Fluid flow around igneous intrusions: from outcrop to simulator

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Igneous intrusions influence local and regional-scale fluid flow through volcanic sedimentary basins. Depending on the petrophysical properties of both sill and host rock and, in particular, the fracturing potential within and around an intrusion, igneous bodies and associated contact aureoles may act as (1) directional high-permeability conduits focusing fluid flow, (2) baffles re-directing fluid flow particularly along the contacts of an intrusion and (3) barriers preventing fluid flow. Given their discordant and tight nature in their un-weathered and unfractured state, doleritic dykes are particularly prone to form baffles, as observed in present-day groundwater fluid flow (e.g. Perrin et al, 2011). In this contribution we investigate different scenarios of fluid flow through volcanic sedimentary basins with three main objectives: (1) to optimize the representation of igneous intrusions in industry-standard reservoir models, (2) to model fluid-flow within, around and through igneous intrusions and (3) to address the issue whether igneous intrusions may promote the pressure compartmentalization of reservoirs.

Ongoing work on the Longyearbyen CO_2 lab project on Spitsbergen, Svalbard (Arctic Norway), has identified a regionally open but locally compartmentalized aquifer at ca. 670-970 m depth; the reservoir is exposed at the surface ca. 15 km from the planned injection site. The injective reservoir is explored as a possible injection site, offering a surprising sub-hydrostatic pressure regime. Numerous hypotheses have been proposed to explain the differential pressure encountered in the wells, including stratigraphic (pinch-outs, lateral facies changes) and structural (faults, permafrost, igneous intrusions) mechanisms. In this contribution we attempt to investigate the plausibility of igneous intrusions forming a fluid flow barrier able to withstand a differential pressure in the order of tens of bar.

Igneous intrusions are investigated in the field in both Svalbard and the Karoo Basin of South Africa. An integrated study, using seismic, LIDAR, satellite imagery, digital elevation models, borehole data and traditional fieldwork has revealed numerous similarities of the Early Cretaceous Svalbard dolerites ("the Diabasodden Suite") and the Early Jurassic Karoo dolerites, which we consider to be well exposed analogues with similar fracture patterns (Fig. 1). Deformation of dolerites during the development of the Tertiary West Spitsbergen Fold-and-thrust belt is considered on Svalbard, compared to the tectonically quiet Karoo dolerites. Fracturing is critical for fluid movement around and across igneous bodies, as exemplified by the Water Resource Commission's field study at Qoqodala in the Eastern Cape (Chevallier et al, 2004).

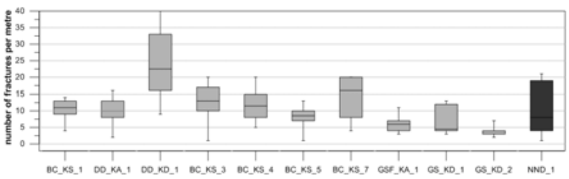

Fig. 1 – Box-whisker plots illustrating the fracture density for selected scanlines from Svalbard (grey) and the Karoo basin (black). The graph illustrates the minimum, maximum, median, lower quartile and upper quartile of fracture frequencies.

Based on the prevalent geometries, igneous intrusions are represented in a static reservoir model. Eleven scanlines were logged across selected dolerite outcrops on Svalbard in order to characterize the natural fractures (total length: 112 m, total fractures: 1295). The Svalbard data set is compared to one logged scanline and numerous "virtual scanlines" from the Karoo Basin. "Virtual scanlines" are constructed from scaled photo-mosaics interpreted using ImageJ, and provide insight into the regional-scale distribution of fractures within igneous bodies. Fluid flow simulations are primarily run as streamline simulations with selected key cases run as full black oil models. Reservoir properties are assigned using published values reported for both igneous and host rocks. Fluid properties are assigned using default values. Models are primarily run using single-porosity and a coarse grid (100*100m, variable cell thickness) to optimize simulation speed, but fractured zones may be represented locally using a dual-porosity, dual-permeability setup. A sensitivity matrix was set up to test the relative influence of critical factors such as sill geometry (size, shape, petrophysics), nature of contact aureoles (fracturing, thickness) and engineering (timing of injection/production).

