereitgestellt. Durch einen digitalen geothermischen Atlas (WEB Applikation im Kärnten Atlas) sollen die dabei gewonnen Erkenntnisse des TRANSTHERMAL-Projektes für eine nachhaltige und wirtschaftlich sinnvolle Nutzung natürlicher Thermalwässer im Grenzraum zwischen Österreich und Slowenien verbreitet werden.

Im Rahmen des Projekts TRANSTHERMAL wurde versucht, das geothermische Nutzungspotenzial in der Region zu analysieren und darzustellen. Dabei wurde nur das tiefe geothermische Potenzial mit Fokus auf natürliche Thermalwasservorkommen berücksichtigt.

Ausgehend von einer grenzüberschreitenden Darstellung der geologischen Rahmenbedingungen und einer zusammenführenden Bearbeitung der geologischen Datenbasis (geologische Karten, geologische Profile) erfolgte eine Analyse des geothermischen Potenzials. Die Darstellung des geothermischen Potenzials im Sinne zukünftiger Nutzungsmöglichkeiten erforderte neben der Analyse der geothermischen Rahmenbedingungen auch eine Darstellung der derzeitigen Nutzungssituation (Thermalbäder, Heizungen, Stromproduktion) und bereits verfügbarer Aquifer-Kennzahlen (z.B. Schüttung, Wassertemperatur, Chemismus). Augenmerk war darüber hinaus auch auf die regionsabhängige Zunahme der Gesteinstemperatur mit der Tiefe (geothermische Tiefenstufe) zu legen, zumal die geothermische Tiefenstufe ebenfalls einen nicht zu vernachlässigenden Wirtschaftlichkeitsfaktor (Steuerung der Bohrkosten) hinsichtlich einer Nutzung geothermaler Ressourcen darstellt.

Das geothermische Potenzial ohne die Entnahme von Wasser aus dem Untergrund (Hot Dry Rock Technologie) ist zum gegenwärtigen Zeitpunkt noch nicht wirtschaftlich umsetzbar. Die zukünftige Wirtschaftlichkeit derartiger Anlagen ist in erster Linie von der Erschließungstiefe heißer Gesteine abhängig (Steuerung der Bohrkosten). Um dennoch diesem zukünftigen geothermalen Nutzungspotenzial Rechnung tragen zu können, wurden im Rahmen der Studie TRANSTHERMAL verschiedene Tiefentemperaturkarten für Tiefenbereiche bis zu 4000 Meter unter Gelände erarbeitet.

Alle wesentlichen Basisdaten zur Beurteilung des geothermischen Nutzungspotenzials des Projekts TRANSTHERMAL sind in einer multilingualen Projektdatenbank abgelegt und über die Verknüpfung mit der GIS-Software ArcGIS 9.2 raumbezogen darstellbar.

Die thermischen Rahmenbedingungen (geothermale Tiefenstufe, terrestrische Wärmestromdichte) wurden auf Grundlage von Bohrlochtemperaturen mit Hilfe gängiger Korrektur- und Modellierungsverfahren erarbeitet. Das geothermische Potenzial wurde entsprechend den geologischen - lithologischen Rahmenbedingungen in ein geothermisches Potenzial in dem Festgestein (Beckenuntergrund oder anstehendes Grundgebirge) sowie in ein Potenzial der sedimentären Beckenfüllung gegliedert. Durch Überlagerung dieser beiden geothermischen „Teilpotenziale" wurde ein geothermisches „Gesamtpotenzial" abgeleitet, welches letztendlich Gebiete mit günstigen geothermischen Untergrundverhältnissen anzeigt.

Durch die Überlagerung und Kombination verschiedener geologischer Informationen und geothermischer Untergrundeigenschaften sowie durch die Einbeziehung von bestehenden Bohrungen und Thermalwassernutzungen wurde ein nachvollziehbares Kartenwerk erstellt. Mit Hilfe dieser Methodenkombination wurde eine effiziente Projektbearbeitung und Ergebnisdarstellung möglich. Ein umfassendes Kartenwerk, zusammengefasst zu einem digitalen geothermalen Atlas der Region, bildet das eigentliche und zentrale Ergebnis des Projekts TRANSTHERMAL.

