Transient subsurface temperatures controlled by land-use, climate warming, and groundwater flow

Victor Bense

Wageningen University and Research, Netherlands

Laval University, Quebec City, Canada
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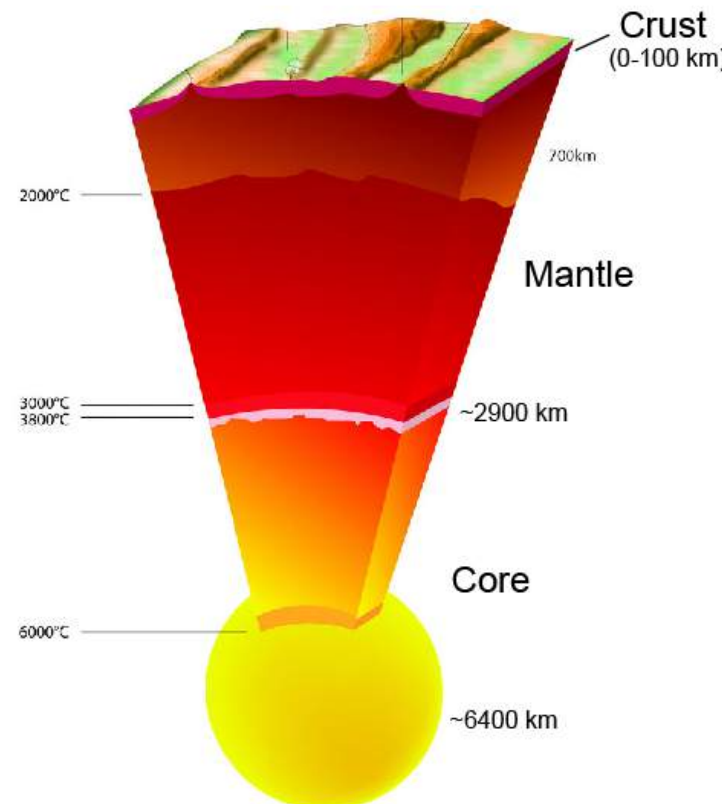
This talk….

- The use of temperature as a tracer for hydrogeological processes is, still, in a renaissance (after a small Ice Age during the 80s and 90s).
- Increasingly however, subsurface temperatures are in a transient state resulting from surface environmental change
- Groundwater flow controls significantly how subsurface temperatures will respond for a given surface temperature change.
- How can the transience of relatively deep (>25 m) temperatures be interpreted for groundwater flow at sub-regional to regional scales?

What is the origin of the Earth's internal heat?

- Primordial heat
  - The Earth has only partially cooled since its formation ~$4.6 \cdot 10^9$ years ago.
- Radioactive decay of uranium-238 and thorium-232.
- Primordial and radioactive heat contribute about 50% each to the total global surface heat flux.

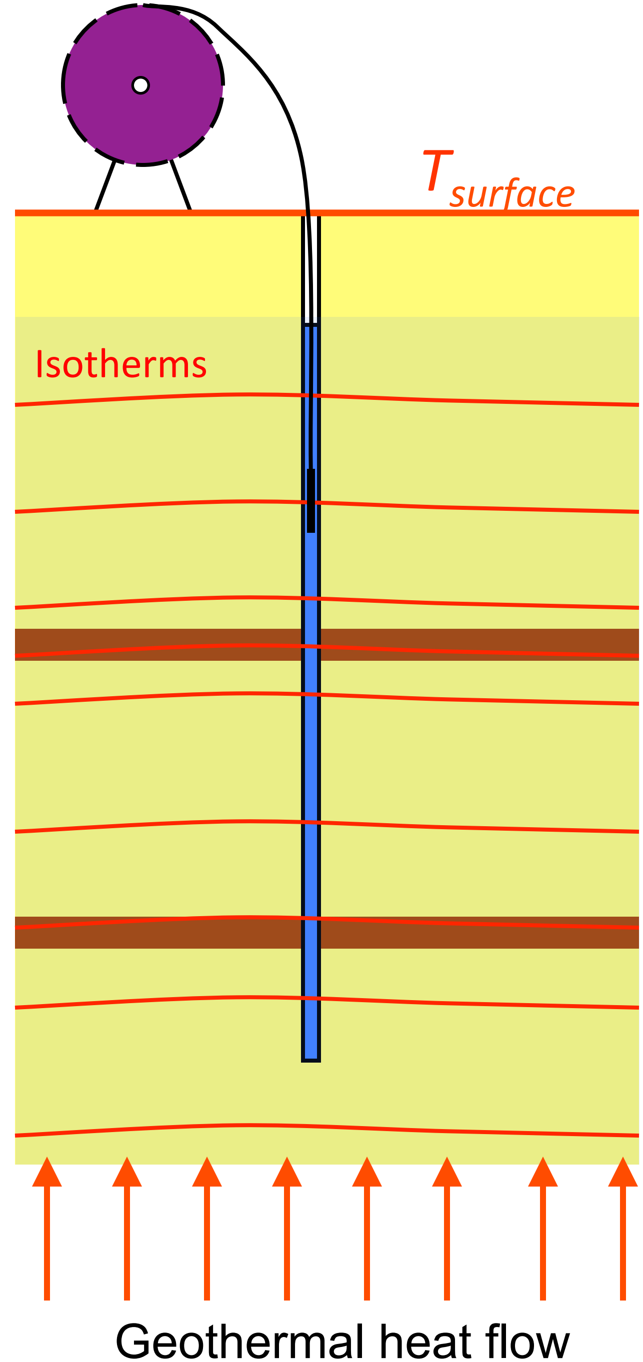


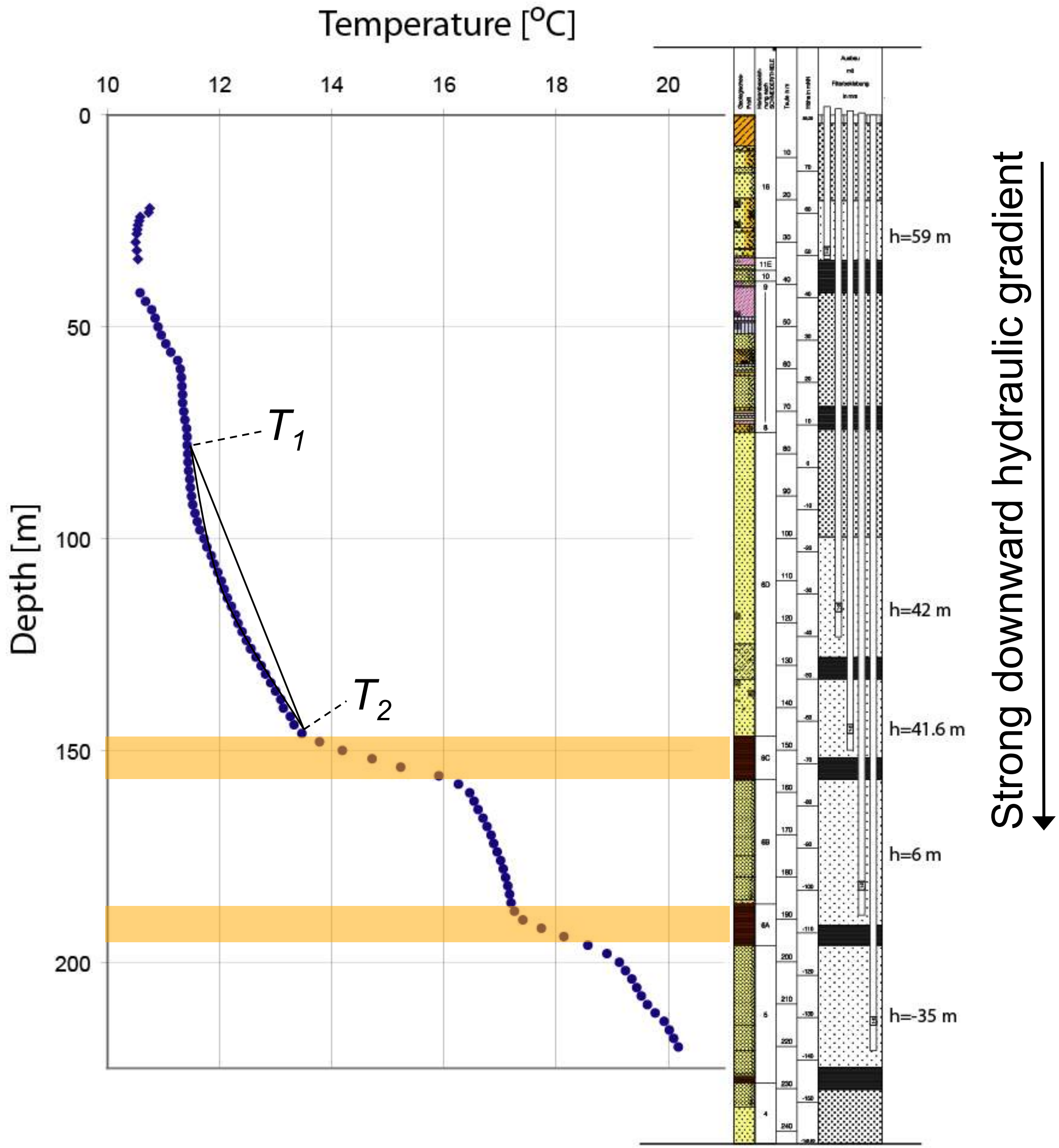
European Synchrotron Radiation Facility, Grenoble, France

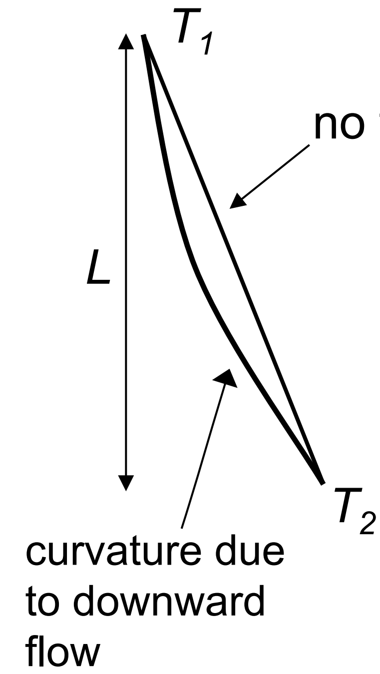
Dye, S. T. (2012). Geoneutrinos and the radioactive power of the Earth. Reviews of Geophysics

Measuring thermal gradients in the subsurface

Data collection Lower Rhine Embayment, Germany







Analytical methods (Bredehoeft and Papadopoulos, 1965) allow to calculate a specific vertical discharge across a distinct interval (*L*) from TD data.

The curvature can be translated into a Peclet number (via type curves) from which then the vertical specific discharge can be inferred.

Interpreting temperature-depth profiles

At the base of the 'seasonal zone' temperature will be at the annual average value.

When the annual average temperature fluctuates (e.g. climate change) transient temperature signals will be present below the seasonal zone.

From deeper, where the temperatures are stable, and in the absence of groundwater flow the geothermal heat flow component can be estimated using Fourier's Law.

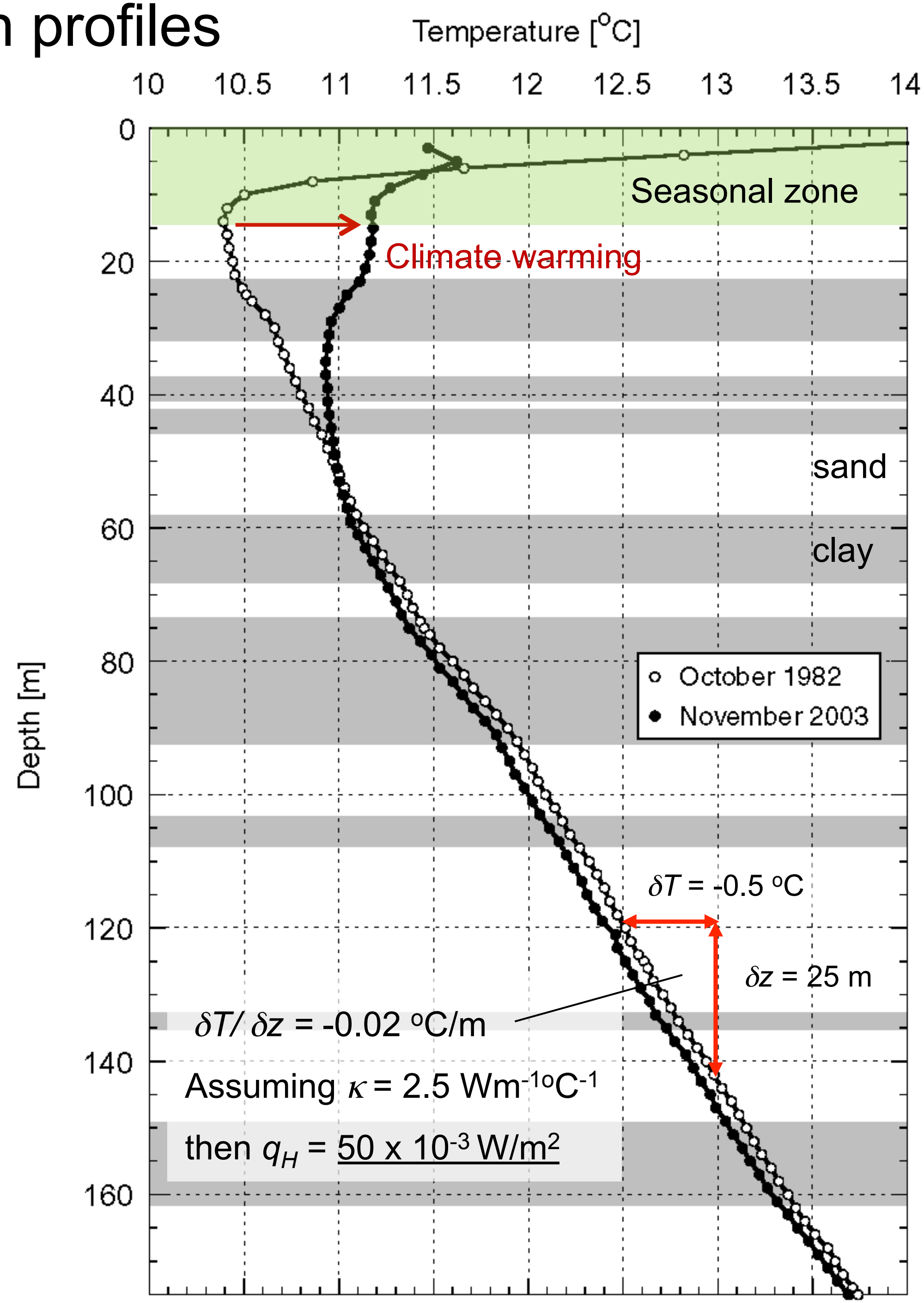
Heat transfer by conduction is described by Fourier's Law:

$$q_H = -\kappa \frac{\partial T}{\partial z}$$

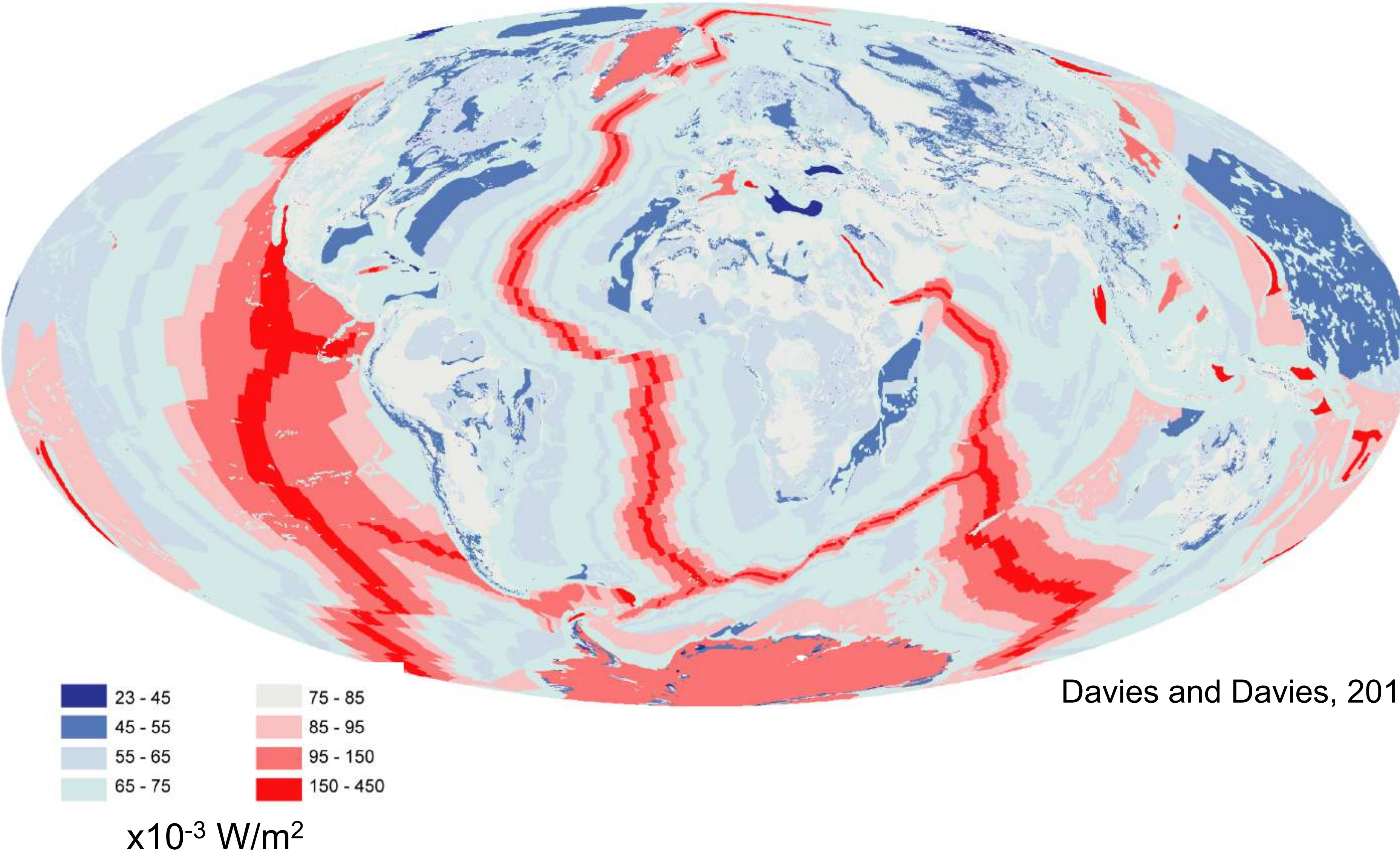
q_H [Wm^{-2}] is the heat flux, κ [$Wm^{-1o}C^{-1}$] is thermal conductivity which can be calculated from:

$$\kappa = n\kappa_f + (1-n)\kappa_s$$

in which n is porosity, κ_f and κ_s are the thermal conductivity of water and rock grains respectively. Since $\kappa_f < \kappa_s$, thermal conductivity decreases with increasing porosity. *e.g.* Sandstone: $\kappa = 2.5$ $Wm^{-1o}C^{-1}$; Clay: $\kappa = 1$ $Wm^{-1o}C^{-1}$.



Global surface heat flux distribution



Davies and Davies, 2010

Thermal regime in the shallow crust

Heat transport by conduction and advection through fluid flow:

$$\nabla \cdot [\kappa_a \nabla T] - C_w \vec{q} \cdot \nabla T = C_a \frac{\partial T}{\partial t}$$

κ_a : thermal conductivity [W/m/K]

C_w : volumetric heat capacity of water [J/m^3/K]

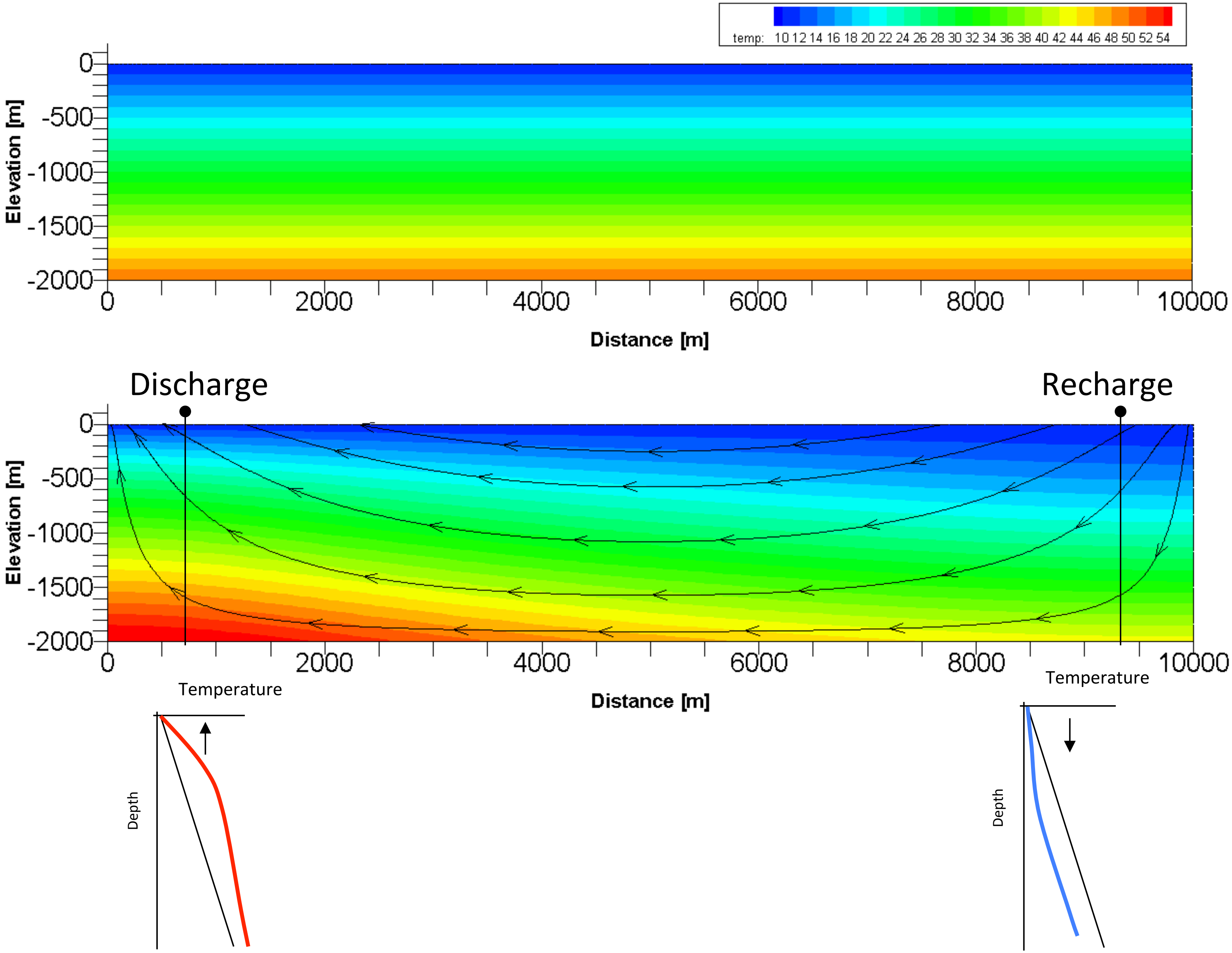
C_a : effective volumetric heat capacity of rock-fluid mixture [J/m^3/K]

$\vec{q}$: Darcy flux [m/s], fluid flow

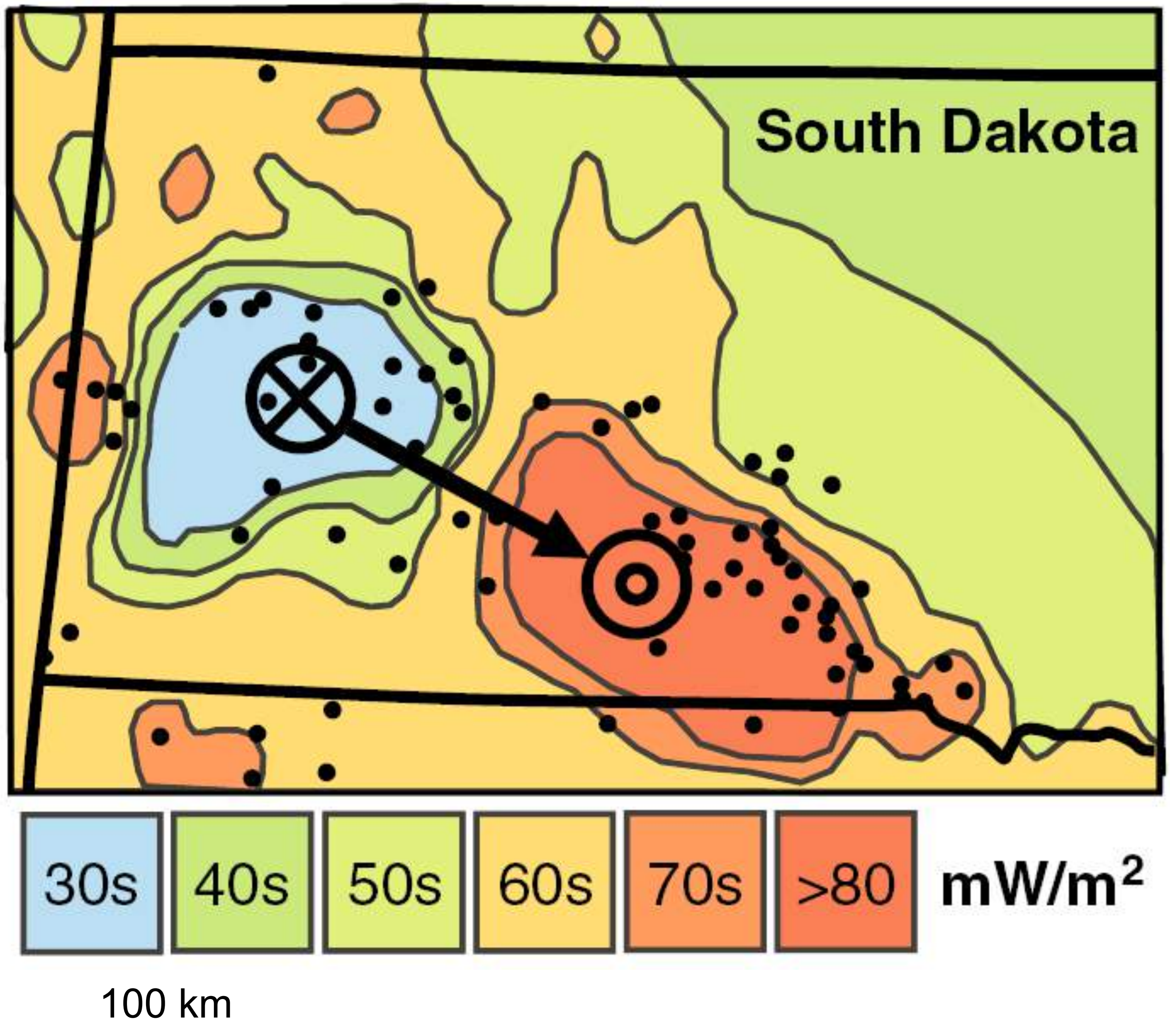
Boundary conditions

- Geothermal heat flow (e.g. 50 mW/m^2)
- Surface temperature conditions and variability (e.g. seasonal, climate, glaciation, land-use change)

