Cermak & Safanda, 2009

Thermal instability of the fluid column in boreholes

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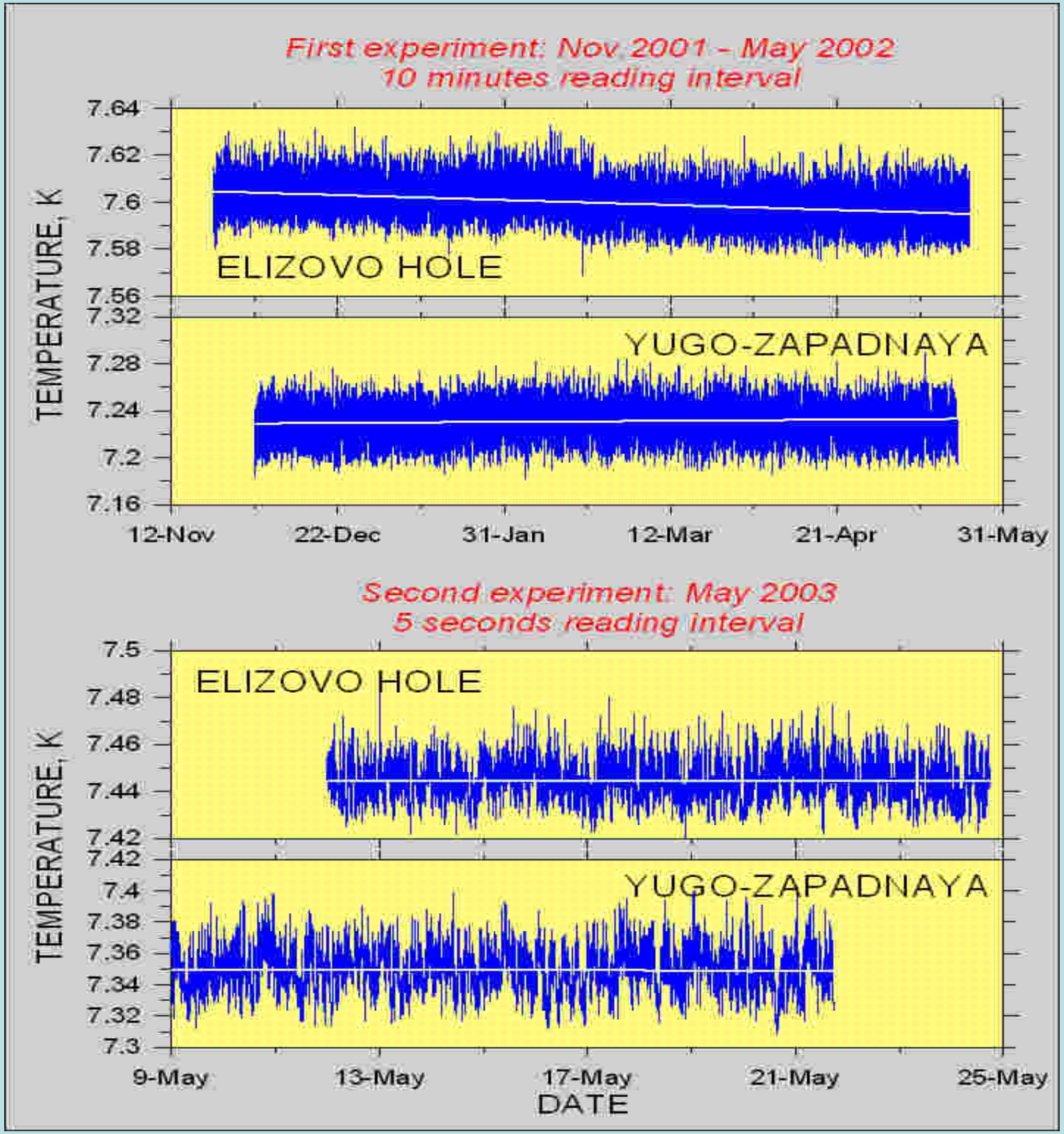
IASPEI Assembly, Cape Town, 2009

BACKGROUND AND BASIC IDEAS

- ***T(z) logs can be suitably completed with T(t) monitoring series.***
- ***Observational evidence proved that even when a borehole is stable; temperature data exhibit certain unrest.***
- ***We demonstrate the results of monitoring experiments in different geological settings (Kamchatka, Mexico) together with studies performed in our test hole in Prague***
- ***T(t) series were of various length (days to months) with sampling intervals from seconds to minutes.***

Those who measured temperature in boreholes in the pioneering days and used a thermistor probe connected to a Wheatstone bridge may remember certain problems to fully stabilize the measuring needle. Needle unrest manifested itself in several forms ranging from trembling to short term variations up to slow divergences.

The problem was discussed by Misener and Beck (1960) and Garland and Lennox (1962). Diment (1967) and Gretener (1967) experimentally proved the instability of the water column of a <u>large</u> diameter hole. They reported that the instability manifested itself in vertical fluid movements of amplitudes of up to several diameters of the hole.



