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Overcoming Spatial Scales in Geothermal Modelling for Urban Areas

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Abstract

A major component in the transition from fossil to renewable energy is the demand for district heating where geothermal energy can be a substantial option. We present results on the controlling factors for the deep thermal field below a large urban area, the city of Berlin. Therefore we analyze 3D thermal models considering conductive and mixed convective heat transport mechanisms as well as different boundary conditions. Of the controlling factors, heterogeneous thermal and hydraulic physical properties of geological units at different depths are key. That data density decreases with depth poses challenges for model assumptions for which we propose solutions.

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Keywords: geothermal energy; 3D thermal model; urban heat supply; Berlin

1. Introduction

In the course of the transition from fossil and nuclear energy to renewable energy, the production of geothermal energy becomes of increasing importance [1] . In particular, in areas with pronounced seasonal temperature fluctuations a major demand of energy is related to the provision of heat needed during the cold season. Today for many large urban areas heating of buildings relies almost entirely on fossil energy [2] . This is also the case for the

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city of Berlin, where more than 90% of heating is accomplished via burning of fossil energy resources such as natural gas, petroleum or coal [3, 4]. One possible alternative source that could play an important role in the future energy mix is geothermal energy [5]. Indeed, earlier work has explored the deep geothermal potential as based on a first generation of 3D models for the subsurface geological configuration [6-8]. More recently, the quality of the shallow configuration of Cenozoic sedimentary units has been improved and a second generation of geothermal models has therefore emerged [9, 10]. On the basis of all previous and relatively new modelling results, we hereby present how deep and shallow influencing factors control the deep geothermal field below Berlin.

Understanding heat transport in the subsurface requires assessing the impact of different physical coupled processes occurring in the underground. Of these, conductive heat transport is usually regarded as the dominant transport process being controlled by variations in the heat budget (mainly from crustal origin) and the heterogeneous distribution of thermal conductivity of the sedimentary sequence [11-13]. In addition heat transport may be influenced by advective and convective transients in the upper few km of the crust [14-16]. A major problem in quantifying this influence by means of geothermal modelling is the lack of knowledge on the thermal and hydraulic conditions at the model boundaries and the relatively high uncertainties in the model parameters and their distribution with depth. A constant temperature or heat flow is often assigned as the lower thermal boundary condition assuming an average geothermal gradient of 30°C/km. However, the average geothermal gradient is either measured or calculated by the individual layer dependent geothermal gradients and their thicknesses. Therefore, assuming a constant geothermal gradient of 30°C/km may lead to significant errors if the deep structure is heterogeneous [17-21]. Considering that the subsurface is composed of different lithological units, conductive heat transport will be influenced by the lithology-dependent distribution of thermal properties (e.g. thermal conductivity and radiogenic heat production) and by variations of heat input from the crust and the mantle [22]. In addition advective heat transport related to regional groundwater flow patterns in the porous geological units of the subsurface may affect the system to different degrees [16, 23]. Thereby, the dynamics of fluid flow are again controlled by the regional structural and hydrogeological setting on the basin-scale over several tens to up to hundreds of km. Examples for such structural heterogeneities are salt structures and their deformed cover layers or large faults. In response to these variations, large lateral temperature differences may be present at a certain constant depth level.

1.1. Geological setting

Geologically, the city of Berlin is located in the southeastern part of the Central European Basin System, an area that subsided over the past 300 million years above a heterogeneous crystalline crust and lithosphere. Accordingly, Berlin is underlain by a sedimentary succession that is up to 5 km thick and contains clastic deposits and a thick unit of Permian Zechstein salt [8, 24, 25].

The latter has been mobilized during the past 150 million years to form salt pillows and diapirs. This resulted in a highly irregular subsurface structural setting (Fig.1a) which is important for the thermal field as salt is twice as thermally conductive compared to the surrounding clastic sediments. As a result the salt structures represent thermal chimneys while the clastic sediments in turn have an insulating effect and lead to thermal blanketing [8, 18, 20, 26, 27]. Two large salt diapirs piercing their cover layers are present near the western and eastern boundaries of Berlin, where the salt is up to 3600 m thick and reaches very shallow depths indicated by circular anomalies (“1” in Fig. 1a) in the depth map of the top salt surface. Furthermore three larger, up to 2 km thick salt pillows are located beneath the western part of Berlin (“2” in Fig. 1a) whereas the salt has been withdrawn from below the central southern part of the city as well as from the NE and NW corners of the study area (“3” in Fig. 1a). These domains instead are filled with clastic insulating sediments.