Zusammenfassend ist festzuhalten, dass einige Regionen im Projektgebiet, allem voran im Bereich des oststeirischen und slowenischen Beckens, aufgrund der geologischen, hydrogeologischen und geothermischen Rahmenbedingungen eindeutig günstigere Voraussetzungen für eine energetische oder balneologische Nutzung von Thermalwässern besitzen. Die geogenen Voraussetzungen zur Gewinnung geothermaler Energie sind im Westen des Projektgebiets als mäßig zu beurteilen. Die Gewinnung von Wärme und Strom auf Grundlage der Erschließung natürlicher Thermalwässer weist in diesen Regionen trotz Beispiele erfolgreicher Versorgung von Thermalbädern (z.B. Therme Köflach, Therme Bad Kleinkirchheim) ein erhebliches Fündigkeitsrisiko auf. Lediglich in einzelnen Beckenregionen (z.B. Lavanttal) ist aufgrund mächtiger Sedimentkörper mit einer mäßigen Verringerung des Fündigkeitsrisikos zu rechnen. Einschränkend ist festzuhalten, dass die vorliegende Studie als Übersichtsstudie zu interpretieren ist und die Erfordernis von weiterführenden, detaillierten Standortuntersuchungen grundsätzlich nicht ersetzen kann.

10.3 Povzetek

Lapanje A., Rajver D.

V okviru projekta TRANSTHERMAL se je raziskal geotermalni potencial obmejnega območja severne in severovzhodne Slovenije ter avstrijske Štajerske in Koroške. Poudarek je bil na raziskavah naravnih hidrogeotermalnih rezervoarjev. Geotermalni potencial, ki bi se izkoriščal s tehnologijo vročih suhih kamnin, v tem trenutku še ni ekonomsko upravičen, prihodnja ekonomičnost pa je v prvi vrsti odvisna od globine do vročih kamnin. Za razmišljanje o prihodnjem izkoriščanju takšnega potenciala lahko uporabimo karto porazdelitve temperatur v globini 4000 m (priloga 12). Prav tako smo zanemarili tudi izkoriščanje toplote tal z zemeljskimi kolektorji, geosondami in toplotnimi črpalkami na podzemno vodo, do globine približno 250 m.

Izhajajoč iz prekomejnega prikaza geoloških pogojev in skupne obdelave geoloških kart ter prerezov je možna analiza geotermalnega potenciala na obravnavanem območju. Obdelava geotermalnega potenciala nakazuje prihodnje možnosti uporabe, zato je nadvse pomembna analiza obstoječih geotermičnih pogojev in sedanje uporabe (toplice, ogrevanje, električna energija). Osrednje orodje obdelave projekta TRANSTHERMAL gradi posebej izdelana podatkovna baza, ki je povezana z GIS-programom ARCGIS 9.2. Vsi podatki so zbrani v podatkovni bazi. Geotermalni atlas, ki je osrednji rezultat projekta, je postavljen iz podatkovne baze s pomočjo prekrivanja in kombinacije različnih geoloških in geotermičnih informacij, obstoječih vrtin ter izrabe termalne vode in prikazan v 15 tiskanih prilogah.

Geotermalni potencial je razčlenjen, glede na osnovne geološke pogoje, na potencial v kamninah v predterciarni podlagi sedimentacijskih bazenov ali v kamninah znotraj ozkih prelomnih con in na potencial v terciarnih sedimentih. S prekritjem poligonov teh delnih potencialov se je ovrednotil združen geotermalni potencial, ki prikazuje območja z najugodnejšimi geotermičnimi pogoji, značilna po povišanem geotermičnem gradientu ali z ugodnimi geološkimi in litološkimi pogoji. Na območjih odkritih karbonatnih masivov je geotermični potencial pogosto lahko le pomanjkljivo opisan na osnovi redkih globokih vrtin. Načelno pa tudi na tem območju ne moremo izključiti možnosti nastopanja naravnih termalnih vod. Kot uspešna primera izpostavljamo toplice v Snoviku in na Bledu. V primerjavi s sedimentacijskimi bazeni na vzhodu je tveganje na teh območjih večje, geotermični potencial pa zmanjšan zaradi povečane debeline Zemljine skorje in s tem nižje GTT. Območja s povišano GTT nastopajo v severovzhodni Sloveniji in na območju vzhodne Štajerske.

Tudi na območju s povečanim geotermičnim potencialom je treba najprej izdelati raziskovalno vrtino, ki lahko potrdi ali ovrže naša predvidevanja. Nejasnosti pri napovedi, ki izhajajo iz osnovnih heterogenih geoloških podatkov, se lahko zmanjšajo le z načrtovanjem novih raziskav. Ne glede na geološko ovrednotenje tveganja, obstaja tudi omejitveni ekonomski dejavnik zajema termalne vode. Stroški vrtanja z globino naraščajo in predstavljajo znaten del naložbe.