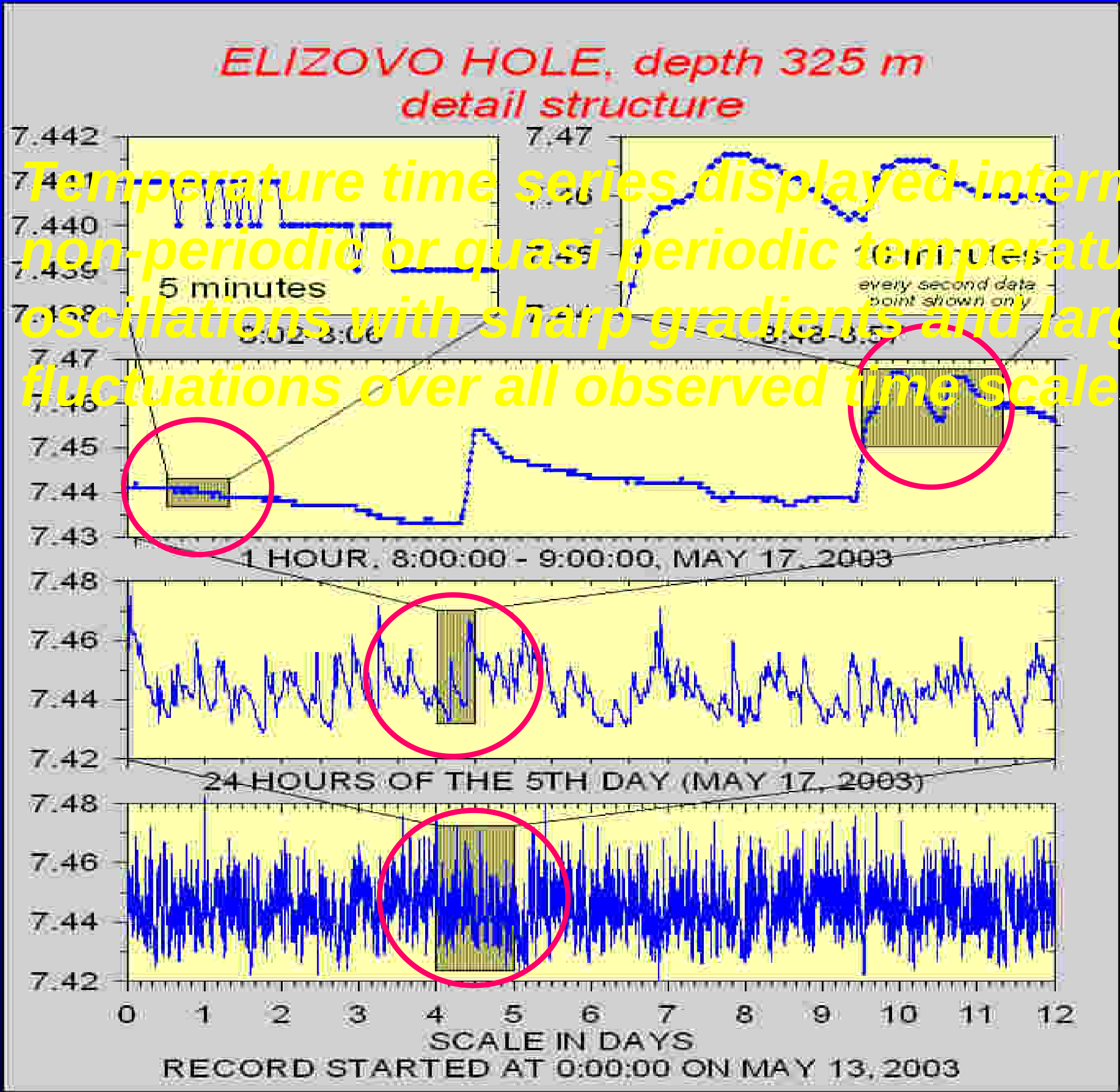
Two experiments, two holes : Yugozapadnaya and Elizovo

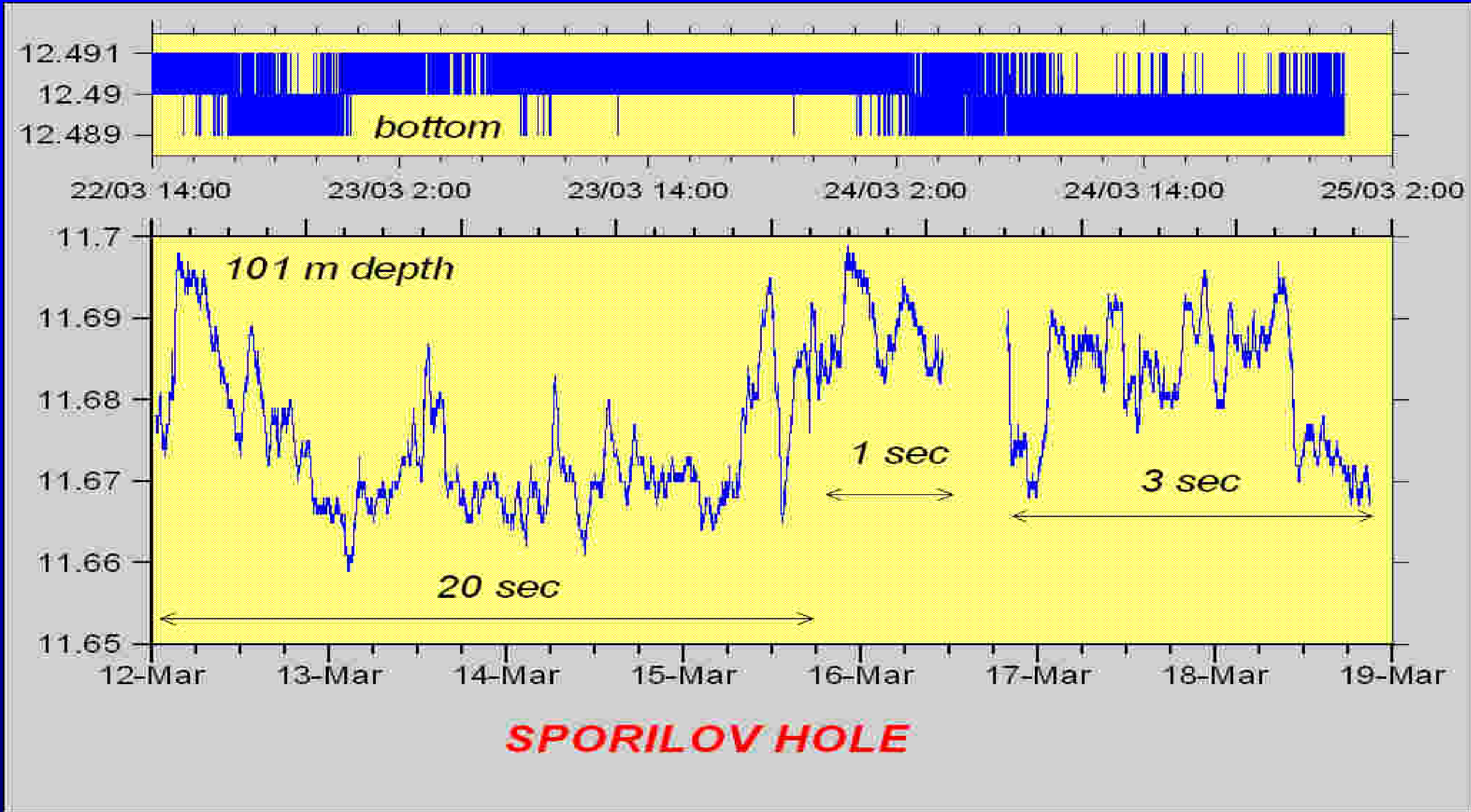
perfect temperature equilibrium
both holes cased
no water level changes
borehole diameter – 15 cm
depth – 109 resp. 325 m
temp.gradient – 30 resp. 60 K/km

