Geophys. J. Int. (1996) **126**, 101–112

Palaeoclimate and structure: the most important factors controlling subsurface temperatures in crystalline rocks. A case history from Outokumpu, eastern Finland

I. T. Kukkonen[1] and J. Šafanda[2]

[1] *Geological Survey of Finland, Betonimiehenkuja* 4, FIN-02150 *Espoo, Finland*

[2] *Geophysical Institute, Academy of Sciences of the Czech Republic, Bočni* II/1401, 141 31 *Praha* 4, *Czech Republic*

Accepted 1996 February 6. Received 1996 January 8; in original form 1995 June 28

SUMMARY

The present work contributes to the study of heat-transfer mechanisms in crystalline bedrock. We present evidence from a thoroughly investigated case history in Outokumpu, eastern Finland, in the Fennoscandian (or Baltic) Shield, which shows that the subsurface temperature field is controlled by the thermal conductivity structure and downward diffusion of palaeoclimatic ground-temperature variations. The subsurface temperature profiles from three continuously cored boreholes (790–1100 m deep) were used for a detailed 2-D modelling of structural, hydrogeological and palaeoclimatic effects on the subsurface temperature field. The boreholes are situated in a subdued topography and they intersect Early Precambrian folded lithologies, such as mica gneisses, black schists, skarn rocks, quartzites and serpentinite-talc rocks. Finite-difference techniques were used in the numerical solution of the heat- and mass-transport equations. The 2-D models of thermal conductivity and hydraulic permeability that were compiled were based on an extensive set of data relating to geological structure, *in situ* hydraulic permeability, groundwater composition and thermal conductivity of drill-core samples down to about 1 km depth. It was found that the thermal effect of topographically driven groundwater convection is very small, with Peclet numbers typically of the order of 10^{-4}–10^{-5}. The effect of anisotropy of thermal conductivity was found to be one order of magnitude smaller than the effects of heat-flow refraction in the inclined rock layers which produce horizontal components of heat-flow density ranging from -15 to 5 mW m^{-2} (basal heat flow 35 mW m^{-2}). Since the advective heat transfer could be neglected, we tried to find a palaeoclimatic ground-temperature history that would explain the measured data. First, an inversion algorithm based on heat conduction in laterally homogeneous media was used for the reconstruction of palaeoclimatic ground-temperature history, but it yielded spurious results because of the strong 2-D conductivity effects. The only means to reconstruct the past ground-temperature changes was forward modelling using a conductive transient 2-D model with time-dependent surface-temperature variations. The surface temperatures at different times (between 100 000 yr BP and the present) and the basal heat-flow density were varied in order to reach a reasonable fit between the modelled and measured borehole temperatures. To reach this goal, the ground-temperature history must include the main climatic events during the last 100 000 yr, such as the last glacial epoch and the Little Ice Age (from about 1300 AD to 1700 AD), followed by warmer temperatures in more recent times. Our results suggests that subsurface temperatures in conditions similar to those of the Outokumpu case can yield a wealth of palaeoclimatic information when an appropriate approach for modelling heat transfer in the bedrock is chosen.

Key words: advection, eastern Finland, heat flow, palaeoclimate, thermal conductivity.

INTRODUCTION

Heat-flow density and temperature gradient often vary with depth in bedrock. These variations may be due to several factors, such as heat transfer by groundwater circulation in the bedrock, transient thermal effects produced by palaeoclimatic changes in ground temperatures, structural effects, including 2- and 3-D thermal conductivity and heat-production variations, and mineral reactions during uplift/subsidence (Haenel, Rybach & Stegena 1988; Kukkonen, Čermák & Hurtig 1993). Identifying which of these factors affects a particular case history is not a straightforward issue, and demands detailed knowledge of the thermal-conductivity structure and hydrogeological properties of bedrock surrounding a measured borehole. Typically such information is not available or is inadequate.

Super-deep drilling projects, such as the Kola project in Russia and the KTB in Germany, have collected extensive sets of data on thermal and hydrogeological properties of crystalline bedrock. These cases have been investigated in detail with respect to heat-flow data by Kremenetsky & Ovchinnikov (1986), Moiseyenko (1986), Galdin *et al.* (1987), Kozlovsky (1987), Burkhardt *et al.* (1991) and Clauser & Huenges (1993). Numerical modelling of heat transfer in the Kola super-deep-borehole area suggests that there is considerable advection of heat by groundwater flow in the uppermost 4 km of bedrock, which can be attributed to the considerable topographic relief of the area (Kukkonen & Clauser 1994). In the KTB case, thermal data can be interpreted with a reasonably small misfit either in terms of advective, structural or palaeoclimatic effects (Clauser & Huenges 1993; Clauser & Mareschal 1995). The super-deep boreholes are, however, not necessarily ideal for investigating these effects, because the boreholes have not yet reached thermal equilibrium and borehole temperatures will deviate from equilibrium values years or even decades after drilling. There is still a lack of well-investigated case histories where the relevant parameters can be constrained from measurements.

Recently, significant efforts have been made in using geothermal data sets of subsurface temperatures for inverting the history of palaeoclimatic ground-temperature changes (Čermák 1971; Lachenbruch & Marshall 1986; Shen & Beck 1991; Beltrami & Mareschal 1991; Wang 1992; Mareschal & Beltrami 1992; Shen *et al.* 1995). The thousands of geothermal borehole measurements that exist in the world could provide a new indicator of past climatic changes, particularly during the pre-instrumental era, which are relevant to the understanding of the background of on-going climatic changes. Since the inversion tools that exist at present are based on 1-D models of bedrock (Wang 1992), the subsurface thermal regime of the bedrock in such investigations should be controlled only by conduction in a laterally homogeneous medium. However, palaeoclimatic effects are obviously present in more complicated geological structures as well. In crystalline rocks, 2- and 3-D structures are generally more representative of the bedrock than 1-D structures. The palaeoclimatic signal is diffusive in character, and it attenuates rapidly with depth. Taking into account the typical resolution and noise levels of geothermal temperature logs, it is estimated that all ground-temperature events having a duration of less than 1000–5000 years decrease to the noise level at depths of about 1 km. At deeper levels only long-period, high-amplitude events, such as glaciations, can be identified.

The aim of this paper is to analyse the subsurface temperatures in a thoroughly investigated site in Outokumpu, eastern Finland, where the local geological structure, hydraulic properties, groundwater composition, borehole temperatures and thermal conductivity of drill-core samples are known in detail down to about 1 km depth. We demonstrate the effects of steady-state advective and conductive heat transfer in the compiled 2-D thermal conductivity and hydraulic permeability structure. The effects of palaeoclimatic ground-temperature changes during the last 100 000 years on borehole temperatures are simulated using numerical forward modelling in the transient mode. For comparison, we also present the results of inverting the palaeoclimatic ground-temperature history with 1-D functional space inversion techniques, and show that such techniques may yield spurious results because the 2-D geological structure is not taken into account. From our results, we postulate that the most important factors affecting subsurface temperatures in the Outokumpu case are actually the thermal-conductivity structure and the past climatic variations in ground temperature.

THE OUTOKUMPU PROFILE: LITHOLOGY, STRUCTURE, HEAT FLOW AND GROUNDWATER COMPOSITION

The Outokumpu area in eastern Finland is known for its occurrences of Early Proterozoic strata-bound massive Cu-Zn-Co sulphide deposits (Koistinen 1981). The ore belt is folded and is more than 200 km long. The main rock type in the area is mica gneiss, in which there are folded interlayers of graphitic black schists, quartzites, skarn rocks, serpentinite, talc rocks and sulphide ores (Fig. 1). Extensive diamond drilling has been carried out in the area by the Outokumpu Company, and several holes reaching more than 500 m below the surface exist.

A drilling profile in the locality of Sukkulansalo, situated 12 km NE of the town of Outokumpu was chosen for this study (Fig. 2). This profile is particularly interesting as many holes have been investigated using geothermal methods, groundwater sampling and chemical analysis, as well as *in situ* hydraulic permeability measurements. The available geological information suggests that the structure, although complicated in cross-section, is continuous along the direction of geological strike and can be considered as 2-D. Local topography, which is characterized by glacially produced landforms (eskers and moraine formations), is subdued and height variations are generally less than 30 m in the surrounding 5–10 km of the boreholes.

