# Study of Some Potential Environmental Impacts of Hydraulic Fracturing Related to Unconventional Hydrocarbons in Hungary

**A. Nádor, Zs. Kovács, Á. Cserkész-Nagy, L. Bereczki, G. Markos, T. Fancsik, A. Cs. Kovács, and T. Szőcs**

**Abstract** Recoverable amount of the already discovered and even prospective unconventional hydrocarbons in Hungary supposedly exceeds 1,500 million tons of oil equivalent, but according to modest estimates, the 30-year perspective of the recoverable amount can reach only 100 million tons by current available technology. The unconventional hydrocarbon extraction is mostly the production of tight gas, but there is a great chance of unconventional shale gas and shale oil exploration and extraction as well. Nevertheless, in Hungary the hydraulic fracturing is a precondition for the exploitation of unconventional hydrocarbon resources.

The environmental consideration of hydraulic fracturing is contradictory; therefore, its regulation and official licensing are sources of conflicts not only in Hungary but all over in Europe. We show a case study of successfully fractured tight sand exploitation in Derecske Trough (E Hungary) in order to emphasise the importance of the analyses of local circumstances and the regulatory steps determined based on those. The study focuses on the two most significant risks specific to fracturing, namely, the effect of hydraulic fracturing on groundwater and the risk of induced earthquake based on a 3D geological model of the area interpreting the real geological conditions. The main conclusions are that (1) the spatial extension of induced fractures is extremely small in the prevailing continuously subsiding geodynamic conditions; and (2) it is almost excluded that a fracturing operation would release so much energy that would cause the development of a new, significant permeable fault (or the reactivation of an existing one). (3) There is at least 2,000 m mostly impermeable and ductile sedimentary succession between the uppermost fractured zone and the bottom of the deepest thermal aquifer. It concludes that (4) the risk of a possible pollution spreading along the communication between formations does not exist and (5) the dissipation capability of young

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S.S. Zhiltsov (ed.), *Shale Gas: Ecology, Politics, Economy*,
Hdb Env Chem (2017) 52: 75–96, DOI 10.1007/698_2016_9,

sedimentary formations is able to absorb the energy released by induced seismicity, which in case of the most disadvantageous technical and tectonic circumstances can trigger most likely earthquakes with a magnitude of ~1.8 in Hungary. Such an activity practically cannot be perceived by humans on the surface.

**Keywords** Environmental impact, Hydraulic fracturing, Pannonian Basin, Seismic monitoring, Underground water

## Contents

## 1 Introduction

Hungary covers more than 60% of its primary energy demand by import. The import rate of petroleum and natural gas is even higher, more than 80% today that comes almost entirely from Russia. Additionally, the import through Ukraine is burdened with risk. The unilateral dependence is particularly significant in the case of natural gas. The decrease in domestic production is offset by household consumption decline in recent years (natural gas: 7.5 billion $m^3$ in 2013) and a benefit from the substantial natural gas storage capacity of 6.2 billion $m^3$.

To decrease the energy dependence and foster domestic production, the unconventional exploration potential is a considerable business in Hungary. For that it is a prerequisite to improve and make cost-effective mining technology solutions and to optimise the regulatory and social (environmental, licensing, etc.) environment, of which the regulation of hydraulic fracturing is a crucial part.

In Hungary as well as in Europe the environmental consideration of hydraulic fracturing is contradictory; therefore, its regulation and official licensing are potential sources of conflicts in many countries. Environmental authorities usually form an opinion of the particular environmental impacts (mainly the risk of earthquakes triggered by fracturing and the potential pollution of groundwater) based on international examples, although some of these (e.g. [1]) draw attention to the importance of the analyses of local circumstances and the regulatory steps determined based on those. The majority of the cited international examples are not comparable with the Hungarian conditions either, considering their geological circumstances and technical levels of operation; therefore, the consequences of those analyses should not be considered. For instance, the most often cited American shale gas deposits are associated by Palaeozoic rocks at a depth of 1,500–2,500 m, usually in uplifting geological settings, being exploited in huge fields consisting of several thousands of wells [2]. At the same time Hungarian shale and tight gas deposits are situated at depths greater than 3,500–4,000 m, in young (Tertiary) sedimentary basins of subsiding characters, where the fields would be explored by fracturing of only a few wells for the time being. Inaccurate interpretation of international examples, information taken out of their original context, can be therefore misleading and unfortunately often impose incorrect reflections in the public.

The Act No. XLVIII. of 1993 on Mining (Mining Act) in Hungary has specific regulations on enhanced oil and gas recovery, and it was among the first ones in Europe that defined unconventional hydrocarbons, well stimulation technologies, and provided a few related provisions. A recent modification in 2015 declared that the licensing of hydrocarbon exploitation operations – including especially hydraulic fracturing and acidising, the injection of water and gas – falls within the competence of the mining inspectorate. The main goal of this addendum was to highlight that the licensing of such technologies requires specific skills available at the mining inspectorate. This was necessary because recent practical experiences showed that the competence of the environmental-, water management- and mining authorities is not unambiguously separated in this respect (whether the scope of the Governmental Decree No. 219/2004 on groundwater protection covers hydrocarbon reservoirs as geological formations, or not). This has led to legal interpretation problems, disputes and controversial categorical official bans on several occasions.

Due to the licensing problems of hydraulic fracturing in Hungary, a dialogue started among the relevant ministries [Ministry of National Development (NFM), Ministry of Agriculture (FM) and Ministry of Interior (BM)], as well as the Hungarian Office for Mining and Geology involving the operators concerned. It was agreed that it is of utmost importance to analyse the environmental impacts of hydraulic fracturing and their potential realistic risks based on Hungarian case studies, considering the geological conditions of the Pannonian Basin.

As Hungary is dedicated to maximise the exploration and production of unconventional hydrocarbons – while ensuring that the public health, climate and environment are safeguarded, resources are used efficiently and the public is informed – the Hungarian Government takes into account the Commission Recommendation of 22 January 2014 on minimum principles for the exploration and production of hydrocarbons (such as shale gas) using high-volume hydraulic fracturing (2014/70/EU).

The aim of this paper is twofolded. First, it provides a concise summary on Hungary's unconventional hydrocarbon resources. Then it summarises some relevant conclusions of a study compiled by the experts of the Geological and Geophysical Institute of Hungary (MFGI) [3] examining the potential environmental impacts of hydraulic fracturing in Hungary. In this paper, we present results for the Derecske Trough, where MOL Plc. has carried out unconventional hydrocarbon exploration, which also provided data on its operations especially results of their first hydraulic fracturing activities. As MOL Plc. has a mining plot for the Derecske area, the Hungarian regulation systems (103/2011(VII.4) Gov. Reg.) required the preparation of a complex sensibility and vulnerability assessment study prior to concessional activities. This study [4] analysed in great details all relevant environmental and water management issues related to future exploration and production. All of these data and information were added to the unique, national geological, geophysical and hydrological spatial database of the Geological and Geophysical Institute of Hungary (MFGI), and their re-evaluation allowed an integrated interpretation in which the effective factors, processes and interactions in space and time can be demonstrated and judged realistically.

