Transient thermal effects below complex topographies

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Abstract

The topographical perturbation of steady-state subsurface temperature fields has been an important issue in geothermal interpretations throughout the past century. This paper reports a numerical study, which considers the possible influence of terrain topography on transient temperature signals. Typical morphological situations over wide areas in central Europe affect most likely that same depth range which also contains the temperature signals resulting from the most interesting ground surface temperature changes (i.e. during the last 200 years). The evaluation of the interaction is performed on a synthetic sinusoidal topography with varying wavelength and amplitude. Vertical profiles (i.e. temperature logs) were extracted from these numerical forward 2-D calculations. Thereby, the error could be estimated by comparing ground surface temperature time-histories inverted from temperature logs both with and without topographic correction. The results show that a topographic correction of temperature data is absolutely necessary to achieve a consistent inversion result. Even rather flat topographies with 20-km wavelengths and 100-m amplitudes may introduce topographical effects which confuse the inversion process. On the other hand, the palaeoclimatically induced temperature signal persists even in rough topographies and will show correct inversion results when data are adequately treated. Only extreme situations cause a lateral interference of these transient signals with depth. The results from such 2-D synthetic models have been confirmed by an analysis of a real situation. The example chosen is the area surrounding the German Continental Deep Drilling (KTB) project. The area is situated in a moderately undulating surface topography with maximum altitude variations of the order of 250 m. The additional 3-D simulation demonstrates that a strong topography-dependent variation of the transient temperature signal can occur even at greater depths. The introduction of corrections for topography influence, reduces apparent differences in profiles from different locations in the surroundings of the KTB site to a maximum of 0.2 K.

Keywords: palaeoclimatic temperature signal; heat flow; KTB project; topography; temperature inversion

1. Introduction

An accurate analysis of temperature data in general is not easily performed since subsurface temperature distribution may be influenced by many factors. In the past, the determination of the regional basal heat flow field has been an important target of geothermal research. This was achieved by subtracting possible temperature effects perturbing a 1-D temperature distribution (topography, transient, erosion, etc.) from a measured temperature log (Bodmer et al., 1979). The result, a steady state 1-D temperature profile, could be easier evaluated and allows a standard geothermal treatment (Bullard plot, Peclet number analysis, etc.). Recently, the evaluation of a former ‘perturbation’, the transient temperature sig-

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nals in subsurface, has become a major topic of geothermal research. Theoretically, the inversion of these signals permits the derivation of the ground surface temperature time-history (GST) at the site where the temperature profile has been measured. The inversion routines assume again a 1-D situation, which necessarily neglect influences of topography, advection or anisotropic, heterogeneous distribution of geological units. Future 2-D inversions will not necessarily improve the GST histories, due to the large number of degrees of freedom (thermal conductivity, heat production, permeability, etc.) to be considered, which in turn require limitation of the expected (a priori) parameter range treated (H. Lehmann, pers. commun.).

In all successful attempts to suppress the ‘noise’ in temperature logs, such as that arising from subsurface heterogeneities (e.g. Shen et al., 1995) or from other effects like vegetation cover and topography, either the temperature data from several boreholes were inverted simultaneously or the simple average of individual GST time-histories was calculated. Until now, quantitative evaluations of individual transient temperature profiles, perturbed by 2-D effects or further heat transport mechanisms (such as thermal advection) can only be performed by forward (predictive) modelling strategies. Clauser et al. (1997) and, in greater detail, Kohl (1998) have evaluated the impact of migrating fluids on transient subsurface temperature signals. It has been concluded that the signals persist even at high fluid velocities which may strongly alter its shape. Kohl (1998) has proposed a strategy on the correction of these signals for the case when the fluid flow field is known.

