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Exploration of Geothermal Systems with Petrel Modeling Software

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EXPLORATION OF GEOTHERMAL SYSTEMS WITH PETREL 3D MODELING SOFTWARE

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A 30 credit units Master´s thesis

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ABSTRACT

In this thesis work an area located in Hungary was examined in order to localize the most promising site for geothermal water extraction for use in electricity production or in direct heat utilization systems.

Hungary is located in the central part of the Pannonian Basin. The geological evolution of the basin was favorable for the formation of low- and medium-enthalpy geothermal reservoirs throughout the country. These resources are already used in the balneology and agriculture sector. The utilization of the natural hot water in district heating systems and for domestic hot water supply has been developing fast in the recent years, while electricity generation from geothermal water is still in research phase.

A three-dimensional (3D) digital geological model of the area was created to support the localization of the best prospective site in the area of interest. For the model's construction, eighteen two-dimensional (2D) seismic sections were used as input data. The Petrel geological modeling software, which was developed by Schlumberger Co, was used for data processing.

Three promising sites were designated in the studied area. Those sites were selected where the old deep and young shallower fractured zones cross each other by creating a locally extensional stress field. Due to the difficulties of the interpretation process the presence of the before mentioned requirements are very likely, but not certain, in the designated areas. Further exploration is crucial.

A comparison made between the computer supported analysis and the manual interpretation of hard copies of the seismic sections revealed that computer aided interpretation process lead to the recognition of more detailed tectonic structures in a relatively shorter time interval.

PREFACE

Kalina cycle systems offer a way to extract heat from low temperature sources for the The aim of the work is to delineate the most promising location of geothermal water reservoirs in the study area. The expected parameters of the water should provide the potential for electricity generation and heating. The main tool is the construction of a 3D geological (structural) model of the area with the use of Petrel software. Licensure for the software was provided for this study by the Schlumberger Co.

The model is based on the analysis of 18 2D seismic section lines in SEG-Y digital format, supplemented by geology data from 12 wells provided by PannErgy Hungary and Mannvit Engineering Ltd.

Similar work with the same initial data was made simultaneously with this thesis at Mannvit, Reykjavík with manual interpretation techniques on hardcopy data. This report also aims to make a comparison between the manual and the computer-aided analysis of the input data.

In the first part of this study the geology and geothermy of Hungary will be introduced with a short overview on the market conditions (chapter 2). The second part contains the methodology and detailed processing steps of the 3D model creation (chapter 3). The results of the prospect analysis are presented in the end of the study (chapter 4).

Many thanks go to PannErgy Hungary and the Mannvit Engineering for providing the geological and geophysical data. This study would not have been possible without the generosity of the Schlumberger Co. During the whole study term the support of the RES – School for Renewable Energy Science was indispensable.

The data used in this work is made available by PannErgy Hungary and Mannvit Engineering and is confidential. The results cannot be used in any way without consulting these companies. Because of the confidentiality of this work the location of the study area will not be revealed in the thesis.

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1 INTRODUCTION

1.1 What is geothermal energy?

By the definition of the International Energy Agency (IEA 2007) it is:

“Available as heat emitted from within the earth's crust, usually in the form of hot water or steam. It is exploited at suitable sites for electricity generation after transformation or directly as heat for district heating, agriculture, etc.”

The most important thing to glean from this definition is that geothermal energy is more dependent on the fluid being present and able to circulate than on the temperature of the rocks. There are several areas near the Earth’s surface where one can find appropriate temperatures, but they are not exploitable due to the absence of carrier fluid. The temperature in the Earth’s crust increases downward with an average of 30°C/km, but to bring this heat to near-surface (up to 3000 m, in extreme cases 4000 m) depths, fluid needs to be present and circulate to transfer the heat from the rocks.

A rather wide range of utilizations and reservoir types come under the definition above. One type of classification divides the geothermal fluids into high- and low-enthalpy geothermal resources, but the specific temperature for the division differs with countries. The most prevalent is 150 °C; low enthalpy fluids have reservoir temperatures lower than 150 °C and high enthalpy fluids have higher than 150 °C. In some sources the medium-enthalpy fluids refer to 100 – 200 °C water temperature.

High-enthalpy fluids are located in the vicinity of volcanically active plate margins, i.e. subduction belts (for example Indonesia, Costa Rica, Italy), oceanic or continental rifting zones (Iceland, Azores, East African ridge) and near hot spots (Hawaii). Reservoir types like steam dominated reservoirs, liquid dominated reservoirs and hot dry rock belong to this group. The utilization of these types of fields started in this order, the hot dry rock reservoir type is still in the development phase.

Low-enthalpy (or low temperature) reservoirs are characterized by wider and denser distribution in the Earth’s surface. These resources are usually utilized directly as heat, for example in district heating systems or for domestic hot water. With binary type power plants this resource can also be used for electricity generation, but in a much less economical way than high- or medium-enthalpy fluids.

Ground source heat pumps can also be considered as low temperature geothermal energy utilization systems, although some of them only use the energy of the Sun, balanced by the soil (shallow-shallow or horizontal systems).

Low temperature water resources (even less than 30 °C, the limit of thermal water in Hungary) can be used for heating purposes through heat-pumps. Heat pumps use electricity to transfer heat from a colder medium to a warmer one. The Coefficient of Performance (COP) describes how many units of thermal energy are created with the use of one unit of electrical energy.

The energy that is stored in the Earth’s interior is enormous. About 99% of the Earth’s mass is more than 1000 °C and only 0.1% is colder than 100 °C. The sources of the Earth’s heat are twofold. On the one hand it conducts from the 4-5000 °C core towards the surface through the layers of the Earth. The last hot layer below the cooling lithosphere is the asthenosphere, where the temperature is more than 1000 °C. The other source of the Earth's heat is the radioactive decay of Uranium, Thorium and Potassium. This process takes place in the external layers of the Earth, at depths less than 200 km below the surface. Those sources create an average temperature gradient of 30 °C/km.

Geothermal energy is a diffused resource like many other raw materials. It can be used economically where it is enriched. Enrichment usually occurs at those areas where the temperature gradient is higher than in general, principally at high-enthalpy fields along tectonic plate boundaries, but also in low-enthalpy reservoirs where the temperature gradient is elevated due to the relative proximity to a heat source.

Geothermal energy is usually considered to be renewable, although it can be overexploited if the fluid, which carries the heat, is not recovered by natural or artificial recharge. Continuous pressure drop signifies this phenomenon. The other way to damage the reservoir is to cause changes in the reservoir dynamics that lead to the cooling of the reservoir. The best way to avoid these problems is regular monitoring that can forecast or indicate any changes in the system in time. The Orkustofnun Working Group, Iceland (2001) suggested a definition for renewable use of geothermal resources: "For each geothermal system, and for each mode of production, there exists a certain level of maximum energy production, below which it will be possible to maintain constant energy production from the system for a very long time (100-300 years)".

1.2 Why Hungary?

The World Energy Council (WEC 2007) wrote of Hungary:

"Hungary possesses very considerable geothermal resources and it has been estimated that the country has the largest underground thermal water reserves and geothermal potential (low and medium enthalpy) in Europe."

There is no electricity generation from geothermal energy in Hungary yet, but several feasibility studies have been conducted in the last few years to estimate the potential of geothermal electricity generation. All surveys showed that the potential is there, it is only waiting to be exploited.

Hungary has good geothermal capabilities because of the elevated heat flow (Figure 1.1). One can experience 90 – 120 mW/m^2 heat flow, whereas the world average is around 60 mW/m^2. This phenomenon can be explained by the thin crust and lithosphere below the Pannonian Basin (Figure 1.2). The use of geothermal energy is not new for the people living in this area. The Romans already used the hot springs for bathing in 100-300 A.D. as did the Turks in the 16th century. Currently there are more than 200 thermal spas throughout the country and since the 1960s the hot water has been widely used in agriculture as well. In terms of installed thermal capacity, Hungary is in the first five countries in Europe. Although there are plenty of usage possibilities, the usage is restricted to agriculture and balneology. The efficiency is rather low and the used, but still warm water is released without any post-processing, which pollutes the surface waters.

To understand the reason for this situation, the geology of the area has to be examined (see page 4). It is also important in order to delineate the best prospective sites.

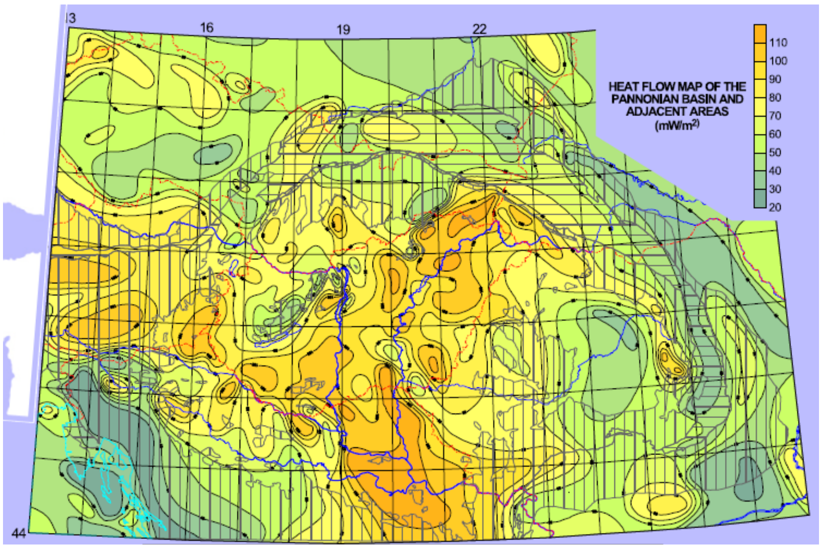

Figure 1.1 Heat flow map of the Pannonian Basin (source: Geothermal Power Project (GPP) 2003-2005)

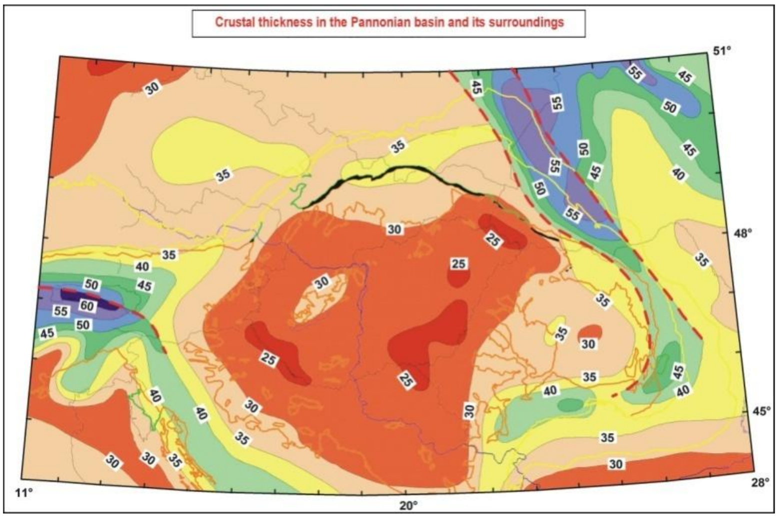

Figure 1.2 Crustal thickness of the Pannonian basin (source: GPP 2003-2005)

2 HUNGARY – THE COUNTRY OF SPAS

Hungary is located in the Pannonian Basin in Central Europe (Figure 2.3). Its high capability for geothermal energy related utilizations originates in that fact. The basin was formed during the Alpine-Himalayan orogeny (mountain buildup) and it is a so called back-arc roll-back basin. The term back-arc refers to the location of the depression compared to the arc, the mountain chain that created in the orogeny by collision of two continental plates. The term roll-back refers to the mechanism of the basin formation. The solid surface of the Earth consists of continental and oceanic plates. These plates are floating on the asthenosphere. They are independent rigid units, and they can move against each other. If a continental and an oceanic plate collide by plate tectonic movements, the oceanic plate moves under the continental plate and sinks into the Earth's mantle. The angle of the subduction grows during the subduction due to asthenospheric flows and the changing density of the oceanic plate. The hinge on the oceanic plate moves backwards. This will pull the continental crust in the direction of the oceanic plate and it will cause extension on the continental plate (Figure 2.1). As a consequence of the extension, the continental crust and the underlying lithosphere of the Pannonian Basin thinned, and the hot asthenosphere got closer to the surface creating an elevated thermal gradient in the area of the asthenosphere dome (Konecny et al. 2002). In favorable geologic situations this elevated thermal gradient can create hydrothermal resources – i.e. water reservoirs with high temperature and sufficient capacity.

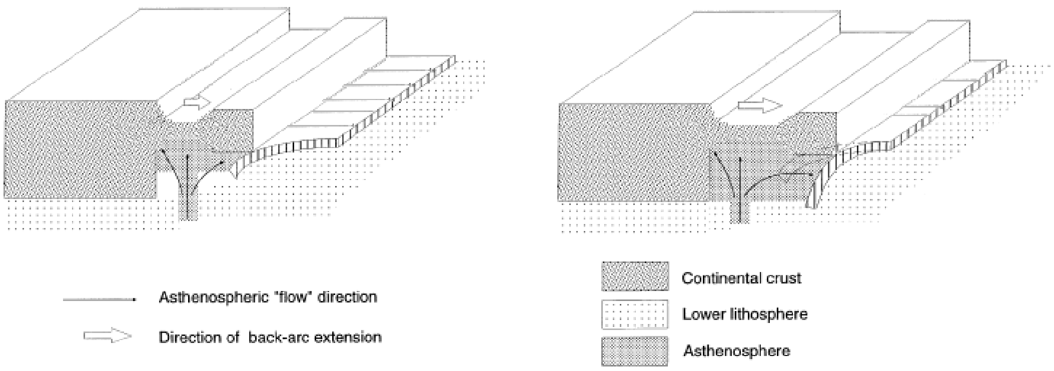

Figure 2.1 Roll-back mechanism (modified after Gelabert et al. 2002)

2.1 Geology of the Pannonian Basin

In the case of geothermal water reservoirs, a favorable geological settings means a high porosity reservoir formed by hot rocks with (possibly circulating) water in it, a thermal insulation above this complex to keep it hot and all these things as close to the surface as possible. In Hungary, the relatively hot temperature is present due to the increased thermal gradient, while mainly two geologic formations have sufficient porosity to become a good aquifer, the fractured Mesozoic and older basement rock – principally Triassic limestone and dolomite – and Upper Pannonian sandstones. These structures formed tens of millions of years ago. To become acquainted with the formation of these structures the geology of the area must be examined starting from the beginning of the Mesozoic (Figure 2.2).

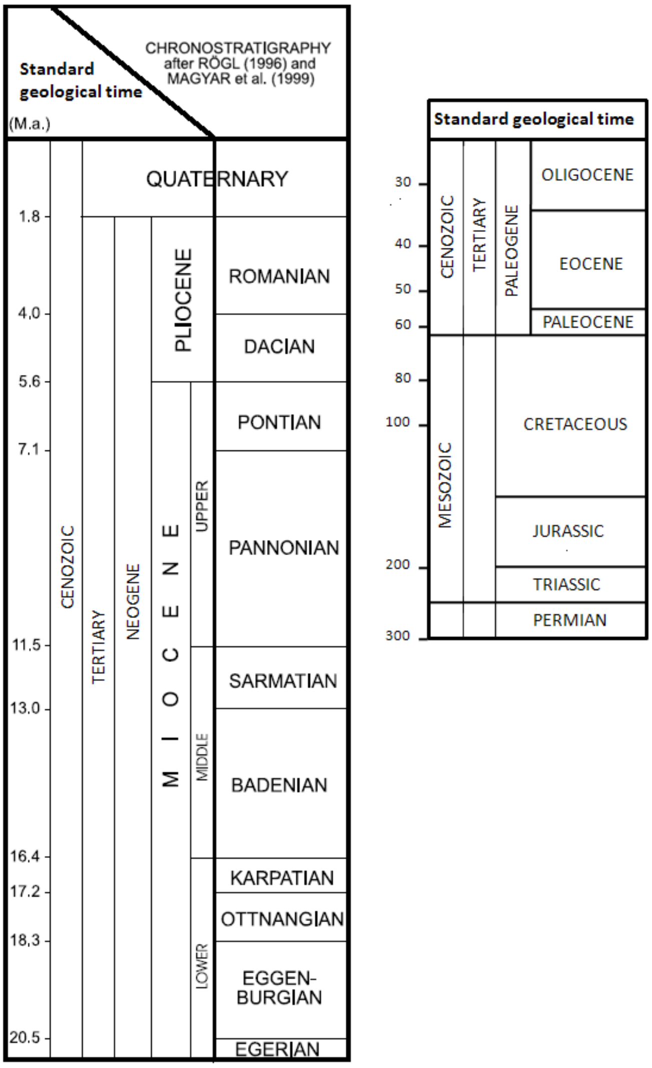

Figure 2.2 Standard international geological time scale and Central Paratethys stages

The Pannonian Basin is surrounded by several mountain chains with an average elevation of 2000-3000 m. These mountains form a circle around the basin and are called (from the North clockwise) Eastern Alps, Western Carpathians, Eastern Carpathians, Southern Carpathians and Dinarides. The basin and the mountain chains around it were formed in the Alpine-Himalayan orogeny, when the European and the African continents were colliding.

The basement of the Pannonian Basin is built up from numerous individual tectonic blocks or plate fragments. These blocks moved individually; sometimes they collided by creating a bigger block or sometimes they detached from a bigger block. The story starts about 250 million years ago and covers the evolution of these tectonic blocks and the oceans that formed between them. A detailed description of the processes can be found in Csontos & Vörös (2004), Csontos (1995) and Schmid et al. (2008).

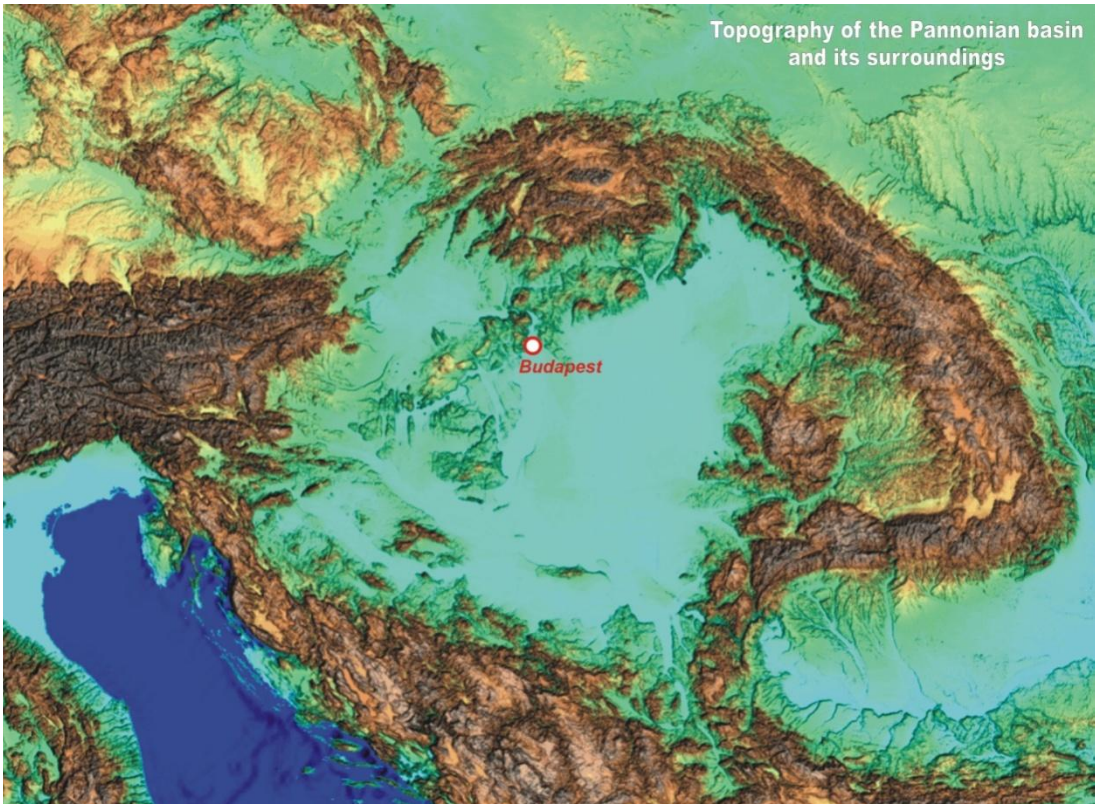

Figure 2.3 Topography of the Pannonian Basin

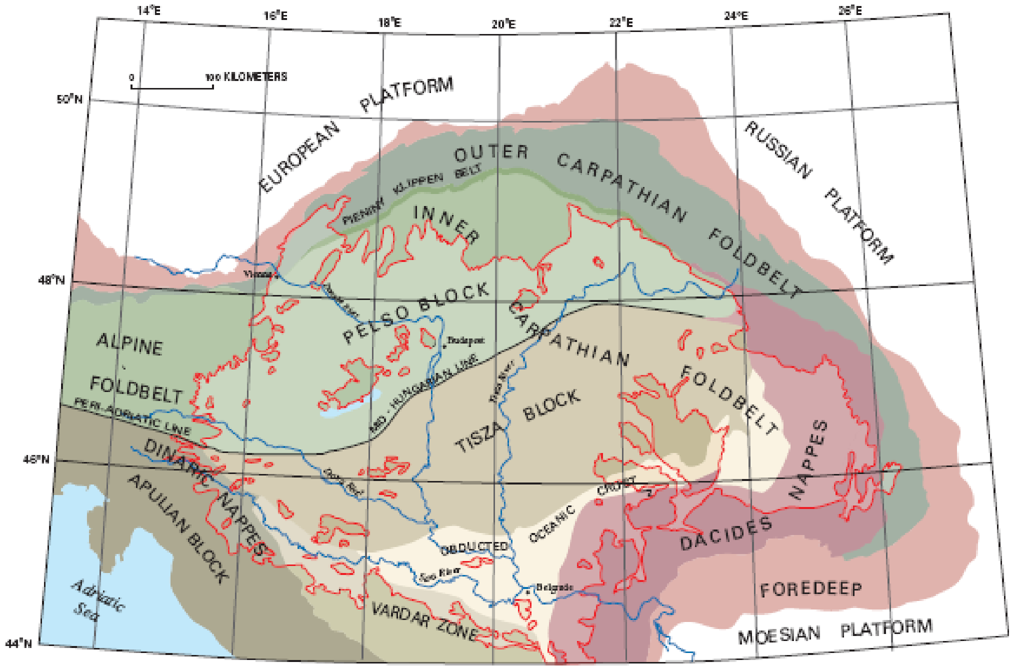

Figure 2.4 Tectonic units of the Pannonian Basin (source: Dolton 2006)

At the beginning of the Mesozoic one big supercontinent existed on the surface of the Earth and this supercontinent had a big bay on its eastern side (Figure 2.5). A whole ocean fit in this bay, and its name was Tethys. This ocean spread along a rift zone in the middle of the bay. The rift zone shifted more and more to the west and cut into the supercontinent.

It broke away small microplates. The oldest rocks in the basement of the Pannonian Basin originate from the supercontinent through these microplates. Above these old rocks – during the evolution of the microplates – younger formations deposited. The spreading continued between the cut microplates and new oceanic crust was created between them. The Triassic was an undisturbed geological interval in terms of tectonic activity. The sedimentation was undisturbed for a long time and in the shallow marine environments, where the sedimentation was the fastest, several kilometers of limestone and dolomite formed. Besides some younger sediments and older crystalline rocks, these carbonates can mostly be found in the study area below the basin fill. Triassic carbonate formations are important in today's geothermal exploration because these rocks host the geothermal waters of the basin basement. In their original conditions these formations have low permeability, but that can be drastically increased if the formation has secondary porosity due to fractures and fissures.