Geothermal measurements have been reported from drill holes OKU-737, -740 and -741 by Kukkonen (1988). Temperature was measured with a resolution of 0.01 K at every 2.5 m and thermal conductivity was determined from drill-core samples at every 10 m using divided bar techniques. Temperature loggings were carried out in 1985–86, more than 4 yr after the end of drilling, which lasted about 1 month for each borehole. The measured temperatures thus represent the equilibrium temperatures with no thermal disturbance from drilling.

The mean heat-flow densities of the holes vary from 32 to 36 mW m^{-2}. The temperature–depth curves show a distinct increase in geothermal gradient with depth, as well as in the

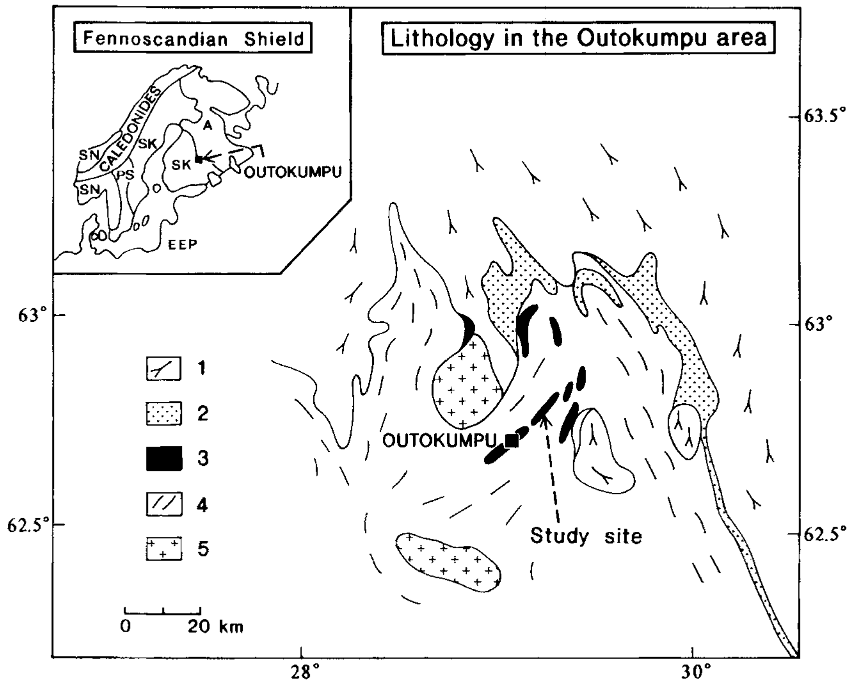

Figure 1. The location and general geological setting of the Outokumpu ore belt. 1: Archaean basement; 2: Early Proterozoic quartzite; 3: Rocks of the Outokumpu association (serpentinite, talc rocks, black schists, skarn rocks, quartzites); 4: Early Proterozoic mica gneisses and schists; 5: Early Proterozoic granitoids. The inset map shows the Fennoscandian Shield. A: Archaean (>2500 Ma); SK: Svecokarelian (2500–1750 Ma); PS: Post-Svecokarelian (1750–1200 Ma); SN: Sveconorwegian (1800–900 Ma); EEP: East European Platform. Simplified from Simonen (1980) and Papunen & Gorbunov (1985).

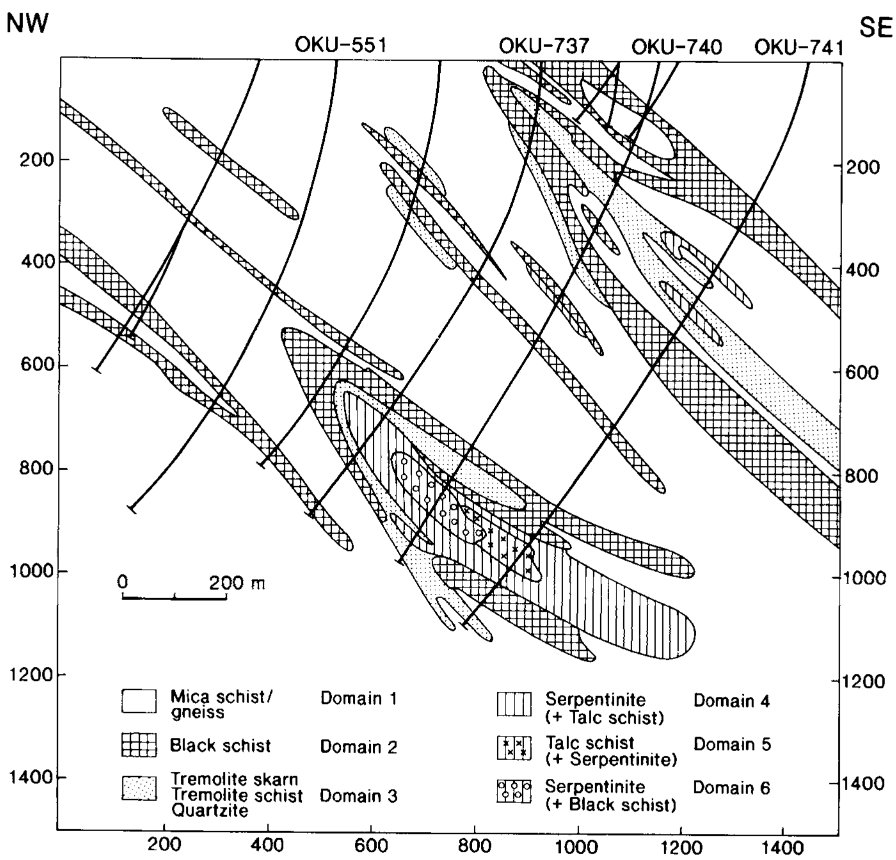

Figure 2. Lithology and location of drill holes in the Outokumpu cross-section. Domain numbers refer to different lithological groups used in the modellings and listed in Table 1.

apparent heat-flow density (Fig. 3; Kukkonen 1988). Average thermal conductivity varies considerably between different lithological types, from 2.8 W m^{-1} K^{-1} in mica gneisses to 7.0 W m^{-1} K^{-1} in serpentinite and other metamorphosed ultrabasic rocks (Table 1). The black schists, skarn rocks and talc schist have intermediate values, which fall between 4.1 and 5.9 W m^{-1} K^{-1}. The anomalous conductivities can be attributed to high concentrations of talc, quartz or graphite, which all have high thermal conductivities (Clauser & Huenges 1995). The mica gneiss is thermally anisotropic and a conductivity anisotropy of 1.5 has been reported (Kukkonen 1987).

Values of radiogenic heat production are quite typical for these crystalline rock types. The data were measured using gamma-ray spectrometry (Kukkonen 1989). Excluding the ultrabasic rock types, heat production in different lithological groups is between 1.9 and 2.4 μW m^{-3}, whereas the serpentinites have very low U and Th concentrations and their heat production is about 0.03 μW m^{-3} (Table 1).

Deep-groundwater sampling and hydrochemistry of the Outokumpu holes have been reported by Nurmi & Kukkonen (1986), Nurmi, Kukkonen & Lahermo (1988), Blomqvist *et al.* (1986, 1987), Ahonen *et al.* (1991) and Ahonen & Blomqvist (1994). The most important finding is that there are saline Ca-Mg-Na-Cl waters (total dissolved solids >10 g L^{-1}) in the deeper parts of the drilled section. In some holes the saline water is already at surface level in the bedrock, which can be taken as an indication of very low flow rates of groundwater. Hydraulic packer tests with packer intervals of 25 m have been carried out in boreholes OKU-551, -737 and -740 (Ahonen *et al.* 1991; Ahonen & Blomqvist 1994). In mica gneisses the hydraulic permeability is between 1×10^{-17} and 1×10^{-16} m^2, which reflects the relatively low fracture frequency of this rock type. Similar permeabilities were measured for the skarn rocks, dolomites, and serpentinites, whereas black schists had a permeability about two orders of magnitude higher, ranging from 1×10^{-15} to 1×10^{-14} m^2 (Table 1).

