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Foreword: Inference of climate change from geothermal data

Over the past century, both anthropogenic greenhouse gases and the Earth's surface temperature have been increasing. While there is little doubt about the increases each of these signals exhibits, there has been considerable debate about a causal relationship between these signals. Is warming at the Earth's surface linked to increases in atmospheric concentrations of greenhouse gases? Is observed warming simply a natural climatic fluctuation or is it tied to industrialization and the concomitant increase in atmospheric concentrations of greenhouse gases? How great has the warming been relative to pre-industrial temperature levels? A key to understanding the anthropogenic impact on post-industrial climate is understanding past climatic fluctuations. Insight into this issue has come from paleoclimatic records of climate change with an emphasis on 'proxy' records of temperature. Traditional proxy records of temperature change include dendroclimatic (tree rings and ring density), ice core and ice melt records, δO^{18} records, and coral records to list a few. These records extend the history of surface temperature into the past prior to the advent of widespread instrumental records.

Geothermal data provide an important supplement to traditional proxy records of temperature change. The thermal regime of the solid Earth is a function of the heat flow from the Earth's interior and the temperature at its surface. The heat flow from the Earth's interior is governed by processes that fluctuate on geologic time-scales, and can therefore be assumed to be in steady-state for time-scales relevant to the shorter time scales of climatic studies (decades, centuries, millennia). Temperature changes at the Earth's surface diffuse into the subsurface by heat conduction, and are manifested at a later time by a perturbation to the background temperature field. The downwards propagation of this disturbance depends on the thermal diffusivity of rock, and because this is a small value (10^{-6} m^2 s^{-1}), boreholes of several hundred meters depth contain a response to ground surface temperature histories over the last millennium. Although high-frequency components of a changing ground surface temperature are suppressed by heat diffusion, temperature–depth profiles contain a robust signal of the long-term surface temperature history. Advantages of temperature–depth data in paleoclimatic studies include: (1) a direct measure of temperature; (2) sensitivity to surface temperature trends over the last 5 centuries or longer; (3) continuous rather than seasonal sensitivity; and (4) potentially good spatial coverage on the continents (Chapman, 1995).

The significance of changing ground surface temperatures was recognized almost as soon as temperature–depth measurements were made in boreholes (Lane, 1923; Hotchkiss and Ingersoll, 1934). However, the objective of these measurements was the heat flow from the Earth's interior, and climatic perturbations to an otherwise linear temperature–depth profile were considered noise and routinely removed in a climatic correction (Benfield, 1939; Bullard, 1939; Birch, 1948). This perspective remained mostly unchanged until Lachenbruch and Marshall (1986) alerted the rest of the geothermal community, that climatic information contained in temperature–depth profiles could fruitfully be used to address concerns about surface warming. Working with temperature–depth data from permafrost regions in northern Alaska, they showed a 2–4°K warming at the Earth's surface over the last hundred years. Ensuing studies have broadly focused in three

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areas: inversion techniques, regional studies, and integration of GST results with other paleoclimatic and climatic data.

The application of modern geophysical inverse theory to the determination of GST histories from temperature–depth data began with the work of Vasseur et al. (1983), using Backus–Gilbert formalism. Although many inverse approaches have been developed to solve for GST histories (e.g., Wang, 1992), three inverse approaches have gained widespread popularity. These include the simple but robust ramp and step models, sometimes referred to as last event analysis (e.g., Lachenbruch and Marshall, 1986), staircase models consisting of a series of steps, which employ a singular value decomposition (SVD) algorithm (e.g., Beltrami and Mareschal, 1991, 1992), and functional space inversions (FSI) (Shen and Beck, 1991). These inverse algorithms have been compared in a series of papers (Beck et al., 1992; Shen et al., 1992). In a study directly comparing SVD and FSI, Shen et al. (1996) suggested that when noise suppression is not an issue, both SVD and FSI techniques yield similar results.

Regional results from North America indicate 1–2°K of warming in central and eastern Canada (Beltrami and Mareschal, 1991, 1992; Wang et al.,1994), warming between 0°K and 2°K for the northern US plains (Gosnold et al., 1997), 1.2–1.5°K of warming in north central Oklahoma (Deming and Borel, 1995), an average of 0.6°K warming in the northern Basin and Range (Chisholm and Chapman, 1992; Chapman et al., 1992), and between 0.5°K and 0.8°K warming in southeastern Utah (Harris and Chapman, 1995). Although the timing of warming is loosely constrained, these studies indicate that ground warming has occurred over the past 100–200 years. Results from Europe show similar characteristics. As a whole, these results show a decrease in the magnitude of warming with decreasing latitude consistent with latitudinal variation observed in SAT records (Hansen and Lebedeff, 1987; Jones et al.,1999), and predicted by General Circulation Models (Barnett et al., 1991).

It has been approximately 8 years since the first special volume on geothermal data and climate change has been published by Global and Planetary Change (Lewis, 1992). These works contributed significantly to this field of research, advancing the use of borehole temperatures to infer surface temperature histories. It is in keeping with this tradition that we set out to form a collection of current research in this area.

The collection of works presented here captures very well the current avenues of research on this subject. Since the publication of the first special issue in Global and Planetary Change, several attempts have been made to reconcile meteorological and proxy records with climatic inferences from geothermal data (e.g. Harris and Chapman, 1997; Beltrami et al, 1995; Beltrami and Taylor, 1995). A preliminary analysis of the worldwide data set for climatic inferences from geothermal data have recently been published (Huang et al., 1997, 2000; Pollack et al., 1998). Furthermore, there are now in existence permanent facilities, monitoring continuously meteorological and subsurface variables. These observatories are specifically designed to understand and evaluate the energy exchanges at the air/ground interface (Putnam and Chapman, 1996; Beltrami, 2000; Beltrami et al., 2000).

Several papers in this issue concentrate on long-term climatic inferences from deeper boreholes (Safanda and Rajver, this issue; Demezhko and Shchapov, this issue). Regional studies are represented by works on Finland (Bodri et al., this issue), Canada (Majorowicz and Safanda, this issue), Portugal (Correia and Safanda, this issue) and Russia (Golovanova et al., this issue). Four works in this issue are focused on the important issue of understanding the energy exchanges at the air/soil interface. These energy exchanges are not well understood due to their complex and complicated character. Beltrami (2001-this issue) reports on the first year of operation of a climatic observatory in Canada. Hinkel et al. (this issue) and Kane et al. (this issue) deal with the important processes determining the upper boundary condition behavior in northern regions at Alaska. They examine the role of soil moisture and non-conductive heat transfer mechanisms on the development of an active layer in regions of permafrost. Schmidt and Gosnold (this issue) analyzed a data set of meteorological and subsurface temperatures from North Dakota, in order to study the coupling of air and ground temperatures.

We are grateful to have found a forum for this research in this journal, and we hope that this issue will contribute to the continuation and advance of the research in this area in the coming years.

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