However, the impact of topography on the transient temperature signals still is not readily known. In published literature, qualitative statements emphasise that the topographical influence is limited by its penetration depth (Wang, 1992). The depth extent of the climatic signal is easily estimated by a 1-D solution for the vertical temperature distribution altered by a singular temperature variation at surface (Carslaw and Jaeger, 1959):

$$T = T_0 \times \text{erfc} \left( \frac{z}{2\sqrt{\kappa \times t_i}} \right)$$  \hspace{1cm} (1)

with $T_0$ the amplitude of the GST change, $z$ the depth, $\kappa$ the thermal diffusivity and $t_i$ the time of the GST change. Since $\text{erfc}(0.5) \approx 0.5$, the depth penetration of 50% of the amplitude of the temperature step can be easily expressed as $z \approx \sqrt{\kappa \times t_i}$. Taking $\kappa = 1.4 \times 10^{-6}$ m$^2$/s, 50% of a GST step has penetrated to approximately 20 m in 10 years, 85 m in 200 years, or 200 m in 1000 years. It is well obvious that the depth range of the most interesting periods (i.e. the last 200 years) may potentially be most perturbed by the typical morphological situations in most parts of central Europe.

In this paper, a numerical study is performed which considers the possible topographical influence on transient temperature signals. Throughout this paper it is thereby assumed that past climatic conditions will only affect all altitudes with an identical GST variation without altering the morphological surface structure. The numerical nature of this procedure in particular permits the estimation of the error encountered in both moderate and complex topographical settings when temperature data are inverted without correcting for the topography effect.

2. Topographical effects

2.1. Steady state

The perturbation of a vertical heat flow field induced by topography has been an important issue in interpretations of geothermal data throughout the past century. First quantitative 2-D descriptions of the effect of differently dipping slopes were presented by Königsberger and Thoma (1906) and by Lees (1910). Jeffreys (1938) described a method to correct temperature gradients by calculating the subsurface temperature perturbation as an integrated effect of individual rings, each having a different mean surface temperature. On the basis of this formulation Bullard (1938) then demonstrated that no corrections to the measured temperature gradient need to be performed for shallow boreholes and flat topography, although high alpine elevation variations will create deep perturbations of the temperature field. Birch (1950) adopted this principle and, as a result, was probably the first to explain a measured tunnel temperature profile by calculating analytically the 3-D temperature field beneath an arbitrary topography. In addition to topographical perturbations, Birch (1950)
also calculated the effects due to transient surface temperature changes and uplift and erosion. At that time an immense amount of effort was required to evaluate such subsurface temperature perturbation. Therefore, Lachenbruch (1968) presented a more rapid treatment for the quantification of temperature fields below typical topographical profiles and isothermal surfaces. Blackwell et al. (1980) introduced a correction method which in addition allows the problem of surface temperatures varying with slope angle and orientation to be treated. This 3-D numerical method is applicable for gridded topography data. One of the first attempts to calculate 2-D topographical effects in subsurface using numerical techniques was made by Sclater et al. (1970). Today the amplitudes of topographical perturbations are assessed almost always using numerical simulations and evaluated even in 3-D (e.g. Kohl and Rybach, 1996). However, few comparisons between numerical and analytical solutions have been performed.

Turcotte and Schubert (1982) have presented a simple analytical treatment for a sinusoidal topography that demonstrates the influence of different parameters to the subsurface temperature distribution. Their approach deserves to be especially noted since in practical cases the formulation of Birch (1950) can be only evaluated numerically and thus does not allow easy quantification of parametric variations. Assuming a flat rectangle with a sinusoidal surface temperature variation calculated from the true sinusoidal topography, Turcotte and Schubert (1982) showed that the amplitude of the perturbation is reduced exponentially with depth. In the case of an isothermal surface whose surface altitude variation has wavelength \( \lambda \), the temperature variation at depth \( z \) is proportional to the factor \( \exp(-2\pi z/\lambda) \), i.e. a topographical variation at surface with an amplitude \( A = 1500 \) m and \( \lambda = 20 \) km would have been reduced to a 0.12 K amplitude in 30 km depth. The concept of a sinusoidal temperature variation has been subsequently taken up by the approaches of Stüwe et al. (1994) and Mancktelow and Grasemann (1997), who evaluated the combined effect of heat advection and topography. Stüwe et al. (1994) have provided an analytical solution to the 2-D problem of heat advection on a true sinusoidal topography.

