New borehole-derived results on temperatures at the base of the Fennoscandian ice sheet

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Introduction

Very deep boreholes play a crucial role for the interpretation of borehole climatology, mainly because shallow boreholes, which constitute the vast majority of available data, are biased by changes of surface temperature back to the last glacial cycle (*Rath et al., 2012*). Ice sheets and their development have important effects for recently measured profile because of the particular conditions at their base. These effects are not only important for paleoclimatic interpretations, but may also allow us a glimpse "from below" at the conditions at the base of the ice sheets.
The current interest for deep boreholes in Fennoscandia resulted from a number of ICDP drilling projects in this region, which include paleoclimatic interpretations of high-quality borehole temperature measurements. Estimating past surface temperature from these measurement is a challenging task, and only will lead to meaningful results when seen in relation to a regional reconstruction. For this reason, a data set of existing deep ($\geq$1000 m) boreholes has been collected which will be interpreted jointly with the new observations form the ICDP projects (including re-logging of older boreholes). Prior knowledge and background information for each single borehole differ strongly in character and amount. Here we concentrate on the Outokumpu borehole (Finland), which was drilled in 2004, and the Russian ultra-deep SG-3 borehole. While the former led to excellent results, SG-3 is not yet fully understood.
Current activity includes the use of independent knowledge from

- an ensemble of outputs from the calibrated glacial system model (MUN-GSM),
- paleoclimatic information from different reconstructions, and
- geophysical results from surface and borehole measurements

in order to obtain consistent picture of their meaning. Here we present inversion results as well as a comparison with Ground surface Temperature Histories (GSTH) derived from the GSM. The most important step is the construction of the "synthetic" GSTHs from basal ice temperatures, driving climate, water cover related to isostatic effects or ice-dams, and GST-SAT transfer functions, which are used as a surface forcing when constructing the recent Borehole Temperature Profiles (BTP). The current procedure is surely rich in assumptions (stable vegetation, additivity of effects), and needs improvement.

Figure : Fig. 1. Location of boreholes in the Fennoscandian region.

Outokumpu Borehole (OKU)

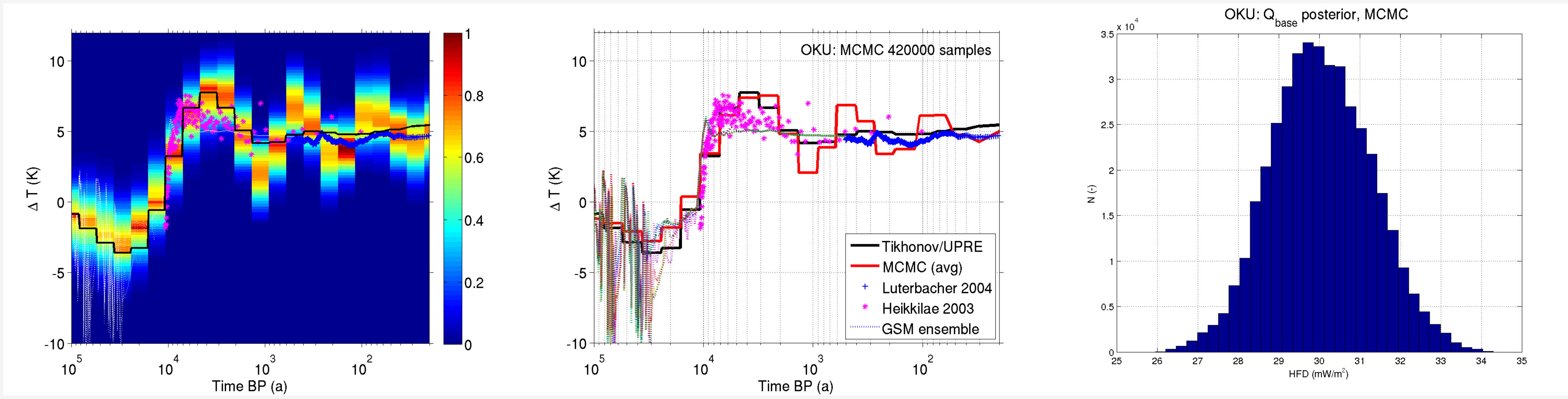

Figure : Fig. 2: Recent inversion results from the top 1800 m of the Outokumpu ICDP borehole. The pseudocolors represent results from an adaptive Metropolis-Hastings MCMC sampling (*Haario et al. 2006*), with a regularized inversion of the Tikhonov type as a prior, assuming an exponential prior covariance. Also shown are the SAT reconstructions from *Luterbacher et al.(2004)* and *Heikkillä & Seppä (2003).* The thin dotted lines are GSTHs derived from a glacial system model. SAT estimates were transformed to GST with a regionally derived linear formula.The models shown fit the observed data with a misfit which is $<$0.05 K above 1800 m. A deterioration of data fit below 1800 m ($<$0.1 K) is attributed to the presence of lateral inhomogeneities.

