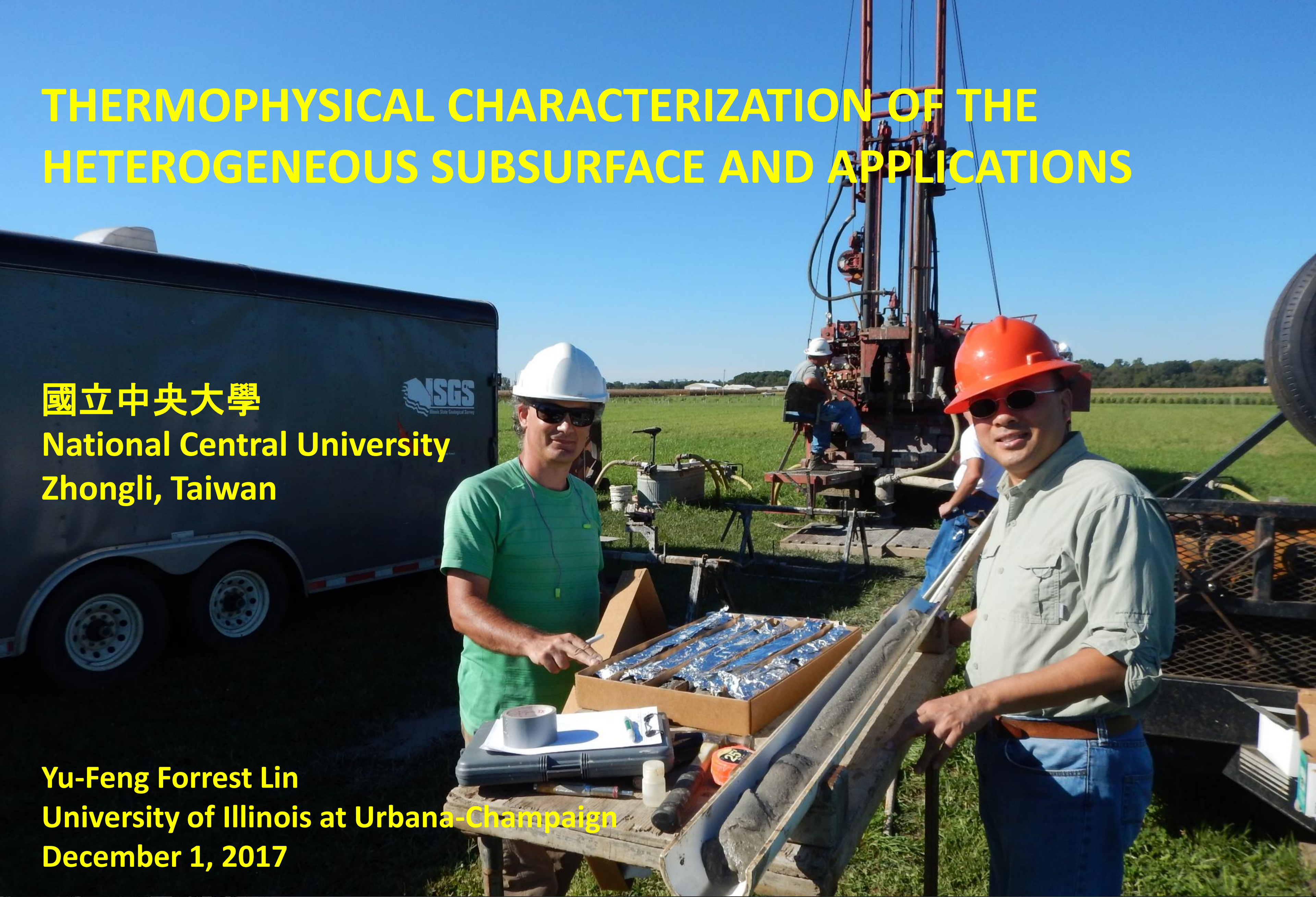
THERMOPHYSICAL CHARACTERIZATION OF THE HETEROGENEOUS SUBSURFACE AND APPLICATIONS



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University of Illinois at Urbana-Champaign