The tectonically relaxed period continued in the Jurassic, but due to the spreading process many fragments of the Pannonian Basin basement ended up in deep marine environments. The sedimentation in those areas continued in a lesser extent (Figure 2.6).

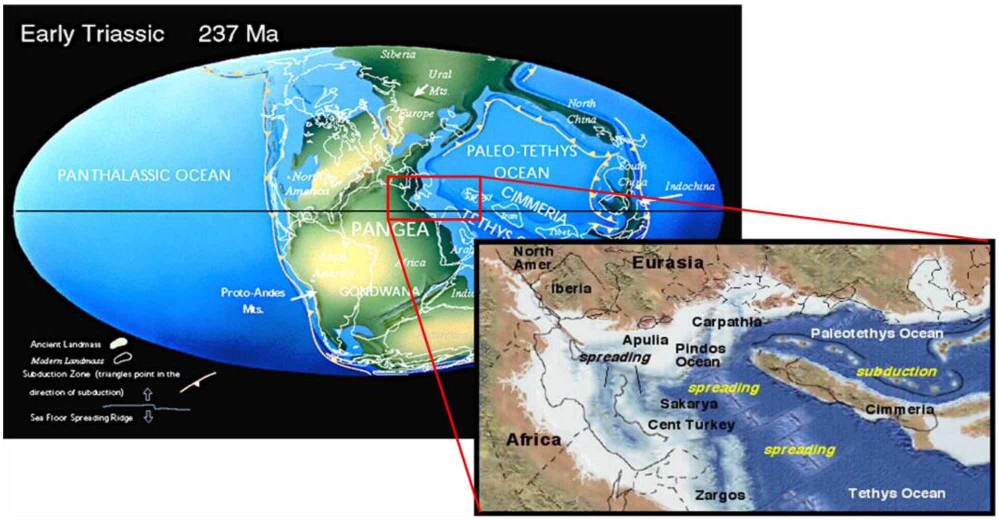

Figure 2.5 Continent arrangement in the Triassic (modified after Scotese n. d. and Sedimentation, Tectonics, and Paleogeography of Southern Europe and the Mediterranean Region)

In the Middle Jurassic a tectonically active age started in the studied area. At that time the ancient Atlantic Ocean started to form west of the bay of the Tethys Ocean. This event induced compression in the Mediterranean region and inhibited further spreading. Compression and subduction of the newly formed oceanic lithosphere took place. The oceans disappeared, but the remnants of the oceanic crust in some mountain chains indicate their former existence (Pamic et al. 2002; Schmid et al. 2008).

The other important process at this time is thrusting. Due to the enormous forces at work in those areas, the thick rock layers of the continental crust fold and thrust. Nappes formed if only the upper layers of one plate thrust upon the continental basement of the other plate.

In the Cretaceous the plate fragments of the study area were also affected by the consequences of regional compression. Complex nappe structures evolved and some areas were uplifted, which caused the erosion of the Cretaceous and Jurassic sediments (Figure 2.6).

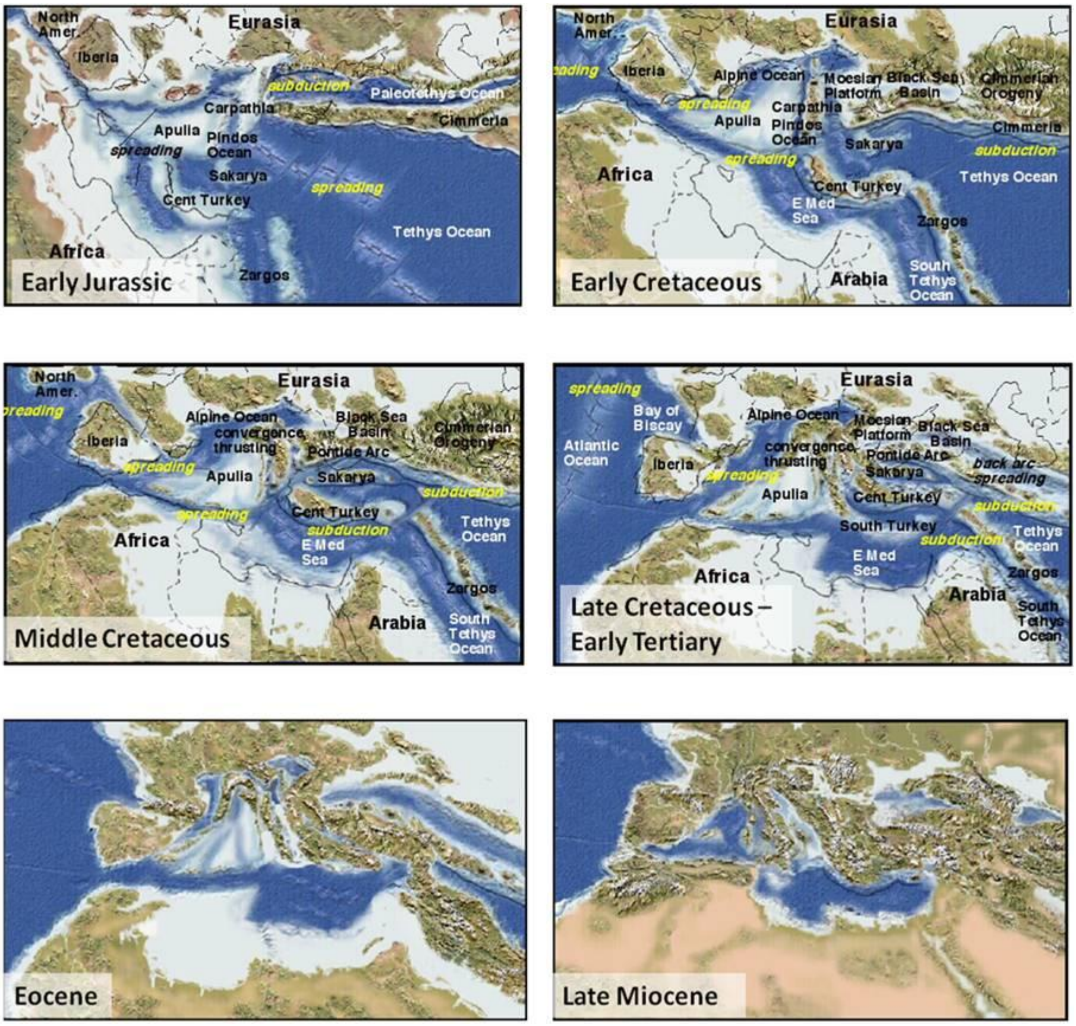

Figure 2.6 Structural evolution of the Mediterranean Region from the Mesozoic (source: Sedimentation, Tectonics, and Paleogeography of Southern Europe and the Mediterranean Region)

By the end of the Cretaceous the two roughly rigid blocks that compose the basement of Hungary welded from smaller crustal fragments and nappes. The currently Northern terrain is called Alcapa (Alps, Capathians, Pannonian), and the southern is called Tisza-Dacia. At the end of the Cretaceous the two terrains were separate, and they evolved in a different way until the end of the Paleogene, when they were squeezed into each other due to the ongoing compression stress in the area. ENE – WSW striking thrust faults formed, right lateral shift and calc-alkaline volcanism occurred along the contact zone, called the Mid-Hungarian Line (Figure 2.4). Most of the sediments that deposited in the Tertiary eroded at that time, except the ones in the deep Paleogene basins. These basins formed during the Paleogene or they were inherited from the Mesozoic. (end of Paleogene – beginning of Miocene)

The study area is located along this crustal scale boundary surface. The Mid-Hungarian Line was the zone of continuous tectonic activities from that time, which also had an intense effect on the neighboring formations of the study area.

The ongoing compression forced the two – and from this time similarly developed – terrains into the Carpathian bay. At the beginning of the Miocene an ocean existed in that bay, with oceanic crust. The terrains shifted to the east and that triggered the subduction of the oceanic crust, while the subduction generated a considerable extension in the lithosphere and the crust of the terrains, due to the roll-back effect. The approximately E – W orientated extensional stress field caused the formation of roughly NW – SE striking normal faulting with ENE – WSW striking transfer faults; and later ENE – WSW striking normal faults with NW – SE striking transfer faults. 3 – 6 km deep sub basins and uplifted basement highs formed in the Pannonian Basin due to this activity. At the same time the Carpathian mountain chain suffered thrusting and uplift (Horváth & Royden 1981; Linzer et al. 1998). At that time the Paratethys occupied the area of the Pannonian Basin. It was a detached part of the Tethys with occasional connection to the main water mass. Sedimentation went on in different environments, ranging from terrestrial to marine, where different sedimentary layers deposited – fault related breccias, carbonates and shales (Saftic et al. 2003 and references therein) (Early – Middle Miocene).

In the Middle Miocene the extension due to the roll-back effect ceased and a much relaxed thermal subsidence started. This is a passive subsidence process due to the cooling of the lithosphere that was warmed up in the previous roll-back extension phase, when the hot asthenosphere created domes below the thinned lithosphere of the Pannonian Basin. From the recently uplifted Carpathian mountain chain vast amounts of clastic erosion detritus deposited in the continuously subsiding basin. At this time, the lake Pannon covered the area that was filled up with a large amount of sediments by the end of the Neogene in the Upper Pannonian stage. This lacustrine deltaic sandstone formation is the thickest basin fill formation that deposited in the Tertiary in the Panonian Basin. It can reach 3000 m in the thickest parts, while the whole basin fill is up to 6000 m in the deepest sub basins (

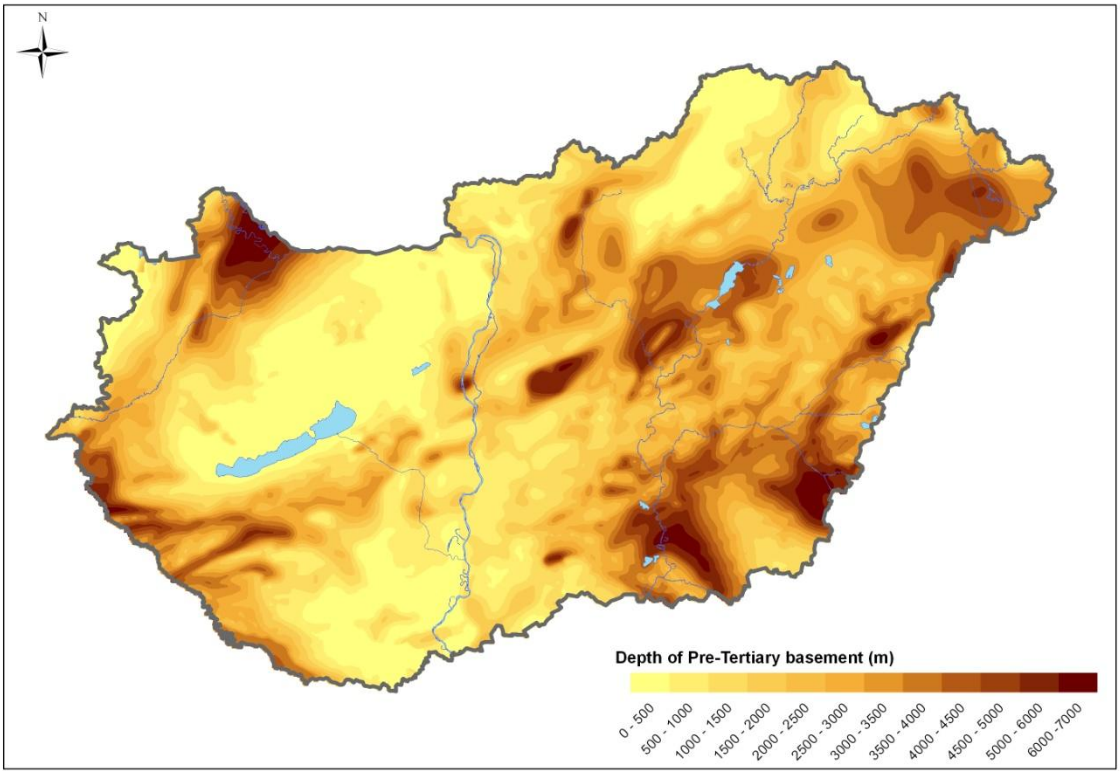

Figure 2.7). This formation has good reservoir characteristics and with thick overlying younger aquitard clayish sediment layers – that insulate the hot water from the cool surface waters – the stored water also has high temperatures. The thickness of the sediment fill is also important for geothermal utilizations. The sediment layers have lower thermal

conductivity than the crystalline or carbonate basement formations and cap the heat of the Earth better than the basement rocks.

Several basin inversion intervals interrupted the thermal subsidence of the basin. During these events the basin was uplifted but not uniformly, with some parts of the basin being uplifted more than other parts. The best preservation in the geological strata occurred at the end of the Middle Miocene, before the Pannonian age. The deposits of the Pannonian start over an erosion unconformity that marks this period in the geological cross-sections. At least one more inversion period occurred according to Horváth (1995), Csontos et al. (2002) and Saftic et al. (2003). It can be characterized by E-W oriented compression and corresponding NE – SW striking deformation belts. The recent stress field (Bada et al. 2007; Fodor et al. 2005) is also compressive. It is NNW – SSE oriented and causes ENE – WSW striking reverse faulting.

The inversion periods are also important in the evolution of the study area. At those periods older normal faults could reactivate. In some part of the area the stress field locally changed, while in other parts – where the inversion had less effect – the preceding processes continued. In the uplifted areas erosion took place that created an unconformity in the sediment succession.

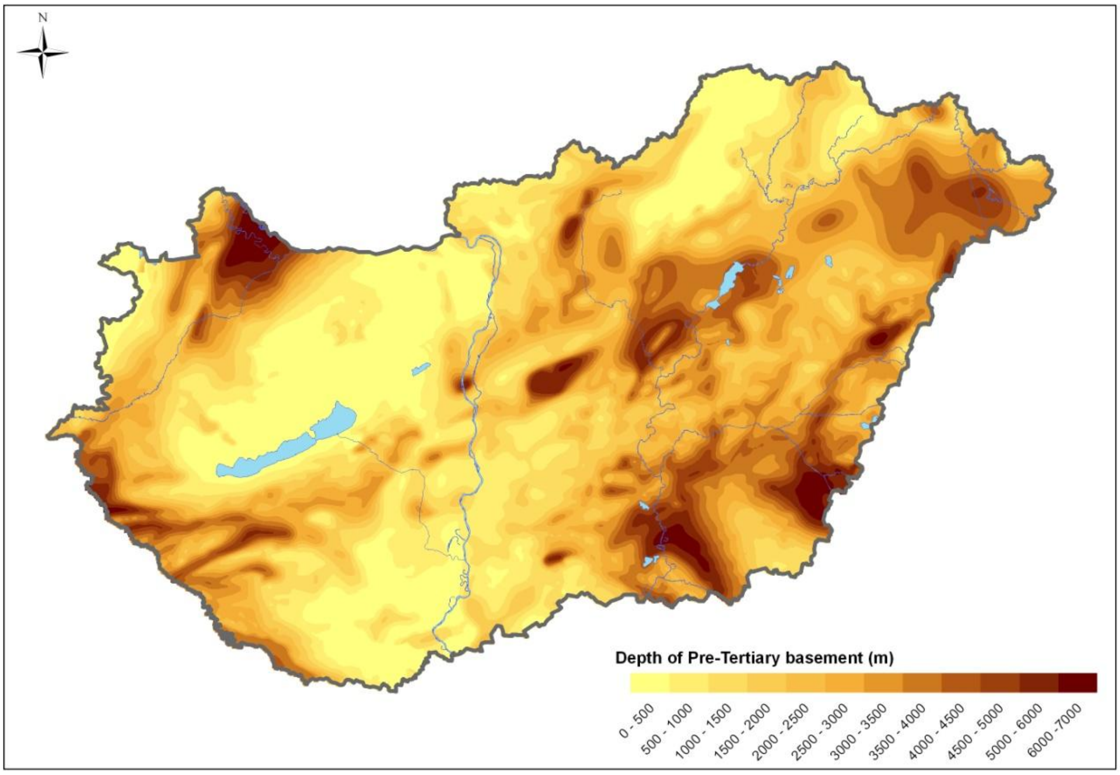

Figure 2.7 Depth of the pre-Tertiary basement in Hungary

2.2 Past, present and future prospects of geothermal energy in Hungary

It is clear from the geologic and geographic description that possibilities for Hungary in the field of geothermal utilization are extensive due to the enlarged geothermal gradient in the Pannonian Basin and the presence of rock formations with good reservoir characteristics.

The total reservoir volume beneath Hungary is estimated to be 4000 km^3, from which 200 km^3 is in the fractured Triassic and older reservoirs and 3800 km^3 is in the Pannonian strata. The effectively renewable reservoir volume with reinjection – i.e. the total volume of natural and artificial recharge – is estimated to be 380 million m^3 annually, which means 63.5 PJ of thermal energy with an average utilization step of 40 °C. No assessment for geopressured reservoirs has been made (Árpási 1995a and references therein).

Total primary energy consumption for Hungary was 11000 PJ in 2004, yet in spite of the vast geothermal resources only 2905 TJ (2.9 PJ) came from direct geothermal use as of 2003 (agricultural, industrial and residential use, without drinking water and balneology) with 342.5 MW_t of installed capacity and 36% capacity factor (Árpási 2005). The distribution of the total energy use between the utilization sectors can be seen in Table 2.1. The agriculture sector is the major consumer of the geothermal heat at about 195 MW_t installed capacity (Árpási 2005), with a traditionally seasonal usage. Heat is used for greenhouse-heating, heating of animal-houses, meat-drying, fish-breeding, etc. (Bobok & Tóth 2003)

An additional 350 MW_t installed capacity and 5040 TJ annual energy use was estimated by Lund (2005) in the balneology sector for 2004. In 2004 there were more than 260 spas in Hungary. Many of them are well-known, such as Budapest, Bük, Hajdúszoboszló, Harkány, Hévíz, Sárvár, Zalakaros, etc.

From the beginning of the 1990's to 2004 the distribution between the sectors changed a bit, whereas the total amount of the utilized geothermal energy only slightly increased, mostly at the end of the period. During this time interval the share of the agriculture sector fell from more than 60% to about 50%. (Árpási 1995a, 2005), while the rate of the space heating and sanitary hot water increased from 3% to 34%. Many new thermal spas were opened in this period, but unfortunately only some of them (altogether 10 at the end of 2003) used the exploited heat for direct uses beside the balneology. The changes of the shares of different sectors from the geothermal direct utilization from 2002 to 2004 are shown in Table 2.1.

Table 2.1 Geothermal direct heat utilization by sectors in 2002 December and 2004 January (source: Árpási 2003, 2005)

geothermal heat utilization (direct use of geothermal energy)		Agriculture	Space heating and sanitary hot water	Other	**Total**
thermal water production (million m^3/year)	2002	12.497	5.65	3.37	**21.525**
	2004	10.498	12.398	3.370	**22.9**
	change %	*-16.0*	*119.4*	*0.0*	***6.4***
installed geothermal capacity (MW_t)	2002	206.67	73.11	44.79	**324.57**
	2004	195.1	103	44.6	**342.5**

	change %	*-5.6*	*40.9*	*-0.4*	***5.5***
utilized geothermal heat (TJ/year)	2002	1785	631	386	**2804**
	2004	1501.8	1016.7	386.8	**2905**
	change %	*-15.9*	*61.1*	*0.2*	***3.6***
average utilization step (ΔT)	2002	34.1	26.6	27.4	**31.1**
	2004	34.1	27.0	27.4	**31.0**

In 2005 10 spas and 130 organizations utilized geothermal heat directly and another 45 settlements used geothermal heat (Árpási 2005). About 9000 flats in 9 cities were heated by geothermal district heating systems. (Bobok & Tóth 2003)

Some other industrial usages of geothermal heat can be found in the oil industry.

Due to the unequal spatial evolution of the basin and the basement, different kinds of geothermal reservoirs have been formed in the Pannonian Basin. In the troughs the Upper Pannonian sandstone aquifers are predominant with thick overlying sediment layers. Plenty of thermal water and hydrocarbon reservoirs have already been found in this formation. The surface water temperatures from this layer range from 30 °C to more than 100 °C (based on data from existing wells (Lorberer n.d.), depending on the thickness and the thermodynamic properties of the overlying sediment, the depth of the astenosphere, the local heat flow and the thermal conductivity of the rocks.

Geothermal waters from the Triassic carbonate reservoirs at the base of the basin have surface temperatures from 30 °C to 170 °C. The primer porosity of these rocks is quite low, 3 -5%, but the secondary porosity due to fractures and fissures can be much higher. Where the base of the basin is close to the surface it is worthwhile to search for geothermal waters in the basement rock. These basement highs were explored – from the 1960s – with hydrocarbon exploration wells dug by the Hungarian Oil company. Many of the recently active wells that tap the geothermal water reservoirs in the basement formations were originally drilled as a hydrocarbon exploration wells.

These types of reservoirs correspond to the low and medium enthalpy reservoirs. The exploited heat can be used for electricity generation (through ORC or Kalina cycle, where surface temperatures are more than 100 °C) and for direct use, such as district heating, domestic hot water supply and other industrial and agricultural uses.

Geopressured type reservoirs are present in the southeastern part of the country. It was proved in the 1980's, when deep wells were drilled in the area of Fábiánsebestyén – Nagyszénás. The well FÁB-4 blew out at the end of 1985. The duration of the blowout was 47 days, while the wellhead pressure (360 bars) and the flow rate (80kg/s) remained constant. The wellhead temperature was 160-170 °C (Bobok & Tóth 2003). In this type of reservoir the pressure of the closed fluid (lithostatic pressure) is higher than the hydrostatic pressure at this depth. It can be formed when a fluid-saturated rock formation with high porosity (in this case Middle Triassic brecciated dolomite) is buried by sediment layers. If the sedimentation process is quicker than the speed with which the closed water can escape from the formation rock – into directions of lower pressure – the water will be buried together with the formation that enclosed it. This kind of reservoir is practically closed, therefore the long term utilization is impossible without reinjection. Two other geopressured reservoirs were explored by wells in the area (Nagyszénás-3, Álmosd-13), and several more possible reservoirs were proved by magnetotelluric surveys (Árpási et al.

2000b). The fluid of these reservoirs is usually enriched in dissolved solids and hydrocarbons (CH_4). Both of them have to be separate from the main fluid mass in order to start the commercial utilization of this resource. The non-condensable gases can cause problems in the condenser while the dissolved solid content can cause scaling problems – mainly in the beginning and at the end of the overall process. The separated CH_4 gas can then be used to increase the efficiency of the thermodynamic cycle by creating more heat with its combustion. The control of the high pressure fluid is another problem which has to be solved before any power plant could run on this resource.

2.2.1 History of thermal water in Hungary

(after Bobok & Tóth 2003 and Lorberer 2002, n.d.)

The history of Hungarian thermal water utilization goes back to ancient times. The warm karstic natural springs were utilized for cooking, bathing and washing by every nation that lived in this area. The first tangible pieces of evidence do, however, come from the Romans. The first spas that utilized the thermal water around Budapest were built by the ancient Romans. The first spas in the eastern part of the country were built some centuries after the Hungarians settled down in the Pannonian basin. Many of the present spas (Rác spa, Király spa and Lukács spa in Buda and the Turk spa in the city of Eger) were built by the Turks during the Turk occupation, in the 16^{th} – 17^{th} century. The first wells were drilled in order to expand the amount of the water in the spas in the 19^{th} century. The natural springs of the old spas are located near the piedmont of karstic mountains. The first artificial wells were located in the vicinity of the natural thermal springs. Some of the early thermal wells that were drilled in the basin area were drilled for water supply. A big effort was made by Vilmos Zsigmondy, the legendary drilling engineer who in 1877 drilled the deepest well in Europe, in Budapest. The work lasted for 10 years, but finally at the depth of 971 m the drilling stopped and tapped 74 °C water in the karstic layers of the Buda natural springs (Csordás 2004). Between the two World Wars hydrocarbon exploration wells were drilled and sometimes revealed huge thermal water reservoirs. The water of these reservoirs was utilized in spas. The extended research for hydrocarbon reservoirs provided new data for the geothermal "industry" as well. Boldizsár recognized the high heat flux and geothermal gradient of the basin and new types of reservoirs – without surface manifestations – were found in the deep basin sediment fill layers and in basement highs.

