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Heat-flow and subsurface temperature history at the site of Saraya (eastern Senegal)

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Abstract

New temperature measurements from eight boreholes in the West African Craton (WAC) reveal superficial perturbations down to 100 meters below the alteration zone. These perturbations are both related to a recent increase of the surface air temperature (SAT) and to the site effects caused by fluids circulations and/or the lower conduction in the alterites. The ground surface temperature (GST) inverted from the boreholes temperatures is stable in the past (1700–1940) and then dramatically increases in the most recent years (1.5 °C since 1950). This is consistent with the increase of the SAT recorded at two nearby meteorological stations (Tambacounda and Kedougou), and more generally in the Sahel with a coeval rainfall decrease. Site effects are superimposed to the climatic effect and interpreted by advective (circulation of fluids) or conductive (lower conductivity of laterite and of high-porosity sand) perturbations. We used a 1-D finite differences thermal model and a Monte-Carlo procedure to find the best estimates of these sites perturbations: all the eight boreholes temperatures logs can be interpreted with the same basal heat-flow and the same surface temperature history, but with some realistic changes of thermal conductivity and/or fluid velocity. The GST trend observed in Senegal can be confirmed by two previous boreholes measurements made in 1983 in other locations of West Africa, the first one in an arid zone of northern Mali and the second one in a subhumid zone in southern Mali. Finally, the background heat-flow is low ($30 \pm 1\,\mathrm{m\,Wm^{-2}}$), which makes this part of the WAC more similar with the observations in the southern part ($33 \pm 8\,\mathrm{m\,Wm^{-2}}$) rather than with those in the northern part and in the PanAfrican domains where the surface heat-flow is 15–20 $\mathrm{m\,Wm^{-2}}$ higher.

1 Introduction

Surface heat-flow provides a direct information on the thermal structure of the lithosphere. In continents, the cratons have been stable for more than 1000 Myr and their temperature distribution is near the conductive equilibrium (Jaupart and Mareschal, 2007), with the notable exception of the near surface perturbed by the past climatic fluctuations and/or the meteoric fluids circulations. Heat-flow is usually obtained at the Earth surface as the product of the temperature gradient measured at thermal equilibrium in shallow boreholes (typically 100 to 1000 m) by the thermal conductivity measured in the laboratory, preferentially on cores from these boreholes. Therefore, where the thermal gradient is recorded is also where the equilibrium is the most likely perturbed and it is therefore essential to understand where and how it is actually perturbed. On the other hand, the perturbations in boreholes related to the climatic fluctuations provide further information on the traditional proxies used to reconstruct the past surface temperature history (Huang et al., 2000), especially on the low-frequency variations (Moberg et al., 2005). The significance of the temperature reconstructions based on boreholes measurements relies therefore on the assumption that no other perturbation exists, but most of time the suspect data are selected arbitrarily.

Heat-flow measurements are not well distributed at the Earth surface and there still exist undocumented areas in Africa or South America. These areas also lack for long term air temperature records and climatic proxies, and therefore new boreholes measurements can provide essential information for the climatic evolution of equatorial and tropical areas. Here we present eight new measurements from a site in the West African Craton (WAC) and also in the Sahel domain, which represents the transition between arid and sub-humid climatic conditions. Although these measurements have been obtained in nearby boreholes, they show differences in the upper 100 m for which we examine the possible causes in order to obtain reliable estimates of both the surface heat-flow and of the past temperature history.

2 Geological context

The heat-flow measurements are located near the village of Saraya, at the south-eastern border of Senegal (Fig. 1). This region belongs to the Kédougou Kénieba Inlier

(KKI) in the WAC, limited by the Panafrican belt (Mauritanides) on the western side and the Phanerozoic sediments of the Taoudeni basin on the eastern side. The KKI consists of Early Paleo-proterozoic terranes (Birimian) formed during the Eburnean orogeny at ~2200–2000 Myr and is composed of a volcano-sedimentary greenstone belt intruded by calc-alkaline granites. Early Proterozoic kimberlitic pipes intrude the Biriminan terranes in the southern part of the WAC, including the Kedougou-Kenieba region where they could be early Cretaceous (Michel, 1996). The Saraya batholith is one of these granitic intrusions as large as 2000 km^2 formed at about 2079 Myr (Gueye et al., 2007). In the area of the heat-flow measurements, it is a two micas syenitic granite with pegmatite equivalents composed of coarse grains with 23–32 percent of quartz, 47–62 percent of microcline (potassic feldspar), 10–15 percent of plagioclase, 1–2 percent of muscovite and 1–2 percent of biotite (Ndiaye, 1994). The upper 20–30 m is formed by saprolithes (laterite, lithomarge and granitic sands from the top to the bottom), which represents the alteration products of granites in a tropical context (Diouf, 1999). The water level is generally shallow (less than 10 m when we did measurements) and the granitic sands above the fresh granite can form good aquifers locally (Diouf, 1999).