December 1, 2017

CZO | INTENSIVELY MANAGED LANDSCAPES
CRITICAL ZONE OBSERVATORY

ILLINOIS

WISCONSIN
UNIVERSITY OF WISCONSIN–MADISON

NSF

Acknowledgments

國立中央大學, National Central University
國立交通大學, National Chiao Tung University
中華民國科技部, Ministry of Science and Technology

Student Sustainability Committee
University of Illinois at Urbana-Champaign

U.S. National Science Foundation

U.S. Department of Energy

U.S. Army Corps of Engineers

6 Universities
1 Government Agency
45 Participants

Terrestrial Subsurface Thermal Regime

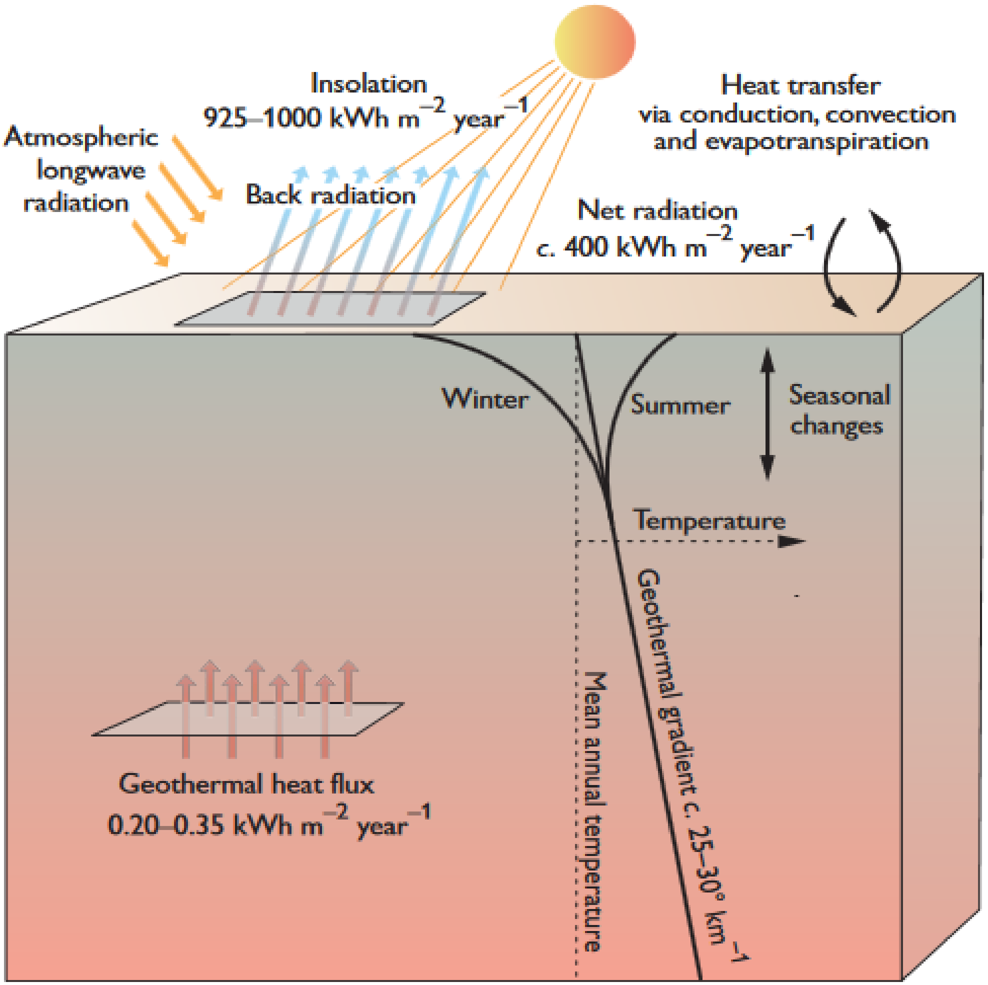
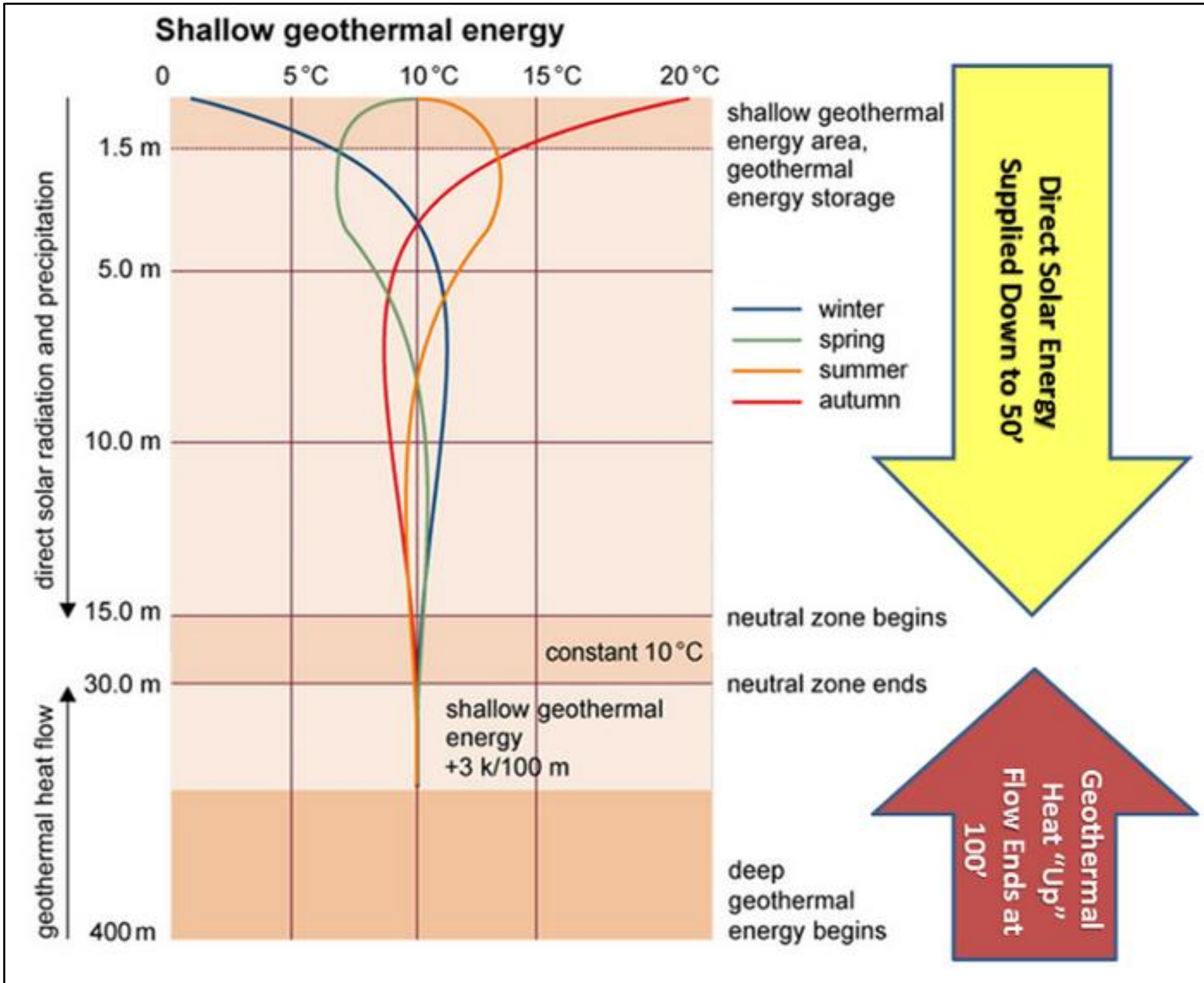


