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Modelling the surface heat flow distribution in the area of Brandenburg (northern Germany)

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Abstract

A lithosphere scale geological model has been used to determine the surface heat flow component due to conductive heat transport for the area of Brandenburg. The modelling results have been constrained by a direct comparison with available heat flow measurements. The calculated heat flow captures the regional trend in the surface heat flow distribution which can be related to existing thermal conductivity variations between the different sedimentary units. An additional advective component due to topography induced regional flow and focused flow within major fault zones should be considered to explain the spatial variation observed in the surface heat flow.

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Keywords: Surface heat flow; conductive and advective heat transport; fault zones.

1. Introduction

Terrestrial heat flow refers to the portion of heat generated within the Earth's interior which flows outward through the lithosphere toward the Earth's surface. Because the primary observable quantity for heat flow is the near surface temperature gradient, available data are restricted to the distribution of

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surface heat flow which can be then used to provide some estimates of the flow of heat in the earth's interior. In most cases, such an extrapolation may be too restrictive and may lead to mask important tectonothermal processes which though acting at greater depths still contribute to the observations gathered at or near the surface. Indeed, it has been long recognized that terrestrial heat flow is affected by several processes including heat advection by thermally-driven or topographically-driven groundwater flow, heat refraction due to variable thermal conductivity, variable crustal radioactivity and mantle heat. Each process shows a different time scale which is linked to characteristic lengths through the relevant material properties controlling the transport of heat in the subsurface. To arrive at a description of these processes and to provide a quantitative characterization of their relative contribution to the surface heat is therefore of special concern for heat flow studies. This is especially the case for applied studies in sedimentary basins because of their socio-economic value as areas of potential natural resources. Despite a high density of geological and geophysical data which are now available, uncertainties remain concerning heat flow and temperature distribution within these settings. One powerful tool to assess the importance of the different processes in the establishment of a given geothermal pattern is to apply a numerical analysis of the system behaviour. If constrained by data and observations, such models help to arrive at an analysis of a broad number of possible cases thus helping in testing hypothesis and drawing conclusions about first order aspects and processes, despite the complexity of the problem at hands.

