The function of faults in hydraulic hydrocarbon entrapment: Theoretical considerations and a field study from the Trans-Tisza region, Hungary

Brigitta Czauner and Judit Mádl-Szőnyi

ABSTRACT

The main focus of this work is the investigation of the hydraulic function of faults, which is dependent upon the fluid-potential field, based mainly on theoretical considerations. The study displays the joint application of different research techniques, particularly hydrogeological methods for the western part of the Trans-Tisza region, Hungary, where thermal water and hydrocarbon accumulations are known. During the research, seismic, well-log, lithostratigraphic, and hydraulic data were analyzed to determine the hydrogeological framework and the fluid-potential field of the study area. As a result, the heterogeneity of a thick (~1000 m [~3281 ft]) and regionally extensive argillaceous aquitard unit was established, which is divided by structural elements and relatively thin (150–200 m [492–656 ft]) sandy aquifer units. Furthermore, two major strike-slip fault zones connecting the overpressured sub-Neogene basement with the uppermost aquifer unit and also intersecting each other were identified. Based on the complex investigation, we determined that the identified faults represent direction-dependent control over the fluid-flow systems of the study area. Both proved to act vertically as conduits but transversely as barriers; they enable pressure dissipation and intensive water upwelling from the sub-Neogene basement, resulting in a fluid-potential anomaly and, at the same time, in hydrocarbon

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entrapment. Consequently, during hydrocarbon exploration, it is not definitely necessary to search for low-permeability faults because high-permeability faults can also be acting as direction-dependent barriers for fluid flow. Moreover, the research also pointed out that hydrogeological methods are effective in hydrocarbon exploration during the evaluation of hydraulic function of faults.

INTRODUCTION

Structural elements generally represent key geologic factors in fluid migration and retention. By enhancing or impeding fluid flows, fractures and faults have a crucial effect on groundwater flow systems, as well as on petroleum systems. Consequently, hydrogeology and petroleum geology also pay considerable attention to the investigation of hydraulic roles of faults, although the aspects of these two disciplines are different.

Hydrogeology mainly examines the effects of faults on groundwater flow patterns, particularly on the basis of hydraulic, hydrochemical, and thermal data analysis, as well as related surface phenomena (Tóth, 1999). Petroleum exploration focuses on fault-sealing analysis primarily based on the petrophysical properties of fault zones and juxtaposed strata (Sorkhabi and Tsuji, 2005a) to determine the function of faults in hydrocarbon migration and entrapment. However, "compared to many other areas of petroleum geoscience, studies on the structural controls on fluid flow in hydrocarbon reservoirs are in their infancy" (Knipe et al., 1998, p. vii). Although petroleum hydrogeology has already applied hydrogeological principles and techniques to petroleum exploration on the basis of the hydraulic theory of petroleum migration (Tóth, 1980), few attempts have been made to study the hydraulic function of faults in hydrocarbon entrapment by hydrogeological methods.

The purpose of this work was to investigate the hydraulic function of faults, which is dependent on the fluid-potential field, in groundwater flows and hydrocarbon entrapment through the joint application of different, particularly hydrogeological, research techniques. A study area was chosen in the Trans-Tisza region of Hungary where three possibly related phenomena have been observed: (1) fluid-potential anomaly possibly induced by fault(s) (Tóth and Almási, 2001), (2) thermal water occurrence (Berekfürdő spa), and (3) hydrocarbon accumulations (Tatárülés-Kunmadaras gas field). Because of these restrictions, we drew conclusions based on theoretical considerations and integrated hydrogeological assessment of the hydraulic function of faults in an overpressured upward flow field and based on the effectiveness of hydrogeological methods in hydrocarbon exploration. The case study results, as well as the approach, can be used also on other research areas for hydrocarbon and geothermal prognosis.

REVIEW OF THE APPLIED THEORETICAL CONSIDERATIONS

Hydraulic Function of Faults in Fluid Migration

Faults can both be barriers (seals) and conduits (leaks) for fluid flow depending on several factors. (1) The petrophysical properties (porosity, permeability, capillarity) of the fault zone and the undeformed host rock are commonly in the focus of petroleum geologic research (Jones et al., 1998; Sorkhabi and Tsuji, 2005b). (2) The relative orientation and dip angle of the fault plane: vertical fractures (e.g., strike-slip faults) are generally more effective than dip-slip faults as conductors of fluids (Gudmundsson, 2001). (3) The present stress field is also decisive. High fault-normal stress reduces aperture, thus inhibiting fluid flow, whereas high fracture-parallel compressive stress increases the ability of faults to stay open and transport fluids (Aydin, 2000). (4) The significance of the function of pore pressure in tectonic processes, such as faulting, is manifest in their interplay. Pore-pressure buildup reduces the effective stress and frictional resistance in the rock mass, which can lead to fracturing. Consequently, a high fluid pressure is capable of opening fractures at any depth and thus facilitating vertical and lateral flows (Aydin, 2000). However, whereas pore-pressure growth causes hydraulic fracturing, opening of fractures results in

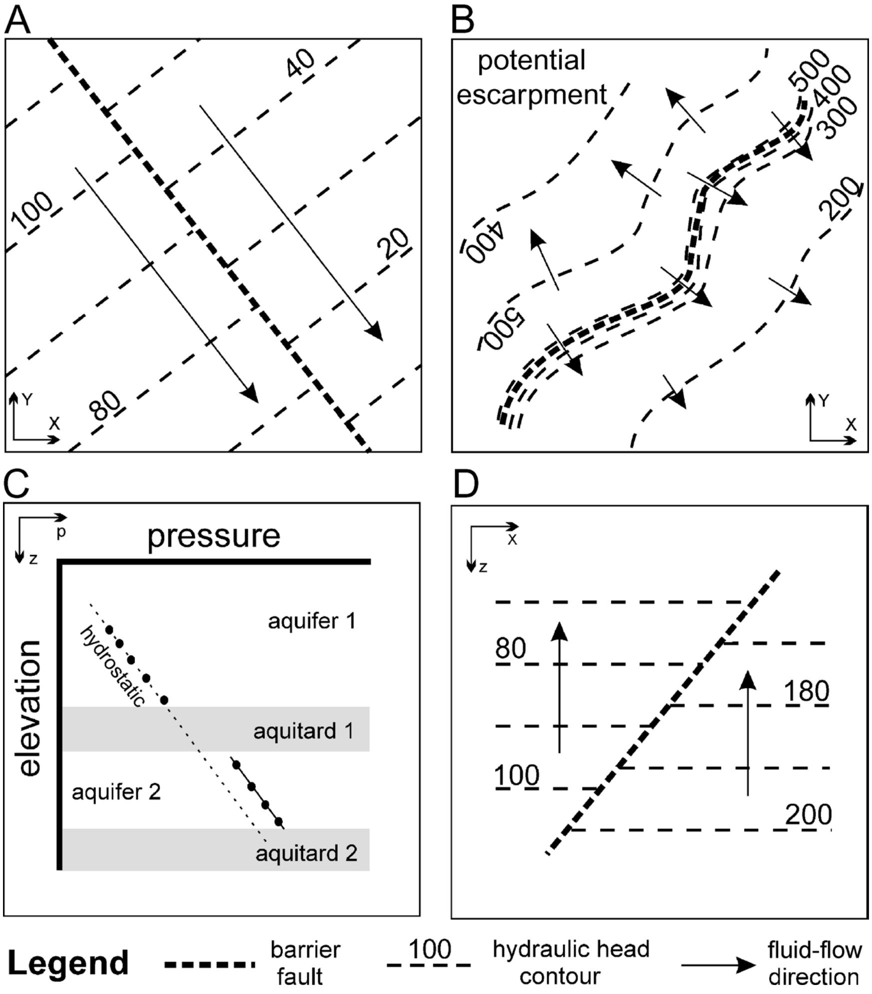


Figure 1. Features of the hydraulically interpreted barrier fault on potentiometric surface maps (A, B), on the *p*(*z*) profile (C), and on the hydraulic cross section (D).

pressure dissipation, yet the presence of faults impeding fluid flows helps maintain the overpressure.

In addition, most of the previously mentioned factors can show spatial and temporal variabilities. Spatial changeability means space and direction dependence too, whereas temporal variability first depends on the fault activity. During the active opening and developmental phases of a structural element, it is commonly more conductive (mainly because of the induced pressure drop) than the host rock. However, in the inactive periods, fractures tend to close, and cementation and other diagenetic processes are more favorable.

Because of the spatial and temporal variabilities of all the known and unknown factors, it is almost impossible to generalize the hydraulic function of faults as conduits or barriers for fluid flow. Data are rarely available from the fault zone itself. However, the subsurface fluid-potential field, the formation water chemistry, and some other hydrogeological phenomena can also be used as indirect indicators of the fault zone hydraulic properties. Among the common hydrogeological research techniques, the hydraulic methods are the most effective in the hydrogeological analysis of faulted sequences. Whereas potentiometric surface maps can examine the horizontal fluid flows (Figures 1A, B; 2A, B), pressure-elevation or *p*(*z*) profiles provide information about the vertical hydraulic communication (Figures 1C; 2C), and hydraulic cross sections in turn allow the study of flows in both directions (Figures 1D; 2D). Moreover, these methods do not necessarily need data from the fault zone itself.

