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The Impact of Reservoir Heterogeneities on High-Temperature Aquifer Thermal Energy Storage Systems. A Case Study from Northern Oman.

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ABSTRACT

We conducted a geoscientific feasibility study for the development of a high-temperature thermal aquifer energy storage system (HT-ATES) outside the capital of Muscat, northern Oman. The aquifer storage is part of a solar-geothermal cooling project for the sustainable and continuous cooling of office buildings. The main concept is that excess solar energy will be stored in the subsurface through hot water injection and subsequently utilised as auxiliary energy source during peak demand times. The characterisation of aquifer heterogeneities is thus essential to predict subsurface thermal heat plume development and recovery efficiency of the storage system. We considered two aquifer systems as potential storage horizons, (i) a clastic-dominated alluvial fan system where individual channel systems in combination with diagenetic alterations constitute the main heterogeneities and (ii) a carbonate-dominated system represented by a homogenous layer-cake architecture. The feasibility study included a multidisciplinary approach from initial field work, geocellular reservoir modelling to finite element fluid flow and thermal modelling. Our results show that for the HT-ATES system, with a high frequency of injection and production cycles, heat loss mainly occurs due to heterogeneities in the permeability field of the aquifer in combination with buoyancy driven vertical fluid flow. An impermeable cap-rock is needed to keep the heat plume in place. Conductive heat loss is a minor issue. Highly complex heat plume geometries are apparent in the clastic channel system and ATES well planning is challenging due to the complex and interconnected high-permeable channels. The carbonate sequence shows uniform plume geometries due to the layer cake architecture of the system and is tentatively more suitable for ATES development. Based on our findings we propose the general concept of HT-ATES traps, incorporating and building on expertise and knowledge from petroleum and reservoir geology regarding reservoir rocks and suitable trap&seal geometries. The concept can be used as guideline for future high-temperature aquifer storage exploration and development.

1. Introduction

The worldwide growing energy demand dovetailed with the pledge of most nations around the globe to reduce greenhouse emission over the next decades, stimulates significant research and development of sustainable and renewable energy sources. Substantial efforts have been devoted to geothermal energy resources, both deep and shallow geothermal energy systems. Shallow geothermal systems are based on the concept to extract energy via heat exchangers from relatively low subsurface temperatures for heating and cooling purposes. One aspect of shallow geothermal systems are underground storage systems where energy is temporarily stored in the subsurface and recovered when needed. These systems are increasingly used in combination with deep geothermal, solar, wind or any other given energy source to utilise excess and surplus energies as auxiliary energy back-up systems during peak demand times (McCartney et al., 2016).

A special case of underground energy storage is aquifer thermal energy storage (ATES) where energy is stored in groundwater horizons via hot water injection in the aquifer system (e.g.: Bloemendal et al., 2014; Lee, 2010; Réveillère et al., 2013). In general, an ATES system is designed as a number of well doublets, consisting of an array of warm and cold wells which simultaneously inject and extract hot and cold water, respectively. Thereby, changing the temperature of groundwater and subsurface lithologies. These open thermal energy storage systems are increasingly used in Europe and North America due to the efficient and sustainable way of storage and reutilisation of excess energy (Bloemendal et al., 2014; Schout et al., 2014). A recent advancement in the field of geothermal energy storage is the combination of ATES systems with solar power (e.g.: Lee, 2010; Paksoy et al., 2000; Parameshwaran et al., 2012; Pinel et al., 2011; Vanhoudt et al., 2011). In that case, solar energy is used to heat up water which drives a heat exchanger and surplus thermal energy is stored in the subsurface. The

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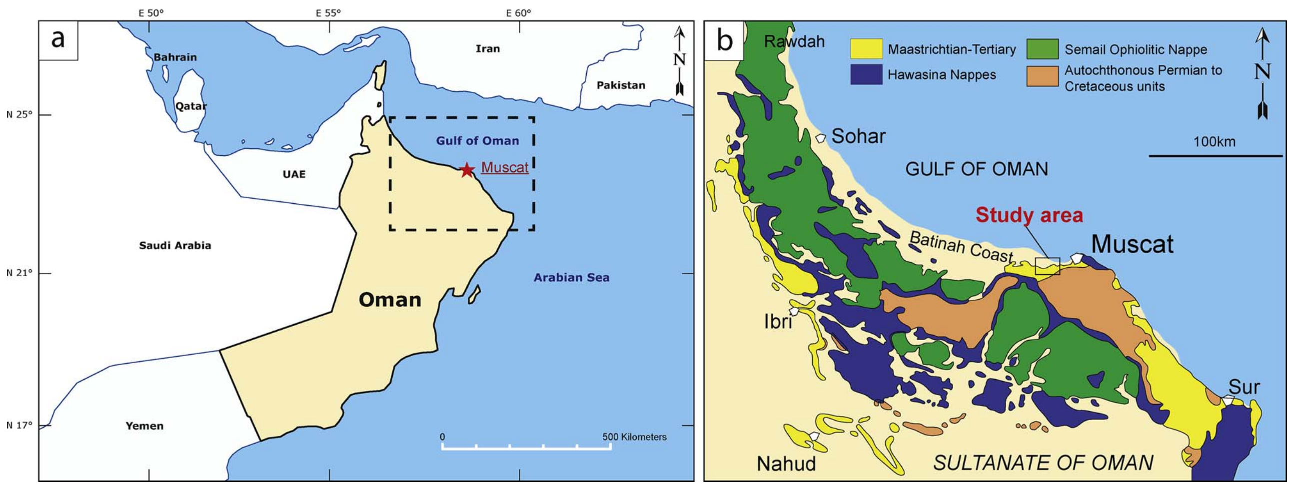

Fig. 1. (a) Map of Oman. Dotted rectangle indicates outline of Fig. 1.b. (b) Geological map of northern Oman. Modified after Özcan et al. (2015).

energy can then be used as an auxiliary energy source during peak demand and night times when no solar energy is available. These combined solar-geothermal storage systems thus depend on the availability of sunlight and high system performances are achieved in areas with arid climates.