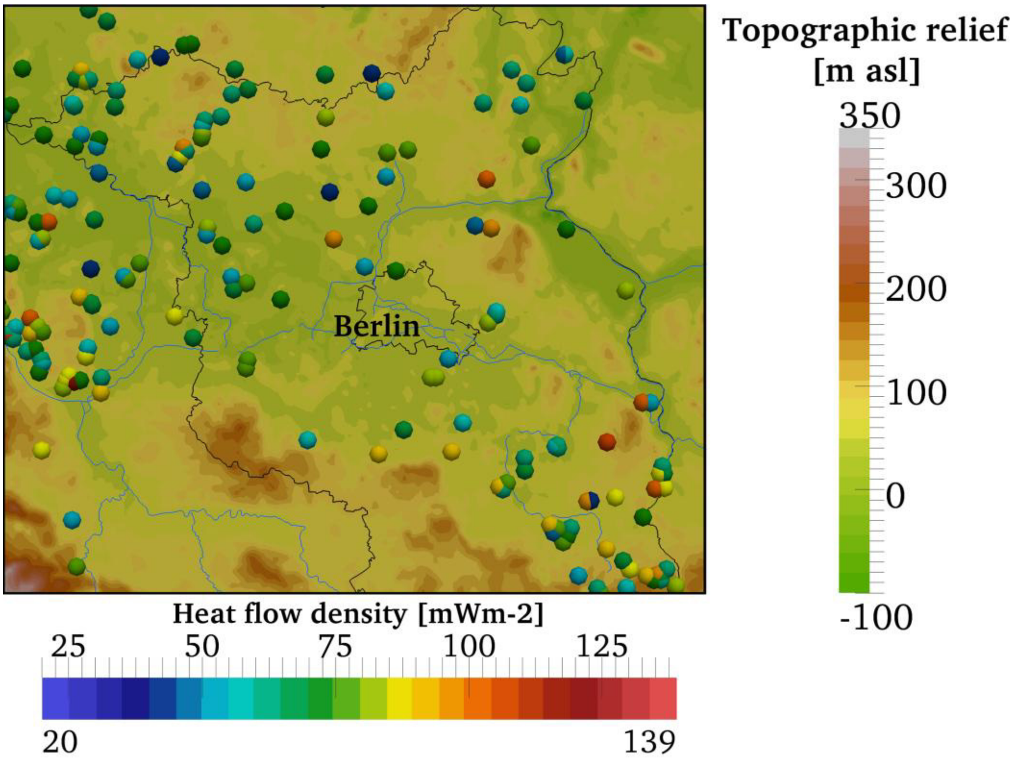

Fig. 1. Heat Flow density measurements as extracted from the heat flow database for Germany as provided by the Atlas of Geothermal Resources in Europe, Hurter and Haenel [1]. The background map shows the topographic relief in the area

This paper focuses on a study of the heat flow distribution in the region of Brandenburg, a subdomain of the larger Northeast German Basin (NEGB) in northern Germany, for which a detailed database of heat flow measurements has been made available, see Fig. 1 and Hurter and Haenel [1]. Based on a recently published lithospheric scale structural model (Noack et al. [2]) the steady state conductive temperature distribution is computed and used as input for the surface heat flow calculation. In a second stage, a comparison between modelled and measured heat flow is carried out in order to provide a quantitative estimate of the background heat flow in the area due to conductive heat transport. The results of this comparative study are used to draw implications for the potential contribution to the measured heat flow as caused by other than conductive processes comprising regional, topographically-driven groundwater flow and convective heat transport along major fault zones.

Therefore the novelty of the manuscripts stems from combining data and modelling techniques to interpret the surface heat flow pattern in a way that enables to describe the dominant methods of heat transfer in the crust.

2. Geological setting and structural model

The study area is located in the south-eastern part of the NEGB a complex sedimentary basin which underwent a polyphase tectonic history. Basin initiation dates back to late Carboniferous - early Permian times. It coincided with an extensive phase of volcanisms documented by the presence of a sequence of volcanic rocks within the lowermost parts of the basin fill which superpose crustal domains of different consolidation ages, Noack et al. [3]. The overlying Permian to Cenozoic sediments attain locally up to 8,000 m in thickness and show a structural configuration which has been modified by deposition and subsequent mobilisation of a thick sequence of Permian salt rock, the Zechstein, see Fig. 2a. The latter shows a complex topological configuration highly structured in numerous salt pillows and diapirs with thickness up to 3,500 m, Noack et al. [3]. The uppermost Tertiary and Quaternary sediments of the NEGB are composed mainly of unconsolidated to poorly consolidated clastics. These layers overly a lower Oligocene clay enriched formation, the Rupelian Clay, which hydraulically disconnects the Tertiary and Quaternary sequence from the lowermost Mesozoic layers. Local connections between these sediments are provided by areas of discontinuity in the Rupelian Clay represented either by non-depositional domains, erosional unconformities or erosive subglacial Quaternary channels cutting through this clay-rich layer, see Fig. 2b.

The southern margin of the basin is dissected by two major WNW-ESE-striking fault zones, namely the Gardelegen and Lausitz Escarpments, a part of the larger Elbe Fault System, see Fig. 2a. The latter represents a weak and stress-sensitive domain at crustal level consisting of several faults arranged in an “en-enchelon” pattern which have been reactivated under a compressive stress regime during late Cretaceous – early Cenozoic times, Scheck-Wenderoth and Lamarche [5]. As part of these reactivated structures, the Gardelegen and Lausitz fault zones cut through all sedimentary layers and show a vertical offset of approximately 4,000 m along the southern margin of the study area.

A detailed 3D structural model for the state of Brandenburg as published by Noack et al. [2] is used to represent the present-day configuration of the main stratigraphic units, that is, the geometry of the layers and thermal properties, for the thermal modelling phase. The structural model is lithosphere in scale and it resolves 14 sedimentary layers, from the Quaternary to the pre-Permian basement, two crustal domains and a single lithospheric mantle layer, see Table 1. More information about the structural model can be found in Noack et al [2]. A brief description of the relevant equations solved for as well as of the boundary conditions adopted in the modelling stage is provided in the Appendix.