From the point of view of hydrogeology, in a simplified case, the fault zone–related barriers have lower permeability than those of the crosscut aquifer, and the flow direction in the aquifer adjacent

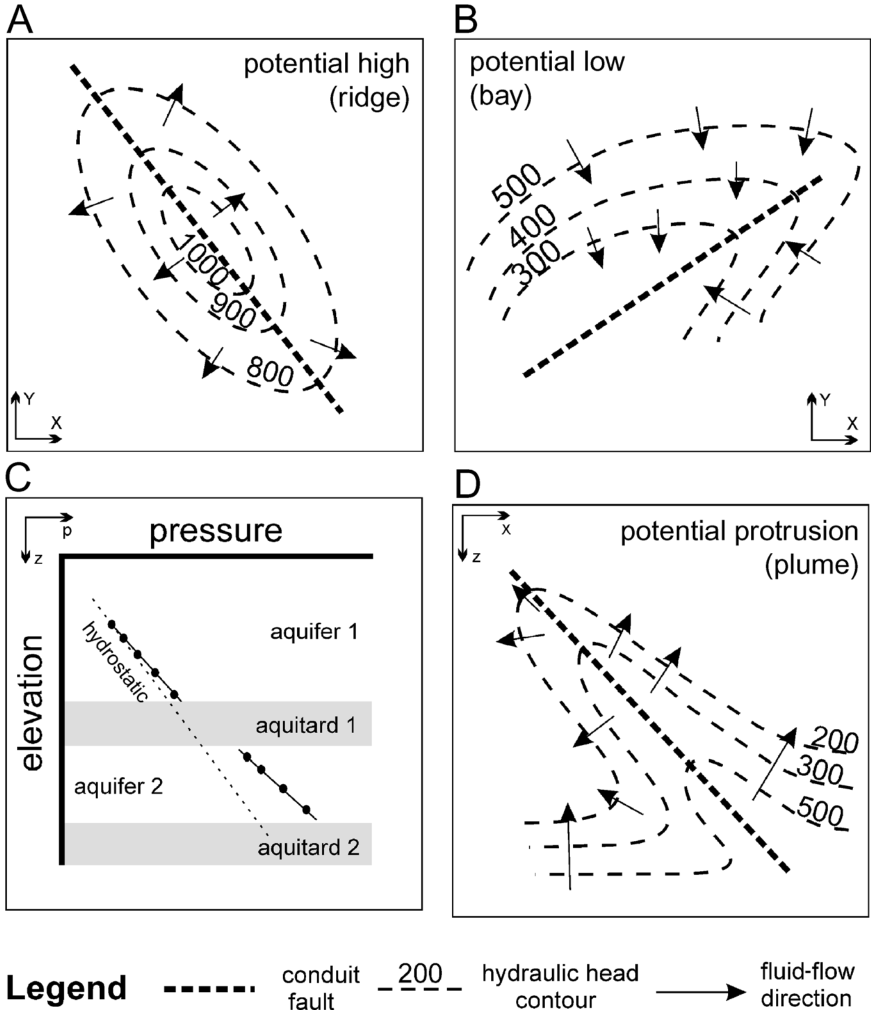


Figure 2. Features of the hydraulically interpreted conduit fault on potentiometric surface maps (A, B), on the *p*(*z*) profile (C), and on the hydraulic cross section (D).

to the fault tends to be parallel to the plane of the fault (Underschultz et al., 2005) (Figure 1A, D). In addition, when only lateral flow is restricted by faults, but updip flow along the fault is allowed, a so-called potential escarpment (Figure 1B) can be generated, which indicates the steep lateral gradient caused by the horizontal flow impediment (Tóth, 2003). In two aquifers separated by a zone of low hydraulic conductivity (i.e., aquitard or low-permeability fault), pressure data from both aquifers define a hydrostatic vertical gradient on a pressure elevation plot (Figure 1C). However, pressure data in the lower aquifer fall above the pressure gradient defined by the data in the upper aquifer, thus indicating the presence of the lower permeability zone between the two aquifers. Besides, corroborating evidences for fault zone barriers can be the accumulation of hydrocarbons on one side of the fault and the discontinuities in the formation water chemistry across the fault (Underschultz et al., 2005).

When permeability is higher along the fault than in the crosscut aquifer, the fault acts as a conduit and the flow direction in the aquifer adjacent to the fault intercepts the plane of the fault (Underschultz et al., 2005). Consequently, conduit faults can induce potential highs and lows (Figure 2A, B), as well as potential protrusions (Figure 2D) and depressions, which are observable on potentiometric surface maps and hydraulic cross sections, respectively (Tóth, 2003). In addition, the connection of leaking faults with the land surface can cause springs with thermal and/or chemical anomalies or can recharge deeper aquifers (Underschultz et al., 2005).

If two vertically separated aquifers are in hydraulic communication across a fault zone functioning as a conduit, pressure data from the two aquifers define dynamic vertical gradients on a pressure elevation plot, and the lower aquifer gradient is higher because of the presence of the lower permeability zone between the two aquifers (Figure 2C).

This ideal situation is more complicated in reality because of the previously mentioned temporal and spatial variabilities of the hydraulic behavior of faults, as well as those of the fluid-potential field. The model of Matthäi and Roberts (1996) shows an example for the latter case when the distribution of fluid potential causes the spatial variability in a fault hydraulic behavior. According to their theoretical results, in a high-permeability fault crosscutting a sand-shale sequence characterized by a single-phase pressure-driven fluid-flow system, the direction of fluid flow in an upper sand layer could be outward of the fault plane. Thus, fluid flow does not occur across the fault, and in such a case, a high-permeability fault also can be acting as a direction-dependent barrier for fluid flow. This conclusion points out that in the course of the investigation of the hydraulic behavior of faults, it is not enough to study just the permeability of the crosscut layers and the fault, but attention also has to be given to the fluid-potential field.

Hydraulic Function of Faults in Hydrocarbon Entrapment

During the study of the hydraulic function of faults, one of the previously mentioned evidences for fault zone barriers is the accumulation of hydrocarbons on one side of the fault. Conversely, possible petroleum traps in the vicinity of barrier faults are also worth exploring. Consequently, in analyzing the fault function in petroleum traps, petroleum geology specifically focuses on fault-sealing analysis, the applicability of that is primarily restricted to normal faults in clastic reservoirs (Sorkhabi and Tsuji, 2005a), and the assessment needs a vast amount of data also from the fault zone itself.

However, during hydrocarbon exploration, searching for low-permeability faults is commonly unnecessary because a high-permeability fault can also be acting as a direction-dependent barrier for fluid flow (model of Matthäi and Roberts, 1996). Because this hydraulic behavior depends mainly on the distribution of the fluid potential, it can be analyzed best by hydrogeological methods. These are particularly appropriate for regional-scale reconnaissance and can also contribute to local-scale research. The greatest advantage of these techniques is that they can determine the spatially variable hydraulic behavior of faults (e.g., vertically as conduit, transversely as barrier) without data from the fault zone itself.

In proposing the hydraulic theory of petroleum migration, Tóth (1980) has already pointed out the significance of hydrogeological principles and research techniques in petroleum exploration; however, as yet, faults have not been added to this concept.

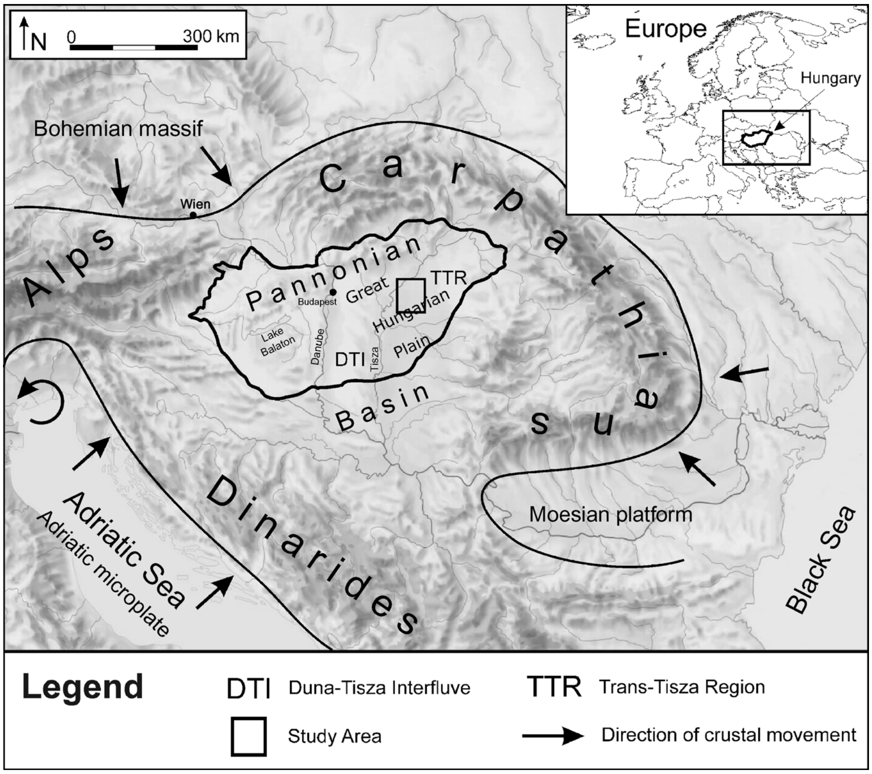
THE STUDY AREA

Location

The study area is located in the Trans-Tisza region of the Great Hungarian Plain, in the Pannonian Basin of central Europe (Figure 3). The area is rectangular and has the following corner points (and side lengths) in the EOV coordinate system (Egységes Országos Vetületi rendszer, the Uniform National Projection system in Hungary) using the horizontal x_{EOV} and vertical y_{EOV} plane coordinate axes: x_{EOV} = from 205 to 250 km (127–155 mi) (45 km [28 mi]), and y_{EOV} = from 765 to 805 km (475–500 mi) (40 km [28 mi]). Elevations are measured on the vertical z_{EOV} axis and referenced to the Baltic Sea level, with the sense being positive upward. In the study area, elevations range from 80 to 100 m (262–328 ft) above sea level (asl).