The Outokumpu structure has a very good potential for investigations of both advective and conductive heat-transfer effects because the thermal and hydraulic parameters can be constrained from measurements. Thus it will be possible to distinguish between different heat-transfer mechanisms and to estimate the contribution of each to the overall thermal situation.

HEAT- AND MASS-TRANSFER SIMULATIONS IN THE OUTOKUMPU STRUCTURE

Steady-state conductive model with isotropic thermal conductivity

The model of the thermal conductivity was based on the values measured from the core samples taken from the boreholes. Conductivity was measured along the drill-core axis, which is approximately perpendicular to the layers of the structure and to the foliation (Fig. 2). These data were combined with lithological profiles and the results of the gravity and magnetic modelling (Hattula 1993) in order to produce a 2-D model of the Outokumpu structure, with a width of 1500 m and a depth of 1500 m (Fig. 2). The Quaternary cover above the Precambrian is thin (<5 m) and it was not included in the model. The temperature field corresponding to the steady-state heat conduction was modelled by solving numerically the 2-D steady-state heat-conduction equation by the finite-difference method using the computer code of Clauser (1988). The applied boundary conditions were (1) constant surface temperature (5°C), (2) constant heat flow at the lower boundary (35 mW m^{-2}) and (3) no flow of heat across the lateral boundaries. The dimensions of the grid were 20 m × 20 m.

The results of the modelling indicate that the high conductivity contrasts between different lithological domains produce considerable refraction of heat flow. The horizontal component of heat-flow density ranges from -15 mW m^{-2} to about 5 mW m^{-2}, and the vertical component from about 33 to 55 mW m^{-2} (Fig. 4). According to the model, the total heat-flow vector in the high conductivity units is diverted by about

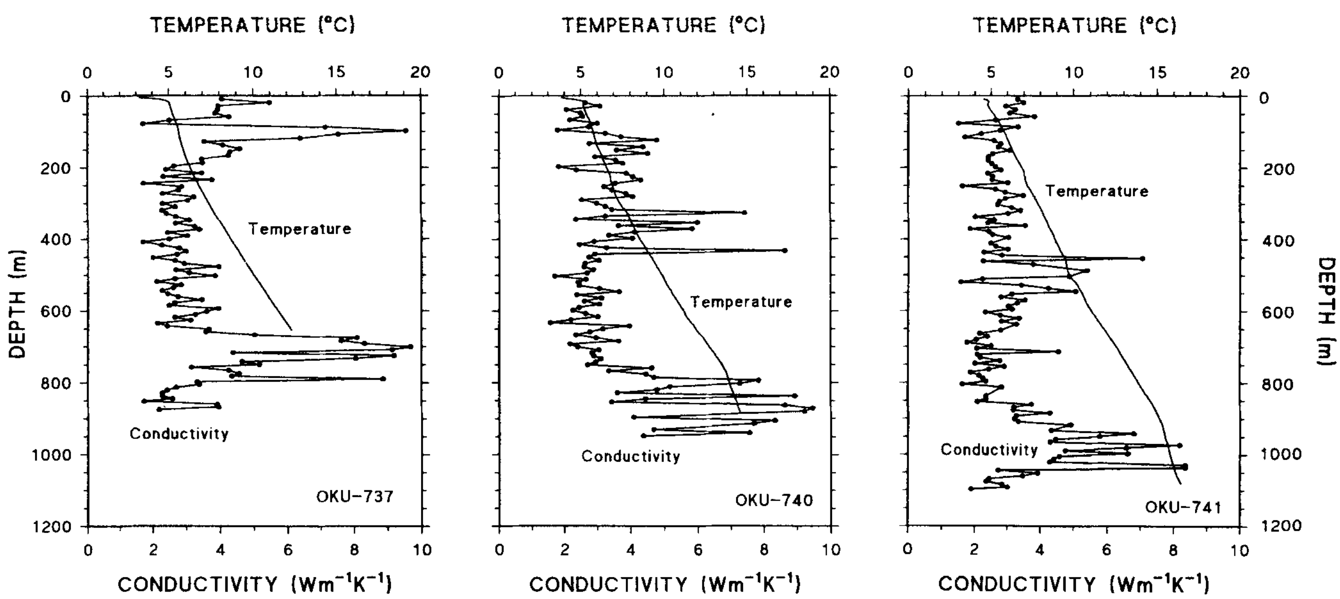

Figure 3. Temperature and thermal conductivity in the drill holes OKU-737, -740 and -741. The depth values are vertical depths corrected for the hole inclinations.

Table 1. Thermal conductivity (k), radiogenic heat production rate (A) and hydraulic permeability (χ) of the main lithological groups in the studied cross-section at Outokumpu. Numbers of samples are given in parentheses.

Rock type	k ($Wm^{-1}K^{-1}$) Mean ± Std	A (μWm^{-3}) Mean ± Std	χ (m^2) Range	Domain number
Mica gneiss	2.78 ± 0.74 (202)	1.85 ± 0.54 (12)	10^{-17}-10^{-16}	1
Black schist	4.12 ± 1.28 (43)	2.36 ± 0.84 (3)	10^{-14}-10^{-15}	2
Tremolite skarn Tremolite schist Quartzite	5.12 ± 1.42 (15)	2.23 - (2)	10^{-17}-10^{-16}	3
Serpentinite (+ Talc schist)	7.04 ± 1.78 (12)	0.03 ± 0.1 (3)	10^{-17}-10^{-16}	4
Talc schist (+ Serpentinite)	5.85 ± 1.43 (7)	-	10^{-17}-10^{-16}	5
Talc schist (+ Black schist)	5.38 ± 2.02 (7)	-	10^{-17}-10^{-16}	6

Thermal conductivity and heat production data were taken form Kukkonen (1988, 1989) and the hydraulic permeability values from Ahonen *et al.* (1991) and Ahonen & Blomqvist (1994).

10–15° from the vertical, as indicated by Figs 4(b) and (c). The geometry of the drill holes (approximately perpendicular to the layering) is not very good for detecting the refraction anomalies in measured heat-flow density in boreholes because the projection of the total heat-flow vector in the direction of the boreholes is nearly at its minimum. In such a situation the measured heat-flow density does not show an anomaly. The measured temperature curves do not match the modelled steady-state temperatures, but many of the structural effects can be observed in the measured values as gradient changes with depth.

Steady-state conductive model with anisotropic thermal conductivity

In order to find out whether the anisotropy of thermal conductivity has an effect on the temperature and heat-flow field, a model including anisotropic thermal conductivity was also investigated. We assumed that the anisotropy factor (1.5) reported for mica gneisses (Kukkonen 1987) is also representative for the other lithological types of the area. Typically, values between 1.2 and 2 have been reported for the anisotropy factor of crystalline rocks (Schön 1983). We assumed that the principal axis of the conductivity tensor dips with an angle of 45°, which coincides approximately with the dip and schistosity of the individual layers of the Outokumpu structure. The structure is very continuous along geological strike within 10–20 km from the investigated section, and the dip of the structures is 40–55° to the SE. Conductivity along the layers is 1.5 times the value perpendicular to layering. Conductivity in horizontal and vertical directions is then an average of both principal values. For this dip angle the non-diagonal components of the conductivity tensor reach their maximum, and thus the effect of anisotropy is at its maximum. The heat-conduction equation was solved in a larger model (width 5.5 km and depth 3 km) using the code of Šafanda (1995), which is also based on a finite-difference solution of the heat-conduction equation, and which uses boundary conditions similar to those described above. The computed temperature and heat-flow fields were compared with the results calculated using the isotropic model, which differs from the anisotropic one only in the zero non-diagonal components of conductivity. The differences between isotropic and anisotropic models range in temperature from -0.11 to $+0.08$ K (Fig. 5), and in vertical heat-flow density from -2.6 to $+3.9$ mW m^{-2}. It can be concluded that the effects of anisotropy of thermal conductivity are about one order of magnitude smaller than the refraction effects, and it would be very difficult to detect them in the real measured data.