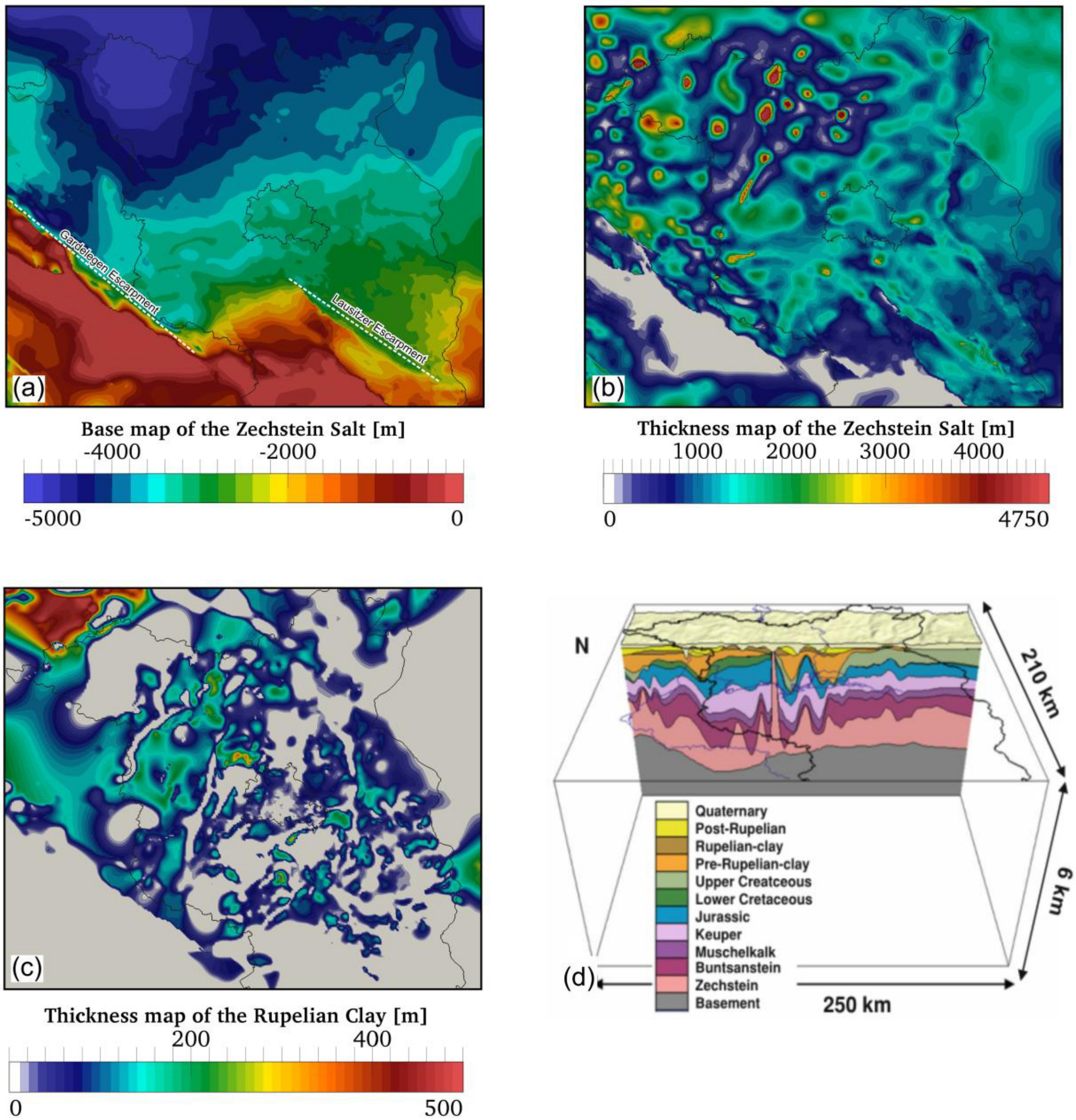

Fig. 2. (a) Depth to the base of the Zechstein salt. Also shown by dotted white lines are the approximated traces of the two major fault zone along the southern margin of the basin. (b) Thickness map of the Zechstein salt. (c) Thickness of the Rupelian Clay. (d) 3D view of the geological model for the sedimentary layers as used for the heat flow calculation, after Noack et al. [2]. Different colours indicate the distinct stratigraphic units