In this paper, the effect of topography on transient subsurface temperature fields will be evaluated numerically. Before simulating real topographies (Section 3), a sinusoidal surface altitude variation of varying amplitudes and wavelengths will be considered. This procedure allows estimates of the topographic influence of an already large number of situations and enables the present analysis to be readily compared with earlier studies.

For the case of \( \lambda = 20 \) km and \( A = 1500 \) m such a comparison is presented in Fig. 1, with the temperature field calculated by the different formulations of Birch (1950), Turcotte and Schubert (1982) and Stüwe et al. (1994), as well as by a numerical finite element approach. All models assumed isothermal \( (T = 0 \)°C) upper boundary and a temperature of 900°C at the lower boundary in 30 km depth. Furthermore, a homogeneous thermal conductivity of 3 \( \text{W m}^{-1}\text{K}^{-1} \) has been taken. On the scale shown, the differences between all approaches become obvious. The largest deviations from the numerical results are obtained by applying the formulae of Turcotte and Schubert (1982), mainly due to the temperature extrapolation on the \( z = 0 \) m level which causes the \( T = 0 \)°C isoline to be partly situated above the topography. The Stüwe et al. (1994) approach regarding the correct topography is exact for 1-D vertical conduction, but fails thereby to predict lateral effects of conduction. For such a 2-D example the application of the 3-D Birch (1950) formulation requires to largely extend the sinusoids into the third dimension. This method shows the smallest deviations below the topographic maxima and minima from the results obtained by the FE method. But, as Lachenbruch (1968) already mentioned, it can be recognised in Fig. 1 that the Birch (1950) method has difficulties in representing the influence of steeper slopes. The method of Birch (1950) will necessarily approach the 1-D solutions below the central part between topographic maxima and minima (at \( x = 5000 \) m) since it calculates the topographic influence from a circular horizontal reference plane situated at the surface. In the considered case of a sinusoidal topography the influence of the higher areas can be outweighed by the influence of the higher areas. It has to be noted that this method also has practical difficulties in estimating optimum values for ring discretizations and for the size of the reference plane. The calculation presented in Fig. 1 assumed a radius of 35,000 m and a ring thickness of 1000 m. By choosing larger
radii and smaller ring thicknesses the finite element solution can be approached more closely below the topographic maxima and minima. It can be stated that the application of the 3-D Birch formulation is suited for rough calculations of topographical influence on the temperature field such as performed for temperature prognosis of tunnel temperatures (e.g. Rybach and Pfister, 1994). However, this should be avoided if higher precision is required.

To obtain the accuracy needed in the present theoretical investigation, we may however consider the finite element (FE) approach as the most appropriate. The discretization of the individual geometrical models will be presented in the next section. Sensitivity runs showed that higher refinement of the FE mesh does not significantly change the solution ($\Delta T < 10^{-3}$ K). In particular, the FE method reveals that the 2-D effects become more pronounced at greater depth. The deviations from 1-D considerations are visible in Fig. 1, by the larger separation of the analytically and numerically calculated isolines. The process behind this effect is best described for a vertical profile below an elevation: with increasing depth the lateral influence of the valley increases and the vertical influence of the upward positioned elevation decreases since the valley represents successively the closest distance to the upper boundary. Therewith, at greater depth the valley influences the temperature field much more strongly than the elevation. It is essential to note that the depth at which the topographically induced temperature perturbation disappears is determined by the amplitude of the valley height and not by the mean topographical altitude as 1-D considerations would predict!

2.2. Transient

In this section it is intended to quantify the error encountered when temperature logs are inverted without a topographic correction having been performed. Therefore, numerical forward calculations are conducted for a 2-D geometry from which vertical profiles (i.e. temperature logs) are extracted. In a second step, the transient temperature signals along these profiles are separated and the synthetic profiles are inverted. Thus, the error in GST history encountered for the individual topography can be given. Later, in Section 2.3 a correction strategy is presented which allows inversion from 1-D models even in complex topographic settings. In this way, the
principal limitation of applying 1-D inversion procedure consisting of lateral interference of transient temperature signals can become visible.