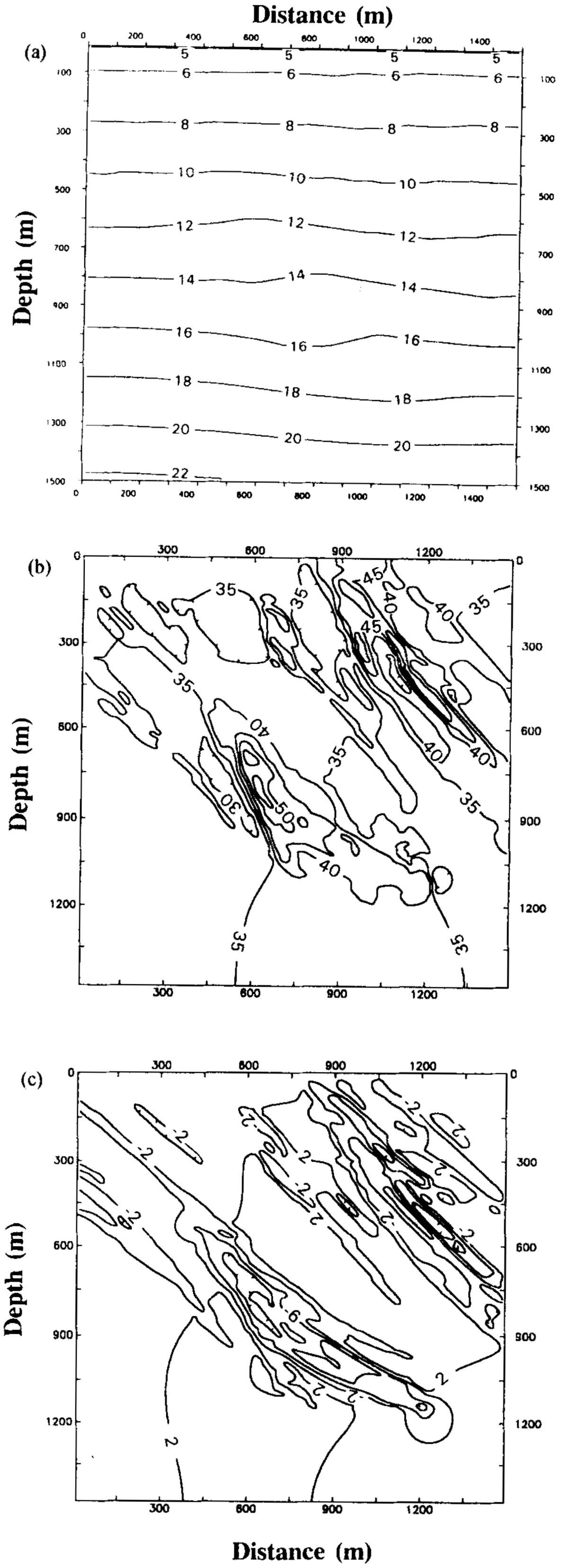

Figure 4. Calculated steady-state conductive (a) temperature (°C), (b) vertical and (c) horizontal heat-flow density (mW m^{-2}) in the investigated cross-section. The vertical component of heat-flow density is shown in contours of interval 5 mW m^{-2} and the horizontal component in contours of ± 2, 6 and 10 mW m^{-2}. The positive direction of horizontal heat-flow density is to the right.

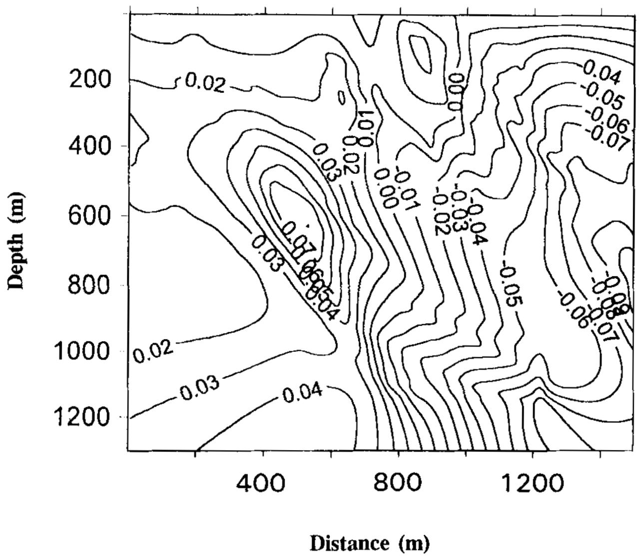

Figure 5. Temperature difference (K) between models calculated with anisotropic and isotropic thermal conductivities.

Steady-state hydrogeological effects

The magnitude of advective heat transfer in the Outokumpu structure was modelled using two different approaches. First, the order of magnitude of advection was determined with the aid of Peclet-number estimation. Second, thermal groundwater flow effects were investigated in more detail using a numerical 2-D heat- and mass-transfer simulation.

The Peclet number is a dimensionless parameter, which is defined for a 2-D aquifer as follows (Van der Kamp & Bachu 1989):

$$Pe = \beta \lambda (dh/dl) DA/\alpha_m, \tag{1}$$

where Pe is the Peclet number, β is the ratio of specific heat capacities of the fluid and the medium (1.83), λ is the hydraulic conductivity (m s^{-1}), dh/dl is the hydraulic gradient, D is the thickness of the aquifer, A is the aspect ratio ($A = D/L$, where L is length), and α_m is the thermal diffusivity of the medium (1×10^{-6} m^2 s^{-1}). Using a high estimate for the hydraulic conductivity (1×10^{-7} m s^{-1}, the corresponding value of permeability is 1×10^{-14} m^2), a thickness of 250 m for the flow system (approximately equal to the thickness of the fresh-water layer participating in the meteoric circulation), and a horizontal length of 2 km (estimated from the local topography), a Peclet number value of about 0.06 is obtained. The measured hydraulic conductivities approach the 1×10^{-7} m s^{-1} level only in the black schist layers; for most of the Outokumpu structure, hydraulic conductivity values are two or even three orders of magnitude lower (Table 1). Conductive heat transfer very probably dominates over advection in the Outokumpu structure.

In order to find out the contribution of the black schist layers, a more detailed numerical model was constructed using the code developed by Clauser (1988), which is able to solve the coupled heat-transfer and groundwater-flow equations using finite differences. The solution was calculated for a steady-state situation, and the porous medium approximation was used. Groundwater was assumed to be fresh in composition. The occurrence of more dense, saline groundwater in the deeper parts of the cross-section actually reduces the tendency of the system towards convective effects.

The following boundary conditions were applied for the flow equation.

(1) On the upper boundary a prescribed hydraulic-head variation simplified from the topography was used. It represents the variation in groundwater table elevation from the local water divide in the NW to a lake on the SE side of the profile.

(2) No flow of water across the lower and lateral boundaries.

The thermal boundary conditions were kept the same as in conductive models.

It was assumed that the hydraulic conductivity follows the results of Ahonen *et al.* (1991) and Ahonen & Blomqvist (1994), and that it varies with lithological domain (Table 1; Fig. 2). In order to make a conservative estimate, the permeability values were increased by one order of magnitude from the median values of the ranges given in Table 1, excluding the black schists for which the median of the measured range was used. In this way the model yields an upper estimate of the possible advective disturbances. Porosity was assumed to be 0.01 for all rock types. The simulation results are shown in Fig. 6. As expected, the high-permeability black schist layers are the most important flow channels. The Darcy velocities are smaller than $1 \times 10^{-10}\ \mathrm{m\,s^{-1}}$ (the corresponding particle velocities are $0.3\ \mathrm{m\,a^{-1}}$). The calculated Peclet numbers in different grid points of the model are of the order of 10^{-4}–10^{-5}. This simulation also confirms that advective heat transfer is not responsible for the vertical variation of temperature gradient and heat-flow density in the Outokumpu structure.

