GeoConnect³d

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# Deliverable 5.2D

# Lessons learned from the Pannonian basin


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# 1. Pilot area description

## 1.1. Traditional geological descriptions

The Pannonian Basin is a young, Neogene basin system on the top of a complex Paleo-Mesozoic crystalline and sedimentary sequences within the Alpine-Carpathian-Dinaridic orogene system. It is built up of numerous sub-basins of slightly different age, and core complexes and emerged island mountains forming its basement.

The geodynamic and plate tectonic evolution of the Pannonian Basin and its basement can be divided into two main phases. The first, longer period - call it here as *Pre-Pannonian phase* (Phase I)- started in the middle Permian and ended in the early Miocene. It is related to the formation of the Alpine orogenic system (Figure 1) by the collision of the stable European Platform and the Adriatic microplate of the African Plate (Argand, 1924, Channell & Horváth, 1976). The collision resulted in complex suture zones of different ages, nappe systems of different vergency, numerous crustal blocks and several oceanic crust fragments that form the basement of the later formed Pannonian Basin.

The second phase – called here as *Pannonian phase* (Phase II)- started sometime in the early and middle Miocene and lasted until recent times. The formation of the back-arc type Pannonian Basin as a young intramountain basin and the main structural phases of the basin evolution can be explained by a thermo-mechanical and isostatic compensational model of Mckenzie (1978). Accordingly we divide the basin forming process (Pannonian phase) into two significant parts: the so called Synrift phase (Phase IIA) and the Postrift phase (Phase IIB).

In the *Synrift phase* (Phase IIA) lasting from Eggenburgian to middle Badenian the roll-back effect of the the subducting slab (Dewey 1980) caused pull force, which led to an extension in the crust, consequently an upwelling of the asthenosphere (Royden & Horváth, 1988). The amplitude of extension was several hundreds of kilometres, with a rate of approximately 1.4–1.6% for the whole territory in the lithosphere (Lenkey, 1999). In practical terms, the subsidence was due to the isostatic movement of the attenuated and low-density crust. The extension activated the fault planes of nappe systems, and the previously buried basement core complexes emerged and moved along listric and steep normal faults originating a very complex system of grabens and half-grabens (Figure 2) (Horváth et al. 2006). Coevally the megatectonic units of the basement were rotated oppositely in several phases: 80º CCW and 100º CW respectively (Márton & Fodor, 2003, Márton et al. 2007, Fodor, 2010). Siliciclastic sequences were deposited in the inner parts of the basin in considerable thickness, while only in limited extension at the shorelines (Figure 2).

The isostasy induced sinking reached balance in the Late Miocene, which resulted in a cooling of the crust, and led to a thermal induced subsidence phase, called as the *Postrift phase* (Phase IIB) (Horváth, 2007). The beginning of this Postrift phase is not contemporaneous in the Pannonian Basin, but generally started from the end of Sarmatian. The docking and collision of main units in the basement resulted in the fall of extensional forces and a quick basin inversion (Horváth, 1995). This post-Sarmatian inversion resulted in the folding of synrift deposits and erosion at certain parts of the basin. In contrast 5000–7000 metres thick sedimentary sequences accumulated in other parts of the basin as a result of the gradual filling up of Lake Pannon with terrestrial sediments deriving from the coevally uplifting Carpathains (Figure 3). At this stage the deformation regime was characterized by low amplitude strike-slip and normal faults, and with atectonic compaction.

At the beginning of the Pliocene, subduction was practically terminated due to the gradual rise of the subduction dip angle and a northern compression of the Adria microplate that rotated counterclockwise (Bada et al. 2007). As a result of all these processes, a compressional stress field developed within the Pannonian Basin. The subsidence turned into an inversion in the mountainous area, while subsidence of deep sub-basins still continued (Horváth, Cloetingh, 1996). According to in situ stress measurements (Gerner et al. 1999), space geodesy methods (Grenerczy et al. 2005) and model calculations (Bada et al. 2007), this stress field is still active in the recent times.

As a result of the above summarized complex evolution, the Pannonian Basin itself - apart from the Vienna and Transylvanian Basins - is a geologically well-defined structure, with different sub-basins, such as the Kisalföld (Small Hungarian Plain or Danube Basin), the Styrian Basin, the Drava- and Sava basins, the Mura-Zala basin, the Eastern Slovakian Basin, and the Alföld (Great Hungarian Plain) with several deep depressions, such as the Jászság-, Derecske-, Békés basins and the Makó Trough (Figure 4).

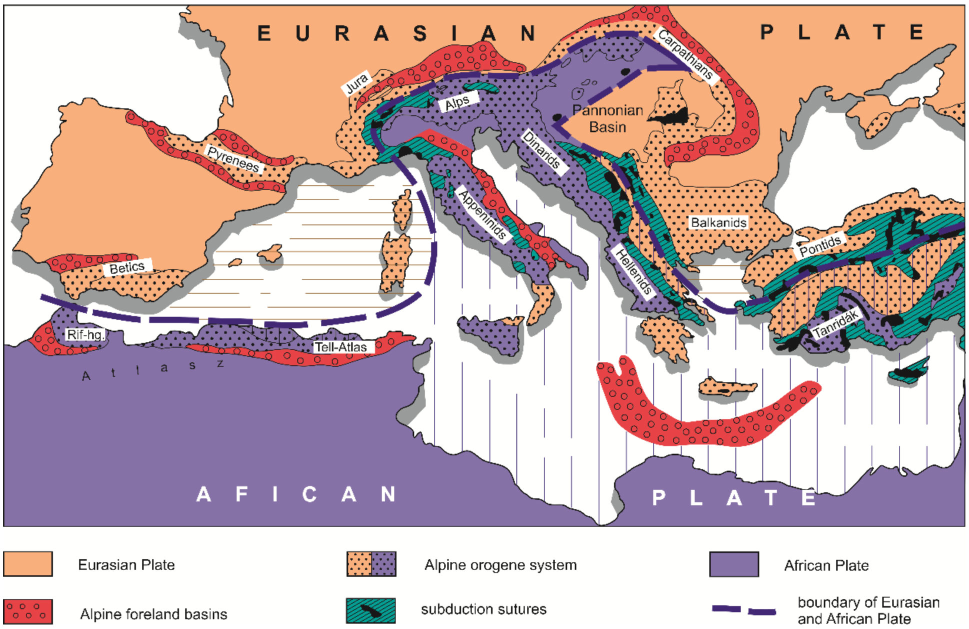


**Figure 1: Geotectonic position of the Pannonian basin within the Alp-Carpathian-Dinaride system (after Haas et al. 2002)**

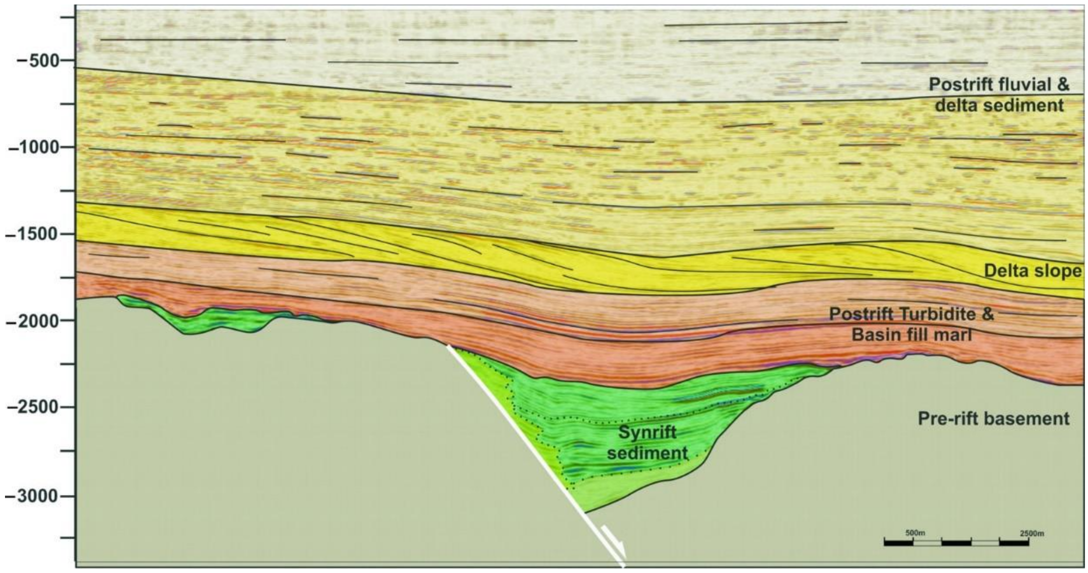


**Figure 2: Typical synrift halfgraben structure with its postrift cover (interpreted seismic profile)**

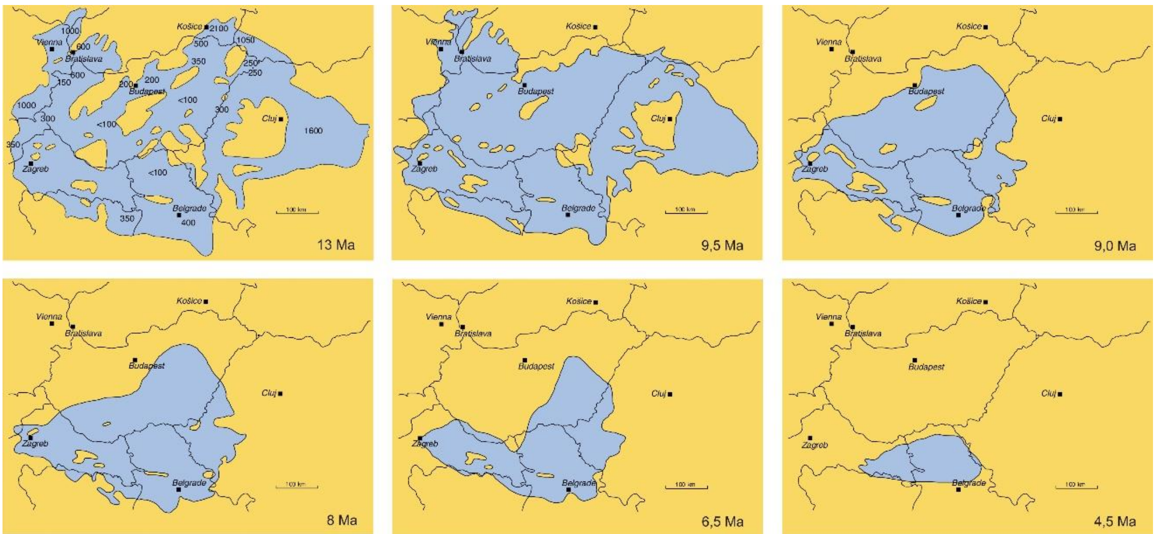


**Figure 3: Evolution of the Lake Pannon (after Magyar et al. 1999)**

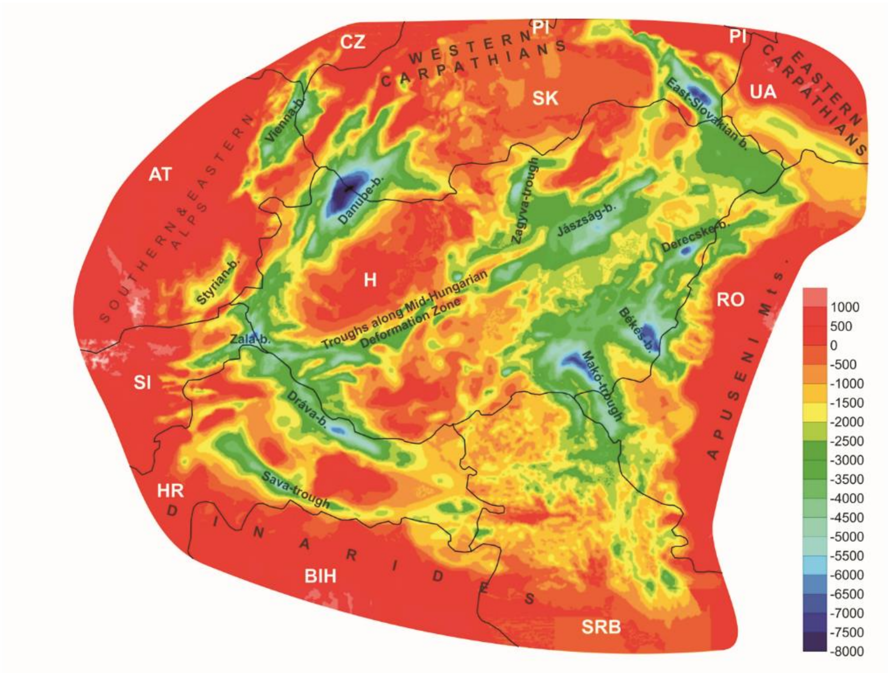


**Figure 4: Main sub-basins in the Pannonian Basin and their depth conditions (Budai & Maros 2020)**

Within the entire Pannonian basin the study of geomanifestations was carried out in 3 pilot areas: in the Mura-Zala basin (Slovenia, Croatia, Hungary), Battonya High (Hungary, Romania) and the Northern Bosnia & Herzegovina territory (Figure 5). As they are situated at various parts of the Pannoninan Basin, their geology is slightly different:

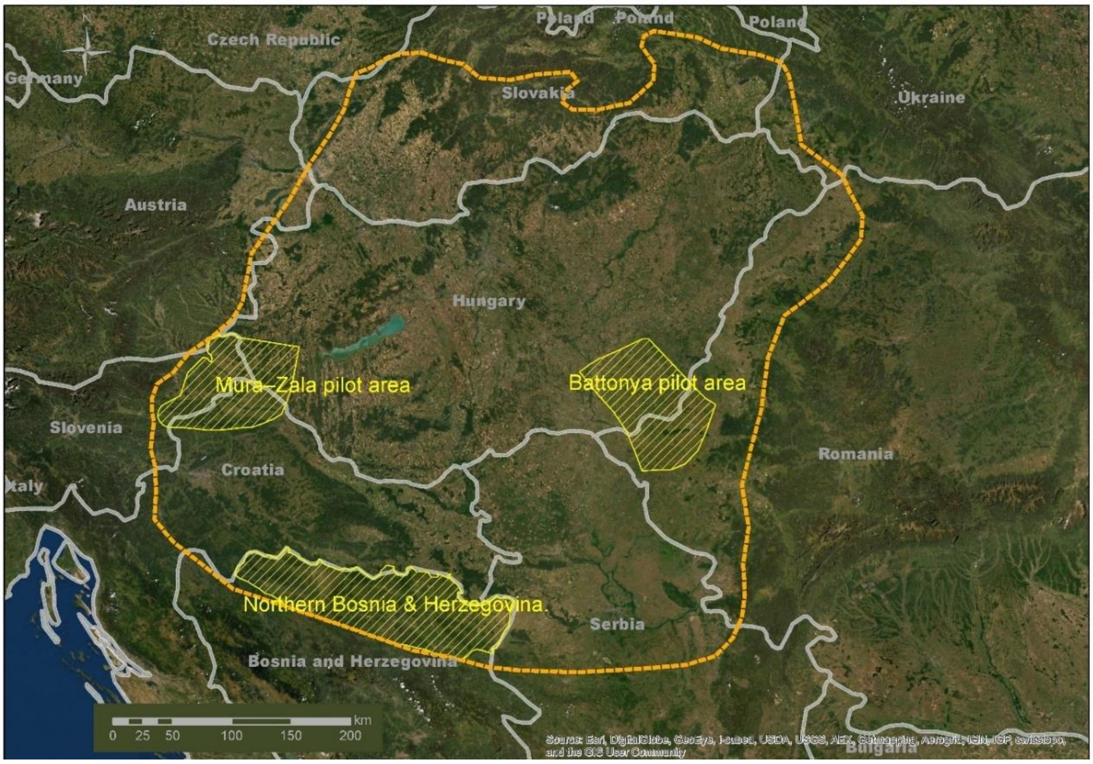


**Figure 5: Location of the 3 pilot areas for the study of geomanifestations within the Pannonian Basin**

In the *Mura-Zala basin,* the basin fill Neogene sedimentary succession has a thickness of 2-3 km on average and reaches its maximum (appr. 5 km) in 2 sub-basins / trenches, whilst the minimum (appr. 1 km) is found above a basement high (Figure 6). The area is characterized by a dense pattern of basement faults, identified in the GeoConnect3d project, showing strong correlation with identified geomanifestations (see Chapters 2 and 3). The largest subsurface use here is represented by exploitation of thermal waters.

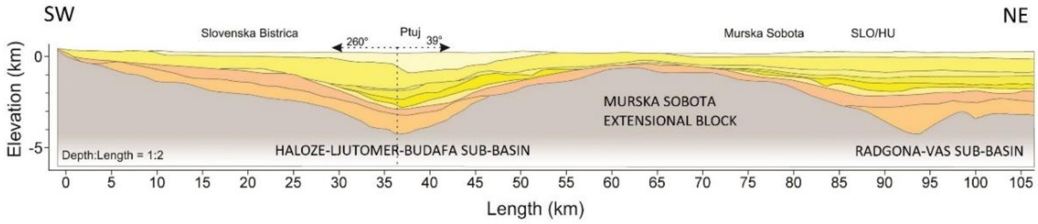


**Figure 6: Geological cross-section with Neogene formations as modified from Šram et al. (2015). The sequence from the surface down is: Ptuj-Grad Fm., Mura Fm. (2 units), Lendava Fm. (2 units), Špilje Fm. (2 units), Haloze Fm. and basement rocks.**

A metamorphic core complex is found in the centre of the *Battonya pilot area*, which is surrounded by two very deep sub-basins which had various depression and emerging history. The buried Battonya–Pusztaföldvár High (basement ridge) is built up of nappe structures, in which the material of a metamorphic basement nappe overthrusted to the Palaeo-Mesozoic sequence by northern, north-western direction. The basement rock masses slipped down along detachment faults gravitationally from the Battonya High in the syn-rift phase of the development of the Pannonian Basin and now forms the basement of the Makó and Békés basins (Horváth, Rumpler 1984, Nemcok et al. 2006, Tari et al. 1999). (Figure 7). Nevertheless, this flat area is far from the borders of regional geological units, therefore identified geomanifestations are mostly linked to various geo-energy exploitations (geothermal boreholes, hydrocarbon fields) and do not show such a strong correlation with structural framework.

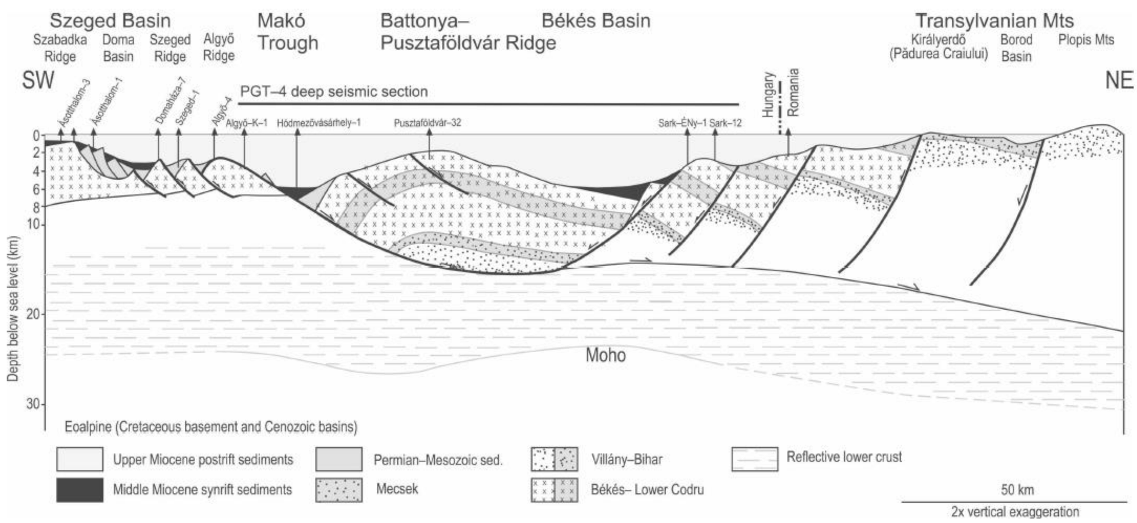


**Figure 7: Regional geological profile in the south-eastern part of the Pannonian Basin (adapted from Tari et al. 1999)**

The *N-ern Bosnia and Herzegovina pilot area* is located on the southmost edge of the Pannonian Basin. It is characterized by a limited sedimentary basin fill sequence and a very complex geological and tectonic basement structure (Hrvatović, 2006) that has led to the existence of numerous geomanifestations in this area, most often related to regional faults among which is the largest Spreča - Kozara fault.

## 1.2. Specific challenges

The Pannonian Basin is a geologically well-defined structure and comprises areas of 9 countries with Hungary lying in its centre, surrounded by territories from Slovakia, Austria, Slovenia, Croatia, Bosnia and Herzegovina, Serbia, Romania and Ukraine (Figure 4). This special position raises several challenges:

1. Geological challenges cover a wide range of contests, including: (a) the hugely alternating level of knowledge of the subsurface at different parts of the basin, (b) different and unharmonised geological nomenclature (e.g. different formation names that impede regional stratigraphic correlations), (c) varying data policies (public geoscientific data are rarely available, many subsurface data are confidential).

2. Obviously, the similar geological structures pre-define common type of the various geo-energy resources (e.g. common types of hydrocarbon traps, common forms of deep geothermal resources / geothermal aquifers, etc.) irrespective of state borders. The individual (at national level) use of these resources – especially near the border regions – can initiate conflicts: e.g. extensive abstraction of thermal water may cause drop in hydraulic head in the neighbouring country. Exploitation of diverse geo-resources might have impacts also on each other. One example is thermal water production (widely spread in the Pannonian Basin, including all 3 pilot areas as well): emissions of waste thermal water into surface streams or shallow groundwater might affect quality of drinking water resources, Another example is hydrocarbon exploitation that might possibly affect geothermal aquifers to some extent. The harmonised management of these resources requires a common understanding of the subsurface, i.e. a consistent 3D geological model / a common structural framework for the entire basin.

3. Countries covering the territory of the Pannonian Basin are mostly EU Member States (Hungary, Slovakia, Austria, Slovenia, Croatia, Romania), however there are Accession Countries (Serbia, Bosnia and Herzegovina) and so-called Neighbouring Countries (Ukraine). This different geo-political situation is reflected in the “maturity” of energy policy issues (i.e. common EU framework providing a binding context for the Member States – i.e. preparation of National Energy and Climate Plans with mandatory targets and measures, whilst less strict though sometimes ambitious energy strategies for the non-member states).

## 1.3. Subsurface management challenges

Although various geo-energy resources – especially deep geothermal energy, including the rich thermomineral waters, and conventional and unconventional hydrocarbons – are widely used in the Pannoninan Basin, their interactions have hardly been studied, despite some play types significantly overlap (Figure 8, Figure 9). A slight exception is related to the use of different secondary (e.g. water injection) and tertiary (e.g. fracking, acidization) technologies used by the hydrocarbon industry to enhance oil recovery (EOR). Nevertheless, these EOR technologies are applied at local scales, and their subsurface impacts – if at all – have also been studied at local levels. Regional interactions among hydrocarbon and thermal water production (e.g. changes in the pressure field) have not been assessed so far.

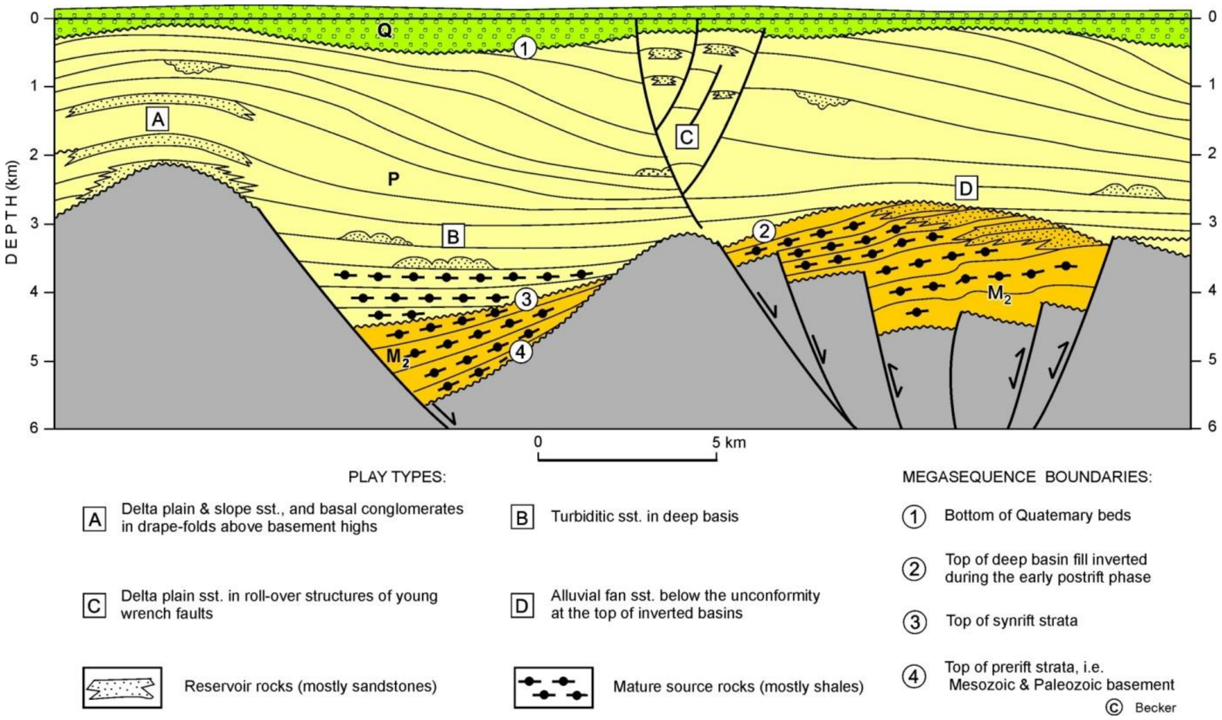


**Figure 8: Petroleum systems of the Neogene basin fill on the Great Hungarian Plain (Tari and Horváth 2006). Delta plain sediments (play types A and C) are the main thermal water bearing units at the same time**

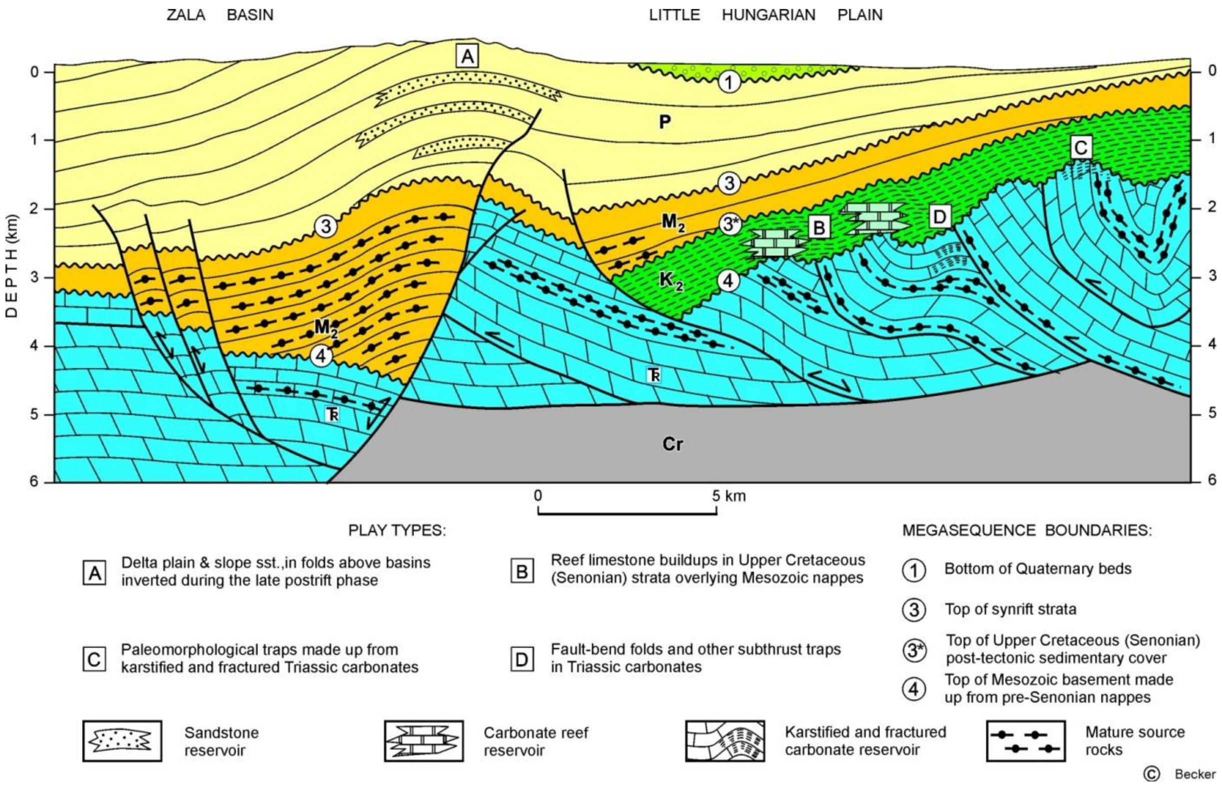


**Figure 9: Petroleum systems of the of the Neogene basin fill in the Zala basin (SW-Hungary) and in the basement of the Little Hungarian Plain (Tari and Horváth, 2006). Delta front sediments (play type A) and carbonates with enhanced porosity (play types B and C) are the main thermal water bearing units at the same time**

In the western part of the Pannonian basin, at Radenci area in Slovenia, $CO_2$ gas seepage resulted in the formation of mofettes and mineral water. There is a large natural mineral water exploitation for bottling, and an issue emerged already in the past, whether the mineral water production (water with lots of free $CO_2$) can affect the mofette flux, as they are protected as natural valuable features.

