Finisterra, **XLIV, 87, 2009, pp. 109-116**

ON THE POSSIBILITY OF USING GEOTHERMAL DATA FOR PALEOCLIMATE STUDIES IN ANTARCTICA: THE EXPERIENCE FROM PORTUGAL

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Abstract – The study of the climate in the past and the climate change in mainland Portugal using geothermal data has started in 1996. Reconstruction of ground surface temperature (GST) history from temperature logs measured in a 200 m deep borehole located 5 km away from the town of Évora in Portugal, indicates a warming of 1K since the second half of the nineteenth century to the middle of the 90s of the twentieth century, increasing considerably in the last 10 years. Results of the reconstruction (based on a functional space inversion – FSI – method) are compared with air temperatures recorded at the Lisbon meteorological station since 1856. The air temperature time series display a warming trend with the amplitude about 1K for the same period. The coupling of the air and ground temperature changes and their downward propagation by heat conduction was confirmed by repeated logging in November 2003, 6.7 years after obtaining the first temperature log. The method can be used in paleoclimatic studies in Antarctica as well as in areas with permafrost.

Keywords: Climate change, borehole temperatures, paleoclimatology.

Resumo – Acerca da possibilidade de utilizar dados geotérmicos em estudos paleoclimáticos na Antárctida: a experiência em Portugal. A utilização de registos de temperatura em furos e o estudo do passado das alterações climáticas em Portugal continental teve início em 1996. A reconstrução da evolução da temperatura na superfície do solo a partir de registos de temperatura obtidos numa sondagem com 200 metros de profundidade, localizado a cerca de 5 km da cidade de Évora, evidencia um aquecimento da ordem de 1K desde a segunda metade do século XIX até meados dos anos 90 do século XX, com um aumento relativamente rápido nos últimos 10 anos. Os resultados da reconstrução da evolução da temperatura à superfície do solo, baseados num método de inversão, conhecido por método de inversão no espaço funcional, são comparados com a série de temperaturas do ar registadas na estação meteorológica de Lisboa desde 1856. A série de temperaturas do ar evidencia, também, um aumento da temperatura média do ar de cerca de 1K para o mesmo período. O acoplamento térmico entre o ar e o solo e a propagação do sinal climático para o

Recebido: 03/12/2007. Revisto: 13/04/2009. Aceite: 19/05/2009.

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interior da Terra por condução térmica foi confirmado através da repetição dos registos de temperatura em Novembro de 2003, 6,7 anos depois de ter sido obtido o primeiro registo de temperatura no furo. A metodologia descrita pode ser utilizada em estudos paleoclimáticos na Antártida e de acoplamento térmico entre o ar e o solo em regiões onde exista *permafrost*.

Palavras-chave: Alterações climáticas, temperaturas em furos, paleoclimatologia.

Résumé – SUR LA POSSIBILITE D'UTILISER DES DONNEES GEOTHERMIQUES POUR DES ETUDES PALEOTHERMIQUES EN ANTARCTIQUE: UNE EXPERIENCE PORTUGAISE. L'étude des climats passés et du changement climatique au Portugal a commencé à utiliser des données géothermiques en 1996. La reconstitution de l'histoire des températures de surface (GST), à partir de séries de températures enregistrées au long d'un sondage de 200 m de profondeur, situé à 5 km de Évora, indique un réchauffement de 1K, depuis la seconde moitié du XIX^{e} siècle jusqu'au milieu des années 90 du XX^{e} siècle, avec une forte accélération pendant la dernière dizaine d'années. Les résultats de cette reconstitution, basée sur une méthode d'inversion fonctionnelle spatiale (FSI), sont comparés avec les données de température enregistrées à la Station météorologique de Lisbonne, depuis 1856. La série des températures de l'air montre une tendance au réchauffement d'environ 1K dans la même période. Le parallélisme entre l´évolution des températures de l'air et du sol et leur propagation verticale par conduction thermique, a été confirmé par répétition de diagraphies de température en Novembre 2003, 6.7 années après l'obtention de la première série de températures. Cette méthode peut être appliquée aux études paléoclimatiques en Antarctique, ainsi que dans les régions à permafrost.

Mots-clef: Changement climatique, sondage thermique, paléoclimatologie.

