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REGIONAL HYDRAULIC FUNCTION OF STRUCTURAL ELEMENTS AND LOW-PERMEABILITY FORMATIONS IN FLUID FLOW SYSTEMS AND HYDROCARBON ENTRAPMENT IN EASTERN-SOUTHEASTERN HUNGARY

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INTRODUCTION AND OBJECTIVES

Structural elements generally represent key geological factors in subsurface fluid flow systems as flow paths and/or barriers (e.g., GE and GARVEN, 1992, 1994; UNDERSCHULTZ et al., 2005), for instance in the formation of hydrocarbon migration pathways and traps (e.g., MATTHÄI AND ROBERTS, 1996; VERWEIJ, 2003). Furthermore, fractures and faults play a more significant hydraulic role in low-permeability formations, as only potential fluid flow pathways. Survey of these flow impeding zones is fundamental in hydrocarbon exploration (e.g., BENNION et al., 1996; SORKHABI and TSUJI (eds), 2005), radioactive waste disposal (e.g., ROBERTS et al., 1999; DISTINGUIN and LAVANCHY, 2007; AVIS et al., 2009), and carbon dioxide geological storage (e.g., WHITTAKER and ROSTRON, 2003; KALDI, 2005; METZ et al., 2005; BACHU, 2008) site-characterization as well. However, it is usually hard to study directly the hydraulic behaviour of faults and aquitards in spite of their significance, since data are rarely available from these zones. Starting from the above considerations, initial purposes of the present study were to i) investigate the faults' and low-permeability formations' regional scale hydraulic function in subsurface fluid flows and hydrocarbon entrapment; and meanwhile to ii) work out a hydrogeologically based methodology, which can be usable in the initial research phase of groundwater/geothermal/hydrocarbon exploration for hydraulic and/or hydrodynamic (hydrocarbon/geothermal) reservoir prognosis, or as a field data-based preparation for numerical modeling. Since our objectives favorably met with the research plans of the MOL Hungarian Oil & Gas Company Plc., a Research and Development (R&D) project came off between the MOL Plc. and the Eötvös Loránd University (duration: 2009-2011, supervisor: Judit Mádl-Szőnyi) that supported my Ph.D. research work with data and financially as well. Accordingly, study areas (~10,400 km^2) were chosen based on their differing geological characteristics in the Great Hungarian Plain (Pannonian Basin, Hungary) where regional hydraulics (TÓTH and ALMÁSI, 2001) and hydrostratigraphy (TÓTH and ALMÁSI, 2001; MÁDL-SZŐNYI and TÓTH, 2009) has already been studied, and also the MOL Plc. represents research interest. Consequently, a regional scale Pre-Neogene basement high (Battonya High), as well as two regional scale depressions (Derecske Trough, Békés Basin) were studied in the following ways.

METHODS

During data analysis and interpretation, first the hydrostratigraphical build-up of the Study Areas was determined. Afterwards, hydraulic data of 3629 (water and hydrocarbon) wells were interpreted in order to map the groundwater flow systems, since moving groundwater as a geologic agent determine the distribution of temperature, salinity, hydrocarbon accumulations, etc. (TÓTH, 1999). Thus the most time and effort were devoted to hydraulic data preparation and processing, while the primary objectives of temperature (data source: DÖVÉNYI et al., 2002) and hydrochemical data analysis considering their reliability as well was i) the support of hydraulic interpretations, and ii) the examination of relationships among hydraulic, thermal, and hydrochemical anomalies. Consequently, the same analyzing methods were chosen and developed according to these aims. Namely, considering the data distribution, first 73 pressure, 49 temperature and 48 TDS (total dissolved content) vs. elevation profiles /p(z), T(z) and TDS(z) profiles, respectively/ were constructed for the same areas with extents of about 5*5 km. P(z) profiles primarily refer to the vertical fluid flow directions, which partly determines the distribution of temperature and TDS as well. Secondly, so-called tomographic fluid-potential, isotherm and iso-concentration maps were compiled for 10 consecutive depth intervals in both Study Areas from z = 200 m asl down to z = (-5000) m asl elevation. By interpreting maps, the lateral flow directions can be interpreted in particular. Finally, 13-13 hydraulic, temperature and hydrochemical cross-sections were made along the same trace lines in order to study the vertical and lateral flow directions in the sections' plane.