Exploitation of thermal waters in west part of the Pannonian basin has also been widely debated and some numerical models of the Neogene sedimentary fill were elaborated (Szőcs et al. 2013; Tóth et al. 2016). Not much focus was yet applied to the basement aquifers, and the need for joint management of all transboundary geothermal resources is still very evident.

## 1.4. Starting material

The term of geomanifestations was initiated by Barros & Pissens (2020) as "To define any distinct local expression of ongoing or past geological processes. These manifestations, or anomalies, often point to specific geologic conditions and, therefore, can be important sources of information to improve geological understanding of an area."

The GeoConnect³d structural framework is composed of *limits* (broadly planar structures such as faults and unconformities) and *units* (bodies such as orogens and grabens), which are referred to as structural framework *elements.*

The two-step Structural Framework- Geomanifestations methodology is summarised in D.4.2. and its adaption to the Pannoninan Basin is shown on Figure 10.

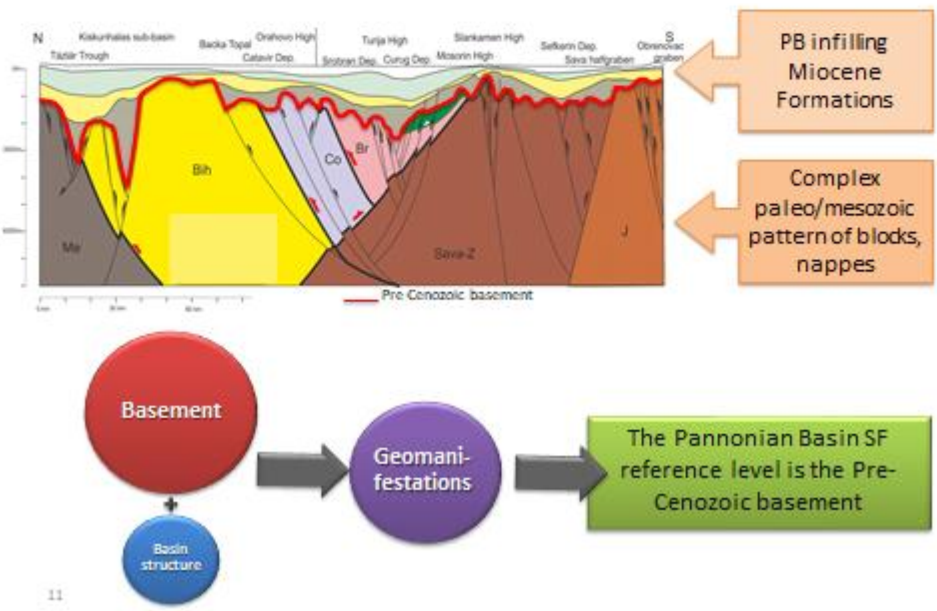


**Figure 10: The adaptation of the Structural Framework-Geomanifestations methodology in the Pannoninan Basin**

# 2. Adopting the Structural Framework and Geomanifestations

## 2.1. Adopting the Structural Framework

The Pannonian basin is in a special situation from the point of view of the structural framework. The area of interest (AOI) is the outline of the basin area. This area is composed of mostly terrigenous basin fill sediments of the different sub-basins, grabens, half-grabens with sporadic island mountains of Pre-Cenozoic and Paleogene formations. The theoretical structure of the Structural Framework which is built up from Units of different geological origin and constitution was hardly adoptable for the Pannonian Basin, because of the very similar sequence of the infilling (basin fill) sediments, which though slightly vary within entire AOI. This identical facies of the basin fill sedimentary sequence is characteristic from the upper Miocene to the recent times. A probable division of the basin-fill sequences into different sub-basins of the area would have been problematic as well, because the different sub-basins formed at slightly different times and – though the infilling processes and patterns were similar within the Pannonian Basin as a whole – have slight variations.

For these reasons it was decided to build the structural framework for the reference level of the Pre-Cenozoic basement top (Figure 10). Under this level a multistage structurally deformed (even in the Cenozoic times) and very diverse Unit hierarchy system can be found with well defined Limits. The difficulty and challenge of the compilation of the Structural Framework for the Pre-Cenozoic level is caused by the thick Neogene cover of the subsided basement Units that are known mostly from the island mountainous area and from deep boreholes. The Limits were studied by seismic surveys.

The sketch of the multiscale hierarchy system of the structural framework with the fault database on the top is shown in Figure 11. The scales and definitions of the structural framework are the following: Pan-European, <1:10 000 000; Pannonian basin scaled, 1: 5 000 000; Regional, 1:2 000 000; Detailed, > 1:500 000.

**Table 1** shows the Unit hierarchy system of the Pannonian Basin.

**Table 1: The hierarchy of the SF Units in the Pannonian Basin**

| Pan-European | Pannonian basin scale | Regional scale | Detailed scale |
|---|---|---|---|
| Adria-derived units | Adria derived allochtons of the Dinarides and the Mid-Hungarian Shear Zone | Bükk | Bükk |
| | | Jadar-Kopaonik nappes | Jadar, Medvednica nappes |
| | | Drina-Ivanjica nappe | |
| | | East Bosnian-Durmitor nappes | East Bosnian-Durmitor nappes |
| | | Pre-Karst and Bosnian flysch nappes | Pre-Karst and Bosnian flysch nappes |
| | | | Pre-Karst nappes (pre-Alpine basement) |
| | | High Karst & Dalmatian zone | High Karst nappes |
| | Austroalpine nappes of the Eastern Alps and Western Carpathians (Alcapa) | Upper Austroalpine upper plate units | Transdanubian Range (cover) |
| | | | Transdanubian Range (pre-Apline basement) |
| | | | Szendrő-Uppony unit |
| | | | Drauzug-Gurktal nappe system |
| | | | Silica nappe |
| | | | Turňa nappe |

| Pan-European | Pannonian basin scale | Regional scale | Detailed scale |
|---|---|---|---|
| | | | Gemer nappe |
| | | Upper Austroalpine lower plate units | Hronic nappe |
| | | | Fatric nappe |
| | | | Vepor nappe (pre-Alpine basement) |
| | | | Vepor nappe (cover) |
| | | Eoalpine high-pressure belt | Koralpe-Wölz nappe system |
| | | Lower Austroalpine, Infratatricum, Tatricum | Tatric nappe (cover) |
| | | | Tatric nappe (pre-Alpine basement) |
| | Southern Alps | Southern Alps | Southern Alps |
| Europe-derived units | Dacia unit | Subbucovinian, Bucovinian, Biharia, Supragetic, Serbo-Macedonian nappes | Ariesani nappes (cover) |
| | | | Supragetic and Bucovian nappes |
| | | | Biharia nappe (pre-Alpine basement) |
| | | Infrabucovinian, Getic nappes | Getic nappe (cover) |
| | Tisza unit | Codru nappe | Codru nappe (cover) |
| | | | Codru nappe (pre-Alpine basement) |
| | | Bihor nappe | Bihor nappe (cover) |
| | | | Bihor nappe (pre-Alpine basement) |
| | | Mecsek nappe | Mecsek nappe (cover) |
| | | | Mecsek nappe (pre-Alpine basement) |
| | Miocene thrust and fold belts of the Outer Carpathians | Silesian nappe | Silesian nappe |
| Remnants of the Neotethys | Eastern Vardar ophiolites | Transylvanian, South Apuseni ophiolites | Transilvanian, South Apuseni ophiolites |
| | Sava zone | Sava zone | Sava zone |
| | Western Vardar ophiolites | Western Vardar ophiolites | Western Vardar ophiolitic nappes (s.s.) |
| | | | Western Vardar ophiolitic melange |
| | | Darnó-Szarvaskő ophiloites | Darnó-Szarvaskő ophiolites |
| | | Meliata nappe | Meliata nappe |
| Remnants of the Alpine Tethys | Southern branch of the Alpine Tethys | Szolnok flysch | Szolnok flysch |
| | | Vahic, Iňačovce nappes | Vahic, Iňačovce nappes |
| | Northern branch of the Alpine Tethys | Pieniny Klippen belt | Pieniny Klippen belt |
| | | Valais, Rhenodanubian, Magura nappes | Rhenodanubian flysch and Magura nappes |
| Senonian sediments | | | |

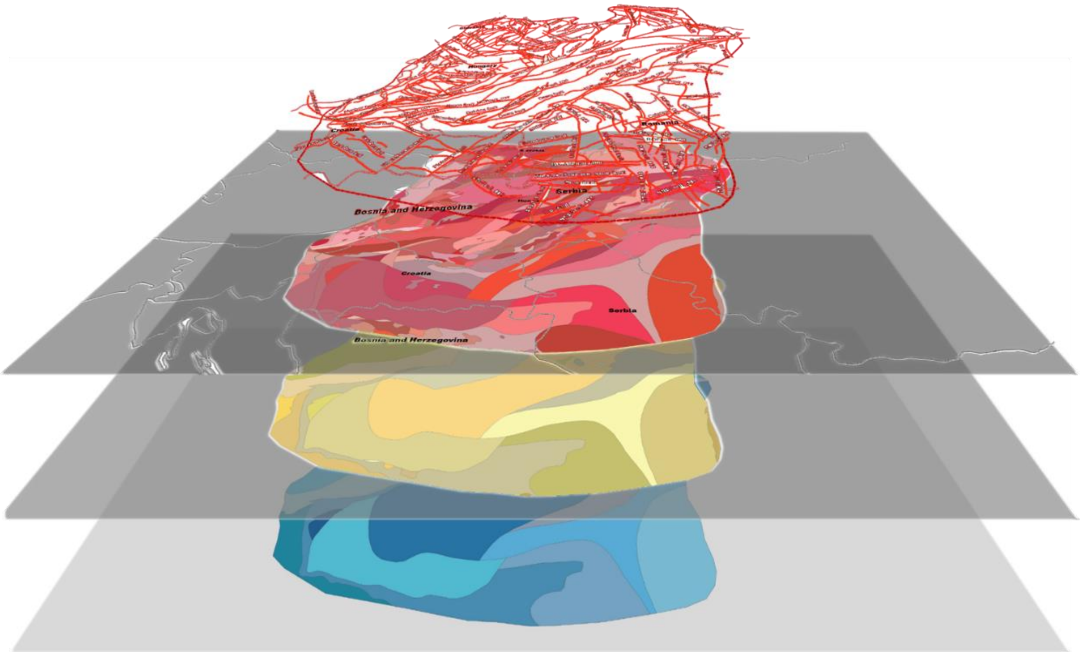


**Figure 11: The multiscale hierarchy system of the structural framework in the Pannonian basin**

Another challenge occurred in the case of the denomination and identification of the Limits. The limits in the Structural Framework of the Pannonian Basin are mostly of tectonic origin. They are basal thrusts, reverse faults, detachment faults and normal faults. Some of them suffered multiple rejuvenation during the structural history of the Alp-Carpathian-Dinaric orogenic event and after that during the formation of the Pannonian Basin. At the phase of the initiation of the Limit's database it was realized that some of the Limits have no identifier, have no name in the geo-tectonic literature. They were "latent" limits. At first, they were identified with an artificial name coming from the neighbouring units. The denomination itself consisted of the two names of the neighbouring units and a type of tectonic boundary. At different scales of the Structural Framework they were named as dislocation zone, nappe system, nappe, fault respectively. At a later stage the artificial names were substituted with the elements of the fault database (Figure 16) created for the GeoERA Fault database project in all cases when it was appropriate.

**Pan-European scale level**

The classification of this structural framework level is based on the original plate tectonic arrangement of the present units (Figure 12).

The Adria derived units (mostly nappes) were sheared off from the Adriatic microcontinent - which was situated between the Neotethys and the Alpine Tethys oceans. These Adria-derived units are incorporated in the Alpine-Carpathian-Dinaric orogeny.

The Europe derived units separated from the European plate by the opening of the eastern branch of the Alpine Tethys during the Jurassic. Later they were accreted to the Carpathian orogeny as nappes.
The remnants of the Neotethys Units were originated on the Neotethys oceanic plate. The Neotethys was a NW-SE oriented branch of the Tethys ocean. The SW margin of this ocean was represented by the Adria continent, whereas the Tisza and the Dacia units situated on the northern and NE margin of the Neotethys. The spreading of the Neotethys started during the Middle Triassic, after long-lasting

Permian to Middle Triassic continental rifting. The closure of this ocean started with intra-oceanic subduction during the Middle Jurassic, which was followed by obduction of ophiolites onto the Adriatic and Dacia margins during the Late Jurassic and Early Cretaceous respectively.