3. Heat Flow database

The data used for this work consists of a database of heat flow measurement as published within the Atlas of Geothermal Resources in Europe, Hurter and Haenel [1]. The Atlas provides information about heat flow density and temperature distribution at different depth levels both at the scale of whole Europe as well as at national and regional scales. In addition, maps characterizing the geothermal resource potential of specific aquifer systems on a regional scale are also included.

Fig. 1 shows the observed heat flow density distribution as extracted for the study area. The average surface heat flow is around 60-70 mWm^{-2} which represents a typical level for continental crust. Though highly scattered in their magnitudes, it is possible to recognize a regional pattern in the heat flow distribution. Overall the areal variation in heat flow is rather smooth, with a gradual trend from high heat flow in the central and eastern domains, to average heat flow values along the southern, northern and western boundaries. Within the smooth regional trend small scale variations are also visible as represented by local heat flow lows (down to 20 mWm^{-2}) and highs (up to 135 mWm^{-2}) giving rise to heat flow anomalies up to 70-80 mWm^{-2} for measurements set few kilometres or less apart.

Table 1. Assigned physical thermal rock properties for the modelling (for the lithological characteristics the dominant lithology is mentioned first)

Stratigraphic unit	Main Lithology	λ_b [$W(m\cdot K)^{-1}$]	H [μWm^{-3}]
Quaternary	Sand, Silt, and Clay	1.50	0.70
Tertiary	Sand, Silt and Clay	1.50	0.70
Upper Cretaceous	Limestone (Chalk)	1.90	0.30
Lower Cretaceous	Clay with Sand and Silt	2.00	1.40
Jurassic	Clay with Sand, Silt and Marl	2.00	1.40
Keuper	Clay with Marl and Gypsum	2.30	1.40
Muschelkalk	Limestone	1.85	0.30
Buntsandstein	Silt with Sand, Clay and Evaporite	2.00	1.00
Zechstein	Evaporite	3.50	0.09
Sedimentary Rotliegend	Clay, silt and Sandstone	2.16	1.00
Permo-Carboniferous Volcanics	Rhyolite and Andesite	2.50	2.00
Pre-Permian Basement	Clastics (strongly compacted)	2.65	1.50
Upper Crust	Granites	3.10	2.50
Lower Crust	Gabbro	2.70	0.80
Lithospheric Mantle	Peridotite	3.95	0.03

4. Modelling results

The results from the modelling captures the regional trend in the heat flow distribution, see Fig. 3. Consistent with the observations, increased heat flow values are mainly found in the central and eastern domains, while heat flow decreases along the north-northwestern boundary of the study area.

Within the central domain small scale variations in the heat flow distribution are also recorded in the modelled heat flow. High heat flow anomalies of small aerial extent represent the major anomalies relative to the background heat flow in this region. These anomalies are spatially confined to areas of increased salt thickness and are therefore to be interpreted as the surface manifestation of enhanced heat transport within salt structures due to relative high thermal conductivity of these rocks. The high resolution of the geological model adopted (1,000 m in both horizontal dimensions) enables an improved representation of these salt structures and therefore it allows to consistently evaluating the thermal effects induced by these structural heterogeneities. This results in a good agreement between modelled and measured heat flow in these areas where the misfit lays in a range of magnitudes covered by errors related to uncertainties in the model parameters adopted in the present study, namely thermal conductivity and heat production rates.

Moving away from these salt structures, in the salt rim synclines, a decrease in heat flow, down to the average background value, is observed both in the modelling results and in the measurements. Once again, the relative good fit between computed and measured heat flow, within the range given by uncertainties in the property assignment, calls for heat refraction due to thermal conductivity contrasts around major salt structures as the responsible process for the observed heat flow pattern.