## 2 Geological Setting and Petroleum Systems of Hungary with Special Respect to Unconventionals

The territory of Hungary covers the largest central part of the Pannonian Basin, which is an extensional Neogene Basin within the Alps–Carpathians–Dinaric system (Fig. 1), experiencing a very complex evolutionary history in the convergence zone between Europe and Africa, summarised recently by Horváth et al. [6].

Basin development started at the beginning of the Miocene by extensional disintegration of orogenic terranes and subsequent events of basin inversion. These deformations resulted in variable basin morphology characterised by deep

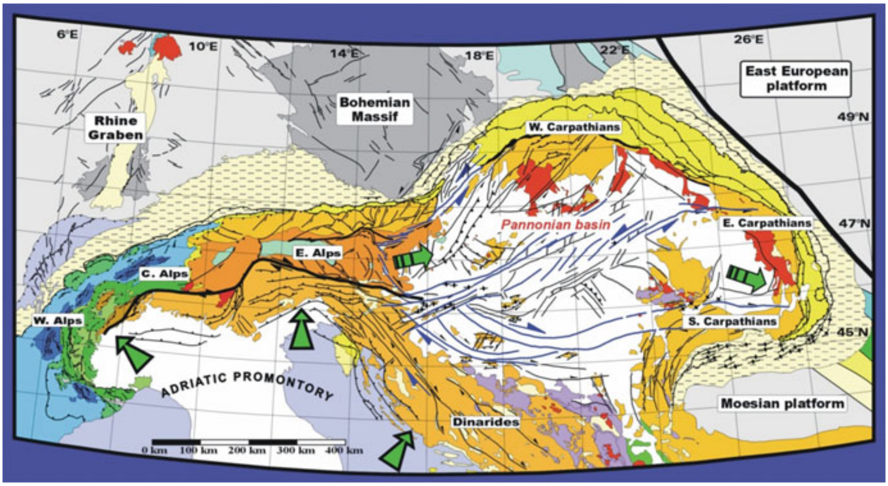

**Fig. 1** Megatectonic setting of the Pannonian Basin [5]

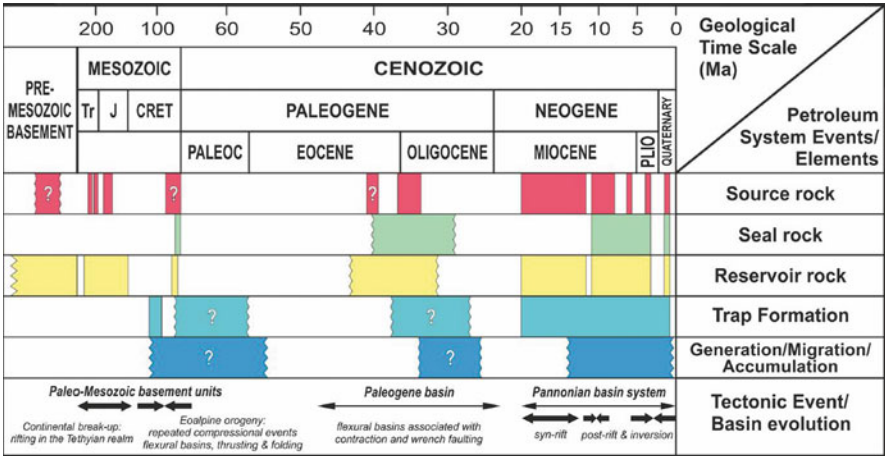

**Fig. 2** Petroleum systems and events of the Pannonian Basin [9]

half-grabens, relative basement highs and island mountains exposing the substrata of the basin. The several thousand m thick basin fill can be divided into two megasequences by the base Pannonian (early Late Miocene) unconformity. In the central part of the basin (territory of Hungary), a relatively thin synrift sedimentary complex is overlain by thick post-rift strata, which were deposited by large prograding delta systems of rivers originating in the surrounding uplifting Alpine and Carpathian mountain belts [7, 8]. A Mio/Pliocene unconformity can be recognised in the basin, and its position indicates thousand metre scale differential movements during the Pliocene–Quaternary.

The different reservoir and source rocks, generation, migration and accumulation as well as different styles of trap formation can be linked to each evolutionary stage of the basin formation (Fig. 2).

Considering hydrocarbon exploration and production in Hungary, four geographical regions can be distinguished with some smaller units: (1) the Great Hungarian Plain (including Kiskunság, Szeged Basin, Battonya High, Nagykunság, Hajdúság, Nyírség and Jászság; for unconventional aspects the Makó Trough, Békés Basin and Derecske Trough), (2) the Zala and the Dráva Basin area (Zala Basin, Somogy, Dráva Basin) (3) the Hungarian Palaeogene Basin and (4) the Danube Basin (Little Hungarian Plain) (Fig. 3).

The Great Hungarian Plain is the most prolific oil- and gas-producing area of Hungary, where the country's largest but mostly depleted conventional hydrocarbon field Algyő can be found. This area is currently the main target of research of the unconventional hydrocarbons (Figs. 4 and 5). Natural gas is known in tight sandstones of the middle Miocene age in the Kiskunság area, Békés Basin area and Derecske Trough area. Gas and condensate in Upper Miocene marls and tight sandstones were drilled in the Makó Trough. The Zala–Dráva Basin in the southwestern Transdanubia region of Hungary is a conventional oil and natural gas

