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Numerical Modelling of Thermal Convection Related to Fracture Permeability - Implications for Geothermal Exploration and Basin Modelling

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Thermal anomalies in deep sedimentary settings are largely controlled by fluid circulation within permeable zones. Convection is of particular interest in geothermal exploration, as it creates areas with anomalously high temperatures at shallow depths. Recent work on the temperature distribution in the Dutch subsurface revealed a thermal anomaly at the Luttelgeest-01 (LTG-01) at 4-5 km depth, which could be explained by thermal convection. Temperature measurements show a shift to higher temperatures at depths greater than 4000 m, corresponding the Dinantian carbonates.

In order for convective heat transport to explain the anomaly, there must also be sufficient permeability. Rayleigh number calculations show that convection may be possible within the Dinantian carbonate layer, depending on its thickness, permeability and geothermal gradient. For example, an average permeability of 60 mD permits convection in a 600 m aquifer, given a geothermal gradient of 31°C/km. If the permeability is reduced to 20 mD, convection can only occur where the thickness of the aquifer is greater than 900 m. Interestingly, numerical simulations were able to come within 5-10 mD of the theoretical minimum permeability values calculated for each scenario.

3D numerical simulations provide insight on possible flow and thermal structures within the fractured carbonate interval, as well as illustrate the role of permeability on the timing of convection onset, convection cell structure development and the resulting temperature patterns. The development and number of convection cells is very much a time dependent process. Many cells may develop in the beginning of simulations, but they seem to gradually converge until steady state is reached. The shape of convective upwellings varies from roughly circular or hexagonal to more elongated upwellings and downwellings. Furthermore, the geometric aspects of the carbonate platform itself likely control the shape and location of upwellings, as well as the fracture network geometry within the aquifer.

In summary, convective upwellings can create significant temperature enhancements relative to conductive profile and in agreement with the observations in the LTG-01 carbonates. This enhancement is critically dependent on the aquifer thickness and geothermal gradient. Given a gradient of 39°C/km and aquifer thickness of 600 m, a temperature of 203°C can be obtained at a depth of 4500 m directly above upwelling zones. Contrarily, downwelling zones result in a temperature of 185°C at the same depth. This demonstrates the strong spatial variability of thermal anomalies in convective fractured aquifers at large depth and can have strong effects on exploration opportunity and risk of prospective areas. Numerical models can facilitate in exploration workflows to assess thermal variation and location of upwelling zones.