Effects of convection on regional scale heat transfer



Impact of convection on regional scale heat flow



from Saar (2011), Hydrogeology Journal

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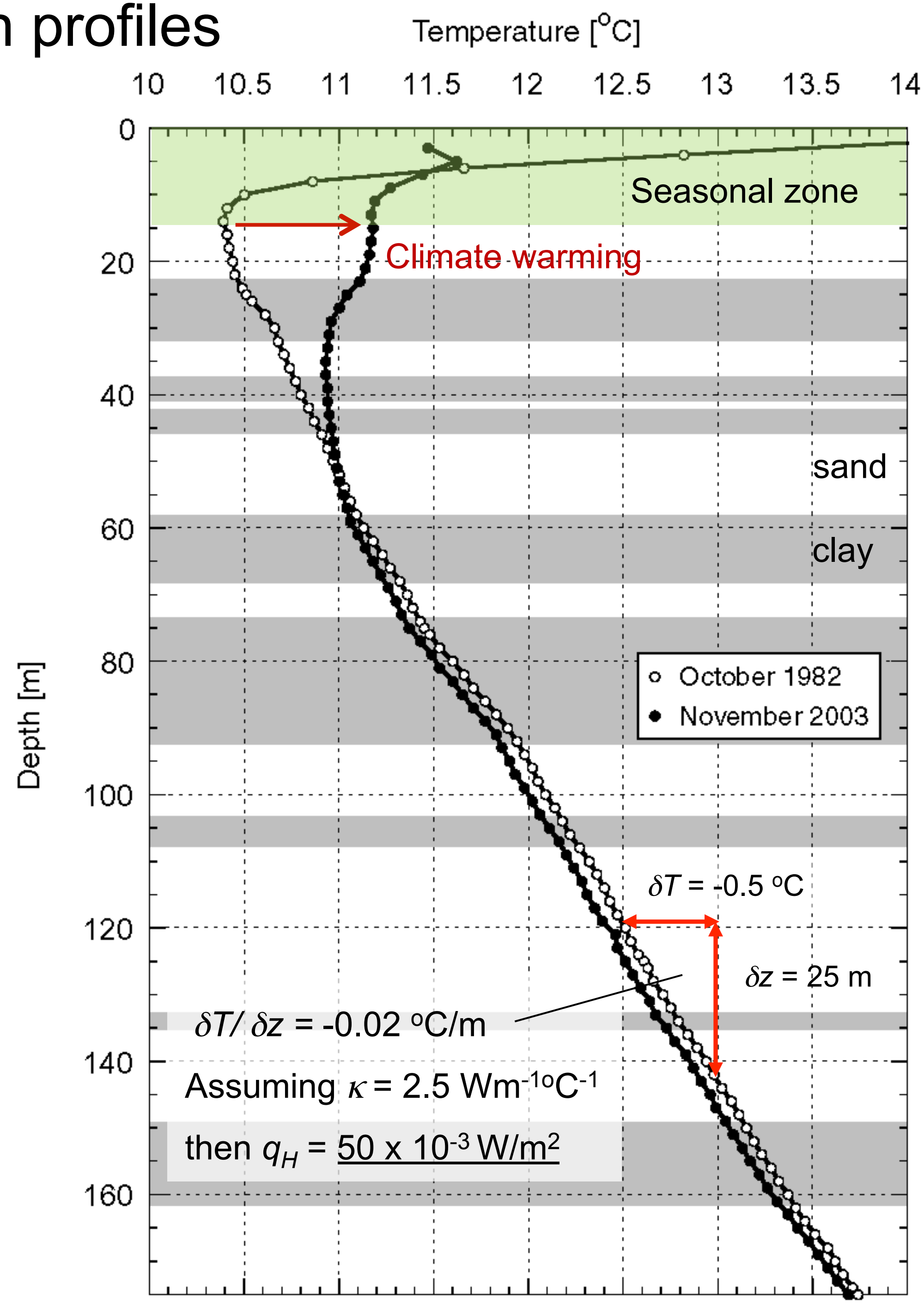
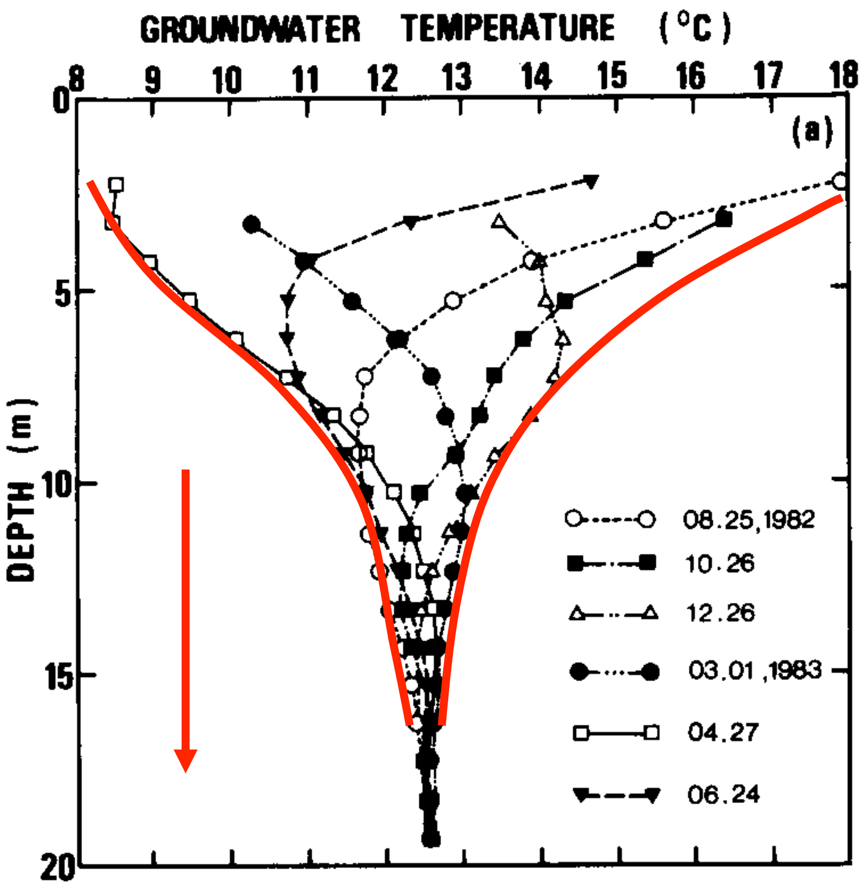
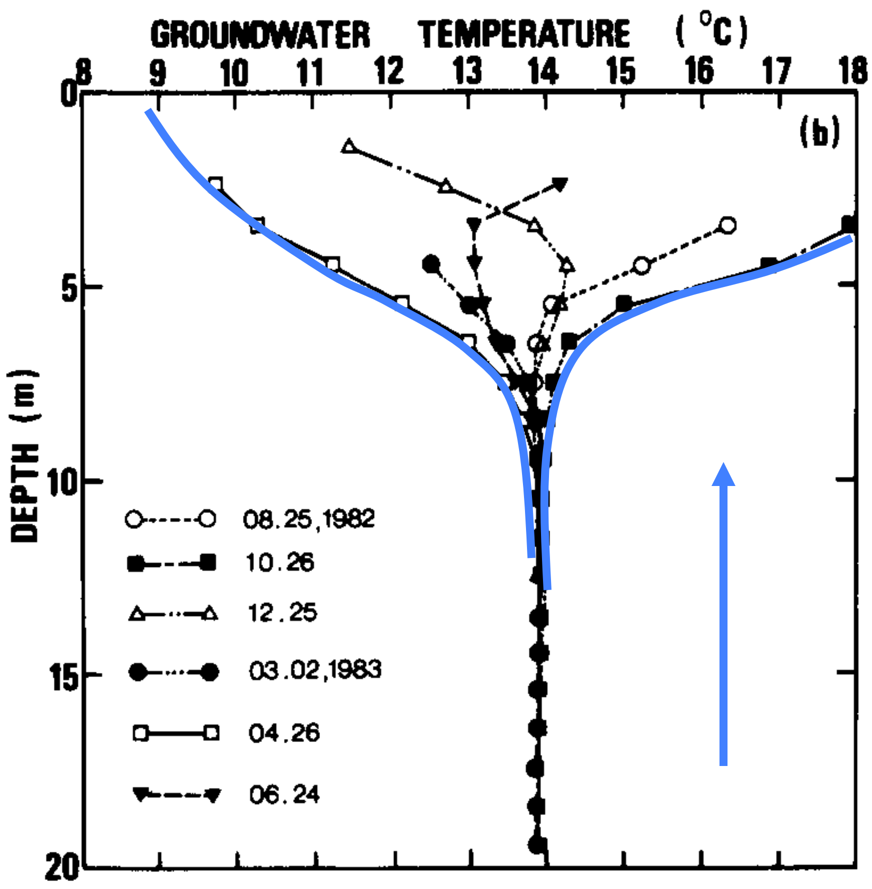


Attenuation of the seasonal signal under the influence of near-surface groundwater flow

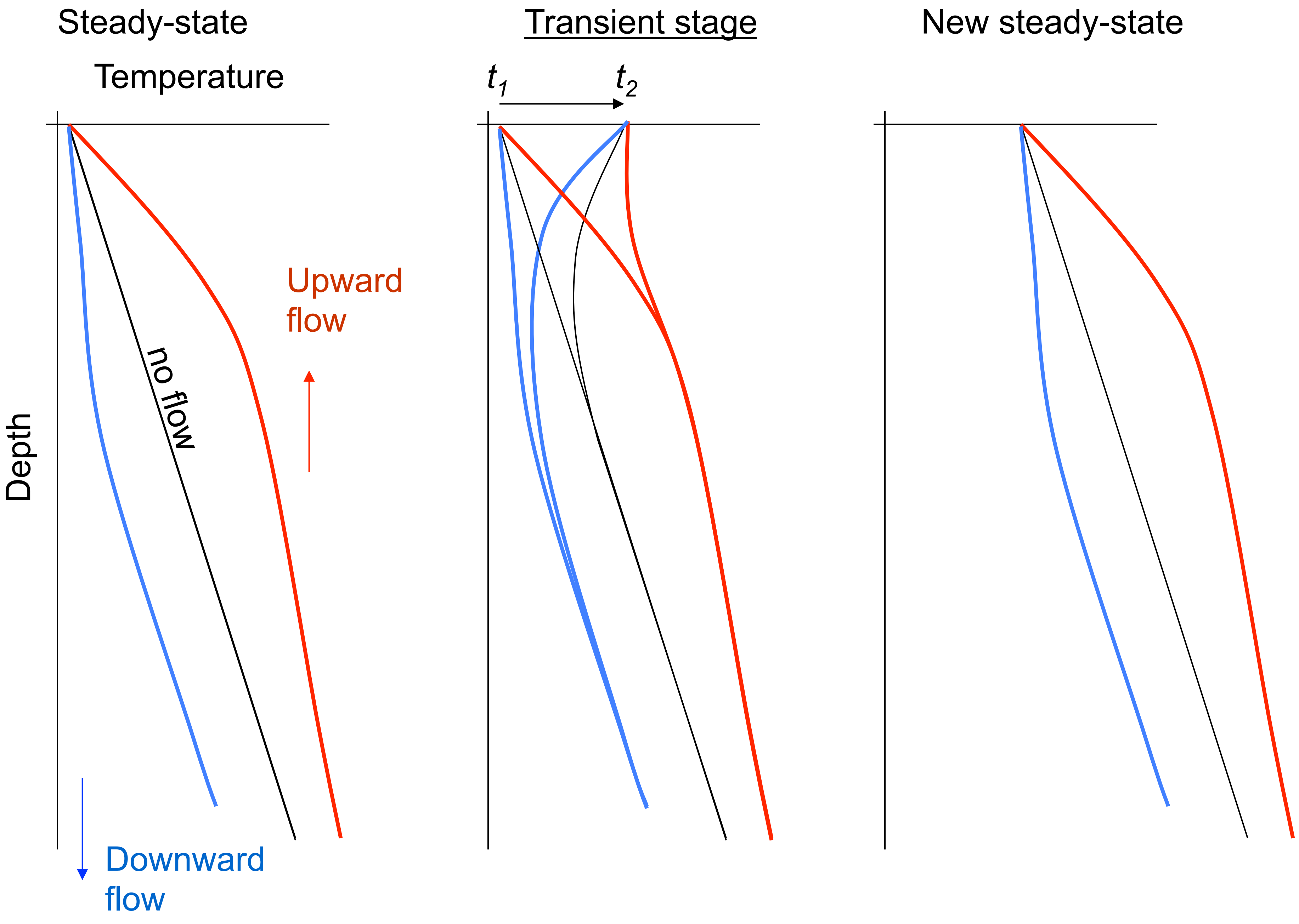




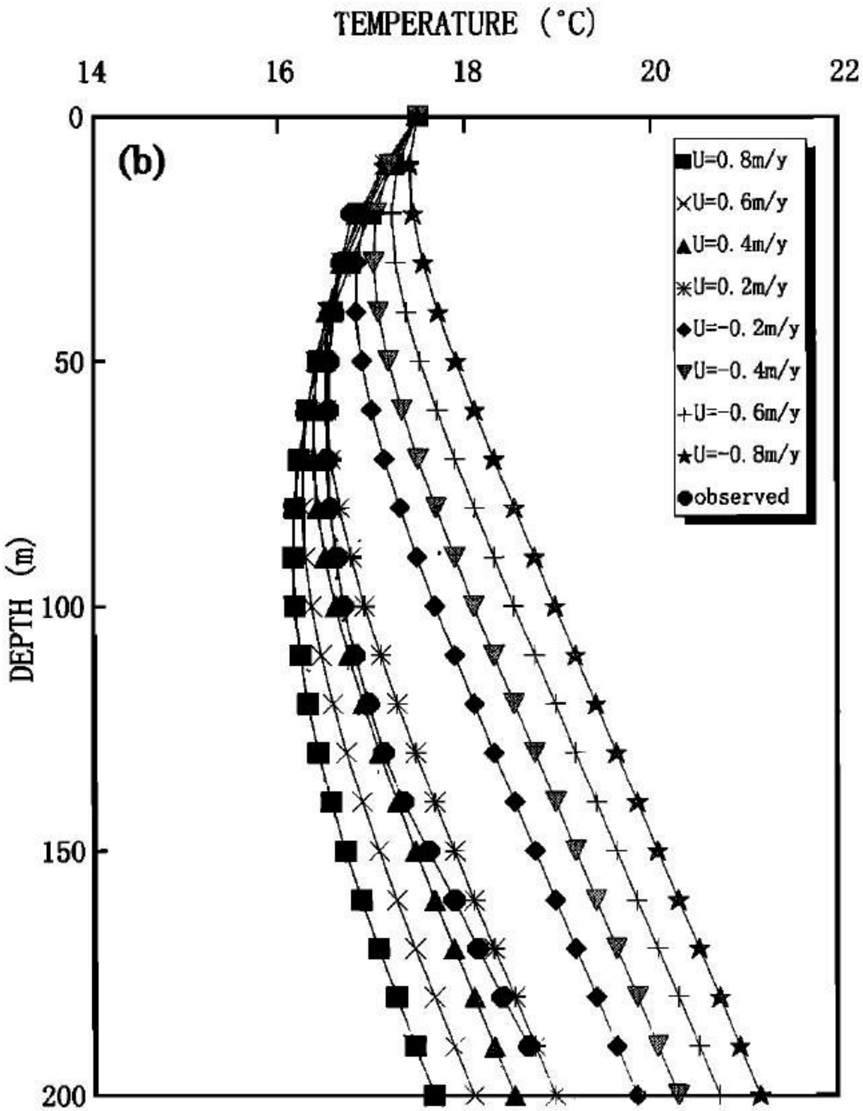
$$\nabla \cdot [\kappa_a \nabla T] - C_w \vec{q} \cdot \nabla T = C_a \frac{\partial T}{\partial t}$$

Taniguchi, WRR, 1993

Impact of vertical groundwater flow on a TD-profile in a warming climate



Taniguchi et al., 1999, WRR – Tokyo metropolitan area



Fit the entire TD profile to analytical curves to infer groundwater flow rate (q_z ~ U):

$$T(z,t)=T_0+T_G(z-Ut)+(b+T_GU)/2U$$
$$\cdot[(z+UT)e^{Uz/\alpha}\mathrm{erfc}(z+Ut)/(2\sqrt{\alpha t})$$
$$+(Ut-z)\mathrm{erfc}(z-Ut)/(2\sqrt{\alpha t})]$$

z Is depth, α is the thermal diffusivity; T_G is the background thermal gradient (based upon Carslaw and Jaeger, 1959)

Only linear warming rate (climate) or step-warming (e.g. urbanisation) can be imposed.