Two different GST histories have been assumed: (1) GST1 describes the influence of a Pleistocene Ice Age with a transient temperature decrease of 5 K between \( t_1 = 50,000 \) years and \( t_2 = 10,000 \) years B.P.; (2) GST2 reflects a recent, short-term climatic variation with a temporary 1 K temperature increase between \( t_1 = 200 \) years and \( t_2 = 100 \) years B.P.

In order to best control the input parameter for the inversion procedure which is performed by the inversion code GST (Wang, 1992) identical boundary conditions were defined for these synthetic numerical models, i.e. a thermal flux at the lower boundary and a fixed temperature at the upper boundary are prescribed. It has been chosen to place the lower boundary at 30 km depth since at that depth a topography amplitude of 1500 m and a wavelength of 20 km (the maximum values considered) will yield a negligible sinusoidal perturbation and let no boundary effects to be expected.

Two characteristic surface amplitudes, \( A \), at varying wavelength have been considered: \( A = 100 \) m which is often encountered in moderately undulated topographies in central Europe, and \( A = 1500 \) m being an extreme value for high Alpine-type mountain belts. The wavelengths ranged between \( \lambda = 1 \) km and 20 km for the \( A = 100 \) m and \( \lambda = 10 \) km to 20 km for the \( A = 1500 \) m case. The latter values might represent the extreme topographic influence encountered in the Swiss Alps (Valais, southern Switzerland). For simplicity reasons homogeneous material distributions have been chosen. The models assumed thermal conductivity, \( K \), of 3 W m\(^{-1}\)K\(^{-1}\), specific heat capacity, \( \rho c_p \), of 2.2 \( \times 10^6 \) J m\(^{-3}\) K\(^{-1}\) and a GST change with altitude of 5 K km\(^{-1}\) which is uniform and does not account for the exposure of the slopes. Since no heat generation had been supplied for this comparative study the mean heat flow in the model is only determined by the basal heat flow value of 90 mW m\(^{-2}\) provided as lower boundary condition.

The numerical calculations have been performed with the finite element (FE) code FRACTure (Kohl and Hopkirk, 1995). The FE scheme in particular is well suited to calculation of topographic impacts since it allows an exact representation of the topography without introducing artificial surface steps which are known for example from standard finite difference discretizations. Fig. 2 shows the FE discretization for the most extreme case calculated assuming an amplitude of 1500 m and a wavelength of 5 km. All other calculations assume a smoother topography with less abrupt vertically distorted meshes. Due to the sinusoidal topography, no-flow boundary conditions could be assumed at the minima of the curve \((x = 0)\) and \((x = \lambda)\). The simulated topographies and GST histories required a rather sophisticated discretization scheme since large-scale topographies yield deep reaching perturbations whereas the recent GST2 history requires a relative fine discretization only near the surface. Furthermore, care had to be taken not to bias topographical effects with numerically induced effects which might sensibly influence the inversion procedure. After several model runs a mesh has been defined with an increasing vertical refinement from 250 m at 3000 m depth to 25 m near the surface. The depth range below 3000 m could be roughly discretized (element lengths >1000 m). Laterally, one wavelength has been discretized into 40 elements. In time, increments of 400 years for the GST1 and 4 years for the GST2 case were adopted. Such discretization in space and time yields a maximum temperature difference of less than \( 2 \times 10^{-3} \) K compared to the 1-D solution (Eq. 1) which can be considered sufficient for the present set of calculations.

As expected, the influence of the topography became much more significant for smaller-wavelength or larger topographical amplitudes. For the case of \( \lambda = 5 \) km and \( A = 100 \) m and the Pleistocene GST1 history the individual temperature and (vertical) heat flow profiles extracted at minimum \((x = 0)\) and maximum \((x = \lambda/2)\) elevation are illustrated in Fig. 3. On the scale shown, the 5 K temperature step at surface due to the GST change during the Pleistocene represents the main difference in the temperature profiles. The difference between steady state and the present profile manifests mainly a greater depth and will reach its maximum at 1200 m. It is obvious that the heat flow is more sensitive to both topographic and transient changes. The heat flow profiles taken at maximum and minimum elevation which represent the topographic influence, differ in the depth range between surface and 1 km depth from 20 to 10 mW m\(^{-2}\). Along the same depth section the profiles...
taken at different periods furthermore differ between 17 and 9 mW m$^{-2}$. It has to be noted that these differences appearing already at 100 m topographic amplitudes are greatest in that depth range with the potentially most important temperature signals (e.g. Wang et al., 1994; Huang et al., 1996).