RESULTS – THESES

1. Regional scale hydrogeological characterization revealed that hydraulic behaviour of the ***Great Plain Aquifer*** (in the shallowest position), as well as the ***Pre-Pannonian Aquifer*** and the ***Pre-Neogene formations*** (in the deepest position) is mostly uniform regionally in both Study Areas. On one hand, the Pre-Pannonian Aquifer and the Pre-Neogene formations are highly overpressured (excess pressure is about 30-60 MPa above the hydrostatic – even more than 200%) and characterized by only slightly superhydrostatic vertical pressure gradients ($\gamma \approx$ 11-14 MPa/km). On the other hand, the Great Plain Aquifer is regionally unconfined and containing gravitational flow systems, which show approximately hydrostatic conditions ($\gamma \approx 9.81 \pm 0.5$ MPa/km) compared to the overpressured system. These phenomena refers to the ***relatively high hydraulic conductivity*** (or permeability) of these units.
2. However, the intervening ***Endrőd Aquitard, Szolnok Aquifer***, and ***Algyő Aquitard*** represent spatially variable heterogeneities. Consequently, these three units ***control the "mode" or "way" of overpressure dissipation*** between the two boundaries of the subsurface fluid flow domain, i.e. the lowest overpressured Pre-Pannonian strata and the

uppermost approximately hydrostatic Great Plain Aquifer. Namely, when the aquifer character prevails, the vertical pressure gradient is relatively low, but it increases (even above 20 MPa/km) with the decreasing hydraulic conductivity.

3. Aside from some local regions, hydraulic behaviour of the ***Algyő Aquitard proved to be the most decisive*** among the hydrostratigraphic units in the overpressure dissipation. Flow impeding effect of this aquitard always manifests in a “break” or “step-like” (upward) pressure drop in the pressure-elevation profiles pending on its relative hydraulic conductivity, i.e. heterogeneity (faults, intercalated sand lenses, etc.), which shows significant spatial variability.
4. ***Appearance of the overpressured system***, i.e. that of the spatially uniform upward flow (everywhere in the Study Areas) can be observed generally down ***from the top of the Algyő Aquitard*** pending its depth within the z = (-1200)-(2000) m asl elevation interval. However, the Battonya High Area represents a regional scale exception where the overpressured system appears only down from about z = (-2000) m asl within the Pre-Neogene basement, while the total overlying succession is in approximately hydrostatic, or even subhydrostatic condition. Consequently, appearance of the overpressured system proved to be rather depth-, than formation-dependent in the Battonya High Area.
5. ***Fluid-potential minimum zones*** were identified along the Battonya High in the z = (-200)-(-400) m asl elevation interval, and in the NW part of the Derecske Study Area in the z = (-400)-(-1000) m asl elevation interval where the overpressured upward flows meet with the gravitational recharge areas’ downward flows. These regional flow converging zones serve as ***hydraulic traps*** for heat and dissolved salts, while hydrocarbon accumulations are known from below, but near by the bottom of these zones building up the upper boundary of upward fluid migration. The zones’ penetration depth and thickness is greater in the Derecske Study Area due to the higher topographic gradient (maximum differences in topographical elevations of the Study Areas are 50 m and 20 m within the DSA and BBSA, respectively). On the other hand, gravitational discharge areas where there is no upper hydraulic boundary of upward fluid migration could be targets for near-surface geochemical hydrocarbon exploration. For instance, in the Békés Basin occasionally high (dissolved) methane content of water wells is a well-known phenomenon, and though the shallow (i.e., above the Algyő Aquitard) biogenic origin of gases cannot be excluded, it may refer to upward flow conditions in the total flow domain.

6. Aside from the local anomalies, vertical ***temperature*** gradient is roughly uniform in both Study Areas representing the Pannonian Basin's average of 50°C/km, which already indicates positive anomaly compared to the world average of 30°C/km, or higher geothermal gradients as well (up to 149°C/km). Regarding the anomalies, heat accumulation can be observed in the fluid-potential minimum zones (hydraulic traps) of converging gravitational downward and overpressured upward flows. In addition, the Battonya High Area represents a positive anomaly /$\Delta T \approx +(20\text{-}40)$°C/ compared to its surroundings in the total studied elevation interval /z = 0-(-4000) m asl/. It could be explained by that the asthenosphere reaches its relatively shallower depth (<60 km) within the Pannonian Basin at the Battonya High Area where consequently the 'heat flow maximum of the Southern Great Hungarian Plain' (100-110 mW/m^2) can be found as well (HORVÁTH et al., 2004).
7. Regarding the hydrochemical conditions, in the Derecske Study Area the ***total dissolved solid content*** (TDS) increasing with depth shows jump-like increase (from the order of magnitude of 1000 mg/L to 10,000 mg/L) below the Algyő Aquitard, while salt accumulation can be observed in the fluid-potential minimum zone (hydraulic trap) of converging gravitational downward and overpressured upward flows. On the other hand, in the Békés-Battonya Study Area data show at least one order of magnitude lower TDS values than in the Derecske Study Area in the total studied elevation interval. Additionally, in the z = (-200)-(-600) m asl elevation interval a TDS maximum (1000-1500 mg/L) can be observed due to the high concentrations of HCO_3^- (≈ 1000 mg/L). Accordingly, the upwelling NaCl-type (ERDÉLYI, 1976; MÁDL-SZŐNYI and TÓTH, 2009) but less saline groundwater may enrich in HCO_3^- by mixing with the gravitational system's $NaHCO_3$-type or (Ca,Mg)-$(HCO_3)_2$-type water (MÁDL-SZŐNYI and TÓTH, 2009). However, origin of the overpressured system's groundwater of anomalously low TDS content could not be explained based on the results of this dissertation. Thus this question requires further studies, while also the data's unreliability has to be kept in mind.
8. In both Study Areas, several ***anomalies*** could be identified in the fluid-potential, geothermal, and hydrochemical field as well, usually around faults and hydrocarbon occurrences. Their frequent coincidence with each other supports the ***diagnostic relationships*** among them. In the cause and effect, as well as usually back and forth acting relation system of their development and that of the hydrocarbon occurrences, the