3 Previous heat-flow measurements

Only few heat-flow measurements are available in the WAC (Fig. 1). The first measurements in the southern part (Leo Rise) revealed low values (Chapman and Pollack, 1974; Beck and Mustonen, 1972) confirmed by later measurements (Sass and Behrendt, 1980; Brigaud et al., 1985). Measurements in the northern part of the WAC (Brigaud et al., 1985; Rimi and Lucazeau, 1987; Lesquer et al., 1989; Takherist and Lesquer, 1989; Lesquer et al., 1991) have conversely shown values 15–20 m Wm^{-2} higher. The Panafrican border also shows higher values in the north (Brigaud et al., 1985; Rimi and Lucazeau, 1987; Latil-Brun and Lucazeau, 1988; Lesquer et al., 1989; Takherist and Lesquer, 1989) than the western border (Latil-Brun and Lucazeau, 1988; Lesquer et al., 1991). Lesquer and Vasseur (1992) have correlated the higher heat-flow in the north to the presence of a regional mantle anomaly that also affects the large scale gravity field and the P-waves propagation.

4 Climatic context

The Senegal climate is at the transition between arid to hyper-arid (Sahara desert) in the north of Senegal and dry sub-humid in the south. This transition zone is known as the Sahel that runs from Senegal to Ethiopia. The Sahel climate is basically controled by the intertropical convergence zone (ITCZ), which determines the dry season (November–April) when it migrates southward and the wet season (May–October) when the monsoon winds flow from the Atlantic. The air temperature varies according to these seasons, with higher values and smaller amplitude during the dry season (Fall et al., 2006). Several meteorological stations have recorded temperatures since the mid 20th century, and the average annual temperature evolution shows a significant increase, mostly caused by the increase during the dry season in the western part of Senegal (Fall et al., 2006). We have analysed the trend of the air temperature at the Kedougou and Tambacunda meteorological stations (the closest from the site of Saraya). The Tambacounda station has almost a continuous record since 1941, while the Kedougou station starts only in 1967 and has many gaps. We filtered the monthly averages (obtained at http://data.giss.nasa.gov/gistemp/station_data/) with a 2 years and a 10 years running window (Fig. 2), which shows an increasing trend of about $0.0215\,^{\circ}\mathrm{C\,yr^{-1}}$ since the 1950s. This trend is less important than in the Western part of Senegal (Fall et al., 2006), but more important than the world average for the same period of time (Fig. 2).

The Sahel zone was also strongly affected in the 1960s by desertification and starvation following the increasing dryness and overuse of agriculture capacities (Zeng, 2003). The increase of SAT in eastern Senegal correlates well with the decrease of precipitations as well as the increase of the agricultural activity (Fig. 2). The relative importance of the forcing factors (human misuse of the land or climatic changes) has long been debated, but some recent models (Giannini et al., 2003) primarily related the southward shift of the ITCZ to the increasing sea surface temperatures in the Atlantic and the positive land-atmosphere feedback. Because of this shift, the region of Saraya which was sub-humid in the 1960s is now in semi arid conditions (Fall et al., 2006; Lebel and Ali, 2009). Additionally, the long-term temperatures recorded by few meteorological stations in the Sahel are weakly but inversely correlated to the rainfall index (Hulme et al., 2001). GSTs derived from boreholes should therefore constrain the temperatures anomalies before surface air temperatures measurements.

5 Boreholes temperature measurements at Saraya

The temperature measurements (Fig. 3) have been obtained in 8 mining exploration boreholes near the village of Saraya. The temperature was determined with a thermistor probe calibrated in the laboratory with a better than 0.005 K accuracy. Measurements were recorded at 5 m depth intervals. We initially started temperatures measurements at 30 m depth (the base of the alteration zone) but later we recorded from 10 m in order to better constrain the climatic signal, as the water level was around 6–8 m when we did measurements. The bottom of the measurements is generally between 230–250 m, but in few of them it was not possible to log below the tubed part (100 m). The temperatures and temperature gradients are very similar in the deep part (depth >125 m), but differ significantly in the upper hundred meters.

6 Rocks thermal conductivity

Thermal conductivity was measured on cores by a divided bar method (Misener and Beck, 1960) at the IPGP geothermal laboratory. Only one (1054) of the boreholes where we obtained temperature measurements was cored and therefore only this one was sampled at 20 m intervals from 125 m to 245 m. A single conductivity determination with the divided bar method relies on five measurements at steady-state, obtained on five different water-saturated plugs with thickness varying from 2 mm to 10 mm. The thermal resistance of each plug is measured and the thermal conductivity is calculated by a least squares linear fit to the resistance/thickness data. This procedure allows the detection of sample-scale variations of mineralogy unrepresentative of the large-scale average rock composition. It also eliminates isolated heterogeneities and yields a truly representative conductivity that characterises large-scale crustal heat conduction. The accuracy of the measurement is better than 3 percent (Mareschal et al., 2005).