When the same topography is used for the GST2 history the topography-induced effects persist; however, the transient effects are reduced due to the shorter GST event at lower amplitude. On the other hand, steeper topographies will dramatically increase the total bandwidth of heat flow variation. For example, for $\lambda = 1$ km and $A = 100$ m the difference between heat flow profiles taken at maximum and minimum elevation increases at surface to nearly 100 mW m$^{-2}$ but decreases quickly below that.
Fig. 4. Present-time temperature signal for the GST1 (a) and GST2 (b) history. The curves illustrate the results obtained for an ‘ideal’ 1-D situation (1) and different topographic wavelengths, each with a 100 m amplitude: $\lambda = 20$ km (2), $\lambda = 5$ km (3) and $\lambda = 1$ km (4). Dashed lines represent the profiles from maximum and continuous lines from minimum elevation.

depth (no difference in 750 m depth). These observations correlate nicely with mathematical 1-D descriptions mentioned earlier (Turcotte and Schubert, 1982), predicting an exponential decrease of the depth range of a topographical perturbation with decreasing wavelength.

However, for the successful inversion of a temperature log, the topography-induced deviations in temperature need to be evaluated. Fig. 4 illustrates the present-time reduced temperature profiles for the GST1 and GST2 histories. Such profiles are obtained by subtracting the surface temperature (here 0.5 K for topographic lows and $-0.5$ K for elevations) and the temperature effect of a uniform gradient (here: basal heat flow divided by thermal conductivity is 0.03 K km$^{-1}$) from the observed data. These reduced temperature profiles also might be considered to correspond to the transient temperature signal in case that, falsely, any topographical influence is ignored. Such data treatment thus would be only based on a 1-D profile starting at the altitude of the wellbore head. Clearly, such data treatment would yield an increasing error the deeper the profile reaches, since the previously noted decrease of topographic effect is now completely neglected: larger wavelengths which penetrate deeply in the subsurface thus cause a continuously increasing difference to a 1-D temperature signal, whereas the difference stabilises for short wavelengths already at relatively shallow depth. Interestingly, the topographic shape may strongly alter the transient temperature signal and thus would lead to erroneous inversion results. The profiles taken from elevations tend to pronounce a GST cooling and to reduce a GST warming, whereas the profiles from the valleys overestimate GST warming and reduce a GST cooling period.

The varying depth extent of the two GST histories can be recognised for the 1-D curves of Fig. 4. GST2 penetrates only down to 200 m, whereas GST1 has penetrated far below 3000 m. Unlike the GST2 models, the shape of the temperature signal from the GST1 history still can be detected even at very small wavelengths. The larger the wavelength, the closer the 1-D curve is of course approached. However, the small 1-D GST2 temperature signal is likely to be extinguished already at moderate topographical undulations. It may be noted that the behaviour of the $\lambda = 1$ km curve is not that uniform, since it even intersects curves of larger wavelengths. We will discuss this point shortly.

Next we will compare the impact of the different topographic temperature profiles on a 1-D inversion routine. The inversion procedure is performed with a code based on the Bayesian inverse technique which estimates the GST history in the Fourier frequency domain (detailed description see Wang, 1992). The
accuracy of the numerical data allows to attribute only small error bars to the $T-z$ data and to parameters such as thermal conductivity, thermal diffusivity, surface temperature or basal heat flow being exactly known due to the synthetic nature (i.e. a standard deviation in the order of the numerical accuracy, i.e. $10^{-3}$ to $10^{-5}$). The treatment of each history required different fundamental periods: 150,000 years for the GST1 history and 1000 years for the GST2 history. The (interpolated) $T-z$ data were sampled every 20 m along the profile down to a depth of 3000 m.