For t_0 a linear TD profile has to be used which implies no groundwater flow at t_0.

This is labeled the ‘CJT’ approach

Taniguchi et al., 1999, WRR – Tokyo metropolitan area

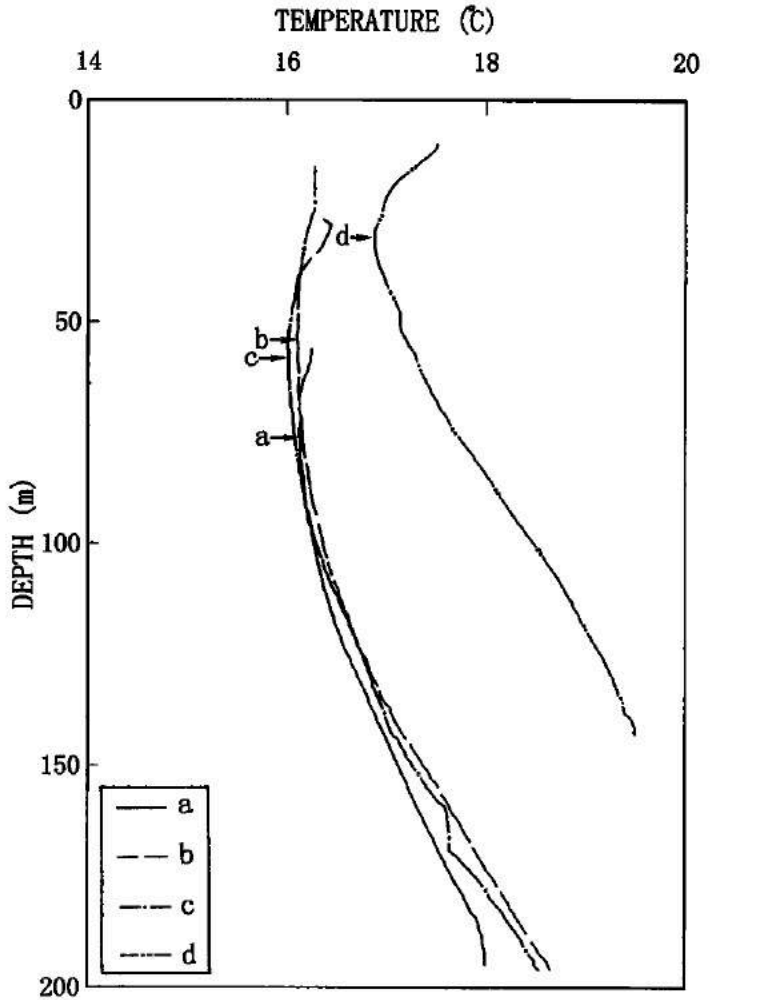
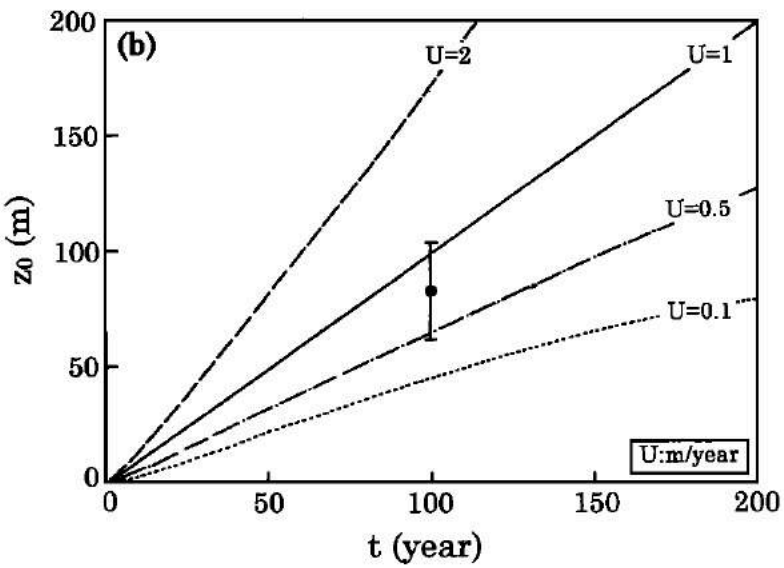


Figure 5. Temperature-depth profiles at (a) well 40 in Musashino terrace, (b) well 1 in Tachikawa terrace, (c) well 2 south of the Tama River, and (d) well 74 in Shitamachi lowland. Arrows show the depths of minimum temperature in the profiles.

Alternatively, relate vertical Darcy flux solely to the position of the 'inflection point' in sets of TD profiles reflecting surface warming.

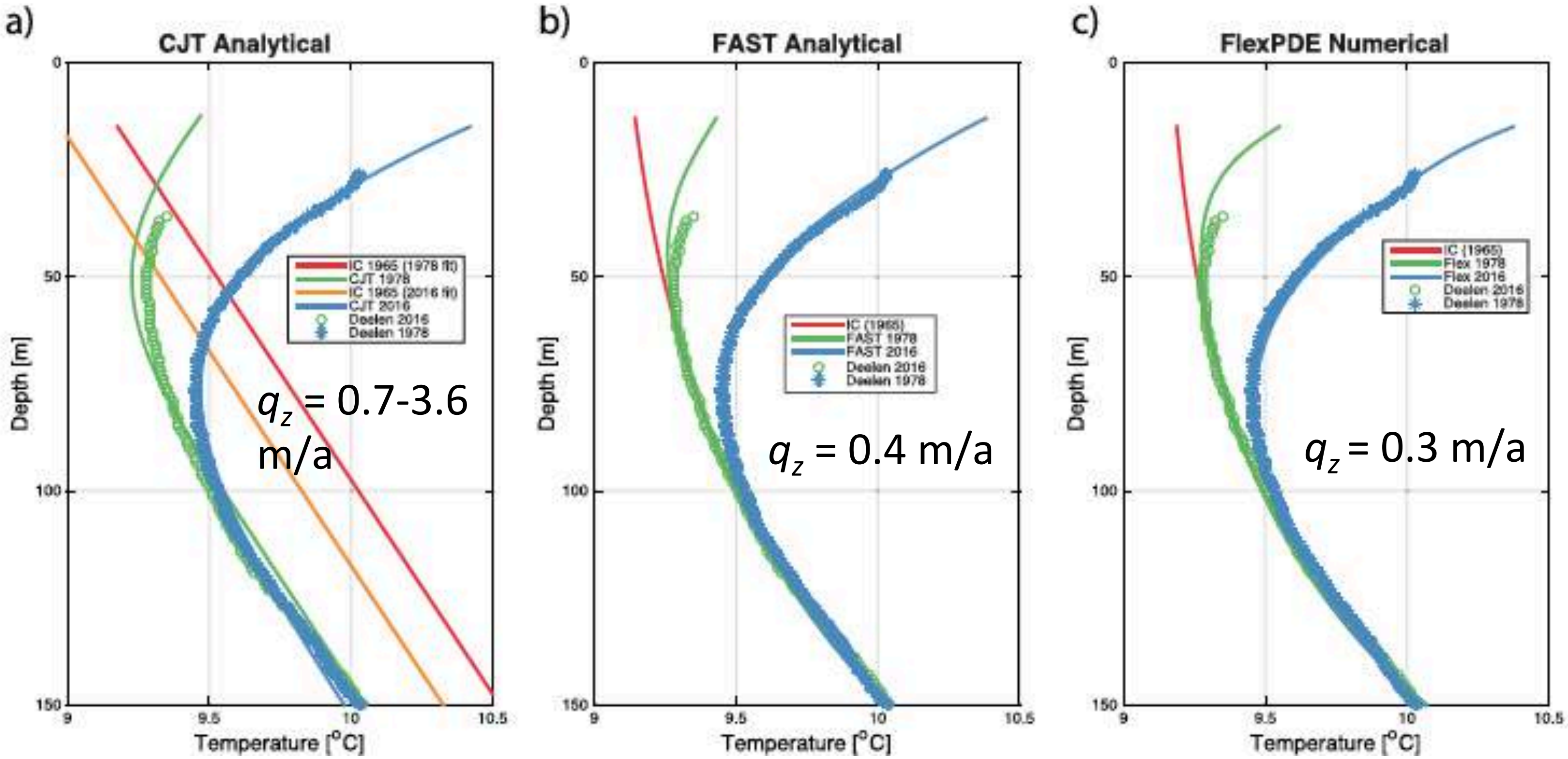
Making use of an analytical solution assuming a linear warming rate since t_0 (ie., the onset of warming) to estimate 'deep' vertical groundwater flow from the position of the inflection point.



Repeated TD logging

- Allows to implement Taniguchi's original idea to track the propagation of the inflection point as a tracer for groundwater flow.
- Measures the true transient.
- Potential to link with records of surface change (land-use and climate) and improve our understanding of how such changes are reflected and propagating through the subsurface.

Testing CJT, FAST and a numerical model and against repeated TD data

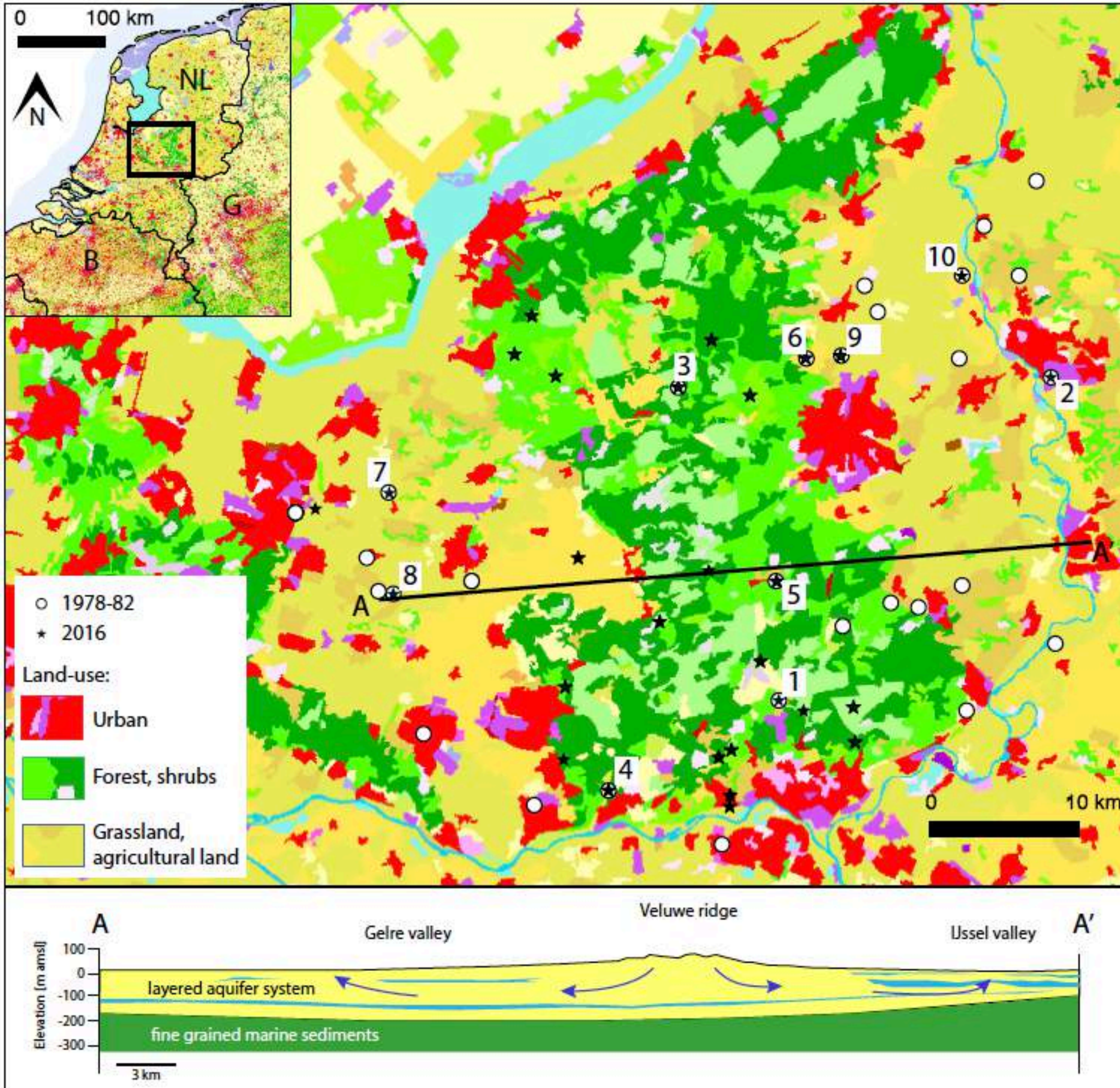


Revealing inconsistencies in the CJT approach leading to overestimates of q_z.
Repeated profiles can not be fitted with the same initial TD profile

