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Regional hydraulic behavior of structural zones and sedimentological heterogeneities in an *overpressured* sedimentary basin

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ABSTRACT

The paper presents the results of a regional scale hydrogeological study conducted in two areas of the Pannonian Basin in Eastern and Southeastern Hungary. The purpose of the study was to investigate the role of fault zones and sedimentological heterogeneities in areas of overpressure dissipation and hydrocarbon entrapment. The Study Areas ($\sim$10,400 km^2 in total) were chosen so as to see the effects of their differing geological characteristics, specifically that of a regional scale Pre-Neogene basement high (Battonya High), and two regional scale depressions (Derecske Trough, Békés Basin). Groundwater flow patterns were inferred for both areas from distributions of fluid dynamic parameters presented on potentiometric surface maps, vertical hydraulic cross sections and pressure-vs.-elevation [p(z)] profiles. The data suggest that both fluid-flow patterns and the potential for hydrocarbon entrapment are predominantly controlled by the dissipation paths of overpressure. In turn, the routes of overpressure dissipation are controlled by the structural and sedimentological heterogeneities of the aquitards. Diagnostic relationships were found between the heterogeneities and fluid-potential anomalies, as well as hydrocarbon occurrences. The observed pattern of overpressure dissipation has allowed the identification of seven regions by seven basic types of pressure–elevation profiles, p(z). As well, a new concept, *"the upper boundary of hydrocarbon migration"* was proposed. Finally, based on the established diagnostic relationships and the deduced type-profiles of pressure–elevation, a hydrogeological methodology was developed which could be used in other areas and for other purposes, e.g., exploration for groundwater and geothermal resources, petroleum and in preparation for numerical modeling.

1. Introduction

Structural elements generally represent key geological factors in subsurface fluid flow systems. They can function as flow paths and/or barriers as, for instance, hydrocarbon migration pathways and traps (e.g., Czauner and Mádl-Szőnyi, 2011; Matthäi and Roberts, 1996). Fractures and faults play a significant role also in slightly permeable formations as the only effective pathways for fluid flow on the medium scale of time. Knowledge of these conductive and/or impeding zones is a requisite in hydrocarbon exploration (e.g., Bennion et al., 1996; Kasap et al., 1996; Lee and Michaels, 2000; Samaha et al., 1996) and in characterization of potential radioactive waste disposal sites (e.g., Avis et al., 2009; Distinguin and Lavanchy, 2007; Roberts et al., 1999) as well. However, the effective hydraulic nature of regional faults and aquitards can rarely be evaluated from in-situ data. Consequently, further questions arise, such as the scale dependence of hydraulic parameters, i.e. the spatial upscaling of in-situ permebaility or hydraulic conductivity data. As a result, most of related studies have been conducted at local scales involving faults or fault systems parameterized from well data (e.g., Aydin, 2000; Bense and Person, 2006; Caine et al., 1996; Jones et al., 1998; Smith, 1966; Sorkhabi and Tsuji, 2005a,b; Underschultz et al., 2005). On the other hand, some investigations by numerical modeling have revealed that formations deemed to be slightly permeable by laboratory measurements, often are of much higher permeabilities at regional scales due to cross-cutting faults and intercalated sand layers/lenses (e.g., Bethke, 1989; Bredehoeft et al., 1983; Király, 1975; Neuzil, 1993).

Thus the question arises: what can be done at a regional, or basin scale without or before numerical modeling? This paper demonstrates a possible answer. It characterizes the regional scale hydraulic role of faults and aquitards in subsurface fluid flow and hydrocarbon entrapment in two Study Areas in the Pannonian Basin. In addition, the hydrogeologically based methodology can be used in the initial research phases of groundwater/geothermal/

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hydrocarbon exploration, for hydraulic and/or hydrodynamic (hydrocarbon/geothermal) reservoir prognosis and as a field data-based preparation for numerical modeling.

2. Study Areas

The Study Areas were chosen in the Great Hungarian Plain (GHP) (Pannonian Basin, Hungary) based on their differing geological characteristics, hydrocarbon occurrences, and the approximate fluid-potential distribution described by Tóth and Almási (2001). The sum total of ~10,400 km^2 research area covers the Eastern-Southeastern part of the GHP. It includes the following regions, with the Study Areas' corner points represented by EOV[1] co-ordinates (Fig. 1): 1) Derecske Trough and its surroundings/Y_{EOV} 800–880, X_{EOV}180-250/(hereafter Derecske Study Area – DSA); 2) Battonya High and Békés Basin/Y_{EOV} 750–840, X_{EOV} 100–170/(hereafter Békés-Battonya Study Area – BBSA).

2.1. Regional geological setting

Geologically, the Pannonian Basin is a back-arc basin almost completely surrounded by the Alpine-Carpathian–Dinaric orogens (Fig. 1). Extensional formation of the basin started in the Early Miocene, whereas its structural reactivation (inversion) has been taking place since Late Miocene to recent times (Bada et al., 2007).