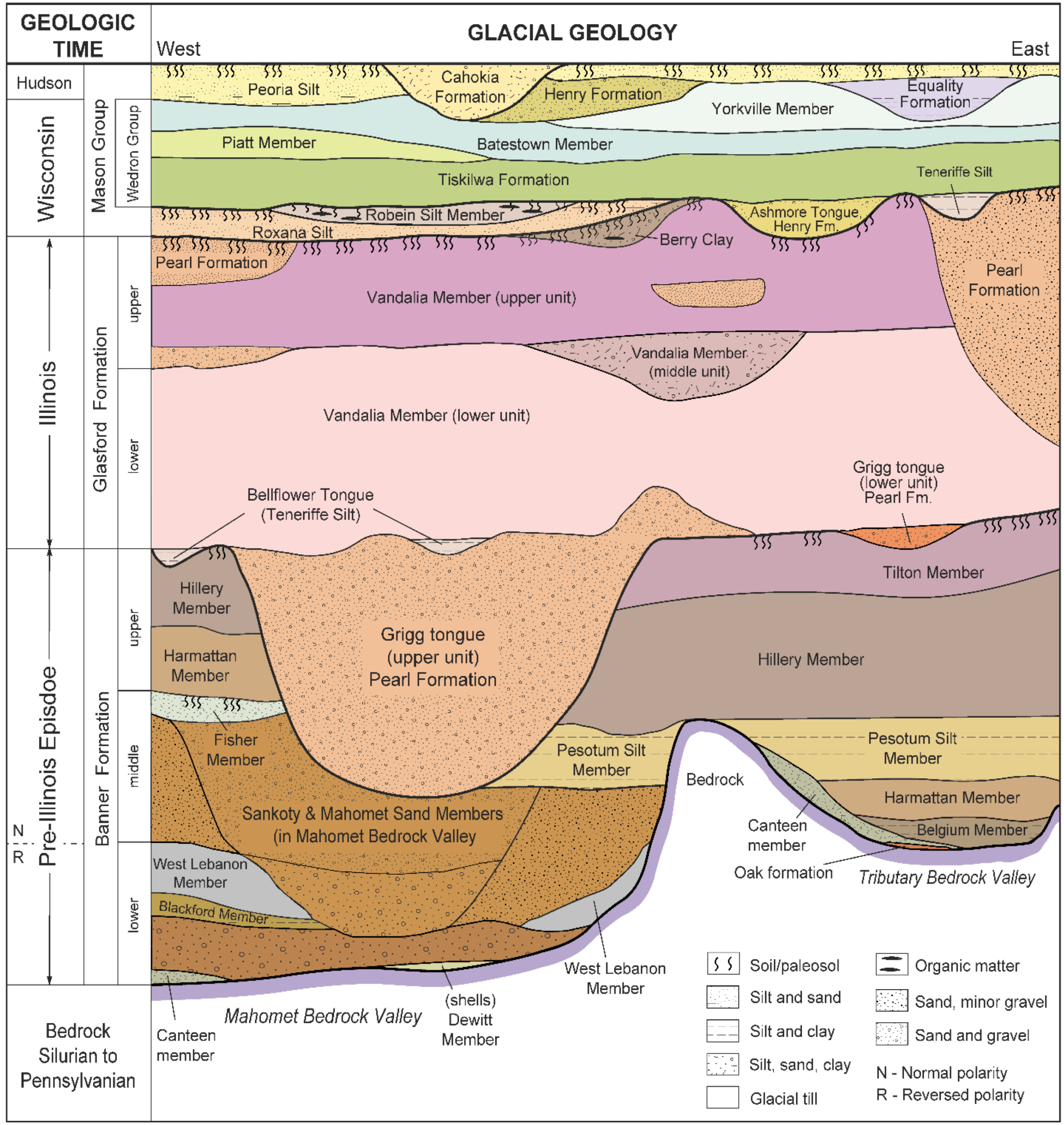
Fig. 1. Schematic block diagram showing the geothermal gradient and magnitude of geothermal heat flux and insolation with average values for Denmark as well as the seasonal zone of fluctuation in temperature (modified from Banks 2008).