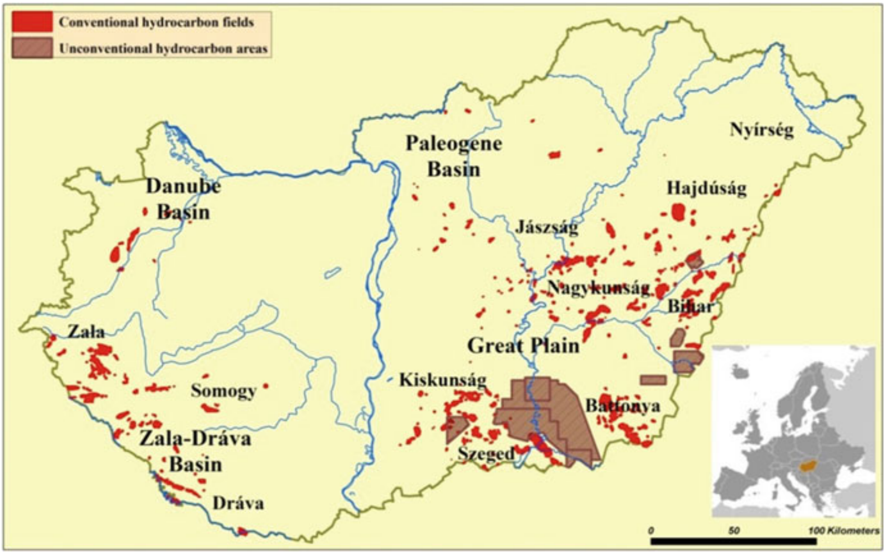

**Fig. 3** Hydrocarbon fields in Hungary

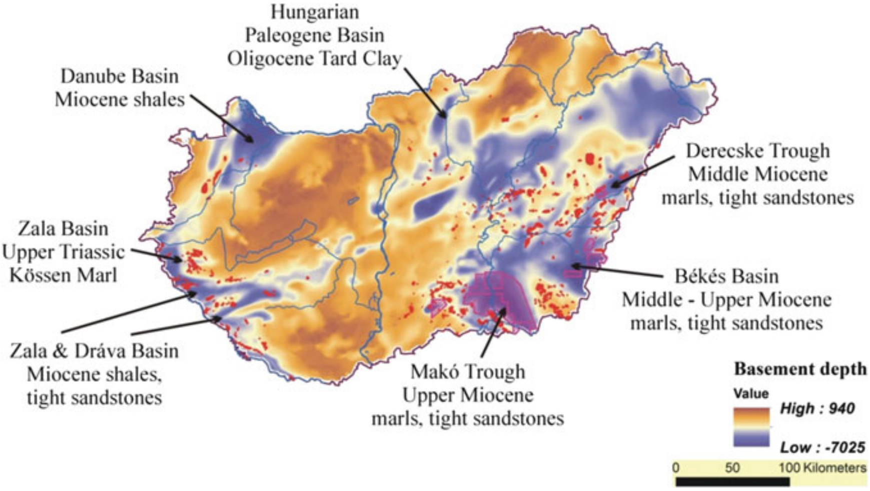

**Fig. 4** Basins with discovered and prospective unconventional hydrocarbon resources in Hungary

exploration and production area that can be a perspective field of research related to the Triassic Kössen Marl unconventional shale oil and to the thick middle Miocene sandstones (tight gas) in the future. In the northwest part of the country, in the Danube Basin, mostly carbon dioxide gas occurrences are known; exploration of unconventionals has not started yet. Oil and gas fields are known in the Hungarian

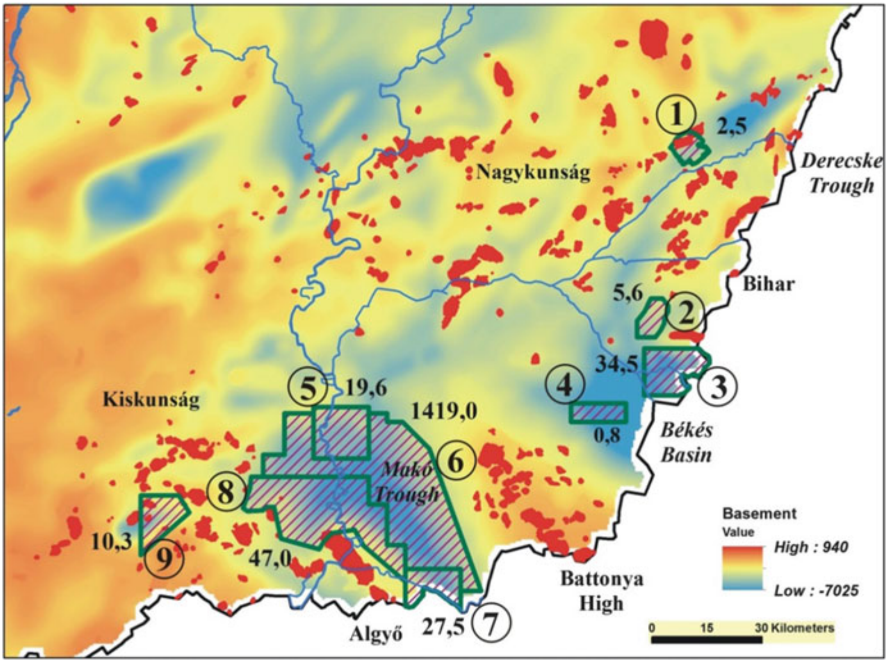

**Fig. 5** Discovered recoverable natural gas resource quantities of unconventional hydrocarbon fields (mining plots) registered in the south-east of Great Hungarian Plain (billion $m^3$). (*1*) Derecske Trough – Berettyóújfalu, Beru wells. (*2*) Békés Basin – Nyékpuszta. (*3*) Békés Basin – Gyulavári. (*4*) Békés Basin – Szabadkígyós. (*5*) Makó Trough (north) – Mindszent. (*6*) Makó Trough – Mako Trough I. (*7*) Makó Trough (south) – Makó. (*8*) Makó Trough (west) – Hódmezővásárhely. (*9*) Kiskunság – Balotaszállás Deep

Palaeogene Basin, and shale oil exploration would be prognostic related to marls and shales of Oligocene age (Fig. 4).

As a curiosity, alginite (oil shale) occurrences are found in the inner basins of the Transdanubian Mountains that may be taken into account as unconventional hydrocarbon resources. Jurassic black coal in the Mecsek Mountains in the southern part of Hungary is counted as unconventional coal bed methane, as huge quantity of methane adsorbed on the surface of coal particles.

According to reports of mining companies, the explored in place resource of unconventional gas quantities cumulatively exceeds 3,900 million $m^3$. Estimates of the producibility also done by the companies suggest that more than 1,500 million $m^3$ can be extracted from the initial in place (Table 1). These numbers are huge compared to the current 2–2.5 billion $m^3$ yearly domestic production of conventional gas [10]. Furthermore, these estimates did not consider the current technology available, market prices, business opportunities and other conditions that may impede production of the large unconventional resources, including the economic yield.

**Table 1** Total hydrocarbon resources on 1 January 2015 status held by the Hungarian Office for Mining and Geology

| | Conventional hydrocarbon quantities | Unconventional hydrocarbon quantities |
|---|---|---|
| Total crude oil initially in place (million tons) | 332.3 | 419.0 |
| Total natural gas initially in place (billion $m^3$) | 416.6 | 3,926.4 |
| Estimated recoverable crude oil initially in place (million tons) | 121.4 | 45.6 |
| Estimated recoverable natural gas initially in place (billion $m^3$) | 307.1 | 1,566.18 |
| Total crude oil production (million tons) | 99.9 | 0.0001 |
| Total natural gas production (billion $m^3$) | 234.2 | 0.0288 |
| Recoverable crude oil (million tons) | 21.5 | 45.6 |
| Recoverable natural gas (billion $m^3$) | 73.0 | 1,566.15 |

There are nine licensed assets for unconventional hydrocarbon exploration and production in the Mineral Resource Register led by the Hungarian Office for Mining and Geology, and most of them are situated in the south-eastern part of the Great Hungarian Plain (Fig. 5). During trial production in these areas, the presence of unconventional natural gas was already proved.