The thermal conductivity (Table 1) is homogeneous in the lower part of the borehole (2.66, 2.75 and 2.62 Wm^{-1} K^{-1} at 205 m, 219 m and 243 m respectively). At 182 m, thermal conductivity is significantly lower (2.22 Wm^{-1} K^{-1}), and then higher (2.97 and 2.78 Wm^{-1} K^{-1}) at 160 m and 142 m respectively. The last core at 124 m gives a value of 2.61 Wm^{-1} K^{-1}. This represents large variations but not exceptional for granites, which can be partly attributed to some changes in the mineralogy (less quartz and more feldspar at 182 m and 124 m). The higher thermal conductivity at 142 m and 160 m is correlated with a lower temperature gradient, insuring a constant heat-flow. At 124 m, the low temperature gradient (8.4 m Km^{-1}) is still influenced by the climatic signal, which explains the absence of correlation with the thermal conductivity. Finally, only one conductivity measurement (182 m) remains unexplained, and we assumed that it is not representative of the overall thermal structure. We assumed therefore that 2.66 Wm^{-1} K^{-1} is representative of the thermal conductivity of the Saraya granite, as it represents both the average of all the measurements as well as the value in the deepest part of the borehole (more than 200 m) where the thermal gradient is not affected by the superficial perturbations.

7 Ground Temperature History

The past temperature variations at the surface of the Earth are recorded as perturbations in the subsurface temperature gradient (Birch, 1948). The depth at which the perturbations are filtered out (“thermal length”) depends on the wavelength of the climatic fluctuations (about 50 centimetres and 10 m for daily and annual variations). For the temperature anomalies recorded in the Saraya boreholes (order of 120 m), one can expect that the surface temperature was perturbed for a period of about 100 yr before measurements. Several previous studies provided algorithms to estimate the ground surface temperature history from the temperatures anomalies measured in boreholes. We have used the singular value decomposition (SVD) inversion method developed by Mareschal and Beltrami (1992), and limited the reconstruction to a period of 310 years before 2010 (date of the measurements). We inverted each borehole profile separately with the same time steps and cutoff values ($f = 0.01$). In all cases, the ground surface temperature increases monotonously, with an acceleration during the second half of the twentieth century. This acceleration is compatible with the air temperature increase recorded at the Tambacounda station since 1940 (Fig. 4). The two main results are first the absence of significant GST increase before 1920–1940 and secondly the amplitude variations of GST in the different boreholes. However, the GST trend observed at boreholes 1054, 1057 and 1059 is the most consistent with the SAT variations recorded at the Tambacounda station (Fig. 4): we expect therefore that sites effects can affect the temperatures record in other boreholes.

7.1 Site effects

Different causes have been invoked to explain such effects: urbanisation, landscape or subsurface changes can affect the climatic signal recorded in boreholes. In Canada, the variable snow cover can control the relation between the air temperature and the ground temperature (Mareschal and Beltrami, 1992). In central Africa, the deforestation before mining exploration has probably caused the local increase of the GST (Sebagenzi et al., 1992). The local effects of hydrology and/or thermal conductivity can be also important according to the repeated boreholes temperature measurements in the Netherlands (Kooi, 2008). At the site of Saraya, boreholes are very close each other (100 to 700 meters) except D1056, which is 5 km away, surface conditions are similar (savanna) with no known recent change. It is more likely that the observed differences are related to subsurface conditions that can change with the local characteristics of the alteration domain (about 30 m below the surface). This alteration domain is generally formed by laterites in the uppermost part which evolve progressively to highly permeable granitic sands at the contact with fresh granite (Diouf, 1999). Thermal conductivity of the laterites is very low (0.5–1.15 $\mathrm{W\,m^{-1}\,K^{-1}}$ according to Meukam et al., 2004), and because their porosity can be locally high (up to 50 percent according to Diouf, 1999, page 52), the thermal conductivity of granitic sands can also be low (water filling the pores has a low thermal conductivity). Permanent circulations of fluids are also possible in the porous and unconsolidated granitic sands, which can also affect the propagation of the climatic signal in the ground. In order to test these different effects, we built a 1-D finite differences model that include the effect of the surface temperature variations at the upper boundary condition and the effect of vertical or horizontal fluids circulations in a superficial aquifer. We considered three types of perturbations in the upper part of the boreholes (lower conductivity λ_a in the alteration zone, horizontal circulation of meteoric fluids at a velocity V_h and/or vertical circulation at a velocity V_z in the aquifer at the bottom of the alteration domain). The surface temperatures variations with time have been fixed at the same values (those recorded at the Tabacounda meteorological station) for all boreholes, but the average value T_s as well as the local heat-flow q_0 can be adjusted separately. There are therefore five parameters (λ_a, V_h, V_z, T_s and q_0) that are inverted by a Monte-Carlo procedure to minimise the RMS difference between observed and calculated temperatures at depth.

7.2 vertical fluid flow in the alteration zone

The climatic perturbations can be amplified (or reduced) by vertical downward (upward) fluid circulations (Kooi, 2008). We have tested several models including climatic fluctuations at the surface and vertical fluid flow. The domain where fluids circulate is between 20 and 30 m, in the granitic sands and in the upper fractured zone of the granite. The models assume that the fluid flow started long before the climatic variations at the surface, and therefore the initial conditions include the effect of a permanent flow.