Terrestrial Subsurface Thermal Regime

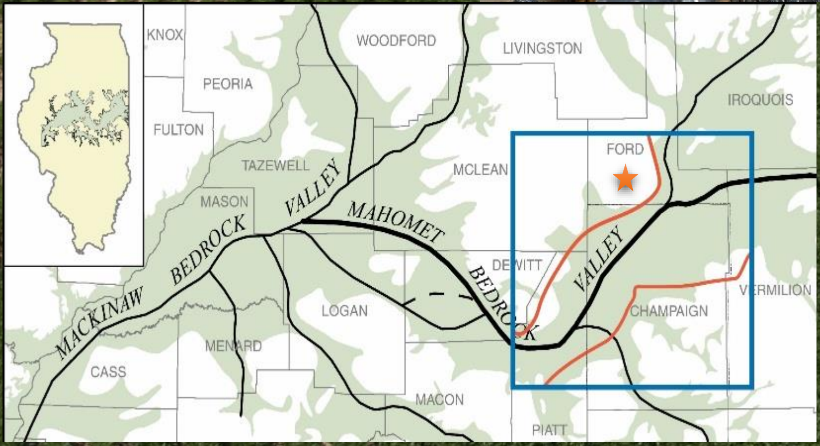


Geology and Hydrogeology Framework

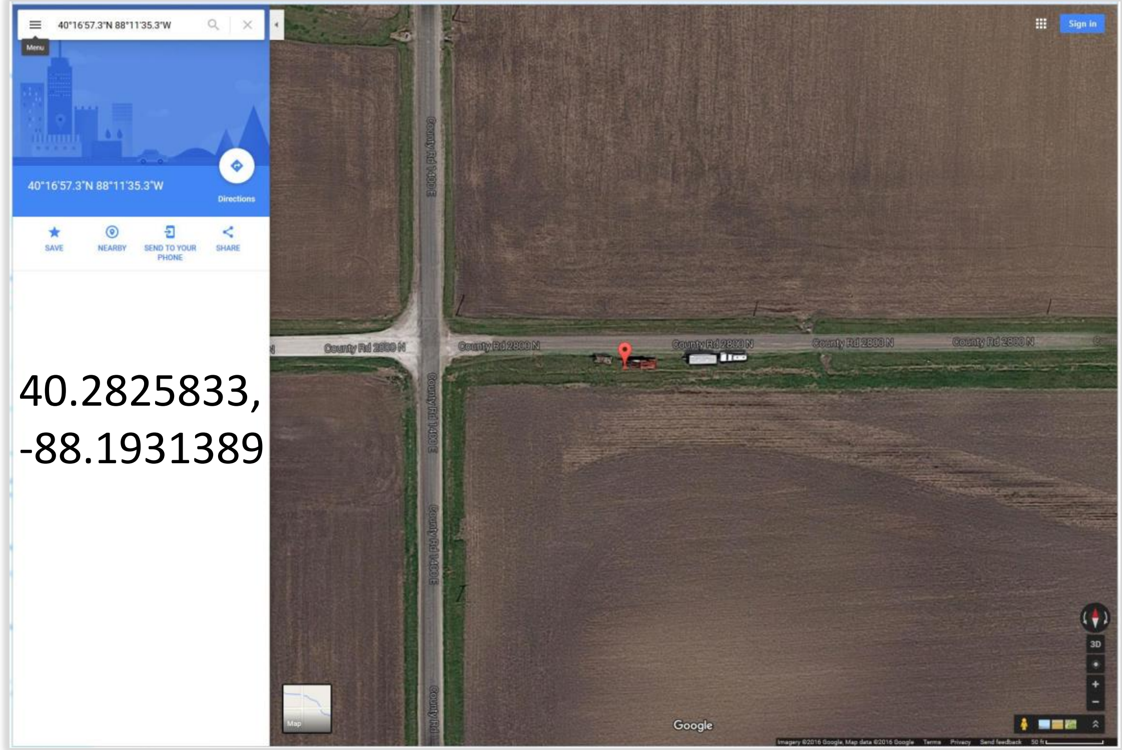
Glacial systems are inherently heterogeneous



Critical Zone Observatory for Intensively Managed Landscapes (IML-CZO)