Transient conductive effects due to palaeoclimatic GST changes

The existing inversion codes for the reconstruction of the ground surface temperature (GST) history from the subsurface temperature profiles were based on the solution of the heat-conduction equation in 1-D models of the subsurface (see Wang 1992 for a review). They are evidently not suitable for the Outokumpu case. The situation is demonstrated with GST-history inversions of the OKU-737 borehole temperature data. The inversions were run for the GSTH during the last 1000 yr. This was carried out using the results of Shen *et al.* (1995). Their results suggest that, in a heterogeneous medium with randomly distributed thermal conductivity, the subsurface climatic effect interferes with the geological noise (i.e. thermal-conductivity variation), and extraction of GST history with 1-D inversion algorithms is restricted to the last 100–200 yr.

Using the code of Shen & Beck (1991) for a layered 1-D medium we processed the measured temperature profile from the hole OKU-737, as well as synthetic profiles of the same hole from forward modelling, in order to investigate the effect of the structure on the inversion. Both steady-state and transient 2-D conductive simulations were used for generating the synthetic profiles. In the transient model only a simple 1 K warming 500 yr ago was considered. In the 1-D inversion model the conductivities and layer boundaries were chosen to be the same as in the drill hole, and we set the *a priori* standard deviation of conductivity to $0.5\ \mathrm{W\,m^{-1}\,K^{-1}}$ and that of the measured temperature to 0.04 K.

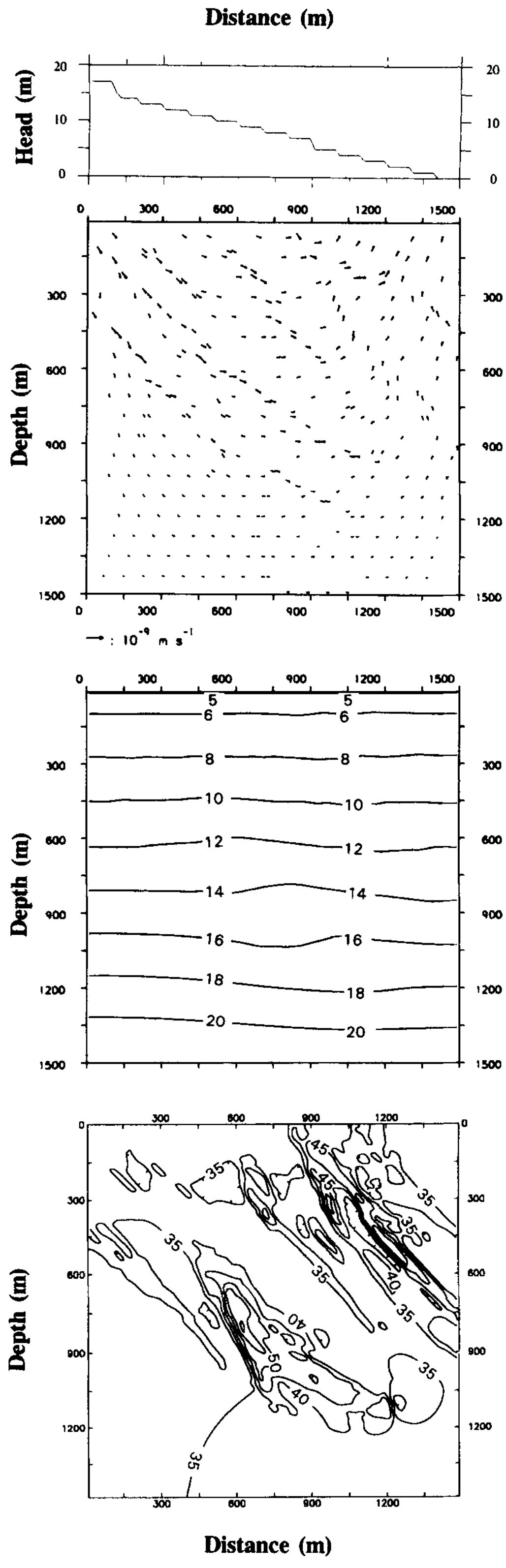

Figure 6. Calculated Darcy velocity ($\mathrm{m\,s^{-1}}$, logarithmic scaling of the flow vectors) and the applied relative hydraulic head variation, temperature (°C) and vertical heat-flow density ($\mathrm{mW\,m^{-2}}$) in a steady-state model including both conductive and advective heat transfer.

Our results (Fig. 7) show that the structural effect is so great that in the inversion the 2-D steady-state profile yields a spurious climatic signal with an amplitude of 2 K. Further, the GST history obtained from the synthetic 2-D transient profile seems to be a superposition of this steady-state spurious history and the 1 K warming spread over the time span of a few centuries. The measured temperature profile gives inversion results similar to the transient synthetic profile. This indicates that the bedrock temperatures have been influenced by palaeoclimatic GST variations, but, in order to extract the GST history, the 2-D conductive structures must be properly taken into account.

At present, the only means to deal with the 2-D structure is forward modelling. We simulated the three measured temperature profiles by solving the conductive transient 2-D model with a time-dependent GST. The model extended to a depth of 5 km. The first approximation of the palaeoclimatic GST history in the Outokumpu area was from the compilation of the palaeotemperatures in Finland (Fig. 8) (Kukkonen 1987). In our model the assumed simplified palaeoclimatic history consists of a glaciation period between 100 000 and 9 000 yr BP, the Holocene optimum, 9000–5000 yr BP, the Little Ice Age, 800–300 yr BP, and the recent climatic warming since the end of the 19th century. A steady-state condition was assumed to have prevailed prior to the glaciation.

The surface temperatures during different time intervals and the basal heat-flow density were varied in order to reach a reasonable fit between the measured and modelled borehole temperatures in the three boreholes. The sequence of different GST history variants tested is illustrated in Fig. 9. The first model (A in Fig. 9) was relatively simple, consisting only of the glaciation and the Holocene climatic optimum. As soon as the deeper parts of the measured temperature curves could be fitted with acceptable residuals, details could be added to the more recent parts of the GST history. We stopped the modelling when the misfit between measured and calculated profiles dropped to the level shown in Fig. 10. The amplitude of the transient signal of the GST model ranges from zero at the surface to about 3 K at 1 km depth, and thus the signal is considerably larger than the accepted residual of the best-fit GST model (Fig. 10). The constant basal-heat-flow density value used in the best-fit model was 35 mW m^{-2}, and the other values tested did not deviate more than ± 3 mW m^{-2} from this value. The temperature profiles are rather sensitive to variations in the basal-heat-flow density value, and a change

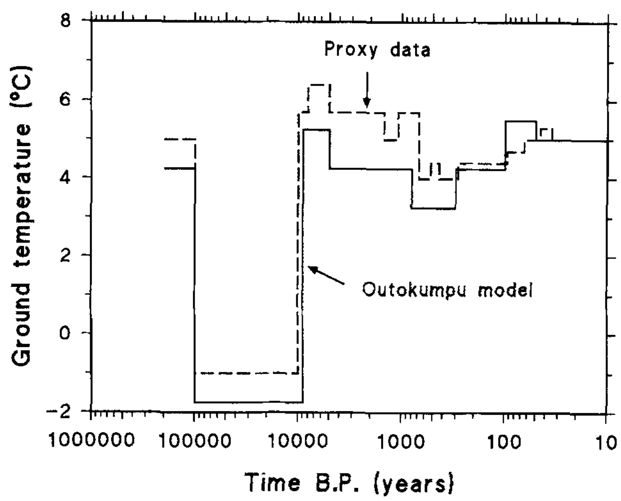

Figure 8. Simplified palaeoclimatic ground temperatures in Finland adopted from the compilation by Kukkonen (1987) and the best-fit history (the same as model H in Fig. 9), which was used in modelling the measured temperatures in the Outokumpu holes.

