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Characterizing flow pathways in a sandstone aquifer: Tectonic vs sedimentary heterogeneities

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ABSTRACT

Sandstone aquifers are commonly assumed to represent porous media characterized by a permeable matrix. However, such aquifers may be heavy fractured when rock properties and timing of deformation favour brittle failure and crack opening. In many aquifer types, fractures associated with faults, bedding planes and stratabound joints represent preferential pathways for fluids and contaminants. In this paper, well test and outcrop-scale studies reveal how strongly lithified siliciclastic rocks may be entirely dominated by fracture flow at shallow depths (≤180 m), similar to limestone and crystalline aquifers. However, sedimentary heterogeneities can primarily control fluid flow where fracture apertures are reduced by overburden pressures or mineral infills at greater depths.

The Triassic St Bees Sandstone Formation (UK) of the East Irish Sea Basin represents an optimum example for study of the influence of both sedimentary and tectonic aquifer heterogeneities in a strongly lithified sandstone aquifer-type. This fluvial sedimentary succession accumulated in rapidly subsiding basins, which typically favours preservation of complete depositional cycles including fine grained layers (mudstone and silty sandstone) interbedded in sandstone fluvial channels. Additionally, vertical joints in the St Bees Sandstone Formation form a pervasive stratabound system whereby joints terminate at bedding discontinuities. Additionally, normal faults are present through the succession showing particular development of open-fractures. Here, the shallow aquifer (depth ≤ 180 m) was characterized using hydro-geophysics. Fluid temperature, conductivity and flow-velocity logs record inflows and outflows from normal faults, as well as from pervasive bed-parallel fractures. Quantitative flow logging analyses in boreholes that cut fault planes indicate that zones of fault-related open fractures characterize ~50% of water flow. The remaining flow component is dominated by bed-parallel fractures. However, such sub-horizontal fissures become the principal flow conduits in wells that penetrate the exterior parts of fault damage zones, as well as in non-faulted areas.

The findings of this study have been compared with those of an earlier investigation of the deeper St Bees Sandstone aquifer (180 to 400 m subsurface depth) undertaken as part of an investigation for a proposed nuclear waste repository. The deeper aquifer is characterized by significantly lower transmissivities. High overburden pressure and the presence of mineral infillings, have reduced the relative impact of tectonic heterogeneities on transmissivity here, thereby allowing matrix flow in the deeper part of the aquifer. The St Bees Sandstone aquifer contrasts the hydraulic behaviour of low-mechanically resistant sandstone rock-types. In fact, the UK Triassic Sandstone of the Cheshire Basin is low-mechanically resistant and flow is supported both by matrix and fracture. Additionally, faults in such weak-rocks are dominated by granulation seams representing flow-barriers which strongly compartmentalize the UK Triassic Sandstone in the Cheshire Basin.

1. Introduction

Quantitative studies for gaining an improved understanding of flow pathways represent a key issue for groundwater protection and catchment planning for all aquifer types. This work focuses on lithified sandstone aquifers and aims to characterize the role various types of sedimentary and tectonic heterogeneities on aquifer behaviour and contaminant transport in the phreatic zone. The rate of passage of inorganic (e.g., NAPL, nitrogen, phosphate and chlorinated solvents) and organic (e.g., bacteria, virus) contaminants flowing through a sandstone matrix are controlled by a range of sedimentary heterogeneities (Lawrence et al., 2006; Mobile et al., 2016; Qin et al., 2013; Rivett et al., 2011; Tellam and Barker, 2006; Zhu and Burden, 2001), such as the presence of relatively low permeability mudstone layers. Alternatively, these contaminants may be transported at higher flow velocities along mechanical discontinuities of tectonic origin, such as bedding parallel