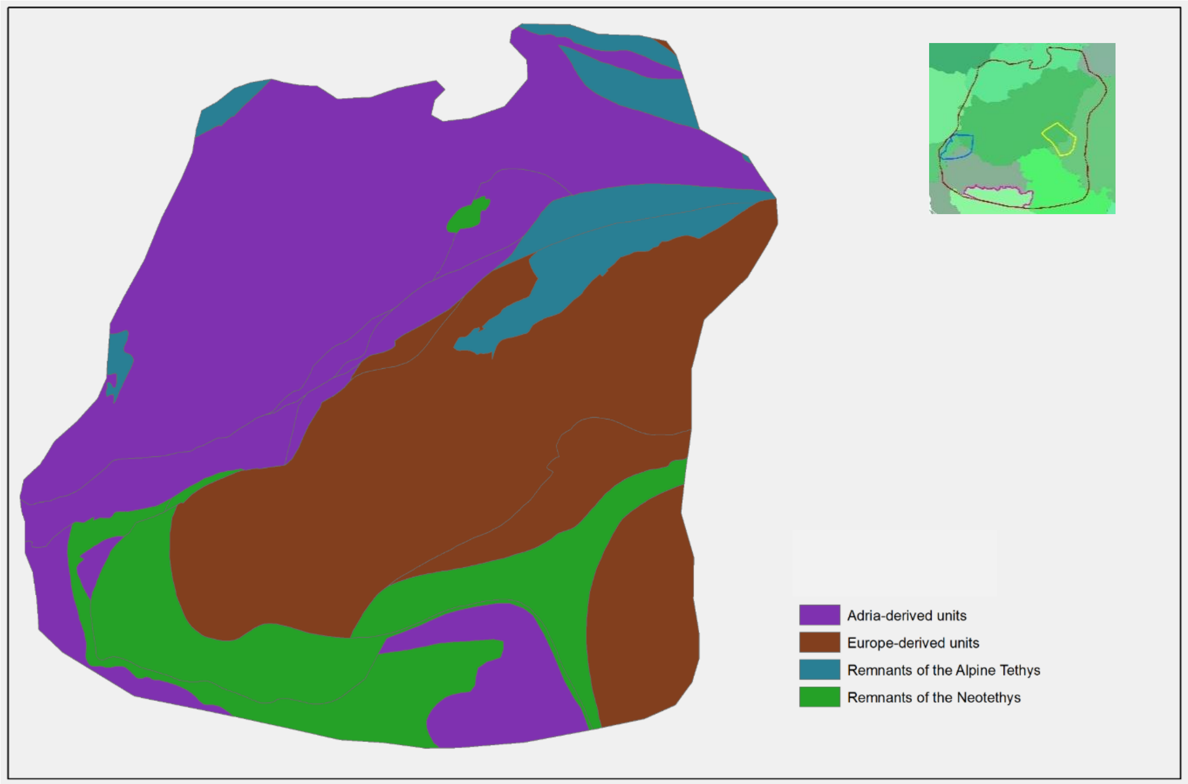


**Figure 12: The Pan-European scale structural framework level for the Units in the Pannonian Basin. Based on Schmid et al. (2020) modified, blue line: Mura-Zala pilot area, yellow line: Battonya pilot area, pink line: Bosnia & Herzegovina pilot area**

The remnants of the Alpine Tethys Units were originated on the Alpine Tethys oceanic plate. The Alpine Tethys was a branch of the opening Atlantic Ocean, between Europe and Adria continents. The Alpine Tethys opened during the Middle Jurassic to Cretaceous following Late Triassic-Middle Jurassic continental rifting. The ocean closed during the Cretaceous - Cenozoic which resulted the collision of the European and Adriatic plate. The Alpine Tethys can be separated into two branches, which are disconnected by continental ribbons in the Western Alps (Briançone) and in the Western Carpathians (Oravic-Pieniny Klippen belt).

**Pannonian basin scale level**

The classification of this structural framework level is based on the different nappe stack systems building up the different plate tectonic units (Figure 13).

The Adria derived nappes of the Dinarides formed as a consequence of Late Jurassic Early Cretaceous obduction of the Western Vardar ophiolites, and Late Cretaceous Cenozoic collision of the Adria and Tisza terranes. A part of these nappes was emplaced by the dextral Mid-Hungarian shear zone during the Cenozoic.

The Austroalpine nappes of the Eastern Alps and Western Carpathians (Alcapa) nappes develeped due to an enigmatic intracontinental subduction zone and/or due to the obduction of the West Vardar ophiolites. The Austroalpine nappe system formed during Late Jurassic to Cretaceous.

Dacia unit is a Cretaceous nappe-system, that forms a major part of the Eastern and Southern Carpathians.

Eastern Vardar ophiolites is a Jurassic oceanic crust of the Neotethys, which was emplaced onto the Dacia unit during the Late Jurassic to Early Cretaceous.

The Miocene thrust and fold belts of the Outer Carpathians are thin-skinned fold and thrust belts detached from the crust of the Alpine Tethys and the European plate.

The Northern branch of the Alpine Tethys ocean is situated between Europe and the Briançone - Oravicum microcontinents. Opening of this ocean took place during the Cretaceous.

The Sava zone is a Cretaceous oceanic relict of the Neotethys, which closed during the latest Cretaceous to Paleogene, causing the collision of the Dinarides (lower plate) and the Tisza-Dacia (upper plate) units.

The Southern Alps is a southward directed Cenozoic fold-and-thrust belt, which represents the retrowedge of the Alpine orogeny.

The Southern branch of the Alpine Tethys opened between the Adria continent and the future Briançone and Oravic microcontinents. Opening of this ocen took place during the Jurassic.

The Tisza unit is a Cretaceous nappe system, which represents the pre-Cenozoic basement of the SE Pannonian Basin.

The Western Vardar ophiolites unit is an obducted ophiolites system of the Neotethys, which was emplaced onto the Adriatic margin during the Late Jurassic.

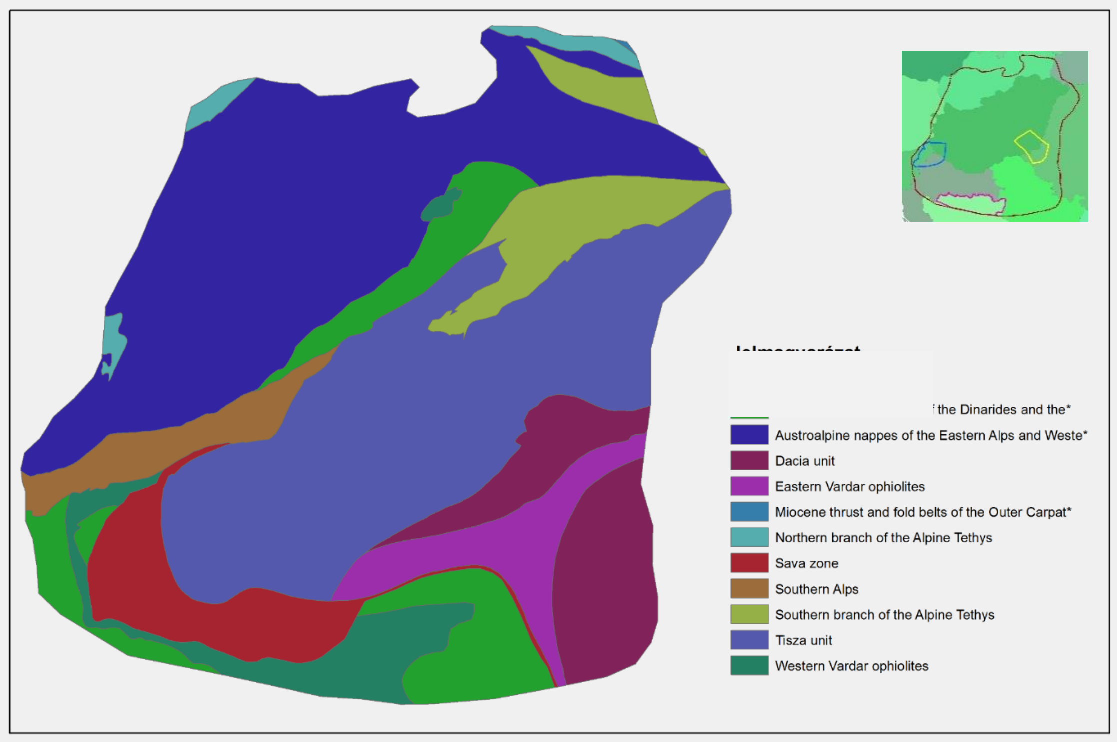


**Figure 13: The Pannonian Basin scale structural framework level for the Units in the Pannonian Basin. Based on Schmid et al. (2020) modified, blue line: Mura-Zala pilot area, yellow line: Battonya pilot area, pink line: Bosnia & Herzegovina pilot area**

**Regional scale level**

The classification of this structural framework level is based on the different nappes building up the different nappe stack systems (Figure 14).

The Bihor nappe system contains thin and thick-skinned nappes, composed of medium-grade Variscan crystalline rocks, and overlying Permian to Cretaceous non-metamorphic succession. Main nappe emplacement occurred during the Late Cretaceous.

The Bükk is a thick-skinned nappe, composed of Paleozoic and Mesozoic sediments. The Bükk unit suffered lower greenshicht facies metamorphism during the Early Cretaceous, and later it was emplaced by the Mid-Hungarian shearzone during the Cenozoic. The Bükk unit can be correlated with the Jadar-Kopaonik nappes.

The Codru nappe is a thin and thick-skinned nappes, composed of Variscan granitoids and Permian to Early Cretaceous non-metamorphic succession. Main nappe emplacement occurred during the Late Cretaceous

The Szarvaskő ophiolites are made up of Jurassic basic and ultrabasic rocks, whereas the Darnó area can be characterized by sedimentary melange where Triassic basalts are incorporated.

The Drina-Ivanjica nappe is a thick-skinned nappes, composed of anchimetamorphic metamorphic Paleozoic and Mesozoic sediments. The age of metamorphism and thrusting is Late Jurassic-Early Cretaceous.

The East Bosnian-Durmitor nappes are thick-skinned nappes, composed of Paleozoic and Mesozoic sediments. The emplacement of the nappe occurred during the latest Cretaceous to Paleogene.

The Eoalpine high-pressure belt is a tectonic belt within the Austroalpine nappes, consiting of high-pressure and ultra-high pressure rocks with "middle Cretaceous" age of metamorphism. The Eoalpine HP belt is related to an intracontinental subduction zone within the Adriatic plate.

The High Karst & Dalmatian zone is composed of thin-skinned nappes of Late Triassic to Cretcaoues platform carbonates. Major nappe emplacement occurred during middle Eocene to Oligocene.

The Infrabucovinian, Getic nappes are thick-skinned nappes, which are made up of Variscan crystalinne rocks and Permian to Mesozoic cover. The main nappe emplacement occurred during the Late Jurassic to "middle" Cretaceous

The Jadar-Kopaonik nappes are thick-skinned nappes, composed of low-grade metamorphic Paleozoic and Mesozoic sediments, similar to those of the Bükk.

The Lower Austroalpine, Infratatricum, Tatricum unit is the lowermost nappe unit of the Austroalpine nappes, which derived from the northern passive margin of the Adria, that faced the Alpine Tethys.

The Mecsek nappe is a thick-skinned nappe, composed of Paleozoic crystalline rocks and metasediments, and Permian to Early Cretaceous non-metamorphic succession. The main nappe emplacement occurred during the Late Cretaceous.

The Meliata nappe is made up of HP/LT metamorphic rocks, and tectonic and sedimentary melange. According to Plasienka (2018) the Meliata unit is an accretion complex. In contrast Schmid et al. (2008) interpret it as a sub-ophiolitic melange below the obducted Western Vardar ophiolites.

The Pieniny Klippen belt is a strongly deformed zone of Jurassic to Paleogene rocks, which deposited on a continental ribbon (Oravicum), that separated the southern (Piemont - Ligurian -Váhic) and northern (Valais - Magura) oceanic domains of the Alpine Tethys.

The Pre-Karst and Bosnian flysch nappes are thick-skinned nappes, composed of Paleozoic and Mesozoic lowgrade metamorphic sediments. The Variscan metamorphic event was overprinted by younger "middle" Cretaceous and Cenozoic metamorphism. The major emplacement of this nappe occurred during middle Eocene to Oligocene and Late Miocene to recent times.

The Sava zone is a Cretaceous oceanic relict of the Neotethys, which closed during the latest Cretaceous to Paleogene, causing the collision of the Dinarides (lower plate) and the Tisza-Dacia (upper plate) units.

The Silezian nappe is a thin-skinned nappes, composed of Late Jurassic to Miocene sediments, deformed during the Miocene.

The Southern Alps is a southward directed Cenozoic fold-and-thrust belt, which represent the retrowedge of the Alpine orogeny.

The Subbucovinian, Bucovinian, Biharia, Supragetic, Serbo-Macedonian nappes are thick-skinned nappes, which are made up of Variscan crystalinne rocks and Permian to Mesozoic cover. The main nappe emplacement occurred during the Late Jurassic to "middle" Cretaceous.

The Szolnok flysch consists of Late Cretaceous to Eocene sediments; it is known just from wells, therefore its tectonic position is enigmatic. According to Schmid et al. (2008) the Szolnok flysch can be interpreted as sedimentary cover of the Alpine Tethys overthrusted by the Tisza unit. In contrast, Haas and Péró (2004) consider the Szolnok flysch as sedimentary cover of the Mecsek nappe.

The Transylvanian, South Apuseni ophiolites unit is a Jurassic oceanic crust of the Neotethys, which was emplaced onto the Dacia unit during the Late Jurassic to Early Cretaceous.

The Upper Austroalpine upper plate units is built from nappes that form the hanging wall of the Eoalpine high-pressure belt.

The Upper Austroalpine lower plate unit's nappes form the footwall wall of the Eoalpine high-pressure belt.

The Vahic, Iňačovce nappes are exposed just in small tectonic windows below the Tatric nappes, they composed of detached sediments of the Alpine Tethys. The Iňačovce unit is represented by serpentinite subsurface bodies, known from wells.

The Valais, Rhenodanubian, Magura nappes are detached deep marine clastic sediments of Early Cretaceous to Oligocene age. They deposited in the northern branch of the Alpine Tethys.

Western Vardar ophiolites unit is a Jurassic oceanic crust of the Neotethys, which represented the upper plate during intra-continental subduction and obduction.