Obstoječa študija je primarno pregledna študija, zato ne more nadomestiti potreb po nadaljnjih detajlnih geotermalnih raziskavah.

11 Literature

CARSLAW, H. S., JAEGER, J.C. (1959): Conduction of heat in solids, 2nd ed., Oxford University Press, New York, pp. 510.

ČERMAK, V., HURTIG, E., (1979): Heat Flow Map of Europe, Enclosure for Terrestrial Heat Flow in Europe, ed. By Čermak V. & Rybach L., Springer Verlag, Berlin Heidelberg.

D' AMORE, F., SCANDIFFIO, G., PANICHI, C., (1983): Some observation on the chemical classification of ground waters, Geothermics vol. 12, pp. 141 – 148, Oxford.

DOMBERGER, G. (2007): Hydrogeological Investigations for a Sustainable use of the Deep Groundwater Resources in the Styrian and Pannonian Basin / Workshop: "Neogene of Central and South-Eastern Europe", 17.5.2007 – 21.5.2007, Kapfenstein.

FLÜGEL, H.W. (1961): Die Geologie des Grazer Berglandes (Erläuterungen zur Geologischen Wanderkarte des Grazer Berglandes 1:100000 [non]. Mitt. Mus. Bergbau Geol. Technik Landesmus. Joanneum Graz. Volume 23. p 1-212, Graz.

FLÜGEL, H.W. (1972): Das Steirische Neogenbecken [K 8] p 199-227, Graz.

FLÜGEL, H.W. (1988): Geologische Karte des prätertiären Untergrundes.- Geologische Themenkarten der Republik Österreich, Steirisches Becken – Südburgenländische Schwelle 1:200.000.- Geol. B.-A., Wien.

FLÜGEL, H.W., NEUBAUER, F. (1984): Geologische Karte der Steiermark, 1: 200.000, Geologische Bundesanstalt, Wien.

FOURNIER, R.O. (1977): Chemical Geothermometers and Mixing Models for Geothermal Systems.

FOURNIER, R.O., TRUESDELL, A. H., (1977): An empirical Na-K-Ca geothermometer for natural waters, Geochimica et Cosmochimica acta vol. 37, pp.1255 – 1275.

GIGGENBACH, W. F. (1988): Geothermal solute equilibria, derivation of Na-K-Mg-Ca geoindicators, Geochimica et Cosmochimica Acta vol. 52, pp. 2749 - 2765.

GOSAR, A. (2005): Seizmične raziskave litosfere v srednji Evropi in debelina Zemljine skorje v Sloveniji; Seismic investigations in the lithosphere in Central Europe and thickness of the Earth's crust in Slovenia. *Potresi (Ljubl.)*, *2005, 2003*, pp. 99-110.

GRAF, F., KOHL, T., MEGEL, T., RYBACH, L., FUCHS, R. (2001): Hydraulic-Geothermal Modelling of Koralm Tunnel into Rock Mass Classification, Felsbau Bd. 19/6 S. 54-59, Salzburg.

HAENEL, R., ZOTH, G. (1973): Heat Flow Measurements in Austria and heat flow maps of central Europe,Zeitschrift für Geophysik Bd. 39, Würzburg.

HOCHSTEIN, P. M. (1988): Assessment and Modelling of Geothermal Reservoirs (Small Utilization Schemes), Geothermics vol. 17/1, pp. 15 – 49, Oxford.

HORNER, D. R. (1951): Pressure Build-Up in Wells, Proceedings Third World Petroleum Congress – Section 11, pp. 503 – 521, The Hagues.

HURTER, S., HAENEL, R. (EDS.), (2002): Atlas of Geothermal Resources in Europe. - European Commission, Research Directorate-General, Publ.No. 17811, Luxembourg, 92 p., 89 plates.

HURTIG, E., ČERMAK, V., HAENEL, R., ZUI, V. (Editors), (1992): Geothermal Atlas of Europe. – GeoForschungsZentrum Potsdam, Publ. 1, 156 pp., 25 maps.

JELEN, B., RIFELJ, H., BAVEC, M., RAJVER, D. (2006): Definition of the so far existing conceptual geological model of »Mura depression«. Unpublished report (in Slovene), Geological Survey of Slovenia.