A second important factor for the thermal field is the nature and configuration of the crystalline crust below the sedimentary units as especially the upper crystalline crust is rich in radiogenic elements and may significantly contribute to the heat budget [13, 19, 28]. Geophysical data and models [29, 30] indicate that the crystalline crust below Berlin may be grossly subdivided in two layers: a more radiogenic silicic upper crustal unit and a less radiogenic mafic lower crustal unit. Interestingly the upper crustal unit is a few km thicker below the eastern half than below the western half of the city of Berlin (Fig. 2a). This provides more basal heat input to the eastern part of Berlin than to its western part resulting in higher temperatures at depths below the sedimentary fill (Fig. 2b).

A third factor influencing the thermal field in the upper few km below Berlin is the flow of underground water in the porous clastic sedimentary units. Previous work [10] showed that this dynamic component is mainly influenced by two factors below Berlin: (1) the, often not accurately known, upper hydraulic conditions and (2) the distribution of the Rupelian clay (Fig. 1b), an aquitard separating the upper fresh water compartment from the deeper saline aquifers. As a result of glacial erosion [23] the Rupelian clay is locally discontinuous (e.g. white domains in map of Fig. 1b, [10]). In those areas where this unit is missing hydraulic communication between the shallow and deep groundwater compartments may occur [23]. This may result locally in cold surface fresh water entering at large depths in the subsurface beneath major recharge areas and in rise of hot deep saline water in discharge areas. In summary, thermal models should consider the cumulative effects of these factors, which requires a workflow that integrates processes from the scale of the lithosphere to the scale of shallow sediments.

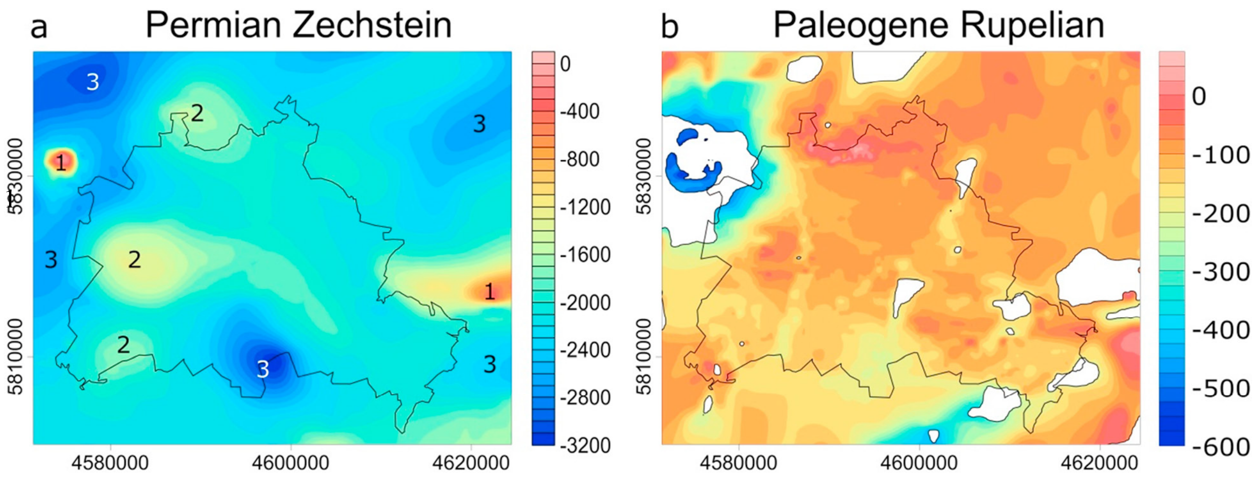


Fig. 1. (a) Elevation of the top salt surface according to the structural model of [8, 10]; (b) Elevation of Rupelian clay surface, both in meters above sea level; Numbers indicate specific structures referred to in the text, coordinates are Gauss-Krüger [m].

