Geophysical Research Abstracts
Vol. 13, EGU2011-5709-1, 2011
EGU General Assembly 2011

Past surface temperature changes as estimated from the Outokumpu deep borehole, Southern Finland: methods and results

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The 2516 m deep Outokumpu Deep Drill Hole in eastern Finland was drilled in 2004-2005 into a Palaeoproterozoic formation with metasedimentary rocks, ophiolite-derived altered ultramafic rocks and pegmatitic granite. The down-hole temperatures have been logged five times after end of drilling and extend to day 948 after drilling. The hole is completely cored (79% core coverage) and thermal conductivity measurements were done at 1 m intervals, complemented by numerous determinations of heat production and wireline logging. The geothermal results on temperature gradient, thermal conductivity and heat flow density yield an exceptionally detailed data set, and indicate a significant vertical variation in gradient and heat flow density. Heat flow density increases from about 28-32 mW m^{-2} in the uppermost 1000 m to 40-45 mW m^{-2} at depths exceeding 2000 m. The estimated undisturbed surface heat flow value is 42 mW m^{-2}.

We present paleoclimatic results from forward and inverse transient conductive models, which suggest that the vertical variation in heat flow can mostly be attributed to a palaeoclimatic effect due to ground surface temperature (GST) variations during the last 100,000 years. The modeling suggests that the average GST was about -3 to -4°C during the Weichselian glaciation. Holocene GST values are within ±2 degree from the present average GST in Outokumpu (5°C). Nearly independent of the parametrization chosen, the post-holocene temperature history appears rather smooth, with neither a significant medieval optimum nor little ice age. In most cases, a reasonable fit could be found for depths <1500 m, with residuals less than 0.1 K for the top 1000 m, increasing up to 0.3 K even for the best cases. This is probably due to the effects of (1) fluid inflow for depths > 1500 m, (2) heterogeneity effects not consistent with 1D assumptions, and (3) a possible residual contribution of post drilling equilibration of temperatures. All these effects are not easily coped with in the framework of 1D inversion, and will be investigated in future studies.

The Outokumpu area was covered by ice sheets perhaps only during the Middle (about 60 kyrs B.P.) and Late Weichselian (about 20 kyrs B.P.) glacial maxima. Paleoclimate proxies as oxygen isotopes in mammoth teeth suggest that most of southeastern Fennoscandia was probably ice-free du in between. The paleotemperatures in the range of -1 ... -3 °C thus obtained are in a good agreement with the Outokumpu geothermal result on Weichselian average GST. The temperatures obtained for the last few thousand years are systematically higher than paleotemperature reconstructions interpolated from nearby locations. Apart from the distance to the proxy sites involved, this could be due to changes in land use and snow cover in the Outokumpu area. The reconstruction finally shows a strong recent warming of about 0.5 K in the last 50 years. The paleoclimatic interpretation of these results reveals many open questions, and up till now only preliminary or even speculative answers can be given.

The results of the current study may be improved by further development of method, e.g. by changing the constraints of the current inversion algorithm. In particular, the far too smooth postglacial warmimg, and in consequence the late occurrence of the Holocene temperature maximum is at least partly an artifact of the smoothing redularization employed. Numerical experiments with method minimizing the total variation of the GSTH will be presented. Uncertainty in the results is dealt with using a MCMC algorithm in a Bayesian framework.