The chosen approach is intended to highlight the difference between the GST functions inverted from flat and topographically perturbed $T-z$ data. Therefore, all other input parameters were left unchanged. They were chosen in a way that the 1-D case reproduces the best possible original GST histories. It was also intended to eliminate ‘wiggles’ close to the steep temperature increase and decrease of the step function. The inversion results for these calculations were little affected by a change in a cut-off period in range between 500 and 5000 years. The results presented in Fig. 5 were calculated with a cut-off period of 4000 years for GST1 and 30 for GST2. Thus, the following results have been achieved under ideal conditions such as are rarely met for the inversion of field data: the values of temperature diffusivity, basal heat flow and original GST history are all known.

The result of this sensitivity analysis reproduces the expectations from the previous graphical illustration of the transient temperature signals. It can be seen in Fig. 5 that the inversion reproduces nicely the different altitude-dependent surface temperatures at present time. Generally, larger wavelengths will better reconstruct the GST history than smaller wavelengths. Due to the high 5°C temperature step, the Pleistocene GST1 history may be reconstructed even at topographical perturbations of smaller wavelength. In contrast, even large wavelengths do not allow reproduction of the recent GST2 history. Moreover, it becomes obvious that practically only the topographic influence is inverted for the GST2 case. Smaller wavelengths have not been plotted since the inverted temperature range would exceed the chosen scale by far. Since the present inversion assumes identical parameters for all temperature profiles, it may be noted that better approximations become possible for an individual profile when the basal heat flow value is allowed to vary for each temperature profile. By adopting corresponding lower (for high points) or higher (for valleys) values the 1-D inversion result will be better matched. However, such

![Fig. 5. Inverted GST1 (a) and GST2 (b) history from the synthetic temperature distribution of a sinusoidal topography. The numbers indicate the chosen wavelength (km); profiles taken from maximum elevation are indicated by dashed lines and minimum elevation by continuous lines. The GST2 history could be reproduced by the 1-D flat model but not by any calculated sinusoidal topography (see text for details).](image-url)
strategy becomes strongly questionable in the case that several boreholes — each of them placed on a different topographical position — will be jointly inverted: by the assumption of a wrong regional heat flow value the GST history of only those boreholes placed on a nearly identical topographical setting can be reconstructed. Adding however the boreholes located on a different topographical setting will automatically result in nearly arbitrary curves.

From these statements, it becomes clear that topology will especially perturb temperature information from recent GST changes which are generally characterised by small surface temperature variations. Even very small topographical undulations then can yield uninterpretable GST information.

2.3. Correction strategy based on multiple data

The results of the simulations represent a perfect basis for developing remediation concepts which should help to obtain useful results from strongly perturbed GST histories. This topic has been addressed by several studies (e.g. Pollack et al., 1996; Beltrami et al., 1997) performing simultaneous inversion and simple averaging of individual inversions. Thus several borehole interpretations could be merged into a single GST reconstruction. The attempt to average the individual GST histories from Section 2.2 represents a straightforward approach which corresponds to the earlier efforts. In the case of GST1, the average has been calculated from the individual histories calculated from ten different topographical situations (original profiles were taken at topographic lows and heights for $D = 1, 2, 5, 10$ and 20 km); for the averaging of the GST2 histories, however, only four different topographical profiles could be used due to the enormous deviations, mentioned before (topographic minima and maxima for $D = 10$ and 20 km). In Fig. 5 it can be recognised that the curve indexed as ‘average’ matches quite well the best possible GST history derived from a 1-D model. For GST1 there is a small, but only insignificant difference to the 1-D result (the average curve shows slightly lower temperatures than the 1-D result) and for GST2 no difference can be established at all.

The averaging treatment presented has involved an ideal constellation. In practice it is rather unlikely that temperature data from boreholes situated at the opposing topographical extremes will be available. The results therefore justify in principal the practice of inversion of data from as many boreholes as possible. Only if a statistically relevant number of boreholes is considered, a successful inversion can be ensured without performing an individual topography correction. In the next section, another type of treatment is presented whereby we will attempt to correct the temperature profiles from single boreholes.