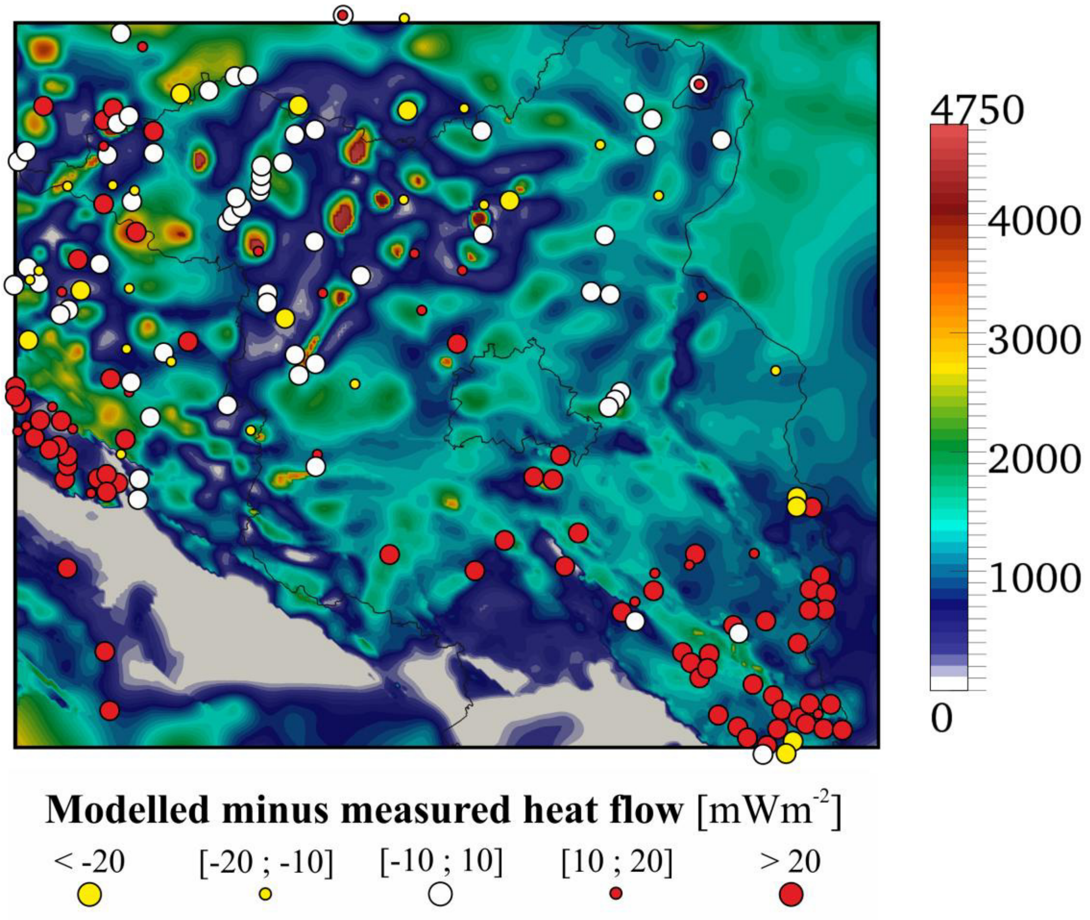

Fig. 3. Differences between modelled and measured heat flow values. The background colour map indicates the thickness of the Zechstein salt layer