Hungary has 80 years of tradition in the production of hydrocarbons. In order to counterbalance the trend of the decreasing conventional reserves, foreign and domestic oil and gas companies have paid attention to the exploration and production of unconventional hydrocarbons, predominantly tight gas and shale gas during the last decade. Until now Hungary has experienced moderate success regarding the exploitation of unconventional hydrocarbon reserves; therefore, the government decided to support this sector by means of smart regulation in order to enhance the production. By the amendment of mining law in May 2015, the royalty of hydrocarbons from nonconventional sources, applying specific extraction procedures, was defined in 2% in contrast to the former 12% that refers to conventional oil and gas.

Concerning the technology of hydraulic fracturing that is needed for the production of unconventional hydrocarbons, Hungary has great experience gained along conventional hydrocarbon harnessing. The first attempts of hydraulic fracturing in Hungary are dated back to 1957. There have been more than 2,000 cases where hydraulic fracturing was applied in conventional fields for well stimulation. The modern trials – targeting at shale gas and tight gas – started in 2006. The efforts were more successful for the tight gas accumulations occurring at 3,500–4,500 m depth in Upper Miocene deposits. The economic extraction of tight gas reserves occurring at greater depth (4,500–6,000 m) in the same sedimentary sequence faces technical difficulties at present.

Almost 40 wells have been drilled for unconventional hydrocarbons on nine licensed areas, of which eight wells were tested by fracking. The atmospheric and water emissions and the noise burden were below the national and the community regulatory limits in case of these wells. No man-induced earthquakes were detected. The tests were performed in vertical wells, where inert proppants were used. In most cases, clean water was used as fracking fluid.

# 3 Environmental Impacts Studied

Extensive international literature discusses the environmental impacts of hydraulic fracturing [e.g. 1, 11–13]. This study deals in details with two impacts of unconventional hydrocarbon production which are debated often and pose the most significant potential risks to the environment, i.e. the effect of hydraulic fracturing on groundwater resources (by potential spread of the fracking fluid between geological formations, along natural or induced faults) and the risk of induced earthquakes. Other aspects such as impacts of the numerous wells on landscape, contamination risks associated with inadequate transport and storage of recovered fracking fluids on the surface, gas emissions to the atmosphere and potential contamination of groundwater due to poor well design and failure are not discussed.

# 4 The Derecske Trough Pilot Area

## *4.1 Geology*

The recent plain surface of the Derecske Trough in East Hungary (Fig. 6) is a result of the basin evolution that started in the Early/Middle Miocene [15]; thus, 3,000–5,000 m thick sediments cover the Pre-Cenozoic basement complex. The basement that made up of mostly Variscan metamorphic crystalline rocks (mica schists, gneiss and locally amphibolite intercalation) with a narrow Mesozoic carbonate zone on the north belongs to the middle nappe of Tisza Mega-unit (Tisia Terrane) [16]. The depth of the basement is highly varying from 1,000 to 6,000 m, and it reaches its lowest point in the SW–NE orientated central trench region.

Miocene extension started in the Karpatian stage led to the formation of the SW–NE orientated Derecske Trough [15]. The deep basin is filled by Miocene siliciclastic (clays, silts, clay marls and sands, sandstones, sandy conglomerates) and volcaniclastic sediment (tuffites and tuffaceous sandstones) formations at least in 300–700 m thickness, which contain the unconventional hydrocarbons (tight gas) as well. The succession was divided into four sedimentary cycles, of which the second, characterised by turbidity-like deposits, involves the siliciclastic unconventional reservoirs, but these formations pinch out on the eastern edge of the trough. As the depocentre shifted to the NE, volcaniclastic sediments became more

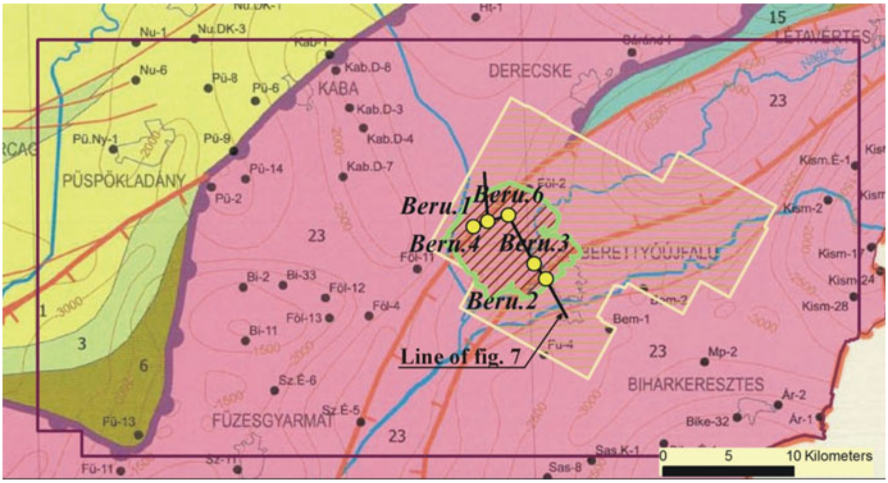

**Fig. 6** The location of the Derecske pilot area: borders of Derecske concession area (*purple square*) and "Földes" 3D seismic block inside (*yellow line*), MOL's mining plot (*green line*) and Beru wells. The background is the Pre-Cenozoic basement map of Hungary [14]: (*1*) Senonian pelagic marls, flysch; (*3*) Senonian continental shallow and deep marine formations; (*6*) Lower Cretaceous platform limestone; (*15*) low-grade metamorphic Mesozoic formations; (*23*) Variscan metamorphic complex

dominant in the area. Thickness of them in the depocentre can reach the thickness of the underlying siliciclastic succession. Interbedded clay marls, sandstones and locally sandy limestones appear in the volcaniclastic sediment formations, which also contain tight gas fields. Middle Miocene clayey and tuffy beds include source rocks in several intervals and together with intercalated sands and sandstones make up a commingled system between 3,200 and 3,800 m depth.

Major subsidence and deposition occurred, nevertheless, in the post-rift phase of basin evolution characterised also by significant strike-slip tectonics [17, 18], while the Derecske Trough was also covered by the brackish Lake Pannon. The 2,500–2,800 m thick succession indicates mostly continuous infill of the trough with only one inversional event about 6.8 Ma [19]. The Upper Miocene–Pliocene (so-called Pannonian) sequence consists of the transgressional formations of Endrőd Marl and Szolnok Formations. The previous one is regarded as important source rock, while the latter, mostly turbidites, also represents remarkable potential as conventional reservoirs in the area. The continuously developing prodelta and delta slope formations (Algyő Formation) are generally clayey marls and siltstones with fine-grained sandstone intercalations. The frequently alternating sandy silty deposits of delta fronts and delta plains (Újfalu Formation), the sandy units of which are the most important regional thermal water aquifers, overlie these. The bottom of Újfalu Formation is approx. 1,300–1,400 m deep within the area. The Újfalu Formation achieves its maximum thickness (1,000–1,200 m) in the central depression of the Derecske Trough, while towards its margins, it is usually 200–300 m thick. Subsequent sandy-clayey deposits of the alluvial plain (Zagyva