Inside this area, a significant positive anomaly of the fluid-potential field, a so-called potential plume can be observed near Berekfürdő and Kunmadaras based on Tóth and Almási (2001). Moreover, thermal water pools were discovered in the 1920s (Berekfürdő spa), and significant gas accumulations were discovered in the 1950s–1960s (Tatárülés-Kunmadaras gas field) (Figure 4).

Figure 3. Location of the study area in the Trans-Tisza region of the Great Hungarian Plain, Hungary (modified from Zentai, 1996) as well as the crustal movement directions in the Pannonian Basin and its vicinity (based on Bada et al., 2007).



Geologic Framework

Geologically, the Pannonian Basin is a back-arc basin almost completely surrounded by the Alpine-Carpathian-Dinaric orogens (Figure 3). Extensional formation of the basin started in the early Miocene, whereas its structural reactivation (i.e., inversion) has been occurring since the late Miocene to Holocene as a consequence of the counterclockwise rotation and north-northeast–directed indentation of the Adriatic microplate, as well as the blocking of the Carpathian subduction zone (Figure 3) (Bada et al., 2007).

The sub-Neogene basement (previously termed pre-Neogene basement by Tóth and Almási, 2001; Mádlné Szőnyi and Tóth, 2007; Mádl-Szőnyi and Tóth, 2009) of the sedimentary basin is divided into several deep local basins and troughs. Lithologically, it comprises brittle flysch, carbonate, and metamorphic rocks (Figure 5). The 100- to 7000-m (328- to 22,966-ft)-thick semiconsolidated to unconsolidated clastic basin fill consists of marine, deltaic, lacustrine, fluviatile, and eolian strata of Neogene age (Figure 5). In the Great Hungarian Plain, the middle Miocene (marine Badenian and restricted marine Sarmatian) sediments of the synrift phase are unconformably overlain by the late Miocene–Pliocene (Pannonian) postrift sediments. The latter upward-shoaling sedimentary succession represents the time-transgressive depositional environments of the fluvial-deltaic systems, which progressively filled in Lake Pannon (11.6–2.6 Ma) (Juhász et al., 2007).

Hydrostratigraphically, the higher sub-Neogene formations make up one unit, the hydraulic properties of which cannot be established reliably because of insufficient data. The Neogene basin fill has been divided into five regional units based on chronostratigraphic divisions, lithologic facies types, and reported values of permeability (Figure 6) (Tóth and Almási, 2001; Mádlné Szőnyi and Tóth, 2007; Mádl-Szőnyi and Tóth, 2009). The lowermost unit of the basin fill is the sub-Pannonian aquifer (previously termed pre-Pannonian aquifer by Tóth and Almási, 2001; Mádlné Szőnyi and Tóth, 2007; Mádl-Szőnyi and Tóth, 2009) with an estimated hydraulic conductivity of $K \approx 10^{-6}$ ms^{-1}, which is primarily caused by tectonic fracturing and faulting. The superjacent Endrőd aquitard is a

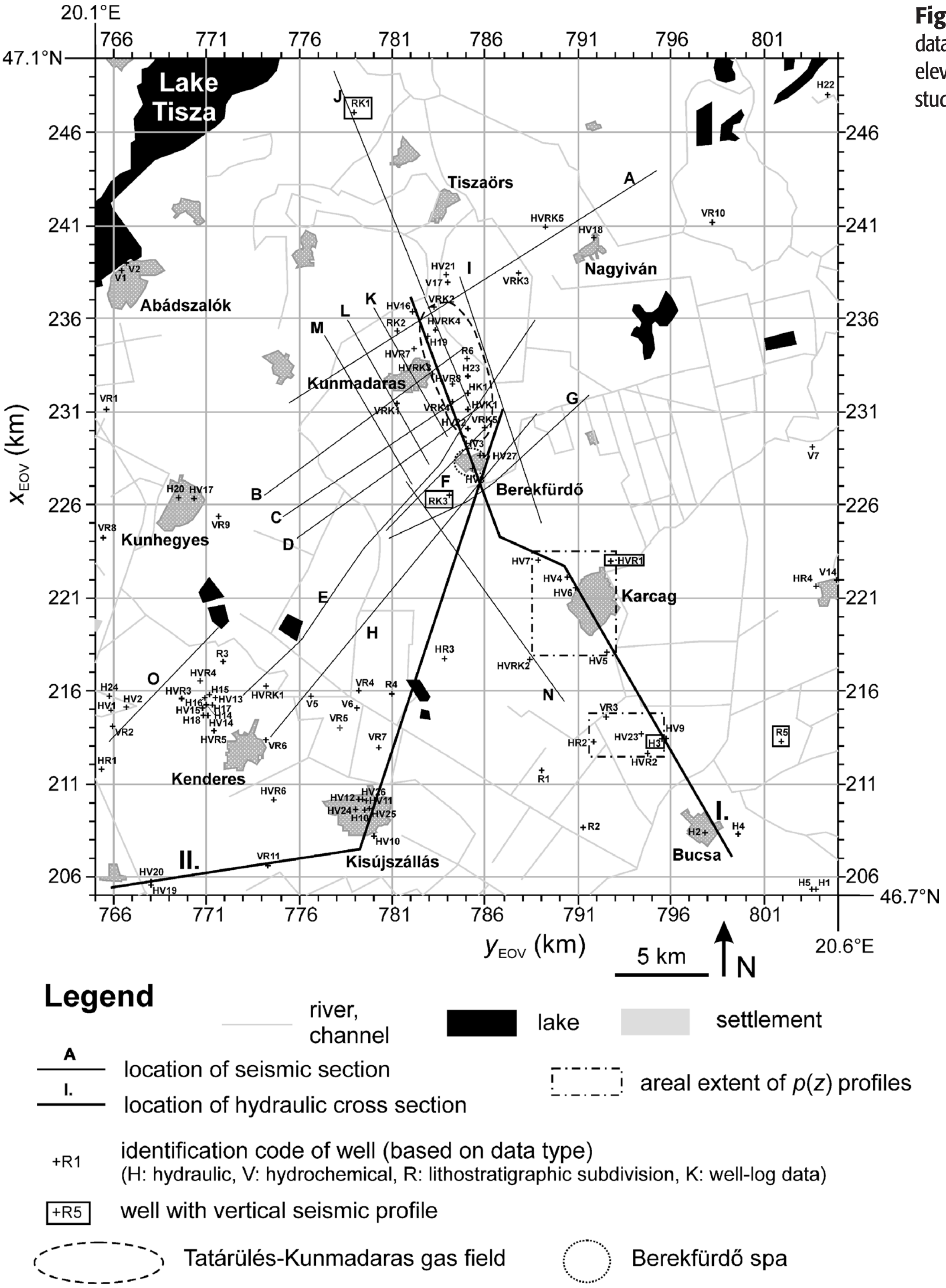
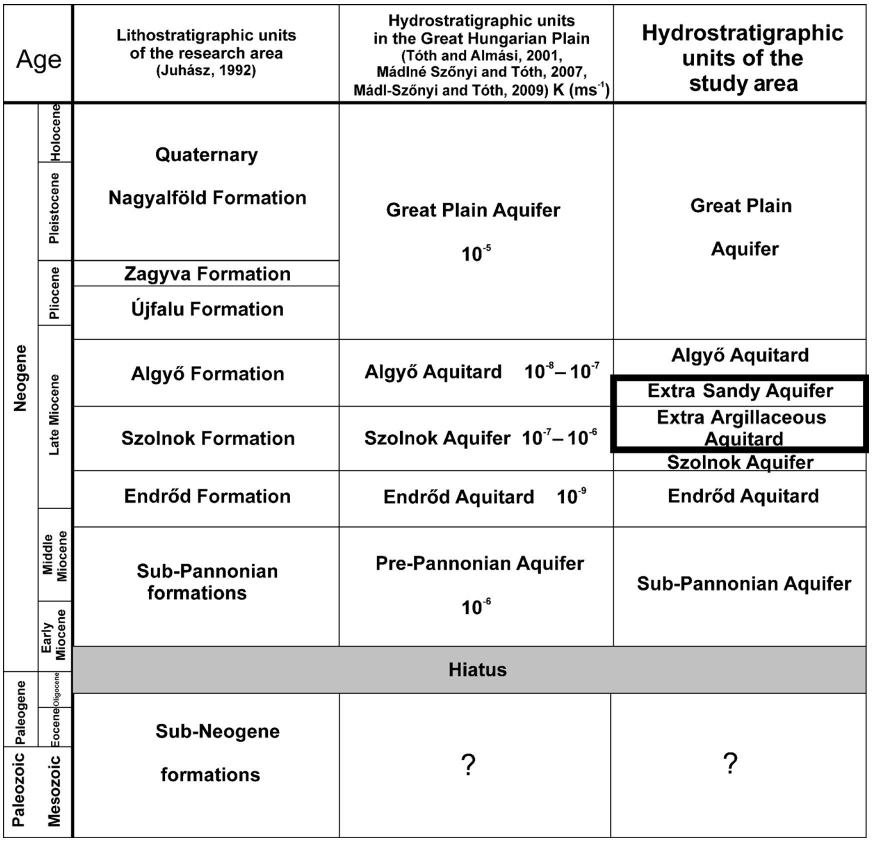