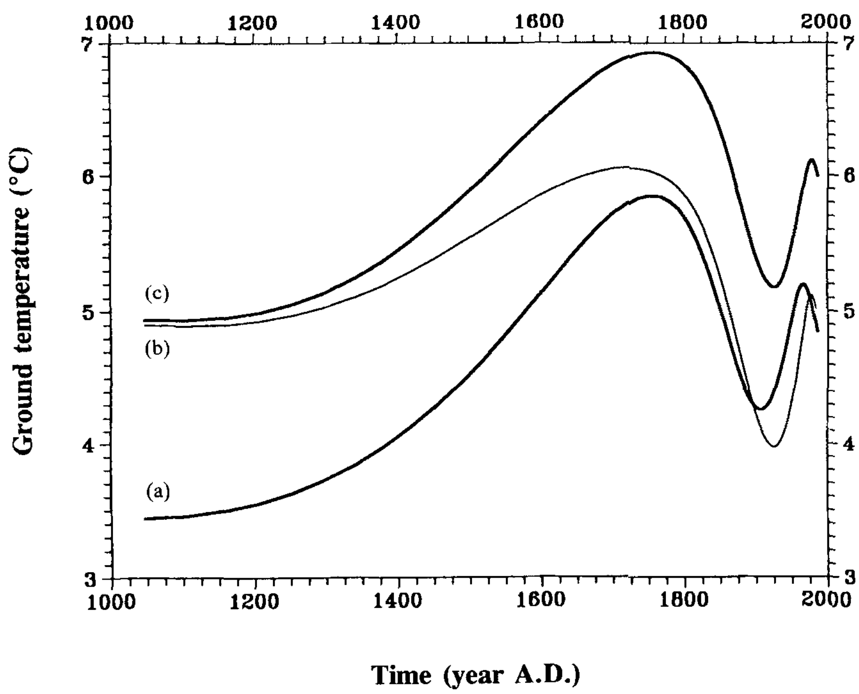

Figure 7. Ground surface-temperature histories for the OKU-737 drill hole reconstructed for the last 1000 yr. The functional space inversion technique was applied to the measured profile [curve (a)] as well as to two simulated drill-hole temperature profiles in the cases of a steady-state conductive regime (no palaeoclimatic effects) [curve (b)] and a transient conductive model [curve (c)], which included 1 K warming 500 yr BP.

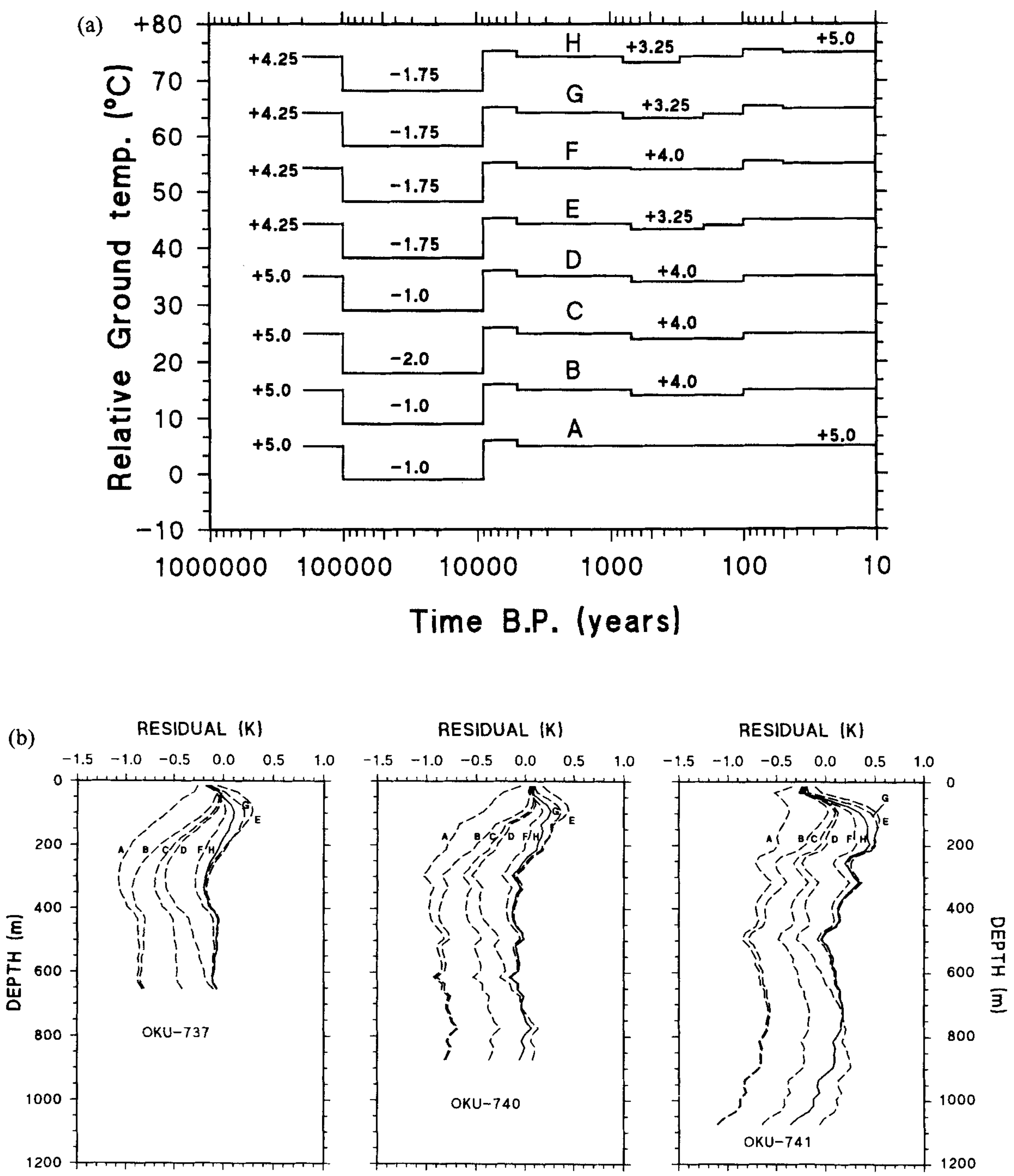

Figure 9. (a) Different GST histories used in 2-D forward simulations of the transient temperature field in Outokumpu. Ground-temperature values are indicated for certain key events; (b) the corresponding residuals between measured and modelled temperatures in the three drill holes.

of 1 mW m^{-2} changes the temperature at a depth of 1 km by about 0.3 K. The other GST histories tested in the simulations (excluding model A in Fig. 9) were all within $\pm$0.5–0.8 K of the final model, H. This can be taken as a measure of the accuracy achieved by simulating variations in GST history and basal-heat-flow density using the present, rather robust, technique.

The curve obtained is close to the original compilation of palaeotemperatures (Fig. 8), with the exception of the warmer period between 50 and 100 yr BP, and a relative shift of -0.75 K prevailing before 300 yr BP. To fit the curves, we needed the low temperatures during both the last glacial epoch and the Little Ice Age (from about 1300 AD to about 1700 AD). At the level of fit reached in the modelling, any further improvement in one borehole brings a deterioration in the fit of the other two. This is an indication that the remaining misfit, shown as residual curves in Fig. 10, has causes other than the ground-temperature history. We cannot exclude a minor hydraulic disturbance due to water flow in the holes from one fracture zone to another, unrecognized conductivity variations, possible 3-D features of the structure or differences in vegetation and land-use history of the individual hole sites

