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Ground temperature history from two deep boreholes in Central France

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ABSTRACT

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Ground temperature histories were inverted from temperature measurements in two deep boreholes (700 and 1000 m) in central France. The study has identified three main climatic episodes over the past 1500 years: (1) a climatic optimum at ca 1000 AD, (2) the little ice ages with a minimum at ca 1600–1700 AD, and (3) recent warming over the past 150–200 years. The results, which confirm a previously published analysis of past climate in France, exhibit trends similar to those found in other parts of the world.

Introduction

Two deep boreholes were drilled in granitic intrusions located in the Limousin region of the Massif Central, in France. The borehole at Auriat (1°36E, 45°53N, alt. 520 m) was drilled to a depth of 1000 m; continuous temperature logging was performed in 1981. Core samples were taken and thermal conductivity was measured by the divided bar method on 100 samples. The 700 m deep borehole at Villechabrolle (1°35E, 46°1N, alt. 500 m) was logged for temperature in 1983. Unfortunately, continuous coring was not performed and only two core samples were acquired for thermal conductivity measurements. The temperature logs obtained in both boreholes exhibit a regular increase with depth, with a gradient of about 30 mK m^{-1}. They do not present any striking evidence for a climatic signal such as a gradient reversal in the shallow part of the borehole observed in some parts of the world. However, the transient perturbation of the temperature profiles is nevertheless present and on the same order as those observed in eastern Canada; this perturbation is even slightly larger than it appears when the effect of the radioactive heat production, which is high (5–6 μW m^{-3}) in these 300 Ma old granites, is included. A brief description of the geological and geophysical setting of these intrusions can be found in Vasseur et al. (1990). The climatic signal in the Auriat borehole has already been analyzed by Vasseur et al. (1983). The Villechabrolle data have not been interpreted so far. The main objective of this note is to present a short summary of the climatic information presently available from these two boreholes in central France. The present study uses an inversion technique slightly different from that of Vasseur et al. (1983) and is based on a much

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simpler and more reasonable assumption of homogeneous conductivity. It confirms the results reported previously by Vasseur et al. (1983). Borehole temperature profiles from central France are affected by the end of the last glaciation and have recorded three main events over the past 1500 yr: (1) a warm period at ca 1000–1200 AD, (3) the little ice ages with cooling starting ca 1500 AD and the minimum at ca 1700 AD and (3) the recent warming starting at ca 1800–1850 AD.

Analysis of the temperature profiles

For an homogeneous, isotropic, source-free half space, the temperature at depth z, $T(z)$, is the superposition of the equilibrium temperature and of $T_t(z)$ the perturbation induced by the time varying surface temperature condition:

$$T(z) = T_0 + q_0 R(z) - AM(z) + T_t(z) \tag{1}$$

where T_0 is the equilibrium ground temperature, q_0 is the surface heat flow density, A is the radioactive heat production, $R(z)$ is the thermal resistance between the surface and the depth z, and $M(z)$ is the moment i.e.:

$$R(z) = \int_0^z \frac{\mathrm{d}z'}{K(z')} \tag{2a}$$

$$M(z) = \int_0^z \frac{z'\,\mathrm{d}z'}{K(z')} \tag{2b}$$

where $K(z)$ is the thermal conductivity measured on core samples and/or evaluated from the lithology.

The inversion problem consists in determining the surface temperature history and the equilibrium heat flow from the temperature vs depth and from the thermal conductivity data. The method used is based on the generalized inverse for a linear underdetermined system of equations (Lanczos, 1961). It is described in detail by Mareschal and Beltrami (1992) and by Beck et al. (1992, this issue).

The present temperature perturbation $T_t(z)$ in a semi-infinite solid with past surface temperature $T_0(t)$, where t is time before present, is given by (e.g. Vasseur et al., 1983):

$$T_t(z) = \frac{z}{2\sqrt{\pi\kappa}} \int_0^\infty T_0(t) t^{-3/2} \exp\left(-\frac{z^2}{4\kappa t}\right) \mathrm{d}t. \tag{3}$$

where κ is the thermal diffusivity.