Figure 4. Locations of data, sections, and pressure elevation profiles in the study area.

regionally extensive but discontinuous unit of generally low-permeability ($K \approx 10^{-9}$ ms^{-1}) calcareous and argillaceous marls. The following Szolnok aquifer shows a cyclic alternation of sandstones, siltstones, and clay-marl beds of the prodelta facies characterized by hydraulic conductivity of $K \approx 10^{-7}$–10^{-6} ms^{-1}. It is regionally discontinuous and occurs only in the deep subbasins containing numerous high-yielding hydrocarbon reservoirs. The lithology of the next Algyő aquitard ($K \approx 10^{-8}$–10^{-7} ms^{-1}) representing delta facies is sand dominated above the basement highs, giving aquifer properties to the

Figure 5. Lithostratigraphic and hydrostratigraphic units of the study area (using data from Juhász, 1992; Tóth and Almási, 2001; Mádlné Szőnyi and Tóth, 2007; Mádl-Szőnyi and Tóth, 2009). The newly identified hydrostratigraphic units are highlighted by the black rectangle.



Age		Lithostratigraphic units of the research area (Juhász, 1992)	Hydrostratigraphic units in the Great Hungarian Plain (Tóth and Almási, 2001, Mádlné Szőnyi and Tóth, 2007, Mádl-Szőnyi and Tóth, 2009) K (ms^{-1})	Hydrostratigraphic units of the study area
Neogene	Holocene Pleistocene	Quaternary Nagyalföld Formation	Great Plain Aquifer 10^{-5}	Great Plain Aquifer
	Pliocene	Zagyva Formation		
		Újfalu Formation		
	Late Miocene	Algyő Formation	Algyő Aquitard 10^{-8} – 10^{-7}	Algyő Aquitard Extra Sandy Aquifer
		Szolnok Formation	Szolnok Aquifer 10^{-7} – 10^{-6}	Extra Argillaceous Aquitard Szolnok Aquifer
		Endrőd Formation	Endrőd Aquitard 10^{-9}	Endrőd Aquitard
	Middle Miocene Early Miocene	Sub-Pannonian formations	Pre-Pannonian Aquifer 10^{-6}	Sub-Pannonian Aquifer
Paleogene	Oligocene	Hiatus		
	Eocene	Sub-Neogene formations	?	?
Paleozoic	Mesozoic			

regional aquitard locally. Consequently, the regionally extensive Algyő aquitard is leaky because of its sedimentologic discontinuities and cross-cutting fractures and faults. The uppermost Great Plain aquifer ($K \approx 10^{-5}$ ms^{-1}) includes the Újfalu and Zagyva lithostratigraphic formations, as well as the surficial Quaternary sediments characterized by the good spatial connectivity of highly permeable bodies of silts, coarse sands, and gravels. The upper part of this aquifer produces large amounts of groundwater, whereas the lower part provides thermal water.

The dense network of structural elements, such as the most common normal faults and strike-slip fault zones, created or rejuvenated by intensive Neogene tectonics, has destroyed the regional integrity of the basement and the basin fill, both in lateral and vertical directions (Horváth and Cloetingh, 1996). These faults sometimes dissect the entire rock framework from the sub-Neogene basement to the Quaternary (Rumpler and Horváth, 1988) and compose lithologic discontinuities, which can become highly conductive avenues to pore-pressure propagation and fluid flow.

Fluid-Potential Field

Based on the interpretation of the observed subsurface fluid-potential patterns, Tóth and Almási (2001) have separated two superimposed and laterally extensive groundwater flow domains characterized by different driving forces and water types in the Great Hungarian Plain. The lower domain of slightly saline water (total dissolved solids [TDS] content, 10,000–38,000 mg L^{-1}) is strongly overpressured (10–35 MPa [1450–5076 psi] in excess of hydrostatic pressure) supposedly because of the tectonic compression of the basement, whereas the upper regime of fresh water (TDS, 420–2500 mg L^{-1}) is driven by gravity because of elevation differences of the topography. The depth of the transitional zone between the two domains is widely variable from 200 to 1700 m (656–5577 ft) and does not coincide with boundaries of lithostratigraphic or

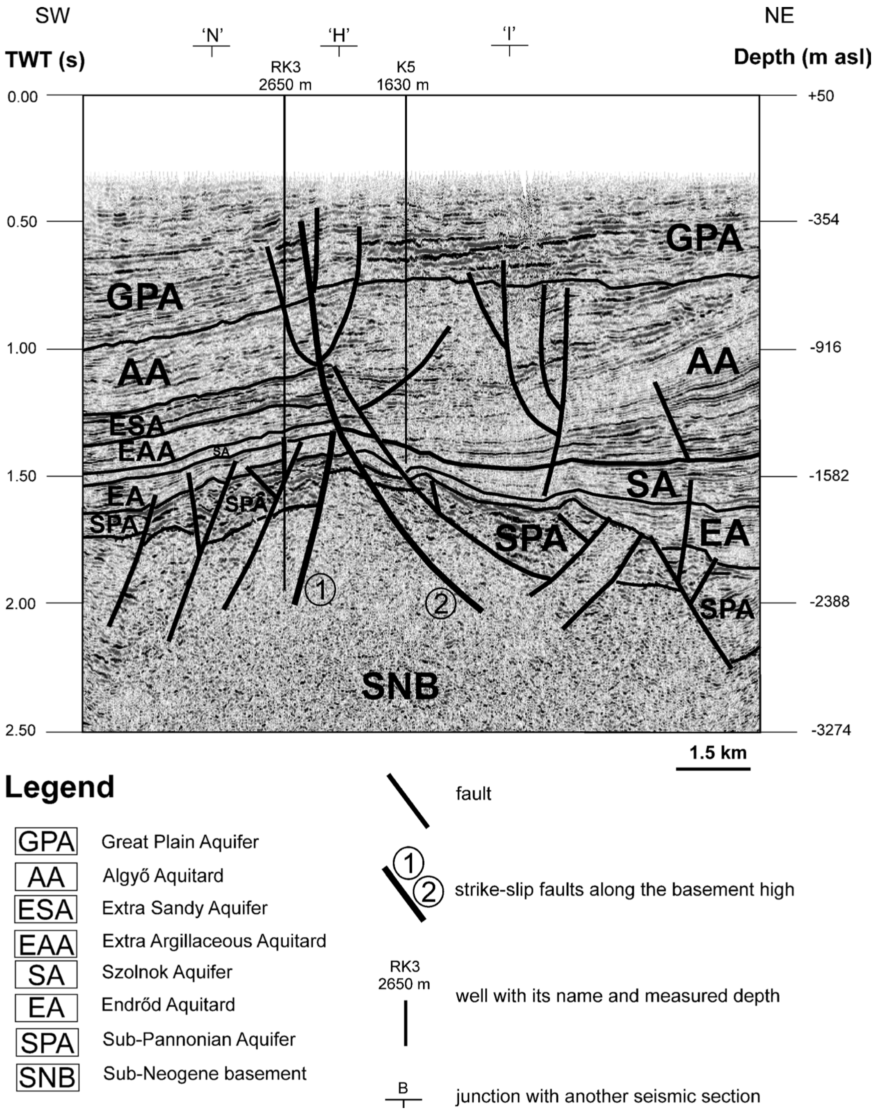


Figure 6. Interpreted seismic section G. asl = above sea level; TWT = two-way traveltime.

hydrostratigraphic units. However, communication between the upper and lower domains occurs by diffusion across geologic strata and/or through discrete high-permeability structural and sedimentologic discontinuities.