The first district heating project also took place between the two World Wars. Some houses and the Budapest Zoo (which is close to the drilling site, where Vilmos Zsigmondy drilled) were heated by thermal water. In the late 1950's new district heating projects were started in southeast Hungary (Szeged, Szentes, Makó, Hódmezővásárhely).

From the end of the 1950's until the end of the 1980's several thermal water wells were drilled in the country for the use of the agriculture sector, industrial sector and balneology. The peak period was in the first half of the 1970's when almost 100 geothermal wells were drilled. The geopressured reservoirs of Fábiánsebestyén area were discovered at that time as well. During the 1990's the development slowed down due to the closure or privatization of the state companies that supported such projects.

2.2.2 Present situation of the Hungarian geothermal sector

As of 2008 there were 1372 thermal water wells in Hungary. About 2/3 of these wells are active. A total of 270 wells and about 120 natural springs are used in spas and pools.

Altogether 385 settlements operate some kind of spa or pool that is served by thermal water (Egészségturizmus n.d.). Besides the thermal water wells, about 10000 CH exploration and production wells were drilled in the country. From those about 3000 are apparently closed. The Hungarian Oil Company (MOL Nyrt.) made a study to find out if any of those wells are suitable for geothermal doublets, (doublets – well pairs for production and reinjection). They found out that after reconstruction works about 800–1000 wells are suitable for geothermal water production, 70–80 of them with a temperature higher than 100 °C (Árpási 2005). They suggested the 3 most promising sites for pilot projects (Andráshida-Nagylengyel, Mélykút-Pusztamérges, Fábiánsebestyén-Nagyszénás). For those sites the MOL Nyrt. had already made pre-feasibility studies, and those gave positive results (see table 4 in Árpási et al. 2000a). The company started well tests at the Iklódbördőce area in 2007, but the yield was not sufficient for economically feasible electricity generation (Kujbus 2008).

2.2.3 Ground source heat pumps

Although a Hungarian engineer, László Heller had an important role in the spreading of heat pumps, heat pumps are not prevalent in Hungary. In 2004 there were only 4 MW installed in Hungary. By 2006 this number had increased to 15 MW (Geothermal Energy Barometer 2007), which is still very low compared to Austria which, for example, has 664.5 MW installed capacity, a bordering country to Hungary with 10% less population. The reason for the low utilization might be the fact that the Hungarian government hardly subsidizes the investment costs of heat-pumps, while natural gas is greatly subsidized.

2.2.4 Geothermal energy – pros and cons

There are several problems concerning the geothermal heat or electricity utilizations in Hungary.

- The systems that already use geothermal resources are outdated and operate with low efficiency.
- The still relatively hot waste water is usually drained into surface waters without any cleaning or cooling. This can affect the environment in a very negative way due to the usually high TDS of the waters from deep wells (including salts, heavy metals, toxic elements) and the warming of the natural surface waters.
- In the balneology sector, the situation is the same or sometimes worse. In some cases the water is too hot for bathing and it is cooled down by cold water. Not only is the excess energy of the exploited hot water not utilized, but a lot of cold water resources are polluted with heat and chemicals.
- Energy-cascading systems are not prevalent, although the heat content of the water would allow it.
- The individual reservoirs are sometimes overexploited with a pressure decrease of some 7 bars in 70 years (Bobok &Tóth 2003). The originally artesian wells of the Great Hungarian Plain are in need of artificial pumping.
- Reinjection is not used in the country (excluding the system of Hódmezővásárhely and some industrial utilizations in the oil industry). The problem of reinjection into the Upper Pannonian clastic reservoirs is problematic because of the plugging of the pores, but there are no technical barriers for reinjection into the karstic basement reservoirs.
- Only the renewable part – the dynamic resources – should have been extracted.

- Regular monitoring and well tests are still not in use. For the best results in reservoir management and maintenance there should be a centralized monitoring system, because different wells very likely tap the same reservoirs. If this is the case the monitoring and managing of these wells should be done together in order to avoid overexploitation of the common reservoir.
- Government subsidizes geothermal development very scarcely, and does not subsidize geothermal development projects or studies.
- Government subsidizes residential gas prices.
- Legislation of geothermal energy is complex. It is legislated in several laws (Mining Law, Electricity Law, Environmental Law, Water Management Law) although in a very contradictory and unorganized manner.
- Geothermal energy for electricity generation is not directly regulated by the law.
- The fixed acceptance price for renewable energy is higher than the cost of electricity generation from gas, but it is still under the cost of geothermal energy based electricity.
- Every phase of the geothermal energy project is taxed. Land use, water use, use of heat content and water discharge into surface waters are also taxed. Due to these taxes geothermal energy projects have long payback periods, which immensely slow down investment into this sector.

In the last few years however, the number of investments has started to grow. The EU goal to increase the share of the renewables in the energy pie to 20% in 2020 had some results in the Hungarian subsidy system too. The government subsidizes any kind of energy-saving related projects up to 30%, although the total money spent on the projects could have been higher. The target number for Hungary is 7.2% in 2010, while in 2008 the same index number was 3.6%.

People also get more and more information on the possibilities of renewable energy, and they are enthusiastic on new renewable technologies. For example in the last 3 years at least 10 more settlements started exploration work in order to create geothermal district heating systems, and in 3 cases the system is already running. Other types of geothermal energy based investments have also started.

- The heat content of discharged hot water is used in Harkány and Zalaszentgrót. Tiszaújváros spa uses the heat content of the excessively hot water directly for heating, while at Bük, heat exchangers are used for the same purpose. More spa and pool managers are starting to think about cascade utilization, because it could make profit for their business.
- New residential and office buildings are heated with ground source heat pumps with borehole heat exchangers (Tulipán residential building block and Pannon office building). Other types of heat pumps are also more prevalent.
- New energy-efficient utilizations started in the industrial sector, as well. For example new meat-drying plants in Szekszárd and Kalocsa, fish-farming in Győr, multistage utilization in greenhouse-heating in Szentes.
- There is a big effort being made to build up the first geothermal power plant in Hungary. Beside the pre-feasibility study of the MOL Nyrt., another similar study was carried out in 2003-2005 for the purpose of developing an integrated feasibility study on installing a small-scale geothermal power plant in Hungary. The project was coordinated by the Hungarian company Geonardo Ltd. and it was supported by the ALTENER II – Energy Framework Programme of the EC. Geological, technical, economical and legal aspects of a small-scale power plant were analyzed, and also

new maps of geothermal properties and geothermal resources of Hungary were created within the confines of the project. (Geothermal Power Project 2003-2005)

- MOL Nyrt. recompleted an abandoned HC well doublet in the Iklódbördőce area and started the first well tests in the beginning of 2007 in order to investigate its potential for geothermal energy generation. Unfortunately the yield of the well was not enough for economical electricity production (Kujbus 2008).
- The next drillings start in 2009 by PannErgy.
- Since 1990 reinjection of used thermal waters is obligatory for every new well. Waters should be pumped back into the same reservoirs from which they originated. This is still a problem for Upper Pannonian clastic reservoirs, although the solution may be close. A reinjection experiment was carried out in Szeged with positive results, and the district heating system of Hódmezővásárhely has been running now for 7 years with reinjection and they have not experienced the plugging mechanism.

Although there are positive signs in geothermal development in Hungary and cost– and energy–efficient systems already exist, there is no comprehensive information system available for the public, which could stop the spread of misinformation. The lack of such a system is detrimental to prospective geothermal projects.

3 BUILDING A THREE-DIMENSIONAL MODEL

A prospect analysis of an area located in Hungary along the Mid-Hungarian Line was made in order to determine the most promising sites for geothermal water exploitation for use in electricity generation. For this purpose the Petrel 3D seismic interpretation and modeling software was used.

The research process was restricted to the promising basement reservoir formations, because the expected temperature of the possible Upper Pannonian sandstone reservoirs is not sufficient for electricity production. The sediment thickness of the basin fill varies from approximately 700 to 3000 m and the depth of the Upper Pannonian layers is less. The thickness of the sedimentary layers is important even in the case of the basement reservoirs. On the one hand the thicker the overlaying sediment succession the hotter the expected water temperature – with 50 – 60 °C for every 1000 m of sediment fill. On the other hand, these sediments have to be drilled through and there are technological and economical barriers for the depth of a well. The optimal depth of the basement is between 2500 and 3000 m, which means 150 – 180 °C water temperature in the reservoir.

Moreover the yield of basement reservoirs is probably higher than the sandstone reservoirs since the meteoric water infiltration through the outcrops of the basement formations in mountain ranges can recharge the deep reservoirs. Also the obligatory reinjection is much easier into the basement carbonate formations than into sandstone reservoirs. The yield of the reservoirs can be increased further with reinjection.

While the primary (matrix) porosity of the basement carbonate formations is low, sites with high secondary porosity should be searched for. Secondary porosity can be created by fracturing the rocks or, as in the case of limestones, karstification can create secondary porosity as well. In the study area, close to the Mid-Hungarian Line – a zone of almost continuous tectonic movements – the fracturing of the rocks is very likely; therefore heavily fractured zones were sought for in the study area. The most visible marker of fractured rock is the displacement of the layers, caused by the fault, which also caused the fracturing in the rock.

The Mid-Hungarian Line is a crustal scale strike-slip fault. The presence of deep (up to 10 km or deeper) faults that can carry deep hot waters to higher reservoirs is also possible. If such a fault could be localized in the area then the possibility of a feasible electricity generating project could be increased enormously, although the opposite process can also happen. If the deep fracture does not transfer the hot water upwards but transfers cold water down instead, the water temperature at that depth will be less than expected. Dynamic hydrological simulations are used to answer this question. Besides the hydraulic properties of the rock formations, the geological model of the area is the input parameter to these simulations.

By the interpretation of geophysical data – in the case of this study that means 18 2D seismic sections – and the subsequent modeling these subsurface structures were hunted. The lack of input data was somehow compensated by the capabilities for computer aided interpretation and modeling and the 3D visualization of the input and interpreted data.

In this chapter the general workflow of the creation of the 3D model of the studied area will be presented. After a short introduction on the used software and the input dataset, the chapters will tightly follow the main steps in the process of using the software.

3.1 The used data

The 3D model of the study area is principally based on 18 2D seismic sections. The extent of the study area is about 600 km^2, a 20 km * 30 km rectangle. The sections were available both in image and in digitalized SEG-Y format. Half of the seismic sections were NW –SE oriented and the other half were roughly perpendicular to them. The sections were shot by the Hungarian Oil Company before 1990. Additionally lithologies from 12 wells were used for quality control in the results. The wells could only be used for an approximate quality check because no check-shot data was available from the area and therefore the interpretation of the seismic sections in milliseconds and the depth in the wells in meters could not be converted into each other. At the end of the whole procedure an approximate velocity model was used to estimate the depth of the selected reservoirs (provided by Mannvit Ltd.). Also, the locations of the wells were too rare to include them successfully in the model by using the approximate velocity model (Figure 3.1).

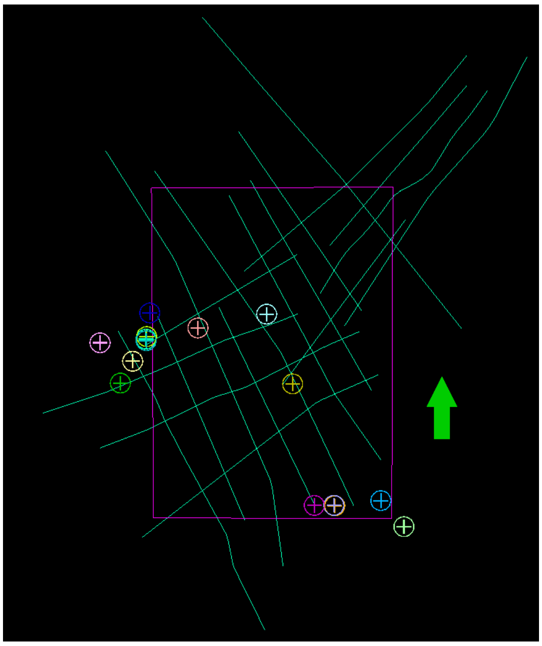

Figure 3.1 Arrangement of the used seismic sections and wells

3.2 The used software

Petrel is a 3D seismic interpretation and modeling software developed by Schlumberger Co. It is designed primarily for coupled work with 3D seismic cubes and well data from the interpretation to the dynamic modeling, with several functionalities directly developed for the analysis of reservoirs. The software has a rather strict general workflow that has to be followed in every application (Figure 3.2).

The procedure starts with the importation of the data. Three main types of data can be imported into the software: the seismic data, the well data (well description and well logs) and the connection between them, the velocity model. The analysis of the seismic data and the well logs are parallel processes. The output of the analysis process of the seismic data is a grid mesh in two-way time as a unit. The output of the analysis of the well logs is a discrete or continuous property along the well, for example stratigraphy, fluvial facies or porosity. The dimension of the well data is length. The parallel threads are connected again after the analysis process, when the data in two-way time – obtained from the seismic – will be converted into length – obtained from well logs. After the conversion, further property (static) or dynamic modeling can be made.

The analysis of the seismic data can be divided into two sub processes: the interpretation and the modeling. The results of the interpretation are included in the modeling as input data. The interpretation part can be divided further into 3 phases, but these phases are not separate ones; rather, they compose a feedback system. These steps are the interpretation of the horizons and faults in the 2D seismic sections and the fault modeling in 3D space. The modeling sub process also includes the fault modeling step, which means the fault model of the area has to be in concordance with the interpreted structures and also with the requirements of the modeling sub process. The modeling can also be divided into 3 more steps: the fault modeling and the creation of the vertical (Pillar gridding) and horizontal (vertical layering of the grid) grid lines. These steps also create an iterative cycle in the modeling sub process.

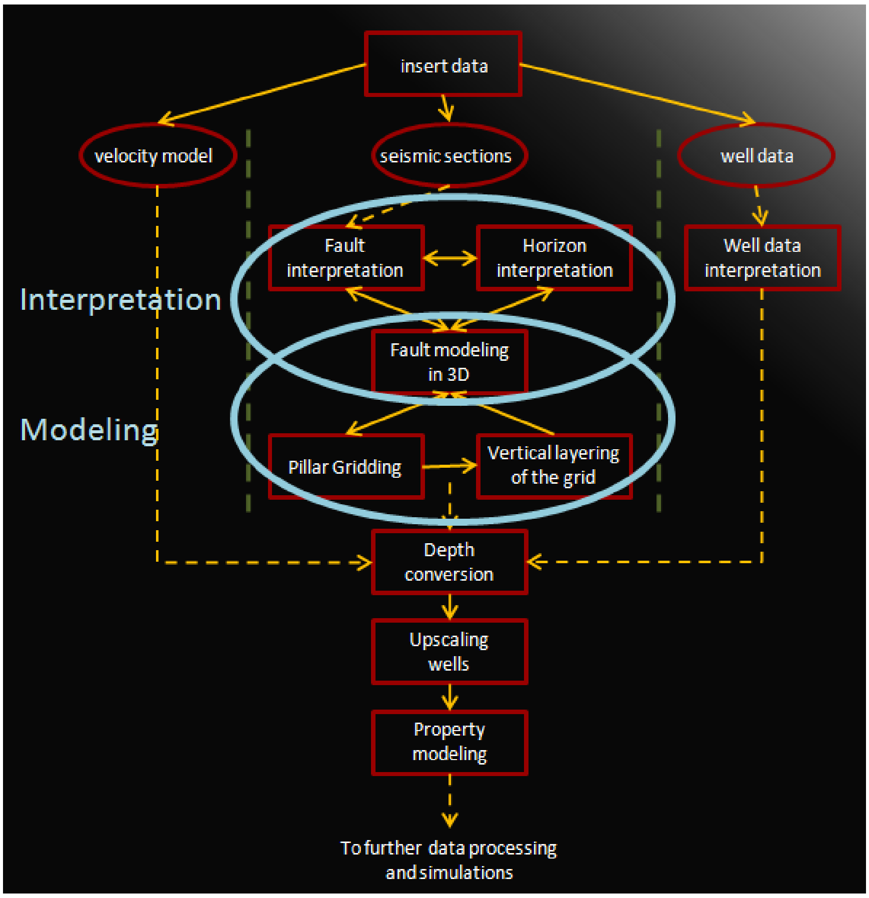

Figure 3.2 General workflow of Petrel

The presence of a geology expert in the interpretation sub process is crucial for proper interpretation of the imprint made by the subsurface structures. Still, the computer can be of help. In computer aided interpretation the scale, the color and the way the seismic section is visualized can be changed. The raw digital data can be manipulated and the use of different image-processing operations is possible, such as filtering for emphasizing a feature on the seismic section (Figure 3.3).

The modeling sub process requires an experienced user of the software because the output is dependent on the used software and even more on the algorithm the software uses. Although for the first approximation the model building process is highly automated and it can create a correct model for a very simple area, for more complex geological environments – something that can depict the real conditions – the computer needs help, sometimes a lot of it to create a reasonable model of the area. The role of the user in this phase is to "explain" to the software how the model should look after the processing. Usually there are restrictions in every software, but the less the restrictions there are the better the software. The user needs to understand these restrictions and the main principles in order to intervene into the automatic procedure successfully. Sometimes it turns out during the model-building step that the interpretation that was made on the input data set is not coherent or it has some other problems. Then the interpretation process has to be repeated and the error has to be corrected.

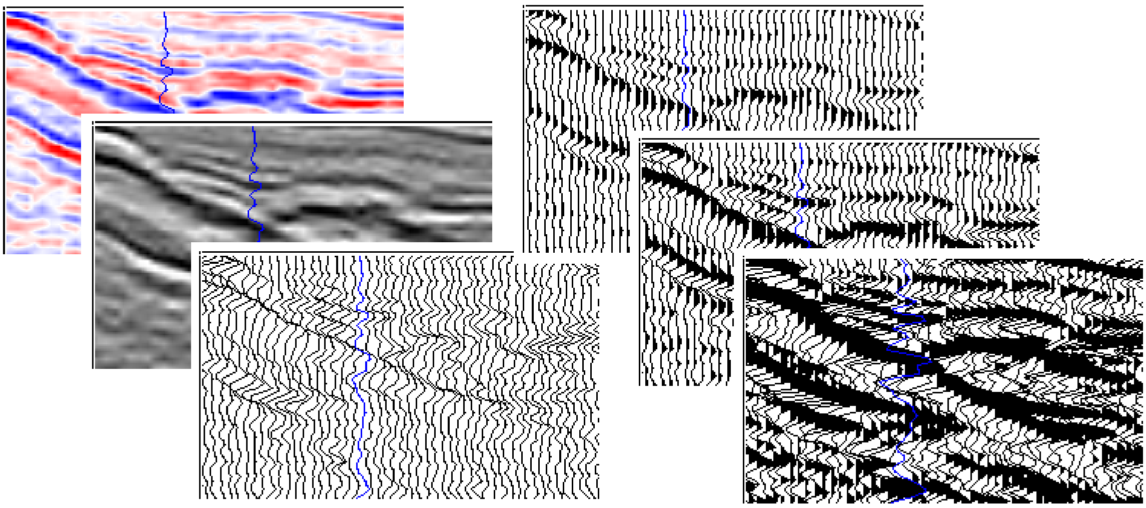

Figure 3.3 Different visualizations of the same piece of a seismic section. Scaling of the vertical and horizontal axes is also possible

A more detailed description of the interpretation process steps and the modeling in general will be given in the following chapters together with the usage of the general workflow in the specific case of this study.

3.3 The interpretation process

Only the seismic data was interpreted since no useful well log data from the area was available. Horizons and faults were interpreted in the seismic sections. They can be interpreted at the same time in a combined process step in the Petrel software, in the 3D space or in a 2D interpretation window. The 2D window interpretation resembles the method used in manual analysis and in conventional 2D interpretation softwares. The possibility of the 3D quality check was found to be a key advantage in this process. (For further information on seismic sections and the interpretation of horizons and faults on it see Appendix A)

3.3.1 General description of the seismic sections

In every section it is apparent that the top and the bottom of the section is different. In the upper 700-1200 milliseconds parallel lines dominate, while below a very definite horizon the lines are mixed up and cannot be followed throughout the section. (Figure 3.4) This very strong, definite horizon is the lower boundary of the Pannonian strata and was deposited at the end of the Middle Miocene. This surface is called base Pannonian horizon.

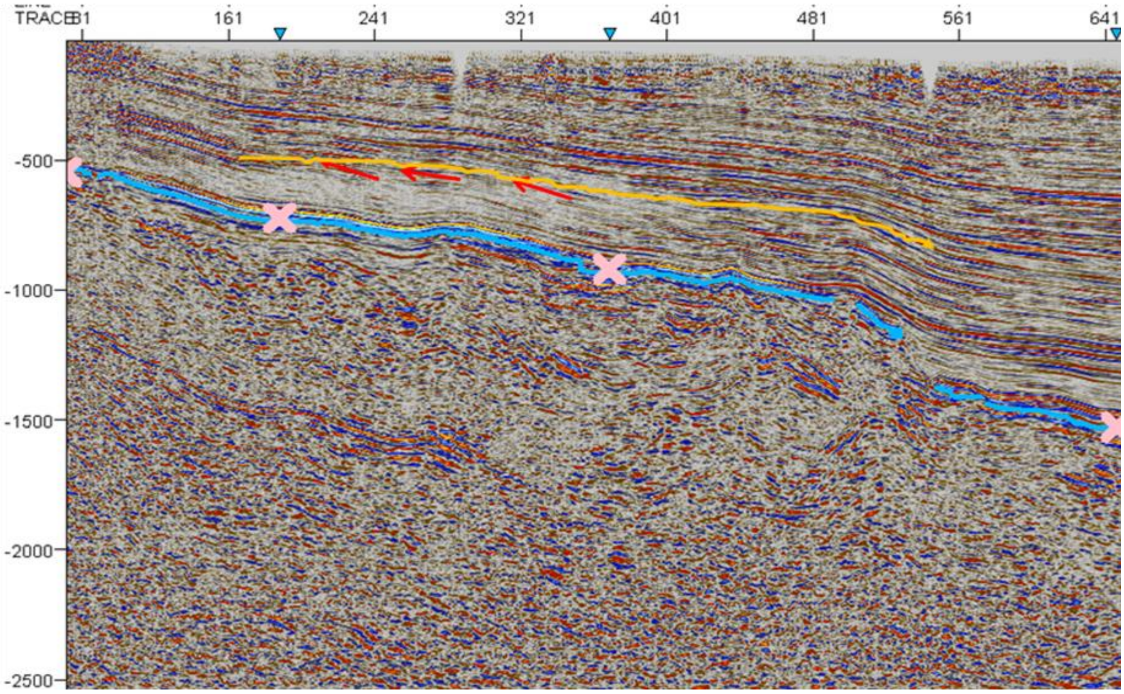

Figure 3.4 A typical seismic section from the study area. The blue line is the interpreted base Pannonian horizon and the orange line is the toplapping younger layer.