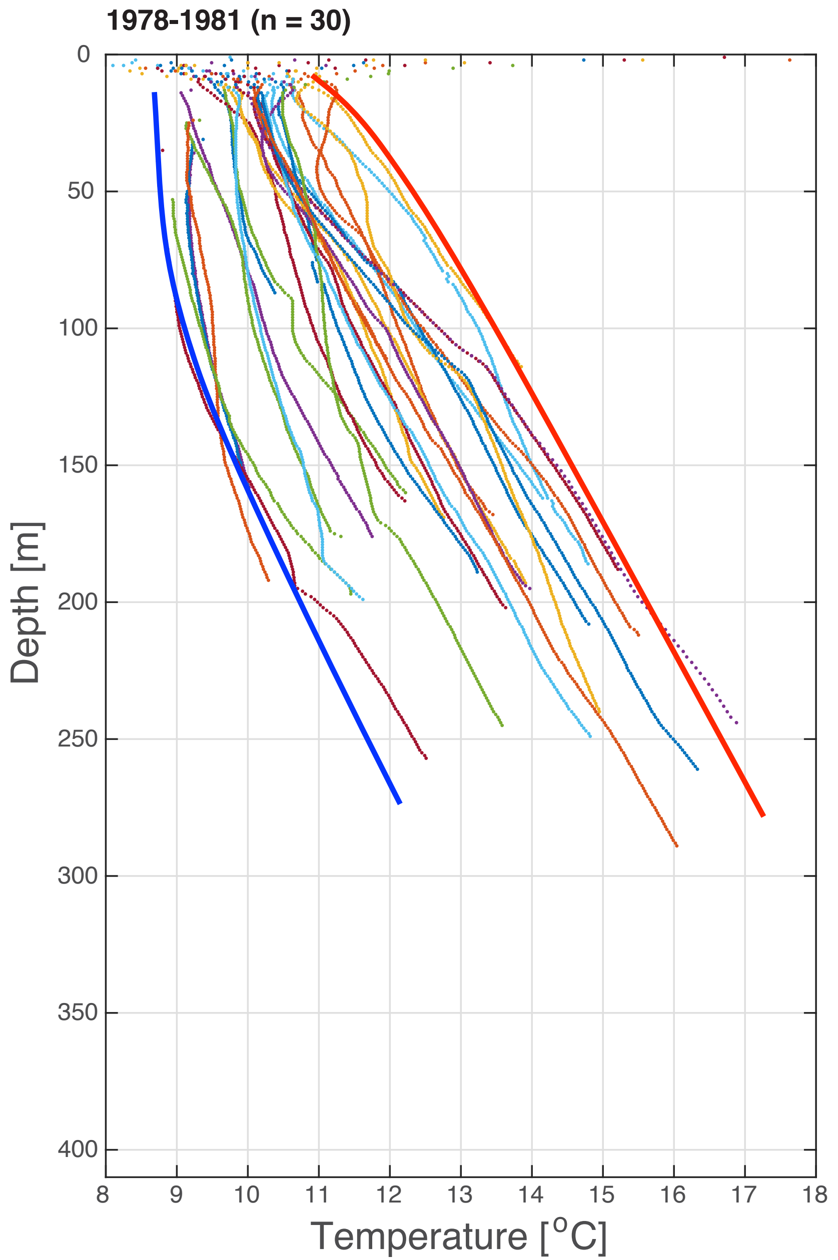
A recent, and more flexible analytical solution (i.e., FAST, Kurylyk and Irvine, 2016) can use non linear initial conditions, and its outcomes are consistent with numerical model results

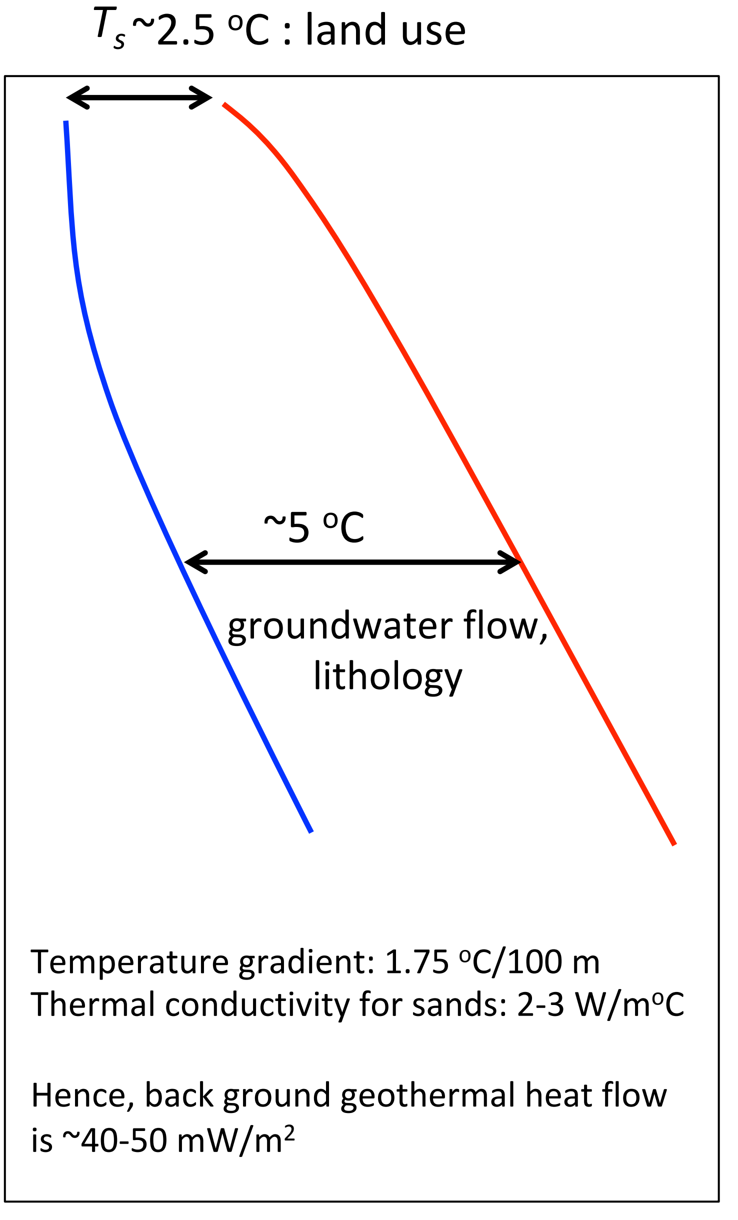
Bense et al., 2017 - WRR

Veluwe area, Netherlands – land use, and location of TD measurements



Historical TD data set – general patterns



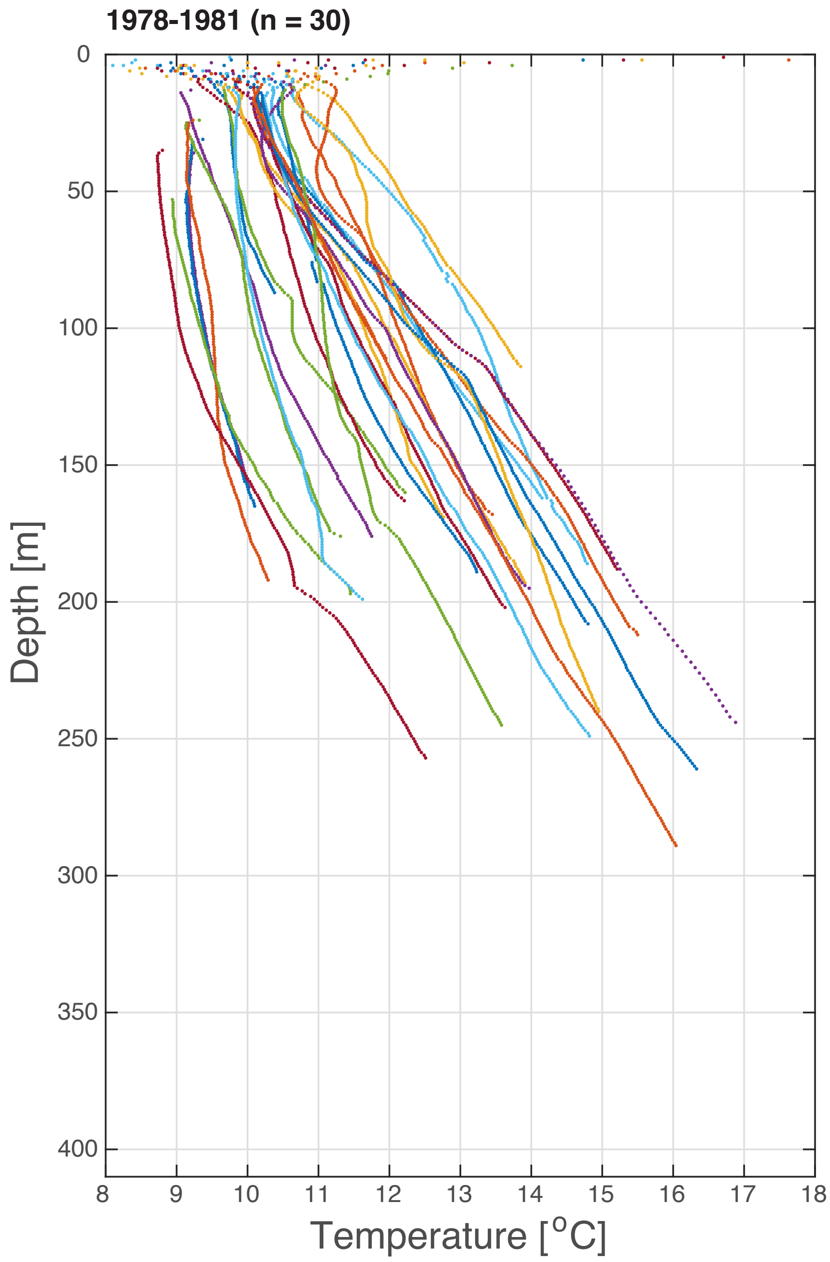


This can be unraveled in more detail using numerical modeling [*Bense et al.*, in prep]

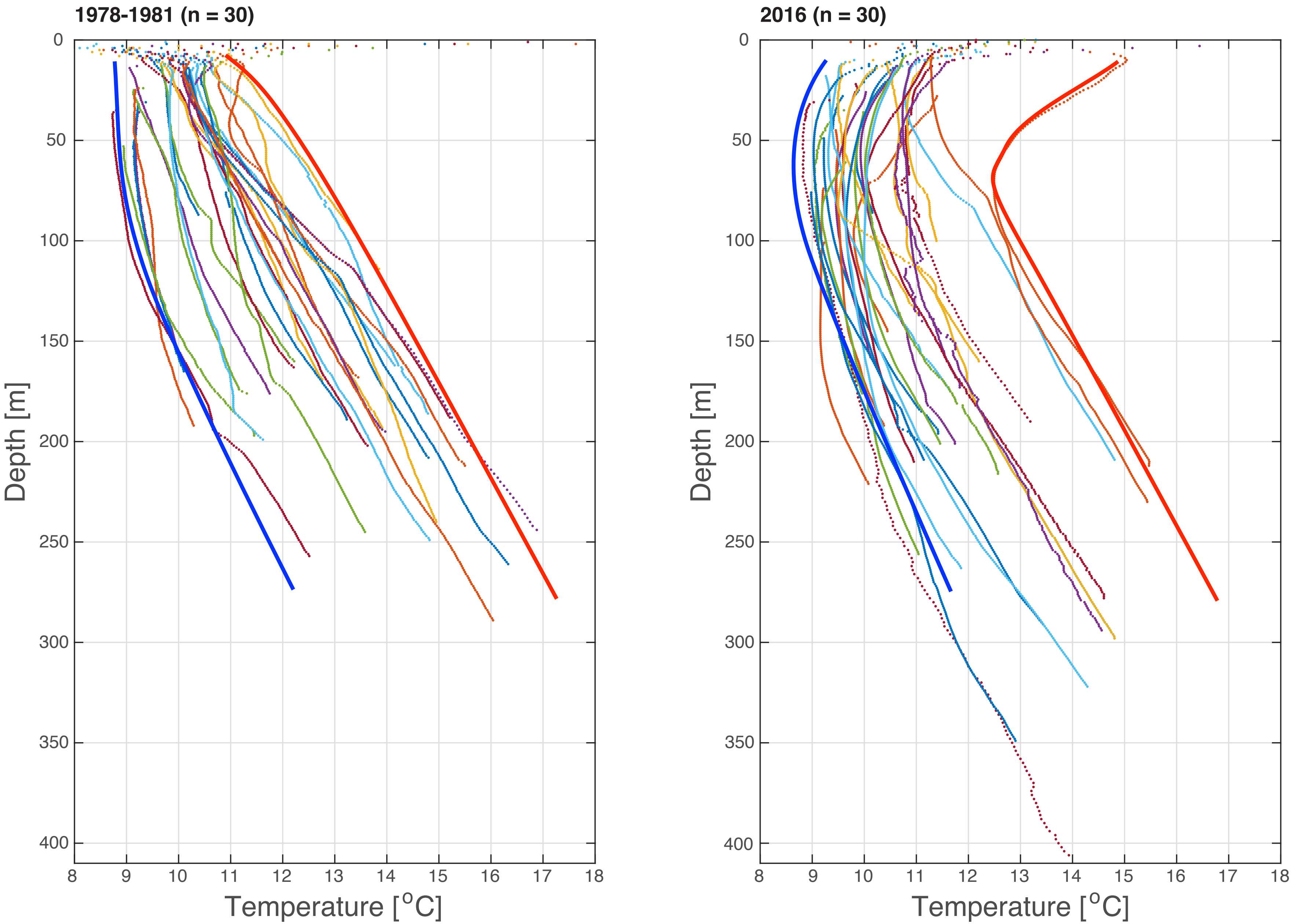
TD logging a borehole (2016)

- RBR soloT, accuracy ±0.002 ^{o}C, 1-2 seconds response time
- Recording every meter depth in 50 mm piezometer tubes