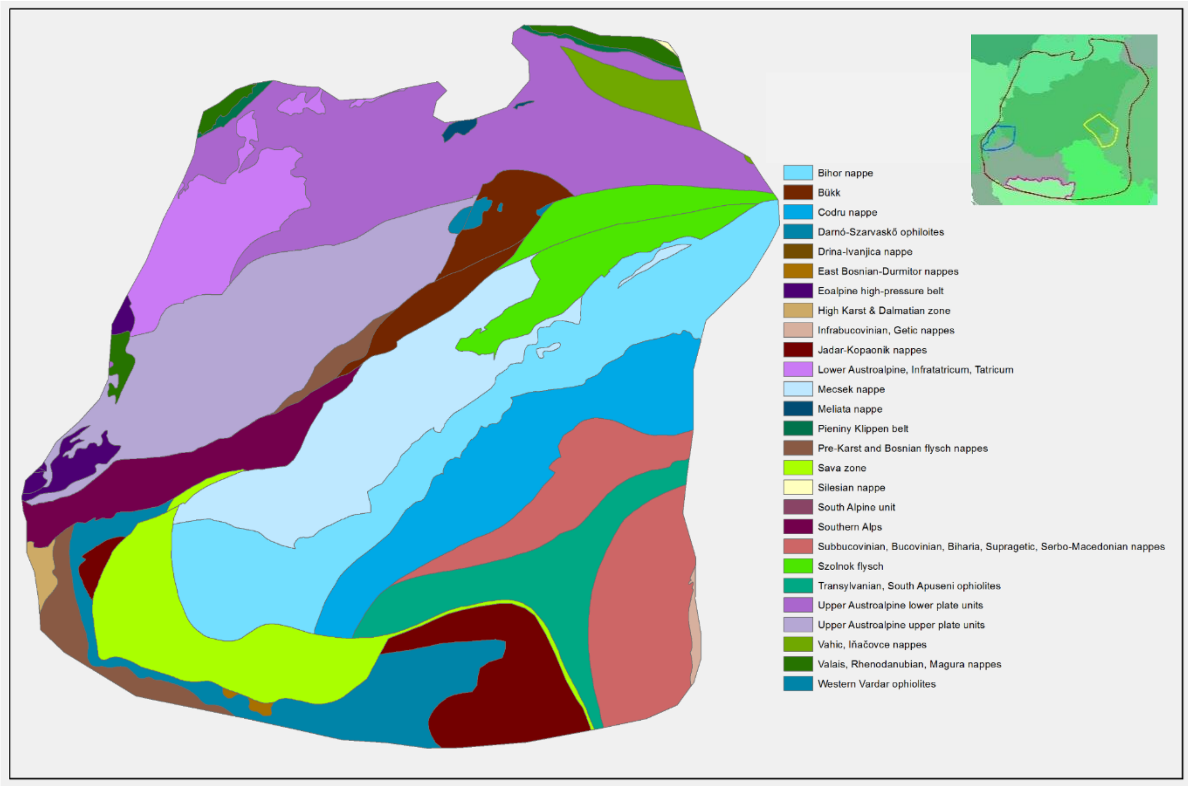


**Figure 14: The Regional scale structural framework level for the Units in the Pannonian Basin. Based on Haas et al. In Kocsis ed. (2018) modified, blue line: Mura-Zala pilot area, yellow line: Battonya pilot area, pink line: Bosnia & Herzegovina pilot area**

### Detailed scale level

The classification of this structural framework level is based on the different subunits building up the different nappes (Figure 15). This text contains Unit explanations not mentioned in the previous scale level.

The Pre-Karst nappes (pre-Alpine basement) are Variscan basement formations of the Pre-Karst nappes.

The Transdanubian Range (cover) is the uppermost thick-skinned nappe of the Austroalpine nappe system. It is made up of Permian to Cenozoic non-metamorphic succession. Main folding and nappe emplacement occurred during the "middle" Cretaceous.

The Transdanubian Range (pre-Apline basement) is the uppermost thick-skinned nappe of the Austroalpine nappesystem. It is made up of Variscan low-grade metamorphic sediments. Main folding and nappe emplacement occurred during the "middle" Cretaceous.

The Szendrő-Uppony unit is made up of Paleozoic and Mesozoic deposits, which suffered greenshist facies metamorphism and folded during the Early Cretaceous.

The Drauzug-Gurktal nappe system is a thick-skinned nappe made up of Variscan low-grade metamorphic succession, and Permian to Mesozoic deposits, locally overprinted by Cretaceous low-grade metamorphism.

The Silica nappe is a thin-skinned nappe composed of Permian evaporite and Triassic sediments. The position and age of nappe emplacement is controversial.

The Turňa nappe is a thick-skinned nappe composed of low-grade metamorphic Paleozoic to Triassic sediments.

The Gemer nappe is a thick-skinned nappe composed of Paleozoic volcano-sedimentary complexes. The Gemer unit suffered greenschist to amphibolite facies Variscan metamorphism, overprinted by low-grade rechristallization during the Early Cretaceous.

The Hronic nappe is a thin-skinned nappe composed of Carboniferous to Lower Cretaceous succession. Major nappe emplacement occurred during the "middle Cretaceous".

The Fatric nappe is a thin-skinned nappe composed of Triassic to Lower Cretaceous succession. Major nappe emplacement occurred during the "middle Cretaceous".

The Vepor nappe (pre-Alpine basement) is a thick-skinned nappe, composed of high-grade metamorphic Variscan volcano-sedimentary succession, and the overlying Permian to Triassic sequence, which suffered greenschist to amphibolite facies Early Cretaceous metamorphism.

The Vepor nappe (cover) is a thick-skinned nappe, composed of high-grade metamorphic Variscan volcano-sedimentary succession, and the overlying Permian to Triassic sequence, which suffered greenschist to amphibolite facies Early Cretaceous metamorphism.

The Koralpe-Wölz nappe system is a thick-skinned nappe system, composed of high pressure paleozoic rocks.

The Tatric nappe (cover) is a thick-skinned nappe, composed of Permian to Mesozoic non-metmorphic succession.

The Tatric nappe (pre-Alpine basement) is a thick-skinned nappe, composed of high-grade metamorphic Variscan rocks.

The Ariesani nappes (cover) are parts of the Biharia nappe.

The Supragetic and Bucovian nappes are thick-skinned nappes made up of medium to high grade metamorphic gneiss of Neoproterozoic to Early Paleozoic age. It is overlain by greenschist to amphibolite facies Paleozoic succession, which is unconformably sealed by Late Carboniferus to Mesozoic strata.

The Biharia nappe (pre-Alpine basement) is the highest nappe of the Apuseni Mountains, which structurally overlies the Eastern Vardar ophiolites.

The Getic nappe (cover) is a thick-skinned nappe made up of medium to high grade metamorphic gneiss of Neoproterozoic to Early Paleozoic age. It is overlain by greenschist to amphibolite facies Paleozoic succession, which is unconformably sealed by Late Carboniferus to Mesozoic strata.

The Transilvanian, South Apuseni ophiolites unit is a Jurassic oceanic crust of the Neotethys, which was emplaced onto the Dacia unit during the Late Jurassic to Early Cretaceous.

The Western Vardar ophiolitic nappes (s.str.) unit is a Jurassic oceanic crust of the Neotethys, which represented the upper plate during the intra-continental subduction and obduction.

The Western Vardar ophiolitic melange unit is an ophiolitic melange situated below the metamorphic sole of the Western Vardar ophiolites. It contains rocks sheared off from the lower subducted plate, and gravitationally re-deposited olistoliths.

The Vahic, Iňačovce nappes are exposed just in small tectonic windows below the Tatric nappes, it composed of detached sediments of the Alpine Tethys. The Iňačovce unit is represented by serpentinite subsurface bodies, known from wells.

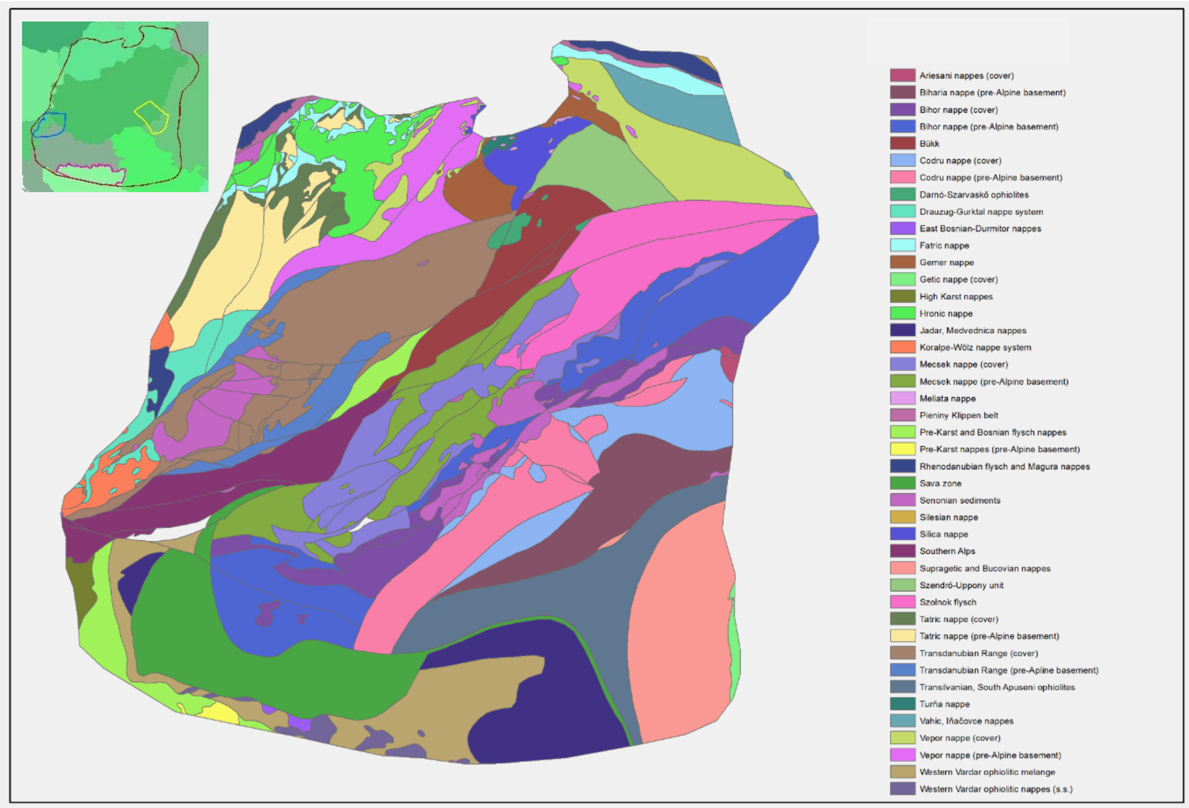


**Figure 15: The Detailed scale structural framework level for the Units in the Pannonian Basin. Based on Haas et al. In Kocsis ed. (2018) and Schmid et al. (2020) modified, blue line: Mura-Zala pilot area, yellow line: Battonya pilot area, pink line: Bosnia & Herzegovina pilot area**

On Figure 16 the fault database can be seen, which formed the base of the identification of the Limits. It contains 146 pieces of dislocation zone, basal thrusts, nappes, faults, and their kinematics, reactivations, etc. The Limits could not be organized to any hierarchy because of the numerous reactivation phase, so their data were surveyed in alphabetical order.

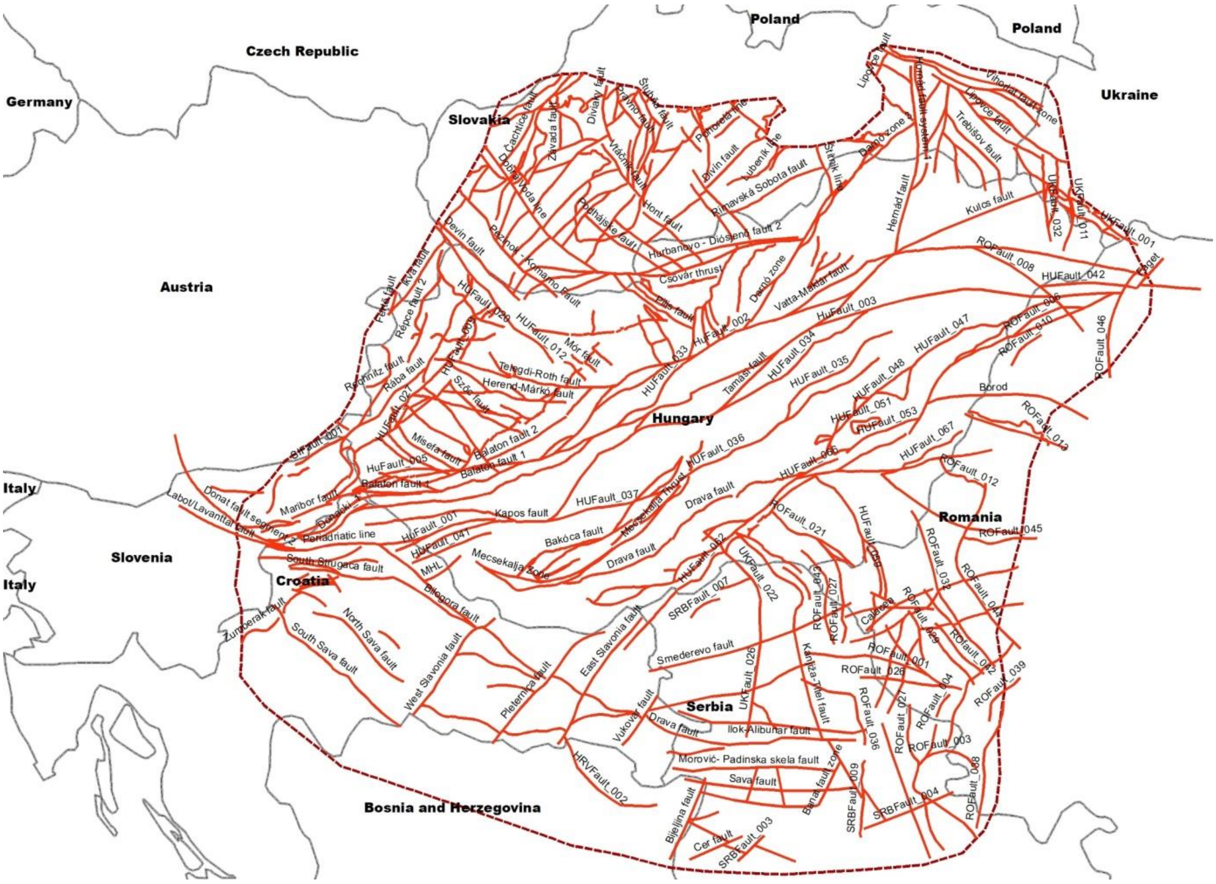


**Figure 16: The fault database adapted to the Limits of the different Structural framework levels in the Pannonian Basin**

## 2.2. Adopting Geomanifestations

In the 3 pilot areas within the Pannonian Basin, a wide range of geomanifestations were identified (2). They are described in full details in D.4.2.