1.1. Methods and input data

The workflow combines lithosphere-scale 3D conductive modelling with basin-fill-scale modelling of coupled fluid and heat transport. To calculate the steady state 3D conductive thermal field the heat equation is solved using a Finite Element Method (FEM) for a 3D structural model resolving the main sedimentary units, two crustal units and the lithospheric mantle. From this model the temperature distribution at 6 km depth (Fig. 2b; [8]) is extracted and prescribed as lower thermal boundary condition for the simulations of coupled heat and fluid transport using the software FeFlow [31]. The physical and numerical background of the method is described in [8, 10]. Accordingly, initial conditions were calculated for steady state conditions in the case of the coupled model, separately for fluid flow and heat flow. The simulation time for the transient simulations in the coupled case were chosen such that quasi-steady state conditions were established. This was the case for a simulation time of 250 thousand years. Physical properties (thermal conductivity, radiogenic heat production, heat capacity, porosity, permeability, Fig. 3b) as well as the upper thermal and hydraulic boundary conditions are chosen identical with the ones described by [9] and Fig. 3 illustrates the respective hydraulic head observed at the groundwater table.

2. Results

In the following we describe the superposed effects of variations in upper crustal thickness, of the distribution of conductive salt versus insulating sediments and of fluid flow in response to variations in permeability and in hydraulic head. All these factors together lead to significant differences in temperature causing lateral variations and partly even inversion in the temperature trends with depth.

This is illustrated in Figure 4 for two representative depth levels: at 300 and at 3000 m depth. Most impressive is the opposite temperature trend at the shallow and the deeper level. A large part of this pattern is controlled by the conductive heat transport as evident by direct comparison of the temperature pattern predicted by the conductive model (left panel in Fig. 4) with the one predicted by the coupled model (right panel in Fig. 4). At 3000 m depth differences between the two models are small, as the influence of fluid flow decreases with increasing depth. This is due to a reduction of porosity and permeability of sedimentary rocks in response to increasing compaction with depth.

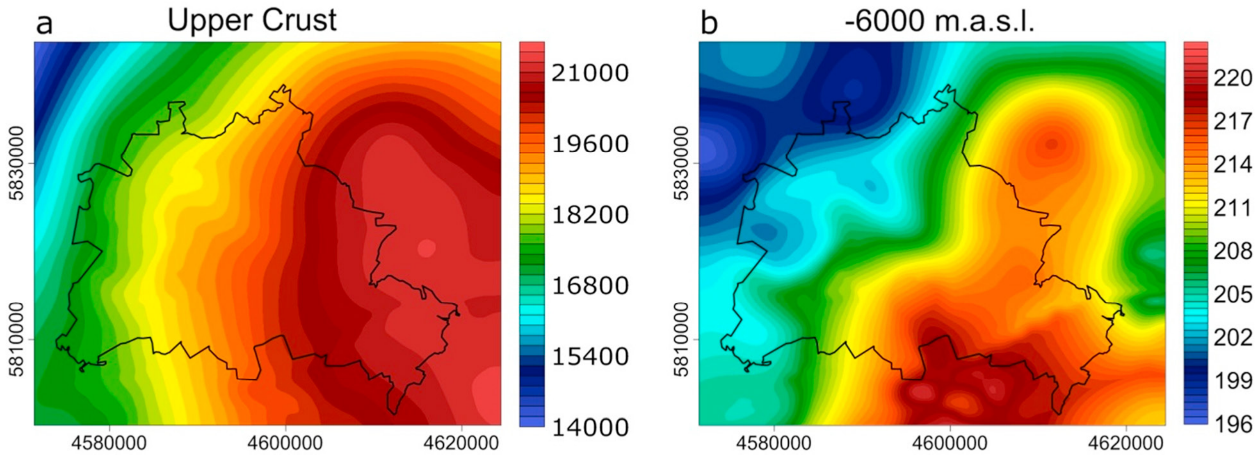
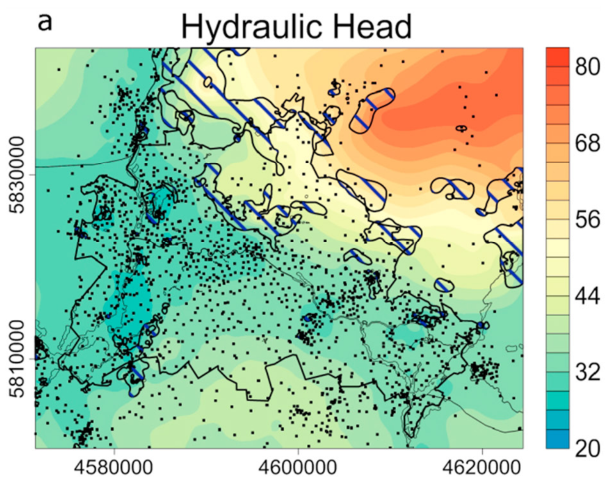