I. INTRODUCTION

Recent climate change (warming or cooling) detected in most temperature logs obtained in wells all over the globe is related with changes in the energy budget at the earth's surface which result from an increasing or decreasing of atmospheric temperature. Oscillations of the temperature at the surface of the Earth resulting from climatic changes penetrate into the subsurface with the high frequency components of the temperature signal progressively attenuated as it propagates downwards. As a result the temperature field at depths that range from tens to hundreds of meters contains information on the history of the long-term ground surface temperature. Therefore, under certain conditions (such as, transfer of thermal energy by conduction only, steady-state thermal regime, negligible water flow in the geological formations and no convection, and unchanged vegetation cover), precise temperature logs obtained in wells can be used to reconstruct the ground surface history which is related to the climate history in the region of the well (Cermak, 1971; Lachenbruch and Marshall, 1986; Lewis, 1992; Pollack and Chapman, 1993; Beltrami and Harris, 2001).

Since 1996 there has been an attempt to study the evolution of the past climate in mainland Portugal using temperature logs obtained for geothermal studies. From an initial set of 90 wells that have temperature logs only eigth were chosen as good for estimating ground surface temperature (GST) in the past (Correia and Safanda, 1999).

These wells were logged since 1989 and the depth range of the temperature logs vary between 155 and 485 meters. To increase the quality and reliability of the temperature reconstructions, in 2005, the Geophysical Centre of the University of Évora has installed a geothermal climate change observatory in a farm 5 km from Évora. In this observatory there is a 200 m deep borehole (TGQC-1) in which 14 platinum resistances are placed at different depths inside the borehole and two other are placed 5 cm and 2 m above the ground surface. A data-logger allows temperatures inside the borehole and in the atmosphere to be recorded every 30 minutes.

In this paper we are going to consider the TGQC-1 borehole only which, since 1997, after being cased, has been used for geothermal studies and, in particular, for GST reconstruction studies. The methodologies performed in this borehole have the potential to successfully be used in geothermal studies in Antarctica with the objective of reconstructing the climate in the past and study the air-ground coupling.

II. METHOD AND RESULTS

To estimate the ground surface history near the TGQC-1 borehole the functional space inversion (FSI) method of Shen and Beck (1992) was used. This inversion methodology allows the incorporation of uncertainties in the data as *a priori* standard deviations. The *a priori* geothermal model for the TGQC-1 borehole was assumed as a homogeneous half-space with thermal properties based on measurements made on rock samples collected from the granitic formations in the region of the well. For thermal conductivity, thermal diffusivity, and radiogenic heat production the values used in the inversion process were 2.8 $Wm^{-1}K^{-1}$, 1.3×10^{-6} m^2s^{-1}, and 2×10^{-6} Wm^{-3}, respectively.

Figure 1 shows the temperature logs obtained at three different times (March 1997, November 2003, and November 2004) in the TGQC-1 borehole. The difference in the temperatures measured in the three logs is also shown for two different periods (dotted lines). From figure 1 it is obvious that there has been an increase in the temperature of the well since 1997, which can be observed to depths as deep as 150 meters. Figure 2 shows the temperature log obtained in 2003 in the same well (curve 1), as well as the steady-state component of the subsurface temperature (dashed line 2) and the reduced temperature (curve 3), which is the difference between the actual temperature log and its steady-state component. Therefore, curve 1 in figure 2 is actually a superposition of a steady-state temperature signal with a transient signal which represents the response of the ground to long-term surface temperature changes.