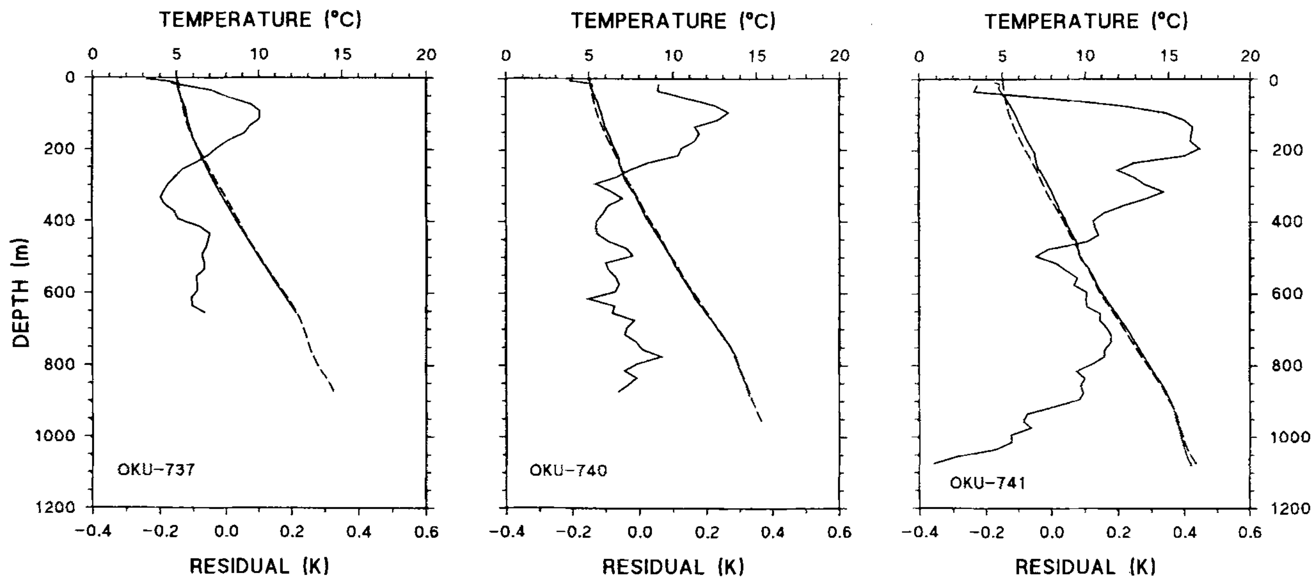

Figure 10. The measured (solid lines) and modelled (broken lines) temperatures in the drill holes, as well as the corresponding residuals. The GST history used was that given in Figs 8 and 9 (model H).

leading to differences in the absorption of solar radiation and GST. Nevertheless, it is remarkable how well the palaeoclimatic history can explain the vertical and lateral variations in borehole temperatures.

DISCUSSION

The present case history represents the conditions in the Outokumpu structure, but we believe that the results have also more general implications, particularly in the field of palaeoclimatic geothermal investigations.

In the Outokumpu case, heat transfer seems to have been mainly conductive. The subsurface temperature field is controlled by the conductivity structure and the downward diffusion of transient palaeoclimatic changes in ground temperatures. To a minor extent there may be small terrain effects, such as differences in vegetation. This is suggested by a GST value in hole OKU-737 (in an open meadow with low bushes) that is 0.2 K higher than in the other two (OKU-740, situated in an area transitional from meadow to forest, and OKU-741 situated in forest).

Thermal conductivity contrasts are extreme in the modelled structure, and in most other crystalline rock sites such contrasts may not be encountered often, and the refraction effects would be smaller. However, this does not mean that they should be overlooked in, for example, palaeoclimatic inversions.

Data on hydraulic permeability of crystalline rocks are still limited in Finland, but the data available so far suggest that permeability decreases with increasing depth (Ahonen & Blomqvist 1994; Niemi 1994). Values above 200 m are between 1×10^{-15} and $1\times10^{-14}\,\mathrm{m}^2$ but data from 200–500 m have values that are much lower, 1×10^{-15}–$1\times10^{-17}\,\mathrm{m}^2$. In the groundwater flow systems that typically prevail in Finland, the transition from conduction to convectively dominated heat transfer takes place when the permeability increases above 1×10^{-15}–$1\times10^{-14}\,\mathrm{m}^2$ (Kukkonen 1995). This transition also depends on the hydraulic head available (the above values are for a gradient of 0.01) and the geometry of the flow system. It would seem that the uppermost parts (<200 m) of the bedrock may be more susceptible to advective disturbances than the parts beneath. This is supported by the observation of the fresh–saline groundwater interface, which is usually at a depth of 200–1000 m in Finland (Blomqvist *et al.* 1986; Nurmi *et al.* 1988). The fresh groundwaters participate in the meteoric circulation, but, as modelled in the Outokumpu case, may have very small flow rates, so the resulting heat transfer is much smaller than by conduction. On the other hand, the existence of saline waters in the formation is an indication of more stagnant conditions of the groundwater. Hydrogeochemical investigations suggest that the saline waters have been produced by a very long-duration interaction between water and the surrounding rock matrix (Nurmi *et al.* 1988; Blomqvist *et al.* 1986, 1987). The uppermost fresh waters are more recent in origin, but their residence times may nevertheless be thousands of years. We cannot draw any conclusions as to whether the conductive situation generally prevails in the crystalline crust of the shield, but in each case the problem can be effectively investigated with the aid of numerical models, if sufficient information is available on hydraulic permeability. As demonstrated in the Outokumpu case, increasing the permeability by one order of magnitude from the measured values caused practically no deviation of the results from the conductive regime. Therefore, it would seem that conductive heat transfer is a good starting hypothesis in investigations of heat transfer in the uppermost bedrock in those parts of the Fennoscandian Shield that have no significant topographic variations.

Given that this is the situation, there should be a good chance to extract palaeoclimatic information from borehole temperature profiles. However, the thermal conductivity structure of the bedrock surrounding a borehole must be taken into account (Shen *et al.* 1995), and the tools used for palaeoclimatic interpretations must be chosen according to the structure. For example, the Outokumpu data produced spurious results when inverted using a 1-D layered earth model, but the results of forward modelling are in agreement with the palaeoclimatic history of Finland derived from various geological, proxy and meteorological data sources. We believe that forward modelling could also be a successful technique in other complicated structures, but a good proxy data model is needed to guide the ground-temperature modelling in order to reduce the ambiguity.

The diffusive nature of heat conduction also limits the resolution of GST history that can be achieved from geothermal data. In general, if there has been a periodic variation in ground temperature it is possible to gain GST information about the last cycle but not about the earlier ones. The effects of earlier cycles have already attenuated to the noise level. This means that GST events can be distinguished in borehole data only if their durations differ by about one order of magnitude, preferably more. Thus it is possible to investigate the recent GST history during the last 150 years superposed on the Little Ice Age effects (event duration of a few hundred years), as well as the Holocene optimum (duration of 3000–4000 yr), and all of these superposed on a glaciation event (duration of about 50 000–100 000 yr). In practice, this is strongly limited by the borehole depth: the maximum temperature signal of the glaciation is currently at a depth of 1.0–1.5 km, whereas the corresponding depth of the Holocene events is 500–700 m, and the recent climatic variation has affected only the uppermost 100–200 m. It should, however, be taken into account that parts of the transient signal anomalies can also be detected at depths shallower than the maxima, and, depending on the amplitude, time and duration of the GST event, it may be possible to model such an event from geothermal data. In the present study the longest wavelength variation in geothermal gradient with depth can be attributed to the glaciation event, although the depth of the maximum temperature disturbance of the glaciation event was not reached in any of the Outokumpu drill holes.

The reconstruction of palaeoclimatic GST history from a borehole temperature profile is not unique, and therefore certain *a priori* information must be considered. We did not try to fit the Outokumpu data to the smallest details, bearing in mind the possible sources of disturbances that could not be taken into account. Such sources include water flow in the holes, unrecognized conductivity structures, or the limited amount of detail which can be presented in the model with the present discretization. However, the use of several holes instead of one, and their coherent results, give us confidence that we are not interpreting noise as GST history.

CONCLUSIONS

The most important factors affecting the subsurface temperature field in Outokumpu are the conductivity structure and the palaeoclimatic GST history. Similar conditions can be expected to prevail in other parts of the Fennoscandian Shield, given that the hydrogeological parameters and topographic variation are similar to those in Outokumpu. The results suggest that there is a wealth of palaeoclimatic information on GST history in the subsurface temperatures, but the geothermal palaeoclimatic method also has its limitations, which result from the diffusive nature of the heat-conduction process. In a 1 km deep hole it is possible to extract information on a GST history that ranges from the glaciation event prior to 10 000 yr BP to the climatic events during the last few hundred years.

ACKNOWLEDGMENTS

We are grateful to the Outokumpu Company for permission to log their holes, take core samples and use unpublished data, as well as to C. Clauser (Niedersächsisches Landesamt für Bodenforschung, Hannover) and P. Shen (University of Western Ontario, London) for permission to use their codes for forward and inverse modelling. L. Rybach (ETH, Zürich) and an anonymous referee are acknowledged for their constructive reviews.

REFERENCES

Ahonen, L. & Blomqvist, R., 1994. Mode of occurrence of deep saline groundwater in Finland based on hydraulic measurements, in *Salt groundwater in the Nordic countries,* pp. 49–59, ed. Olofsson, B., Research Council of Norway, Oslo, NHP Report 35.