1) half year experiment – 10 minutes sampling interval, over 25000 data points

2) two-week eperiment – 5 sec sampling, over 240000 data points

Temperature time series displayed intermittent, non-periodic or quasi periodic temperature oscillations with sharp gradients and large fluctuations over all observed time scales.





Test hole Sporilov, drilled in 1993, 150 m deep, 10 cm in diameter, inside plastic tube (5 cm diameter) to prevent any disturbances three experiments at 101 m depth, sampling intervals 20, 1 and 3 sec vs. bottom

PRELIMINARY CONCLUSIONS

1. ***The spectral analysis revealed a high level of stochasticity***

2. ***Statistical techniques revealed presence of at least two distinct temperature forming processes. One can be related to heat transfer in the structurally complex subsurface. The second presents the bulk of the measured signal, and reflects intra-hole convection.***

3. ***The "oscillatory" convection occurs due to instability in the horizontal boundary layers. In spite of the fact that the convection is relatively slow, the oscillatory intra-hole flow and temperature pattern may exhibit features of turbulence.***

POSSIBLE MECHANISM

In the presence of geothermal gradient heavier cold fluid located above warmer and lighter fluid moves downwards

The system becomes unstable.

The instability is opposed by frictional action of the fluid viscosity

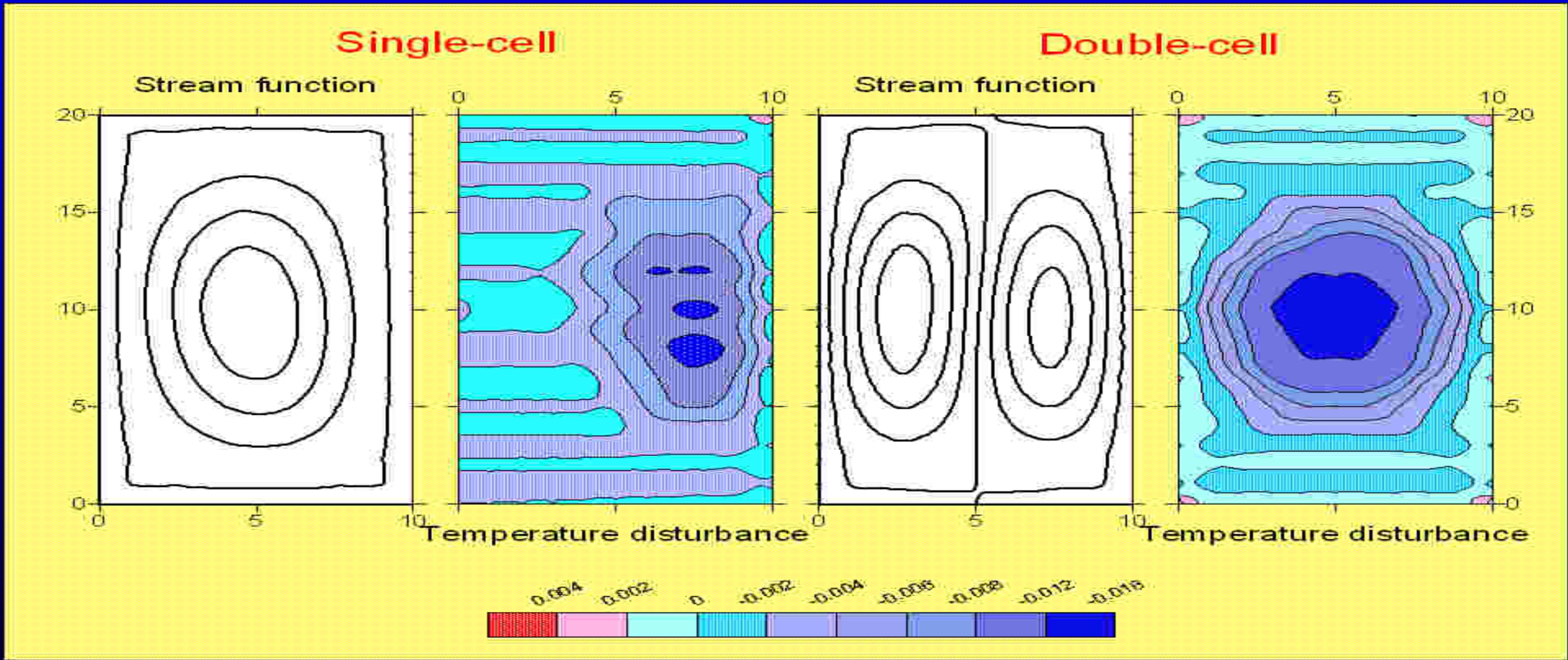
Thermal conductivity tends to equalize the temperature difference between the rising and sinking masses.