KAPPELMEYER, O., HAENEL, R.. (1974): Geothermics with special reference to application. Gebrüder Borntraeger, Berlin, Stuttgart, pp. 238.

KOLLMANN, K. (1980): Steiermark und Burgenland, Veröff. aus d. naturhistorischen Museum Wien – Neue Folge, Bd. 19 C, Wien.

KRALJ, P. (2007): Die Mineralwasserquellen von Bededik, Der Mineralbrunnen Bd. 57/7, S. 222 – 225.

KRALJ, P., RAJVER, D. (2000): State-of-the-art of geothermal energy use in Slovenia. In: E. Iglesias, D. Blackwell, T. Hunt, J. Lund & S. Tamanyu (eds.), Proceedings of the World Geothermal Congress 2000, Kyushu-Tohuku, Japan: International Geothermal Association, pp. 267 – 275. Der Mineralbrunnen Bd. 57/7, S. 222 – 225.

KRALJIĆ, M., LISJAK, L., KASABJI, A., 2005: Poročilo o izgradnji vrtine Benedikt-2 (Be-2). Nafta Geoterm, d.o.o., Lendava.

LACHENBRUCH, A.H., BREWER, M. C. (1959): Dissipation of the temperature effect of drilling a well in Arctic Alaska, Geological Survey Bulletin Vol. 1083 C, pp. 73-109, Washington.

LEBLANC, Y., PASCOE, L.J., JONES, F. W. (1982): A comparison of two methods of estimating static formation temperature from well logs, Geophysical Prospecting Vol. 30, pp. 348 – 357.

NAFTA GEOTERM, (1998 – 2007): Results of temperature and pressure measurements in oil and other wells in north-eastern Slovenia. In: Programs of hydrodynamic measurements in wells in north-eastern Slovenia. Nafta Geoterm d.o.o, Lendava (in Slovenian, unpubl. results).

POLJAK, M. (2007a): Structural-tectonic map of Slovenia in the scale 1:250.000, Geological Survey of Slovenia.

POLJAK, M. (2007b): Structural-tectonic map of Slovenia in the scale 1:250.000 (explanatory notes), Geological Survey of Slovenia.

POWELL, W. G., CHAPMAN, D.S., BALLING, N. & BECK, A.E. (1988): Continental heat-flow density. In: R. Haenel, L. Rybach and L. Stegena (Editors), Handbook of terrestrial heat-flow density determination, Kluwer Academic Publishers, Dordrecht, Boston, London, pp. 167-222.

PRELOVŠEK, P., URAN, B. (1984), Generalised hot wire method for thermal conductivity Measurements, *J. Phys. E: Sci. Instrum*., G. Britain *17*, 674-677.

RAJVER, D., RAVNIK, D. (2002): Geotermična slika Slovenije - razširjena baza podatkov in izboljšane geotermične karte; Geothermal pattern of Slovenia - enlarged database and improved geothermal maps. *Geologija*, *45, 2*: 519-524 Iin Slovenian, with English abstract).

RAJVER, D., RAVNIK, D., ŽLEBNIK, L., ČEBULJ, A. (1995): Utilization of geothermal energy in Slovenia. In: E. Barbier, G. Frye, E. Iglesias, G. Palmason (eds.), Proceedings of the World Geothermal Congress, 1995, Florence, Italy : International Geothermal Association, Auckland, Vol. 1, 321 – 326.

RAJVER, D., RAVNIK, D., PREMRU, U., MIOČ, P., KRALJ, P. (2002): Slovenia. In: S. Hurter and R. Haenel (Editors), Atlas of Geothermal Resources in Europe. European Commission, Research Directorate-General. Publ. No. EUR 17811, Luxembourg.

RAJVER, D., KRALJ, P., ŽLEBNIK, L., DROBNE, F., KRANJC, S. (1994): Structural map of Mura depression, in scale 1 : 100 000. Project: Programme for the efficient energy use and use of renewable energy sources. Unpublished report (in Slovene), Institute for Geology, Geotechnics and Geophysics.

RAJVER, D., LAPANJE, A. (2005): The current status of geothermal energy use and development in Slovenia.In: R. Horne, E. Okandan (eds.), Proceedings of the World Geothermal Congress, 2005, Antalya, Turkey: International Geothermal Association, 24 – 29.

