The role of fluid flow in the thermal history of sedimentary basins

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CHAPTER 7

Summary and conclusions

The aim of this thesis is to improve knowledge on the thermal effects of groundwater flow in sedimentary basins on geological timescales. To study the link between past and present-day subsurface temperatures and flow systems this thesis focuses on detailed data analysis and model studies of a single sedimentary basin, the Mesozoic-Cenozoic Roer Valley Graben in the southern Netherlands. To achieve this aim the first part of this thesis focuses on evaluating and improving methods and modeling techniques for the reconstruction of present-day subsurface temperatures and the thermal history of basins. The second part of this thesis is devoted to model-data comparisons which explore the thermal effects of both basin-wide and localized hydrothermal flow systems in basins.

Chapter 2 demonstrates a new physics based model to estimate subsurface temperatures from data that are disturbed by the thermal effects of mud circulation during drilling. This new model provides more accurate results than often used empirical approaches and also allows an assessment of the uncertainty of temperature data. The reconstructed temperature field in the Roer Valley Graben suggests that there is no thermal signature of crustal extension, in contrast to a number of other rift basins in the European plate that were active during the Cenozoic. The reconstructed temperatures do however show a trend of increasing geothermal gradients from the southeastern part to the northwestern part of the basin, and a number of local anomalies that exceed +10 °C. Model experiments show that these variations cannot be explained by variations in thermal properties of the subsurface. Instead, the subsurface temperature anomalies may show the thermal effects of groundwater flow.

In chapter 3 we focus on reconstructing the thermal history of the Roer Valley Graben. In this chapter we address a key challenge for deriving the thermal history of basins using thermochronological data: the interference of the inherited thermal signal of source areas. To improve the interpretation of thermochronological data of sediments, we developed a new model that combines basin and provenance history. The variation of provenance thermal histories within samples is addressed using end-member scenarios for the thermal evolution of source areas, which were based on independent geological and thermochronological data. The application of this model to the Roer Valley Graben showed that for 7 out of 13 boreholes the thermal history could be explained using realistic burial and provenance history scenarios. The inferred amount of exhumation during the Late Cretaceous phase of compression reaches values of up to 1.0 km and is highest along the northeastern boundary fault of the basin. However, in six boreholes fission-track results of apatite samples could not be explained by realistic burial history scenarios. Two of these boreholes contained inverted fission-track age-depth trends that point to a vertically confined heat pulse. As these boreholes are not located close to magmatic intrusives the most likely source is a transient hydrothermal system.

The uncertainty that results from the scarcity of high-temperature geological time scale benchmarks for the apatite fission-track method is explored in chapter 4. Current annealing models are based on geological timescale benchmark from the Otway basin in southeastern Australia. Chapter 4 summarizes geological and thermochronological data that shows that large parts of this basin were affected by inversion during the Miocene, which was not taken into account in calibrating fission-track annealing models. In chapter 4 we show that incorporating several 100s of meters of inversion during the Miocene would resolve differences between the Otway basin dataset and a second benchmark dataset in southern Texas, which has so far not been used to constrain annealing models. These results imply ~15-20 °C higher annealing temperatures on geological timescales than suggested by current annealing models. Studies that derive geological histories from apatite fission-track data may therefore have underestimated burial depths and exhumation.

The thermal effect of basin-scale groundwater flow was explored in chapter 5. The fresh-salt water boundary in the Roer Valley Graben is located up to 1 km below the transition of continental to marine sediments. This points to an active topography-driven flow system in the basin, in spite of the low relief of 130 m and topographic gradients that do not exceed ~0.2 %. The extent and thermal effect of this flow system was assessed by calibrating a 2D model of topography-driven flow using both temperature and groundwater salinity data. The model simulates the evolution of topography-driven flow system following the Miocene to present transition to continental conditions in the basin. The high uncertainty of permeability of the basin fill was addressed by employing a new permeability upscaling algorithm that relates the modeled permeability to the variability of clay content within lithological units. The salinity data can only be matched by model scenarios with a relatively strong flow system, which results in cooling of the southeastern part of the model domain of up to 40 °C. The results explain the observed low present-day temperatures in the central and southeastern part of the basin and the low values of basal heat flow that was inferred from apatite fission-track data in chapter 3. These results demonstrate that topography-driven flow can strongly affect subsurface temperatures in sedimentary basins, even in settings where the topography is relatively low.

While previous research has shown that Mesozoic hydrothermal mineralization is common in the western European plate, data or model studies on the thermal effects of hydrothermal systems are scarce. In chapter 6 we couple a new simple numerical model of heat and fluid flow with apatite fission-track thermochronology. Two boreholes in the Roer Valley Graben intersect Lower Cretaceous magmatic intrusives, which may have driven a hydrothermal flow system that could explain anomalously young fission-track ages in 6 out of 13 boreholes in the basin, as discussed in chapter 3. The model results show that the anomalous apatite fission-track data can be explained by a simple hydrothermal system in which hot fluid flow sideways into an aquifer connected to a feeder fault. However, the results also show that this hydrothermal event could not have been contemporaneous with the magmatic intrusive events 133 My ago, but took place 80 My ago during a phase of basin inversion. A large set of model scenarios was tested to constrain the thermal and flow parameters of this flow system. The inferred heating in three boreholes of >+75 °C >+150 °C requires the upward flow of fluids along permeable faults from depths of at least 4 km. The two potential sources for these fluids are meteoric water and compaction-induced overpressure. The inferred fluid volumes are too large to be generated by the expulsion of overpressured fluids along faults. Instead, the most likely driving force of this flow system is the increased topography during basin inversion, which drives deep circulation of meteoric water. The results demonstrate the potential of combining numerical models and thermochronological data to constrain the key characteristics of hydrothermal systems and to study not only their age but also flow characteristics and temporal evolution.

In summary, both the data and model results presented in this thesis demonstrate the potential of both regional topography-driven flow in shallow (<1.5 km) sediments and deep fluid flow along faults to strongly affect subsurface temperatures in sedimentary basins. While this study was confined to a single sedimentary basin, the results are applicable to a wide range of geological settings as the results demonstrate that even modest topography can drive strong regional flow systems. In addition, the results highlight the potential thermal effect of non-magmatic hydrothermal systems and suggest that these flow systems may be common in inverted sedimentary basins due to the combination of the increase in topography and fault permeability caused by fault movement and compressional tectonics. These thermal effects of fluid flow potentially hamper the tectonic or geomorphological interpretation of thermochronological data. However, this thesis also demonstrates that the combination of numerical modeling and thermochronology provides new opportunities to study the evolution of flow systems on geological (My) timescales.