Integration of Eq. (3), for an instantaneous change of the surface temperature T_i at times t_i before present, yields:

$$T_t(z) = T_i \operatorname{erfc} \frac{z}{2\sqrt{\kappa t_i}} \tag{4}$$

where erfc is the complementary error function.

Because short period variations can be neglected, the surface temperature can be approximated by the average surface temperature over K time intervals of equal duration Δ, i.e:

$$T_0(t) = T_k \quad (k-1)\Delta \le t \le k\Delta \tag{4a}$$

Equation 1 can then be written as:

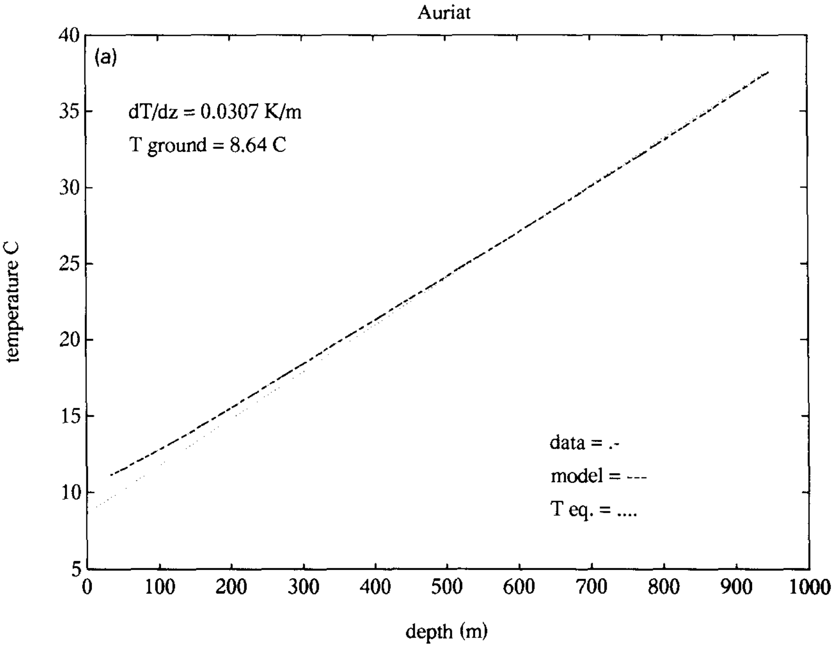
$$\Theta_j = A_{jl} X_l \tag{5}$$

where Θ_j is the measured temperature at depth z_j corrected for the heat production between the surface and that depth (i.e. $AM(z)$ in Eq. 1), X_l is a vector containing the unknowns $\{T_0, q_0, T_1, \ldots, T_K\}$ and A_{jl} is a matrix each row of which contains 1 in the first column, the thermal resistance to depth z_j, $R(z_j)$, in the second column, and the K elements formed by evaluating the difference between complementary error functions at depth z_j and time $t_{k-1} = (k-1)\Delta$ and $t_k = k\Delta$:

$$A_{jk+2} = \operatorname{erfc}\left\{\frac{z_j}{2\sqrt{\kappa t_{k-1}}}\right\} - \operatorname{erfc}\left\{\frac{z_j}{2\sqrt{\kappa t_k}}\right\} \tag{6}$$

This yields an underdetermined system of linear equations which can be solved for T_k by singular value decomposition (SVD) (Lanczos, 1961; Jackson, 1972; Menke, 1989). This approach is theoretically attractive because SVD can be used to effectively reduce the impact of noise and errors on the solution. Practically, the effect of noise and errors on the solution is reduced by discarding the part of the solution corresponding to the smaller singular values which is most affected by small changes in the data. This effectively attenuates the instability of the solution, but it also lowers the resolving power of the method. The selection of a singular value cutoff is thus the result of a trade-off between resolution and stability.

