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Hybrid numerical modelling of fluid and heat transport between the overpressured and gravitational flow systems of the Pannonian Basin

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ABSTRACT

Fractured rock bodies are especially important in Hungary, where numerous hydrocarbon reservoirs and geothermal fields occur in the fractured crystalline basement of the Pannonian Basin. To simulate a 3D fracture network for both near well regions and at reservoir scale, a fractal geometry based DFN (discrete fracture network) modelling system (RepSim) was used.

To perform numerical simulation of the geological-hydrogeological problem, in which the hydraulic interaction is investigated between porous and fractured rock bodies, a finite element modelling system called FeFlow was applied. Modelling results suggest that the protruding basement highs govern heat transfer and fluid flow like a “hydro-geothermal chimney” owing to their stratigraphic and structural position as well as favourable hydraulic and thermal conductivities. Thus such fractured basement highs are deemed prospective for further geothermal investigations.

1. Introduction

Deep fractured reservoirs have been explored for geothermal energy production and hydrocarbons. Thermal springs attest to the viability of fractured reservoirs as potential sources of sustainable production of renewable geothermal energy. About 35% of the world’s productive oil fields were discovered in naturally fractured carbonate reservoirs, while nearly half of the produced hydrocarbons are stored in such reservoirs (Nelson, 2001).

Geothermal systems are commonly grouped as conventional and non-conventional systems according to the heat conveyance mechanism. Conventional geothermal systems have a natural heat source, the reservoirs have high porosity and permeability, and natural groundwater flow systems convey the heat (Tóth, 2015). Non-conventional systems have a natural heat source but the reservoirs are either engineered and/or the fluids are artificially circulated.

Geothermal technology development has focused so far on extracting naturally heated steam or hot water from natural hydrothermal reservoirs. However, geothermal energy has the potential to make a more significant contribution on a global scale through the development of the advanced technologies, especially the exploiting of petrothermal resources using enhanced geothermal systems (EGS) techniques that would enable energy recovery from a much larger fraction of the accessible thermal energy in the Earth’s crust. In the IEA geothermal roadmap vision 2011, geothermal energy is projected to provide 1 400 TWh annually for global electricity consumption by 2050 (IEA, 2011).

The existing term ‘enhanced or engineered geothermal system’ (EGS) has its roots from the early 1970′s when a team from Los Alamos National Laboratories began the hot dry rock (HDR) project at Fenton Hill, USA (Cummings and Morris, 1979). HDR was also known as hot fractured rock because of either the need to fracture the virtually impermeable formations or the presence of natural fractures in the hot reservoir (Breede et al., 2013). The Massachusetts Institute of Technology defines EGS as “engineered reservoirs that have been created to extract economical amounts of heat from low permeability and/or porosity geothermal resources. EGS would exclude high-grade hydrothermal but include conduction dominated, low permeability resources in sedimentary and basement formations, as well as low grade, unproductive hydrothermal resources” (Tester et al., 2006). According to Potter et al. (1974), the most suitable rock types for EGS are granite or other crystalline basement rocks at depths of 5–6 km. Most hydraulic fracturing projects, aiming to create an EGS, target granitoids, because of their favourable petrophysical properties (virtually no porosity and permeability; high thermal conductivity) and their geological settings below > 5 kms where sufficient heat is available for power production purposes (Rybach, 2010).

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In the Pannonian Basin, regional gravitational flow system is located below the Hungarian Great Plain which is separated by sedimentary layers from the fluid system stored in the deep, overpressured, fractured crystalline and carbonate basement regime (Stevanovic et al., 2015; Horváth et al., 2015). The basement complex is not impermeable in spite of its great depth and fluids of various age and content are stored in there due to the secondary porosity and permeability. The overpressure has generally been maintained and the flow system has been separated from the overlaying hydrostatic regime where thick quasi-impermeable covering sediments were deposited. However the hydraulic connection could be developed between the two zones (Tóth and Almási, 2001; Varsányi and Kovács, 2009; Mádlné Szőnyi et al., 2005) in such not uncommon geological-hydrogeological situations where the insulating sedimentary layers are extenuating or missing due to the basement morphology. The presence of the saline water with high total dissolved solid content in the deeper overpressured system has been detected in the Pannonian and Pleistocene layers by geochemical methods at several locations. These areas could have significant importance for hydrocarbon and geothermal energy exploration (Pogácsás et al., 1994; Dövényi et al., 2005). As there is only very limited information about the hydrodynamic interplay between the two different reservoir regimes, numerical flow and heat transport modelling together with fracture network modelling would serve an effective tool to obtain more information and help understanding such a geological-hydrogeological system.

The main objective of this paper is to analyse the feasibility of hydraulic and thus hydrothermal communication between the overpressured deep basin zones and the shallow normal pressured flow system through the fracture network of the metamorphic highs. Furthermore, we discuss how this hydrodynamic situation can modify the potential field inside and above these crystalline highs, and which direction the basement fluids get supply from, which flow paths can be realistic. The second part of the investigation is to model the rate of anomaly caused by conductive and convective heat flow in the temperature field of the basement metamorphic domes.