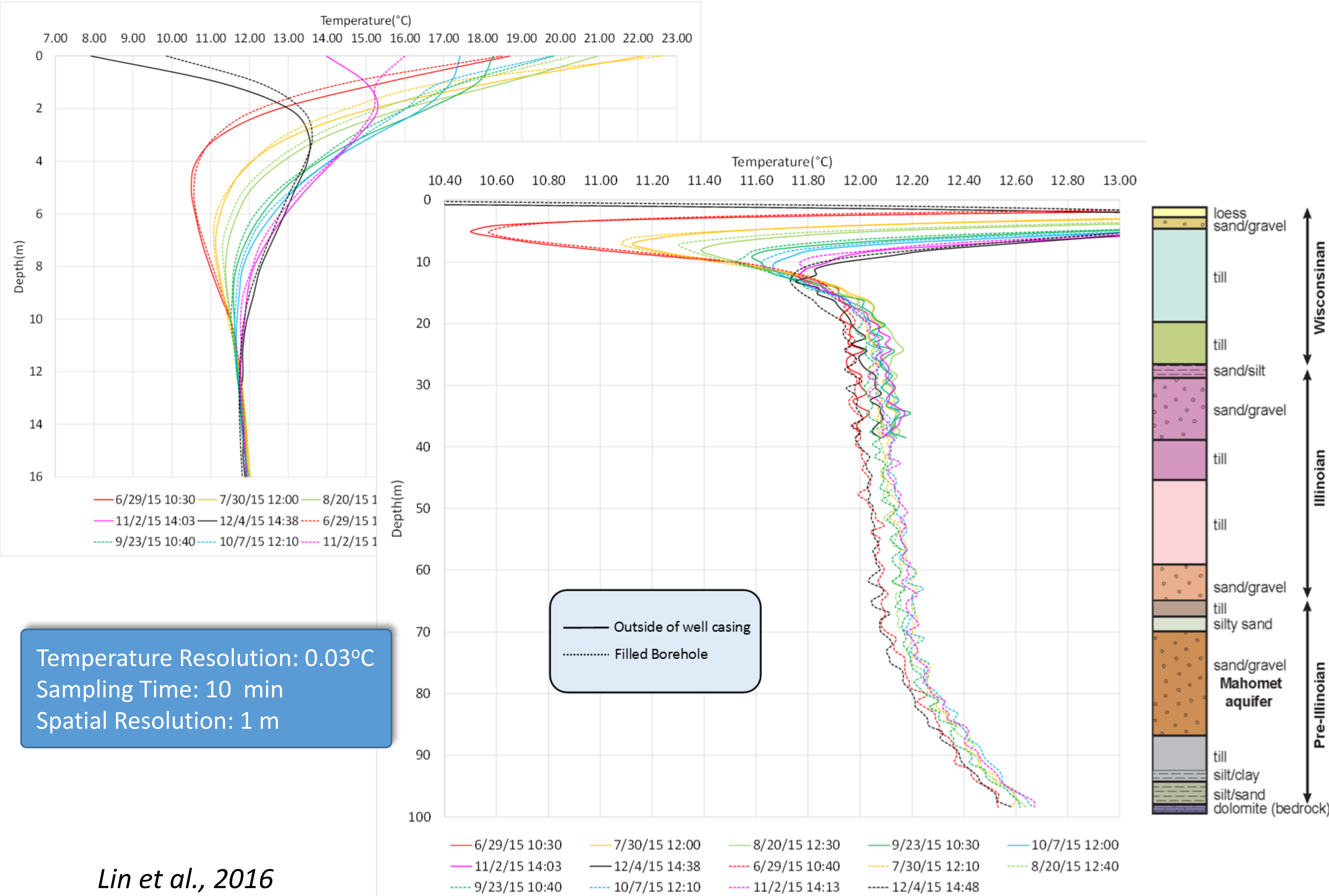
West Rantoul



40-m well screened in Glasford aquifer

100-m hole penetrating Mahomet aquifer

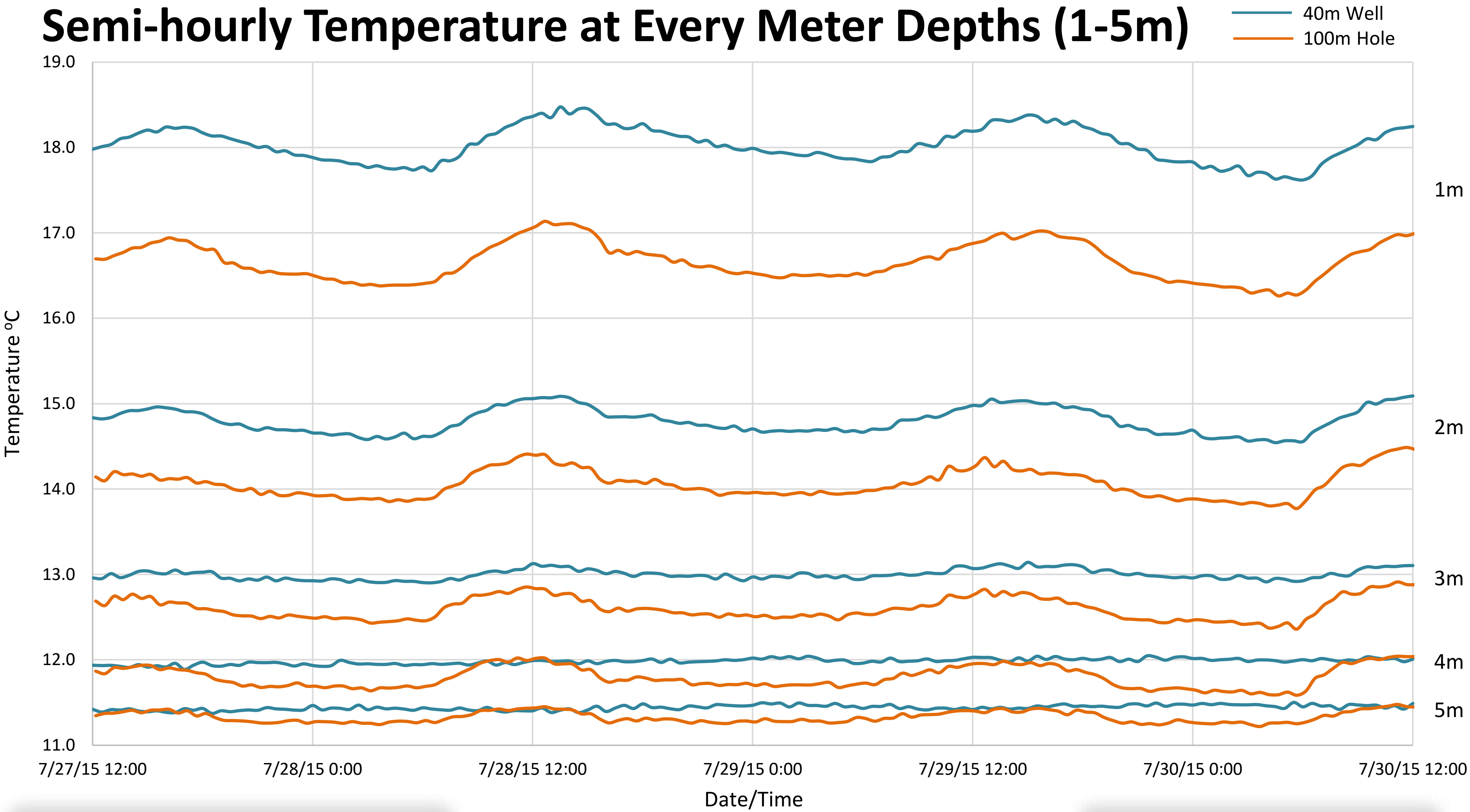
Monthly Temperature Comparison from June-December, 2015



Temperature Resolution: 0.03°C
Sampling Time: 10 min
Spatial Resolution: 1 m

Lin et al., 2016

Semi-hourly Temperature at Every Meter Depths (1-5m)