Fig. 2. (a) Thickness of radiogenic upper crystalline crust; (b) lateral variations in temperature at 6 km depth predicted by the conductive lithosphere-scale model that was used as lower thermal boundary condition for the coupled simulation of heat and fluid transport.



b

	Geological unit	λ^b [W/mK]	S [W/m³]	c^s [J/kgK]	φ [-]	κ [m/s]
Quaternary	Holocene to Weichselian	2.71	9.0E-06	1570	0.32	1.42E-05
	Eemian to Saalian	2.59	9.0E-06	1580	0.31	4.04E-06
	Holstein	2.17	9.0E-06	1670	0.30	1.91E-08
	Elsterian	2.35	9.0E-06	1610	0.30	8.98E-07
Tertiary	Miocene	2.47	1.0E-05	1560	0.30	6.88E-07
	Cottbus	2.62	1.3E-05	1700	0.31	1.15E-06
	Rupelian	1.64	1.3E-05	1810	0.24	3.23E-08
	Pre-Rupelian	2.48	1.3E-05	1700	0.30	6.56E-07
	Upper Cretaceous	2.82	6.0E-06	2290	0.11	4.81E-07
	Lower Cretaceous	2.36	1.5E-05	2290	0.11	4.81E-07
	Jurassic	2.71	1.5E-05	2250	0.19	4.81E-07
Triassic	Keuper	2.35	1.6E-05	2320	0.13	9.62E-09
	Upper Muschelkalk	2.3	1.0E-05	2250	0.15	9.62E-09
	Middle Muschelkalk	2.3	1.0E-05	2250	0.04	impermeable
	Lower Muschelkalk	2.3	1.0E-05	2250	0.12	5.77E-10
	Upper Buntsandstein	3.0	1.8E-05	2190	0.03	6.44E-09
	Middle Buntsandstein	2.0	1.8E-05	2390	0.14	5.84E-07
	Lower Buntsandstein	1.84	1.8E-05	2390	0.05	1.25E-09
Permian	Zechstein	4.5	4.0E-06	1940	0.01	impermeable
	Sedimentary Rotliegend	3.0	1.4E-05	2180	0.08	5.06E-08
	Permo-Carboniferous	2.5	2.9E-05	2600	0.03	8.66E-10
	Basement	2.2	2.8E-05	2300	0.01	impermeable

Fig. 3. (a) Hydraulic head [elevation in m a.s.l.] prescribed as upper hydraulic boundary condition in the coupled model obtained from groundwater measurements at numerous wells (black dots). (b) Physical properties and units for the geological units resolved: thermal conductivity λ^b; radiogenic heat production S, heat capacity c^s, porosity φ, hydraulic conductivity κ