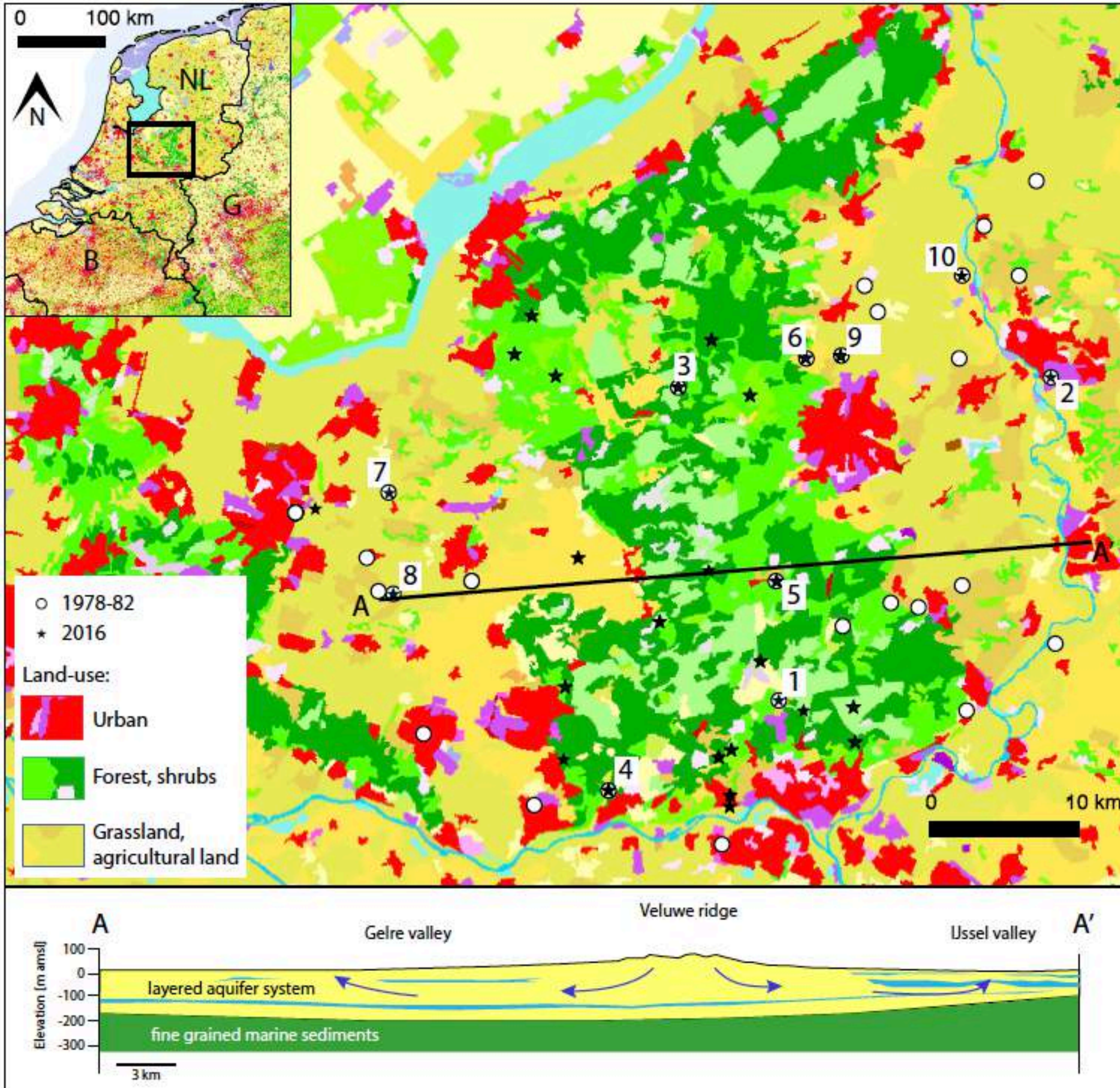
Historical TD data set compared to present day

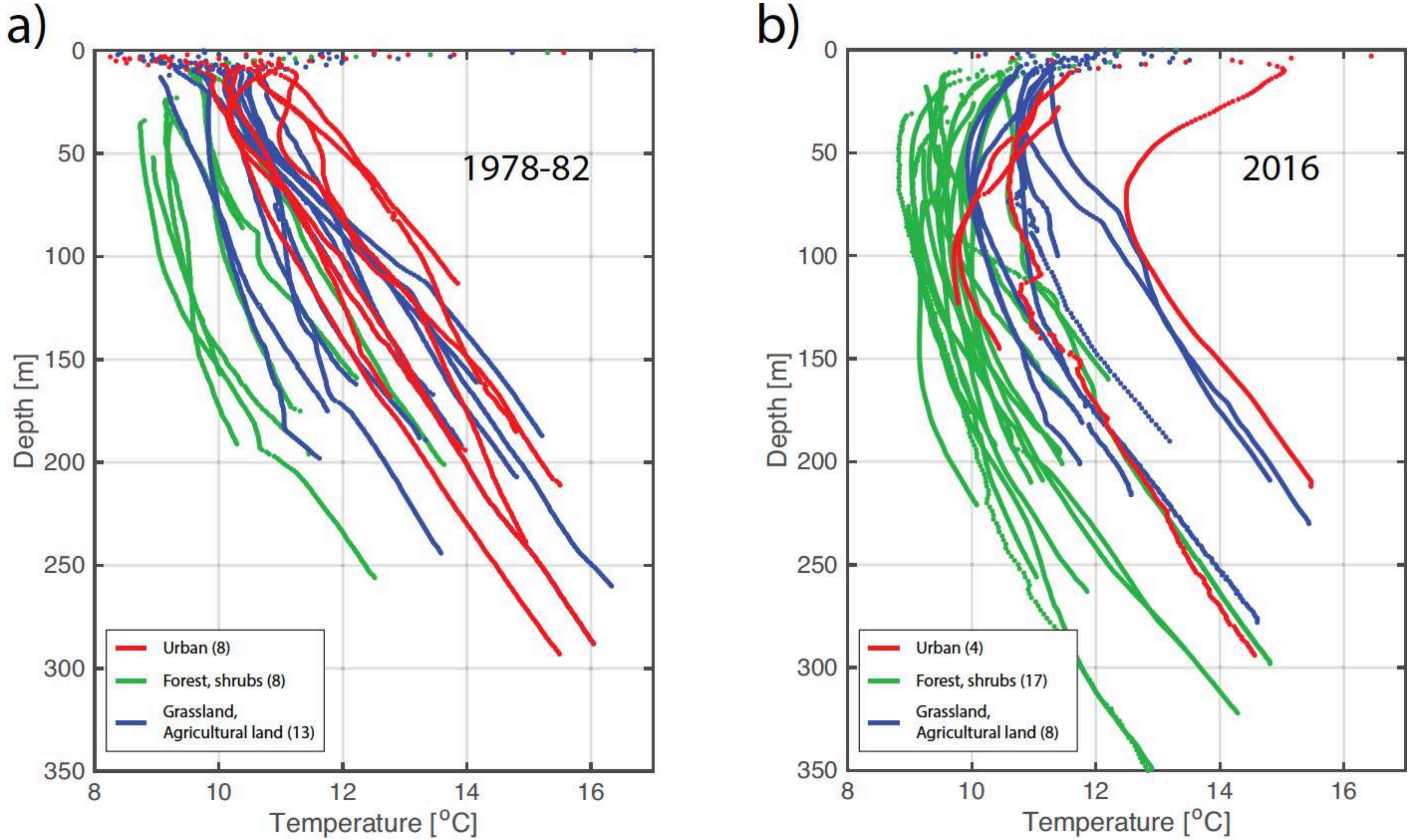


Historical TD data set compared to present day situation



Veluwe area, Netherlands – land use, and location of TD measurements





Bense and Kurylyk, GRL 2017

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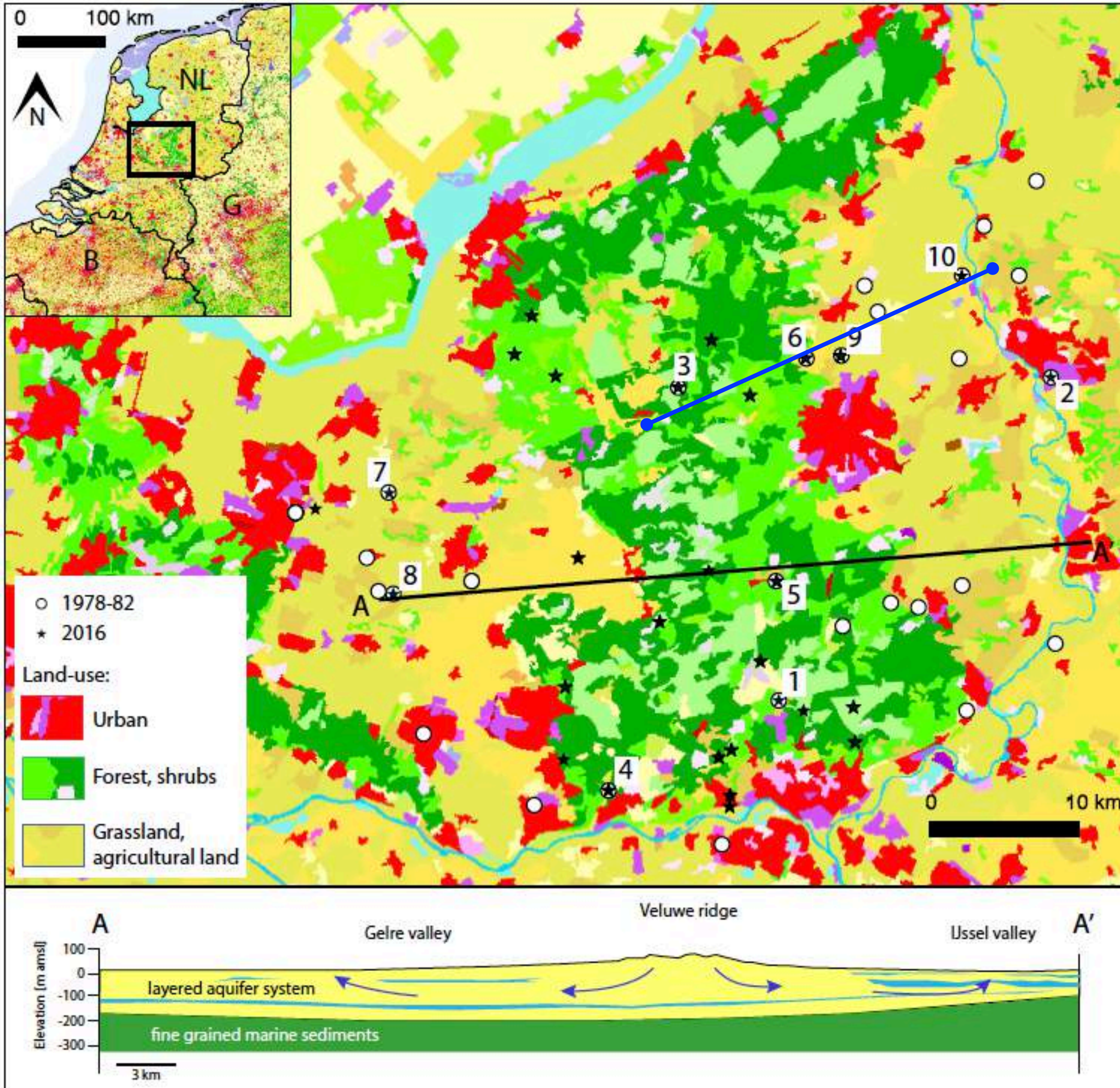
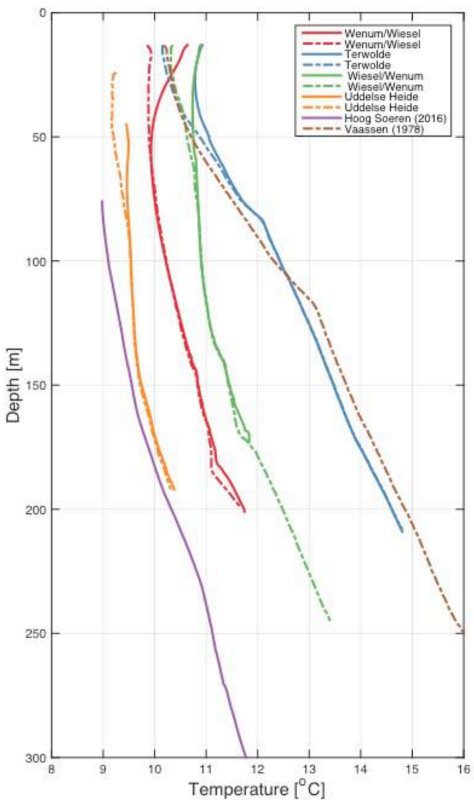
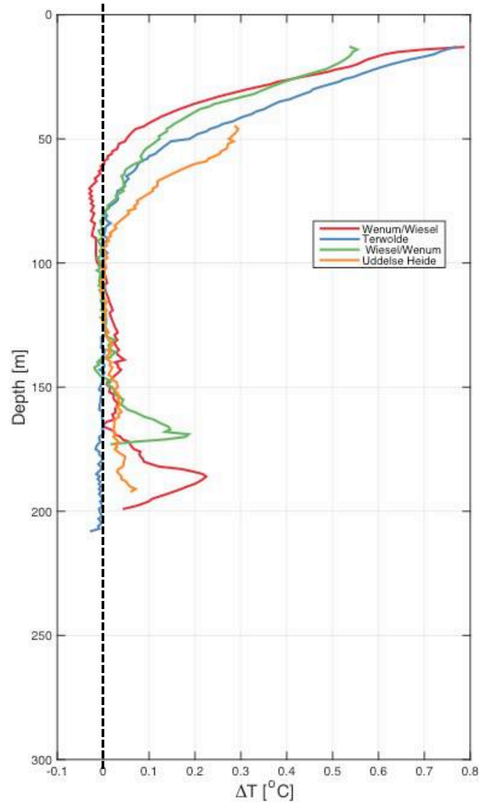


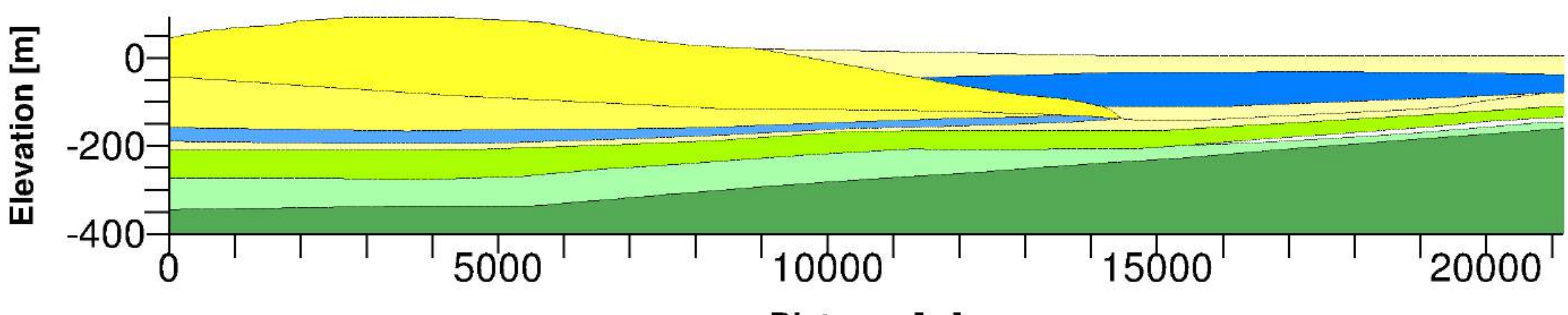
Comparing TD data in time and space



Temperature change
($T_{2016} - T_{1978\text{-}81}$)