2. Geological setting

Due to its complex tectonic evolution during the Neogene (for details see e.g. Tari et al., 1992; Albu and Pápa, 1992; Lőrincz, 1996; Csontos and Nagymarosi, 1999; Tari et al., 1998), the Pannonian Basin is at present a mosaic of deep sub-basins and uplifted basement highs. Although, these crystalline domes are in many details different concerning their metamorphic and structural evolution, most of them consist essentially of diverse gneiss and amphibolite type rocks (Tóth and Schubert, 2000). Following the post-Variscan uplift of the metamorphic terrain under unknown circumstances and the widespread nappe tectonics during the Cretaceous (Tari et al., 1998), the most important brittle events of the basement belong to the subsidence of the Pannonian Basin in the Neogene. This episode coincided with a multiphase tectonic evolution with subsequent compressive, extensive and strike-slip events (Tari, 1994; Bada and Horváth, 1998).

The Szeghalom High (Fig. 1) is one of the most investigated among the basement highs in the Villány-Bihor and Békés-Codru tectonic units, therefore it was used as a standard according to the geological structure.

The basement consists of intermediate and high grade metamorphic rocks, primarily of amphibolite and gneiss, and secondarily of mica schist. The boundaries of the rock blocks, characterized by different metamorphic evolutions, are delineated by post-metamorphic strike-slip zones (Tóth and Redlerné Tátrai, 2008); the basement high is divided into several smaller units by normal faults of approximately NW strike orientation. A detailed study of fracture filling mineral phases infers formation during decreasing temperature that probably was governed by basement exhumation (Juhász et al., 2002). Terrestrial pollens enclosed in vein filling calcite crystals infer that fracture network formed in the Middle Miocene Badenian age (Tóth et al., 2003). Fracture filling quartz crystals contain tiny HC-bearing fluid inclusions, which are of different chemical compositions even in case of a single high (Schubert and Tóth, 2003; Schubert et al., 2007). These data suggest that at the time of migration of the ancient oil into the basement, several separated fluid regimes co-existed in the fractured metamorphic realm. Pap et al. (1992) report a similar situation about a recent well, from which fluids of different compositions are produced at different depths. These and numerous similar data imply that the fractured rock mass of the metamorphic basement does not form a single conductive network; it possibly breaks down into several independent percolation clusters.

The sedimentary cover of basement rocks also differs in the high and basin areas significantly. In the sub-basins sandy and pebbly sediments occur, which are covered by a thick layer (at places even 200 m) of impermeable lacustrine marl. Above the uplifted crystalline domes these marls usually are missing and a fine to coarse grained sandstone follows instead.

Hydrodynamically, the Pannonian Basin can be subdivided into an upper and a lower regime (Almási, 2001; Tóth and Almási, 2001; Szanyi and Kovács, 2010). The upper one is a gravity driven system (Erdélyi, 1976), while overpressured zone was developed in the lower regime essentially due to tectonic compression (Almási, 2001; Tóth and Almási, 2001). Vertical compaction and aquathermal pressuring were also attributed to the origin of overpressure according to earlier interpretations (Somfai, 1970; Szalay, 1982, 1983). Another theory assigns lateral tectonic compression as an indirect cause to explain vertical compaction (Horváth, 1995; Horváth et al., 2015; Van Balen and Cloetingh, 1994). The reservoir of the upper regime consists of shallow marine and delta facies sediments (Bérczi, 1988) with good porosity and permeability. On the contrary, the lacustrine clays and marls of the lower zone can isolate pressure resulting in an overpressure of even 15–20 MPa within a 100–200 m depth interval (Almási, 2001). The overpressure can also be detected in the fractured metamorphic basement. It is well-known that inside the sedimentary basin the overpressured regime is in hydraulic connection with the upper zone through high permeability fault zones (Tóth and Almási 2001; Almási, 2001). A question arises whether those uplifted metamorphic domes, which are not covered by the very low permeability clay – clayey marl layers, may play the same role in the hydraulic system of the Pannonian Basin.

The average geothermal gradient in the Pannonian Basin is ~50 °C/km (Dövényi et al., 1983). The mean annual temperature at the surface is ~ 11 °C giving ~60 °C and ~110 °C as a typical rock and water temperature at 1and 2 km depths (Dövényi and Horváth, 1988). The main reason for such an uncommon behaviour is that beneath the Pannonian Basin the crust is only ~25 km thick. As a consequence, the heat flux is high (~ 90.4 mW/m^2) (Dövényi and Horváth, 1988). In addition, crystalline rocks usually have better heat conductivity than porous sedimentary sequences resulting in anomalously high temperatures inside the metamorphic domes (e.g. there is 290 °C at a depth of 4800 m inside a gneiss dome, while in the neighbouring sedimentary basin 250 °C is typical at a depth of 5200 m, Posgay et al., 2006). All these parameters make the whole region rather promising for diverse geothermal utilizations.

3. Methods

The fracture network of the basement rocks has a key role as both concerning fluid migration and storage capacity and it was studied in details for many cases. To simulate 3D fracture network for both near well regions and at reservoir scale, a fractal geometry based DFN (discrete fracture network) modelling system was used. For modelling we measured the most essential geometric parameters of the fractures (length distribution, orientation, spatial distribution of fracture seeds, length–aperture relationship) using selected rock specimens and CT images (Tóth et al., 2004).