Ahonen, L., Blomqvist, R., Kurimo, M. & Kuivamäki, A., 1991. Kalliopohjavesiolosuhteet Outokummun Sukkulansalossa: Vuoden 1990 tutkimukset (Deep bedrock hydrogeological conditions in the Sukkulansalo area, Outokumpu: Results of 1990) *Geol. Surv. Finland, Nucl. Waste Disposal Res.* Rept YST-75 (in Finnish with abstract in English).

Beltrami, H. & Mareschal, J.-C., 1991. Recent temperature changes in eastern Canada inferred from geothermal measurements, *Geophys. Res. Lett.,* **18,** 605–608.

Blomqvist, R., Lahtinen, R., Lahermo, P., Hakkarainen, V. & Halonen, S., 1986. Kalliopohjavesien geokemia: tutkimustulokset syvistä kairarei'istä vuonna 1986 (Geochemistry of deep groundwater in bedrock in Finland: Results of the investigation in 1986). *Geol. Surv. Finland, Nucl. Waste Disposal Res. Rept,* YST-53, (in Finnish with English abstract).

Blomqvist, R., Halonen, S., Pacholewski, A. & Lindberg, A., 1987. Kallioperä-pohjavesi-vuorovaikutus heterogeenisissä kivilajiympäristöissä: tutkimustulokset Outokummun alueelta (Water-rock interaction in non-granitic crystalline bedrock environments: Results of investigations in the Outokumpu area), *Geol. Surv. Finland, Nucl. Waste Disposal Res. Rept,* YST-56, (in Finnish with English abstract).

Burkhardt, H. *et al.* 1991. The measured and predicted temperature profile in the KTB pilot-hole, *Sci. Drill.,* **2,** 244–257.

Čermák, V., 1971. Underground temperature and inferred climatic temperature of the past millenium, *Palaeogeog. Palaeoclimat. Palaeoecol.,* **10,** 1–19.

Clauser, C., 1988. Untersuchungen zur Trennung der konduktiven and konvektiven Anteile im Wärmetransport in einem Sedimentbecken am Beispiel des Oberrheintalgrabens, *PhD thesis,* Fortschritt-Berichte VDI, VDI Verlag, Düsseldorf, Germany, Reihe 19, No. 28 (in German with English abstract).

Clauser, C. & Huenges, E., 1993. KTB thermal regime and heat transport mechanism—current knowledge, *Sci. Drill.,* **3,** 271–281.

Clauser, C. & Huenges, E., 1995. Thermal conductivity of rocks and minerals, in *Handbook of Physical Constants, Vol. 3, Rock Physics and Phase Relations,* pp. 105–126, ed. Ahrens T.J., AGU, Washington, DC.

Clauser, C. & Mareschal, J.-C., 1995. Ground temperature history in central Europe from borehole temperature data, *Geophys. J. Int.,* **121,** 805–817.

Galdin, N.E., Lubimova, E.A., Nartikoyev, V.D., Popov, Y.A., Semashko, S.A., Skornyakov, V.M. & Smirnova, E.V., 1987. Rock thermal properties, in *The superdeep well of the Kola Peninsula,* pp. 383–386, ed. Kozlovsky, Ye. A., Springer, Berlin.

Haenel, R., Rybach, L. & Stegena, L., 1988. *Handbook of terrestrial heat-flow determination,* Kluwer Academic Publ., Dordrecht, Netherlands.

Hattula, A., 1993. Geofysikaalinen mallintaminen malminetsinnässä, in *Malminetsinnän Menetelmät I*, pp. 79–89, eds Haapala, I., Hyvärinen L. & Salonsaari, P., Yliopistopaino, Helsinki (in Finnish).

Koistinen, T.J., 1981. Structural evolution of an Early Proterozoic strata-bound Cu-Co-Zn deposit, Outokumpu, Finland, *Trans. R. Soc. Edin., Earth Sci.*, **72,** 115–158.

Kozlovsky, Ye.A. (ed.), 1987. *The superdeep well of the Kola Peninsula,* Springer, Berlin.

Krementsky, A.A. & Ovchinnikov, L.N., 1986. The Precambrian continental crust: its structure, composition and evolution as revealed by deep drilling in the USSR, *Precamb. Res.*, **33,** 11–43.

Kukkonen, I.T., 1987. Vertical variation of apparent and palaeoclimatically corrected heat flow densities in the central Baltic Shield, *J. Geodyn.*, **8,** 33–53.

Kukkonen, I.T., 1988. Terrestrial heat flow and ground water circulation in the bedrock in the central Baltic Shield, *Tectonophysics,* **156,** 59–74.

Kukkonen, I.T., 1989. Terrestrial heat flow and radiogenic heat production in Finland, the central Baltic Shield, *Tectonophysics,* **164,** 219–230.

Kukkonen, I.T., 1995. Thermal aspects of groundwater circulation in bedrock and its effect on crustal geothermal modelling in Finland, the central Fennoscandian Shield, in *Heat Flow and Thermal Regimes of Continental Lithosphere,* eds. Balling, N. & Decker, E.R., *Tectonophysics,* **244,** 119–136.

Kukkonen, I.T. & Clauser, C., 1994. Simulation of heat transfer at the Kola deep-hole site: implications for advection, heat refraction and palaeoclimatic effects, *Geophys. J. Int.*, **116,** 409–420.

Kukkonen, I.T., Čermák, V. & Hurtig, E., 1993. Vertical variation of heat flow density in the continental crust, *Terra Nova,* **5,** 389–398.

Lachenbruch, A.H. & Marshall, B.V., 1986. Changing climate: geothermal evidence from permafrost in the Alaskan Arctic, *Science,* **234,** 689–696.

Mareschal, J.-C. & Beltrami, H., 1992. Evidence for recent warming from perturbed geothermal gradients: examples from eastern Canada, *Clim. Dyn.*, **6,** 135–143.

Moiseyenko, F.S., 1986. The Kola superdeep drillhole and some problems of interpreting deep-level geophysical investigations, *Int. Geol. Rev.*, **28,** 1021–1030.

Niemi, A., 1994. Modeling flow in fractured medium. Uncertainty analysis with stochastic continuum approach, Technical Research Centre of Finland, *VTT Publications,* **184.**

Nurmi, P.A. & Kukkonen, I.T., 1986. A new technique for sampling water and gas from deep drill holes, *Can. J. Earth Sci.*, **23,** 1450–1454.

Nurmi, P.A., Kukkonen, I.T. & Lahermo, P.W., 1988. Geochemistry and origin of saline groundwaters in the Fennoscandian Shield, *Appl. Geochem.*, **3,** 185–203.

Papunen, H. & Gorbunov, G.I. (eds), 1985. Nickel deposits of the Baltic Shield and Scandinavian Caledonides, *Bull. Geol. Surv. Finland,* **333.**

Šafanda, J., 1995. Effect of thermal conductivity anisotropy of rocks on the subsurface temperature field, *Geophys. J. Int.*, **120,** 323–330.

Schön, J., 1983. *Petrophysik,* Ferdinand Enke Verlag, Stuttgart, Germany (in German).

Shen, P.Y. & Beck, A.E., 1991. Least square inversion of borehole temperature measurements in functional space, *J. geophys. Res.*, **96,** 19 965–19 979.

Shen, P.Y., Pollack, H.N., Huang, S. & Wang, K., 1995. Effects of subsurface heterogeneity on the inference of climate change from borehole temperature data: model studies and field examples from Canada, *J. geophys. Res.*, **100,** 6383–6396.

Simonen, A., 1980. The Precambrian in Finland, *Geol. Surv. Finland Bull.*, **304.**

Van der Kamp, G. & Bachu, S., 1989. Use of dimensional analysis in the study of thermal effects of various hydrogeological regimes, in *Hydrogeological Regimes and Their Subsurface Thermal Effects,* pp. 23–28, eds Beck, A.E., Garven, G. & Stegena, L., Geophys. Monog. **47,** AGU, Washington, DC.

Wang, K., 1992. Estimation of ground surface temperatures from borehole temperature data, *J. geophys. Res.*, **97,** 2095–2106.