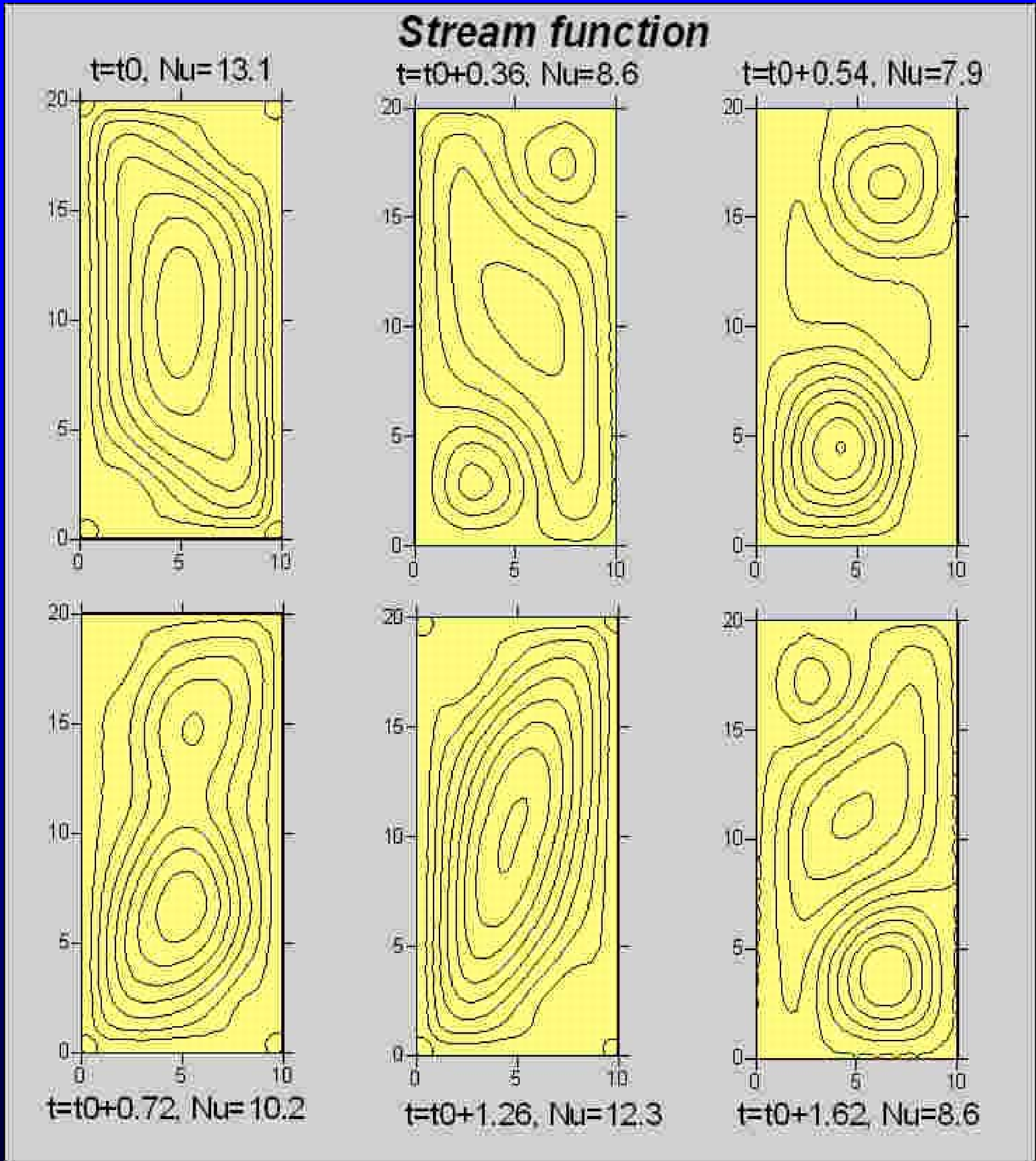
Experimental observations in laboratories revealed a large variability of the convection patterns ranging from quiescent, periodic, quasi-periodic, oscillatory to weakly turbulent.

Simple 2D-case, occurring at slightly above critical Rayleigh numbers, is a single or double convection cell extending through the lengths 2-3 times the diameter of the borehole.

When Ra increases, the longer cells disintegrate into several nearly circular cells with vertical size comparable with borehole diameter.

The temperature pattern is perturbed, the strongest disturbances emerging in the central parts.





Advection to conduction ratio is characterizes by Nusselt number. Intensity of advection changes at different stages of the cycle.

Temperature instabilities need not be strictly periodic. The motion has quasi-regular character, possessing qualitative repeatability only, the shape of the cells in each cycle does not repeat the previous configuration.

Convection occurs when the Rayleigh number exceeds its critical value.