way of overpressure dissipation plays the primary determining role, which is defined by the geological build-up, and particularly by its discontinuities and heterogeneities.

9. Based on the regional hydrogeological characterization and the diagnostic relationships seven ***regions*** (#1-7) were distinguished within the Study Areas that can be characterized by seven ***basic types of pressure-elevation profiles*** traced back to the differences in the geological build-up and consequently in the way of overpressure dissipation.
10. In the ***Derecske – North region*** (#1) the significant overpressure (~20-25 MPa excess pressure above the hydrostatic value) gradually, i.e. diffusively dissipates through the densely faulted and thus relatively high-permeability Algyő Aquitard allowing of upward hydrocarbon migration even into the Great Plain Aquifer. On the other hand, in the ***Derecske – South region*** (#2) the more significant overpressure (~20-30 MPa excess pressure above the hydrostatic value) can dissipate only concentrated along a few faults, while the low-permeability matrix of the Algyő Aquitard effectively maintenances the overpressure and retains hydrocarbons below. In shallower depth also the possibility for hydraulic entrapment is given in both regions.
11. Around the ***Furta, Biharnagybajom, and Szeghalom Highs*** (#3) overpressure (~30-40 MPa excess pressure above the hydrostatic value) emerges into shallow depth with the basement highs, then Algyő Aquitard impedes fluid flows effectively in spite of its small thickness (~200-600 m in contrast with the average 800-1000 m), probably due to its low-permeability matrix cross-cut only by some inactive faults.
12. Around the ***Szarvas and Békés Highs*** (#4) overpressure (~40-50 MPa excess pressure above the hydrostatic value) decrease to hydrostatic conditions through the low-permeability Szolnok Aquifer with practically impossible, higher than lithostatic vertical pressure gradients. These gradients and scatter of the data refer to that fluid flow could be materialized most probably in (natural) hydraulic fractures in the Szolnok Aquifer, which impedes upward hydrocarbon migration as well.
13. In the ***Fábiánsebestyén-Nagyszénás-Orosháza Area*** (#5) where the most significant overpressures are known in the Pre-Neogene basement and Pre-Pannonian Aquifer of the Study Areas (>60-70 MPa), the largest (upward) pressure drop at the bottom of the low-permeability Algyő Aquitard can be observed as well. Hydrocarbon occurrences are not known and cannot be expected in shallower strata than the Szolnok Aquifer.
14. In the ***Battonya High Area*** (#6) overpressure appears form about z = (-2000) m asl, while in shallower depth the total Pre-Neogene – Neogene succession is in approximately hydrostatic condition containing hydrocarbons as well due to the lack of regionally

effective aquitards among the Pannonian strata. Additionally, a closed potential depression can be observed in the central part of the High in the z = (-600)-(-1800) m asl elevation interval. The results of this dissertation cannot explain the formation of this regional scale negative potential anomaly, however some considerations were taken, particularly excluding some options (e.g., effects of fluid production in the area). Also the hydrochemical analysis showed a regional negative anomaly that cannot be explained by the results of this dissertation, while the positive geothermal anomaly could be traced back to the shallow depth of the asthenosphere (<60 km).