Apart from the above described heat flow highs and heat flow lows that are well captured by the modelling results, local inconsistencies also occur at locations in which measured heat flow is found to be considerably lower than modelled one. In these areas the misfit between modelling results and observations is above the range given by uncertainties in the material properties assigned to the different units, an observation which may indicate that pore-fluid related processes, either thermally-driven or hydraulic head-driven, together with heat conduction are the main means of heat transfer in these areas. To explain such deviations from a background conductive heat flow requires flow velocities to be high enough to lead to significant thermal perturbations in the subsurface. This in turn can be only conceivable under reasonable hydrogeological conditions as provided by high topographic gradients in conjunction with the existence of relative thick aquifer systems of regional extent but hydraulically connected at depths. The existence of a regional groundwater flow system has been documented in previous studies applied to the whole NEGB (Kaiser et al. [5]) as well as for studies which concentrated on the region of Brandenburg (Noack et al. [6]). These studies regarded the effects of such a regional flow system on the temperature distribution within the basin to be significant especially in down levelling the temperature distribution within the shallower aquifer domains above and below the Rupelian aquitard, where local hydraulic connections between the different hydrogeologic systems may be favoured by the presence of heterogeneities in the topology of this layer (hydrogeological windows in the Rupelian Clay and Quaternary glacial channels). Within the central domain, higher than observed heat flows are found along the edges of such geologic discontinuities in the thickness of the Rupelian aquitard or nearby mayor Quaternary channels, see Fig. 4a and Fig. 4b. Based on the results obtained from this modelling exercise in conjunction with previous findings as briefly described above, it can be speculated that the observed variation from the background level in the surface heat flow distribution in the central area could be due to advection of heat by regional topographically-driven groundwater flow with a significant vertical flow component within preferential hydraulic pathways as provided by natural hydrogelogic heterogeneities in the shallow configuration of the system.

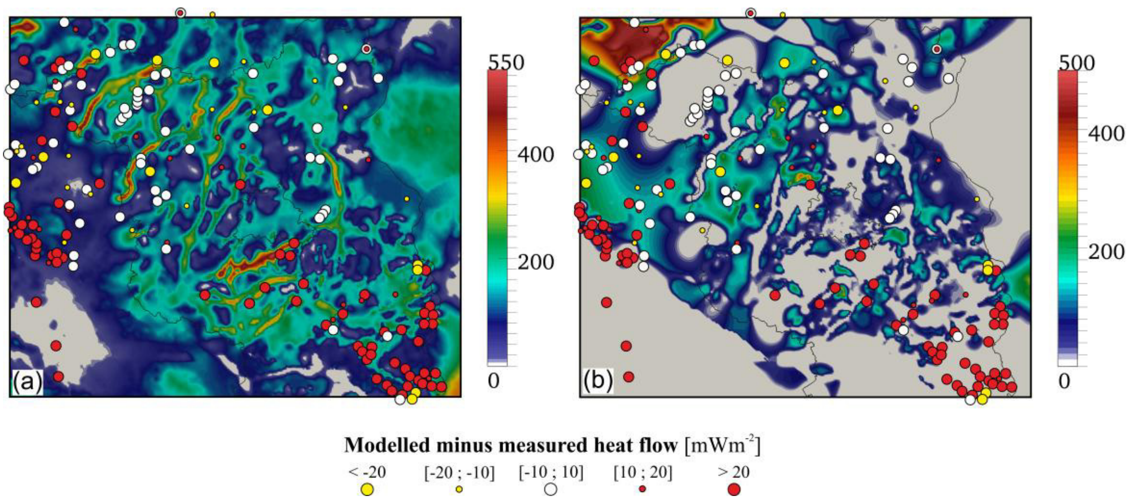

Fig. 4. (a) Differences between modelled and measured heat flow values. The background colour map indicates the thickness of the Quaternary layer. (b) Differences between modelled and measured heat flow values. The background colour map indicates the thickness of the Rupelian Clay