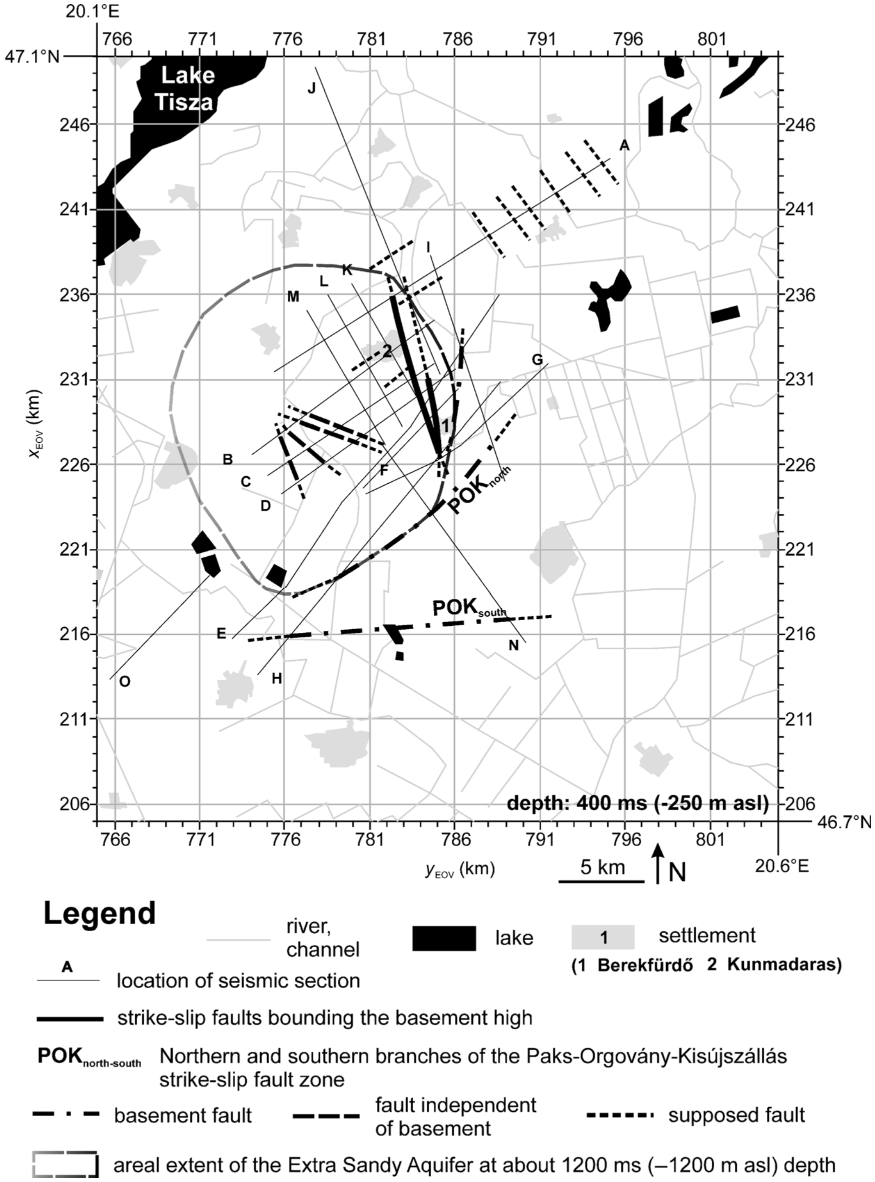
In the study area of this article, near Berekfürdő and Kunmadaras, a significant positive anomaly was observed in the fluid-potential field during the previously mentioned regional-scale hydrogeological study of Tóth and Almási (2001). The anomaly appeared as a potential plume rising from a sub-Neogene basement high (–1500 m [–4921 ft] asl) and approaches the surface by 400 m (1312 ft). Tóth and Almási (2001) explained the development of this phenomenon by hypothesizing the presence of structural elements, which cut through the thick and regionally extensive low-permeability Neogene strata (e.g., Endrőd and Algyő aquitards), and facilitate water upwelling and pressure dissipation from the basement into the shallower aquifers. This assumption was later supported by the gravitational and hydrobotanical investigations of Kiss and Szalma (2007).

APPLIED METHODS

According to the study's objectives, more data types were analyzed, and several methods were applied in this work.

In the beginning, 15 two-dimensional digital reflection seismic sections (Figures 4, 6) and digital geophysical logs (spontaneous potential) were used

Figure 7. Structural map at 400 ms (−250 m [−820 ft] above sea level [asl]) depth.



to interpret the hydrotectonics and hydrostratigraphy of the study area. The data and a landmark workstation for the interpretation of seismic and well-log data were provided by the MOL Hungarian Oil & Gas Plc. Lithostratigraphic subdivision data of Juhász (1992) were also applied during the hydrostratigraphic interpretation of the available well logs (Figure 4). Because the vertical scale of seismic sections is measured in time, an approximate time-depth conversion being typical of the study area was also conducted by applying vertical seismic profiles from five wells (Figure 4). The structural interpretation was accomplished by creating two structural maps at 1700- and 400-ms depths, respectively. Only the second one, which refers to −250 m (−820 ft) asl is displayed in this study because it crosses the stratigraphic column near the top of the potential plume (Figure 7).

Subsequently, archival hydraulic data were analyzed in a depth interval extending from the sub-Neogene basement to the shallowest appearance of the plume to study the hydraulics of the study area. The data were collected from the original well documentation of government institutions and MOL Hungarian Oil & Gas Plc. The regrettably unfavorable quality and deficient quantity of data necessitated a profound culling, which consisted of the filtering and qualifying of hydraulic and

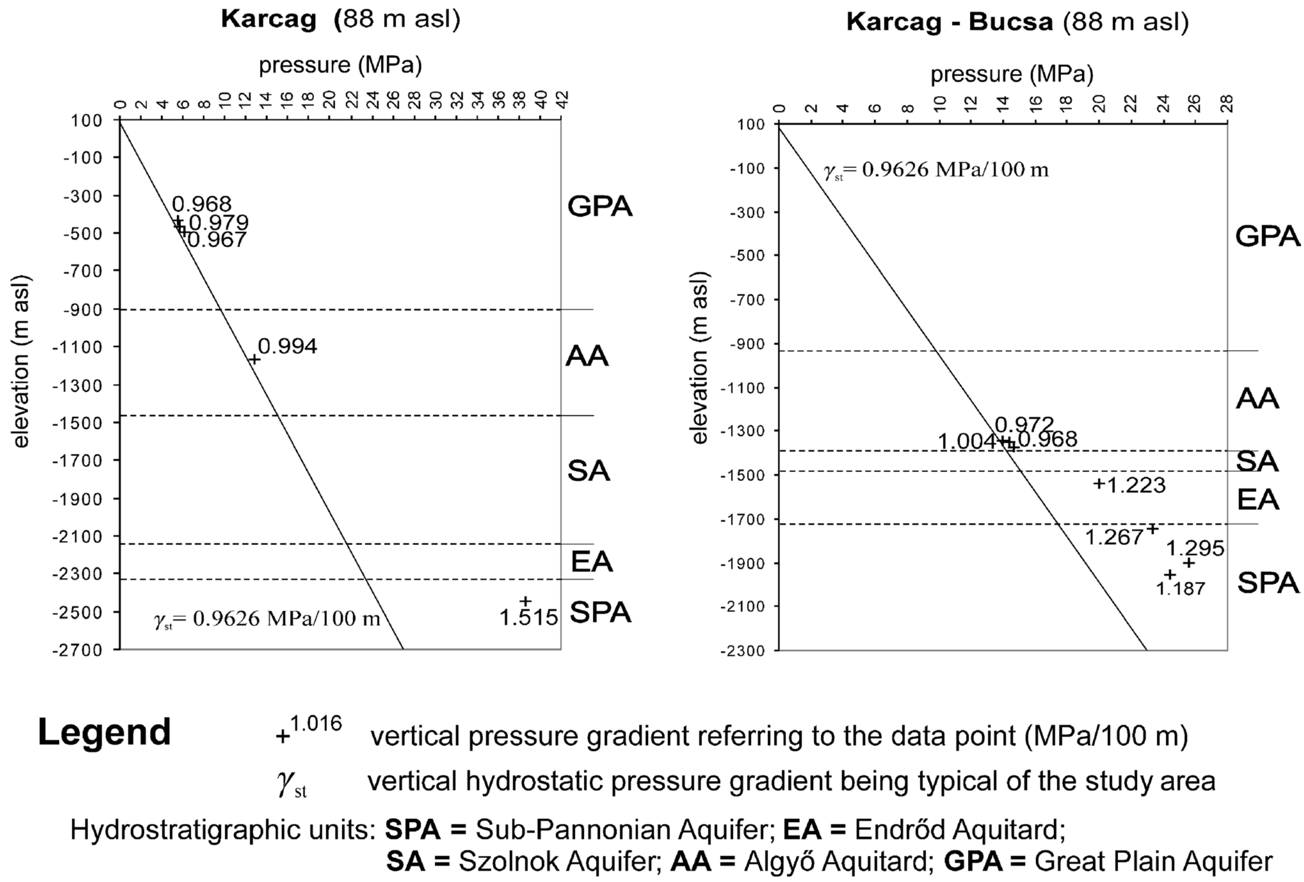


Figure 8. Pressure elevation profiles. asl = above sea level.

water chemical data. The main selecting criteria were the (1) date of drilling, (2) date of measuring, (3) start of water or hydrocarbon production, and (4) type of measurement (water level or drill-stem test measurement, water sample from the well head, or the screened interval). After these first steps of data processing, 61 hydraulic (pore pressure and stabilized water level) data samples from 50 wells were chosen for further evaluation among 100 data samples from 64 wells (Figure 4).

