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# Characterizing flow pathways in a sandstone aquifer at multiple depths

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Sandstone aquifers are commonly assumed to represent porous media characterized by a permeable matrix. However, such aquifers may be heavily fractured where 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. This presentation reports well-test results and outcrop-scale studies that reveal how strongly lithified siliciclastic rocks may be entirely dominated by fracture flow at shallow depths ($\leq$ 150 m), similar to limestone and crystalline aquifers. The Triassic St Bees Sandstone Formation of the UK East Irish Sea Basin represents an optimum succession for study of the influence of both sedimentary and tectonic aquifer heterogeneities in a strongly lithified sandstone aquifer-type. This sedimentary succession of fluvial origin accumulated in rapidly subsiding basins, which typically favour preservation of complete depositional cycles, including fine-grained mudstone and silty sandstone layers of floodplain origin interbedded with sandstone-dominated fluvial channel deposits. Vertical joints in the St Bees Sandstone Formation form a pervasive stratabound system whereby joints terminate at bedding-parallel discontinuities. Additionally, normal faults are present through the succession and record development of open-fractures in their damage zones. Here, the shallow aquifer (depth $\leq$150 m BGL) was characterized in outcrop and well tests. 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 typically represent $\sim$ 50% of well transmissivity. The remaining flow component is dominated by bed-parallel fractures. However, such sub-horizontal fractures become the principal flow conduits in wells that penetrate the exterior parts of fault damage zones, as well as in non-faulted areas. Optical televiewer logs show development of karst-like conduits in correspondence of bedding fractures and faults up to 150 m below the ground surface, where recharge water containing dissolved carbonic acid enlarges fractures; these features may be responsible for the relatively high field-scale permeability (K$\sim$0.1$^{-1}$ m/day) of the phreatic zone at these depths. Below this 'karstifed' zone, field-scale permeability progressively decreases from K$\sim$10$^{-2}$ to 10$^{-4}$ m/day from 150 m to 1100 m depth. Notably, differences between plug and field-scale permeability, and frequency of well in-flows seen in temperature and conductivity logs, also decrease between intermediate (150 to 450 m) and elevated (450 to 1100 m) depths. This confirms how fracture closure leads to a progressively more important matrix contribution to flow with increasing lithostatic stress, leading to intergranular flow dominance at $\sim$ 1 km depth.