An alternative parameterization of the ground temperature history has also been used where the distribution of the time steps is no longer uniform but follows a logarithmic law. The latter approach has two advantages: (1) the increasing duration of the time intervals compensates for



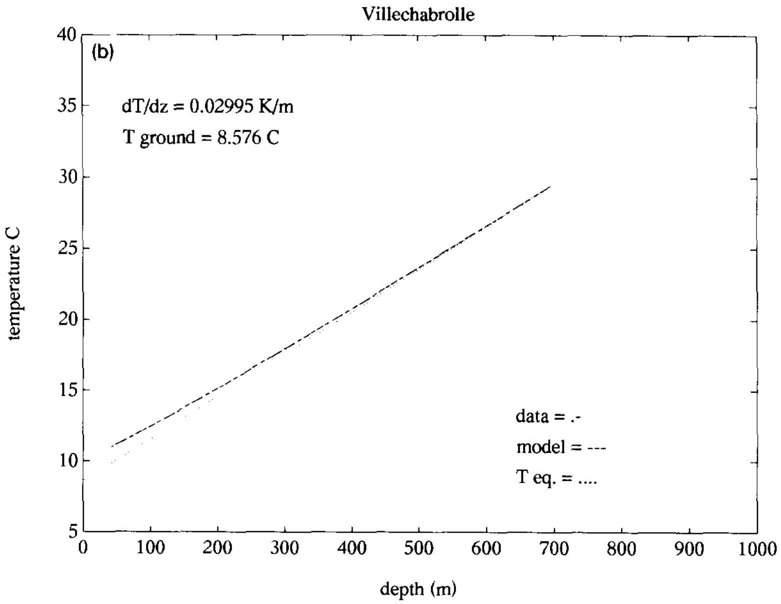


Fig. 1. Temperature profiles at (a) Auriat and at (b) Villechabrolle. The dot–dash line is the measured temperature, the dashed line is the model line and the dotted line is the equilibrium temperature determined by inversion.

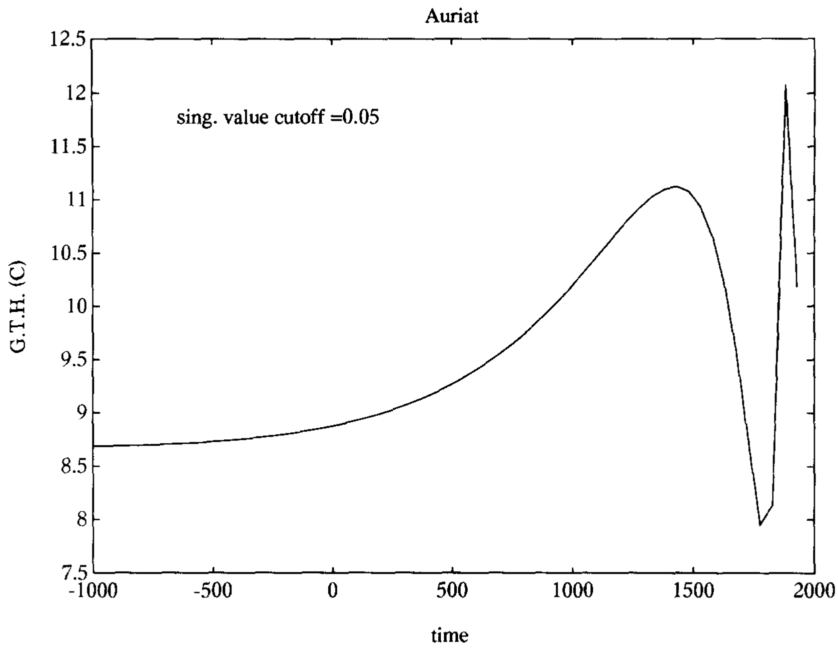


Fig. 2. Ground temperature history of the past 3000 yr at Auriat. The ground temperature history is approximated by 60 intervals of 50 yr each. The time is in yr AD.

the decreasing resolution at the early times, and (2) a long temperature history can be approximated with a limited number of parameters without loss of resolution for the very recent past.