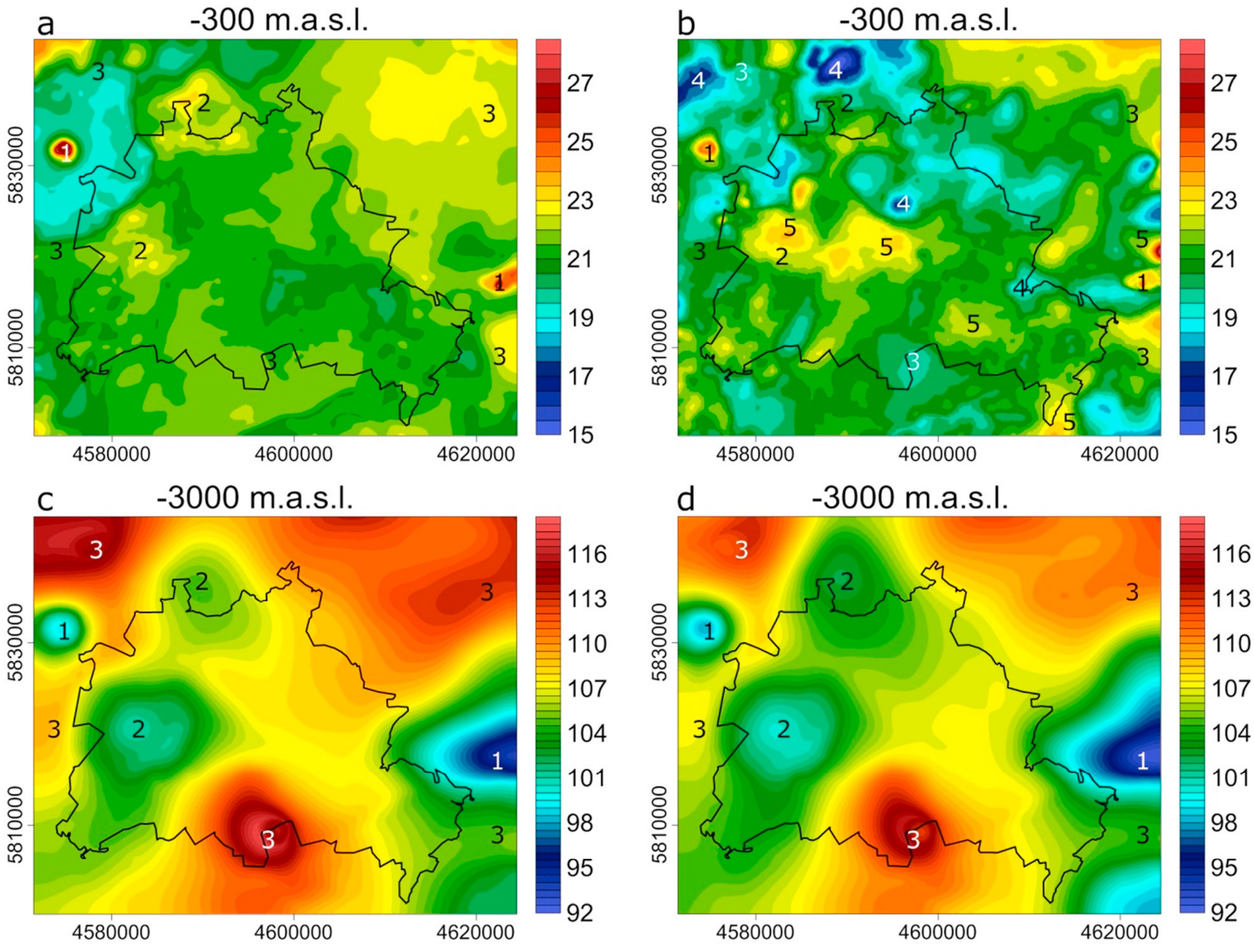


Fig. 4. (a) Temperature distribution at 300 m depth predicted by steady-state conductive model; (b) temperature distribution predicted by coupled simulation of fluid and heat transport at 300 m depth; (c) temperature distribution predicted by the steady-state conductive model at 3000 m depth; (d) temperature distribution predicted by coupled simulation of fluid and heat transport at 3000 m depth. Numbers indicate specific structures that are referred to in the text.

The general trend of higher temperatures below the eastern half of the city at 3000 m partly follows the variations in basal heat input (Fig. 2), but the pattern strongly deviates from the one imposed by the lower thermal boundary condition (Fig. 2b). Accordingly these variations must be caused by the heterogeneities in thermal properties considered in the sedimentary succession. The strongest contrast in thermal properties in this context is the one between salt and clastic sediments. A comparison between the top salt surface (Fig 1a) and the modelled temperature distributions (Fig. 4) reveals a spatial correlation between the position of salt structures and thermal anomalies: at shallow depth (300 m) highest temperatures are predicted above the two salt diapirs ("1" in Fig. 1a and Fig. 4) and the salt pillows ("2" in Fig. 1a and Fig. 4). In contrast, negative thermal anomalies are associated with salt diapirs and pillows at larger depth as visible in the temperature maps for 3000 m depth. This inverse pattern of high temperatures above and low deep temperatures below salt structures is caused by the more efficient heat transport within the conductive salt compared to the insulating surrounding sediments. The heat therefore is extracted towards the surface, but cannot reach the latter as the salt structures are covered by insulating sediments. This results in heat storage above the salt causing the positive circular temperature anomalies above the diapirs and the larger positive anomalies above the salt pillows. In contrast, in areas where the salt has been replaced by insulating clastic sediments ("3" in Fig. 1a and in Fig. 4), heat storage affects the entire sedimentary succession causing positive thermal anomalies at larger depth.