Above this layer the sedimentation is undisturbed. One horizon that toplaps onto other lines can only be seen in the higher regions, which means erosion in those areas (Figure 3.4). This horizon is the base of the Upper Pannonian strata that formed in the Late Miocene. Below the lower boundary of the Pannonian strata the lines are disturbed. This is the result of the tectonic movements that affected the originally flat layers during or after their deposition. These movements affected the formations several times. As a result of this tectonic activity some areas emerged while others submerged. Erosion took place on the basement highs while in the deep troughs sedimentation continued. During the subsequent tectonically active time the opposite could have occurred. The former highs submerged and formed deep troughs while the former troughs emerged. In the seismic sections the troughs or smaller sub basins are layered structures below the base Pannonian horizon. Above basement highs these Tertiary sediments are missing, although that does not mean that they did not deposit; they could have also eroded after their deposition. During these active times the fragments of the basement not only emerged or submerged, but also rotated and shifted. The result of a complex evolution can be seen on the seismic sections.

3.3.2 Horizon interpretation

The interpretation of the horizons is important in order to find out the depth of the desired layer and to gather information on the evolution of the area. Three horizons were interpreted in the seismic sections. The topmost interpreted horizon is the base of the

Pannonian strata. This horizon corresponds to a Late Miocene inversion period in the entire basin and it is very easily visible on the seismic sections because it separates the layered basin fill sediments and the chaotic structures that can be seen in the lower parts of the sections.

The lowest and the most important interpreted horizon is the top of the pre-Tertiary formations. In most cases the targeted Triassic carbonate formations can be found directly below this horizon due to the uplift and the erosion of the younger sediments in the Cretaceous. The complex tectonic evolution in the area created complex and often superposed structures, therefore the top of the pre-Tertiary horizon was hard to see and the its interpretation was difficult.

A third horizon was also interpreted between the other two. This unconformity horizon corresponds to an Early Miocene inversion period, but this inversion period was not as comprehensive as the Late Miocene inversion. This horizon was sometimes easy, but sometimes hard to interpret.

The Petrel software offers different functionalities for horizon interpretation, with 4 different levels of human intervention, from the completely automatic interpretation for 3D seismic cubes to the fully manual interpretation of the hardly visible horizons. It is important to choose the appropriate one for a given horizon.

For example, in the case of the base Pannonian horizon the guided 2D autotrack method was used, which traces the most possible path of the horizon between two points given manually by following the highest or lowest amplitude values of the trace lines. That method can follow a horizon characterized by high amplitude reflectors even if it is curved.

There was no continuous reflector to follow in the case of the middle and even less reflector in the case of the top pre-Tertiary horizons. In these cases only the manual interpretation could be used.

A 2D surface was interpolated by using the output of the horizon interpretation process (

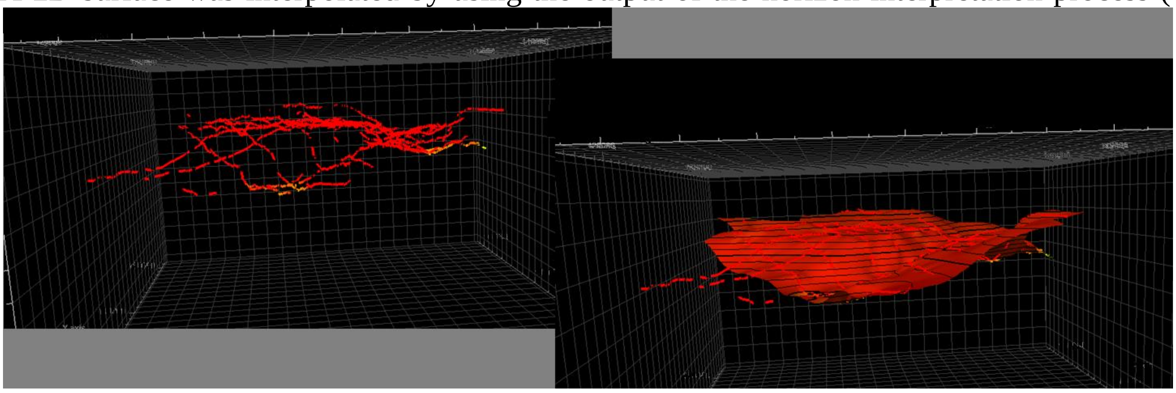

Figure 3.5). The interpolation algorithm can be chosen from several options.

There are two deep depressions in the study area. One of them located in the south, with an ENE – WSW direction, starting from the SW corner of the field. Only the west ending of the other depression is visible in the NE corner. This trough has a NE – SW orientation. These two main depressions are separated by a relatively high area. These structures are present in both the base Pannonian and the top pre-Tertiary horizons, but on the top pre-Tertiary horizon the basement high as well as the depressions are more dissected than on the base Pannonian horizon.

The highest structures are located in the central and western part of the area and in the NW corner another depression starts to form.

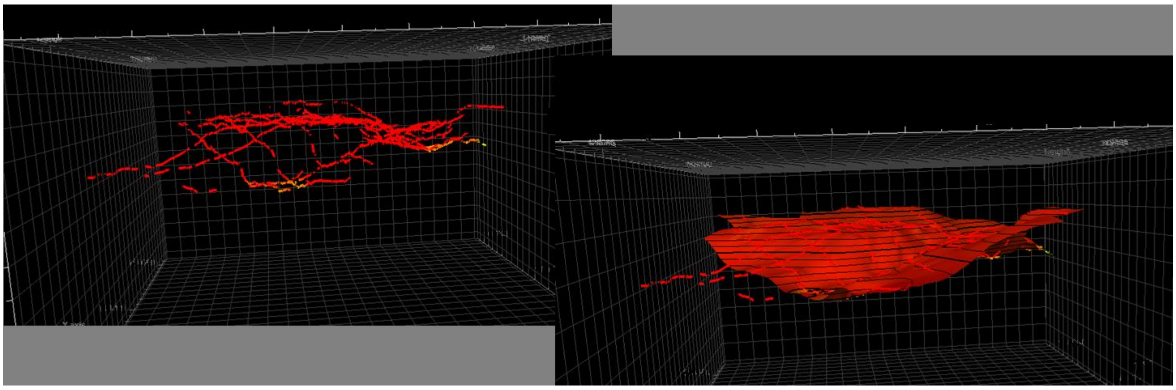

Figure 3.5 Interpolation of a surface from interpreted lines

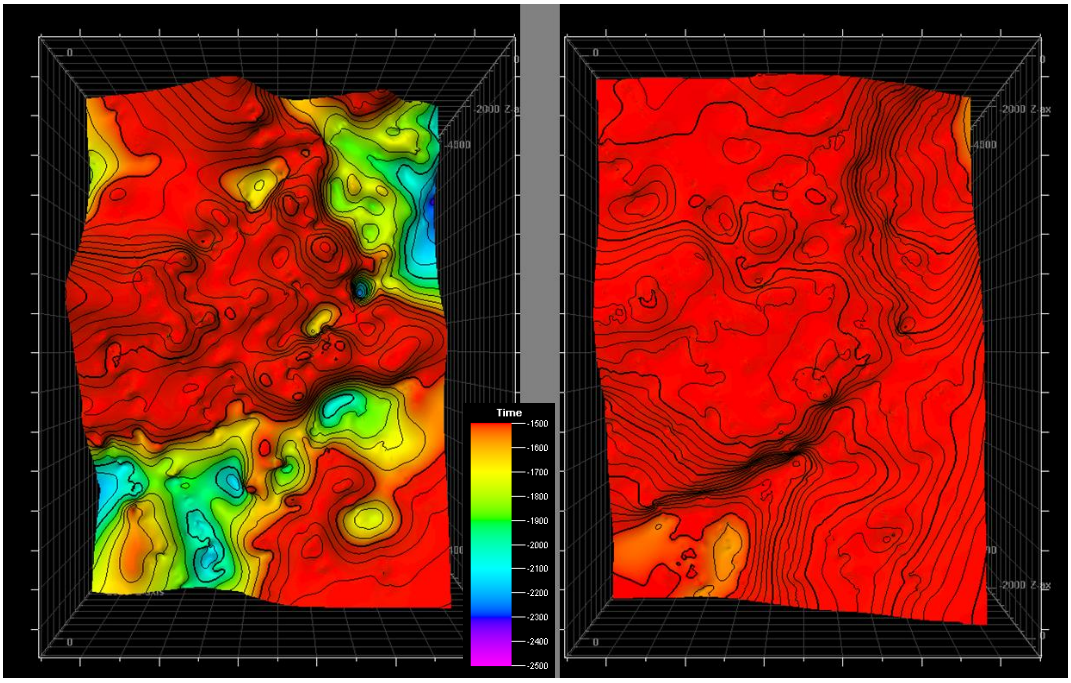

Figure 3.6 top pre-Tertiary and base Pannonian horizons from above

3.3.3 Fault interpretation

The fragments of the basement are shifted away from each other along faults. Different kind of faults and fault groups can be seen in the seismic sections. They differ in the type of resulting movement and in the affected layers of the movements.

The affected layers give information about the age of the fault. The fault is older than the oldest layer that is not affected by the fault. It is written above that there were several tectonic episodes with different age in the Pannonian Basin. The age of the faults can be determined by the inspection of the rock formations and seismic reflections displaced by the fault.

In the study area a lot of different types of fault structures and fault groups have evolved. The most common looks like a tree; going upward, more and more individual faults branch off from the deeper faults. (Figure 3.7) Usually the whole structure has only one deep fault as a root. This fault arrangement is called a flower structure. These structures can evolve along strike-slip faults, if the strike-slip fault has a compressive or tensile component (Figure 3.8). If this is the case, there is a shortening or diluting of the space along the strike-slip fault. To accommodate the rock fragments in the space at the two sides of the fault, they must have a vertical component in their movements. They move up if the stress field is compressive – a positive flower structure – and they move down if the stress field is extensive – a negative flower structure. There is no need for regional extension or compression. If the strike of the strike-slip fault is not straight, which is common due to the inhomogeneous flexible properties of the rocks, local extension and compression fields can be experienced even in short distances – a few kilometers in the case of this study. These structures are very common in the study area; they can be seen in almost every seismic section. The reason for this prevalence is that the study area is located in a big strike-slip zone.

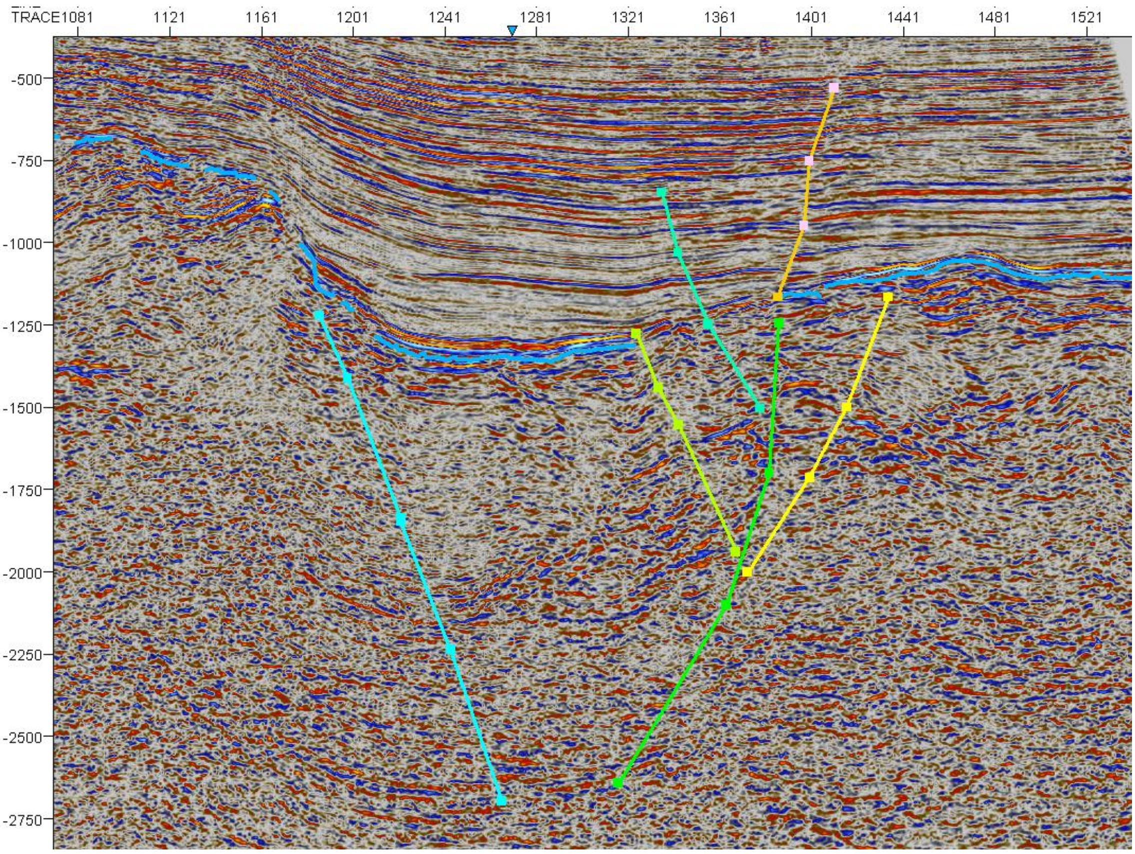

Figure 3.7 A flower structure on the seismic section

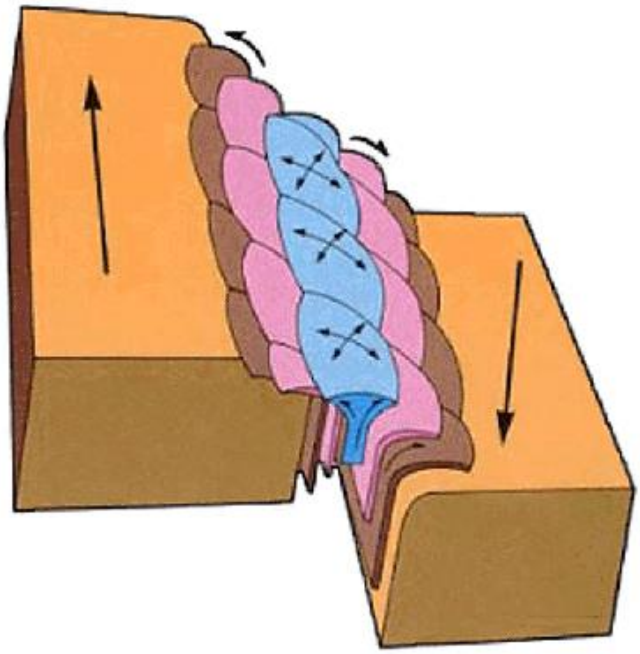

Figure 3.8 Formation of a positive flower structure in a transpressive environment

The flower structures on the seismic sections have deep roots and mainly affect the basement formations. It can be seen in several seismic sections that some of the individual branch faults that reach the top of the pre-Tertiary go higher and affect the upper sediments, including the Pannonian strata or even the youngest Quaternary layers. (Figure 3.7 at trace nr. 1401) In some other cases the strong, definite line of the base Pannonian is disturbed above the flower structure.

According to these observations the story of the flower structures can be told. They were formed after the sedimentation of the basement rocks – in this case mainly Mesozoic; and in most of the cases they are older than the 11.5 Ma old base Pannonian horizon. In some cases – where the base Pannonian horizon was disturbed – the faults were still active in the Middle and Late Miocene, during the sedimentation of the Pannonian strata. Something else happened in those cases, where only one fault cuts younger sediment layers. In those cases the main tectonic episode was finished by the Middle Miocene, but in a subsequent tectonic episode one branch of the old fault system reactivated. In those cases, where a reactivated fault is rooted in a disturbed base Pannonian horizon, both of the previously described events occurred.

Old normal faults and reverse or thrust faults can be seen in the basement formations, although the seismic resolution at that depth – below 2–3000 milliseconds – is too low to tell unequivocally the accurate position and the accurate type of the fault. These movements are old, because they have no effect on the younger sedimentary succession. The structure of the basement is very variable in some seismic sections. Bunches of parallel seismic lines, homogeneous pieces and even pieces with very low reflections are located next to each other, but the certain tectonic structures – faults or folds – that put those pieces next to each other are hard or impossible to see because of the combined effect of the poor resolution and the complex structure.

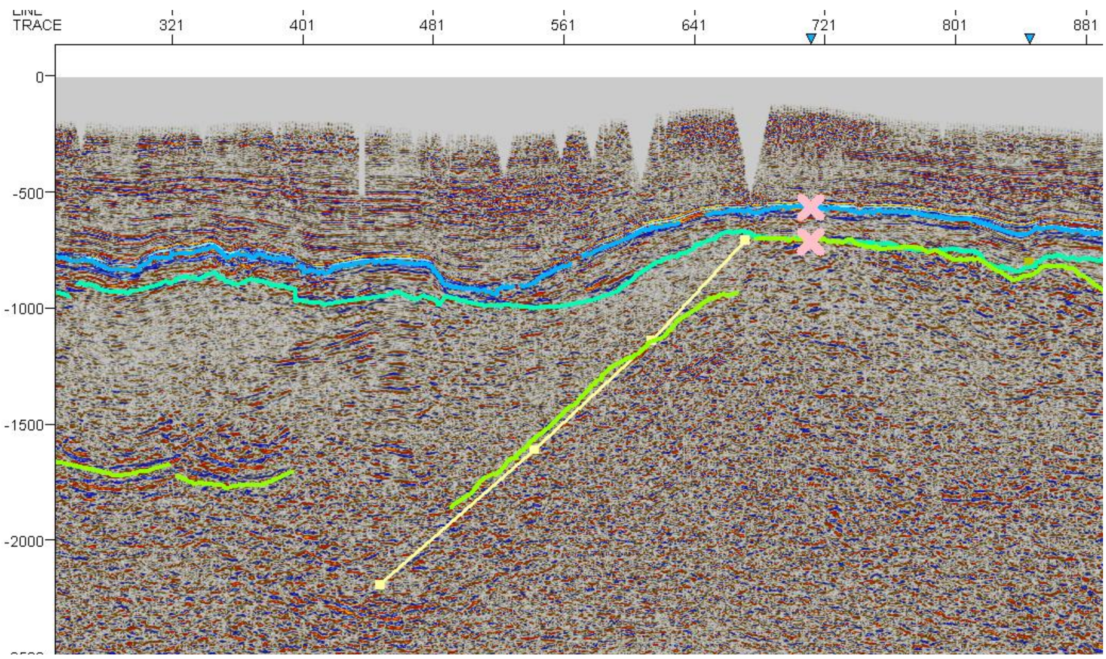

Figure 3.9 Reverse fault

There are younger reverse faults as well. At these reverse faults the Early Tertiary and the older (basement) layers are affected and the whole structure is overlaid by Early or Middle Miocene sediments (Figure 3.9). This means that the faulting took place before the sedimentation of the overlying layers and after the sedimentation of the affected ones. These faults also exhibit signs of reactivating in the most recent times. The sediment succession above these reverse faults is gently bent and forms anticlines. These faults can be found in the middle and the northwestern part of the study area.

There is an interesting fault that occurs in the northwestern corner of the study area. It is a low angle normal fault with an interesting structure above it: bands of parallel seismic reflection lines with different dipping angles (Figure 3.10). The first impression for the explanation of this structure was that this is a roll-over structure on the hanging wall. The hanging wall slides down on the fault plane with decreasing dip angle and creates a hiatus between the hanging wall and the foot wall at the top of the fault plane where the dip angle is relatively big. The matter of the hanging wall will fill this hiatus by creating a subsidence above the fault plane. Sedimentation starts at that place and if the fault renews again and again and the sediment layers move down together with the hanging wall the observed structure can evolve. This would confirm the existence of the long-lived low angle normal fault, but no similar structure could be seen on the parallel seismic sections. In that case the solution was on the cross-section. The seismic section with the interesting structure was shot in the middle of a strike-slip fault. If, for example, a positive flower structure evolved there, it could arrange the sediment layers in the space in such a way that they would form this deceptive structure. Although this specific structure was not able to see on the parallel sections, the low angle normal fault was visible.

Another interesting phenomenon can be seen in this part of the area on the cross-section that is perpendicular to the seismic section described above and parallel to the strike of the low angle normal fault. The structure of the depression that was formed by the normal fault can be seen on this section. Above a chaotic bunch of seismic lines that can correspond to an earlier stage of the evolution of the trough, the reflection lines are easy to follow from one side of the trough to the other side. The lines have depression above the trough and continue at a higher level on both side of it. Younger horizons also show the same feature, except that the formed depression is less deep. (Figure 3.11) That means the distance between the horizon lines is bigger above the trough than in the sides. The evolution of this structure can be explained as follows: In the originally shallower trough a thicker sediment layer deposited than the one in the edges and filled up the pit. While this happened, the faults that created the trough were still active and the pit subsided coeval with its refilling. The deep trough is only a deep trough today; at the beginning of the Pannonian period it had almost the same elevation as its edges. The fault that is active during the sedimentation is called a growing fault. This also means that the deep fault, which created the trough, was active until very recently or it is still active.

The active status of a fault can be important regarding the reservoir porosity. Faults create secondary porosity in the rocks and the rock becomes capable of storing and circulating significant amounts of water. These waters are usually saturated with several minerals. If those minerals precipitate from the water – for example due to the pressure change in the fault cavity – they can seal the fault. If the fault is active, the rock will break again, and the cavity made by the fault will not have enough time to be sealed. The carbonates that compose the basement of the study area are highly capable of this sealing process. Dolomite and, to a greater extent, limestone are soluble in the infiltrated water, therefore formation waters will be saturated in calcite and calcite precipitates if the pressure decreases.

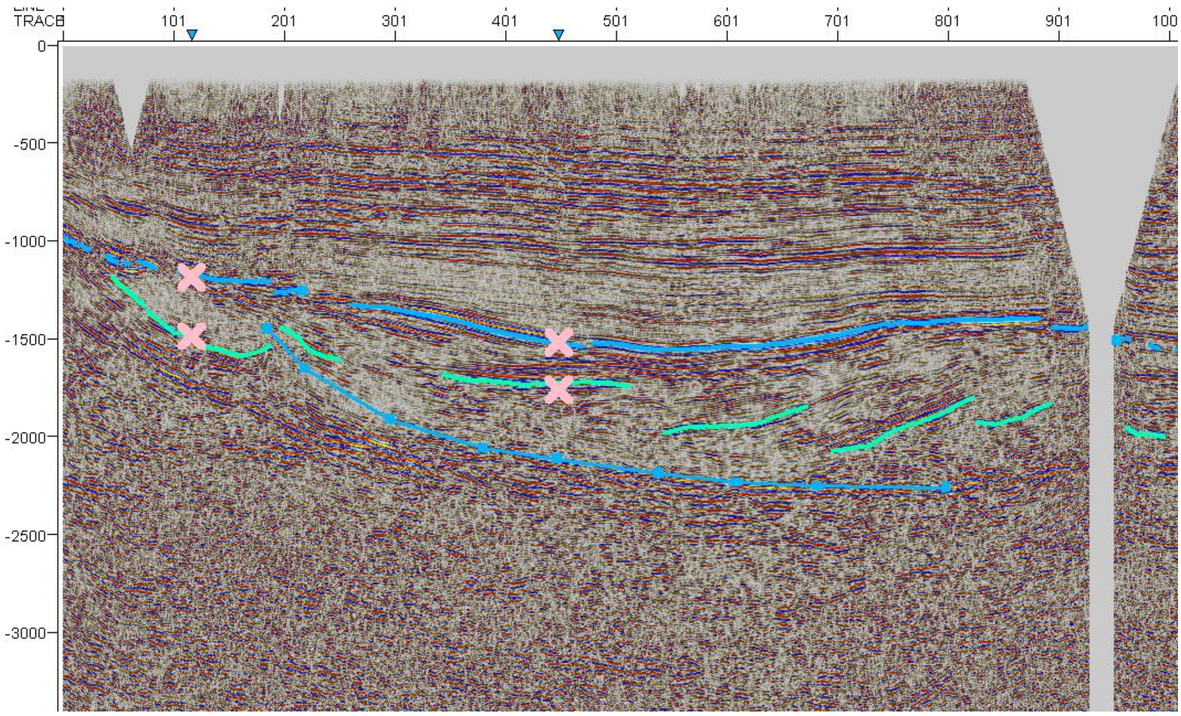

Figure 3.10 The low angle normal fault with the strike-oriented cross section of a strike slip fault.