The highest frequencies of past surface temperature variations that can be detected depend on the parameterization and on the singular value cutoff. For the logarithmic parameterization, the

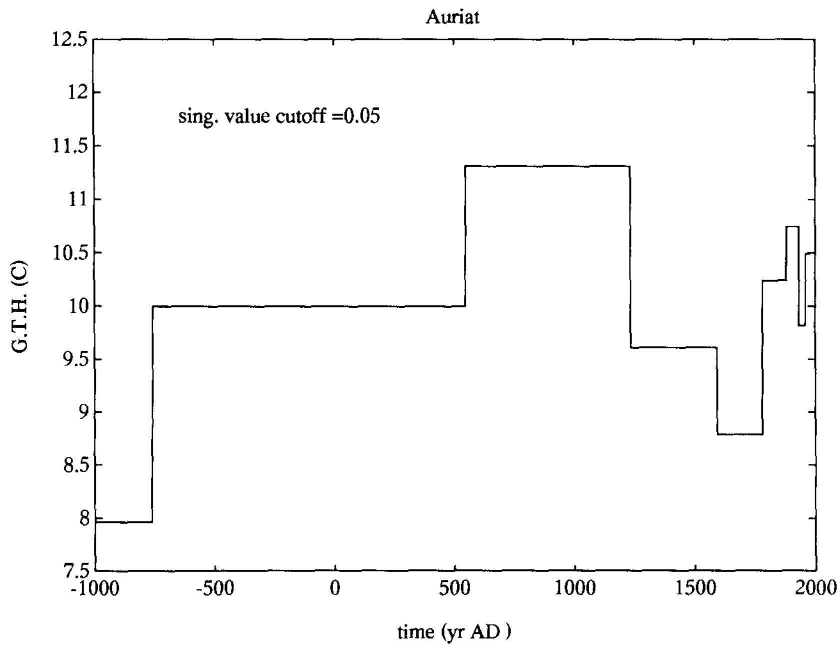


Fig. 3. Ground temperature history of the past 3000 yr at Auriat. The distribution of time steps follows a logarithmic law.

period of the oscillations that can be resolved is about one-third the time when they occured. For the uniform distribution of steps, the period depends strongly on the singular value cutoff: for a cutoff value of 0.05, which was used in this study, it is about 500 yr for an oscillation that took place 1000 years ago.

Ground temperature history of central France

Figure 1 shows for the two sites the measured and the equilibrium temperature profiles that was determined by inversion. The shallowest 40 m of each temperature log were discarded because of distinctive effects of water circulation. At both sites, the maximum difference between the measured and the calculated equilibrium temperature is about 1.4°C at 40 m depth.

Figure 2 shows the ground temperature history (GTH) obtained for the borehole at Auriat with a uniform distribution of time intervals (60 intervals of 50 yr each). For the present inversion, the thermal conductivity was assumed constant and equal to the mean of 100 measurements. This assumption differs from the one used in the previous inversion of the same data where the variations of conductivity with depth were included. Actually, there is no reason to assume that there is a horizontal layering of conductivity in this granite despite the strong variability of individual sample's conductivity (between 2.9 and 3.4 $Wm^{-1} K^{-1}$). The heat production in this granite is relatively high (5.8 $\mu W\ m^{-3}$) and the effect of radioactive heat production was included in the calculations. The GTH shows three main periods: (1) a strong warming peaking at ca 1100 AD, (2) cooling starting between 1400 and 1500 AD with a minimum at ca 1700 AD, (3) recent warming starting at ca 1800 with a maximum between 1900–1940, followed by cooling and warming. These most recent oscillations are very poorly constrained because the shallowest part of the temperature profiles was discarded.