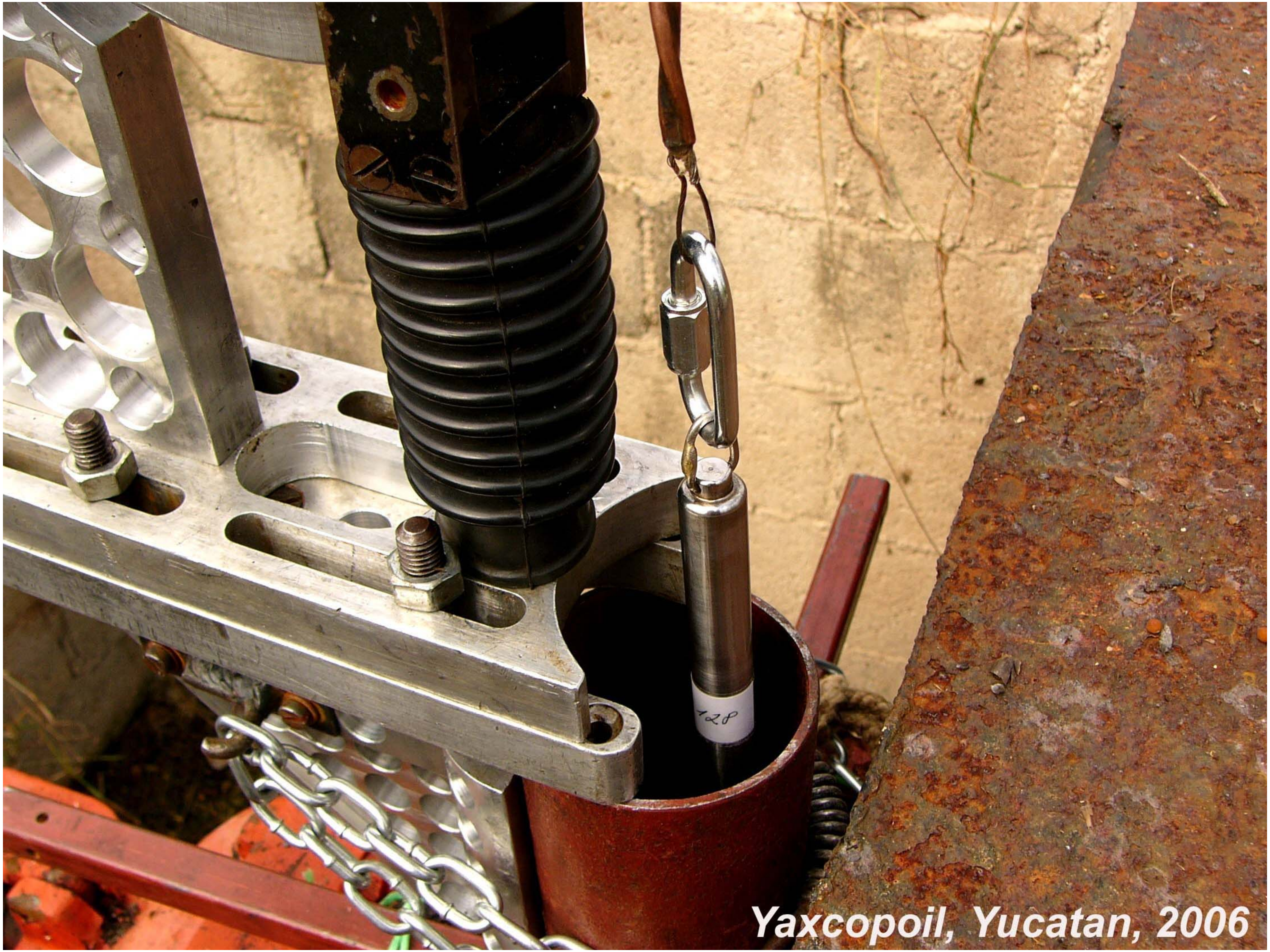
The total Nu of the oscillatory system varies between 8 and 13.

The Rayleigh numbers for Kamchatka range within 10^4-$4x10^5$, i.e. above critical value (oscillatory regime range)

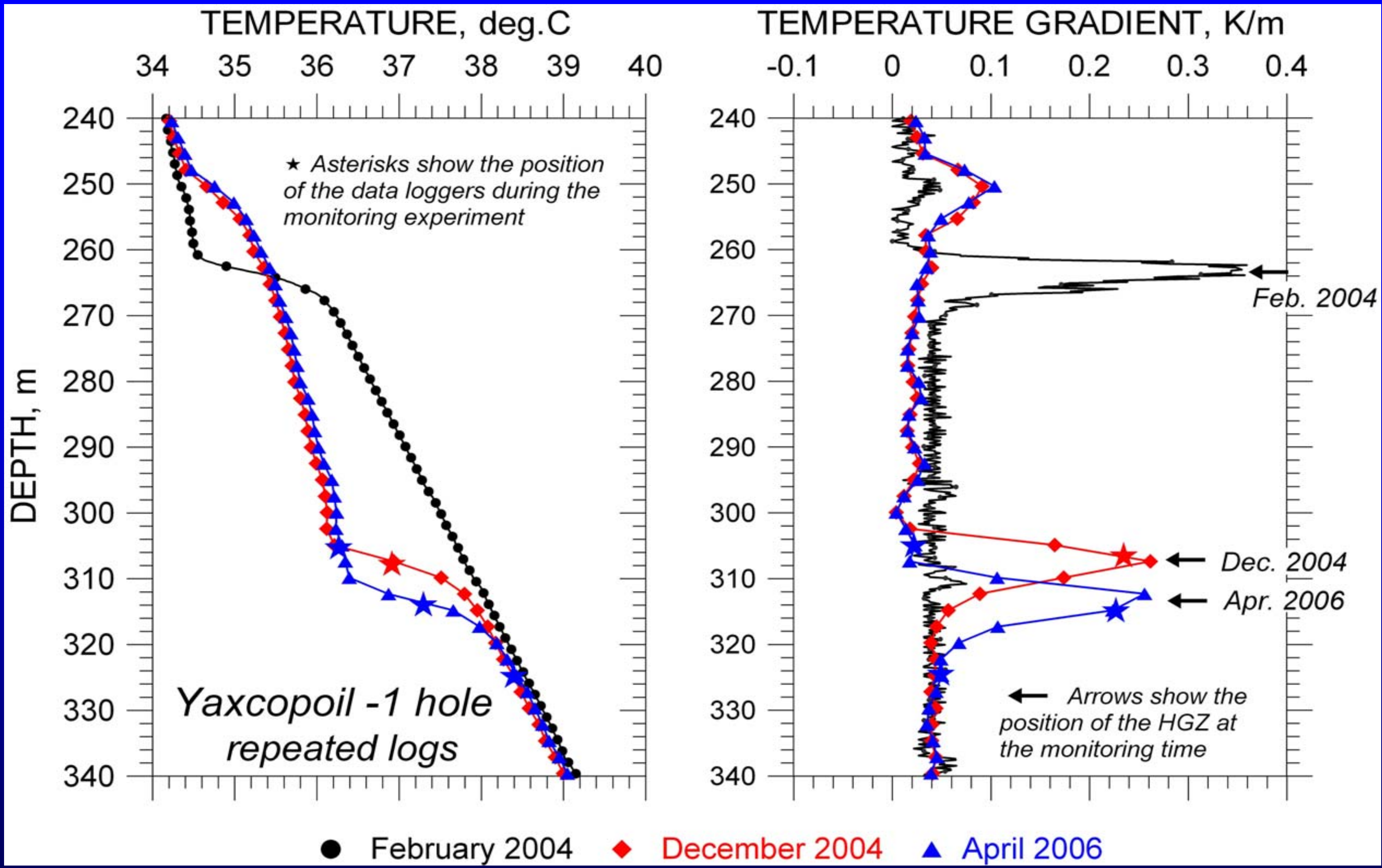
Moving fluid carries heat total heat transfer increases compared with a pure conduction

Maximum Nu number characterizes the single long cell, when the system disintegrates into diagonal and corner cells total Nu number decreases.