**Table 2: Geomanifestations in the three Pannonian basin pilot areas**

| | Mura-Zala basin | Battonya High | Bosnia & Herzegovina |
|---|---|---|---|
| Country | SI-HR-HU | HU-RO | BiH |
| natural mineral water | 8 | 0 | 0 |
| mineral water | 6 | 17 | **12** |
| thermal water | 22 | **163** | **13** |
| thermomineral water | 17 | | **16** |
| Convection cells | 9 | many | No data |
| Mofettes | 8 | 0 | 0 |
| Mantle He exhalation | 17 | No data | No data |
| Mineral occurences | 4 | No data | No data |
| Coal | 78 | No data | No data |
| Oil spring | 1 | 0 | 0 |
| Oil and gas fields | 28 | **Numerous** | No data |
| Seismic events | **910** | 19 | No data |
| Overpressured zone | No | Yes | No data |

In the Mura-Zala basin between Croatia, Hungary and Slovenia, we listed 9 wells with convection cells, 8 mofettes, 8 natural mineral waters, 6 mineral waters, 22 thermal and 17 thermomineral waters (Table 2). There are actually more objects (wells) existing, as in Slovenia we reported only one well as a representative for the whole site when several wells or springs tap the same water/aquifers. Mineral occurrences are rare, only 4. Organic matter occurrences are abundant, 78 coal sites, 1 oil spring, 5 gas fields, 6 oil fields, and 17 oil and gas fields. Mantle helium exhalation is evident at 17 sites.

Thermal waters occur at various systems. The ones linked to warm spring systems emerge along (regional or local) faults in carbonates at basin outskirts, being strongly connected to structural framework, while most waters are tapped from stratified Neogene strata in the sedimentary basin.

At Battonya High between Hungary and Romania, we identified convection cells causing geothermal anomalies, hydrocarbon accumulations, over-pressured zones, density-driven flow systems, 17 mineral and 163 thermal waters and only 19 seismic events. Here, geomanifestations are only partly linked to fault zones in the basement, and mostly to weathered zone on top of it and Neogene sedimentary structures.

In north Bosnia and Herzegovina, we identified 12 mineral, 13 thermal and 16 thermomineral waters along the Spreča-Kozara fault zone, which represents the border between the Pannonian Basin and the Dinaride Ophiolite Zone. However, different types of mineralization (Cu, Pb, pyrite and others) as well as seismic active zones (e.g. Banjaluka region) are known in the region but were not investigated within this project.

All geomanifestatons are described in details in D.4.2.

## 2.3. Combining Structural Framework and Geomanifestations

The reference level for the established structural framework in the Pannonian Basin is the Pre-Cenozoic basement level (Figure 10). It means that we focused more on geomanifestations that can be linked to the structural framework and basement faults. Nevertheless, there are numerous geomanifestations associated with the thick sedimentary succession of the basin fill, therefore cannot be linked to tectonics directly but are mostly dependent on the heterogeneous permeability of the Neogene sedimentary basin fill, as well as rejuvenated faults and other structural elements. Therefore, we grouped geomanifestations into two categories, both are interpreted within the individual pilot areas:

I. Geomanifestations with clear structural links
II. Geomanifestations with indirect links to structural framework

### 2.3.1. Geomanifestations with clear structural links

Geomanifestations in the Mura-Zala basin occur within the Austroalpine nappes of the Eastern Alps t Pannonian basin scale level (mofettes, mineral and thermal waters, mantle Helium exhalation...), and at their contact with the Southern Alps (especially earthquakes, mantle helium exhalation, some thermal waters...;Figure 13,Figure 17). Within the Austroalpine nappes of the Eastern Alps on the regional Units level, geomanifestations occur especially at the northern contact of the Upper Austroalpine lower and upper plate units (Figure 14). In the detailed scale, the Ljutomer fault follows the extent of the lower Transdanubian Range (Figure 15), and within it regional several fault lines were delineated (Figure 16). It is very clear that the mantle helium exhalations in the south occur at the triple section of the Labot, Donat and Periadriatic fault zones (Figure 19). This is still a seismically very active area, with many earthquakes indicating the fault-line positions. However, the fault zones in the north along the Raba fault zone are yet not so clearly interpreted, furthermore mineral waters and mantle helium exhalations are not so clearly associated with the detailed fault zones, but more linked to the contact among the Upper Austroalpine units. As we presume that the contact is mostly tectonic, this would explain the geomanifestations. However, to better define these fault zones in a detailed scale, the available data sources were not sufficient at the moment (poor quality of geophysical cross-sections, poor information on basement rocks, etc.).

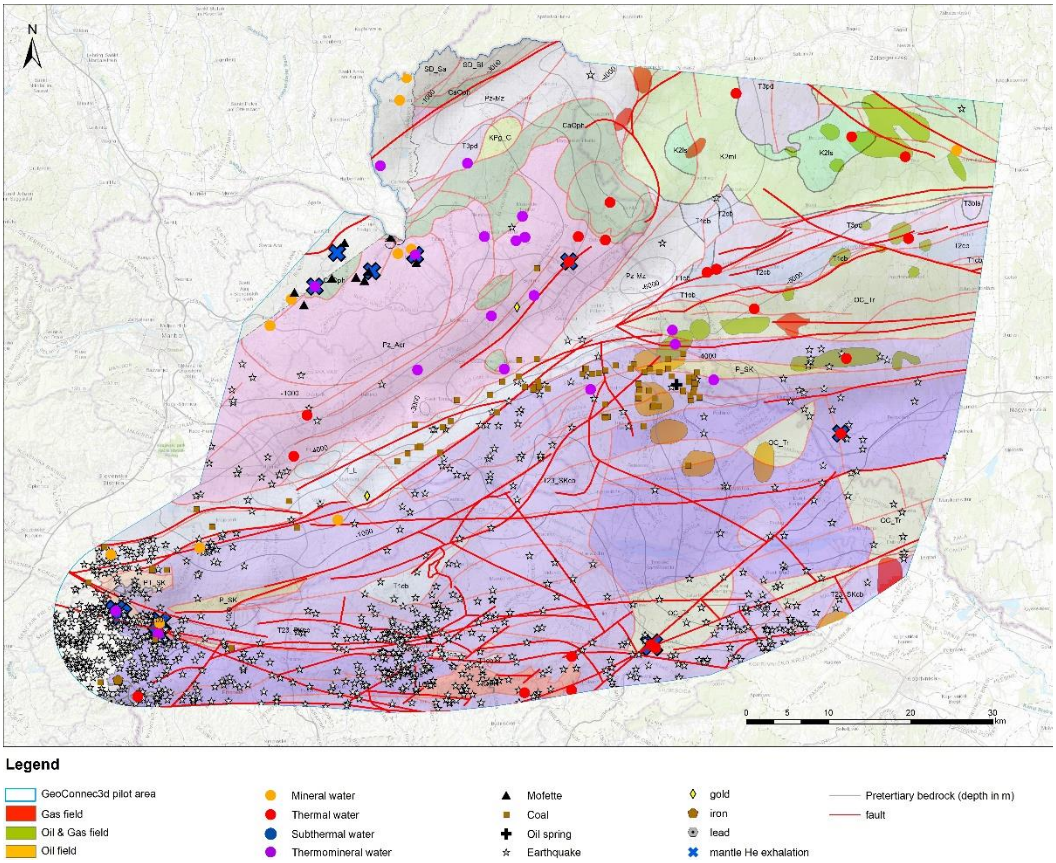


**Figure 17: Presentation of all listed geomanifestations in the Mura-Zala pilot area. The area is limed by the SI-AT state border in the north, with the numerical model border in the NE and E, with the major fault zone in the south, and the rough extent of the most interesting geomanifestations in the west. Notice two different backgrounds. The colored lithology is a geological model of basement rocks and its structures according to DARLINGe project while bold red lines are newly interpreted faults within the GeoConnect3d project.**

One of the most outstanding examples is the *effect of* fissured and partly karstified (at least assumed to be as some evidence on carbonate rocks exist) *Ljutomer fault zone on the regional temperature field* and its role in the evolvement of convection cells in the pre-Neogene basement rocks, which was modelled by FeFlow using 4 different scenarios. Modelled temperatures clearly confirmed the possibility of convection cells in the basement fissured metamorphic or carbonate rocks. Beside the effects of this zone, the temperature distribution at top of basement mostly follows the topography (basin deepening).

Locally, the SW part of the model, for example near Ptuj in Slovenia, we see that at the temperature fringes in the Ljutomer fault zone are narrower than expected by topography . This is a recharge zone for geothermal aquifers and cold water, which infiltrates within the shallower parts of the Ljutomer fault zone moves along the regional flow path faster in the fault zone and, therefore, locally cools down the western part of the model. This is also in accordance with previous investigations which tried to explain lower temperatures in this area (e.g. Dědeček et al. 2012, Šafanda et al. 2007).

On the opposite side, the heated outflow plume is evident in NE part of the model in Hungary, in all scenarios, because of convection cells in the pre-Neogene basement rocks.

The results showed no noticeable effect of convection in the Ljutomer Fault zone on the temperature distribution at the bottom of the shallower, about 1-2 km deep transboundary geothermal aquifer. This occurs in the basin fill sediments of the Mura/Ujfalu Fm. and is widely exploited for thermal water production in Slovenia and Hungary (Rman et al. 2020). Exploitation effects are mostly evident as (also transboundary) regional groundwater level and pressure decrease (Tóth et al. 2016) and no temperature changes have yet been reported (Rman, 2016). This is in accordance with our results and confirms that the heat transfer in the Neogene sequence is mostly/only due to conduction of heat, where the top-basement rock temperatures provide only the boundary temperatures of the whole sequence. Therefore, almost horizontal temperature distribution is simulated in shallower parts of the Mura-Zala basin (Figure 18).

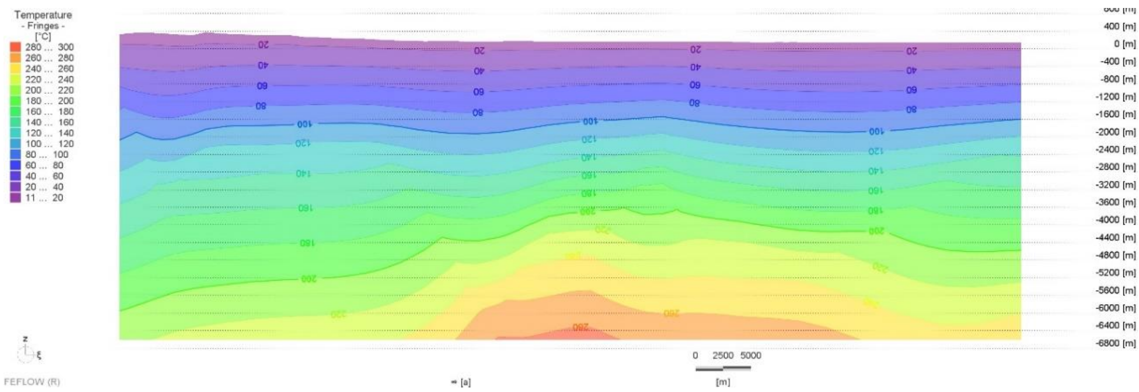


**Figure 18: Temperature cross-section roughly in NW-SE direction, from Goričko in Slovenia to Croatia which shows heat upwelling in the Ljutomer fault zone in the basement rocks - Scenario 2 of numerical models**

Other clear examples of geomanifestations dependent on structural framework are the *Helium and $CO_2$ gas seeps*, mostly identified in the Mura-Zala pilot area in Slovenia. We identified 17 sites with more than 5% of mantle helium, of which only one each were in Croatia and Hungary, and the rest in Slovenia. It is worth noticing that noble gas analyses are made for probably all used mineral and thermal water wells in the three countries in the pilot area, so the objectivity of this result is very high.

The northly positioned mantle He enrichments occur at Radenci (71-88%), Benedikt (77%), Ščavnica valley (79-87%) and Nuskova (95%), and are connected to the Raba fault system. However, from our currently delineated faults at a detailed level of the SF, these sites are somewhat distant from the main line (Figure 19). There are several possibilities to interpret this. First, local faults attached to the main Raba fault are obviously not evident on used datasets, and therefore we could not interpret their location in detail. The other possibility is that the horst-graben structure is limited by faults in both directions of the sub-basin, however, we showed only a line of the most evident fault on the map. The third possibility is that the emissions progress from the mantle to the basement top along the delineated Raba fault zone, but then thick layered structure of the Neogene sediments pushes this fluid flow along the weathered top of the metamorphic basement along steep edges of the sub-basin, and therefore emanations occur along these areas at the surface, where the basement slope is the shallowest (see pre-Tertiary bedrock depth contour in Figure 17). In Rogaška Slatina (73-97%), helium emanations are attributed to the active Šoštanj and Labot fault zones, and obviously much clearly linked to the fault lines of the SF (Figure 19).

On the opposite side, there are areas where very low share of mantle helium was measured. One such area is represented by the thermal waters in Ptuj in Slovenia with only 1.5%, but most thermal wells in Hungary and Croatia have the share of mantle helium even below 1%. This supports the structural framework control, i.e. the sealing capacity of clayey Neogene clastic sequence in deeper parts of the basin, and lack of active open faults in these areas. Still, there are thermomineral water wells close to the Slovenian-Hungarian border, which do have 5-15% of mantle helium contribution (Figure 19). This is probably a consequence of hydrocarbon accumulations in Lower Pannonian formations in the vicinity (located below the geothermal aquifers), and noble gases have travelled together with oil and earth gas fluids. The gas can get into boreholes in two ways. Old boreholes usually end in the depleted hydrocarbon reservoirs directly, even though this usually produces below 5% of total water. The other possibility is that some faults, which cut the Pre-Neogene basement, continue to the Neogene sedimentary layers, obviously at least till the hydrocarbon reservoirs. At the moment, both possibilities are likely at most sites.