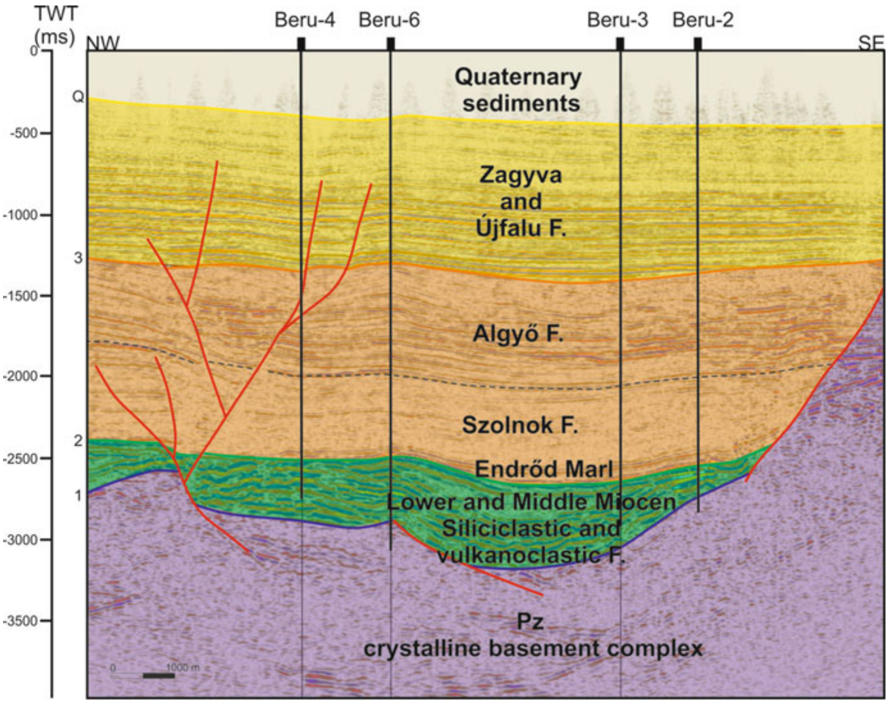

**Fig. 7** NW–SE geological cross-section of the Derecske Trough. Main horizons used in 3D modelling are indicated by Arabic number. See location on Fig. 6

F.) are hardly distinctive from the underlying Újfalu Formation, and they are more than 800–900 m thick within the Derecske Trough, while in the north-western and south-eastern parts of the area, their thickness is only 100–300 m. The sedimentary succession ends with the continuous development of variegated clays of Pliocene – Quaternary lacustrine–alluvial formations in 400–500 m thickness (Fig. 7). This thick fluvial sedimentary succession representing a continuous sedimentation from the Late Miocene to the beginning of the Quaternary Period indicates a continuous subsidence of the region. Such geodynamic conditions favour the closing and clay formation of existing fractures, which is an important aspect related to the creating/renewal of faults resulting from hydraulic fracturing.

## *4.2 Hydrogeology*

The first important aquifer is situated in the Pleistocene fluvial floodplain sediments and in the underlying Pliocene lacustrine–alluvial formations. The majority of public water supply wells use the upper 100–300 m thick sandy formations of these units, which are easily accessible by relatively shallow wells, and they store water of adequate quality.

This shallow aquifer system is hydraulically connected to the underlying Upper Pannonian fluvial, floodplain, lacustrine and paludal sediments. These formations accommodate the intermediate groundwater flow system of the porous sediments of the basin.

The deepest part of the regional groundwater flow system is accommodated in the sandy units of the Upper Pannonian Újfalu Formation, which are underlain by the clayey Algyő Formation. The latter one is considered as an aquitard and therefore forms the bottom of the porous, regional flow system of the basin. Thermal waters stored in the upper part of the formation shallower than 700–800 m are $NaHCO_3$-type waters, whose approx. 1,000–3,500 mg/l total dissolved solid (TDS) content and chloride content are generally rising with the depth. $NaHCO_3Cl$-type water and 1,950–6,500 mg/l TDS content is a characteristic of aquifers lying deeper than 700–800 m.

The pressure conditions of Upper Pannonian and Quaternary formations are equal to the hydrostatic pressure.

The Lower Pannonian formations achieve their maximum thickness in the central part of the Derecske Trough, which should be highlighted because due to its aquitard nature it can significantly slow down the migration of possible pollutants deriving from the fracturing of the deeper, older Miocene formations. Waters situated deeper than 1,700–1,800 m are typically $NaHCO_3Cl$ and NaCl type. Based on the available data TDS content is mainly 5,700–10,000 mg/l; higher salinity ($>$10,000 mg/l) is characteristic of water situated deeper than 1,700–1,800 m.

The TDS content of groundwaters stored in Lower–Middle Miocene sediments varies between 10,000 and 15,000 and 24,700 mg/l with a few exceptions, and they are NaCl type.

Carbonate facies and interbeddings of Pre-Pannonian Miocene formations rank among the local porous, double-porosity systems in the study area. The waters stored in Miocene carbonate formations usually have a TDS level of 13,600–15,300 mg/l and are NaCl type or less frequently NaCaCl type implying that the aquifer is confined.

Pressure conditions in Lower Pannonian formations are hydrostatic or slight overpressure, while Miocene formations can be characterised by significant overpressure.

As the Pre-Cenozoic basement rocks are mostly fractured-karstified metamorphites and carbonates, an enhanced permeability characterises the upper several tens or possible hundred m thick zone. The waters stored in the Mesozoic formations are characterised by NaCl type and 12,200–22,200 mg/l TDS content, while waters stored in Variscan metamorphic rocks mostly contain 10,000–27,000 mg/l TDS and are $NaClHCO_3$–NaCl type. These deep aquifers are characterised by significant overpressure.

## 4.3 Unconventional Hydrocarbon Exploration

At the beginning of 2000s, the MOL carried out drilling exploration in Derecske–Berettyóújfalu–Földes region aiming to explore natural gas in geological structures lying deeper than 3,000 m (Fig. 7) [20]. Within the framework of this exploration programme, five wells were drilled (Fig. 6); Beru-1 and Beru-2 wells proved the in place gas resources. Beru-2 well produced 1,000–3,000 $m^3$/day gas influx from the basement and 500–700 $m^3$/day from Miocene formations. Beru-1 well tests indicated a high-pressure (57.1 MPa) and high-temperature (200°C) environment with an average porosity of 8% and an average permeability of 0.07–0.09 mD, including a good quality wet gas system. The initial test results (without formation stimulation) showed low yield and fast pressure decrease, implying the occurrence of so-called tight gas, the production of which was not economical.

Three addition wells (Beru-3, -4 and -6) were drilled to increase the gas quantities initially in place and to explore resources in deeper position. In 2011 Beru-4 well was stimulated by hydraulic fracturing. During the operation three zones were fractured between 3,450 and 3,726 m. Vertically the height of fractured zones was 60–65 m [20]. In Beru-4 well the pressure and temperature (645 bars and 209°C in 3,700 m) are also high. During hydraulic fracturing the total amount of fluid injected in three zones was 1,569 $m^3$, and the amount of proppant was 414 t [20].