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fractures, vertical joints or fault-related fracture corridors (Barker et al., 1998; Berkowitz, 2002; Bradbury et al., 2013; Cilona et al., 2015; Faulkner et al., 2009; Hartmann et al., 2007; Huyakorn et al., 1994; Odling and Roden, 1997; Rutqvist and Tsang, 2003; Steele and Lerner, 2001). The relative importance of matrix versus fracture flow is known to vary as a function of depth, owing to different sensitivities to geochemical alteration (e.g., diagenesis) and overburden pressure (Akin, 2001; Howard, 1988; Zoback and Byerlee, 1975). Thus, a specific study, which combines hydraulic tests (pumping tests, flow logging) at different depths, may provide an improved understanding of the relative importance of porous matrix versus fractures in controlling groundwater flow and contaminant transport in sandstone aquifers (Gellasch et al., 2013; Tellam and Barker, 2006). Multilevel sampling arrays have been used to detect traces of contaminants in relation to bedding parallel fractures in sandstone aquifers (e.g., Gellasch et al., 2013; Powell et al., 2003). The hydrogeology of faults represents a further specific key issue in groundwater protection since such structural discontinuities can act as either barriers or preferential pathways for contaminants (Bense et al., 2013; Bottrell et al., 2008; Caine et al., 1996; Mohamed and Worden, 2006). Furthermore, water wells have been recognized both as preferential pathways for and sources of contaminants (Avcι, 1992). Hence, pollutant plumes may be exacerbated by the interaction between groundwater and boreholes (Avcι, 1992; Hammond, 2016; Rivett et al., 1990). The use of well tests in a fractured media allows us to test the interaction between all preferential pathways for contaminant transport which are represented by boreholes, tectonic open fractures and permeable sedimentary layers (Bauer et al., 2004; Odling et al., 2013).

Previous quantitative studies, involving hydraulic tests in lithified sandstone aquifers (Brassington and Walthall, 1985; Gellasch et al., 2013; Hitchmough et al., 2007; Lo et al., 2014; Price et al., 1982; Runkel et al., 2006), have focused on determining only the role of sub-horizontal discontinuities on water flow, including their connections through vertical stratabound joints. In contrast, past studies of the hydrogeology of faults in sandstone aquifers have focused on plug-scale fault rock samples and mini-permeameter outcrop experiments. Such studies have aimed to quantify the sealing potential of normal faults on hydrocarbon reservoir analogues (e.g., Antonellini et al., 1994; Balsamo and Storti, 2010; Torabi and Fossen, 2009; Tueckmantel et al., 2012). Consequently, quantitative hydraulic studies that encompass multiple aquifer heterogeneities, such as sub-horizontal stratigraphic discontinuities linked by multi-layer vertical fractures and extensional faults, are lacking.

This work investigates the sandstone aquifer of the Triassic St Bees Sandstone Formation, which represents the basal part of the Sherwood Sandstone Group – the second most important UK aquifer in terms of the amount of groundwater abstracted (Allen et al., 1997; Binley et al., 2002; Smedley and Edmunds, 2002). The Sherwood Sandstone Group has been the object of recent studies of sedimentary heterogeneities (e.g., Medici et al., 2015; Newell and Shariatipour, 2016; Wakefield et al., 2015). Results from these works have demonstrated how the St Bees Sandstone Formation represents an optimum analogue for the characterization of sedimentary heterogeneity in analogous subsurface hydrocarbon reservoirs of fluvial origin that accumulated in rapidly subsiding basins, such as those of the East Irish Sea Basin (Akhurst et al., 1998; Chadwick et al., 1994). Such conditions typically allow preservation of low-permeability units, including mudstone lenses that occur interbedded in otherwise sandstone-dominated successions (Colombera et al., 2013; Miall, 1977). Notably, the St Bees Sandstone aquifer is entirely characterized by a stratabound fracturing system (sensu Gillespie et al., 2001; Odling et al., 1999; Odonne et al., 2007; Rustichelli et al., 2013, 2016), which is particularly pervasive in this aquifer due to its layered nature coupled with high mechanical resistance (Ameen, 1995; Bell, 1992; Daw et al., 1974). Fault zones in this aquifer are characterized specifically by the development of open fractures and a paucity of low-porosity deformation bands (Knott, 1994). Consequently, the St Bees Sandstone aquifer represents an optimum laboratory to test a wide range of aquifer heterogeneities of both tectonic (e.g., vertical joints, bedding parallel and extensional fractures) and sedimentary origin (e.g., mudstone layers), which are especially well represented in this aquifer (Ameen, 1995; Bell, 1992; Jones and Ambrose, 1994; Knott, 1994; Medici et al., 2015). Additionally, parts of the St Bees Sandstone aquifer that are buried at depths >180 m, have been the object of a hydro-geophysical characterization, which commenced in the early 1990s as part of the planning of the proposed Sellafield nuclear waste repository (e.g., Appleton, 1993; Michie, 1996; Milodowski et al., 1998; Nirex, 1992a,b,c, 1993a,b,c; Streetly et al., 2000, 2006). Thus, this study area offers the opportunity to compare hydro-geophysical studies undertaken at different depths, thereby allowing the opportunity to distinguish the depth-sensitivity of tectonic flow pathways versus matrix flow.