Some results with vertical fluid circulations are shown in Fig. 5: as expected, the downward flow increases the climatic perturbation while the upward flow reduces it. The best model for borehole 1059 is the conductive assumption, while borehole 1050 requires an upward vertical velicity of $\sim 3\,\mathrm{m\,yr^{-1}}$. This could be possible only in a closed convective system as this value exceeds the annual rainfall (Fall et al., 2006) and would occur in the less permeable part of the alteration zone.

7.3 horizontal fluid flow in the alteration zone

Assuming that superficial aquifers are parts of a system where meteoric fluids recharge at the surface, a permanent horizontal circulation can remove some of the conductive vertical heat-flow, and therefore limit the propagation of the climatic wave to the depth. In order to estimate how much fluid flow is required, we assumed that this effect is equivalent to a heat sink proportional to the difference between the rock temperature T_r and the fluid temperature T_f, and to the fluid velocity V:

$$\rho_f c_f V (T_r - T_f) \tag{1}$$

ρ_f and c_f are the density and specific heat of the fluid. In a first approximation, we assume that the temperature of the fluid equals the temperature T_s at the surface and that the permeable zone where fluids can flow is located between 20 and 30 m. Some results are shown in Fig. 6 and compared to the observations of two temperatures profiles at borehole 1059 and 1050. The temperature profile in the first one is best explained by a small horizontal circulation ($0.02\,\mathrm{m\,yr^{-1}}$), while it requires 0.10–0.15 $\mathrm{m\,yr^{-1}}$ to explain the attenuation of the upper temperature anomaly in borehole 1050.

7.4 Low thermal conductivity in the alteration zone

Similarly, we have tested the effect of low conductivity (between 1 to $2\,\mathrm{W\,m^{-1}\,K^{-1}}$) in the alteration zone (0–30 m) with respect to the standard "normal" value of granites ($2.65\,\mathrm{W\,m^{-1}\,K^{-1}}$). Figure 7 shows that the lower the conductivity in the alteration zone, the lower the apparent climatic perturbation in the borehole. The best value of the thermal conductivity to explain the temperature profiles at boreholes 1050 is $1.25\,\mathrm{W\,m^{-1}\,K^{-1}}$. This is a likely value for granitic sands with 50–60 percent porosity as well as for laterite (Meukam et al., 2004).

7.5 Monte Carlo Inversion

We used a Monte Carlo inversion to determine the best solutions according to variations of the five parameters: the thermal conductivity λ_a in the alteration zone between 0 and 30 m, the horizontal fluid velocity V_h in an aquifer between 20 and 30 m, the vertical fluid velocity V_z at the base of alteration zone and the top of the granite (between 20 and 30 m), the reference surface temperature T_s to which a perturbation depending on time is added and the basal heat flow q_0. The quality of results is estimated by the total RMS defined by:

$$\mathrm{RMS} = \frac{1}{n}\sqrt{\sum_{i=1}^{n}(T^i_{\mathrm{obs}} - T^i_{\mathrm{calc}})^2} \qquad (2)$$

where n is the number of temperatures measured in the borehole. The best solution obtained for the lowest value of the RMS is given in Table 2 and in Fig. 3 for all the Saraya boreholes.

8 Discussion

8.1 Origin of the local anomalies

The temperature profiles in the eight boreholes at the site of Saraya are all affected by the surface air temperature increase during the twentieth century, but they do not all record the same amplitude of this increase. Two boreholes (1050 and 1014) show a lower perturbation than the others. Because all of these boreholes are very close each others and because there is no obvious change of the local surface conditions, we have attributed the causes of these differences to the subsurface conditions and more specifically to the nature of the alteration zone. The drilling record mentions for instance difficulties at site 1050 related to the stability of the saprolith and one other borehole was totally collapsed during our visit. The base of the alteration zone is formed by coarse grains granitic sands, which can be locally aquifers. We have no details on the exact nature of this saprolith, but we did simple numerical models including either the changes that can affect the conductive structure (high porosity decreases thermal conductivity significantly) or the circulation of fluids. The observed temperature profiles can be generally explained by several processes or combinations of processes (vertical, horizontal fluid flow or thermal conductivity). The best model is not necessarily the only way to explain the observations: for instance, we give a combination of low conductivity, horizontal and vertical velocity for borehole 1014, but it could be explained as well by a horizontal circulation with a velocity of $\sim 0.2\,\mathrm{m\,yr^{-1}}$ consistent with the 0.15 $\mathrm{m\,yr^{-1}}$ velocity found for borehole 1050.