The Outokumpu borehole was drilled in 2004 as part of the ICDP, It reached a depth of about 2500 m, and because of the scientific purposes, a large body of observations were available. Thermal properties and their temperature dependence were determined by lab and in-situ measurements. In addition to more than 800 high-precision measurements of thermal conductivity also estimates of volumetric heat capacity could be derived. An independent analysis of shallow soil temperature measurements in Finland yielded a linear SAT-GST relationship (*Kukkonen 1987*), which was successfully used for the construction of synthetic GSTHs as described above. Furthermore, a careful analysis led to the conclusion, that there is no significant contribution of advective heat transport. Details can be found in *Kukkonen et al. (2011)*.

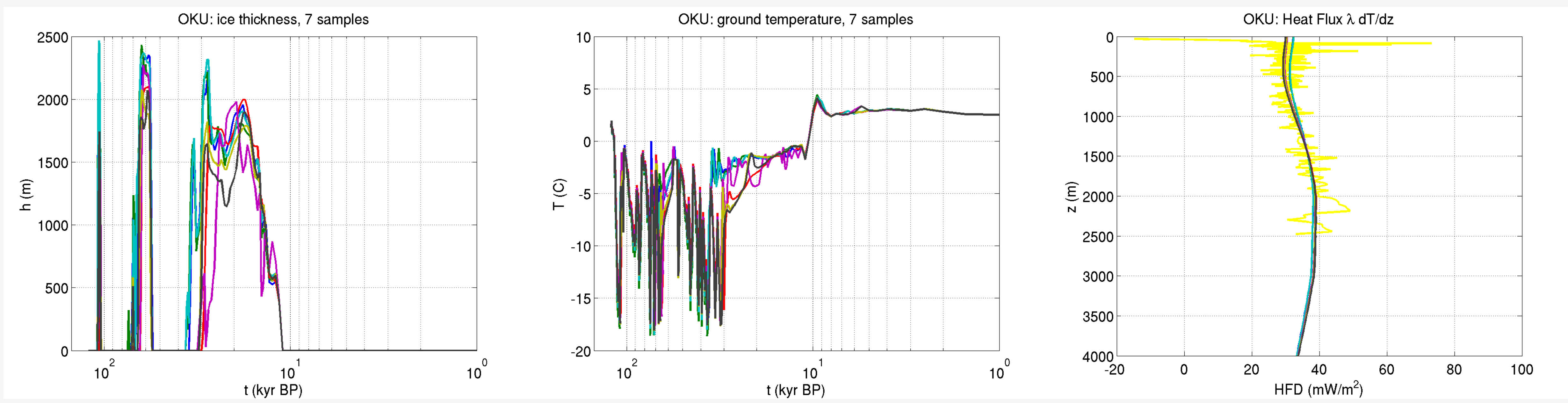

Figure : Fig. 3: GSM results for the OKU site. From left to right ice thickness, GSTHs and derived anomalous heat fluxes are shown. Note the logarithmic time axes for the former two.

Acknowledgments

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Kola Superdeep Borehole SG3

The situation at this borehole is much less clear. The large variation of heat flow with depth observed in the main SG3 borehole could not be attribute clearly either to paleoclimate influence or to fluid flow. A large number of alternative approaches were taken to solve this enigma. One- to three-dimensional models at different scales (paleoclimate, regional flow, influence of topography, nearby open-pit mining) did not lead to an unique conclusion. This is partly due to the lack of accurate meta-data and other data-related problems, as an unexplained temperature shift of the top 1000—,m of SG3 with respect to all newly measured shallow boreholes mentioned below.