Natural *$CO_2$ springs or mofettes* with very pure gas are only known to exist in the Slovenian part of the Mura-Zala pilot area, close to Radenci and the Raba fault zone, where 8 sites are reported. They are directly linked to the mantle He exhalation (sites were analysed for noble gases), so their link to the structural framework is the same as for mantle helium occurrences.

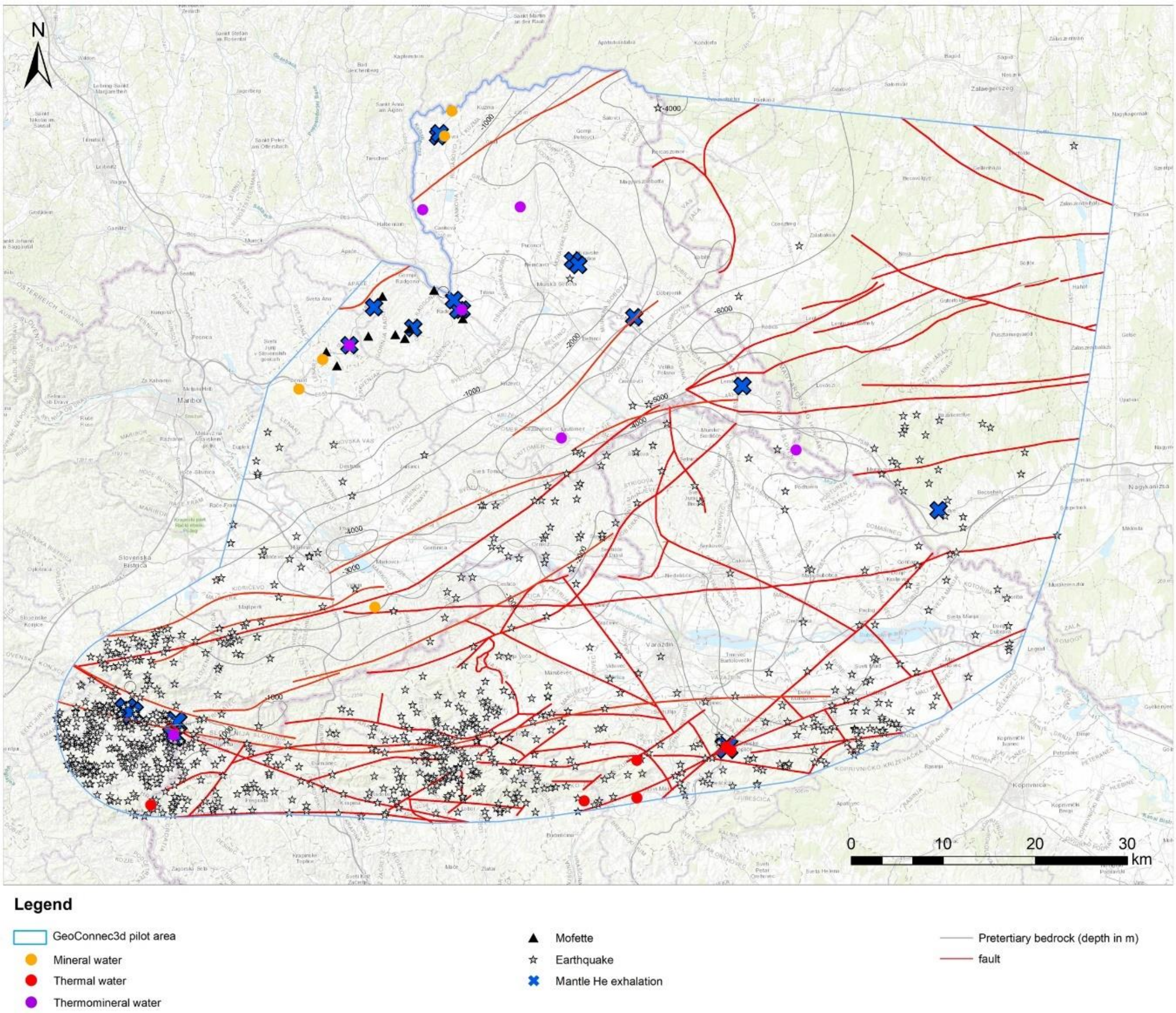


**Figure 19: Geomanifestations, which are most probably linked to basement structures and the detailed fault zone database**

Another type of geomanifestations clearly linked to the basement structural framework and deep structures are the *earthquakes.* The permeability of faults and fracture systems is influenced by numerous conditions, and seismic movements can contribute significantly in a positive (increasing) direction. In this way, seismic activity can be an indicator of the potential for deep vertical flow along faults. Since the hypocentres of the earthquakes are below the observable part of the basin by geophysics or boreholes, their direct connection to the fault zones is questionable.

Seismic events are reported both, from the Mura-Zala and the Battonya pilot areas.

In the Mura-Zala basin, two local seismicity clusters stand out in Slovenia (Figure 20). One diffuse seismicity cluster appears to be related to the Ljutomer fault zone; epicentres are located to the south of the fault tip surface projection, consistent with the southward dip of the fault. This may be interpreted as indications of the activity of the fault, however, more precise relocation of hypocentres will be required.

The second cluster of seismic events is located at the extreme SW end of the project area. In this part, the faults of the Mid-Hungarian Zone and two major faults of the Periadriatic fault system (PAL) – the Šoštanj and the Labot faults – converge. Locally very strong long-term transpression and uplift is evidenced by the basement outcrops at the Boč mountain. Fault activity, extreme depth and openness are confirmed by extreme mantle helium share and free $CO_2$ concentrations (see also Bräuer et al. 2016). But it is interesting that along these lines in Croatia such emissions are very rarely observed in thermal waters, so obviously extension is replaced by compression here.

North from the Ljutomer Fault zone in Slovenia and in the east part of the pilot area, in Hungary, there is very little seismicity. The area of the Raba fault system is therefore considered of very low activity or likely to be inactive. This is quite the opposite as observed in the southern Rogaška Slatina area, where very active faults enable deep fluid flow towards the surface. In the seismically inactive Raba faults zone, mofettes and extremely high mantle helium support the hypothesis that faults in the basement are evidently still open enough to enable strong and constant geogenic gas flux.

The Hungarian part of the Mura-Zala pilot area is seismically very inactive in general, as it encompasses a thick sedimentary basin deposits, and this is also the case in the Battonya pilot area (Figure 23).

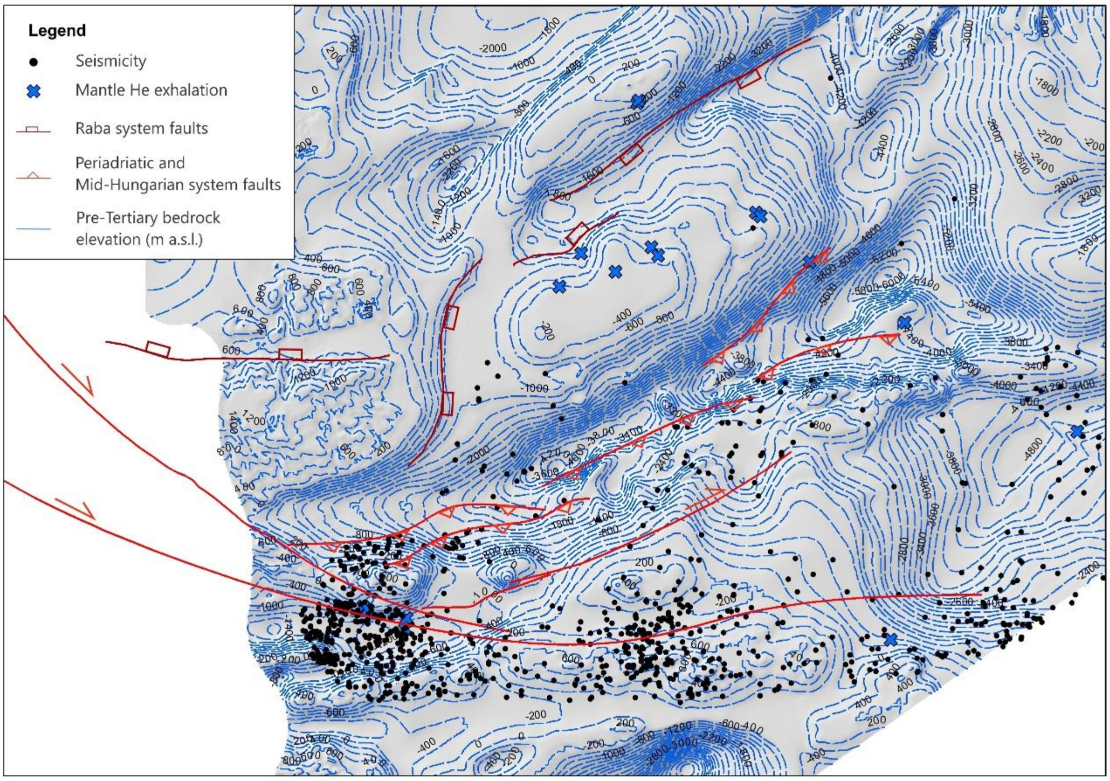


**Figure 20: Generalized map of structures in northeast Slovenia with structural elements from the text. Fault traces at pre-Neogene basement level are approximate and generalized. Dark red indicates (probably) inactive faults, bright red active and probably active faults. For general use only. Data sources: Graczer et al. 2002-2018; Grünthal et al. 2013; Herak et al. 1996, 2020; Živčić, 2021.**

In *Bosnia and Herzegovina*, the pilot area is positioned in a very narrow belt where three units meet - the Adria derived allochtons of the Dinarides in the south (also East Bosnian-Durmitor nappes at the regional level) is in contact with the Western Wardar ophiolites, and the Sava zone (both have the same regional Unit name) in the north (Figure 14). Geomanifestations (only thermal waters were evaluated) mostly occur in the Western Wardar ophiolites, where melange and nappe structures are interpreted at a detailed level.

Here, interpreted phenomena of structure controlled geomanifestations are *mineral, thermal and thermomineral waters* which occur along the regional Spreča-Kozara fault zone (Figure 21). This represents the border between the Pannonian Basin and the Dinaride Ophiolite Zone. In general, hyperalkaline waters are accumulated in ophiolite rocks or have some contact with them, while thermal water aquifers are usually limestones and dolomites of Mesozoic age. Salt waters are accumulated in Miocene clastites (Tuzla Basin), while $H_2S$ waters are formed in Tertiary clastites (Mlječanica and Rasol-Priboj). $CO_2$ waters occur in zones of deep faults and their springs are often arranged linearly in the space.


**Figure 21: Geomanifestations in Bosnia and Herzegovina**

### 2.3.2. Geomanifestations with indirect links to structural framework

Among geomanifestations that do not show direct links to the established structural framework we identified hydrocarbon fields, coal sites, thermal and thermomineral water sites where water is produced from the transboundary geothermal aquifer of the Upper Pannonian formations (so not from the basement rocks), over-pressured zone etc. All these occur in Neogene sediments. The metal occurrences are very few, so we did not take them into detailed interpretation.

*Structure-controlled hydrocarbon reservoirs and coal deposits* are identified in folded Neogene structures mainly, e.g. the Ormož-Selnica Antiform formed between two regional reverse faults – the Ljutomer Fault and the Donat fault in the Mura-Zala pilot area (Figure 22). Coal quality and quantity in this area is currently not identified as economically interesting.

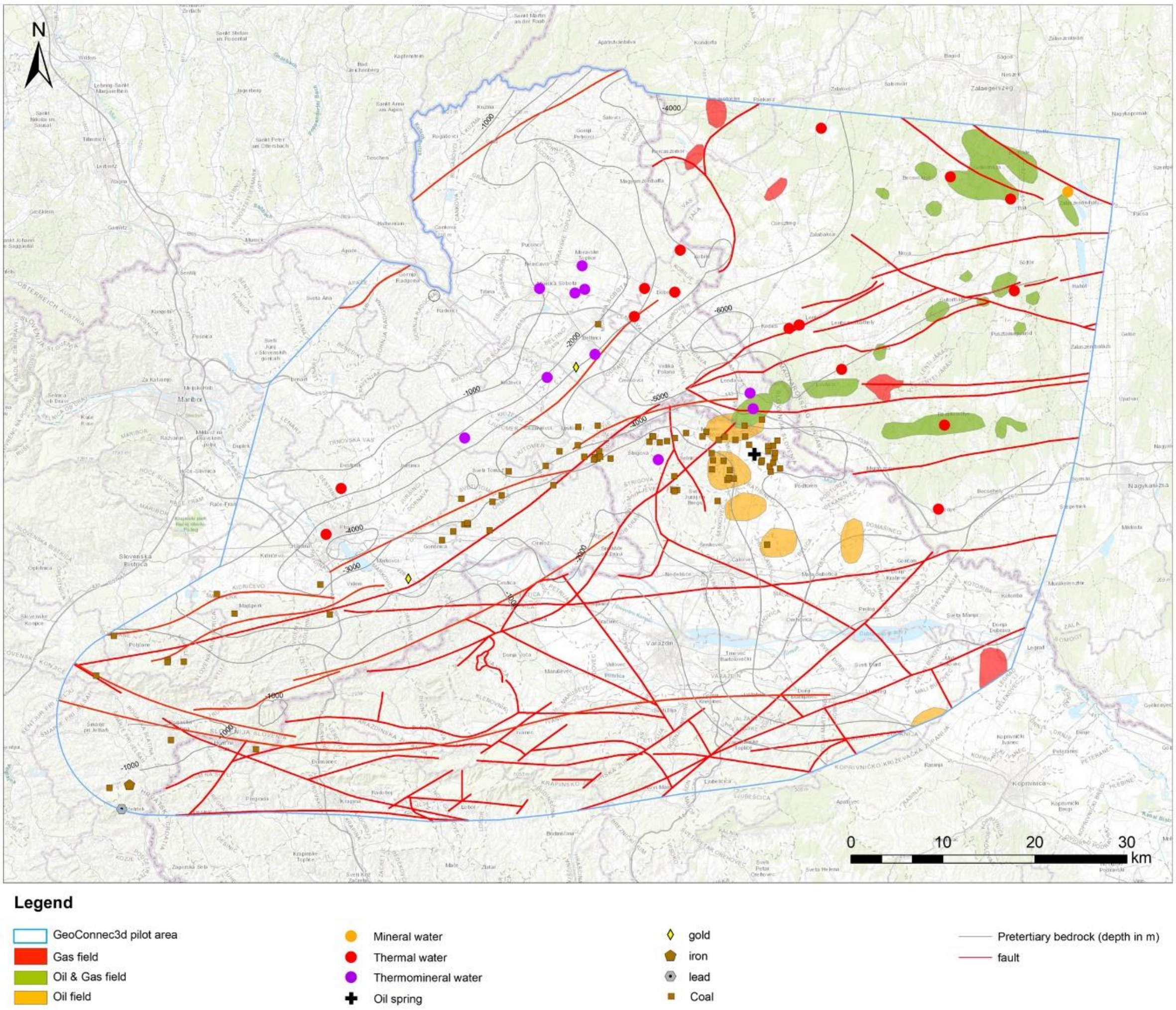


**Figure 22: Geomanifestations, which are most probably linked to basin fill sedimentary structures and projection of the detailed fault zone database in the Mura-Zala pilot area**

In the Battonya High pilot area in Hungary, some fracture-controlled *hydrocarbon reservoirs* (Figure 23) are also known from the upper, fractured zone and fragmented, weathered surface of the Palaeozoic basement rocks, from the fractured Palaeozoic metamorphic granites, Lower Triassic fractured sandstones and from Middle Triassic fractured, brecciated dolomites.