8.2 Past surface temperature history in West Africa

According to the heat conduction theory, cyclic variations of the surface temperature are attenuated at a depth depending on the wavelength ("thermal length"). At the site of Saraya, the maximum depth at which temperature is perturbed is about 100 m, which means that only perturbations from the twentieth century are recorded. This is illustrated by the ground surface temperature history resulting from the inversion of boreholes data, which does not show significant increase before 1920. The only other data published for this part of Africa have been obtained in Niger by Chapman and Pollack (1974) and the GST history available on line (http://www.ncdc.noaa.gov/paleo/borehole/reconstruction/ne-k6b.html and http://www.ncdc.noaa.gov/paleo/borehole/reconstruction/ne-donkolo4.html) have been analysed by Huang et al. (2000). The temperatures have been recorded in 1972 and only from the depth of 50 m (Donkolo) and 80 m (Kourki K6B). Therefore, the inverted GST does not catch the increase of temperature in mid twentieth century (Fig. 8). We have also processed boreholes data at two sites in Mali published by Brigaud et al. (1985): these measurements have been acquired in March 1983, but upper parts of the temperature profiles show a gradient inversion similar to that observed at Saraya. The GST history inversion leads to the same conclusions: there is no major change of the surface temperature before the mid twentieth century, but a major increase after. The Sahel and the Sahara regions are considered in the projection of IPCC (Christensen et al., 2007) as the most vulnerable to the temperature increase (3.5–4 °C at the end of the century), and the rapid change in the mid twentieth century inferred from boreholes suggests that this scenario could be underestimated anyway. The reference surface temperature inferred from the boreholes is 29.2 ± 0.2 °C, which is about 1 °C higher than the SAT at Tambacounda; however, as this meteorological station is rather distant, it is not possible to establish if this offset is related to the complexity of surface heat transfers or only to the locations of measurements.

8.3 Heat-flow and thermal regime of the WAC

The heat-flow at Saraya is low ($30 \pm 1\,\mathrm{mW\,m^{-2}}$), confirming the previous measurements ($33 \pm 8\,\mathrm{m\,Wm^{-2}}$) in the southern domain of the West African Craton (Leo Rise) and extending the areal distribution of these low values. Such low values are always observed in Archean cratons and associated with low radiogenic heat-production in the crust: for instance, the heat-flow at Voisey bay in Canada (Mareschal et al., 2000) is $22\,\mathrm{m\,Wm^{-2}}$, but the heat-production is only $0.4\text{–}0.7\,\mathrm{\mu Wm^{-3}}$, which is consistent with a mantle heat-flow of $\sim 10\text{–}15\,\mathrm{m\,Wm^{-2}}$.

The heat production of the Saraya granite and of the lower crustal rock below are not however well known. There are only few Uranium and Thorium data (Ndiaye, 1994; Ndiaye et al., 1997; Pawlig et al., 2006) that lead to a high estimate of the heat-production ($1.85 \pm 0.78\,\mathrm{\mu Wm^{-3}}$). Other Birrimian granites in West Africa have also rather high value: in Guinea and Sierra Leone (Thiéblemont, 2008 personnal communication) the average heat production is 1.5 µWm^{-3}. In Ghana (Harcouët et al., 2007), the average heat production of monzogranites is 1.04 ± 0.44 µWm^{-3}. In Burkina Faso, the Tenkodogo–Yamba granitoids have an average heat production of 1.35 ± 0.49 µWm^{-3} (Naba et al., 2004). Such values do not support the existence of a thick granitic layer, as the lithosphere cannot exceed 200–250 km in West Africa according to the tomographic studies (Ritsema and van Heijst, 2000; Sebai et al., 2006; Pasyanos and Nyblade, 2007; Priestley et al., 2008). The thermal lithosphere defined as the intercept of the continental geotherm and the mantle solidus can be also estimated. The continental geotherm can be calculated with some assumption on the thermal conductivity, providing that the surface heat-flow and distribution of heat source are known. But we can also search for the thickness of the enriched granitic layer that can fit the lithospheric thickness. For a lithosphere thickness of 250 km, there is no solution if the heat-production in the lower crust is equal to 0.4 µWm^{-3} as assumed by Lesquer and Vasseur (1992). If it is only 0.3 µWm^{-3}, then the thickness of granite can be estimated to 3–4 km maximum. The mantle heat-flow in that case is 13–14.5 m Wm^{-2}, which is comparable to similar estimates in Canada (Mareschal et al., 2000). The site of Saraya is also located in a diamondiferous province (Fig. 1), which requires for the genesis and the preservation of diamonds a heat-flow lower than 40 m Wm^{-2} and a lithosphere thicker than 150 km (Morgan, 1995).

9 Conclusions

The measurement at the site of Saraya, in the Precambrian window of the Kédougou-Kéniéba-Inlier, confirms the existence of a very low heat-flow in the southern part of the West African Craton, consistent with the thick lithosphere revealed by several tomographic studies and the occurrence of diamond bearing kimberlites. The measurements at the site of Saraya also reveal a recent surface temperature increase of at least 1.5 °C since the mid twentieth century, consistent with the surface air temperature increase observed at meteorological stations, and extend the surface temperature history in the past, which did not change significantly before. The dramatic change in the mid twentieth century is therefore more likely related to the global warming that appears stronger in this part of Africa.

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Table 1. Thermal conductivity measured at site 1054.