## 4.4 Results of Microseismic Monitoring

The hydraulic fracturing was accompanied by successful microseismic observation and evaluation carried out partly by the Geological and Geophysical Institute of Hungary in cooperation with other subcontractors that made possible to outline the spatial position of induced fractures and the magnitude of released energy (and this way the possibly triggered seismicity risk).

The seismic monitoring system of fracturing consisted of conventional geophones (instruments used for 2D/3D seismic measurements) placed on the surface (10 Hz eigenfrequency geophone group) and a data acquisition system. During the measurement altogether 1,106 observers have been used in the approx. 4 × 4 km study area (in a grid of 50 × 300 m) (Fig. 8). As a consequence of great depth and the geological conditions (sedimentary basin), the energy of detected signals was small (its average attenuation is $10^{-10}$) and it was under the background noise level (the energy of signals induced by the traffic significantly exceeded even the energy generated by the perforation of steel casing and fracturing, which was identified as highest). They could have been observed only by sensitive instruments and could not be observed by human beings at all. Since only the

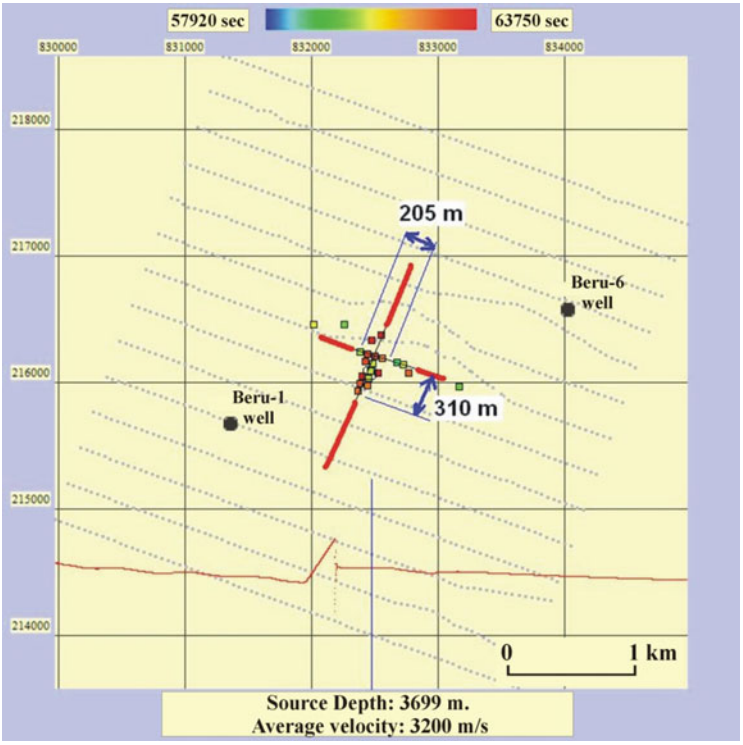

**Fig. 8** The results of microseismic monitoring carried out in the neighbourhood of Beru-4 well [21]

vertical movement of the wave field has been registered on the surface by the numerous channels used during the measurements, the depth has not been determined in terms of seismology. The depth of events was considered equal to the depth of fracturing.

Figure 8 illustrates the point set of microseismic events detected during the deepest (3,700 m) fracturing. Seismic events triggered by fracturing occurred within ~300 m of the drill hole. The events can be found along two definite directions (NNE–SSW and WNW–ESE), which is in line with the main tectonic directions of 3D seismic measurement "Földes-K" determined at the same depth. The vertical size of the zone where microseismic events occurred due to fracturing is not likely to exceed the 300 m zone determined horizontally. It concludes that the zone directly affected by fracturing cannot be larger than the 300 m zone demonstrated during the microseismic monitoring, i.e. formations further than that are not influenced by the operation carried out in the drill hole.

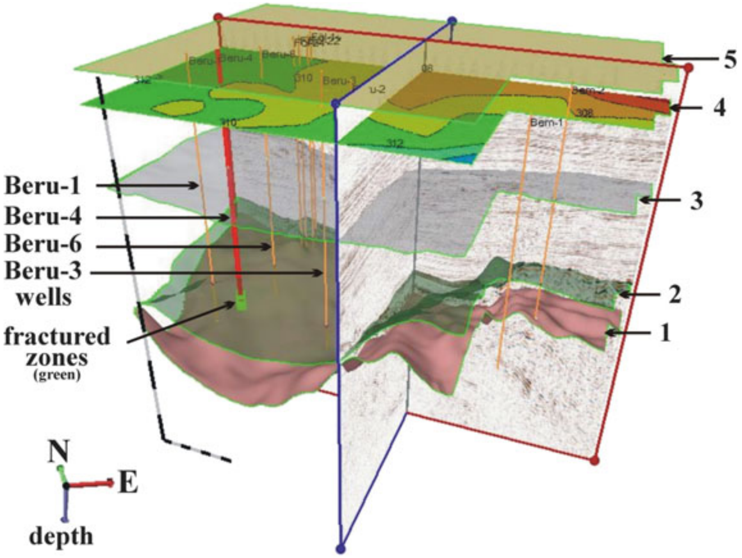

**Fig. 9** The surface and the main geological levels, as well as Beru-4 well and the real spatial extension of the induced fractured zones (highlighted in *green* at the lower part of Beru-4 well) in Földes-K 3D block in Jewel software model. *Vertical* and *horizontal scale* is indicated by the scale bar where a sign means 500 m

## *4.5 3D Modelling of the Study Area*

The analysis of the pilot area focused on the development of a voxel geological model made in JewelSuite (JewelSuite Subsurface Modelling 2014) 3D modelling software environment. Two models were elaborated: a regional model covering the whole area mostly based on existing and available geological data and subsurface maps and a more detailed model on the eastern part of the study area based on the interpretation of the Földes-K 3D seismic block (Fig. 6). Thirty-seven borehole successions were applied to the regional model and 11 boreholes to the detailed model. In order to show data in real depth, results of VSP (vertical seismic profile) measurements have been applied from five boreholes.

The interpretation focused on the 3D visualisation of key geological horizons relevant in terms of analysing the impacts of hydraulic fracturing, especially on groundwater resources; therefore, the main boundaries of the most important aquifers were also incorporated. Hungary is extremely rich in thermal waters (defined as water having an outflow temperature higher than 30°C), widely used for various purposes [22]. Furthermore 70% of drinking water resources of the country are from shallow groundwater resources; therefore, the protection of both the thermal- and the cold-water aquifers is of utmost importance.