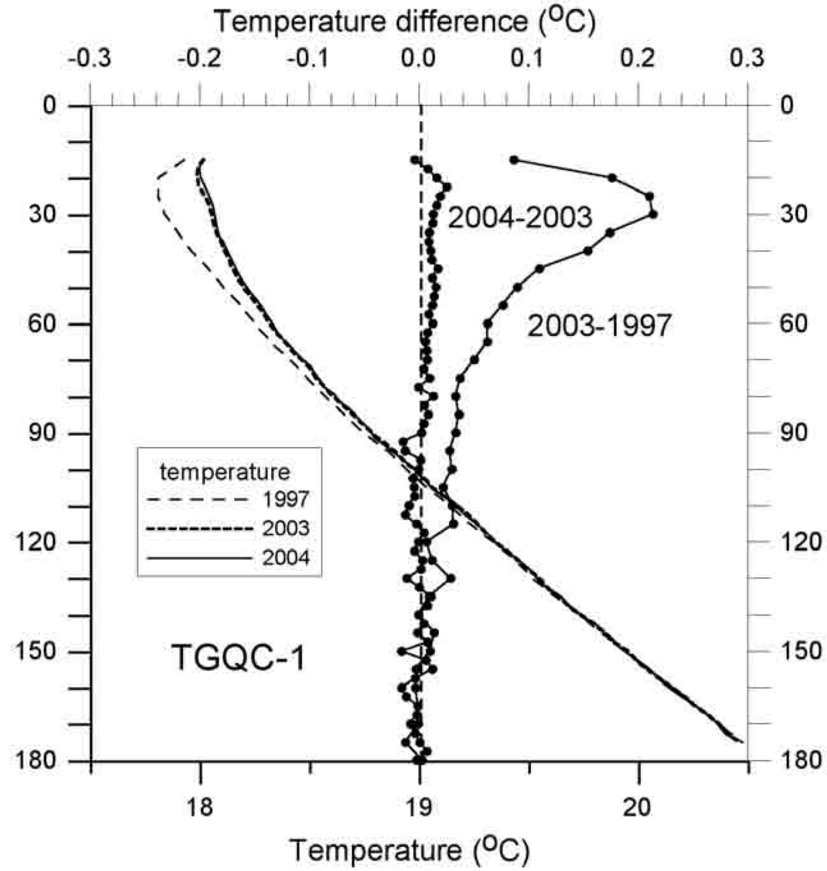

Fig. 1 – Three temperature logs (solid lines and dashed lines) obtained in March 1997, November 2003, and November 2004 in the TGQC-1 borehole. The dotted lines represent the difference of temperatures between the 2003-1997 and 2004-2003 temperature logs.
Fig. 1 – Três diagrafias de temperatura (linhas a cheio e a tracejado) obtidas no furo TGQC-1 em Março de 1997, Novembro de 2003 e Novembro de 2004. As linhas ponteadas representam a diferença de temperatura entre 2003-1997 e entre 2004-2003.

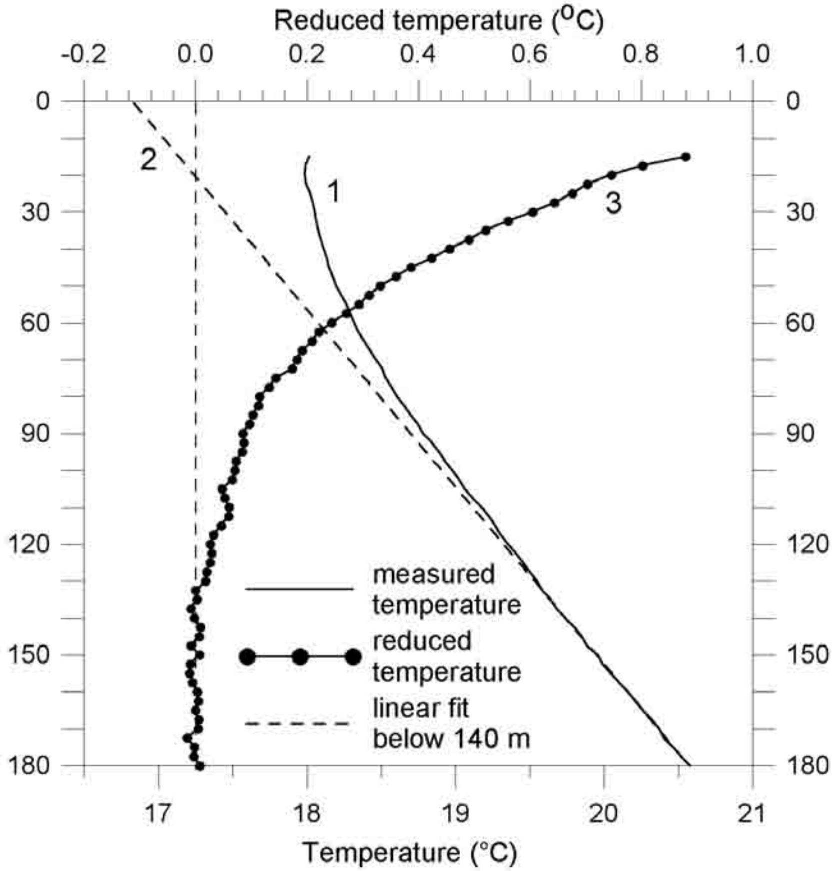

Fig. 2 – Temperature log obtained in 2003 in TGQC-1 borehole (line 1), as well as the steady-state component of the subsurface temperature (dashed line 2), and the reduced temperature (line 3), which is the difference between the actual temperature log and its steady-state component. Line 3 represents the climatic signal in TGQC-1 borehole.
Fig. 2 – Diagrafia de temperatura obtido em 2003 no furo TGQC-1 (linha 1), componente estacionária da temperatura do solo (linha 2) e temperatura reduzida (linha 3). A temperatura reduzida é a diferença entre a temperatura actual e a componente estacionária da temperatura do solo. A linha 3 representa o sinal climático no furo TGQC-1.