Depth (m)	Thermal Conductivity ($Wm^{-1}K^{-1}$)	(s.d.)
124.00	2.61	0.05
141.55	2.78	0.05
160.50	2.97	0.05
182.40	2.22	0.02
204.50	2.66	0.08
218.90	2.75	0.06
243.00	2.62	0.06

Table 2. Heat-flow and temperature gradient at the site of Saraya. (1) Borehole number; (2) Longitude; (3) Latitude; (4) Measurement depth range (m); (5) Temperature Gradient ($\mathrm{m\,K\,m^{-1}}$) in the lower part of the borehole; (6) heat-flow ($\mathrm{m\,W\,m^{-2}}$) resulting from the Monte Carlo inversion; (7) Reference surface temperature (°C); (8) Thermal conductivity in the alteration zone (10–30 m) ($\mathrm{W\,m^{-1}\,K^{-1}}$); (9) Vertical fluid velocity between 20 and 50 m ($\mathrm{m\,yr^{-1}}$); (10) Horizontal fluid velocity between 10 and 20 m ($\mathrm{m\,yr^{-1}}$); (11) Total RMS (°C).

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
1054	–11.75585	12.84058	30–235	11.94	30.8	29.16	2.65	0.0	–0.75	0.0204
1057	–11.75506	12.84041	30–235	12.19	31.0	29.05	2.65	0.0	–0.74	0.0170
1059	–11.75522	12.84144	30–225	12.04	30.4	29.26	2.65	0.021	0.0	0.0207
1055	–11.75570	12.84772	30–235	11.59	29.7	29.40	2.65	0.070	0.0	0.0113
1050	–11.75474	12.84882	30–245	12.61	31.1	29.21	2.65	0.153	0.0	0.0173
1056	–11.72043	12.87992	10–90	16.47	30.0	29.04	2.65	0.0	–1.29	0.0134
1014	–11.75387	12.84637	10–145	15.57	30.6	28.96	1.65	0.052	–0.99	0.0342
1015	–11.75784	12.84575	10–110	13.74	29.9	29.31	2.65	0.059	0.0	0.0321

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4, 599–626, 2012

Heat-flow and subsurface temperature history

F. Lucazeau and F. Rolandone

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

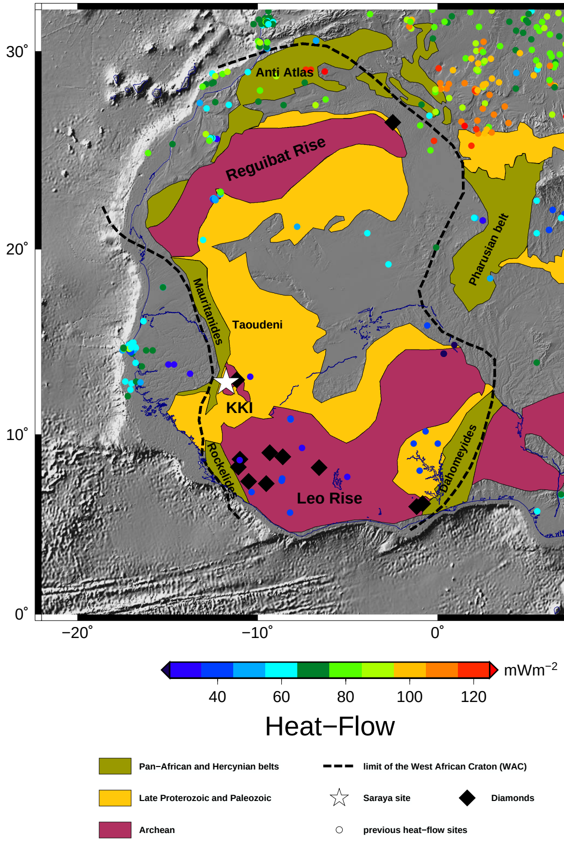

Fig. 1. Location of the Saraya site in the Kédougou Kénieba Inlier (KKI). The main geological units are reported from Gueye et al. (2007) and the heat-flow data from an updated version of the global heat-flow database (Goutorbe et al., 2011).