Specific research objectives are as follows: (i) use hydro-geophysics to constrain all the potential flow heterogeneities using imaging and wireline well-logs; (ii) quantify the role of individual structure types in terms of their contribution to flow using fluid temperature, conductivity and velocity logs; (iii) compare the hydro-geophysical characterization undertaken at shallow depths (≤150 m) as an outcome of this work, with previous studies that characterized the aquifer properties at greater depths (180 to 400 m); and (iv) compare the hydraulic characteristics of the St Bees Sandstone aquifer with those of less-mechanically resistant sandstone aquifers.

2. Hydrogeological background

The Sherwood Sandstone Group (Lower Triassic) is a red-bed succession that has long been ascribed to a mixed fluvial and aeolian origin (e.g., Bashar and Tellam, 2011; Ixer et al., 1979; Mountney and Thompson; 2002; Tellam and Barker, 2006; Thompson, 1970; Turner, 1981). This sandstone-dominated succession represents the UK's second most important aquifer. Contamination has arisen due to agricultural activity, and the release of industrial waste and sewage in urban areas (Barrett et al., 1999; Bottrell et al., 2008; Bloomfield et al., 2001; Cassidy et al., 2014; Gooddy et al., 2002; Powell et al., 2003; Rivett et al., 1990; Rivett et al., 2012; Zhang and Hiscock, 2010, 2011). In West Cumbria (Fig. 1a, b), the Sherwood Sandstone Group attains a typical thickness of 1300 m (Jones and Ambrose, 1994; Nirex, 1997) and is formally divided into three different formations: the St Bees, Calder and Ormskirk Sandstone formations (Barnes et al., 1994; Holliday et al., 2008). The St Bees Sandstone aquifer, which is the focus of this study, is predominantly characterized by fine- to medium-grained sandstone of fluvial origin that passes upwards into the aeolian-dominated succession of the overlying Calder Sandstone Formation (Jones and Ambrose, 1994; Holliday et al., 2008). The Cumbrian Coastal Group, which underlies the St Bees Sandstone aquifer, is characterized by shale and gypsum, anhydrite and dolomite evaporite deposits, and represents a basal aquiclude lithology for the St Bees Sandstone aquifer (Fig. 1; Holliday et al., 2008; Smith, 1924; Strong et al., 1994).

The field site is located in the St Bees-Egremont area in NW England (Fig. 1a, b) where the St Bees Sandstone aquifer is confined by glacial and alluvial Quaternary deposits (McMillan et al., 2000). The St Bees Sandstone Formation is divided into two members: the North Head Member and the overlying South Head Member (sensu Medici et al., 2015). The two members are differentiated primarily based on the abundance of fine-grained mudstone layers which range in grain size from clay to coarse silt (Jones and Ambrose, 1994; Medici et al., 2015; Nirex, 1997). The basal 35 m of the lower North Head Member is arranged into an alternation of fine-grained sandstone and mudstone beds. This basal part of the aquifer passes upwards into a succession dominated by sandstone, with mudstone layers representing only 10% and 5% of the entire succession in the upper North Head and South Head members, respectively (Barnes et al., 1994; Jones and Ambrose, 1994; Nirex, 1997). Water boreholes in the St Bees Sandstone aquifer