Figure 3 shows the results of applying the FSI method to the transient component of the temperature log obtained in the TGQC-1 borehole with different levels of noise (curves 1-3) and for the thermal parameters mentioned above for the region of the well. The results of the inversion are also compared with the air temperature measured in the weather station of Lisbon, about 100 km from the location of the well. The air temperature time series for that weather station, which have started to be collected in 1856 (Leite and Peixoto, 1996), are shown in figure 4. The main observation from this figure is that there is an average increase of the air temperature of about 1.1ºC for the entire period of measurements (about 0.0075ºC/year) with a noticeable increase of the warming trend after 1970 (about 0.048ºC/year). In figure 3 the relative amplitude of the mean annual temperature is compared with the FSI inversion of the transient component of the temperature log obtained in the TGQC-1 borehole in November 2003. Even though the fit is not very good, the warming trends in curves 1-3 and curve 4 are similar, in particular in the last 30-40 years.

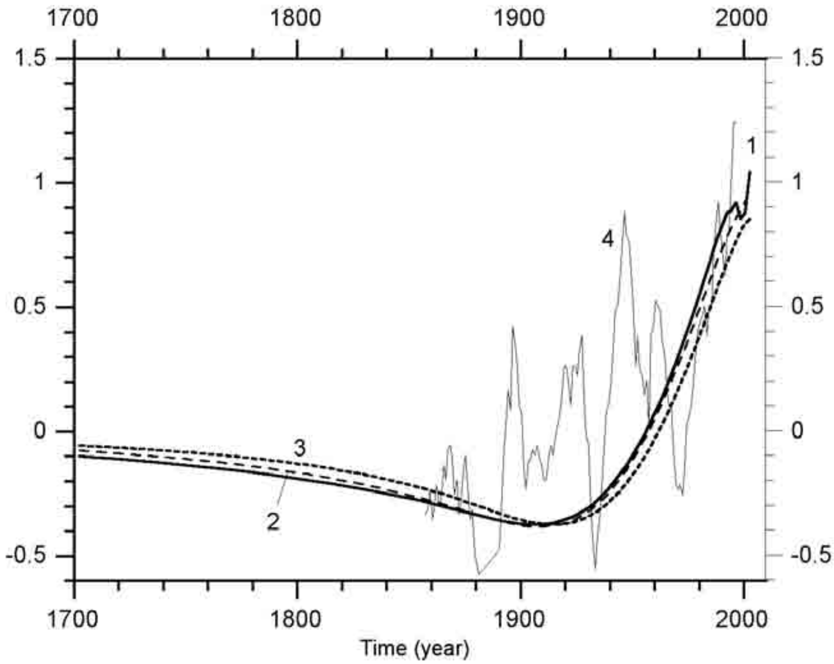

Fig. 3 – Ground surface temperature reconstructions obtained by applying the FSI method to the transient component of the temperature log obtained in the TGQC-1 borehole, with different levels of noise (lines 1-3) and for the thermal parameters mentioned in the text. The reconstructions were performed assuming a priori standard deviations in the thermal conductivity and in the temperature of: 0.5 W/m.K and 0.02 K, for line 1; 1.0 W/m.K and 0.05 K, for line 2; and 2.0 W/m.K and 0.10 K, for line 3. Superimposed in the reconstructions is the mean annual temperature time series from Lisbon weather station (line 4). The fit is good for the last 30-40 years of the plot.

Fig. 3 – Reconstruções da temperatura do solo por aplicação do método de inversão no espaço funcional à componente transiente do diagrama de temperatura obtido no furo TGQC-1, com diferentes níveis de ruído (linhas 1-3) e para os parâmetros térmicos definidos no texto. As reconstruções foram realizadas assumindo desvios padrão a priori da condutividade térmica e da temperatura de: 0,5 W/m.K e 0,02 K, para a linha 1; 1,0 W/m.K e 0,05 K, para a linha 2; e 2,0 W/m.K e 0,10 K, para a linha 3. Sobreposta às reconstruções apresenta-se a série de temperaturas médias anuais da estação meteorológica de Lisboa (linha 4). Para os últimos 30 a 40 anos existe uma boa coincidência entre as diferentes reconstruções e os dados meteorológicos.