Figure 3 shows the GTH calculated for Auriat with a logarithmic distribution of time steps. It consists of 10 steps distributed between present and 10,000 yr B.P. Only, the most recent 3000 yr are shown to make the two parameterizations easier to compare. The main trends of the recent history do not depend on the parameterization and the same features (recent warming, little ice ages, middle ages optimum) appear for both parameterizations. The amplitude of the oscillations that accompany the recent warming is reduced

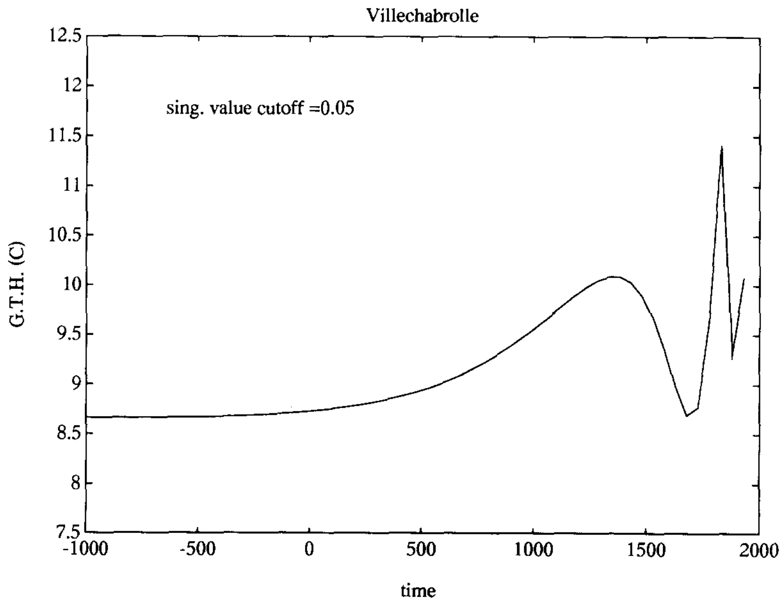


Fig. 4. Ground temperature history of the past 3000 yr at Villechabrolle for a uniform parameterization of time steps.

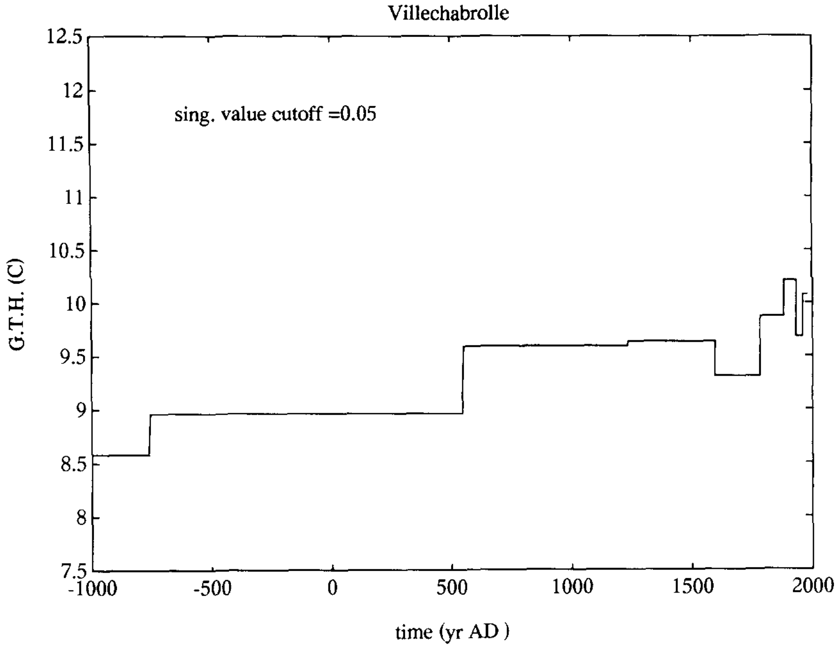


Fig. 5. Ground temperature history of the past 3000 yr at Villechabrolle for a logarithmic parameterization of time steps.

and seems more reasonable than that obtained with the uniform distribution of time steps. The peak of the middle ages optimum seems a bit shifted and is now just before 1000 AD. Also, the ground temperature history could be extended further back in time and includes the end of the