1.1. The GeoSolCool HT-ATES System in Northern Oman

The GeoSolCool project is a collaborative research programme between the German Research Centre for Geoscience, Potsdam (GFZ) and The Research Council of Oman (TRC), which aims to develop and implement an innovative concept of a sustainable thermally driven cooling system in combination with a high-temperature (~100 °C) ATES in northern Oman. Oman is one of the hottest and driest countries in the world and a substantial part of the country's energy consumption, sourced by fossil fuels, is required for air conditioning (Omri, 2013; Ramanathan, 2005). A renewable energy source for sustainable cooling will thus significantly contribute to Oman's energy transition.

The cooling system will be installed at the new research facilities of the TRC outside of Muscat (Fig. 1.a&b) and will use an absorption chiller for cold supply, which requires water of around 100 °C as energy source. Solar collectors will provide the thermal energy and energy surpluses during daytimes will be stored to ensure a continuous operation of the cooling system. An integral part of this project is the development of an efficient HT-ATES for the temporal storage and subsequent recovery of thermal energy through hot water injection in subsurface aquifer horizons at the TRC headquarters. Thus, an accurate geological, thermal and fluid flow characterisation of potential reservoir horizons is essential to ensure optimal efficiency of the cooling system.

A common procedure in initial ATES development phases is thermodynamic modelling of the storage system and simulation of thermal energy recovery. The majority of these modelling workflows are conducted from an engineering point of view and storage horizons are often assumed homogenous and isotropic (e.g.: Lee, 2013; Schout et al., 2014; Xiao et al., 2016). However, subsurface heterogeneities and preferred fluid flow pathways may pose a major control on ATES performance which is increasingly recognised by researchers (Bridger and Allen, 2013; Ferguson, 2007; Ferguson, 2012; Possemiers et al., 2015; Sommer et al., 2013). ATES reservoirs are relatively small (several 10 to 100 m) and thus small-scale heterogeneities (cm-m scale) influence the subsurface porosity and permeability and consequently the hydraulic field (Bayer et al., 2015; Bianchi et al., 2011; Ronayne et al., 2010). This includes geological layering, sedimentological features and facies distributions. Thus, subsurface conditions have to be studied in detail in order to monitor injected thermal energy distribution (heat plume), to prevent thermal short-circuiting between well pairs and between adjacent ATES systems.

In this paper, we present the results of a geological feasibility study for the planned solar-driven HT-ATES system for continuous cooling of the TRC research facilities, ranging from initial field work to coupled fluid flow and thermal reservoir simulation with special focus on the geological characteristics of the potential storage aquifers. The aim of this paper is to investigate the influence of subsurface heterogeneities on the heat plume evolution of two potential storage horizons situated in two different geological settings at the field area, the clastic dominated Barzaman Formation and the shallow-marine carbonates of the upper Seeb Formation. In the first part, we present in detail the geological evaluation of the study area with special focus on subsurface heterogeneities. In the second part, we discuss the 3D thermal and fluid flow modelling and ATES forecasting analyses.

2. Geological setting

The study area is located at the Batinah coast of northern Oman, approximately 30 km to the West of Muscat (Fig. 1.a). The main geological entity in this area are the Oman Mountains, located at the southeast margin of the Arabian Plate (Abbasi et al., 2014; Cooper et al., 2014). The broad subdivision of this unit in ascending stratigraphic order is: Palaeozoic to Mesozoic sediments of the southern passive margin of the Tethys, allochthonous oceanic and ophiolitic rocks (Semail ophiolite) and late Cretaceous to Cenozoic post-obduction sediments (Fig. 1.b). The following paragraphs will focus on the latter sediment sequences as they represent the main geological formations in the study area.

The general stratigraphy and depositional systems of the post-obduction sediments deposited at the Batinah coast have been outlined by Nolan et al. (1990). Sedimentation was initiated after the obduction of the Semail ophiolite complex onto the Arabian platform during the late Campanian. The onset of the succession is represented by siliclastic sediments of late Cretaceous age, originating from the unroofing of the emergent proto-Oman Mountains (Al Khawd Formation). Following a major regional unconformity, separating Paleogene and Cretaceous strata in the central Oman Mountains, the late Palaeocene to early-Eocene shallow-marine carbonates of the Jafinayn Formation were deposited (Özcan et al., 2015; Tomás et al., 2016). These deposits are followed by the early-Eocene Rusayl Formation, characterised by fluvial and lagoonal sediments (shale and fine-grained limestones) (Dill et al., 2007). A marine transgression during the middle Eocene resulted in the deposition of the open marine, carbonate-dominated Seeb Formation. (Beavington-Penney et al., 2006; Racey, 2001). The Seeb Fm. is characterised by a carbonate ramp geometry with km-wide uniform