RAVNIK, D. (1991): Geotermične raziskave v Sloveniji; Geothermal investigations in Slovenia. *Geologija, 34*: 265-303 (in Slovenian, with English summary).

RAVNIK, D., KOLBAH, S., JELIĆ, K., MILIVOJEVIĆ, M., MIOŠIĆ, N., TONIĆ, S., RAJVER, D. (1987): Geothermal Atlas of Europe, Yugoslavia, 15 p. + 7 maps. Archive of Geological Survey of Slovenia.

RAVNIK, D., KOLBAH, S., JELIĆ, K., MILIVOJEVIĆ, M., MIOŠIĆ, N., TONIĆ, S., RAJVER, D. (1992a): Yugoslavia. In: E. Hurtig, V. Čermak, R. Haenel and V. Zui (Editors), *Geothermal Atlas of Europe*. Geoforschungszentrum Potsdam Publ., 1:102-104, 152-153.

RAVNIK, D., RAJVER, D., ŽLEBNIK, L., KRALJ, P. (1992b): Geološke strukture: viri termalnih in mineralnih vod v Sloveniji. In: P. Kralj (Editor), Mineralne in termalne vode v gospodarstvu in znanosti Slovenije, III. Posvet, Ljubljana, pp. 9-32 (in Slovenian, with English abstract).

RAVNIK, D., RAJVER, D., POLJAK, M., ŽIVČIĆ, M. (1995): Overview of the geothermal field between the Alps, the Dinarides and the Pannonian basin. *Tectonophysics 250*, 135-149.

RYBACH, L. (1988): Determination of heat production rate. In: R. Haenel, L. Rybach and L. Stegena (Editors), *Handbook of terrestrial heat-flow density determination*, Kluwer Academic Publishers, Dordrecht, Boston, London, pp. 125-142.

RYBACH, L. (1981): Geothermal systems, conductive heat flow, geothermal anomalies. In: L. Rybach, L.J.P. Muffler (Editors), *Geothermal Systems: Principles and Case Histories*. John Wiley & Sons Ltd., Chichester, etc., 3-36.

SADNIKAR, J., JUVANČIČ, V., ŽELEZNIK, B., ILOVAR, S. (1996): Geotermalna raziskava v Okonini.

Technical report of the end of 2.phase, GEOKO, d.o.o. (in Slovenian, unpubl.)

SCHMID, M.S., FÜGENSCHUH, B., KISSLING, E., SCHUSTER, R. (2004): Tectonic map and overall architecture of the Alpine orogen.- Eclog. Geol. Helv., 97/1, S. 93-117, Basel.

SCHUSTER R. (2003): Das eo-Alpine Ereignis in den Ostalpen: Plattentektonische Situation und interne Struktur des Ostalpinen Kristallins.- Arbeitstagung 2003: Blatt 148 Brenner, S 141-159, Geol. B.-A., Wien.

SMITH, W.H.F., WESSEL, P. (1990): Gridding with continuous curvature splines in tension. – *Geophysics, 55, 3*, 293-305.

SOVILJ-LEGČEVIĆ, J. (2001): Catalogue of temperatures in deep wells of north-eastern Slovenia. Nafta Lendava d.o.o., Lendava (in Slovenian, unpubl. table).

ŠAFANDA, J., RAJVER, D. (2001): Signature of the last ice age in the present subsurface temperatures in the Czech Republic and Slovenia. *Global Planet. Change, 29*, 241-257.

WESSEL, P., SMITH, W.H.F. (1998): New, improved version of Generic Mapping Tools released. – *EOS Trans. Amer. Geophys. U., 79*, 47, 441, p.579.

ZÖTL, J., ZOJER, H. (1979): Bericht über die Erstellung einer Karte der geothermischen Tiefenstufe für den Bereich des südlichen Burgenlandes, Bericht Bund/Bundesländer-Rohstoffprojekt B-A-006/79, Joanneum Research, Graz.

ZOJER, H. (1977): Untersuchung der geothermischen Tiefenstufe mittels Temperaturmessungen bei artesischen Brunnen in der Oststeiermark und im südlichen Burgenland, Verhandlungen der Geol. B.A. Bd. 1977, S. 393 – 403, Wien.

Table of supplements

Acknowledgements

The Nafta Geoterm d.o.o. from Lendava as well as the OMV AG and Rohöl Ausuchungs AG are greatfully acknowledged for supplying temperature data of elder and recent measurements in many oil and gas wells within the Transthermal project area.