2.4. Single borehole correction strategy

The procedure consists firstly in evaluating the topographic influence of the previously calculated synthetic temperature field and secondly in subtracting this effect from the transient temperature data. It was stated in Section 2.1 that the most accurate calculation of topographic influence is performed by the numerical approach, since the formulation of Birch (1950), at the present implementation, can only be used to perform first-order topographical corrections of temperature data. Furthermore, numerical methods will generally be preferred to calculate the impact of heterogeneous media.

The correction is performed now by subtracting steady-state temperatures with identical surface temperature from the transient synthetic temperature profiles. Fig. 6 shows the inversion result for the topographies with different wavelengths and amplitudes of $A = 100$ m and $A = 1500$ m. For $A = 100$ m the calculations for $\lambda \geq 5$ km all reproduced nearly perfectly the 1-D result. (Note: the equivalent not corrected models could even not been represented on the scale of Fig. 5!) At $\lambda = 2$ km and especially at $\lambda = 1$ km the calculations deviate from the 1-D case. This behaviour is entirely due to the fact that the GST change affects all altitudes at the same time, causing the individual temperature signal to interfere in the subsurface. In the example treated in Fig. 6, the temperature signal from the elevation seems to be retarded, whereas the signal from the valley seem to precede. For $A = 1500$ m the interference between the temperature signals becomes more pronounced. However, taken realistic topographical wavelengths (>10 km) even in such an Alpine environment a successful inversion still can be performed.
3. Three-dimensional field example

In this section it is intended to apply the findings from the previous synthetic models to a real field example. Therefore, the topographical situation of the moderately undulating (maximum altitude variation approx. 250 m) surroundings of the well investigated Continental Deep Drilling (KTB) project in Germany has been selected. The complex thermal field at the KTB has been investigated by several authors in the past (e.g. Rybach, 1992; Clauser and Mareschal, 1995; Kohl and Rybach, 1996; Clauser et al., 1997). Due to its depth extension the KTB borehole revealed the clear temperature signal originating from the climatic conditions during the last Pleistocene Ice Age (Rybach, 1992; Clauser et al., 1997). It became evident that this event represents the most dominant palaeoclimatic signal in central Europe. The temperature logs at the KTB pilot hole could be accurately (±0.3 K) fitted by a 3-D finite-element model (Kohl, 1998) which combines the (measured) values of thermal conductivity, heat production and surface topography with a geologically based model of lithology distribution, a slightly simplified palaeoclimatic GST reference history (starting at \( t = 75,000 \) years B.P.) and an assumed basal heat flow. Thermal advection seems to have a second order effect.

For the present study of the topographic influence on transient temperature signals the same 3-D model extensions of Kohl (1998) could be used since its lateral boundaries, all placed on ridges or low points, had been carefully selected (Fig. 7). Thus, as in the previous synthetic sinusoidal approach, minimal side effects from the lateral boundary are to be expected. Clearly, due to the boundary conditions and to the model’s extension, effects of the topography can become visible only up to a wavelength of 24 km in the E–W direction and 8 km in the N–S direction (i.e. twice the lateral length). If a larger area had been calculated, the calculated topography perturbation would change only slightly, since the large-scale regional area does not strongly exceed the considered altitude range. The lower boundary was placed at a depth of 10 km; at the surface, a uniform GST variation with altitude of 7 K km\(^{-1}\) \((T_{z=0} = 11.5^\circ \text{C})\) was assumed. Vertically, the model was discretized with increasing mesh density towards the surface (minimum increment 25 m). The model comprised 36,000 nodes and 25,000 elements. Sensitivity analysis has demonstrated that less refined models with 9200 nodes and 8200 elements yield nearly the same results (maximum deviation 10\(^{-1}\) K). Since this model is intended to highlight topographical temperature perturbations at depth rather than to fit measured temperature profiles uniform thermal...
Fig. 7. Extension of the 3-D model around KTB with the three surface location of selected profiles. Topographic isolines are drawn in 20 m increments. The scale is centred at KTB. Due to the selection of the boundaries the area is not rectangular (see Kohl, 1998).

conductivity (3.0 W m$^{-1}$K$^{-1}$) and heat production (1.0 $\mu$W m$^{-3}$) parameters were used. The topography effect should be elucidated by three sites, each characterising a different morphological setting (see Fig. 7): (1) the Kühberg elevation, approximately 8 km west from the KTB site at 714 m altitude; (2) the KTB site at 507 m altitude; (3) the Fichtelnaab valley, approximately 3 km southeast from the KTB at 463 m altitude. Both, the Kühberg and Fichtelnaab location represent the maximum temperature perturbation possible on the considered area.