Based on these considerations, the following horizons were built into the models (Figs. 9 and 10):

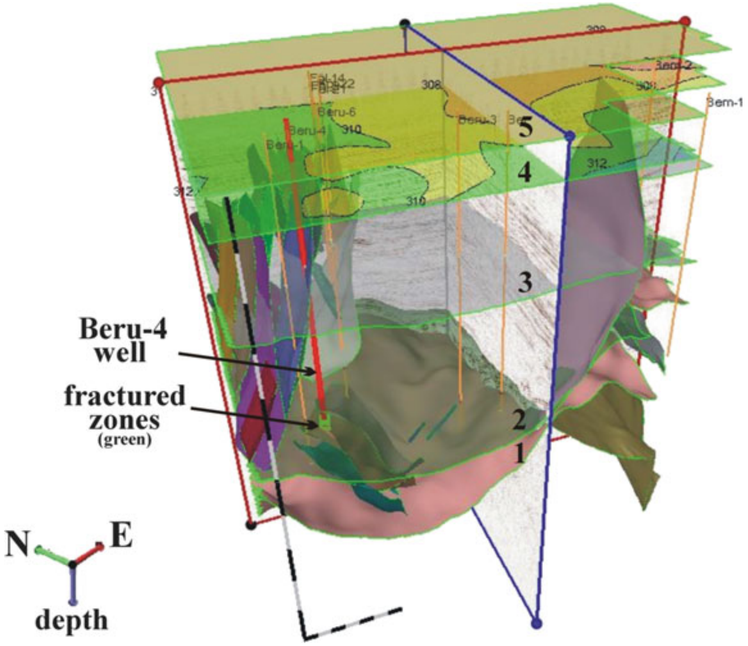

**Fig. 10** Geological levels, tectonic planes, as well as Beru-4 well and the real spatial extension of fractured zones (highlighted in *green* at the lower part of Beru-4 well) in Földes-K 3D block in Jewel software model. *Vertical* and *horizontal scale* is indicated by the scale bar where a sign means 500 m

(1) The Pre-Cenozoic basin floor (top of the Palaeozoic and Mesozoic basement formations)
(2) The top layer of Lower and Middle Miocene formations (geological units that are associated with unconventional hydrocarbons)
(3) The bottom layer of the Újfalu Formation which is considered the main thermal water aquifer in Hungary
(4) The depth grid of the 30°C isotherm aiming to indicate the top of the thermal water aquifers, above which cold-water aquifers are situated
(5) The surface

The interpretation of each horizon was carried out by using 20 in-line and crossline intervals, at some parts – where the complexity of structural elements is required – along ten, five or even one line. Based on interpreted horizons, surfaces were generated by simple kriging and triangulation, which were used for making 3D Jewel grids with resolution of 500 × 500 m. Geological attributes belong to each cell of the grid model. In addition to the geological horizons, structural elements (faults) were also identified during the assessment of the seismic block as they have key importance as possible pathways in fluid migration.

## 5 Discussion

The spatial position of fractures developed during well stimulation of the Beru-4 well was built in the 3D model as well. Figure 9 clearly shows that the spatial extension of induced fractures is extremely small, and there is at least 2,000 m mostly impermeable (clayey Lower Pannonian and compact Miocene) sedimentary succession between the uppermost fractured zone and the bottom of the deepest thermal aquifer (bottom of the Újfalu Formation, shown by a grey layer on Figs. 9 and 10); so it concludes that the risk of a possible pollution spreading along the communication between formations does not exist.

In case of a potential pollution transport faults may also serve as conductive media, so their roles are analysed below. The faults identified based on the seismic interpretation were also built in the geological model. Figure 10 illustrates that the block is densely crossed by fault planes. However, according to both seismic interpretation and data from literature [17], the development of flower structures, which cut cross the Pannonian sediments and are related to the strike-slip movements associated with basin formation, was finished 8 million years ago in Derecske Trough; therefore, the faults cross only the several hundred, occasionally thousand m thick clayey and sandy formations (Endrőd, Szolnok, Algyő Formations).

When considering the faults' ability to conduct fluid, the material of the tectonised rock and the activity of faults have significant roles in addition to the fault geometry and the nature of stress field. The flow from the fractured Miocene formations is directly hindered by the clayey (argillaceous) components of the overlying Endrőd Marl; fractures close almost immediately after the break due to the occurrence of expansive clay minerals. The much thicker Algyő Formation, considered as an aquitard, acts similarly. The compression stress field, which is typical of the Pannonian Basin during the Pliocene and Quaternary [23], is also favourable for the closure of faults. However, it cannot be excluded that certain faults of the fault system have been periodically active recently [18, 24]. The migration along faults – at least in case of gas – is suggested by the small gas fields related to strike-slip zones explored in Upper Pannonian formations, whose source rocks are supposed to be Miocene and Lower Pannonian formations. However, it should be highlighted that these presumed hydrocarbon migrations take place in geological timescale.

If considerable amount of water flowed from the depth (e.g. along permeable faults and fractures), it would significantly modify the hydro-geochemical composition of groundwater. The chemical type of porous thermal aquifers shows that higher-salinity water may occur in Upper Pannonian formations especially in its lower part; however, it is mainly typical of basin parts where the Upper Pannonian formations lie directly on the basement or on very thin, Lower Pannonian–Miocene formations. As a consequence, higher-salinity water from deep, overpressure formations can get directly into the Upper Pannonian thermal aquifers, but it is carried out by very slow migration (measurable only on geological and not human timescale). The general hydro-geochemical diagram of the Great Hungarian Plain

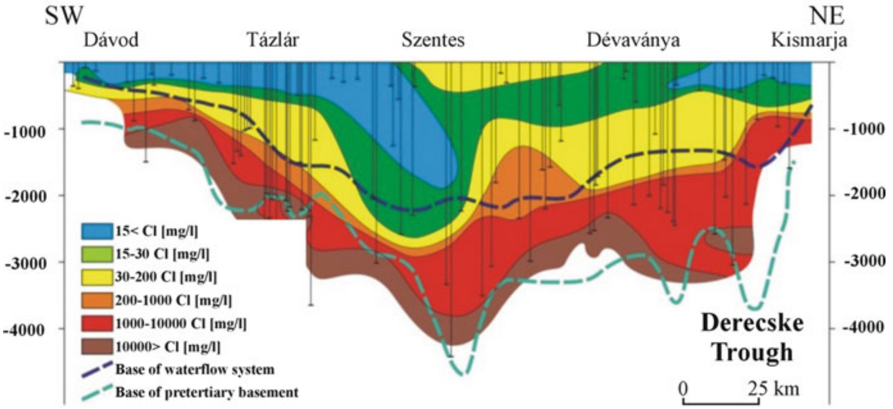

**Fig. 11** Hydro-geochemical deep section in Great Hungarian Plain. The chloride ion concentration is a good indicator of deep high-salinity waters (Tóth et al. [3])

(Fig. 11) shows well separable hydro-geochemical "bedding" in line with the spatial position of the main hydrostratigraphical units; and independently of fracturing, no local mixing zones can be indicated where deep, high-salinity brines rising along a possible permeable zone would occur in less salty thermal water and which might be negatively influenced by fracturing.