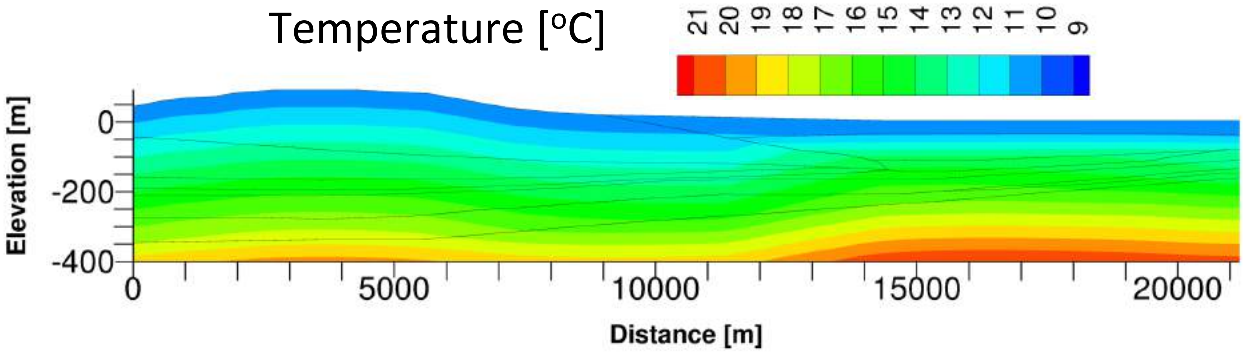


Aiming to unravel impacts on temperature distributions of geological build-up, land-use and groundwater flow (+ surface warming)

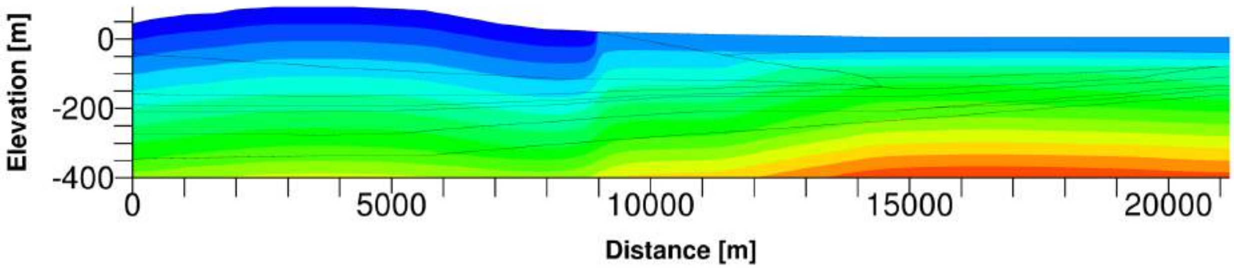


2D modeling, land use and groundwater flow

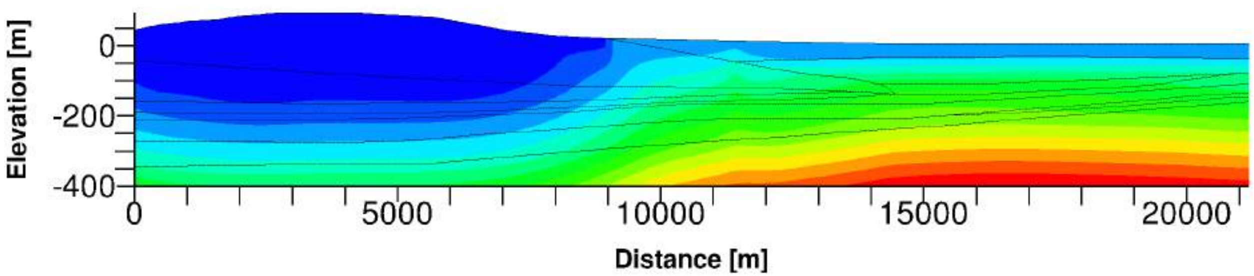
Temperature [^{o}C]



Heat conduction only, uniform surface temperature

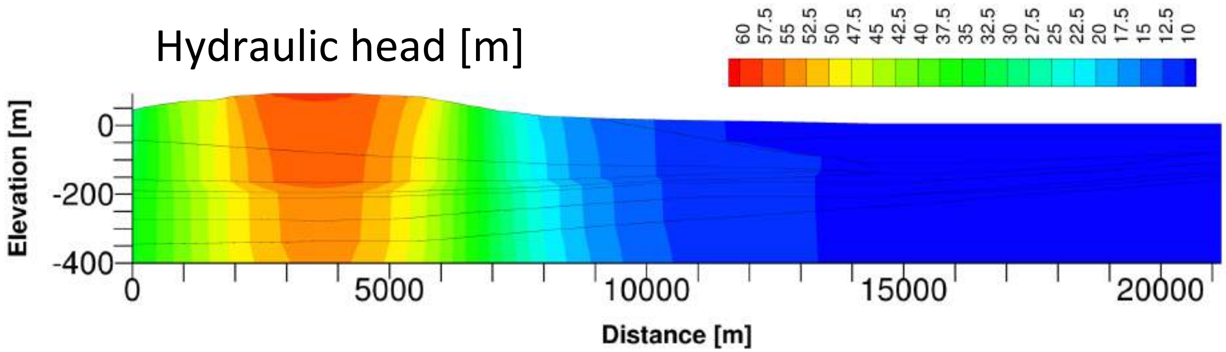


Heat conduction only, cooling effect of forest



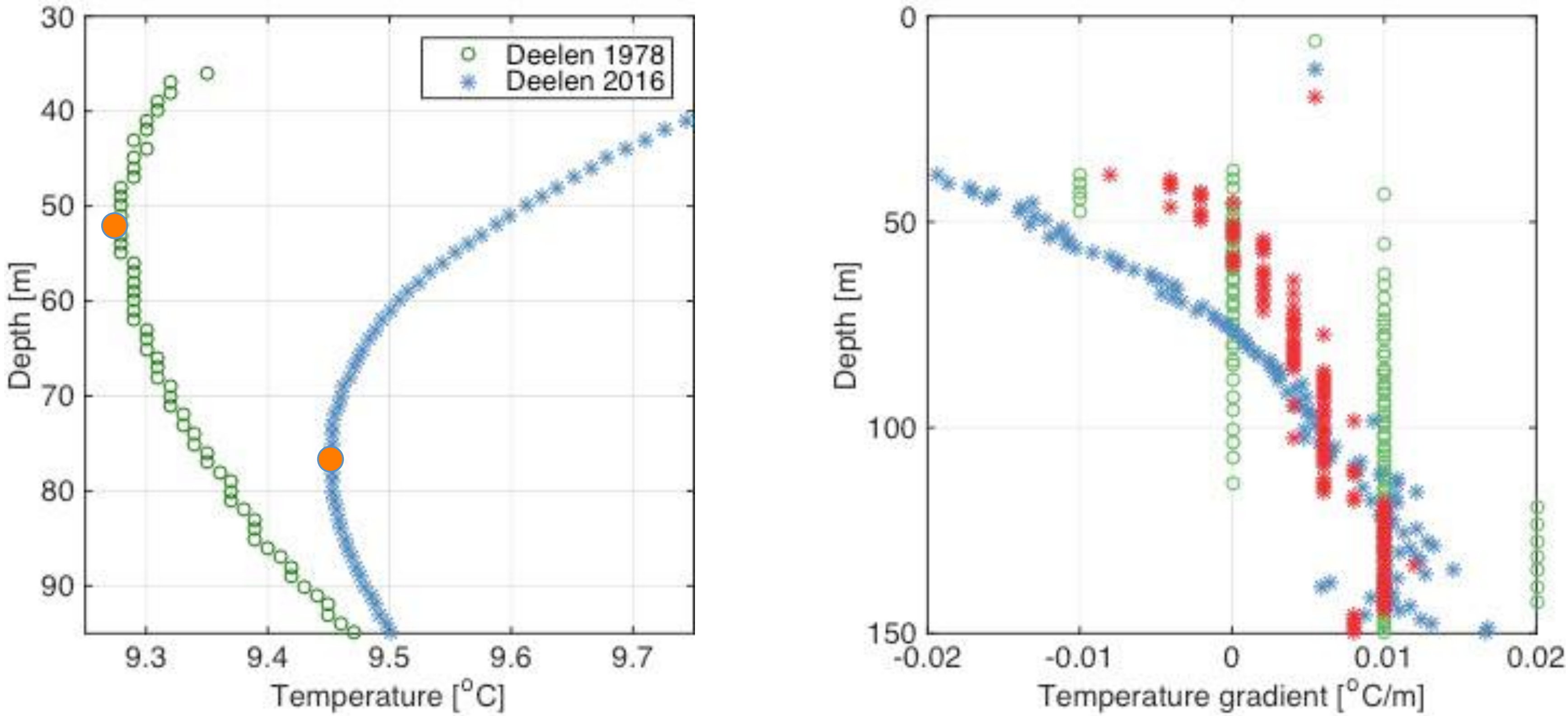
Heat conduction only, cooling effect of forest + groundwater flow

Hydraulic head [m]



In progress!

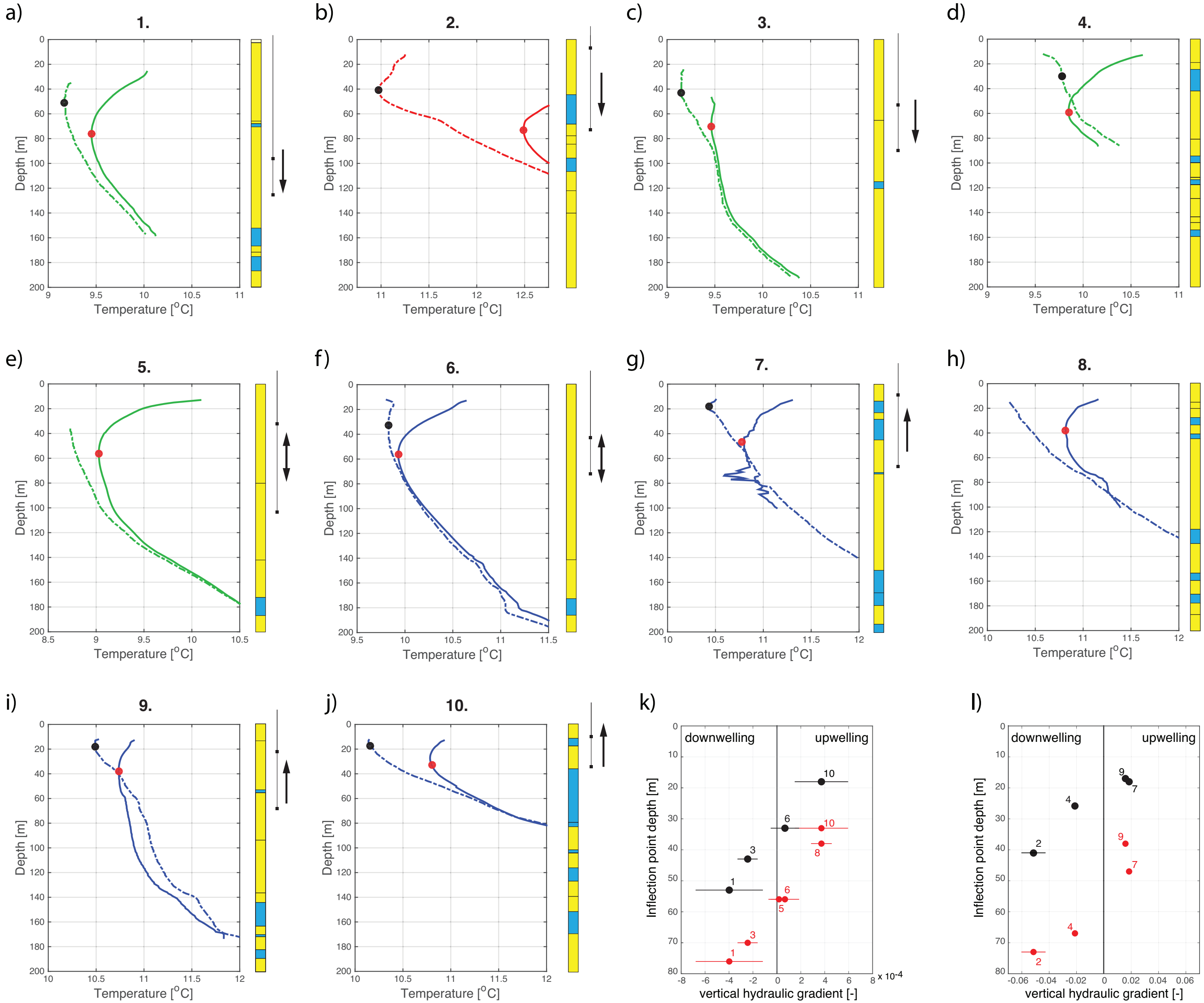
TD data quality: 1978-81 vs. 2016 - inflection point

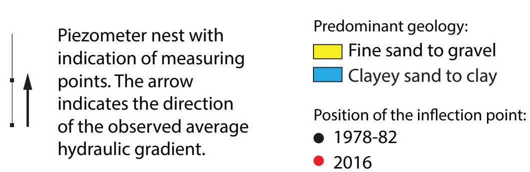


The depth (z_0) where the temperature-depth gradient is zero can be found for each repeated TD profile and plotted in time.

Data quality is an issue for the accurate determination of this inflection point in the TD record.