In Fig. 8a the plotted temperature profiles of these locations are reduced by a mean gradient of 25.2 K km$^{-1}$ and by the heat production effect. The influence of topography is evident: locations on a ridge have lower temperatures and locations on topographic low points have higher temperatures. The value of the mean gradient has been chosen to fit the KTB profile as closely as possible to the theoretical 1-D temperature signal of the assumed GST history and not from model characteristics which would require much lower gradients. However, this procedure corresponds to a data analysis which considers effects from heat flow, heat production and influence of a GST history but not from a topographically induced temperature perturbation. For the KTB location this procedure yields the surprising result that the topography effect becomes negligible: a difference of less than 0.2 K to the 1-D temperature signal is encountered (not visible on the scale of Fig. 8a). Therewith, it can be stated that the topography effect may be balanced by a variation of the assumed basal heat flow. The same effect is also visible in Fig. 4b for longer wavelengths and has been already mentioned in Section 2.2. Even for the nearby Fichtelnaab valley location a reduction by a uniform temperature gradient value to 28.2 K km$^{-1}$ would result in a reasonable close agreement with the 1-D temperature signal. However, it will not be possible to balance the topographic temperature perturbation at the Kühberg location due to the steep slopes northeast of this location.

Clauser and Mareschal (1995) attributed inconsistent results inverting temperature logs of shallow
borehole in the surrounding area at the KTB to heterogeneous thermal conductivity distribution or to advective influence. Our interpretation, however, shows that especially topography might have the most dominant effect and needs to be adequately treated.

The strategy from Section 2.3 is adopted to correct the topography effect at the considered area. Fig. 8b shows that the temperature signals almost perfectly agree among all profiles. The corrections for the valley and KTB profiles have been so accurate that only negligible differences to the 1-D case are encountered which even cannot be illustrated on the scale shown.

4. Conclusions

On the basis of sinusoidal topography it has been shown that the interpretation of transient temperature data is very sensitive to the surface structure. Over wide areas in central and southern Europe characterised by a moderately undulating topography the subsurface temperature field is influenced by the surface altitude and temperature distribution. By correcting measured temperature profiles for the topographic perturbation, the transient temperature signals can be accurately extracted.

However, if the topographic perturbation is not adequately considered the surface structure strongly influences the inversion process: profiles taken from elevations tend to pronounce a GST cooling and vice versa. Such effects may even occur in moderate topographies. In practice, by adopting individual basal heat flow values (i.e. lower values for elevations and higher values for lows) the equivalent 1-D temperature signal can in general be matched. However, as the considered 3-D example has shown, no general rule can be applied to this.

Care has to be taken especially for joint inversions when a uniform basal heat flow is assumed for all temperature profiles. Such strategy might only be successful if the boreholes are situated at the opposing extremes of topographic variations. In general, topographic effects and GST signals will be mixed and a joint inversion might yield arbitrary results.

In this analysis other possibly important source of ‘noise’ for transient temperature signals have not
been treated such as surface temperature varying with slope angle and orientation or with vegetation cover. It may be estimated that these effects are less important than the topography effect due to the generally lower temperature variation at surface than at depth (air lapse rate \textasciitilde 1 K km\(^{-1}\), temperature gradient \textasciitilde 30 K km\(^{-1}\)). However, for individual locations with strongly varying surface cover, the magnitude of these changes can adjust itself. The present investigation therewith strongly recommends to evaluate the site-specific effects before using an inversion routine. Possible ‘noise’ can be eliminated by simple forward calculations and the transient temperature signals can then be well inverted. The possibility that lateral diffusive interference will perturb these signals is only encountered for extreme Alpine-type topographic situations.

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