Marine and Petroleum Geology 78 (2016) 738–749

Contents lists available at ScienceDirect

Marine and Petroleum Geology

journal homepage: www.elsevier.com/locate/marpetgeo

Research paper

Evolution of fluid flow and heat distribution over geological time scales at the margin of unconfined and confined carbonate sequences - A numerical investigation based on the Buda Thermal Karst analogue

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ARTICLE INFO

Article history:
Received 1 March 2016
Received in revised form
18 August 2016
Accepted 3 October 2016
Available online 3 October 2016

Keywords:
Numerical modelling
Gravity-driven groundwater flow
Thermal convection
Tectonic uplift
Carbonate karst systems

ABSTRACT

Hydrogeological processes acting at the margins of confined and unconfined thick carbonate sequences are particularly interesting due to a complex system evolution including partial uplift of fully confined carbonate systems and subsequent erosion of cover layers. We provide insights into this evolution by simulating coupled density-dependent fluid flow and heat transport based on the Buda Thermal Karst (BTK) system (Hungary) in a 2D vertical plane. Applying an equivalent porous medium (EPM) approach using the Heatflow-Smoker finite element model, scenario modelling of three evolutionary steps was carried out between the fully-confined carbonate stage through to partly and completely unconfined conditions over the western ridge. The numerical simulations were used to derive the main evolutionary characteristics of groundwater flow and heat transport patterns for the unconfined and confined parts of the hydrogeologic system. The initial fully-confined state led to the development of thermal convection cells due to the insulating role of the low-permeability confining layer, which facilitates buoyancy-driven flow by restricting the dissipation of heat. Over geological time, these cells were gradually overprinted by gravity-driven flow and thermal advection due to uplift of the west ridge. The limited thickness of the cover allowed sufficient water infiltration into the system, which led to increased cooling. Further uplifting led to a prevalence of gravity-driven groundwater flow. The results highlight the critical role of confining formations on flow patterns, and their effect on heat distribution and dissipation over geological time scales. The results have important implications for heat accumulation as well as for the development of a deep geothermal energy potential in confined carbonates.

1. Introduction and goals of the study

Deep regional groundwater flow systems are not static - they evolve continuously during the geological history of their host sedimentary basins (Ingebritsen and Sanford, 1999). Transient hydraulic and thermal conditions will evolve, for example, in response to a variety of changes including those related to climate, thermal conditions, sediment compaction, erosion, geochemical reactions, tectonic uplift and stress (Deming, 2002). Understanding the transient history of subsurface fluid flow systems, therefore, could help to explain the role of deep groundwater in a number of geologic processes including diagenesis, hydrothermal flow and ore genesis, as well as petroleum migration (Bredehoeft and Norton, 1990), porosity enhancement and hypogene karstification.

Understanding the main hydrogeological processes within thick carbonate deposits is challenging. A particularly interesting situation arises at the margin of confined and unconfined carbonate sequences, which was demonstrated for the steady-state case in the context of the Buda Thermal Karst (BTK) system (Alföldi et al., 1968; Alföldi and Kapolyi, 2007; Zsigmondy, 1878) by Mádl-Szőnyi and Tóth (2015). However, the transient evolution of hydrogeological flow systems from partial uplift of fully confined carbonate systems and subsequent erosion of cover layers has not yet been examined.

This paper aims to address several important groundwater flow and heat transport process-related questions which arise from this geological evolution, namely: i) What are the main effects of low-permeability confining formations overlying a permeable carbonate system?; ii) What are the main characteristics of the flow field

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http://dx.doi.org/10.1016/j.marpetgeo.2016.10.001
0264-8172/

and temperature distribution in these carbonate systems with decreasing cover thickness at one ridge?, and iii) What is the relative importance of gravity and buoyancy as driving forces in the different geological evolutionary stages with different confining layer thicknesses?

Insights into deep regional hydrogeological processes can be significantly improved with numerical models, as was shown, for example, by Gleeson and Manning (2008), who defined the salient controls on regional groundwater flow in 3D mountainous terrain by systematically varying topographic and hydrogeologic variables. Cardenas and Jiang (2010) pointed out the importance of depth-dependent heterogeneity on groundwater flow, transport, and residence time distributions of subsurface fluids via numerical flow and transport models. Sandeep et al. (2016) highlighted the effect of temporal evolution of permeability and flow fields through several simulations with various combinations of initial permeability as well as with transitional flow regimes in the presence of through-flow with different fluxes.

In the current study, semi-synthetic snapshot models of coupled density-dependent flow and heat transport were used to better understand the paleohydrogeology and thermal history of marginal areas of confined and unconfined carbonate sequences within the context of the Buda Thermal Karst system. Based on these snapshot simulations, we follow the effects of changing conditions on the fluid-potential and heat distribution during the geological evolution of the basin. Effects of transient flow evolution on geochemistry and permeability in carbonate basins can then be interpreted based on these results.

2. Analogue area

The Buda Thermal Karst system in Hungary is considered an analogue pilot area for numerical studies since it is situated at the margin of unconfined and confined carbonate systems. A simplified geological and hydrogeological conceptual model of this system can be used to provide realistic hydrogeological conditions and parameters for the numerical study.