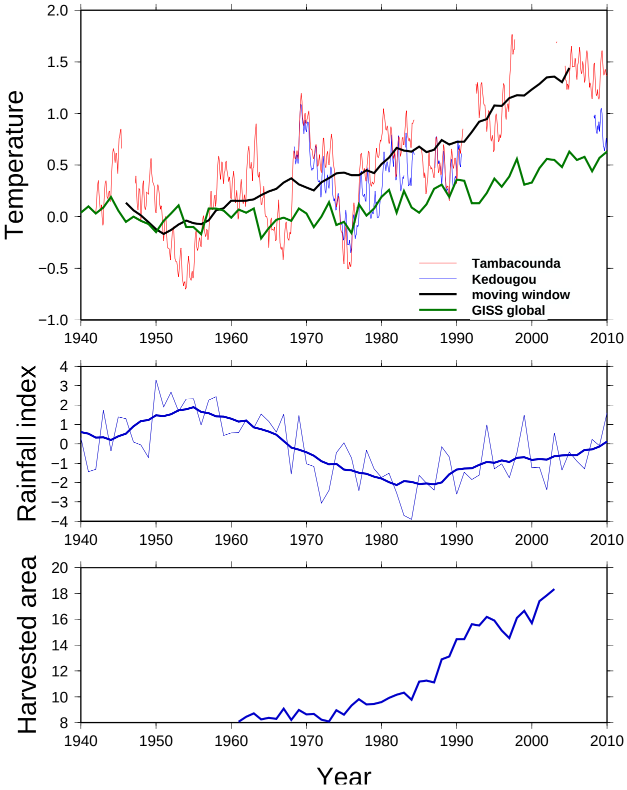

Fig. 2. Upper part: 2 and 10 years running average air temperatures at the meteorological stations of Tambacounda and Kedougou. The world annual average from the Goddard Institute for Space Studies (http://data.giss.nasa.gov/gistemp/graphs/Fig.A2.txt) is also shown. Middle part: Sahel precipitations (cm/month) from NOAA NCDC (http://jisao.washington.edu/data/sahel/). The thick line is a 10 years moving window. Lower part: Area (10^6 ha) devoted to crops in the Sahel since 1960 (Kandji et al., 2006).

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀▮
▶▮
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

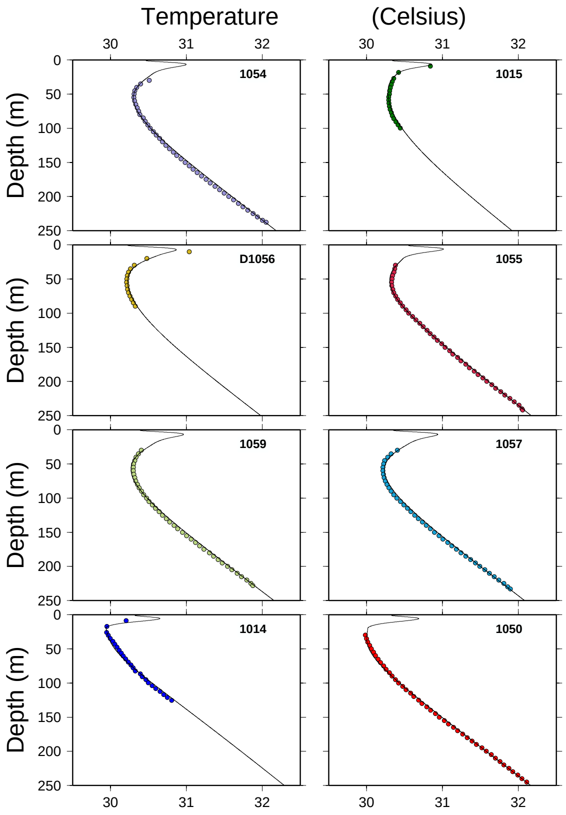

Fig. 3. Temperature versus depth profiles. Circles are measurements, thin lines are results of the numerical model including both the variations of surface temperature and the site effects. Parameters of the models are specified in Table 2 (see also discussion section).

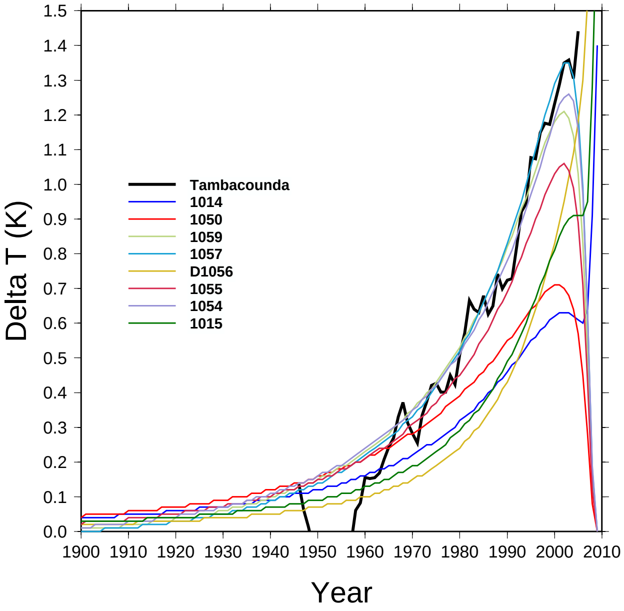

Fig. 4. Ground temperature history inverted at each borehole compared to the trend at the Tambacounda meteorological station. Only the period 1900–2010 is shown as the surface temperature variation is negligible between 1700–1900. The decrease observed after year 2000 in several boreholes is an artefact of the inversion when the upper 30 m are not constrained by data (this does not appear for boreholes where we measured temperature between 10 and 30 m).

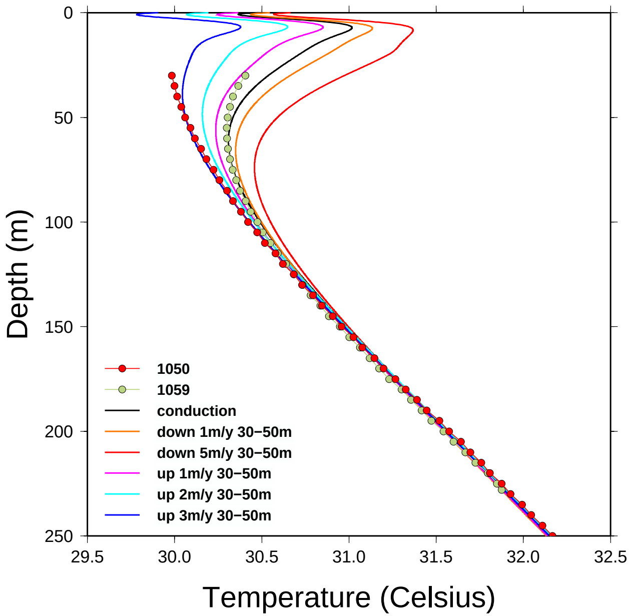

Fig. 5. Temperature logs at 1050 and 1059 compared to model results including the surface temperature variations recorded at the Tambacounda meteorological station and a vertical fluid circulation at the base of the alteration zone (20–50 m).