The overpressure character of the deep lying aquifers also suggests that they do not have a local discharge (e.g. along an active fault plane); otherwise a significant drop in pressure would be present.

Ultimately, the question arises whether hydraulic fracturing can result in such an energy release which causes the reactivation of faults or generates new significant permeable faults. To discuss this, various aspects have to be considered:

(1) The energy of fracturing can create only a local fracture system affecting only a few hundred m zone around the well (Fig. 8), and induced microseismic activity can be detected only by highly sensitive instruments; therefore, it is almost excluded that a fracturing operation would release so much energy that would cause the development of a new, significant permeable fault (or the reactivation of an existing one).

(2) Regarding induced earthquakes, the maximal magnitude of an earthquake in a certain region is equal to the stress stored in the underground formations (that much energy can be released). Generally, the seismicity of Hungary and the Carpathian Basin is considered medium. Based on the observations so far, annually four or five earthquakes with magnitudes of 2.5–3.5 can be expected, which are perceptible but do not cause damage. Earthquakes causing moderate damage occur every 15–20 years, while stronger, more damaging earthquakes with magnitudes of 5.5–6 are triggered every 40–50 years. The distribution of quakes is not homogenous; the surrounding orogenic areas, which are the most active parts of the region in terms of seismicity, significantly differ from the

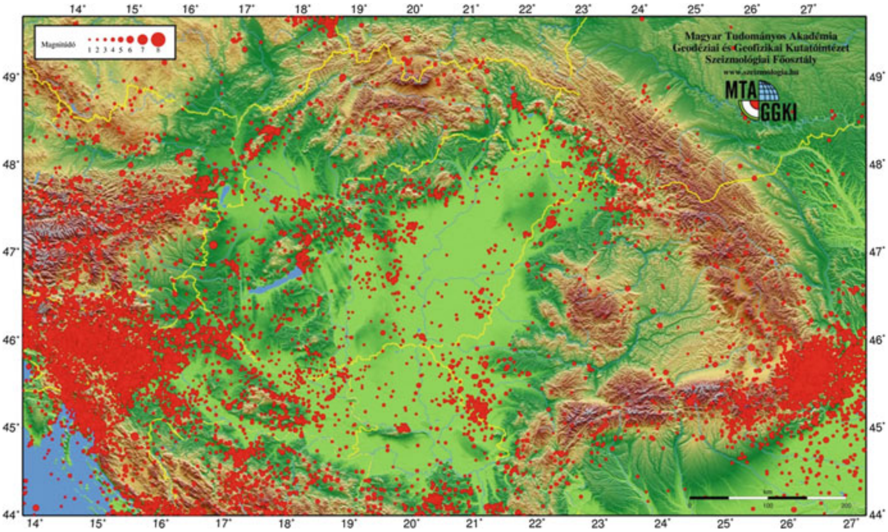

**Fig. 12** The areal distribution of earthquakes occurred in the Carpathian Basin and its neighbourhood between 456 and 2006. The size of symbols is proportional to the Richter magnitude of earthquakes (1–8) (www.seismology.hu/images/cikkek/seismicity/a_karpat-medence_foldrengesei.jpg)

inner part of the basin. Areas affected by hydraulic fracturing (primarily the Great and Little Hungarian Plain) are the less active parts of Hungary (Fig. 12). If unfortunately energy is released from a tectonic zone during fracturing, the quantity of the released energy can be estimated. The statistical analysis of determined earthquakes [25] clearly points out that flexible energy accumulated in the part of the Pannonian Basin affected by hydraulic fracturing can most likely generate earthquakes with magnitudes of 1–2.5 under natural conditions (Fig. 13). Induced seismicity releases a part of the accumulated stress so in case of the most disadvantageous technical and tectonic circumstances earthquakes with a magnitude of ~1.8 can be triggered in Hungary most likely. However, the dissipation capability of young sedimentary formations able to absorb energy should also be considered, thanks to which such an activity practically cannot be perceived by humans on the surface.

(3) The development of brittle fracture is moderated in the porous and intercalated sediments (e.g. clays, silts, sandstones, etc.) characterised by lower strength, preventing energy absorbance and fault development. Growing temperature acts also against the development of brittle fractures, increasing the viscous nature of the rock and this way its energy absorbability. This effect is significant at great depths of the Pannonian Basin because of the geothermal gradient over the world average.

The upper on average 3 km (0–6 km) thick young (Neogene) sedimentary part of the Pannonian Basin is made up of low strength, porous, clayey rocks, which on the

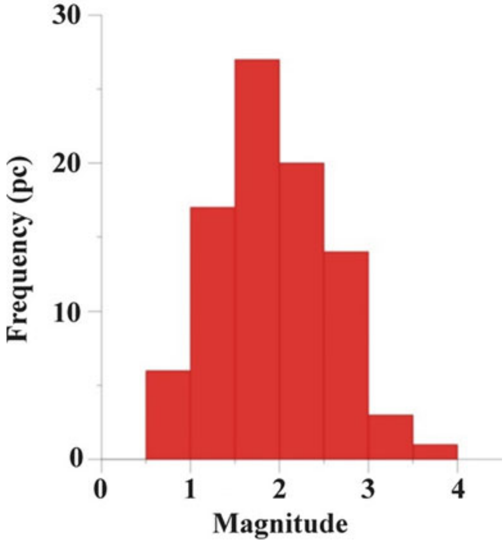

**Fig. 13** The distribution of magnitudes of earthquakes in the above 10 km of Pannonian Basin based on literary hypocentre and magnitude data determined so far

one hand can significantly diminish the energy of earthquakes and on the other hand are not favourable in terms of seismic activity. Due to the considerable amount of young sediments as well as the high geothermal gradient improving the plasticity and viscosity of deep rocks, the seismic activity in Hungary differs (positively) from the world average. In other words, because of the above-mentioned factors, the seismic activity in the Pannonian Basin is lower than in several other basins of the world.

Consequently the risk of induced seismicity and its surface impact is low due to the geological conditions of Pannonian Basin.

## 6 Conclusion

Hungary is dedicated to maximise the exploration and production of unconventional hydrocarbons, for which the hydraulic fracturing is a precondition by the introduced geological conditions of the Pannonian Basin. However, contradictory environmental consideration and resulting licencing problems of hydrocarbon exploitation operations – including especially well stimulations – call attention of the importance of the analyses of local circumstances and the regulatory steps determined based on those. Therefore, the experts of the Geological and Geophysical Institute of Hungary compiled a study for examining the potential environmental impacts of hydraulic fracturing in Hungary based on a 3D geological model of a relevant study area [3]. The study clearly shows that the risk of a possible pollution spreading along the communication between the fractured and aquifer formations does not exist, and it is almost excluded that a fracturing operation would release so much energy that would cause the development of a new, significant permeable fault (or the reactivation of an existing one), so the risk of induced seismicity and its surface impact is also low due to the geological conditions of Pannonian Basin.

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