A typical fracture frequency of 5-20 fractures/metre (f/m) is evident from both Svalbard and Karoo dolerites (Fig. 1), with local fracture frequency of up to 40 f/m. This is significantly higher than fracture frequencies reported from sedimentary rocks from the same study site on Svalbard (average 3-12 f/m). The same pattern is exemplified by a scanline crossing an igneous body at Nonesis Neck, Eastern Cape province, South Africa (Fig. 2). Calcite-cemented fractures near intrusions signify past fluid flow along the contact zones, probably reflecting hydrothermal fluid circulation at the time of emplacement. Fractures are subsequently represented in selected zones (contact aureoles in particular) of the reservoir model.

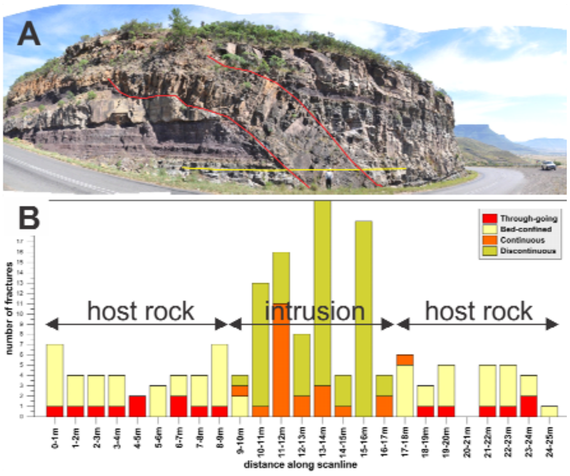

Fig. 2 – (a) Igneous intrusion in Triassic sediments at Nonesis Neck, Eastern Cape. (b) Frequency plot across the igneous body, illustrating the increased fracturing within the dolerite compared to surrounding host rock. The location of the scanline is illustrated on the photo-mosaic (yellow line).

Initial tests performed on a synthetic case loosely based on the saucer-shaped sills from the Eastern Cape province of South Africa indicate that large pressure differentials on the order of several 10s of bar may develop within a saucer-shaped intrusion capped by an impermeable shale following steady-rate production (Fig. 3b). Work is ongoing to test the feasibility of the development of pressure cells with igneous intrusions, and identifying the critical factors that can lead to hydraulically contained aquifers.

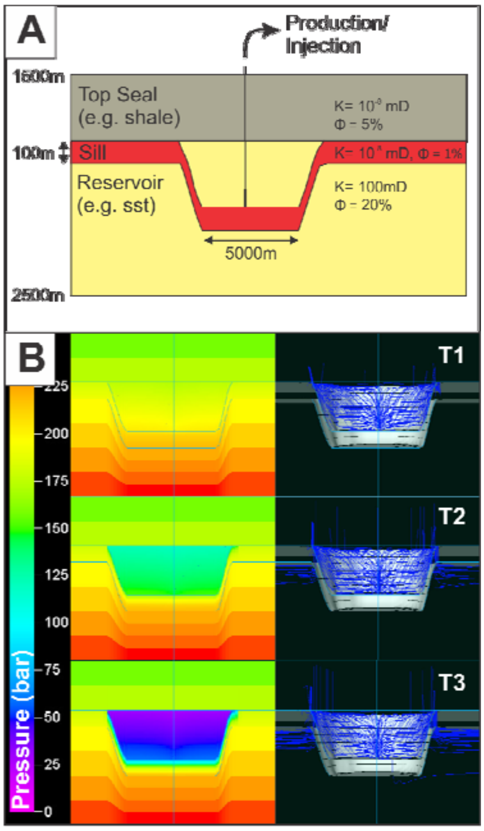

Fig. 3 – (a) Base case cross-section across static 3D model set-up, including petrophysical properties. (b) Initial modeling results illustrating the decrease in pressure in the saucer-shaped compartment following water production in three arbitrary time steps (T1-T3). Corresponding streamlines (blue) indicate increased breakthrough of fluids through the sill.

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