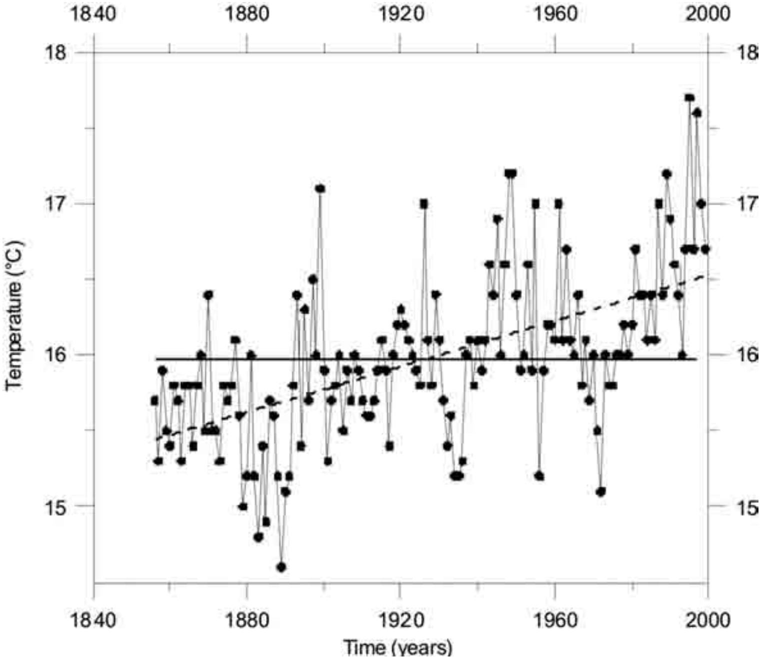

Fig. 4 – Air temperature time series for Lisbon weather station (dots). Also shown are the average temperature (solid line) and the linear fit to the to the temperature data (dashed line).
Fig. 4 – Série de temperaturas do ar para a estação meteorológica de Lisboa (círculos). A linha a cheio representa a temperatura média para todo o período das leituras e a linha a tracejado a regressão linear que melhor se adapta aos dados de temperatura do ar.

Much more work is needed to evaluate the climatic change in the territory of mainland Portugal using geothermal data; however, the results presented here are encouraging. Further research is thought for the area of the TGQC-1 borehole. In particular, monitoring temperatures above, at, and below the ground surface to study the air-ground coupling and understand the energy transfer at the boundary layer between the ground and the atmosphere. It is expected that the geothermal climate change observatory installed in the TGQC-1 borehole in 2005 will provide the necessary temperature data to start those studies.

III. CONCLUSIONS AND APPLICATION OF THE METHODOLOGY TO ANTARCTICA

By measuring the temperature in the well TGQC-1 (since 1997) it is possible to state that the non-linear component of the temperature logs represents a transient component of the subsurface temperature (climatic signal), which has increased in the last years.

The air temperature measured in the weather station of Lisbon since 1856 shows an increase of the mean annual air temperature of about 0.0075ºC/year with an increasing warming trend of about 0.048ºC/year after 1970 and the same temperature increase is observed in the TGQC-1 well which is located about 100 km.

The implication of these results is that the temperature increase observed in the temperature logs of the TGQC-1 borehole is a consequence of the long-term air temperature increase and the ground temperatures lag the air temperatures.

The methodology briefly described here can be applied to boreholes in Antarctica. However, because of the low thermal conductivity of rocks and ice, the imprint of any climatic signal for the last century can only be detected in boreholes with depths of about 150 meters. As a matter of fact, the annual oscillation of the air temperature can be detected to depths of about 10-20 metres. Therefore, for reconstructing the ground surface temperature for the last decades of the XX century boreholes 50 m deep or deeper are needed. Shallow boreholes around 25 m deep will not provide any information about the air temperature evolution in the last century; however, they might provide information about the mechanisms of heat transfer between the air and the ground, and so help to understand the thermal evolution of regions with permafrost, as is the case in the Antarctic continent.

ACKNOWLEDGMENTS

Part of the research presented in this paper was done with the support of Fundação para a Ciência e a Tecnologia, Portugal, and the Geophysical Centre of the University of Évora. The anonymous reviewers are thanked for the valuable suggestions to improve the paper.

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