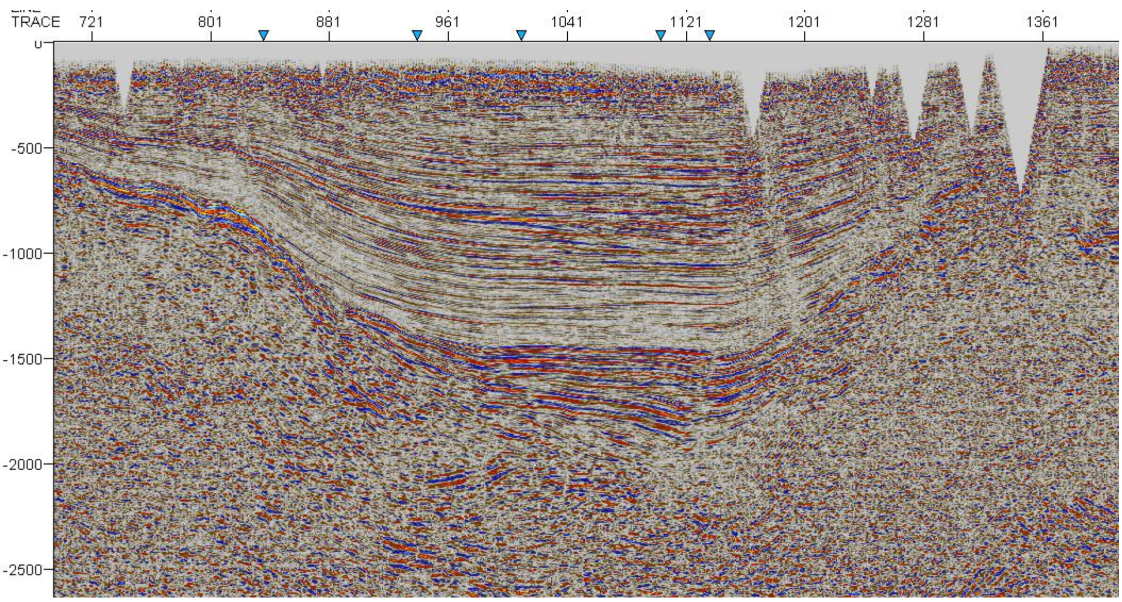

Figure 3.11 Depression that is growing simultaneously with the sedimentation

3.3.4 Full interpretation of one seismic section

All the seismic sections were analyzed separately as parts of the complex interpretation of the structures and the reconstruction of the evolution of the study area. The analysis of a section is presented here as an example of this process. Many of the before mentioned structures can be seen in this section (Figure 3.12). The fault structures of different age are superposed on each other in this seismic section. The goal of this process is to find out their time-sequence. First the individual events have to be separated. At the western end of the seismic section west dipping normal faults can be seen under an undisturbed base Pannonian horizon (Figure 3.12, trace 1-160). A small basin with parallel reflection lines is located above them as a result of this event (trace 81 at 750 milliseconds). The eastern margin of this fragment is a sharp east dipping fault (trace 161). This fault cuts the base Pannoinian horizon and even the younger layers (this is not shown). On the western side of the fault the base Pannonian horizon is flat and the successive younger layers are parallel to it. On the east side of the fault the base Pannonian horizon is gently bent and the younger layers onlap it (trace 241-321). That means the reflections of the younger layers terminate on the older one. This structure evolves if the formation of the depression took place before the sedimentation of the younger layers. If the sedimentation of the younger layers took place before the formation of the depression, the parallel reflections of the sedimentary layers would have bent together. The imprint of the subsurface structures on this seismic section shows something between these two ends. The younger layers are also bent gently in a decreasing rate and thicken to the east in the same way as can be found along growing faults.

This section crosses the northeastern part of the study area where the growing fault – the low angle normal fault – is located, so in this section more evidence for this process can be seen. But in this section it can also be seen that a shallower depression existed before the sedimentation of the younger layers started.

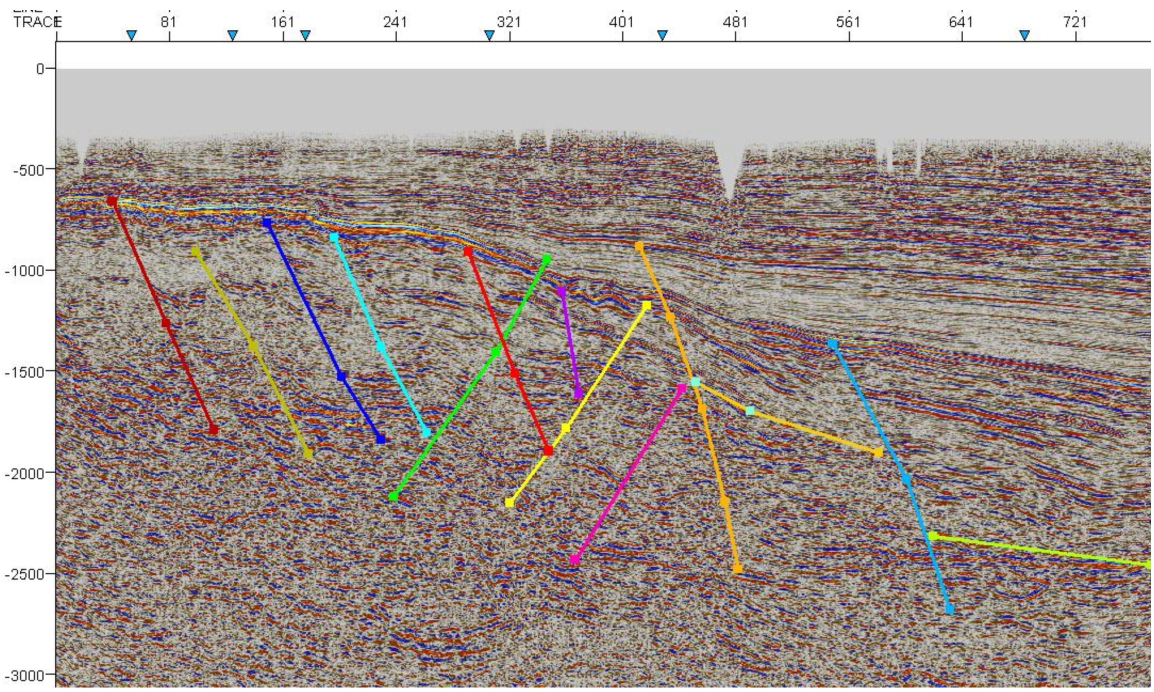

Figure 3.12 Different fault structures superimposed on each other

East from the east dipping fault several more faults can be seen on the section. They can be grouped by their type. At the east side of the east dipping fault that separates the west part of the seismic section (trace 161) two flower structures of a different kind can be seen. One of them is positive and the other one is negative with a narrow area, where they cross each other. Over this narrow zone the young sediment succession is also affected (trace 321). The two flower structures close to each other can be the result of a curve in a strike-slip fault with a strike parallel to the seismic section. The faults that run parallel with the seismic section cannot be seen on this section, they are only visible on the cross-sections. Indeed, some kind of fault is noticeable on cross-sections.

The middle part of the eastern (the negative) flower structure is folded (between trace 321 and 401). It might be the consequence of a successive tectonic event and a reverse fault at the east side of the flower structure (trace 441). This reverse fault cuts and overthrusts the base Pannonian horizon and some more layers above and also folds those layers in the footwall. The younger layers are gently folded above this structure. The gentle fold of the Neogene (the youngest) strata can also be seen over the already mentioned east dipping fault (trace 161) and above the area, where the two flower structures cross each other (trace 321). That indicates the active status of these faults until very recently. There is one more fault at the eastern end of the seismic section above which the base Pannonian horizon is bended and the younger layers are disturbed. This fault might be an older strike-slip fault with a slight compressive component that was reactivated later (trace 561).

The probable order of these structures can be determined in time if the affected layers and the interactions of the faults are considered. In this approach the first tectonic events were the normal faulting on the western side and the growth of the low angle normal fault in the eastern side of the seismic section. These faults can be connected to an extension stress field with E-W orientation. In the next phase the flower structures developed. This episode can be connected to a strike-slip faulting with NE-SW orientation. This episode is responsible for the juxtaposition of the two different fragments at the western margin of the structure (along the fault that is presented at trace 161) and the cut of the western end of the low angle normal fault at the eastern margin of the structure (trace 481). It is possible that the development of the two flower structures didn't happen exactly at the same time, but they formed in the same time interval.

After that time the stress field of the area remained quite stable and less powerful, which lead to the sedimentation of the only slightly disturbed Pannonian and Neogene strata. During the sedimentation of these strata some reverse faults were active in the western and middle part of the seismic section, although in the middle there was a more powerful event that caused overthrusting and folding of the older layers of the Pannonian succession. These events indicate compression in the area.

3.4 Fault modeling

Faults are 3 dimensional structures. In the previous process only the intersection lines of a fault plane and the seismic section had been interpreted, while in this phase the previously interpreted fault indications are connected to find out the 3D extents of the faults planes. The previously interpreted faults and the 3D visualization can provide much help in this phase.

Faults can be interpreted manually in the Petrel software through the succession of seismic sections. The software offers automatic fault interpretation for 3D seismic cubes through the Ant Tracking and Automatic Fault Extraction process, but the output of this automatic process has to be supervised closely.

The study area is situated in a very tectonically disturbed part of the Pannonian basin. The number of the interpreted faults was between 5 and 20 on every seismic section.

For the first sight, the orientations of the fault planes were not obvious. Some faults did not have continuation on the next seismic sections, while others had more possible continuations. The flower structures can be as small as a few kilometers, while the sections about the study area have an average offset of 4 km. That means it is highly possible that some of the interpreted flower structures are only visible on one seismic section without any continuation to the adjacent ones. For this reason only the main fault planes, the ones that were able to follow through more seismic sections, were interpreted. This problem does not come into sight if a real 3D seismic cube would be used. In that case the distance between the data points is a few tens of meters and fault planes can be followed easier throughout the 3D seismic cube.

This step creates a connection between the first interpretation part and the second, computerized, algorithm driven model-building part. The links between these two parts are the Key Pillars. These objects are used to tighten the fault planes in the 3D space, and these are also the objects that describe the result of the interpretation for the computer in the next phase. The algorithm of the next phase has restrictions on the arrangement and the connections of the Key Pillars. Those restrictions have to take into account when the fault model of the area is created. In practice, of course, it is not made in one single step. First the faults are placed into the 3D space and then they are modified to fit to the restrictions. This phase creates a consensus between the demand of the user and the capability of the computer.

3.4.1 The fault model of the area

The fault model of the area is shown in (

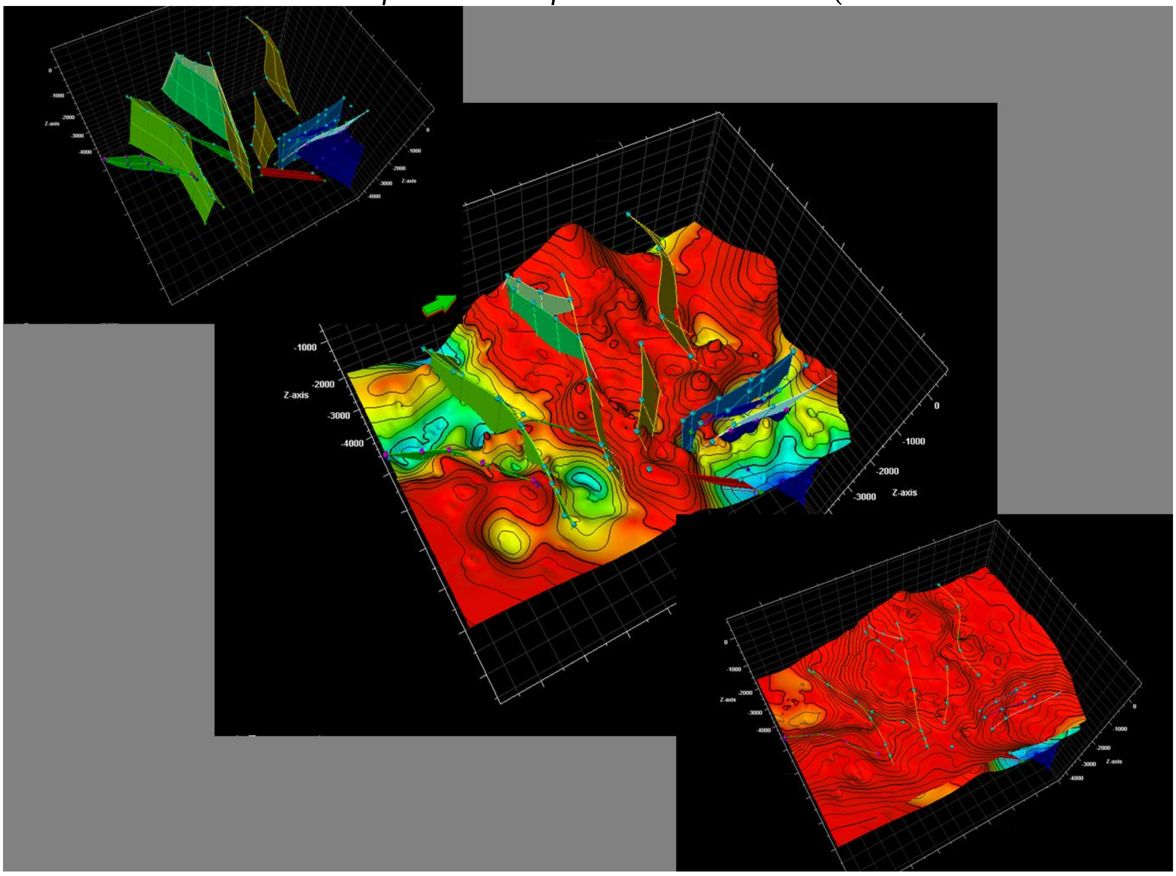

Figure 3.13). Faults have close relations with the inequalities of the surfaces because movements that are responsible for these disturbances took place along fault planes. According to this observation the interpreted seismic horizons should be inspected in detail

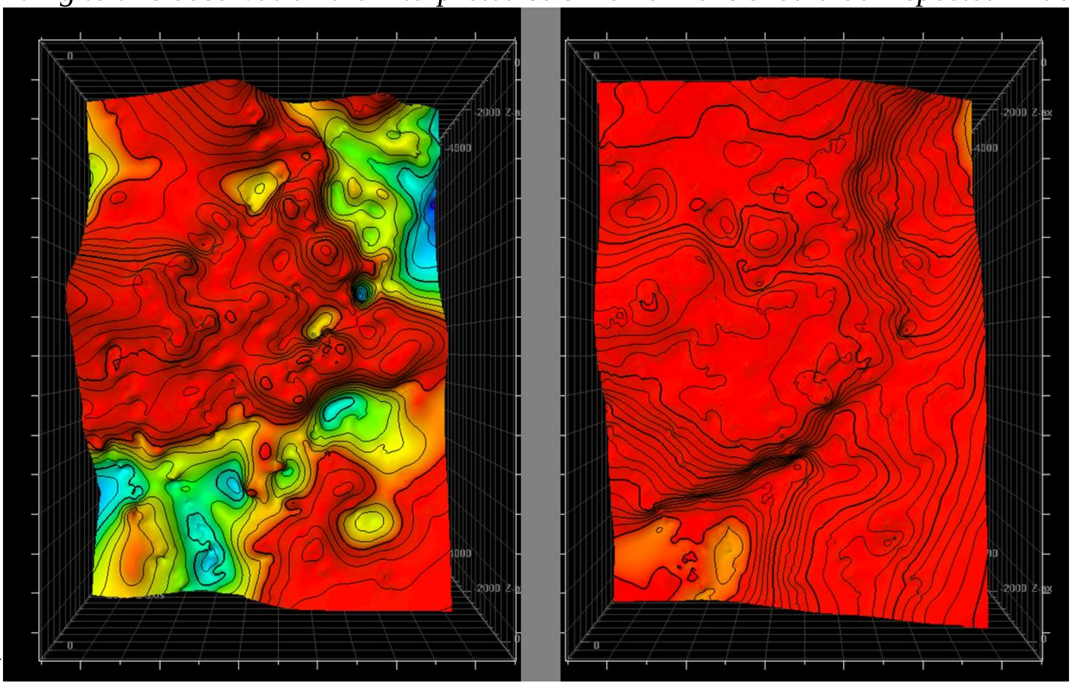

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Figure 3.6).

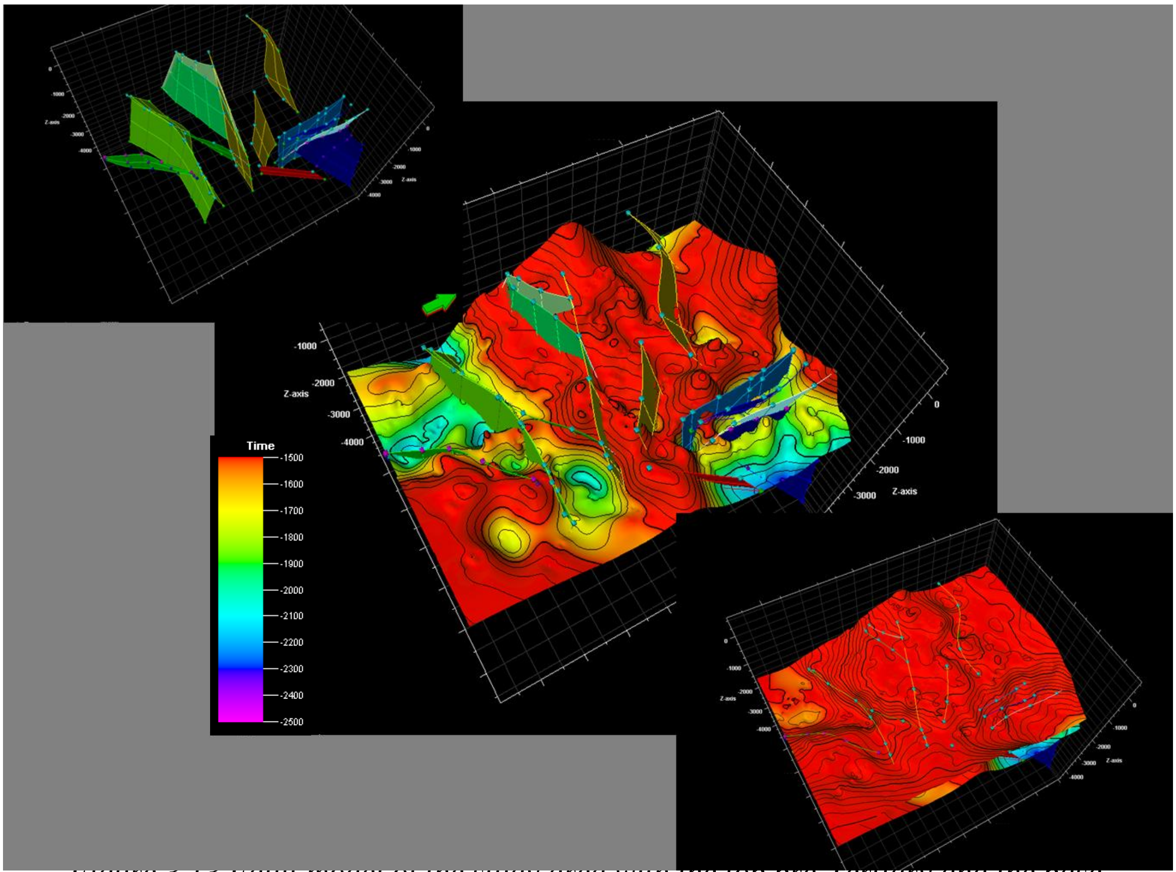

Figure 3.13 Fault model of the study area with the top pre-Tertiary and the base Pannonian horizons

Based on the direction of the strike and on the type of fault, the faults of the area can be grouped. The first group is the roughly NE – SW oriented faults in the SW corner of the area (green colored faults on

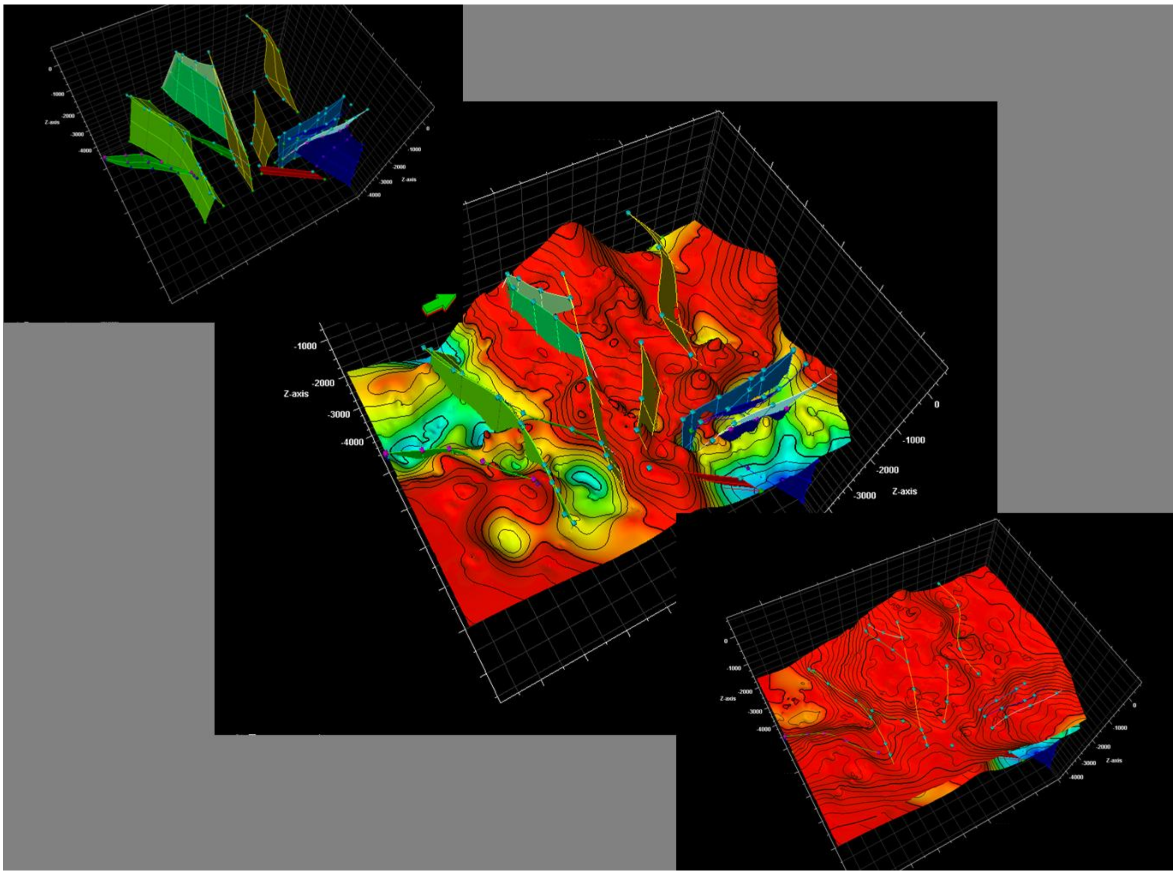

Figure 3.13 and Figure 3.14). These fault planes cause visible displacement on the seismic sections that are perpendicular to the strike direction of the faults. The fault plains can be followed through 5-6 seismic sections with NNW – SSE orientation. On the seismic sections that are parallel to the fault plains the intersection lines are less or not even visible.