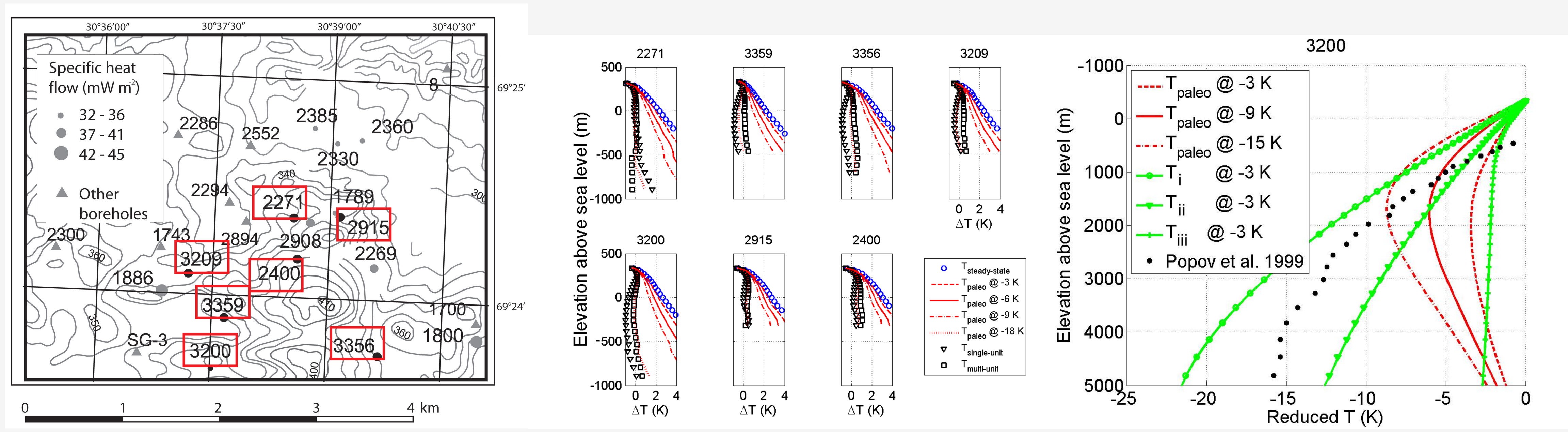

Figure : Fig. 4: Location of boreholes in the neighborhood of the SG3 borehole. The red sites in the right panel are the sites chosen for this study. Data fit for the inverted model. The right panel is an example demonstrating the ambiguity.

A considerable set of shallower boreholes (500 - 1300 m) exists in the neighborhood of SG3 (*Clauser et al. 1999*). For this reason we undertook a full 3-D inversion of the observations, which we considered reliable. The independent results are not able to resolve deep flow, but could be compared to the deeper data from SG3. This inversion includes a highly simplified zonal model, exponential variation of permeability with depth, and a boxcar-like paleoclimate. Results confirmed the ambiguity with respect to the competing effects (deep fluid flow, paleoclimate). The behavior can be explained either by an exceptionally large pre-holocene temperature step ($\approx$20 K), or very high permeabilities at depths of about 4 km, or a combination of both effects. The GSTHs from the GSM ensemble members do not explain the behavior of the heat flux with depth, though - taken for reality - may constrain the permeability estimates. Given glacial isostatic adjustment, the constant permeabilities with time may be regarded as improbable.

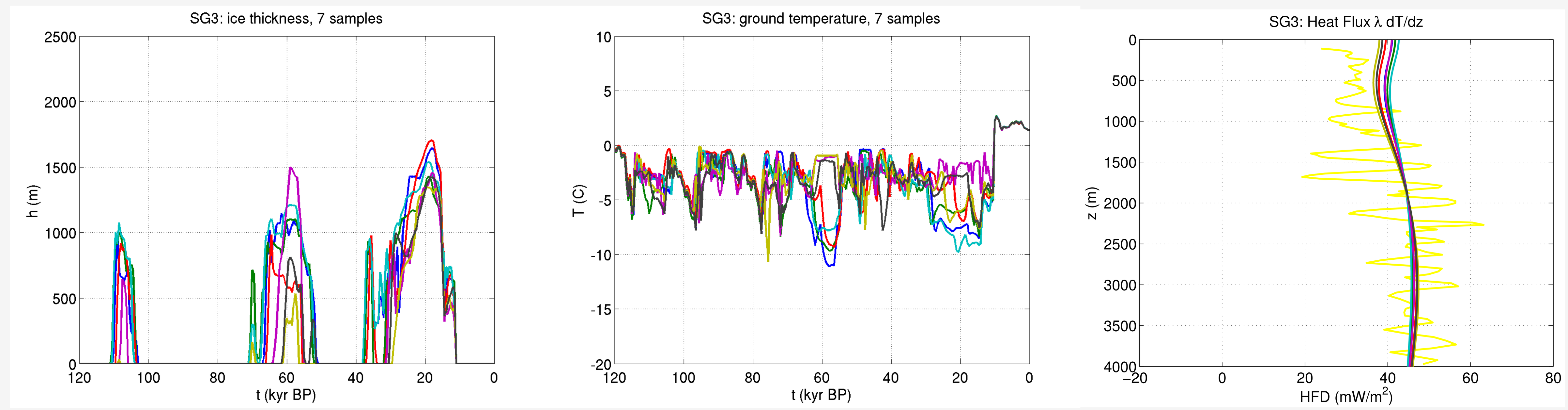

Figure : Fig. 3: GSM results for the SG3 site. From left to right ice thickness, GSTHs and derived anomalous heat fluxes are shown.

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