In addition to these salt-related temperature variations the temperature pattern predicted by the conductive and the coupled models is considerably different at shallow depth (300 m). These differences illustrate the influence of heat transported by moving fluids. In domains where the Rupelian aquitard separating shallow freshwater and deeper saline waters is discontinuous (Fig. 2b) and where the hydraulic gradient is high (Fig. 3), cold surface water flows to deeper levels leading to local negative thermal anomalies (indicated as “4” in Fig. 4). Inversely, where the hydraulic head is low and the separating aquitard is continuous and shallower than 300m, hot deep water may rise and cause positive thermal anomalies at shallow depth (indicated as “5” in Fig. 4).

Comparing the purely conductive model predictions for 3000m depth (Fig. 4c) with the temperatures at the same depth predicted by the coupled model (Fig. 4d), shows that the general pattern is very similar but the coupled model indicates a more complex hydrodynamics affecting the shallow temperature distribution and resulting in a net cooling effect induced by fluid flow and relatively colder conditions.

3. Discussion and Conclusions

The results of this study illustrate, that physically meaningful predictions of subsurface temperatures in areas of potential geothermal energy production need to consider influencing factors acting at different scales. First-order influences are to be expected from the deep crustal and lithosphere structure that need to be explored in order to capture variations in the basal heat input. In addition lithological heterogeneities in the upper few km may overprint the basal heat signal in two ways: (1) large contrasts in thermal conductivity as between salt and clastic sediments may focus heat flow to preferential directions and depth levels and (2) advective heat transport may lead to significant local cooling or heating.

For the area of Berlin, highest shallow temperatures are expected beneath the central western part of the city based on the conductive and the coupled models, where up to 24°C are reached at 300 m depth according to the predictions of the coupled model. Such areas would be interesting targets for shallow geothermal energy production. In contrast local low-temperature anomalies may be encountered as well, like below the NE part of Berlin where only 15 °C may be reached at 300 m. Such areas should be avoided if shallow geothermal energy production is planned. An important conclusion from the work presented is that the pattern of shallow temperatures is not representative for deep temperature anomalies and the deep temperature anomalies may even be inverted with respect to the shallow temperature pattern.

Areas with the best potential for deep geothermal energy production are located in the central southern part of the city and in the eastern half of the city in general. There thick successions of insulating and permeable clastic sediments have accumulated in salt rim synclines and could be best targets for the production of deep geothermal fluids. High temperatures combined with high heat flow are expected within the upper portions of the Zechstein salt structures. These domains are however tight as salt is impervious. Therefore closed system borehole heat exchangers may be the technology suitable for exploitation of deep heat in these domains.

These results show that considering geothermal heat as a potential contributor to the future energy mix and in particular to urban heating is a realistic option. However, simple concepts of a uniform average temperature increase with depth in the subsurface will definitely fail to predict the geothermal potential. Even if the scale of a city is small with respect to the thickness of the crust or lithosphere, the thermal field may be considerably influenced by regional heat transport processes. This is not only true for the basal heat input coming from the deeper crust and mantle but also for the heat transported in the subsurface by differently conductive rocks and by moving groundwater in the shallower levels below the urban area. Accordingly, exploration concepts related to the utilization of geothermal energy in urban areas should assess the geological and hydrogeological heterogeneities first and consider possible regional influences. In addition to these natural conditions also socio-economic factors as the need for energy in a specific district need to be evaluated. Finally, the assessment of the natural situation and of the areal demand for energy should be complemented by the anticipation of consequences and feed-back processes induced by the production of deep fluids.

Acknowledgements

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