Larger Ra values imply for a more intensive convection in Kamchatka holes compared with Sporilov hole.



Yaxcopoil, Yucatan, 2006



Note the HGZ, it is slowly moving downwards

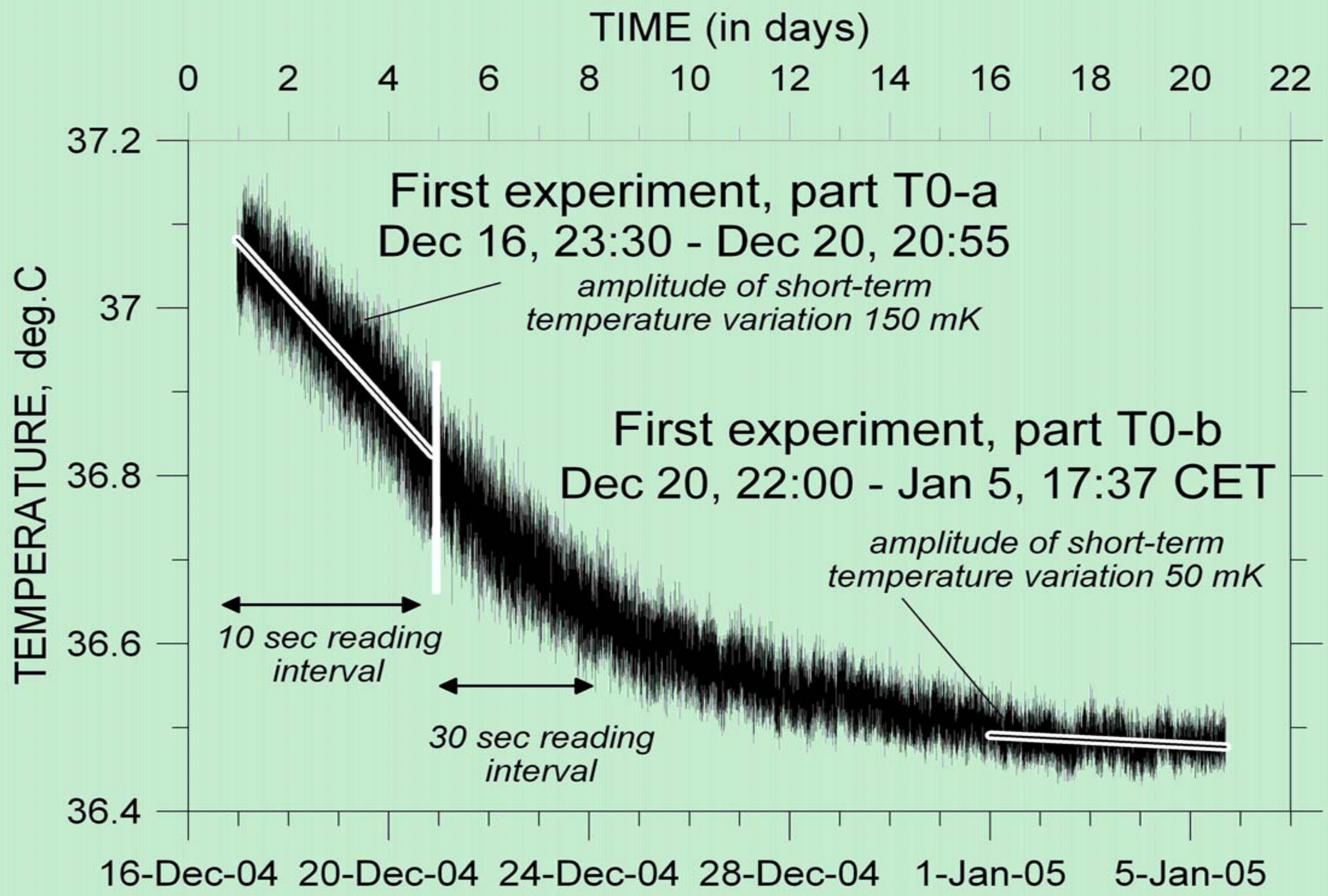