The Pre-Neogene basement of the sedimentary basin is divided by elevated highs into a number of deep local basins and troughs (Fig. 1. E.g., Battonya High; Békés Basin; Derecske Trough). Lithologically, it comprises brittle flysch, carbonate and metamorphic rocks. The 100–7000 m thick semi- to unconsolidated clastic basin fill consists of marine, deltaic, lacustrine, fluviatile and eolian strata of Neogene age. In the GHP, the Middle Miocene (marine Badenian and restricted marine Sarmatian) sediments of the syn-rift phase are unconformably overlain by the Late Miocene–Pliocene (Pannonian) post-rift 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). The GHP's generalized Neogene stratigraphy, hydrostratigraphy, petroleum system elements and the main tectonic events (based on Horváth, 2007; Tóth and Almási, 2001) are shown in Figure 2. The generalized diagram of the stratigraphy and the petroleum system is presented in Figure 3.

2.2. Geologic and hydrostratigraphic characteristics of the Study Areas

In this sub-chapter only the distinctively area-specific geologic and hydrostratigraphic characteristics of the Studied Areas are summarized as compared to the general features (Fig. 2; Fig. 14).

The Derecske Trough opened as a pull-apart basin in a shear zone between two wrench fault zones (Fig. 1). The strike-slip movement that started in the Middle Miocene has continued, probably with reduced activity until recent times. This is suggested by the mainly negative flower structures which cut through even the uppermost Pannonian strata (Rumpler and Horváth, 1988). The pre-rift basement exceeds 6500 m in depth today in the central part of the Trough, while its hydrostratigraphic classification is questionable. The Pannonian delta system came at the Trough from the NE (Bérczi and Phillips, 1985), and filled it up by sediments in a maximum thickness of about 6000 m. Areal extension of the Endrőd Aquitard is restricted to the deepest, central part of the Trough. Lithologically, low-permeability clay marls dominate the formation, which consequently shows effective aquitard characteristics. The Szolnok Aquifer can be found also in the axial, central part of the Trough where it can reach 1000 m in thickness, but pinches out northward toward the Trough's margins (Juhász, 1992). On the other hand, the Szolnok Aquifer can be observed in a maximum of 500 m thickness in the southern surroundings of the Trough. Compared to the Szolnok Aquifer in the Békés Basin, the Trough facies is coarser-grained probably due to the closer sediment supply, as well as it has higher porosity and permeability (8–16% and 10^{-14}–10^{-13} m^2, respectively). In the NE part of the trough the generally 200–1000 m thick Algyő Aquitard contains also the pelitic overbank and slope apron deposits of the deep water facies (Juhász, 1992). Consequently, in these areas, and also where the Szolnok Aquifer is missing (usually in the marginal areas), the Algyő and Endrőd Aquitards could build-up one thick and effective, slightly permeable aquitard unit. However, in some places, such as above basement highs and in their forelands facing the direction of sediment transport, sand lenses and intercalations can be frequently observed. On the northern flank of the Trough, the formation is more densely cut by fractures and faults than in the south of the Trough. In conclusion, the Algyő Aquitard, which is generally thought to be a regionally extensive and effective low-permeability unit, is actually quite heterogenous in the region of the Derecske Trough.

The Battonya High is an elevated Pre-Neogene basement 'high', which approaches the land surface within about 1000 m at its (Hungarian) apical part, then gradually subsides northeastward below 3000 m depth, while east- and westward into the Békés Basin and Makó Trough, respectively (Fig. 1). In the mostly undisturbed Pannonian strata, only rejuvenations of the bounding normal faults, as well as some growth faults along the ridge's margins can be observed. The Pannonian delta system arrived at the Battonya High at latest (<6 Ma (Magyar, 2010), thus this area was the last unfilled part of Lake Pannon inside the present borders of Hungary, i.e. in the study area. Consequently, the calcareous marl member of the Endrőd Aquitard was deposited in a starving basin far from the siliciclastic sediment sources. This condensed formation can be found in the whole area of the Battonya High, but usually in a thin (10–200 m) and areally diachronous layer in the summit zone with up to 95–100% carbonate content (Magyar et al., 2001). The formation is usually strongly fissured and fractured in these areas presenting aquifer rather than aquitard features. The Szolnok Aquifer is insignificant or missing in the summit zone of the Battonya High. However it is thickening toward the surrounding basins where it usually represents low-permeability conditions to such a degree that it rather behaves as an aquitard unit (7% porosity and 10^{-16} m^2 permeability). The Algyő Aquitard contains more sandstone intercalations above the ridge region (K. Juhász et al., 1989), and consequently the Algyő Aquitard is more heterogenous than usually.

The Békés Basin is a structural unit located to the south of the Derecske Trough and to the east of the Battonya High (Fig. 1) and it contains over 6500 m of Neogene sedimentary rocks. The still ongoing subsidence of the basin started in Early Badenian times (Szentgyörgyi, 1989). However, except for the rejuvenations of the surrounding NW and E–SE striking wrench fault zones on the northern and western margins of the basin, and some growth faults located also on the margins, the Pannonian succession is relatively undisturbed. The Pre-Neogene basement's lithologic build-up is unknown in the deepest central and southeastern part of the basin (Haas et al., 2010). The average thickness of the Pre-Pannonian

[1] EOV: 'Egységes Országos Vetületirendszer', the Uniform National Projection system in Hungary using the vertical (northing) Y_{EOV} and horizontal (easting) X_{EOV} plane-co-ordinate axes. The co-ordinate axes are orthogonal along which distances are expressed in meters/by six-digits/(or kilometers by triple-digits).