The first group of faults is located along one of the deep troughs. They form positive and negative flower structures in the individual seismic sections. These structures have large variations from one section to another in the 3D space. The sub faults that branch from the main faults are hard to identify on the successive sections. It is also probable that they terminate before the next seismic section. Some of the branch faults can also act as a new main fault. In this case fault 5 originates as a branch of fault 4, but they diverge more and more to the west and a depression is formed between them. In the other case, just north from this structure, fault 7 bifurcates to the east. A depression is formed between the two branches – fault 7 and fault 6 – on the pre-Tertiary horizon, but these two faults encircle a relatively higher area on the base Pannonian horizon (Figure 3.14). That indicates the different movement of that block compared to the neighboring blocks. There are two more faults in this block. They indicate the northern margin of the zone of the flower structures. This margin also bifurcates in space, and ends up in two nearly parallel main faults.

Another fault with the same strike orientation is located on the southern margin of the NE located trough (red fault on

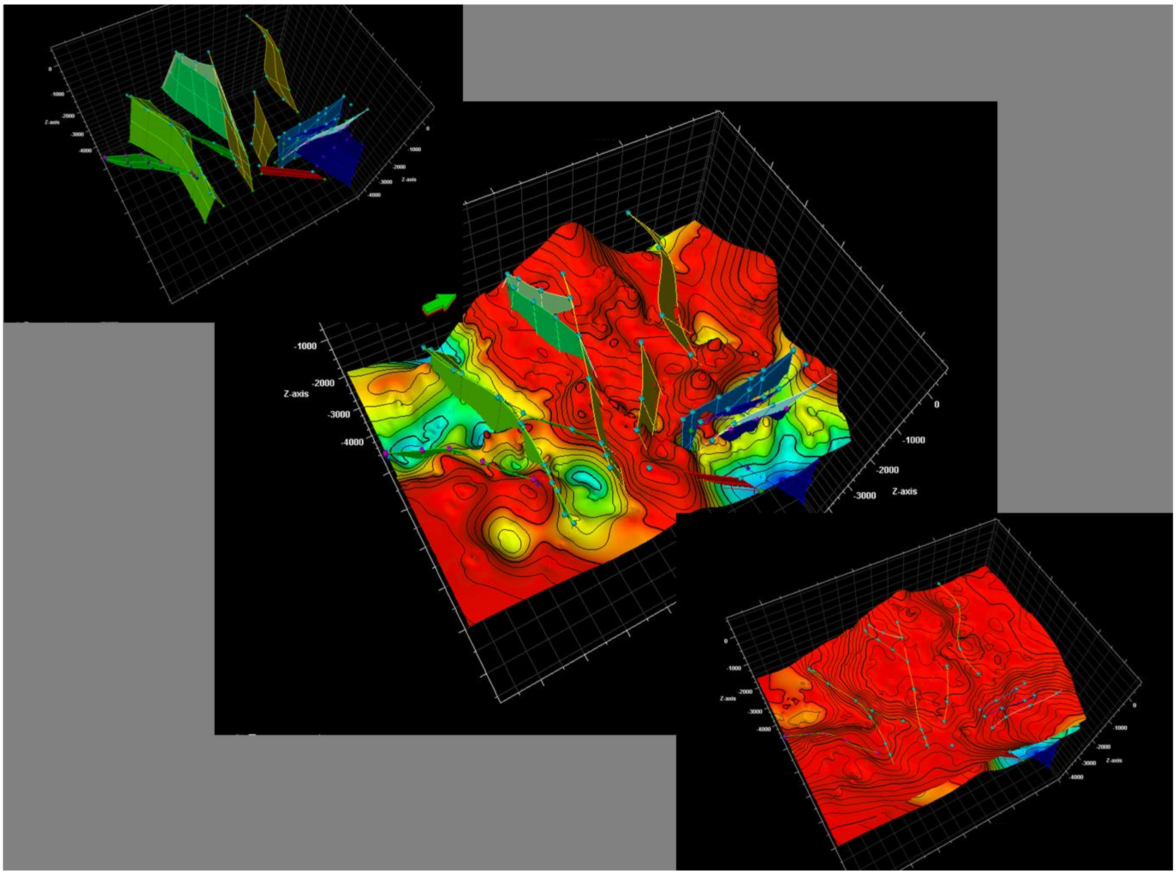

Figure 3.13). This fault is one among many (at least 3) at that location. They are parallel to each other and both of them are normal faults. These faults, along with the low angle normal fault located north of them – a blue fault in the NE corner of the area – are growing faults. They are responsible for the creation of that deep trough.

The low angle normal fault composes the next "group" of the faults. Csontos et al. (2005) described more faults of this type in the same trough, E – NE from the study area.

The next group of faults has the same direction of strike as the low angle normal fault, and is located to the east of it (blue faults in

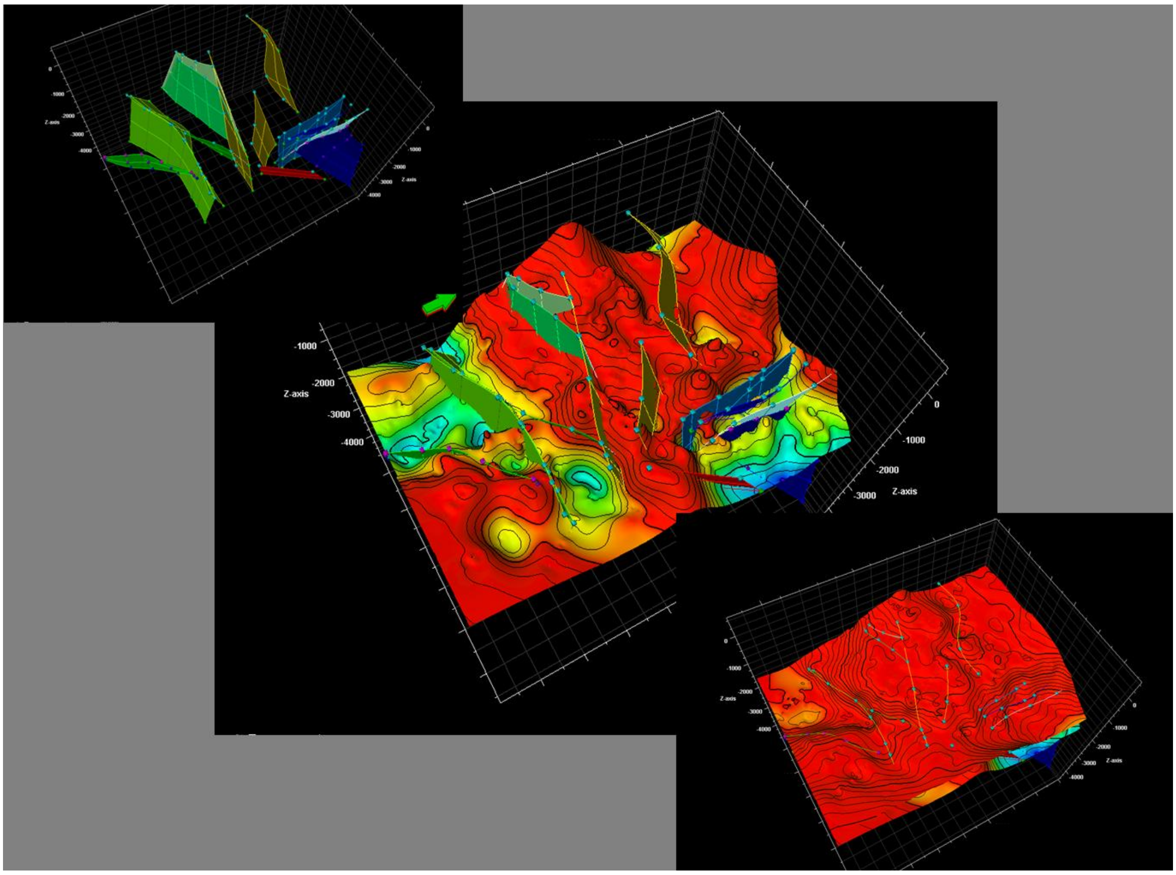

Figure 3.13). It is another complex group of faults composed of fractures with different ages and types (see page 28). The old steep normal fault is cut by the younger system of faults that compose a flower structure. The old fracture reactivated in this tectonic episode and acted as a main fault in the flower structure. The westernmost piece of this group terminates the low angle normal fault.

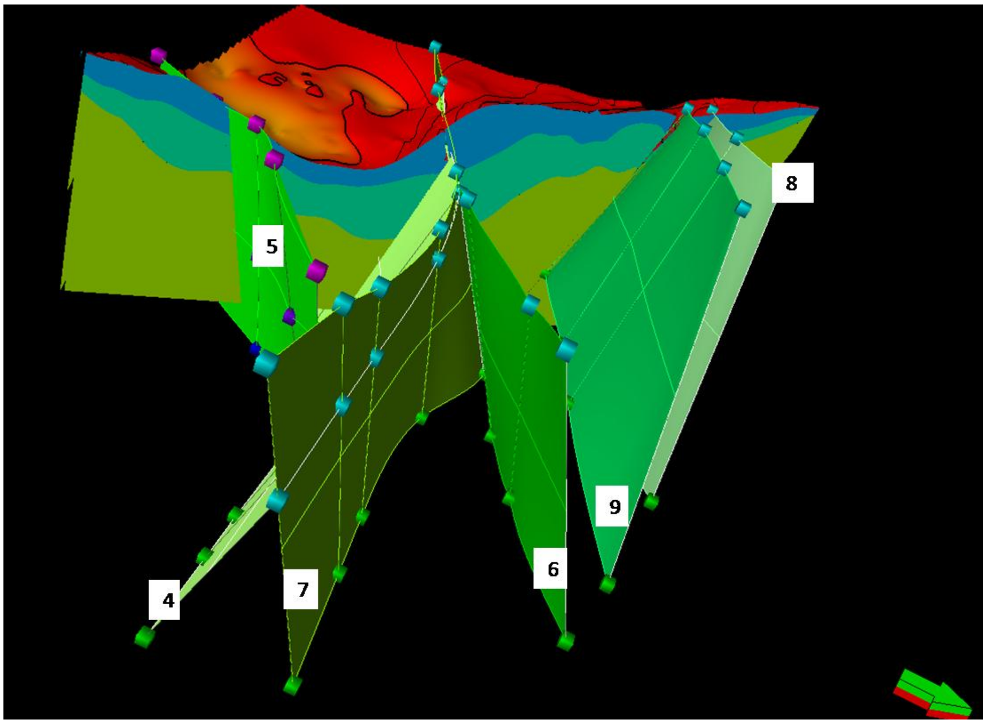

Figure 3.14 NE – SW striking fault group at the SW corner of the study area

The next group of faults is the NW – SE to WNW – ESE oriented group in the center and northwestern part of the area (yellow faults on

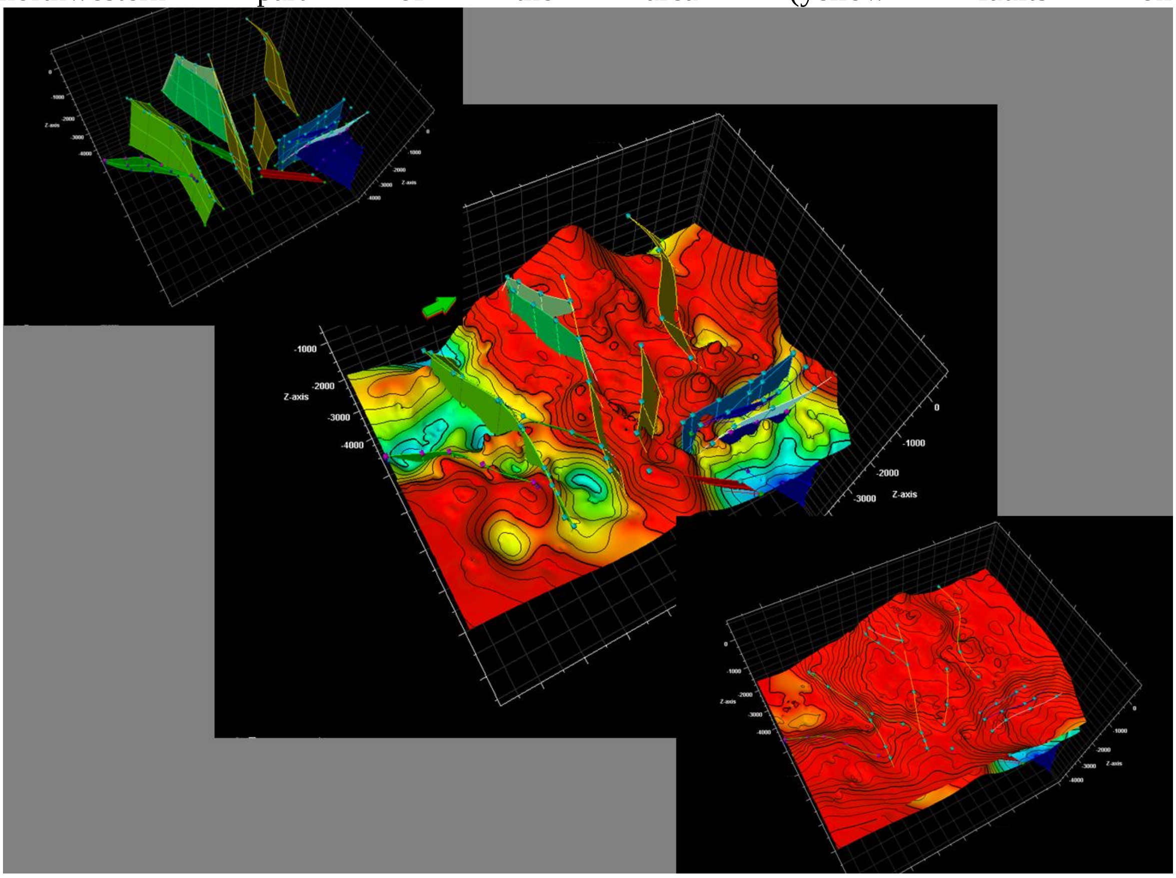

Figure 3.13). These are the thrust faults formed probably at the beginning of the Miocene and reactivated later. Some of these faults terminate the members of the first fault group.

The reactivation of these faults could be connected to these flower structures, at least to those that were active until recently.

There is one more question that emerged during the analysis of the seismic sections of the area. How are the depressions of the area connected? Both of the two depressions of the area were created in the beginning of the Tertiary as it can be seen from the thick Early Tertiary sediment layers at the bottom of the depressions. Were they connected at that time, and did they separate later? Or did they form as separate troughs? The tectonic structures of the two depressions are quite different, which would suggest the second hypothesis. But they have similar strike direction and the basement high that separates them only exists on the base Pannonian horizon, the area is more chaotic on the pre-Tertiary horizon. Further research is needed to answer this question precisely. Only one seismic section crosses the north and three more cross the southern part of the area of basement high between the depressions, but there is no data from between them and the seismic sections around this area have large differences from one to another.

3.5 Modeling process

3D digital geological and structural models are used primarily as input data for subsequent simulation and modeling processes, for example temperature and water flow simulations or property modeling. The visualization of the area is a secondary purpose, although from the view of a human being it is of special importance.

In general a model is a representation of some object or event in the real world. A model is good if it adequately describes the property or some properties of the real world that is relevant to the study. For example, a 3D geological model of an area is good if it gives back the values of the real world in reservoir simulations and reservoir modeling. According to the definition above, for various purposes different models will provide the best results. In today’s 3D geological modeling this is not the practice. In the course of computer aided 3D geological modeling only one model is used for hydraulic flow modeling, for reservoir volume modeling, for visualization, etc. Even though the future is unambiguously the use of different models, only a few different types of models are currently used.

- The geological model of an area is used for modeling the distributions of different geological, geophysical or petrologic properties of a subsurface body. These properties together with the extent of the area are continuous parameters which have to be digitalized. The common approach is to divide the volume into little pieces and to give a single value of a property for the whole piece. To achieve the best results, this model contains all the available geometrical and geological features of the area, as accurately as possible. For this reason the grid resolution is usually high, and the cells of the grid adapt to the presented geometry. The number of the cells can be some millions.
- The structural model of an area is used for further dynamic simulations, for example for modeling heat or fluid flows. It contains the important features of an area from a geological point of view – main faults, folds, sedimentary layers, volcanic bodies, etc. – but it also has to match the requirements, e.g. the cell volumes have to be equal, the cells have to be orthogonal and the number of the cells has to be in consonance with the capabilities of the computer. That usually means some ten

thousands of cells in a structural model. The structural model is usually created by coarsening of the geological model.

- In the geothermal science conceptual model is a qualitative model of every important feature of a geothermal system, such as heat and water recharges and discharges. It is not used for calculations.

Although the common principles are the same in the geological models, the realizations are unique. The main difference is the gridding process. Several techniques exist to create the 3D grid. All of these techniques make simplifications and compromises between orthogonal cells and smooth faults and border-lines of the formations. The Petrel software uses the "Corner Point 3D Grid" technique for generating the geological grid in the Pillar Gridding process. In this technique the cells can have curved edges and they are stored in the software by those curvilinear coordinate lines and the depth of the cell corners. The surfaces of the cells can be tilted or curved, so this technique can correctly represent fault plains and formation border-lines (Figure 3.15). But it also has limitations. The gridding of a complex area is very time-consuming; the created grid is not flexible, even if minor changes are needed, and it has problems with complex fault structures, for example Y-faults or low angle faults. The last deficiency originates in how the grid is created.

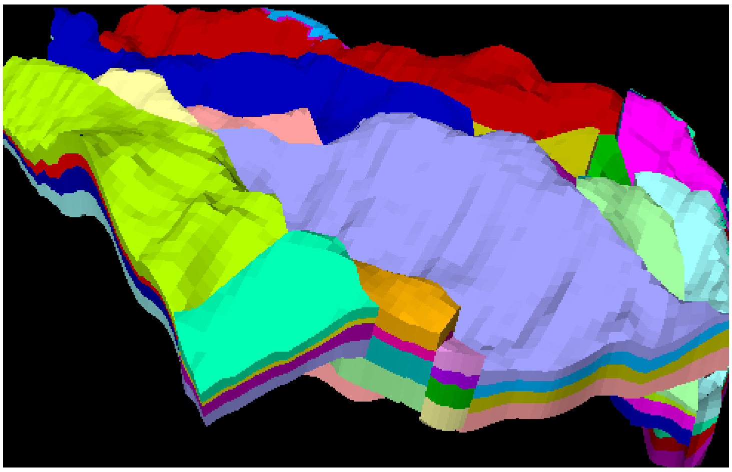

Figure 3.15 Example for a geological grid in Petrel

The coordinate lines of the grid follow the horizons – border-lines of the formations in x-y coordinates –, while they are determined by the Key Pillars of the fault planes in the z direction. For this reason all the Key Pillars of the faults are extended to the upper and lower boundary of the grid. This approach leads to a good quality grid if the fault planes are nearly vertical – or orthogonal to the formation layering – and the faults are nearly orthogonal to each other. Unfortunately this almost never happens in reality. Faults bifurcate and cross each other; secondary faults grow from main faults and fault structures evolve, in which case several fault planes cross each other in a narrow zone. Those phenomena can be the reason for the errors during the gridding process. The user's responsibility is to solve these problems by connecting or truncating faults. Connections of faults means the addition of one common Key Pillar for both fault planes, while truncations means that all the Key Pillars have to be truncated, i.e. terminated, on another fault plane and should not be extended to the grid boundaries. In tectonically complex areas it is typically impossible to incorporate all the faults into the grid. Low angle faults can extremely stretch and rotate the grid (Figure 3.16). If two fault planes cross each other in a low angle intersection line, the result is the same as in a low angle fault because the intersection line must be a key pillar in this technique. Sometimes users have to leave a fault out from the whole gridding process because of the restrictions of the software. For example in Petrel a Key Pillar cannot be truncated by another similarly truncated key pillar – i.e. truncated on the top or in the bottom –, although it is common in the seismic sections in the flower structures.

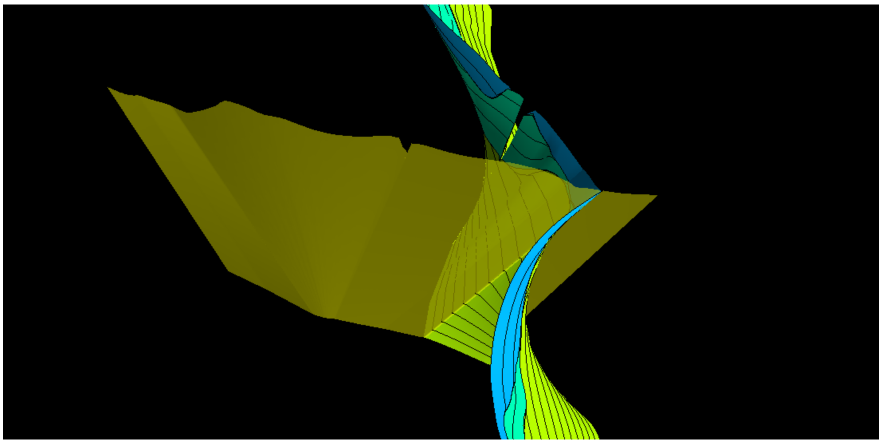

Figure 3.16 Rotation of the geological grid on a tilted fault

To solve these problems the faults have to be redrawn in the Fault Modeling process step.

- First of all, the key pillars have to be parallel to each other and roughly vertical. If not, they have to be redrawn or new pillars have to be created in the same fault plane instead of the old ones. This process can inevitably change the fault plane a bit.
- If a key pillar has to be tilted more than the others in the fault plane – for example a key pillar at a crossing line – the user has to tilt the other key pillars too, in order to smooth the tilt of the pillars from a vertical one until the tilted one.
- If there are truncated faults in the area, then the key pillars of the two fault planes have to be orthogonal to each other in map view to achieve the best result for the gridding process.
- In order to obtain a smooth grid, the top and the bottom ends of all key pillars have to be in the same elevation level.

If it is not enough to smooth the grid, Petrel offers several functionalities.

- The users can give trends for the faults. There are two trends, i and j, and they have to be as orthogonal as possible. If a trend is added to a fault, then one of the coordinate lines of the grid will follow the fault plane. Faults without trends can cut grid cells.
- Trends can be added between faults or between faults and the border of the area or between any two points. The trend-line will behave the same as a fault with a trend, and can straighten the grid lines around it.
- The user can define the rotation angle of the main directions of the grid. The program automatically calculates an optional rotation from the fault and truncation directions, but it can be changed manually.

- The grid points can be manipulated one by one, but this is a very time consuming method if the number of the points – thousands or millions of generated points – is considered.

Petrel also gives an alternative solution for the problem of inflexibility. It divides the gridding process into separate steps. In the first step only the faults will be incorporated into the grid (Pillar Gridding), while creating the top, the middle and the bottom planes of the grid. The surfaces or formation layers are built in only in the next step (Make Horizons). The grid will be three dimensional only after that process. For further refinement of the grid in the vertical direction, zones and layers can be included in the Make Zones and Layering process. There are other features to modify manually or semi-automatically the grid. These features are smoothing, definition of fault-horizon intersection lines, etc. In Petrel surfaces cannot have multiple z values, but the horizons can. If fault-horizon intersection lines are added as a supplementary input parameter to the horizon making process, the reverse faults can be modeled with the multiple z-values.

After this step our model is ready for incorporating the property data. But before any data obtained from a well can be added to any cell of the grid – originally obtained from the seismic sections – the depth of the grid has to be transformed from two-way-time to depths.