Figure 2. First high-resolution temperature monitoring

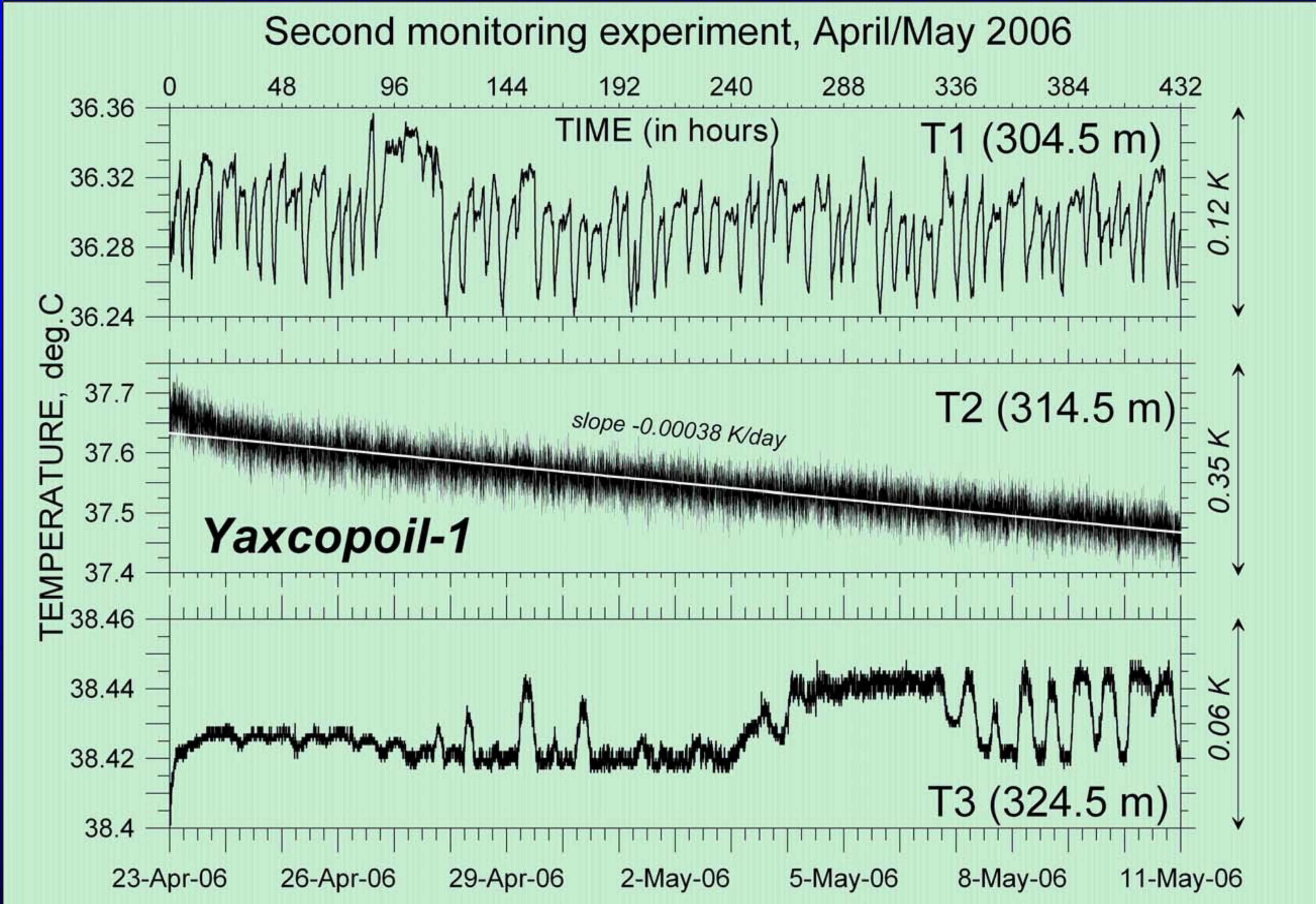


Figure 3. Second high-resolution temperature monitoring

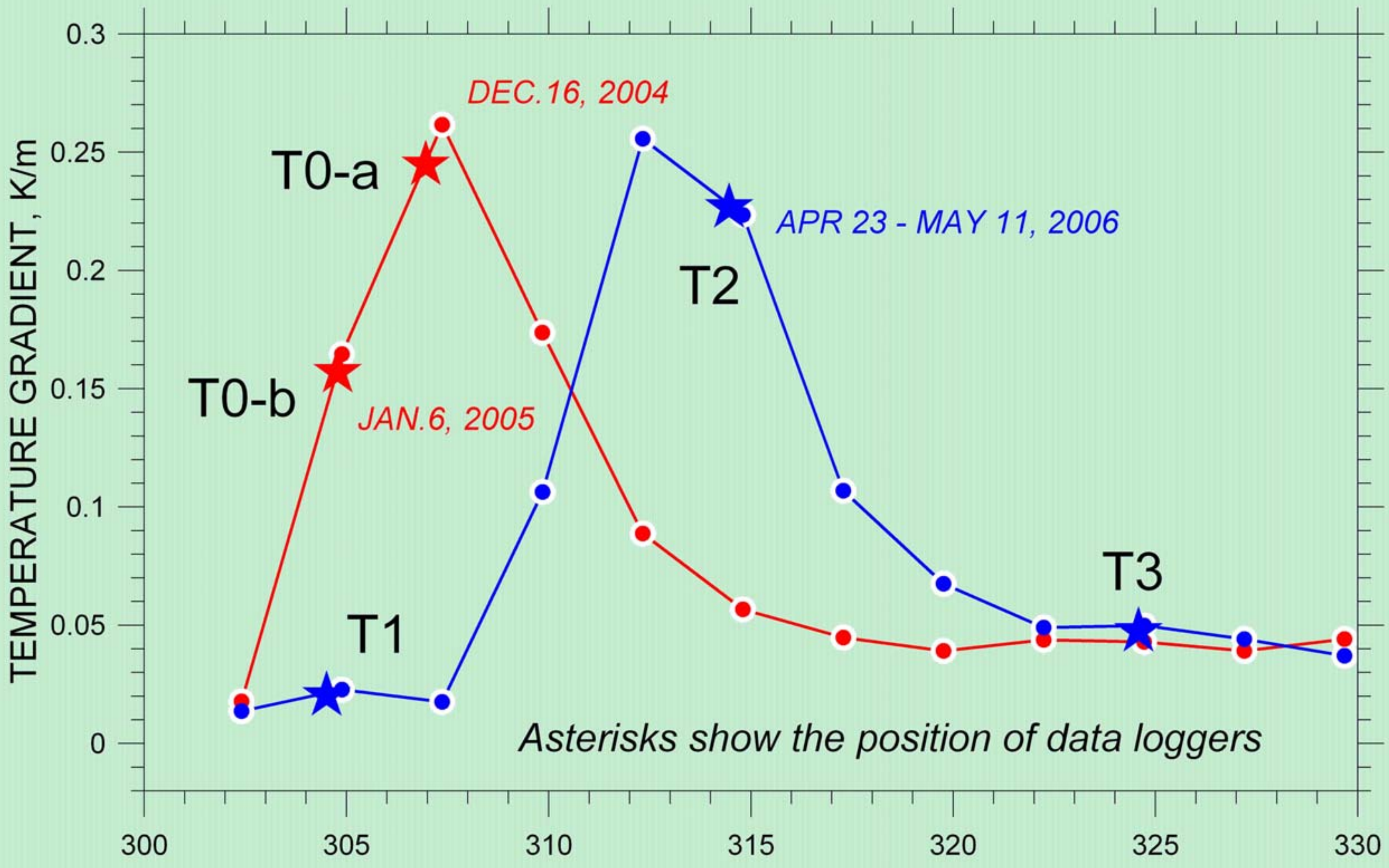
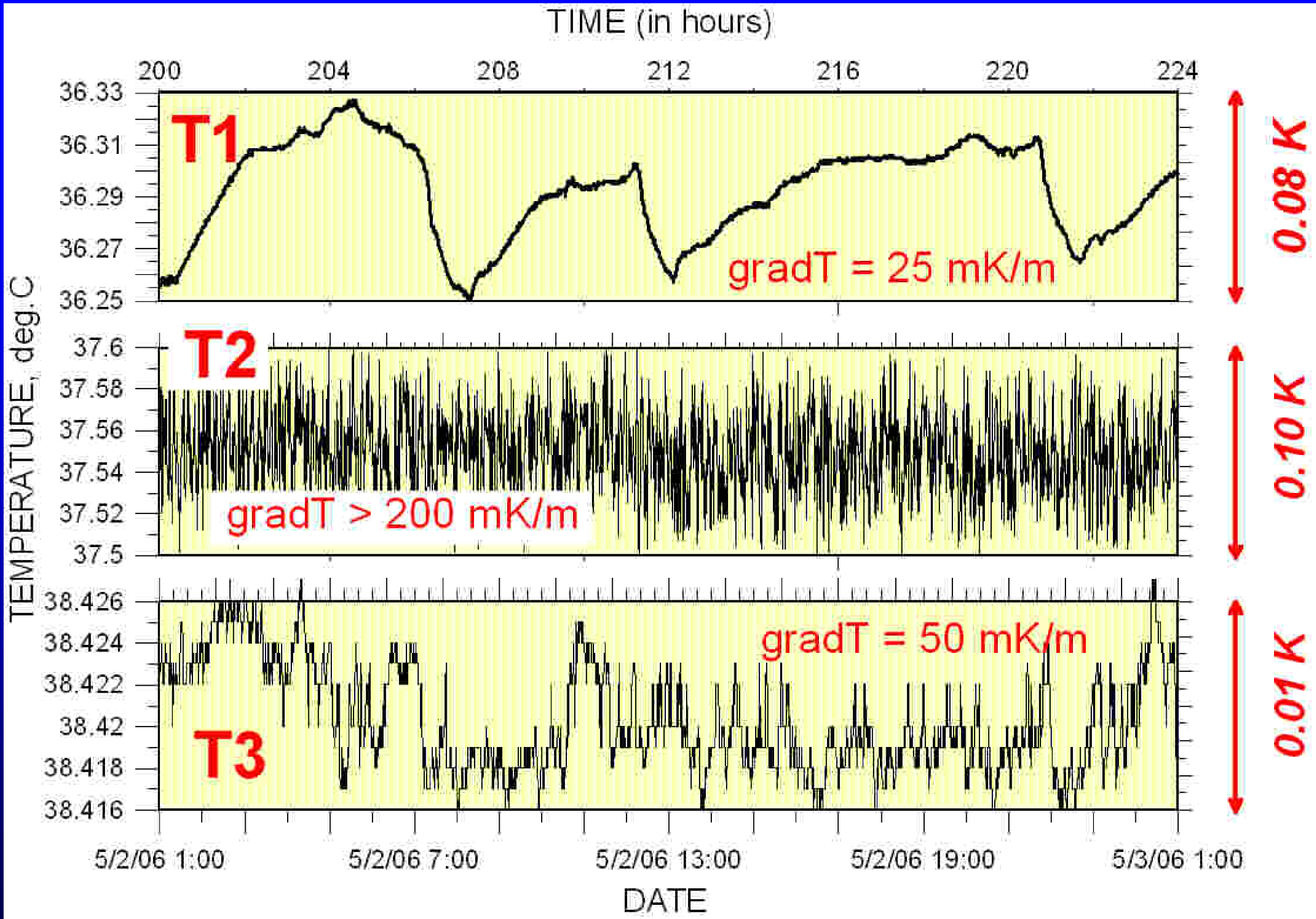