Globally, this hydrogeological situation is not unique as many other systems are also characterized by similar geological settings, for example the Upper Floridan aquifer system in west-central Florida, USA (Gulley et al., 2014), the Jinan karst aquifer system in east China (Wang et al., 2015), the Frasassi Anticline on the eastern slope of the Apennine mountain chain in Italy (Galdenzi et al., 2008), as well as the Black Hills in South Dakota, USA (Palmer and Palmer, 2000).

The BTK is an active karst system, where extensive geological, speleological and hydrogeological information is available. It is located at the north-eastern margin of the Transdanubian Range (TR) in Hungary, in the central part of the Pannonian Basin. The Mesozoic carbonate suite of the TR (Haas, 1988) is downfaulted and continues deep on the basin side (Pest plain) to the east of the Danube River, under a thick Neogene siliciclastic sedimentary cover (Fig. 1). Under the Pest plain these confined carbonates are suitable for geothermal development (Mádl-Szőnyi et al., 2015), and some areas also contain hydrocarbon reservoirs (e.g. Milota et al., 1995). Several studies have been made in order to gain insight into the recent hydrogeological system (Erőss et al., 2008, 2012) and to understand the paleo-fluid migration processes (Poros et al., 2012). Hydraulic studies have identified gravity as the main driving force of the system (Erhardt et al., 2013) while buoyancy due to thermal gradients and permeability conditions can also be important. The base level of erosion is the Danube River.

From the Late Miocene, inversion of the Pannonian Basin contributed to the uplift of certain blocks (Horváth et al., 1988), including the Buda Hills as part of the Transdanubian Range. East of the Danube, uplift of the Gödöllő Hills Region started somewhat later and has been ongoing for the past 4 million years (Ruszkiczay-Rüdiger et al., 2006, 2007). During this uplifting, a watershed east of the Danube developed, which defines the eastern boundary of the BTK (Mádl-Szőnyi et al., 2015). Due to the thinned lithosphere below this basin, the entire area is characterized, even today, by an elevated heat flux (an average of 100 mWm^{-2}) (Lenkey et al., 2002).

Beginning in the Miocene, meteoric fluid has infiltrated the western part of the system as this area became subaerially exposed due to the partial erosion of the Paleogene sequence. Poros et al. (2012) estimated that 800 m of sediments have been eroded since the late Early Miocene based on measured entrapment temperatures and pressures of fluid inclusions in calcite veins. The contribution of basinal fluids from the Pest plain east of the Danube to the Buda Karst was raised by Alföldi (1981) and later identified by Erőss (2010) as well as in the diagenetic study of Poros et al. (2012). Vertical leakage of basinal fluids across the confining layer east of the BTK was first proposed by Mádl-Szőnyi and Tóth (2015).

3. Simulation approach

Characteristic patterns of groundwater flow and thermal energy transport at the margin of the unconfined and confined carbonate region were generated using numerical simulations. We consider different thicknesses of the cover formation during three distinct evolutionary stages of geological evolution.

Several numerical investigation methods have been developed to describe groundwater flow in karstified carbonate systems, including equivalent porous media (EPM), dual continuum, combined discrete-continuum, discrete fracture network (DFN) and discrete channel network approaches (Ghasemizadeh et al., 2012). Selection of an appropriate method primarily depends on the given hydrogeological problem to be solved and questions to be answered, as well as additional issues including the system scale, the degree of karstification and data availability (Scanlon et al., 2003).

As found by Kiraly (1975) and demonstrated by Sauter (1992), the average permeability in carbonate formations increases with increasing scale due to deep fractures and major faults and conduits, which can form preferred groundwater flow paths. At the basin scale, however, these local effects are less important (Wellman and Poeter, 2006), and the flow system can be considered as representing an integrated ensemble of matrix, fracture and channel processes. Local effects of karstic heterogeneities on formation permeability, such as karst conduits, tend to average out over larger areas, and may be neglected on this scale as suggested by Abusaada and Sauter (2013).

Since the current study focuses on regional groundwater flow patterns and heat transport processes rather than on more detailed, local predictions of flow directions or rates, an equivalent porous medium (EPM) approach (Teutsch and Sauter, 1991) was applied. We thus apply bulk parameters instead of incorporating small-scale matrix properties and individual fractures and conduits based on Lapcevic et al. (1999). The EPM approach has been used effectively in the past to simulate groundwater flow on regional scales and for slightly karstified carbonate aquifers (ex. Loáiciga et al., 2000; Rodríguez et al., 2013; Scanlon et al., 2003; Wellman and Poeter, 2006). The applicability of the EPM approach and the concept of gravity-driven regional groundwater flow for such carbonate systems was justified by Mádl-Szőnyi and Tóth (2015) based on the principle of hydraulic continuity, which was derived and shown effective for carbonate basins by Klimchouk (2009). Local heterogeneities in hydraulic conductivities were also neglected by Wellman and Poeter (2006) in order to evaluate the regional effect of the water table. Instead of focusing on local heterogeneities, in