4 RESULTS

4.1 The model of the study area

The horizontal extent of the 3D model of the study area is 22.5 km times 31 km and from -2500 milliseconds to about -500 milliseconds vertically. Only fourteen from the fifteen interpreted fault planes of the area were incorporated into the Pillar Gridding process due to the restrictions and difficulties during the creation of the smooth grid. The Make Horizon process was used to refine the grid vertically. The three interpreted horizons and a fourth artificial horizon at -2500 milliseconds depth were used in this process. The top of the model is the base Pannonian horizon. An extra arbitrary horizon above it is not included because the analysis of those geological formations are not included in this thesis and also because the fault structure of the formations above the base Pannonian horizon is different from the fault structure below. It could be a problem during the gridding process because all the faults are extended to the top and the bottom horizons in the Pillar Gridding and Make Horizon process. Thus, the model has 4 horizons and 3 zones between them. It is possible to mark the surfaces that will be used for the refinement as erosional type or base type. The erosional type surface will cut all those parts below surfaces that have higher elevation than the erosional type surface. Both surfaces are interpolated surfaces and therefore this case is very usual. The base type surface cuts the parts of the higher surfaces that are too low. If those parts did not cut by the horizons, it would make problems in the grid; the grid cells would “turn out”. A Layering process was also used for further refinement of the grid into 28 layers. The model has more than 3 million cells with an average size of 110 * 110 * 130 m. This is a geological grid for property modeling – for simulation purposes the grid needs to be coarsened. The intersection of the model with the zones, the faults and the grid lines can be seen on Figure 4.1. The construction of the model was approximately one month.

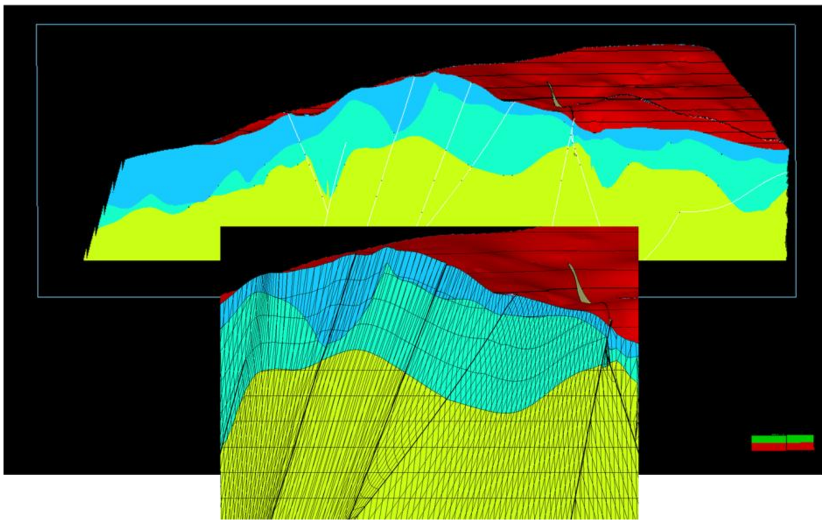

Figure 4.1 Cross-section of the 3D model

4.2 Prospective areas for geothermal fluids

An area is prospective regarding geothermal energy utilizations if a formation with good reservoir characteristics, formation fluid and high temperature is presented at the same place with high probability. At this very first stage of the exploration – no new measurements were acquired in the area and all the surveys were made before by other companies – it is only possible to tell which sites are capable for all the necessary elements of geothermal energy exploitation. In the next phases it has to be proved that those elements are really present at the proposed site and that the project is technologically viable, economically feasible and environmentally friendly.

Although 87% of the thermal wells in Hungary tap the reservoirs in the Pannonian strata, its temperature is too low (30-100 °C, with an average of 68 °C) for economical electricity generation. For this reason this thesis work intended to analyze the deeper basement formations where higher reservoir temperatures are expected. While the porosity of these formations is originally low, only fractured areas were marked as prospective with elevated porosity values due to fractures and fissures. It is also important to find these cracks open. There is a high probability of finding open fractures if the fault that created the fractures is related to extensional stresses or has recently been active.

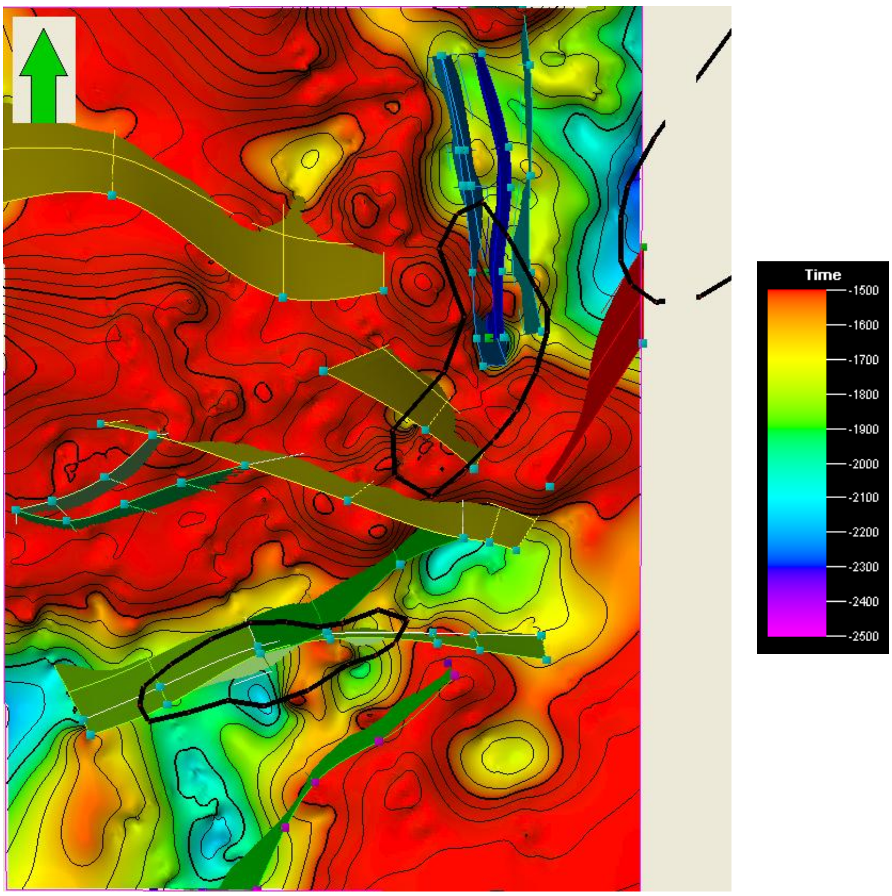

Figure 4.2 Most prospective areas for geothermal energy utilizations – with the top pre-Tertiary surface in the background

The most promising areas for geothermal water exploitation according to this thesis work are shown in Figure 4.2. In both of the cases further research is needed to prove the presence of the resources at the sites and also for the better impoundment of the best prospective areas.

4.2.1 Site Nr.1

This site is located on the northern margin of the depression in the southwestern corner of the study area (Figure 4.3). It is characterized by deep transtensional strike slip faults and the connected flower structure that formed later in a compressive stress field. The affected Pannonian strata suggest that the older deep faults probably reactivated as reverse faults at that time. The thickness of the Tertiary formations at this site is up to 2000 milliseconds, which corresponds to an average 3000m (Tulinius, H., pers. comm.). At that depth the average temperature in Hungary is about 150 °C, which is hot enough for electricity generation. If the deep fracture is located in an upwelling zone, this value can be higher, but if it is situated in a downwelling zone the temperature will be lower – a hydrological flow simulation for the area can resolve this question.

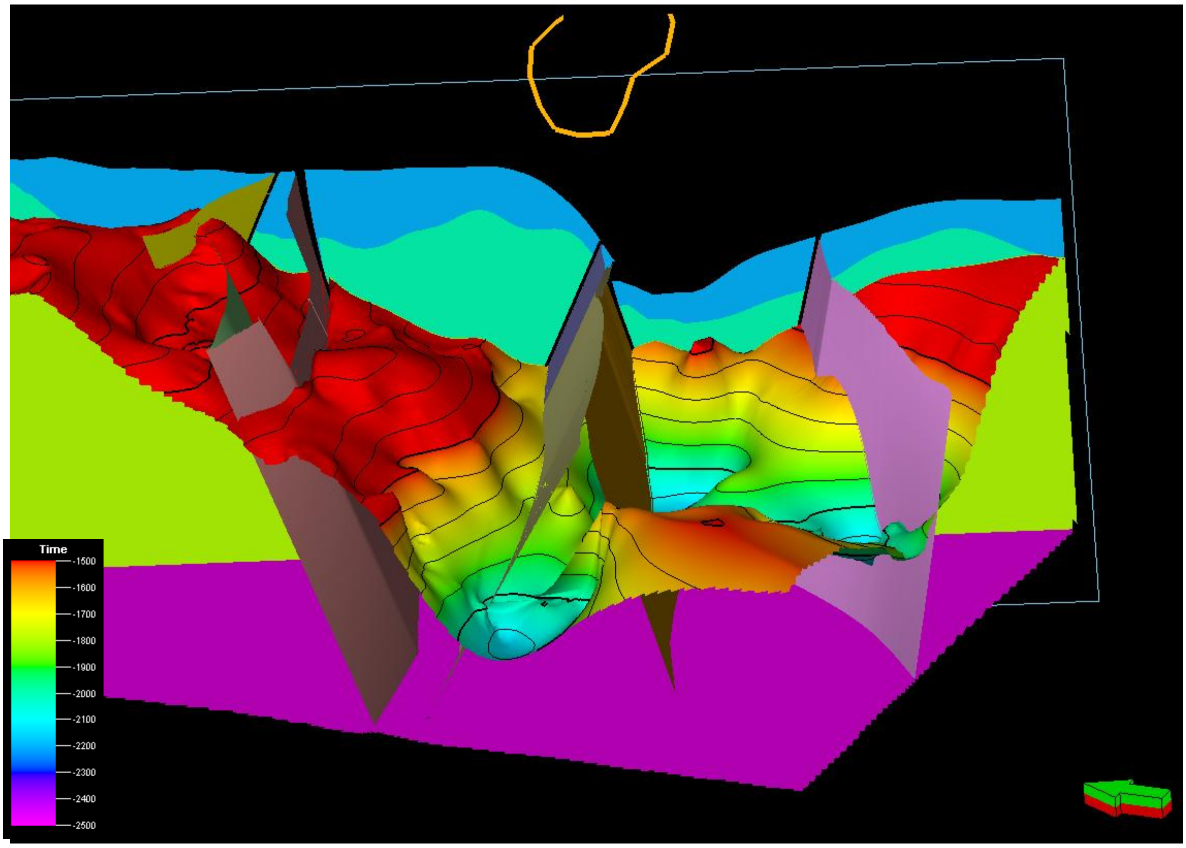

Figure 4.3 Site Nr.1 in the model. View from SW.

The porosity of the site is probably enlarged by the dense fractures and fissures created by the flower structure. The sufficient amount of water recharge can originate from the basement high north from the area. It has a relative elevation of 750 milliseconds – about 1500 m – or a bit further 1250 milliseconds – 2250 m. At this basement high – at a depth of 700 – 800 m – a well was already drilled with geothermal water at 70 °C.

Although those faults are very likely present in the site their compressional origin makes it somewhat more risky to drill into these formations. The created fractures can be squeezed in the compression stress and as a consequence they won't show the expected increase in porosity values. Further exploration is needed. For example, a borehole caliper or image data analysis from the site area could give a more certain solution to this problem.

4.2.2 Site Nr.2

Site Nr.2 is located in the center of the study area and a bit further to the NE. It comprises the western termination of the depression in the northeastern corner of the study area and the area of the elevated basement between the southwestern and the northeastern depressions (Figure 4.2).

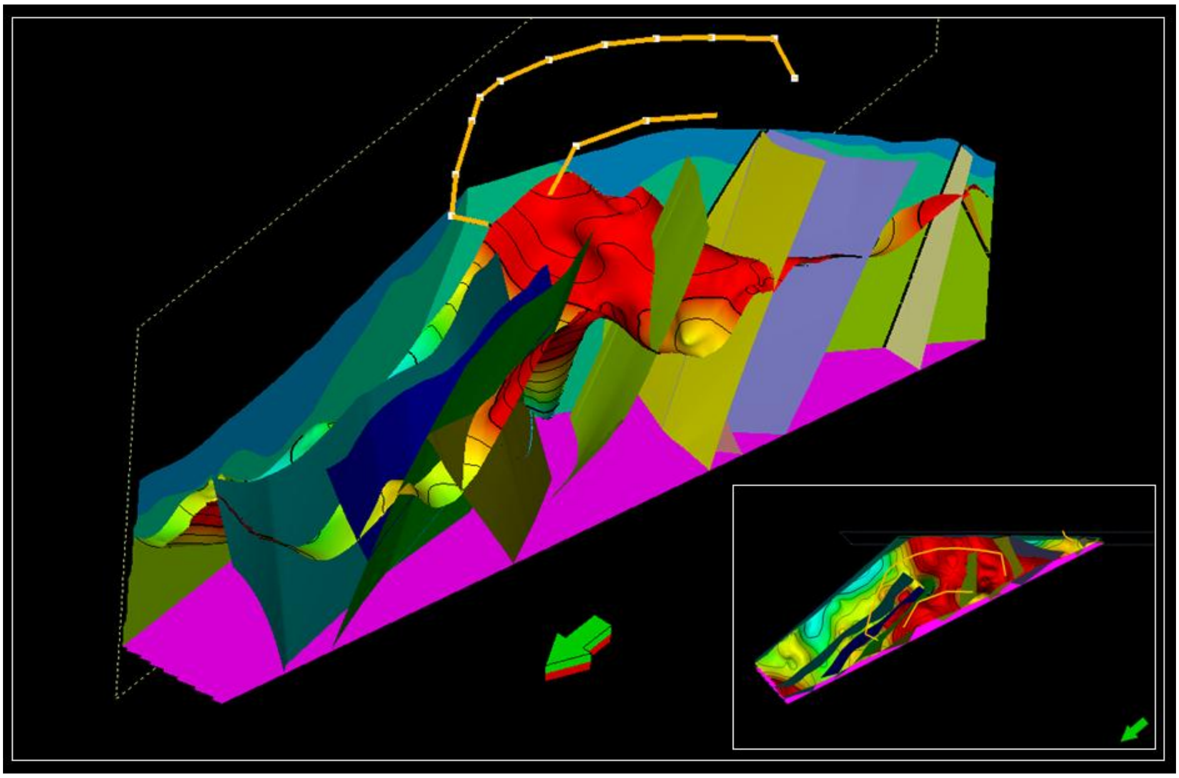

Figure 4.4 Site Nr.2 in the model.

The second proposed site has a more complex tectonic structure than the first site. At this site the faults have three different strike directions and they were formed in several different time periods. The interaction of these faults with different type and strike directions make this site very prospective for geothermal water based electricity generation. At the northern part of the proposed site both the N – S striking faults – for detailed discussion see page 28 – and the SW – NE striking normal faults affected the basement formations and created a very complex structure of fractures. This part of the site might have excellent reservoir characteristics. In the middle an old basement block is situated in an elevated position. This block is cut by old normal faults and uplifted by younger thrust and reverse faults. The southern part of the site is also affected by two fault systems, an ENE – WSW striking flower structure and a WNW – ESE striking thrust, the same one that uplifted the old block in the middle. All these structures probably form one interconnected reservoir (Figure 4.4).

The depth of the pre-Tertiary formations in this site is about 2000 – 2500 m. The uplifted block is located about 1000 m higher.

Due to the complexity of this site further research is also needed in this area.

4.2.3 Site Nr.3

The third prospective site is almost not located inside the boundary of the study area, but two seismic lines cross it. It is located on the southern margin of the northeastern depression and characterized by several parallel north dipping deep normal faults. This area is not included in the model, but the interpreted seismic section that crosses the site can be seen on Figure 4.5.

The faults are more clearly extensive at this site and also show features that suggest an active status of the faults. In this case this area has the lowest risk in future developments.

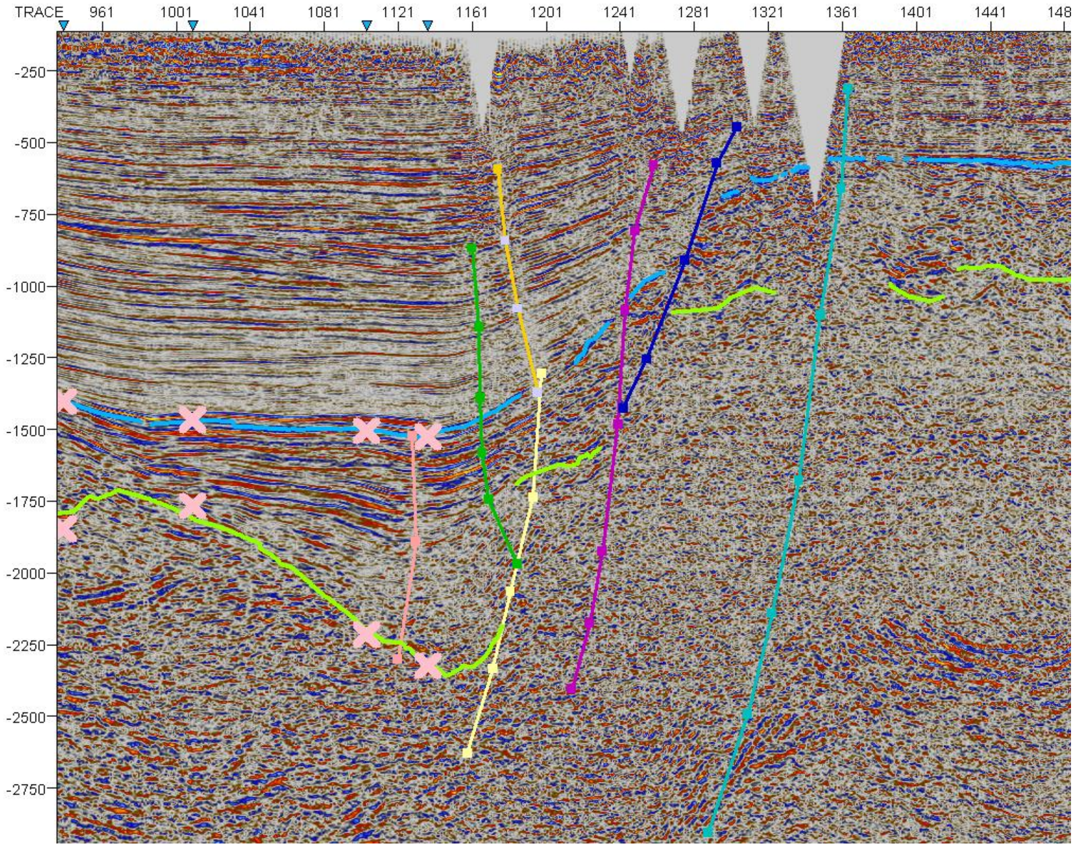

Figure 4.5 Cross section of the third prospective site

4.3 Conclusions of the work

4.3.1 Conclusions of computer supported versus hard-copy interpretation

In parallel with this thesis project, a similar study was made by Mannvit Ltd. An analysis was made of the available seismic sections for the region studied in this thesis and the surrounding regions, for a total area about three times greater than that covered by this thesis. The purpose of their study was the same, to delineate the most prospective sites for geothermal energy exploitation.

Hard-copy seismic sections were interpreted by the company. The seismic sections were printed out in 1:20000 scale. All the cross section lines and well locations close the seismic sections were marked on the seismic sections before the interpretation process. The velocity model for the area was also created by matching the layers in the well geology with the corresponding seismic reflection line. The rest of the wells – those not included in the velocity model – were converted into two-way-time and were also drawn onto the seismic sections. The interpretation of the seismic section and the creation of the velocity model were made simultaneously.

In order to achieve better spatial correlation, the interpreted horizons and faults were entered into a GIS, a Geographic Information System. These systems are usually used to create layered, georeferenced maps with computer support. The site of the drilling and the site of a future power plant needs to fulfill many infrastructural, environmental and technology-related criteria. Of course it has to be in the vicinity of the prospective subsurface reservoir, but it cannot be in the neighborhood of any settlements; it cannot be in nature reservation areas or in water protection areas; and also the road system and the transmission lines have to be taken into consideration when the final locations of the facilities are chosen. This procedure also has to be made if the interpretation and modeling is made by the Petrel software, but the spatial data can be transferred into the GIS software directly, therefore there is no need for digitalizating the analog or image data.

The main difference between the workflows appears in the interpretation of the seismic sections. By using the computer aided interpretation, the horizontal and vertical scale of the seismic sections can easily be changed, as can the visualization between many possible selections. Basic image processing functions can also be used to enhance different features of the seismic sections. It is also easier to change the view to the cross section in order to check the interpretation in another view. The possibility to look at the dataset in 3D space can be of great help when trying to imagine the usually very complex spatial structures.

Different structures can be seen with different visualization methods. It is also good to change the visualization to check the formerly interpreted structures in another view.

The main conclusion of the comparison of the interpreted structures was that with computer supported interpretation much more faults were interpreted than with the manual hard-copy interpretation made by Mannvit. The reason for this is the fact that the resolution of the seismic sections at the deeper parts was low and the larger structures probably disappeared on the quite big seismic sections. Also, the visualization mode of the sections was probably not the best for the interpretation process. The comparison of the interpreted faults can be seen in Figure 4.6. The manually interpreted faults show less variability in strike directions and in the central part of the area they do not have that change in their characteristic that was observed with the computer supported method. The faults in the northeastern corner were also interpreted differently, but only two fault indication points were found at that part of the area by manual interpretation.

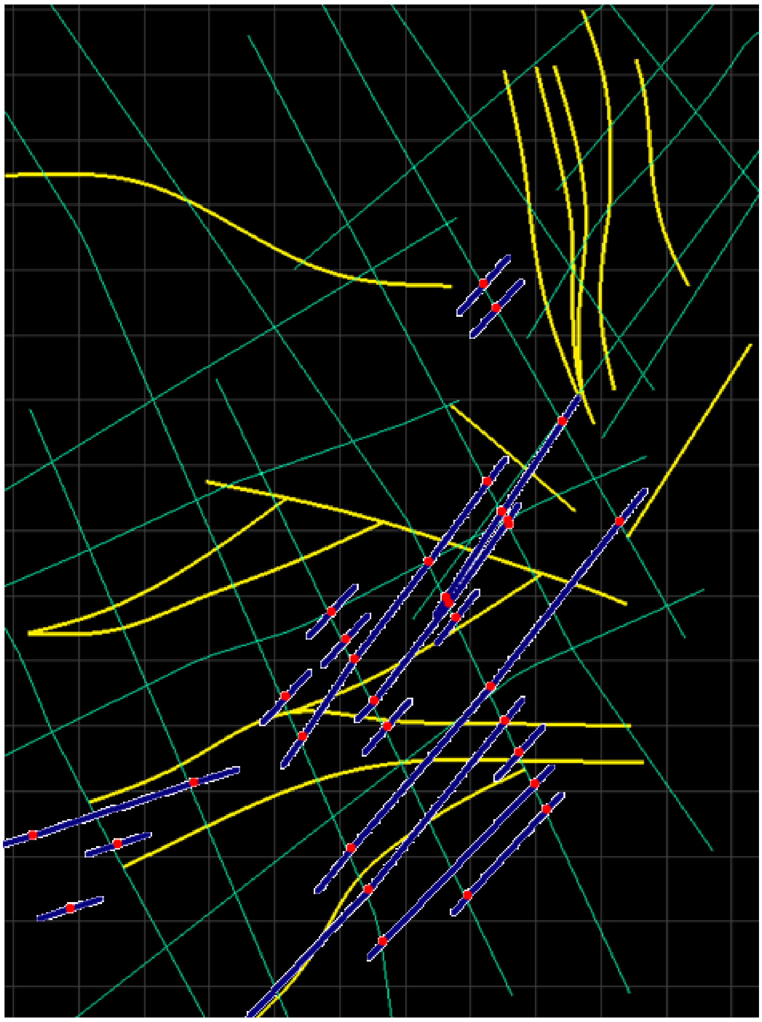

Figure 4.6 Comparison of the faults by manual interpretation (red dots are the fault indication points in the seismic sections and blue lines are the interpreted faults) and computer aided interpretation (yellow lines are the interpreted faults). The green lines show the used seismic sections.