Figure 4. Location of data loggers relative to temperature gradient



Detail of 24 hour-record

Summary for T1, T2 and T3 series

1) Temperature variation 0.117 – 0.186 – 0.147 K
> Temperature variations monitored above and below HGZ-zone are comparable, but within HGZ increase 1.5-2 times.
2) The maximum values of temperature changes: 0.015 - 0.103 - 0.006 K
> Temperature change in HGZ may "jump" by an order of magnitude
3) Roughness coefficient R characterizes the "smoothness" of measured signal. (straight line has R=0, sine waves with periods of π, 2π and 4π, resp., have R of 0.04, 0.01 and/or 0.0025.
In our case, the calculated R-values amount to 0.015, 0.139 and 0.094
> T1 has roughness comparable with conventional sine wave, the latter two series display the roughness values by an order of magnitude higher.
4) The noise amplitudes: 5.46 - 12.11 - 2.39
> Noise amplitude sharply increases in the central part of HGZ and resumes back to low values outside HGZ.

The dimensionless parameter, Rayleigh number Ra

$$Ra = \frac{\alpha \, g L^{3} \Delta T}{k \, \nu},$$

where α, υ, k are thermal expansion coefficient, kinematic viscosity and thermal diffusivity, g is gravity acceleration, L characteristic vertical length and ΔT is temperature difference ($\approx$ gradient). Gradient values equal to 25, 225 and 50 mK/m at corresponding depths

The smallest height of stable convection cell equals approx. to borehole diameter (D=245 mm for the Yaxcopoil-1 hole). Thus, D value represents the lowest possible characteristic length.

For L=D the Rayleigh numbers are: $1.3x10^{6}$, $1.5x10^{7}$ and $3.3x10^{6}$, resp.

Conclusions

1. ***Intra-hole fluid convection is responsible for the bulk of observed temperature fluctuations.***
2. ***Convection is not stable. A relatively small change of the temperature gradient caused by external influence, may produce change of the Rayleigh number and can initiate a "switch" from one regime to another (bifurcation).***
3. ***At low gradient dynamics is stable and mono-periodic. Double gradient increases a transition to (still) stable, but a relatively more complex multi-periodic dynamics.***

A pronounced (order of magnitude higher) increase of gradient gives rise to oscillatory convection regime with highly erratic temperature fluctuations.

Such behavious was reported in laboratory experiments focused on free convection, but it is observed for the first time in nature conditions, such as borehole fluid convection.

THANK YOU