During the hydraulic calculations, pore-pressure data were converted to hydraulic heads and vice versa, depending on which data were available. The conversion was based on the equation, which assumes constant fluid density along the flow path:

$$h = z + p/(\rho g) \qquad (1)$$

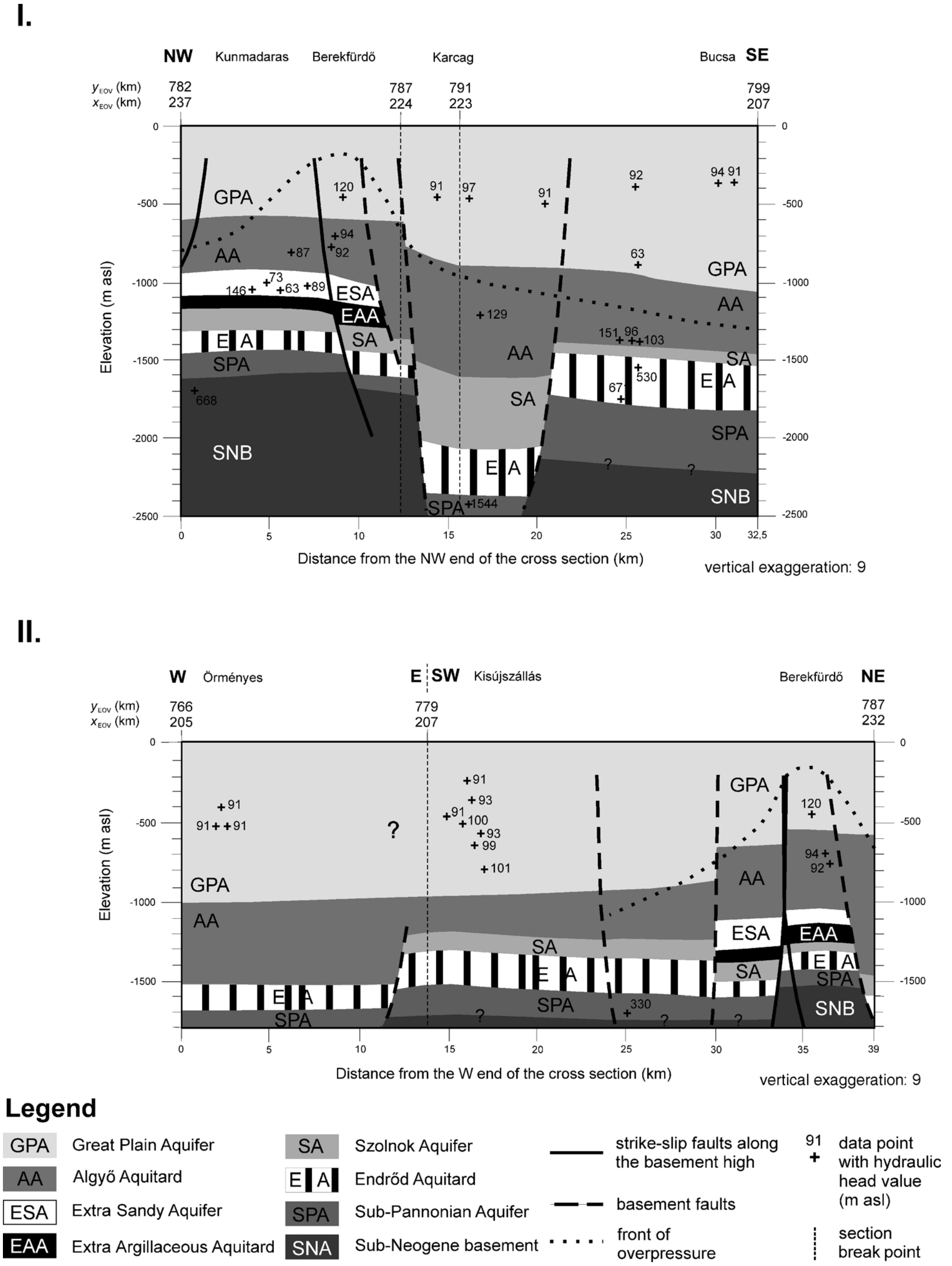
where h is the hydraulic head; z is the elevation of the measuring point with respect to a datum plane, commonly sea level; p is pore pressure; and ρg is the specific weight of the fluid, which is numerically equal to the vertical pressure gradient in a column of static fluid of density ρ. As a constant fluid density, the average value (981.6 kg m^{-3}) being typical of the study area was used in equation 1.

Afterward, the results of the analyses were interpreted based on creating five $p(z)$ profiles and two hydraulic cross sections. However, potentiometric surface maps could not be made because of the inadequate quantity and spatial distribution of data. The hydrostatic pressure gradient (9.6263 MPa km^{-1}) indicated on the $p(z)$ profiles was determined by applying the previously mentioned average density value. In this article, two representative $p(z)$ profiles and the hydraulic cross sections are presented (Figures 4, 8, 9).

RESULTS

Based on the evaluation of seismic profiles, a north-south–striking sub-Neogene basement high located between Berekfürdő and Kunmadaras was identified

Figure 9. Hydraulic cross sections (locations marked on Figure 5).



(Figures 6, 7). The shallowest depth of this high is approximately –1600 m (~–5249 ft) asl, and then it subsides below –2500 m (–8202 ft) asl in roughly every direction within a distance of approximately 10 to 15 km (~6.2–9.3 ft).

This basement high is bounded by two fault zones—marked by solid fault lines on Figures 6 and 7—on its western and eastern margins. These strike-slip faults are rejuvenations of basement normal faults, and both approach the land surface. In addition, they intersect each other to the south of Berekfürdő at approximately –1200 m (~–3937 ft) asl depth (Figure 6).

A third fault zone was identified on the southern part of the research area as a southwest-northeast–trending wrench fault zone (Figure 7) belonging to the almost 200-km (124-mi)-long Paks-Orgovány-Kisújszállás sinistral strike-slip fault zone (Pogácsás et al., 1989).

Based on the seismic and well-log hydrostratigraphic analyses, beside the well-known aquifer and aquitard units of the Great Hungarian Plain

(Tóth and Almási, 2001; Mádlné Szőnyi and Tóth, 2007; Mádl-Szőnyi and Tóth, 2009), two more units could be identified on the study area (Figures 5, 6). One of them is an argillaceous aquitard unit on the top of the Szolnok aquifer, whereas the other is a sandy aquifer unit between the newly identified (extra) argillaceous aquitard and the Algyő aquitard. These units are tectonically bounded by the strike-slip fault zones to the east (Figure 6) and south (Figure 7), but their extents are unknown to the north and to the west (Figure 7). The pools of the Tatárülés-Kunmadaras gas field accumulated in the turbiditic sandstone groups of the extra sandy aquifer unit and the Szolnok aquifer located above the basement high and between the two strike-slip fault zones.

The pressure elevation profiles denote a deep source of hydraulic energy, which causes significant overpressure in the sub-Pannonian aquifer and Endrőd aquitard, as well as consequently causes fluid upwelling (Figure 8). Although most of this energy is consumed during fluids flowing across the Endrőd aquitard, moderate overpressure can be observed even in the Algyő aquitard. Because of the quality and quantity of the available data, the pressure style of the Great Plain aquifer is somewhat uncertain, but it might be characterized as close to hydrostatic.

On the hydraulic cross sections, the stationary fluid-flow field could not be established because of the lack of data and because of the fluid-potential–reducing effect of gas and water production being typical of the study area (Figure 9). However, a boundary surface could be assigned. Below this boundary, the system is overpressured, and above it, the system is approximately hydrostatic within the limits of analytical error. The peak of this overpressure front coincides with the basement high and the junction of fault zones in the south of Berekfürdő.

DISCUSSION

The combined results of the complex seismic and hydraulic analyses have allowed elucidation of the hydraulic function of those identified faults, which intersect each other near Berekfürdő (Figures 6, 10). Furthermore, the presence of the thermal water at Berekfürdő, as well as the Tatárülés-Kunmadaras gas field, was also explained.

Both fault zones are acting as a conduit for fluids in the vertical direction. Consequently, the overpressure can dissipate from the basement along the fault and, at the same time, cause water upwelling (Figure 10), as well as the development of the potential plume in the fluid-potential field.