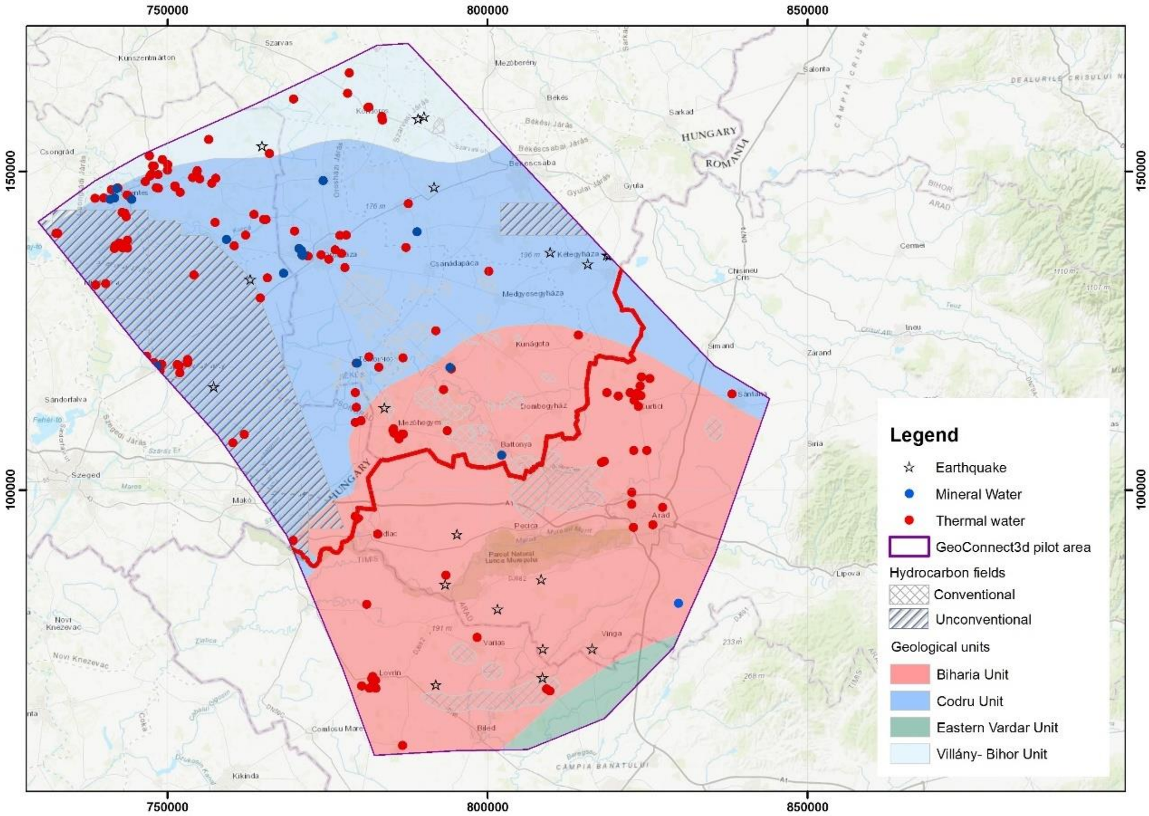


**Figure 23: Geomanifestations in the Battonya High**

Many geomanifestations in the Battonya pilot area do not show direct links to the established structural framework, as the area is far from the boundaries of any geological units. This area is positioned between the Tisza unit in the north (regional Units Bihor and predominately Codru nappes) and the Dacia unit in the south (regional Unit the Subbucovinian, Bucovinian, Biharia, Supragetic, Serbo-Macedonian nappes), with the southern most part just reaching the Eastern Vardar Unit (regional Unit the Transylvanian, South Apuseni ophiolites).

Here, *thermal water reservoirs and hydrocarbon traps* are associated with the more permeable (sandy) units of the thick basin fill complex (e.g. Middle–Upper Miocene, Badenian and Sarmatian conglomerates, sandstones, biogenic limestones, Pannonian turbiditic sandstones, Pannonian delta plain facies, various types of point bar and river bed sandstone successions, poorly consolidated sands).

*Over-pressured zones*, where the pore pressure exceeds the hydrostatic pressure, are relevant in deep trenches, e.g. those ones on the two flanks of the Battonya High.

*Density driven flow system* locally cause unexpected flow patterns in deeper Neogene layers.

Presence of *convection cells* is confirmed by numerical modelling, showing positive thermal anomaly of the high by the deep fluid flowing through the loose weathered zone, i.e. it is of convective origin (Figure 24).

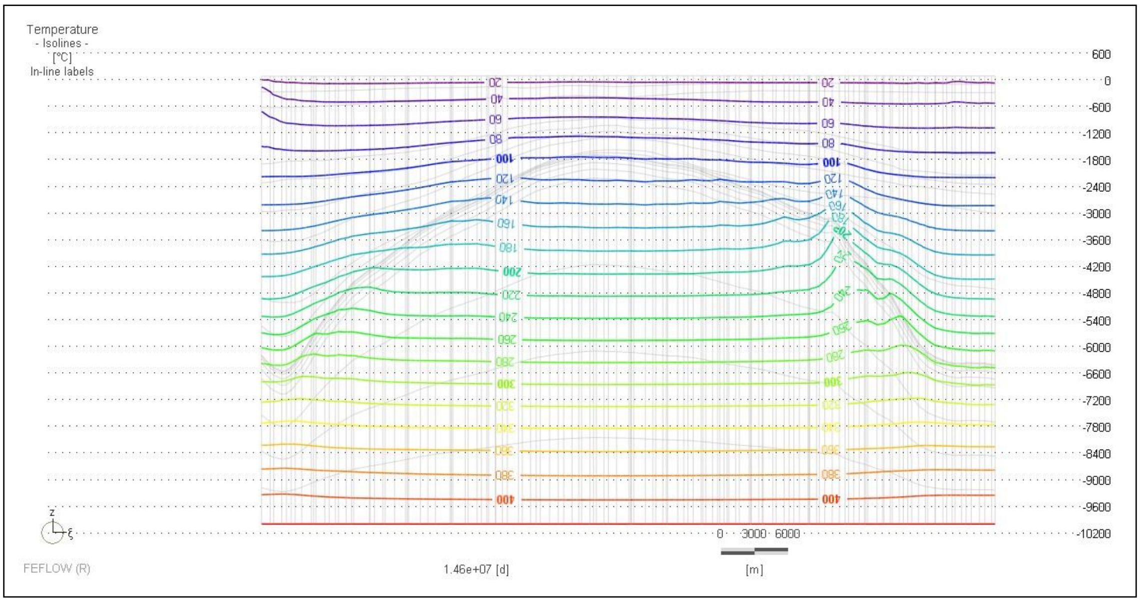


**Figure 24: Modelled isotherm distribution (40 thousand years of run, no production) on vertical section [°C]**

# 3. Evaluating Structural Framework and Geomanifestations

## 3.1. Added value

The approach of combining structural framework and geomanifestations has shown to be very useful from several points:

- It is an »interdisciplinary« approach. Structural geologists, geochemists, hydrogeologists, geophysicists have to cooperate for an integrated evaluation, each providing its part of information.

- It enables that very diverse information is joined and a »big picture« is gained, importantly enhancing the usual understanding of the subsurface (and from there challenges in management of its exploitation). This is the first time, to our knowledge, when various geomanifestations (as named now) were joined in one map for all pilot areas, so we can evaluate their vicinity and possibility of interferences and potential conflicts to a much better level than before.

- Combining structural framework and geomanifestations is essential to interpret the geological-structural evolution and current geo-potentials of an area more accurately. Only joined data revealed clear interconnection of some geological processes (of which most were already assumed, but not so much interpreted in the past), e.g. active fault zones and deep fluid emissions, regional convection in fault zones, etc. It also showed quite clearly which geomanifestations can be linked to properties and processes in the basement rocks. Therefore, when their management is discussed, not only (surface) land use has to be accounted for the exploitation of different geomanifestations (e.g. mofettes, mineral water springs...), but it is essential to understand the processes of their sources (e.g. faults and reservoirs in the basement rocks), to enable their successful long-term exploitation.

## 3.2. Problems

At the same time, the combined methodology of Structural Framework and Geomanifestations raises several concerns:

- data-related questions, e.g. their availability, quality, and level of current interpretations. As various data sets of different quality are joined (especially the case in transboundary areas with different national datasets), one must be careful by interpreting and deciding on relevant datasets and not supporting the hypothesis unanimously. As we focused on basement rocks which extend from outcrops to 5 km depth, the amount and quality of (mostly geophysical) data seriously decreased with depth, so often indirect indications of some structures, or faults had to be used to re-interpret the geological structure of the area. Availability of deep geophysical datasets is a severe issue (especially close to areas with hydrocarbons). 2D (and especially 3D) seismic datasets are often confidential and not allowed to use by the oil companies. One of the issues is also how to combine dataset of different level of resolution – e.g. there are very detailed local geological models elaborated in some areas, while very general and "old" interpretation exists in the surroundings. Harmonization of such scales and generalization can be very challenging.

- time-consumption questions: We did reinterpretation of existing data, however, not only copy-pasting past findings but trying to get the original raw data and interpret them by newest methodology and approaches, strictly referencing the original data sources. In the case of a large area, this can be extremely time-consuming.

- sequence in methodology questions: structural framework should be done first, followed by geomanifestations, and then jointly interpreted. As new methodology was yet developed, we did it parallel, so we could not combine the two thematic layers till the very end of this project.

### 3.3. Recommendations for further improvements

Within this project we gained and presented mostly 2D information (published as maps as seen in figures), so in future it is essential to extend this information to 3D – to regionally link the geomanifestations and extent of fault zones to the elevation and geological formation in which they occur.

Another area of improvement is related to acquisition of new and good quality data on the deep structures. This is also essential for the calibration of the numerical models, especially under dynamic conditions. Addition data collection is also required, e.g. for noble gases, we collected only data from mineral and thermal water wells and not from any fresh groundwater wells (because they have yet not been analysed). Now, we could focus on investigating some such shallow waters also, and analyse those sites where some e.g. seismic activity is evident and deep fluid flow might be geologically possible closer towards the surface.

## 4. Applying Structural Framework and Geomanifestations for Policy Support

Applying Structural Framework and Geomanifestations has been proven to be a useful tool for the more precise prediction of geo-potentials, e.g. temperature distribution with depth, identification of high permeable zones with convection cells in the Pannonian Basin pilot areas. The newly produced temperature maps can be used to explore new sites for higher-temperature geothermal applications more successfully.

Tectonic lines have a significant role in fluid, also hydrocarbon, migration. Therefore, knowledge on structural framework of the basement is important, maybe also for exploration of new unconventional hydrocarbon sites.

Moreover geomanifestations in combination with structural framework makes possible the identification of operational issues before they occur, and so technology can be adjusted accordingly, e.g. in areas with high $CO_2$ gas flux, drilling methods have to be adjusted to prevent blowouts, carbonate scaling is expected to occur in pipes, reinjection is seismically active areas can be an issue for induced seismicity, etc.

The method has high potentials to evaluate potential conflicts among various types of geomanifestations/exploitation of geo-resources, e.g. if geothermal and hydrocarbon reservoirs are one above each other, they might be vertically hydraulically connected, and therefore, depletion of one would affect also the other. To be able to do that a progress towards 3D models is required. Knowing that natural and anthropogenic interconnections among geothermal and hydrocarbon reservoirs exist at some sites, this should be accounted to prevent conflicts of use when managing the subsurface.

Another important area of potential interaction of deep geo-energy assets is with drinking/ natural mineral water resources, where the “geomanifestation” approach may help in solving management issues.  E.g. mofettes and mantle helium exhalations in the Raba fault zone occur at the same area where mineral water resources are known, and are used either as natural valuable features (protected and publicly accessible), or for bottling of natural mineral water Radenska. In the past, there have been questions raised whether such mineral water production with lots of $CO_2$ can cease due to overexploitation in long-term. From interpretations of the gas origin, the current hypothesis is that the natural flux of mantle emissions (helium together with $CO_2$) would not be affected by the industrial mineral water production. It is not expected that the quantity of gas would be reduced over time, but water resources could get depleted, resulting in ‘’other”, probably less mineralized water intrusions.

Information on current seismic activity is extremely important for development of new deep geothermal applications in the Pannonian basin. Very high temperatures (above 200 °C) are measured at 3,8 km close to Lendava in Slovenia, and even higher temperatures are known from deep-seated granites in the Battonya pilot area, both sites are future candidates for EGS projects. Reinjection under high pressures might have effects on the local seismicity as reported from many EGS projects in Europe, therefore, our approach has pointed out high importance to evaluate the local stress field in more details before the geothermal project is developed to reduce the risks at a later phases.

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