Bense et al., 2017, WRR

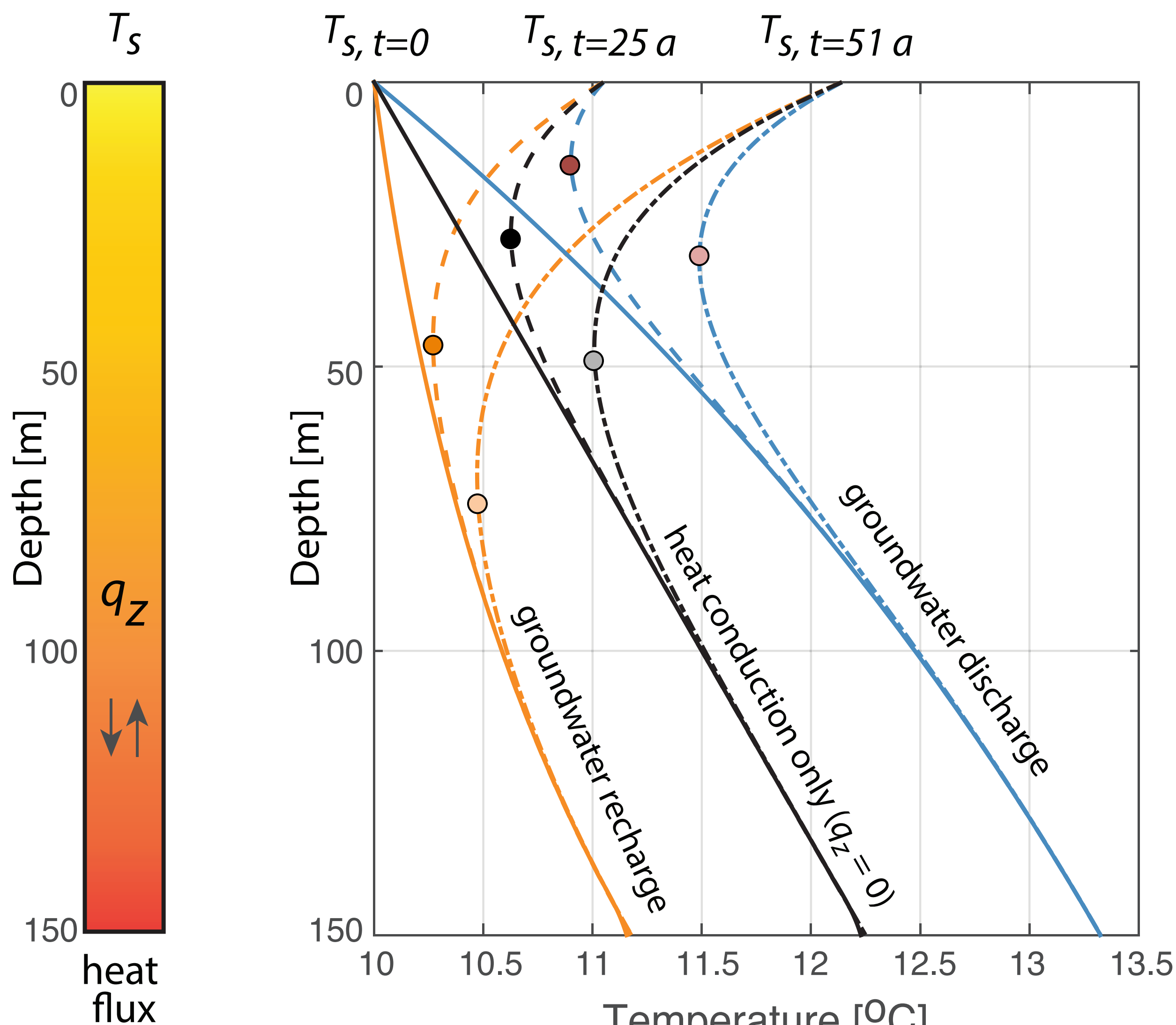




Inflection point migration between 1978/82 and 2016

Bense and Kurylyk, GRL 2017

Inflection point propagation for contrasting groundwater flow conditions in a warming climate

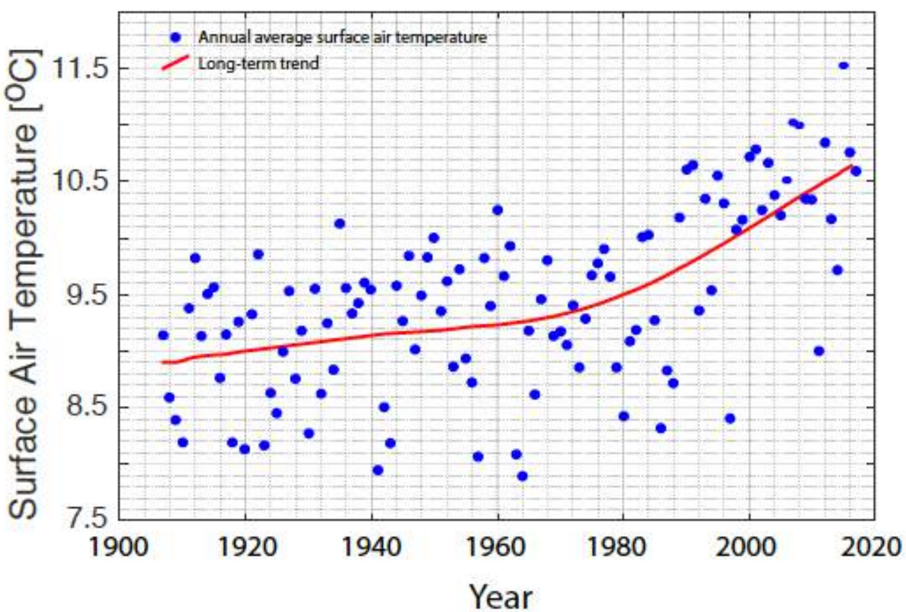


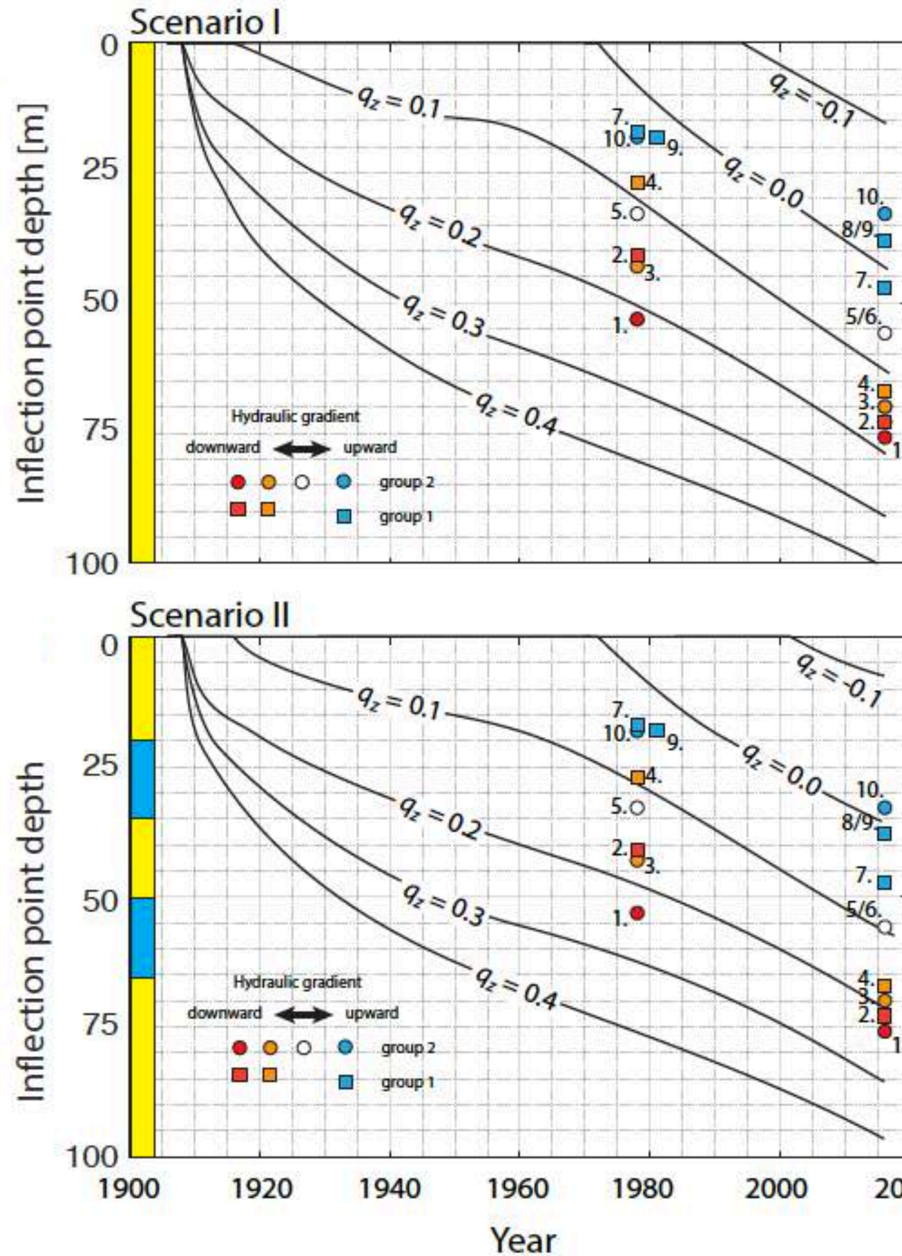
Bense and Kurylyk, 2017, GRL

Model results using long term Surface Air Temperature as the top boundary condition

For sites 1-7 downwelling rates are inferred between 50-250 mm/year;

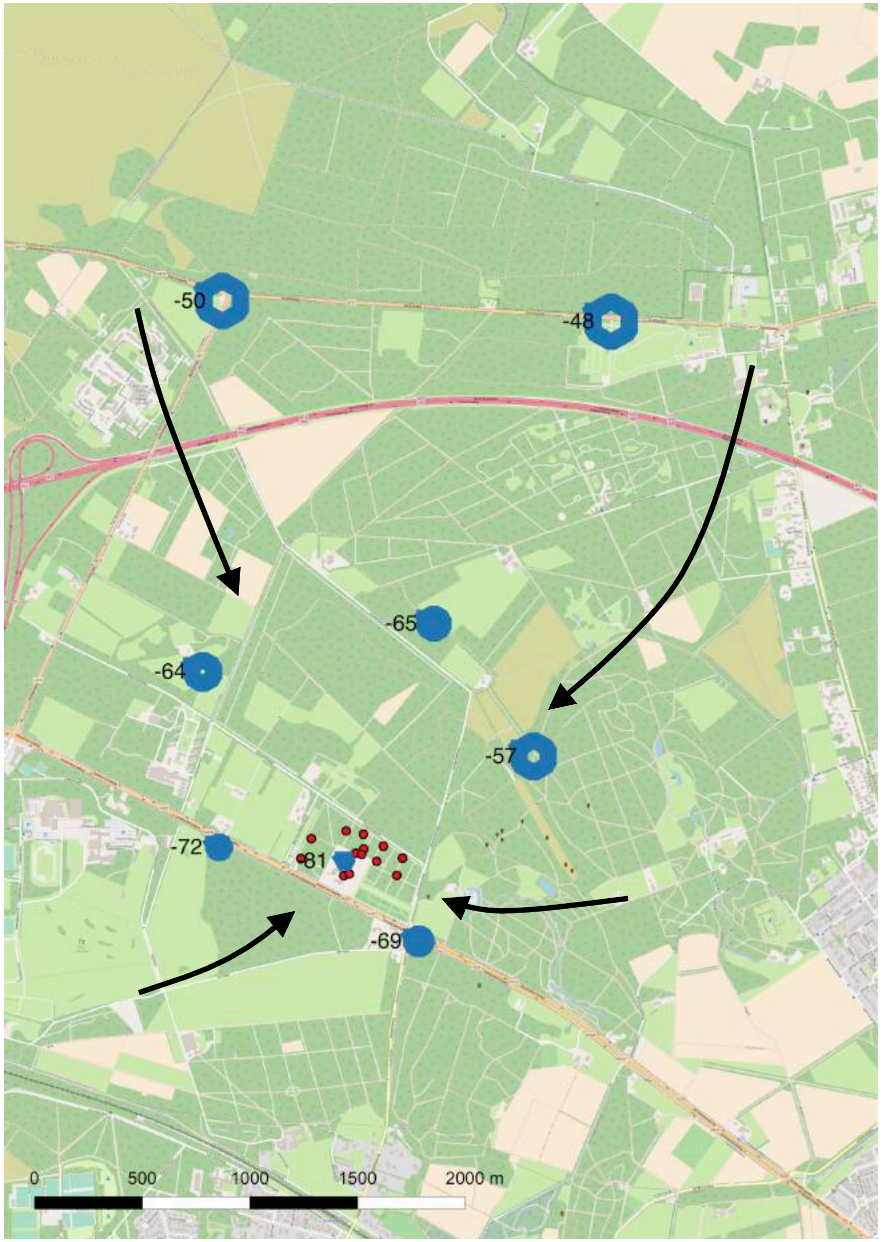
Sites 8-10 have little groundwater vertical flow to upto ~25 mm/year of seepage.





Bense and Kurylyk, GRL 2017

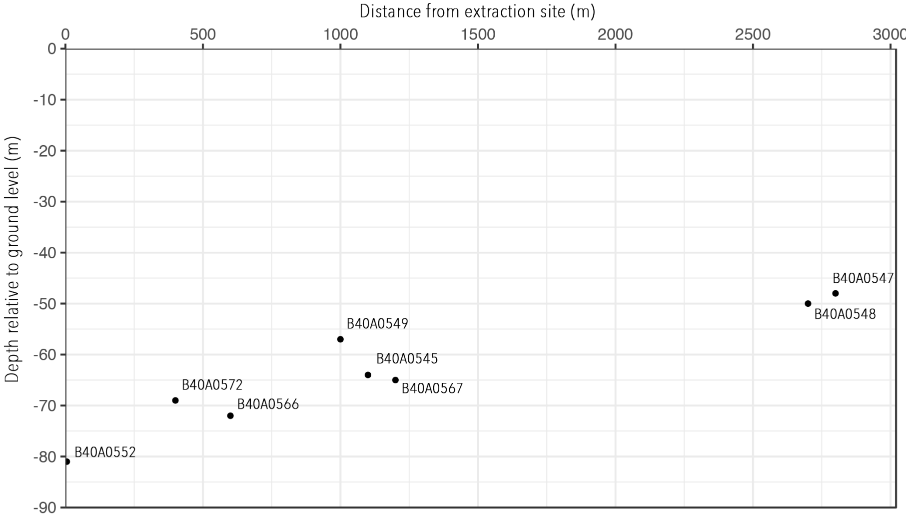
Groundwater abstraction sites



Major groundwater abstraction station in the Netherlands (9 Mm^3/a).

Inflection point depths in TD profiles surrounding the station, increase in accordance with increasing vertically downward fluxes nearer the the abstraction field.

Likely, that a 2/3D coupled heat-fluid flow model is needed for a quantitative interpretation.



Wrapping up…

- Deep subsurface temperatures are increasingly in a transient state, due to surface environmental change, requiring novel techniques to interpret those for groundwater flow
- Taniguchi's original analytical solution to interpret transient TD profiles has shortcomings and is better replaced by either a numerical model, or a more flexible analytical schemes (e.g., FAST)
- Where more complex systems, e.g. groundwater abstraction sites, are considered it appears that inflection point depths on their own can serve as a useful diagnostic for groundwater flow conditions
- Detailed numerical modeling is underway to unravel effects of geology, groundwater flow, land-use, and climate warming on thermal regimes

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