The computer supported and hard-copy interpretations of the base Pannonian and the top of the pre-Tertiary horizons were compared to each other. The seismic reflection at the base Pannonian horizon is very intense; therefore the interpreted horizons were quite similar for both methods (Figure 4.7). There were bigger differences in the detailed interpretation of the top pre-Tertiary horizon due to the poor visibility of that horizon and the complex tectonic structure of the area (Figure 4.8), although the main observed trends are common. In several parts of the seismic sections it was not possible to interpret that horizon with either method.

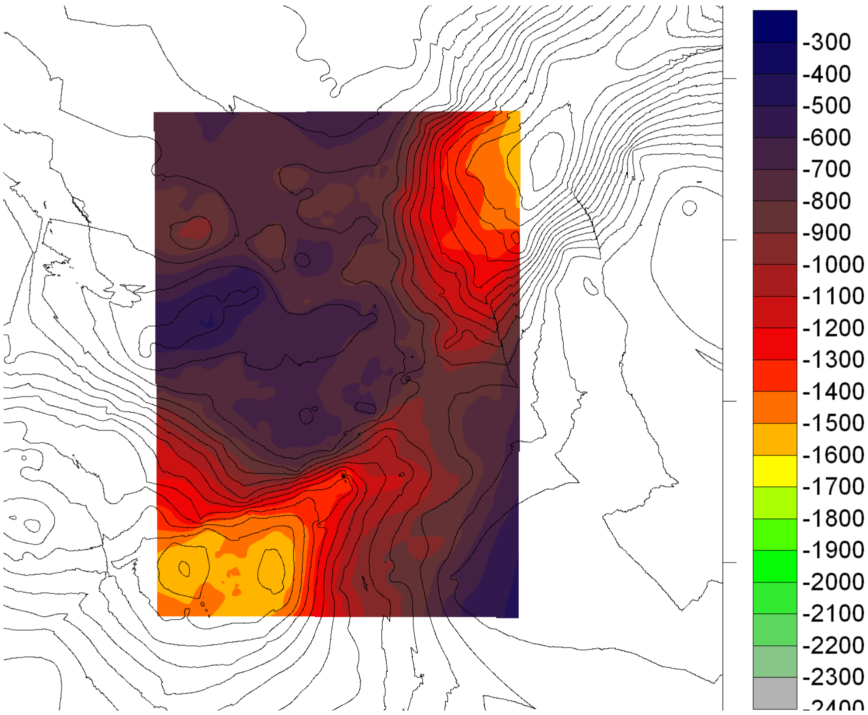

Figure 4.7 Comparison of the interpreted base Pannonian horizon by manual interpretation – contour lines – and by computer supported interpretation – the colored area

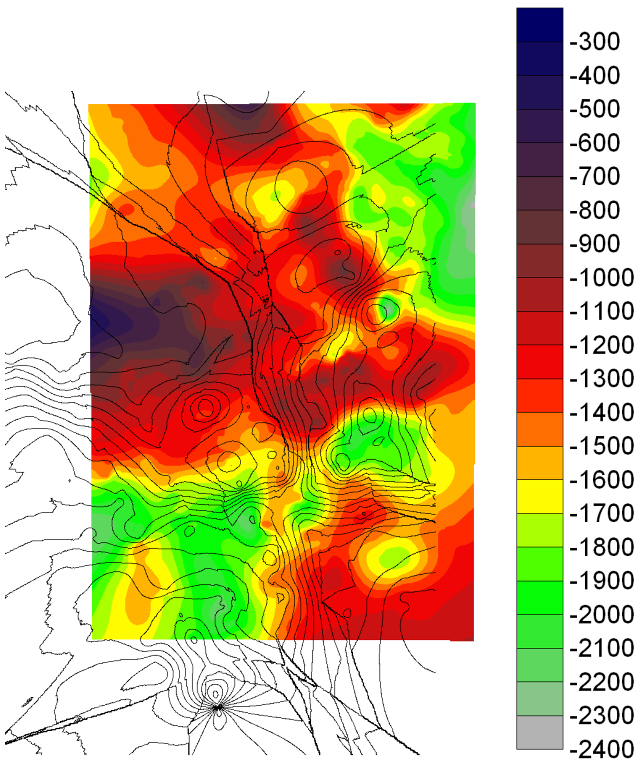

Figure 4.8 Comparison of the interpreted top pre-Tertiary horizon by manual interpretation – contour lines – and by computer supported interpretation – the colored area

The comparison of the prospective areas is shown in Figure 4.9. The difference of the areas is mostly based on the fact that in this study only the seismic sections were used for the analysis. These revealed less certain and therefore bigger areas, but covered whole study area, while the study made at Mannvit used the results of an MT survey as well. This gave more accurate interpretation of the areas, but it was restricted to the MT survey line.

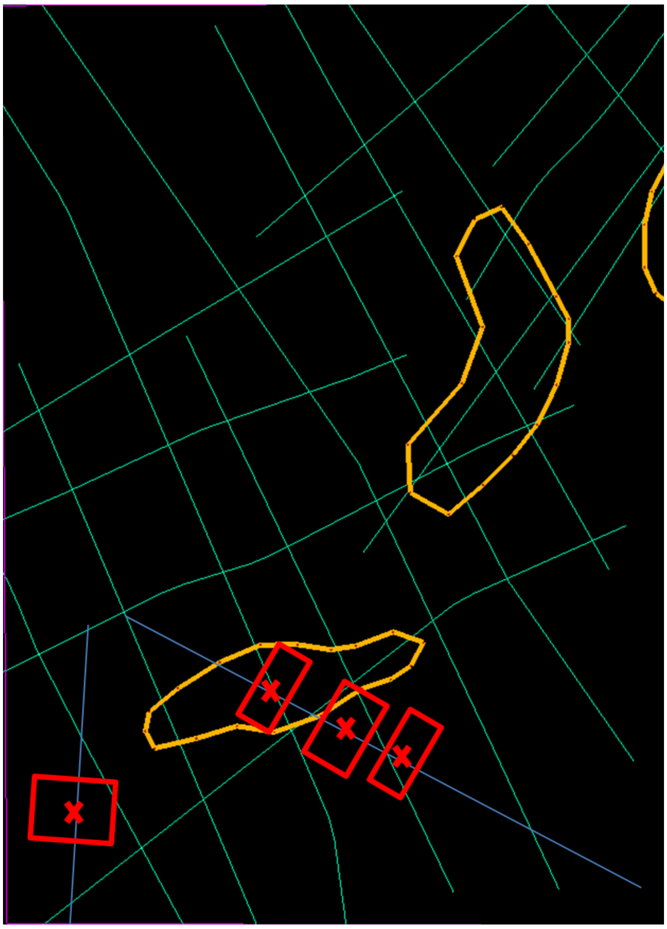

Figure 4.9 Comparison of the prospective areas of this study – yellow polygons, based on seismic section analysis – and the study made by Mannvit – red rectangles, based on seismic section and MT survey analysis. Seismic sections are shown in green, the MT survey lines are shown in blue colors.

4.3.2 Conclusions of model building in Petrel

Although the Petrel software offers several functionalities for creating a desirable grid that fits the structure of the area, the structural modeling remains the most time consuming part of the model building process – including the interpretation phase. It is time consuming because the processes of the structural modeling – i.e. the Fault Modeling, the Pillar Gridding and the Make Horizons processes – "should always be considered together and the user will normally go back and forth between them. Problems with the fault model will often not be obvious before you begin Pillar Gridding, and problems with the pillar grid may not be obvious before you build your horizons in Make Horizons. Similarly, many problems identified when using Make Horizons will require an edit of the Pillar Gridding options or even the fault model." (quoted from the Petrel help file)

5 CONCLUSIONS

NOTE 1:

Based on the study of the geothermal potential in an area located in Hungary, the geological evolution of the studied area was determined to be favorable for the exploitation of geothermal resources in the region. Hungarians already use that potential in direct utilizations, such as balneology and heating in the agriculture sector. However, despite the elevated potential the number of modern geothermal utilizations that can replace the usage of polluting hydrocarbons is low.

NOTE 2:

Three different areas were delineated as the most promising sites for geothermal reservoirs in the basement formations. Two of them are entirely included in the study area, while only a marginal area of the third one is located in the study area. Those areas were selected where the seismic interpretation revealed fractured basement rocks, where the possibility of an open deep fracture and the fractured rock volume in drillable depths were found to be presented.

NOTE 3:

A 3D geological model was made to support the determination of those sites. For this purpose the Petrel seismic interpretation and simulation software were used and the whole procedure was done in that computer aided environment.

NOTE 4:

Faults with different age, type, strike direction and depth were interpreted on the seismic sections. In several areas these faults were superimposed onto each other, which could create elevated secondary porosity in the basement formations, which is paramount for good reservoir characteristics.

NOTE 5:

Further research and exploration works are needed to answer to those questions that were not answered by this study, such as

- What is the best place for drilling?
- Are there sufficient water reserves present in the areas?
- Is there any negative effect that cools down the waters from the expected temperatures?

NOTE 6:

Comparing the computer supported interpretation to the analysis of hard-copy seismic sections, the benefit of the computer is clear. It can offer numerous functionalities that highly promote and speed up the interpretation process.

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APPENDIX A – BACKGROUND INFORMATION ON SEISMIC DATA AND FAULTS

Seismic data acquisition

Seismic data are among the several types of geophysical data that are used by geoscientists to find hidden, subsurface structures. This data is obviously important in the mining and oil industry, but can also be useful in many other fields of application. It is important in any kind of undersurface construction, but can also be useful in the construction of earth-quake safe buildings. Shallow seismic sections are used in flood-protection and agriculture, and deep seismic lines reveal the deep lithospheric structures of an area while helping to understand the processes that take place inside the Earth.

Seismic data acquisition is done by using flexible seismic waves to gather data. The seismic waves are generated artificially. At first researchers generated waves by blasting in shallow wells. Today they use vibrations – usually with different frequencies – for wave generation. Seismic waves have the same physical properties as sound waves – at least the properties that are used in seismic surveys. The artificially generated seismic waves penetrate the surface layers of the Earth and reflect, refract or diffract on layer boundaries and return to the surface. These effects take place only if the seismic wave velocities at the two sides of the boundary are different. The returning waves are recorded on the surface a distance away from the wave source by geophones. The recording mechanism is based on the conversion of the gentle movements of the surface into electrical impulses by a suspended magnet in a fixed coil. (Figure 0.1) According to the newest developments some units use MEMS (Micro Electro-Mechanical Systems) technology.

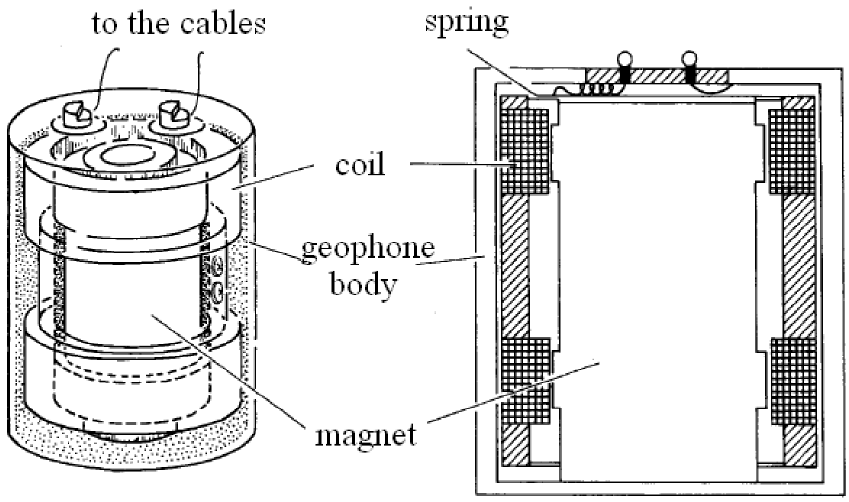

Figure 0.1 Geophone (modified after Meskó 1994)

The recorder units are usually arranged in a line to gather a 2D section of subsurface layers perpendicular to the surface along the line. If more parallel recorder lines and more wave sources are used, researchers can gather 3D seismic cubes of the study area.

Seismic surveys are classified by the physical effect used during the data acquisition. In refraction seismic the waves go along layer boundaries, while in reflection seismic researchers are interested in the waves that reflect off these boundaries. After the acquisition of data, pre-processing is needed to emphasize the important data and reduce the random and systematic errors. Random errors are white noise and background noise, while systematic errors are, for example, multiple reflections and interferences. There are sophisticated techniques for cleaning the data, such as filtering and summation of different channels. The interpretation process starts after all these procedures.

How seismic lines look like?

A seismic section looks like Figure 0.2 up close:

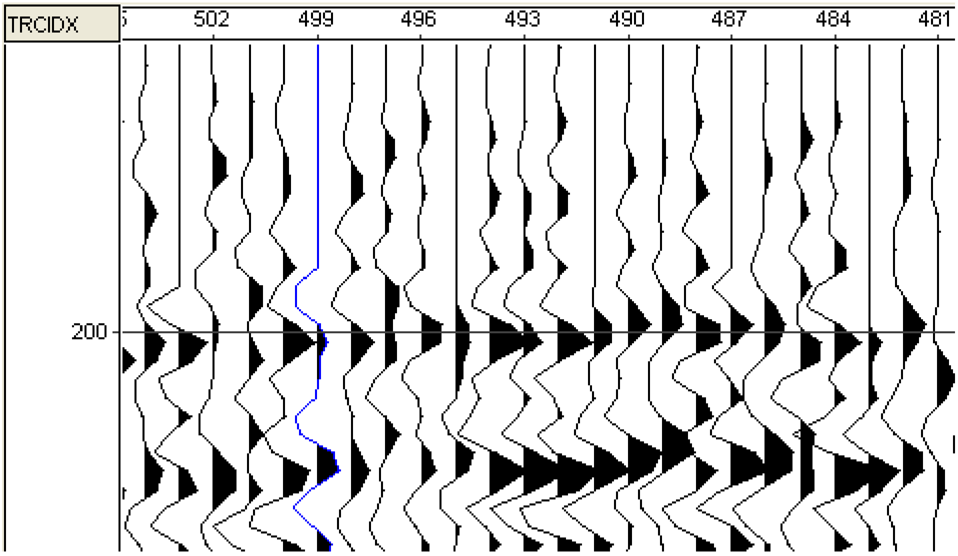

Figure 0.2 Seismic section at a close view

The traces can be found on the x axis. One trace represents one geophone location. The two way time (TWT) is on the y axis. It is the corrected time that is needed for the seismic wave to return from a specific depth if the wave source would have been in the place of the geophone. Every trace line then shows the recorded movements of the surface versus this corrected time. If there was a boundary at a specific depth under the surface the reflection wave that was reflected from that specific boundary will cause movements on the surface. These movements are recorded by the geophones. The amplitude of the trace line at a specific time is proportional to the amplitude of the surface movement caused by the reflected wave.

In visualization the trace lines are put close to each other. If a specific boundary can be seen in more trace lines, they are fused together and we can only see a line if we see the seismic section from a distance (Figure 0.3).

By now it is obvious that geological formation boundaries – called horizons – are shown as lines in the seismic sections, but what distinguishes faults? Faults can only be seen in the seismic sections if they caused the two sides of the fault to move compared to each other. In that case the fault can be seen as an abrupt stop in the horizon. In the case of pure normal or reverse faults, the same horizon sequence can be found on the two sides of the faults, they are only shifted vertically. If the fault has a strike-slip component as well, which is the most common case in study area of this thesis, different horizon sequences might be present at the two sides of the faults.

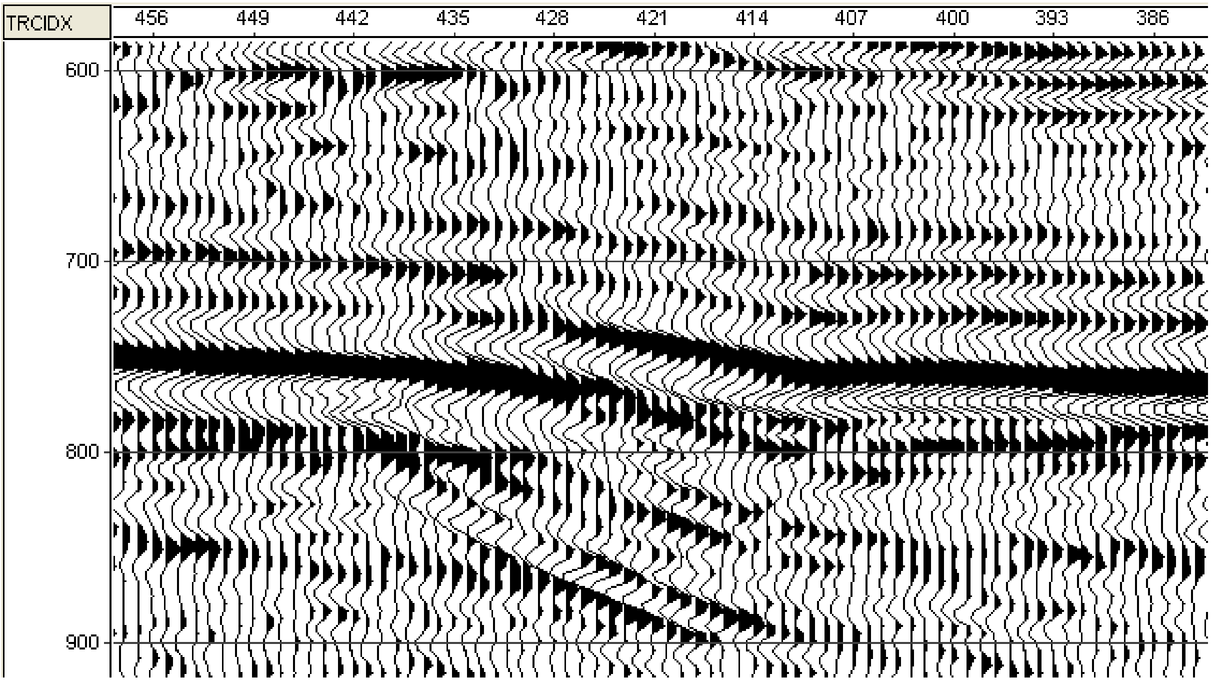

Figure 0.3 Seismic section from a distance

There is one major problem with the seismic sections. They do not give any information about the real depth of the indicated boundaries. The only thing that can be determined is the time that was needed for the seismic wave to return from that boundary. The solution for this problem is not easy. The seismic wave velocities are different in different layers and can also differ even in one layer due to inhomogenities.

The common solution for the problem is to correlate the boundaries that have been found on the seismic lines with borehole geology data from a nearby well. In professional life researchers use the following method: they make a borehole seismic survey in the borehole to find out the seismic traveltime from a known depth to the surface, then the two way time will be the twice as the measured. This is called a check-shot survey. If there are enough check-shots from the study area, the interpolation of the seismic two way times between check-shots can be sufficiently accurate.

Forces, stress-fields, and faults

From the online Schlumberger Oilfield Glossary a fault is “A break or planar surface in brittle rock across which there is observable displacement. According to terminology derived from the mining industry, the fault block above the fault surface is called the hanging wall, while the fault block below the fault is the footwall.”

There are three main types of faults which exist in theory: normal faults, reverse faults and strike-slip faults. In a normal fault the hanging wall moves downward relative to the footwall, while in reverse faults the hanging wall moves upward. At strike-slip faults the blocks at the two sides of the fault only move horizontally along the fault plain; there is no vertical displacement. A strike-slip fault is called dextral if the block across the fault moves to the right and it is called sinistral if the block across the fault moves to the left (Figure 0.4).

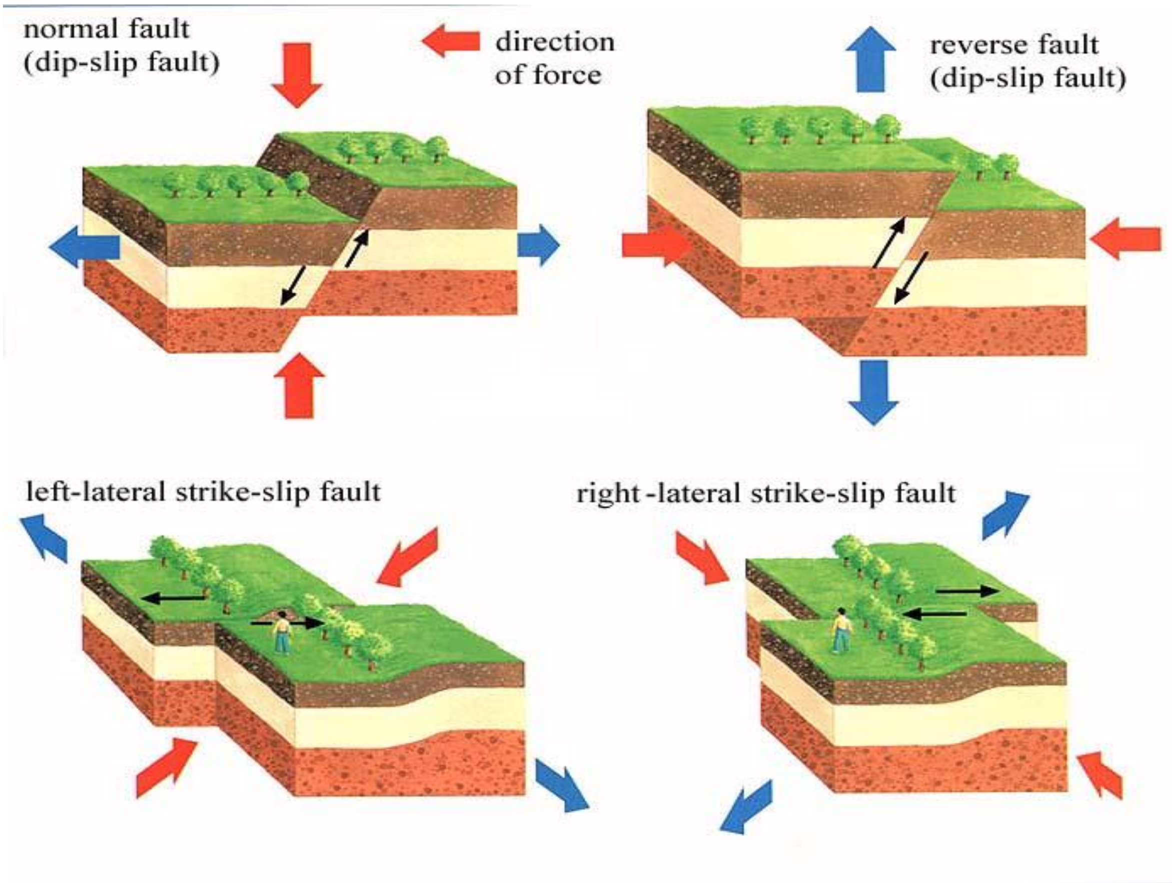

Figure 0.4 Connection between the orientation of the stress field and the resulted fault structure

The difference in the type is the result of the apparent stress field. If the stress field is compressive the space gets shorter in the direction of the strongest compressive force. That stress field causes reverse faulting and thrusting with a strike direction perpendicular to the direction of the strongest compressive force and normal faults when the strike direction is parallel to it.

If the stress field is extensive – and the strongest compressive component is vertical – the space dilates. This stress field causes normal faulting with a strike direction perpendicular to the direction of the lowest compressive force, i.e. the direction of the maximal extension; and also causes a normal fault perpendicular to the former ones.

The directions of the forces of a stress field that causes strike-slip faulting are shown in the Figure 0.4.

If the directions of the main stress-field components are not parallel or perpendicular to the surface, the above cases can mix. In a transpressive stress-field strike-slip faults have a normal component; and in transtensive stress-field strike-slip faults have reverse component.

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