15. In the ***Békés Basin*** (#7) hydraulic data were available only from the Great Plain Aquifer (down to z = (-2100) m asl), which represent slightly superhydrostatic conditions in the bottom zone of the Aquifer. Considering the geological analogies with the other regions, the thickness of the Neogene succession (maximum ~7000 m), as well as the low-permeability character of at least the aquitards, the Pre-Neogene basement should be highly overpressured. Hydrodynamic conditions of the Szolnok Aquifer should be similar to that of the Szarvas and Békés Highs. Lateral flows might be directed from the basin centers towards the margins, and particularly towards the Battonya High representing the lowest fluid-potential conditions in the Study Areas. However, the potential amount of movable fluids is questionable, since increasing overpressure could stop mechanical compaction (i.e. increase of effective stress) and fluid release from storage, thus fluid migration. Hydrocarbon occurrences are not known so far. However, if migration could materialize from the Endrőd Aquitard (or deeper units) towards the Szolnok Aquifer, impelling forces would drive hydrocarbons towards the basin margins and particularly towards the Battonya High where pinching out of the Szolnok Aquifer could provide stratigraphic traps as well. If migration could not be realized, *in situ* accumulation could be expected. Finally, also the Algyő Aquitard might be an effective flow barrier having small grain size, large thickness (800-2600 m), and only a few cross-cutting faults.
16. During the working process a hydrogeologically based ***methodology*** was worked out, modulated, and also controlled for ***determining the regional fluid migration pathways and hydraulic/hydrodynamic trap forming potentials***. Namely, a method was worked out in the Derecske Study Area where several data were available, then controlled in the Békés-Battonya Study Area where the successful application confirmed the justification of the method. This method is based on the processing of (I) geological data derived from boreholes and seismic interpretations, as well as of (II) hydraulic data of water and hydrocarbon wells also complemented by temperature and hydrochemical data. Based on

the diagnostic relationships, both ways (i.e. (I) and (II)) lead to the generalization of ***pressure-elevation type profiles***, which represent differing geological settings characterized by differing and typical fluid-potential, geothermal, and hydrochemical features, as well as hydrocarbon entrapment potentials.

17. As a basic methodological development, improvement of the ***p(z) profile*** interpretation was carried out, which allowed of the examination of faults' and low-permeability formations' ***regional scale hydraulic*** behaviour.
18. As another methodological object, ***the average groundwater density values being typical of the Study Areas*** were also determined (993 kg/m^3 in the Derecske Study Area, and 985 kg/m^3 in the Békés-Battonya Study Area), which however ***do not cause significant deviations*** (maximum (+39) m or 2%, and (+106) m or 4% deviation in hydraulic heads in the Derecske and Békés-Battonya Study Areas, respectively) from the results of calculations where constant density value is required applying the 1000 kg/m^3 density value. In other words, hydraulic conditions interpreted based on the original and calculated pressure and hydraulic head data were concordant.
19. A further segment of the method development was the ***correction of hydraulic calculations in case of pressure data measured in gas columns***. As a result, the possible maximum error in calculated hydraulic heads in the Study Areas can vary between +113 and +254 m that could cause apparent fluid-potential anomalies in shallower depth than about 2000 m. However, even if ***gas-induced potential anomalies*** can lead to false deductions about the faults and low-permeability strata's hydraulic behaviour, these could be the ***diagnostic indications of hydrocarbon, and particularly gas accumulations*** as well. In addition, the presence of hydrocarbon accumulations could also refer to the conduit behaviour of the ambient faults at least in their past.
20. In areas being out of hydraulic data, but providing some basic geological data the ***method*** (described in thesis #15) ***can be applied inversely based on geological analogies***. Since the p(z) type-profiles can be generated from two ways (i.e., from geological and/or from hydraulic data), only one direction should be enough to determine the boundary conditions of fluid migration. Namely, being in possession of the topographic map, some seismic interpretations (usually the first data during hydrocarbon exploration), and possibly some borehole data of a research area it is feasible to forecast the regional fluid-potential (pressure) distribution and the related spatial ***boundaries of hydrocarbon migration***, thus the regional hydraulic/hydrodynamic entrapment potential on a formation, facies, or depth interval base. In the present Ph.D. work, inverse application of

the method was partly necessary in the Békés Basin. Consequently, this methodology applied directly or indirectly can be used most effectively in the ***initial phase of a research project***, or as a ***status assessment*** serving the ***base for numerical modeling*** of past or present processes, to name but a few.

CONCLUSIONS

Based on the amount and distribution of well-data and faults, as well as by the improvement of p(z) profile interpretation, regional scale conclusions could be drawn about the fault zones' and low-permeability formations' hydraulic function. Furthermore, the generalizable geological determining factors of fluid-potential distribution (in an overpressured sedimentary basin), and the related geothermal, hydrochemical, and accumulation phenomena succeeded to define. Additionally, feasible locations and zones of in-situ and regional hydraulic entrapment were identified hydrogeologically. Finally, based on the exploration of the diagnostic relationships among these issues and the deduced pressure-elevation type-profiles, a hydrogeology-based methodology was worked out, which can be usable in the initial research phase of groundwater/geothermal/hydrocarbon exploration, or as a field data-based preparation for numerical modeling.

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