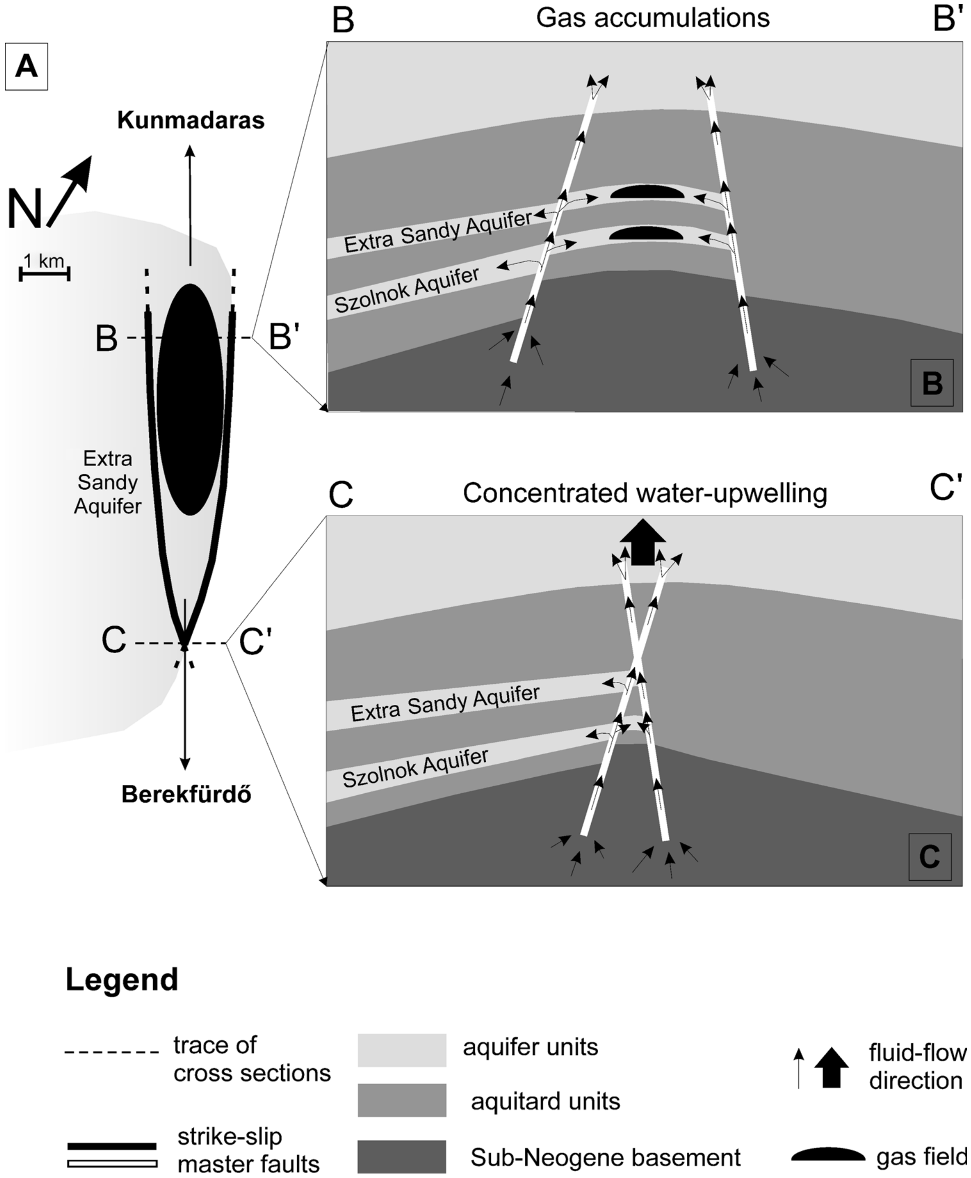
Both fault zones are also acting as barriers for the transverse fluid flow, although the reasons are different. The eastern fault (zone) impedes fluid flow across the fault plane because a thick and homogeneous low-permeability sequence (Algyő aquitard) was juxtaposed on the eastern side of the strike-slip fault zone against the Szolnok and extra sandy aquifers on the western side (Figure 10B). In the western fault (zone), no fluid flow across the fault acting as a vertical conduit is observed because the ascending fluid flows out of the fault zone into the intersected sands of the Szolnok and the extra sandy aquifer unit (Figure 10B). Eventually, these transverse barrier fault zones may act as lateral seals of the Tatárülés-Kunmadaras gas field and might also ensure the active water pressure of the reservoir system.

The junction of the vertically conducting and transversely sealing fault zones represents the southern limit of the hydrocarbon-bearing Szolnok and extra sandy aquifer (Figure 10C), that is, the gas field. At the same time, the junction of these faults causes more intensive water upwelling (Figure 10C), which induces the peak of the overpressure front near Berekfürdő (Figure 9). The Berekfürdő spa produces its thermal water from this overpressure peak or potential plume.

CONCLUSIONS

Based on the previous theoretical considerations, the generalized results of the represented case study are summarized in a diagram (Figure 11), which demonstrates the hydraulic function of highly permeable faults in hydrocarbon entrapment. The

Figure 10. Schematic diagram of the interpreted phenomena in the study area representing a map (A) and two cross sections (B and C).



geologic framework consists of two near-horizontal aquifer units separated by low-permeability strata. However, the sequence is crosscut by two highly permeable faults (Figure 11A), which make contact between the aquifers despite the presence of the aquitard unit. The fluid-potential field is characterized by higher pore pressure in the lower than in the upper aquifer. Subsequently, fluids flow toward the faults in the lower aquifer, then upward along the faults, and eventually outward of the faults into the intersected upper aquifer. In such a case, three possible places for hydrocarbon accumulation exist.

In the lower aquifer, hydrocarbons can be trapped in the vicinity of the faults because of the basic change in direction of water movement from lateral to upward (Figure 11A, trap type 1). In this case, a permeable fault induces a local energy minimum and, furthermore, leaks water and retains hydrocarbons as a hydrodynamic trap.

If hydrocarbon entrapment is not lithologically enhanced in the lower aquifer, or the trap cannot retain more hydrocarbons, or the aquitard unit is acting as a source rock, hydrocarbons can be trapped also in the upper aquifer in two ways. In the case of one fault, a monocline could form a hydrodynamic

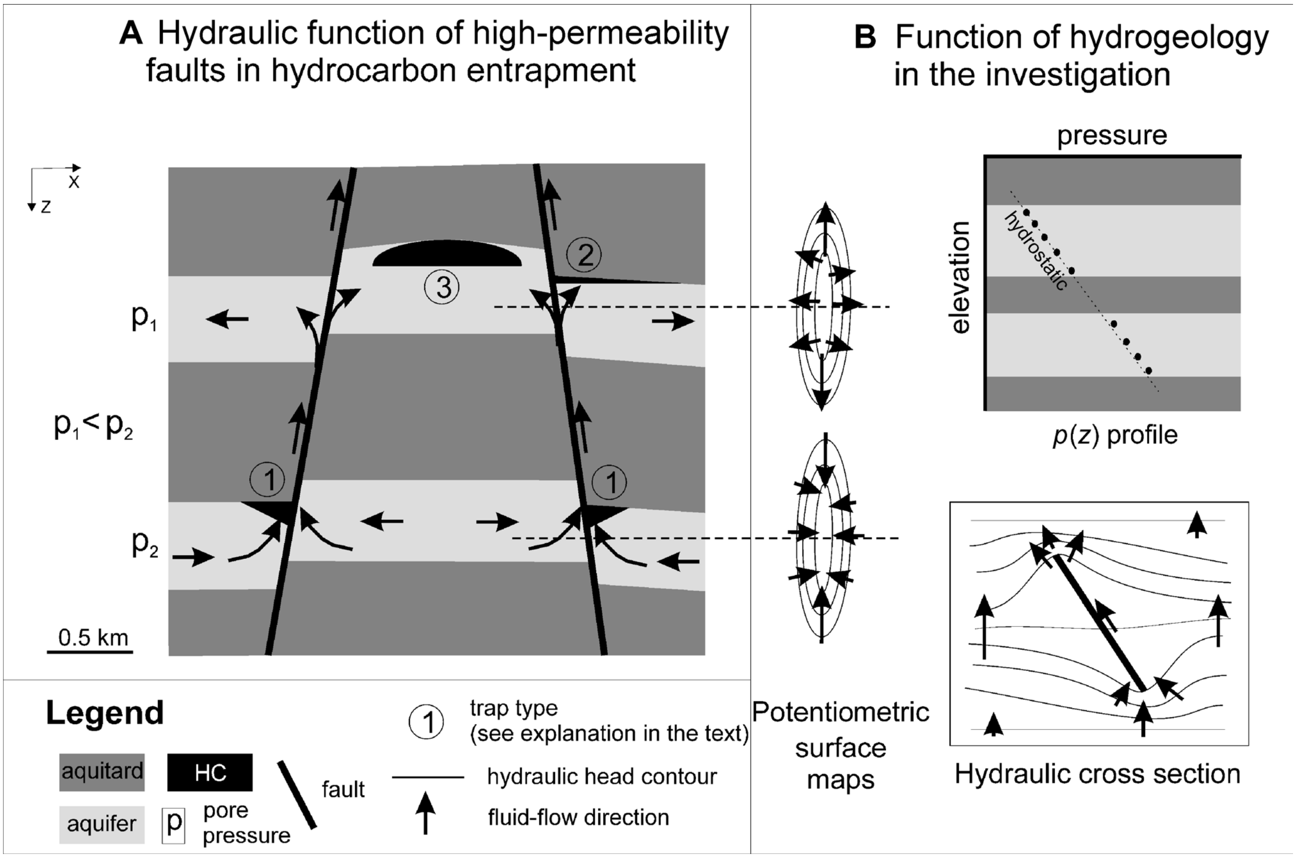


Figure 11. Hydraulic function of high-permeability faults in hydrocarbon entrapment and the function of hydrogeology in the examination of that.

trap (Figure 11A, trap type 2). However, between two faults, which are acting vertically as conduit and transversely as barrier avenues for fluids, hydrocarbons can accumulate because of the previously presented fluid-potential distribution (Figure 11A, trap type 3). In this case, the opposite flow directions and the sealing cap rock cause the hydrocarbon entrapment. Examples for this kind of trap could be identified in the course of the presented research in the study area.