Moving to the southern boundary of the study area, anomalously high heat flow values, higher than the measured ones, are observed. In this area the misfit between modelling results and observation is the largest, differences are up to $50mWm^{-2}$, and cannot be accommodated by systematic variations in thermal conductivities alone. The observed heat flow distribution could be caused by transient thermal features induced by a spatially focused groundwater flow. This in turn, would require the existence of sub-vertical pathways connecting the different aquifer systems at depths. Indeed, within this area, such preferential hydraulic pathways may be provided by the two major fault zones, the Gardelegen and Lausitz Escarpments, which may lead to a connection between shallow and deeper aquifers that would be otherwise separated by interbedded confining units. Focused downward fluid flow along these faults will lead to a considerable cooling of the system and will act to maintain a hydraulic head drop across the fault thus hampering a lateral migration of the induced thermal anomalies within the confining sedimentary units far away from the fault. The net contribution of this advective component to the surface heat flow will be to lower the background conductive level in the domain nearby the two faults thus providing a possible physical explanation to the observed misfit found between modelled and measured heat flow in these areas. The amount of cooling induced within the system will be a function of the permeability, magnitude and degree of anisotropy of the fault zones as well as of the hydraulic head gradient over the two faulted domains. To test these hypotheses novel and more detailed studies are needed and are on-going in which to consider these additional processes and to quantify the hypotheses put forward with this manuscript.

5. Conclusions

A lithosphere scale geological model has been used to determine the surface heat flow component due to conductive heat transport for the area of Brandenburg. The modelling results have been constrained by a direct comparison with available heat flow measurements. The calculated heat flow captures the regional trend in the surface heat flow distribution which shows a smooth transition from low to average (20 mWm^{-2} to 70 mWm^{-2}) along the southern and western boundaries to average to high values (70 mWm^{-2} to 135 mWm^{-2}) in the central and eastern domain. Relatively high heat flow values within the central domain may be accounted for by heat refraction between the anomalously conductive Zechstein salt layer and the less conducting confining sedimentary units.

Local inconsistencies found between modelling results and observations are to be attributed to additional heat transport by groundwater flow in the subsurface which is not taken into account in the present model. Regional topographically-driven groundwater flow, locally disturbed by existing heterogeneities in the sedimentary sequences, hydrogeological connections, and focused flow along major fault zones may disturb the near-surface heat flow causing a departure of the heat flow distribution from the conductive component. The results from the modelling exercise and the comparative study with available observations already provides some quantitative estimates about the conductive contribution to the surface heat flow. In addition, the study enables to draw implications for the potential contribution of processes the influence of which could go unnoticed if only based on observation made on the surface heat flow pattern. Therefore our findings have important implications for a proper assessment of the additional role that regional groundwater flow and fault zones have in affecting the internal thermal configuration in sedimentary systems.

Acknowledgements

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Appendix A. Numerical modelling: basic governing equation and boundary conditions

For the purpose of the present study, we assume conduction as the only active heat transport mechanism. Therefore, the diffusion equation is derived by Fourier's law which relates the heat flow, $q\ [Wm^{-2}]$, to temperature gradients, $\nabla T\ [Km^{-1}]$, via the bulk thermal conductivity, $\lambda_b\ [WK^{-1}m^{-2}]$, which in its differential form can be formulated as:

$$q = -\lambda_b \nabla T \qquad (1)$$

In order to determine the heat flow distribution following Equation 1, the temperature distribution at each nodal point of the model should be first calculated. By applying a simple thermal energy balance in a control volume and under the assumption of steady state condition, the relevant equation to be solved for can be written as:

$$\nabla \cdot (\lambda_b \nabla T) = H \qquad (2)$$

The term on the right hand side of Equation 2, $H\ [Wm^{-3}]$ is the internal radiogenic heat production. Equation 2 is a boundary value problem of the second order in the primary variable temperature the solution of which requires the definition of a proper set of boundary conditions. Given this information, the approximated solution of the problem can be obtained by applying the Galerkin finite element method for spatial discretization with linear interpolation functions as implemented in the software package GMS, Bayer et al., [1997]. Lateral boundaries are considered as close, no flow boundary, and first order type thermal boundary conditions are imposed along both the top and the bottom of the model. As top boundary condition a constant temperature of T=8°C is set at the topmost surface of the model which correspond to the Earth's topographic surface. To define the lower boundary condition, we assume the base of the model, which in our case corresponds to the Lithosphere-Asthenosphere Boundary (LAB) to represent the T=1300°C isotherm, where mantle peridotite begins to partially melt. Its location is constrained by seismological observations and by 3D gravity modelling, Maystrenko and Scheck-Wenderoth [7].