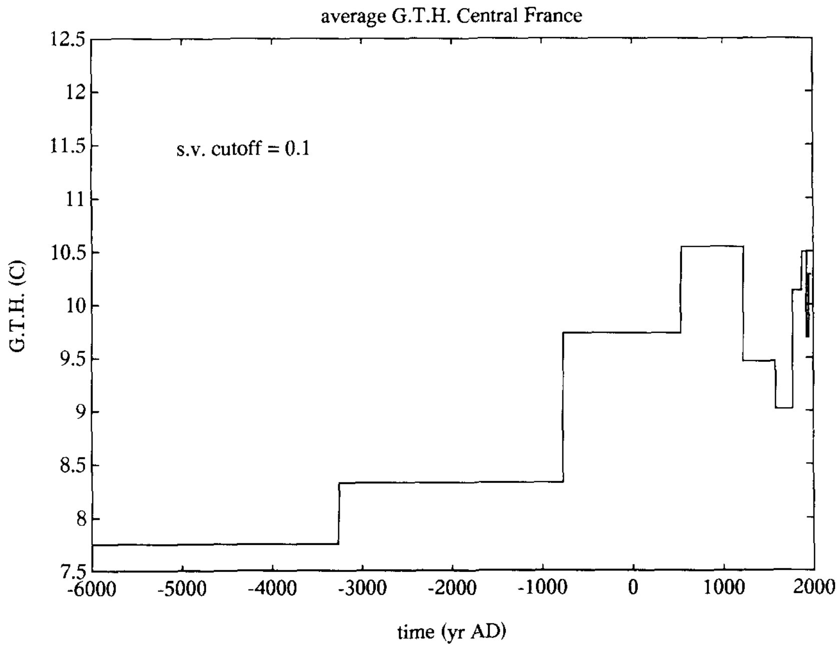


Fig. 6. Average ground temperature history of the past 8000 yr for Central France with logarithmic distribution of time steps.

last glacial period, although the resolving power is not sufficient to determine accurately the time of ending of the last glacial event or to detect any episode between this glacial period and the middle ages optimum.

Figure 4 shows the GTH calculated for Villechabrolle. It shows the same trends as Auriat, but the amplitude of the temperature variations is much weaker than at Auriat. This is also seen on Fig. 5 which shows the GTH calculated for Villechabrolle with a logarithmic distribution of time steps. Although the two histories for Villechabrolle and Auriat differ in some of the details (there is a small time lag between the two histories and the amplitude of the variations seems smaller at Villechabrolle, in particular for the middle ages optimum), both GTH contain essentially the same features. The differences between the two GTHs can be due to several factors: (1) the Auriat borehole is deeper and the older events like the middle age optimum are better resolved, (2) the assumption of a uniform conductivity might not be valid, and (3) the assumed heat production is incorrect at Villechabrolle. Unfortunately, the two latter hypotheses could not be checked because only two core samples were collected at Villechabrolle.

The two sites that are analyzed here are very close and they are in a similar geographic setting, west of the Massif Central. They should thus have recorded a similar climatic history. This seems to be indeed the case and it is therefore possible to determine the ground temperature history of the entire region by inverting simultaneously the data of both sites and assuming that they have experienced the same variations in surface temperature. The resulting average GTH is shown in Fig. 6. The surface temperature is an average between both sites and has no real significance, but the variations from the average are meaningful. The amplitude of the ground temperature variations during the past 1000 yr is on the order of 1.5°C.

Conclusions

The analysis of the temperature measurements from two boreholes in France yields information about the ground temperature history of the entire Holocene. No other deep borehole temperature data in the region are available to confirm this analysis. The major features of the inferred ground temperature history are quite similar to the ones reported previously by Vasseur et al. (1983) with a slightly different technique. Both studies have also detected climatic trends that are consistent with other interpretations of the past 1000 yr climatic history of Europe (e.g. historical records, study of glacial advances and retreats in the Alps, dendrochronology, etc.) (LeRoy Ladurie, 1983; Lamb, 1977). These main trends are very similar to those obtained in eastern Canada (e.g. Beltrami et al., 1992). The consistency between GTH obtained from borehole temperature measurements and other climatic indicators gives strong support to the proposition to analyze systematically borehole temperature data in order to extract information on the recent climatic history.

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