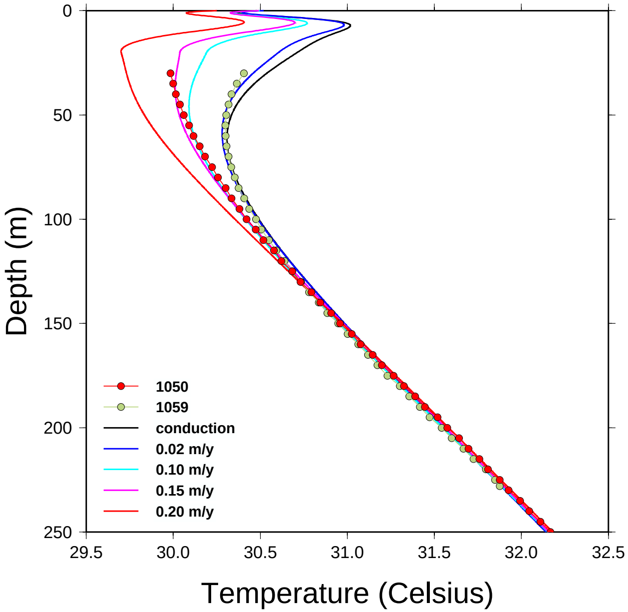

Fig. 6. Temperature logs at 1050 and 1059 compared to model results including the surface temperature variations recorded at the Tambacounda meteorological station and the horizontal fluid circulation in an aquifer between 10 and 20 m.

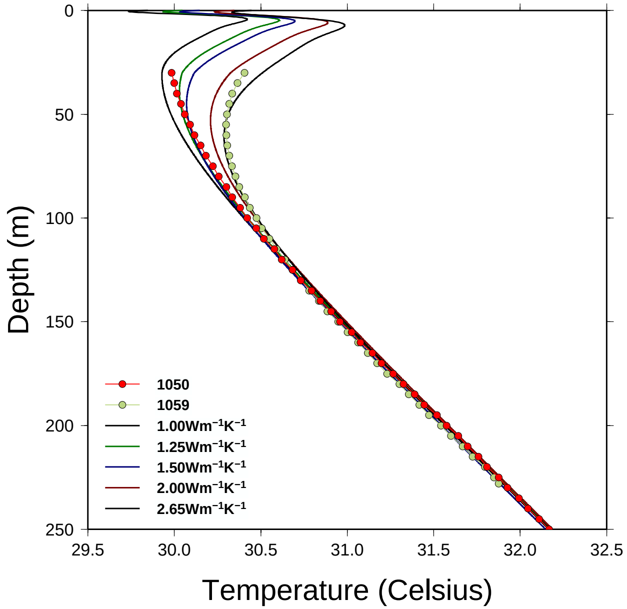

Fig. 7. Temperature logs at 1050 and 1014 compared to model results including the surface temperature variations recorded at the Tambacounda meteorological station and a low thermal conductivity in the laterite and saprolithe between 0 and 30 m.

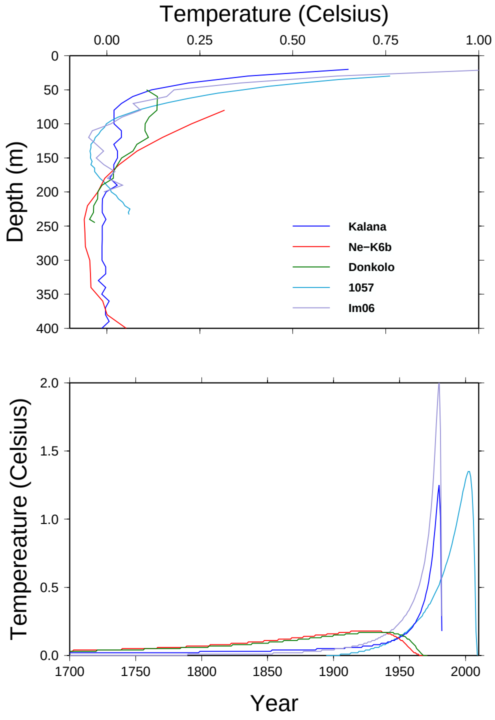

Fig. 8. Comparison of the ground surface temperature from boreholes data in West Africa. Upper Part: Temperature offset from the linear gradient; Lower Part: Ground Surface Temperature history. Data from Huang et al. (2000) at sites Ne-K6b and Donkolo have been reinterpreted with the same procedure as other boreholes.