During the investigation of the above displayed kinds of potential traps, hydrogeology provides simple and effective methods. Although the identification of structural elements and hydrostratigraphic units unconditionally requires the use of conventional geologic methods (interpretation of seismic, well-log, and lithostratigraphic data) the function of faults as a direction-dependent controller over the fluid-flow systems can be determined by hydrogeological methods without data from the fault zone itself.

According to Matthäi and Roberts (1996, p. 1775), "Flow directions in sands should be predictable only if the permeability of intersecting faults is known." This statement is also true vice versa, as this article demonstrates: if the fluid-potential distribution is known in the faulted aquifers, the hydraulic function of faults can be determined. Pressure elevation profiles can denote the hydraulic communication between the faulted aquifers, whereas potentiometric surface maps indicate the local energy minimum and maximum caused by the lower and upper terminations of the conduit fault, respectively (Figure 11B). Eventually, hydraulic cross sections, confirmed by the $p(z)$ profiles and potentiometric surface maps, demonstrate the vertical and horizontal flow directions. In addition, barrier faults can be identified by the same research techniques.

SUMMARY

The main focus of this article is the theoretical evaluation of the hydraulic behavior of faults, which is dependent on the fluid-potential field, regarding fluids (water, hydrocarbons). The work is supported by a field study in the Trans-Tisza region of the Great Hungarian Plain, Hungary. Based on the previous considerations and the results of the case study, we conclude that during hydrocarbon exploration, it is unnecessary to search for low-permeability faults because high-permeability faults can also be acting as direction-dependent barriers for fluid flow. Faults are representative examples of this assertion acting as vertical conduits and transverse barriers. These originally highly permeable structural elements are also able to trap hydrocarbons because of the distribution of fluid potentials. Furthermore, whereas a fluid-potential field can be analyzed by hydrogeological methods and without data from the fault zone, the joint application of different geologic and hydrogeological research methods proved to be suited for identifying possible hydrocarbon traps, as well as thermal water resources influenced by permeable faults.

REFERENCES CITED

Aydin, A., 2000, Fractures, faults, and hydrocarbon entrapment, migration and flow: Marine and Petroleum Geology, v. 17, p. 797–814, doi:10.1016/S0264-8172(00)00020-9.

Bada, G., P. Dövényi, F. Horváth, P. Szafián, and G. Windhoffer, 2007, Jelenkori feszültségtér a Pannon-medencében és alpi-dinári-kárpáti környezetében (Present-day stress field in the Pannonian Basin and the surrounding Alpine-Carpathian-Dinaric orogens): Földtani Közlöny, v. 137, no. 3, p. 327–359.

Gudmundsson, A., 2001, Fluid overpressure and flow in fault zones: Field measurements and models: Tectonophysics, v. 336, no. 1–4, p. 183–197, doi:10.1016/S0040-1951(01)00101-9.

Horváth, F., and S. Cloetingh, 1996, Stress-induced late-stage subsidence anomalies in the Pannonian Basin: Tectonophysics, v. 266, p. 287–300, doi:10.1016/S0040-1951(96)00194-1.

Jones, G., Q. J. Fisher, and R. J. Knipe, eds., 1998, Faulting, fault sealing and fluid flow in hydrocarbon reservoirs: Geological Society (London) Special Publication 147, 319 p.

Juhász, Gy., 1992, A pannóniai (s.l.) formációk térképezése az Alföldön: Elterjedés, fácies és üledékes környezet (Pannonian s.l. formations in the Hungarian Plain: Distribution, facies and sedimentary environments): Földtani Közlöny, v. 122, no. 2–4, p. 133–165.

Juhász, Gy., Gy. Pogácsás, I. Magyar, and G. Vakarcs, 2007, Tectonic versus climatic control on the evolution of fluvio-deltaic systems in a lake basin, eastern Pannonian Basin: Sedimentary Geology, v. 202, p. 72–95, doi:10.1016/j.sedgeo.2007.05.001.

Kiss, J., and E. Szalma, 2007, Tündérrózsák és a gravitációs tér? (Water-lily and the gravity field?): Magyar Geofizika, v. 48, no. 2, p. 1001–1014.

Knipe, R. J., G. Jones, and Q. J. Fisher, 1998, Faulting, fault sealing and fluid flow in hydrocarbon reservoirs: An introduction, *in* G. Jones, Q. J. Fisher, and R. J. Knipe, eds., Faulting, fault sealing and fluid flow in hydrocarbon reservoirs: Geological Society (London) Special Publication 147, p. vii–xxi.

Mádlné Szőnyi, J., and J. Tóth, 2007, "A Duna-Tisza köze vízföldtani típusszelvény" és a szikesedés összefüggései (Relationships between the "Danube-Tisza Interfluve Hydrogeological Key Profile" and alkalization): Földrajzi Közlemények, v. 4, p. 343–360.

Mádl-Szőnyi, J., and J. Tóth, 2009, A hydrogeological type section for the Duna-Tisza Interfluve, Hungary: Hydrogeology Journal, v. 17, no. 4, p. 961–980, doi:10.1007/s10040-008-0421-z.

Matthäi, S. K., and S. G. Roberts, 1996, The influence of fault permeability on single-phase fluid flow near fault-sand intersections: Results from steady-state high resolution models of pressure-driven fluid flow: AAPG Bulletin, v. 80, no. 11, p. 1763–1779.

Pogácsás, Gy., L. Lakatos, A. Barvitz, G. Vakarcs, and Cs. Farkas, 1989, Pliocén-kvarter oldaleltolódások a Nagyalföldön (Pliocene-Quaternary strike-slip faults in the Great Hungarian Plain): Általános Földtani Szemle, v. 24, p. 149–169.

Rumpler, J., and F. Horváth, 1988, Some representative seismic reflection lines from the Pannonian Basin and their structural interpretation, *in* L. H. Royden and F. Horváth, eds., The Pannonian Basin, a study in basin evolution: AAPG Memoir 45, p. 153–169.

Sorkhabi, R., and Y. Tsuji, 2005a, The place of faults in petroleum traps, *in* R. Sorkhabi and Y. Tsuji, eds., Faults, fluid flow, and petroleum traps: AAPG Memoir 85, p. 1–31.

Sorkhabi, R., and Y. Tsuji, eds., 2005b, Faults, fluid flow, and petroleum traps: AAPG Memoir 85, 343 p.

Tóth, J., 1980, Cross-formational gravity-flow of groundwater: A mechanism of the transport and accumulation of petroleum (The generalized hydraulic theory of petroleum migration), *in* W. H. Roberts and R. J. Cordell, eds., Problems of petroleum migration: AAPG Studies in Geology 10, p. 121–167.

Tóth, J., 1999, Groundwater as a geologic agent: An overview of the causes, processes, and manifestations: Hydrogeology Journal, v. 7, no. 1, p. 1–14, doi:10.1007/s100400050176.

Tóth, J., 2003, Fluid-potential patterns and hydrocarbon deposits in groundwater flow-fields induced by gravity and tectonic compression, Hungarian Great Plain, Pannonian

Basin: Journal of Geochemical Exploration, v. 78–79, p. 427–431.

Tóth, J., and I. Almási, 2001, Interpretation of observed fluid-potential patterns in a deep sedimentary basin under tectonic compression: Hungarian Great Plain, Pannonian Basin: Geofluids, v. 1, p. 11–36, doi:10.1046/j.1468-8123.2001.11004.x.

Underschultz, J. R., C. J. Otto, and R. Bartlett, 2005, Formation fluids in faulted aquifers: Examples from the foothills of western Canada and the North West Shelf of Australia, *in* P. Boult and J. Kaldi, eds., Evaluating fault and cap rock seals: AAPG Hedberg Series 2, p. 247–260.

Zentai, L., 1996, A Kárpát-medence domborzata (Topography of the Carpathian Basin), http://lazarus.elte.hu/hun/summer.jpg (accessed July 17, 2009).