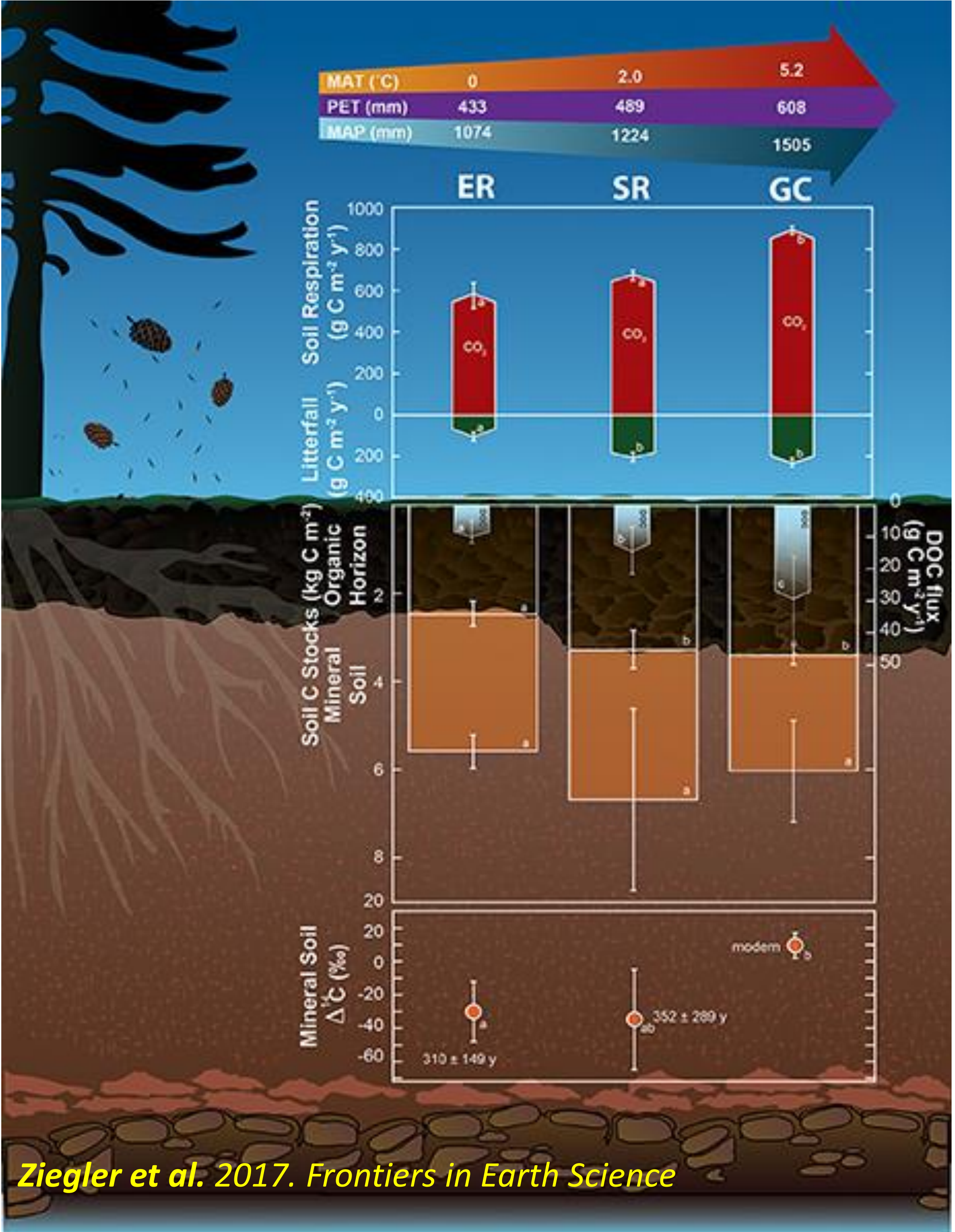
Semi-hourly summer temperatures at 1-meter depths (1–5 meters) reflect amplitude attenuation and phase shifts as heat is conducted in the subsurface.

Lin et al., 2015

The preliminary results indicate:

- The derivative of the subsurface temperature alone depth corresponds to the hydrostratigraphic characterization and groundwater flow.
- A well might act as a temperature buffer to potentially interfere with the natural geothermal regime.

A regional rule-of-thumb temperature gradient of 1 °F/100 ft and an annual average temperature of 62 °F (16.6 °C) at 100 ft (30.5 m) below surface based on 40 years of observations and measurements in the Illinois Basin. (Frailey et al., 2004).



Ziegler et al. *2017. Frontiers in Earth Science*

Short- and Long-Term Temperature Sensitivity in the Subsurface

<u>Shallow Critical Zone</u>

↑ Temperature and ↑ Precipitation

↓

↑ Soil respiration by ~55%
↑ DOC fluxes to the mineral horizons by 300%
↑ Mobilization and subsequent loss of soil C

Deep Critical Zone?

Thermophysical and Hydrogeological Characterization??

Climate Change and Anthropogenic Influence

- Vertical Temperature Profiling with Climate Changes

- Well Interference
- Agriculture Influence
- Energy

Thermal Analysis for Geothermal Energy Alternatives 2016-2017

USDOE

- > 66% electrical energy and > 40% of natural gas is consumed in a building’s utilities in US.
- In residential and commercial buildings, space heating and cooling consume 47% of the electrical power, and water heating accounts for an additional 12%.

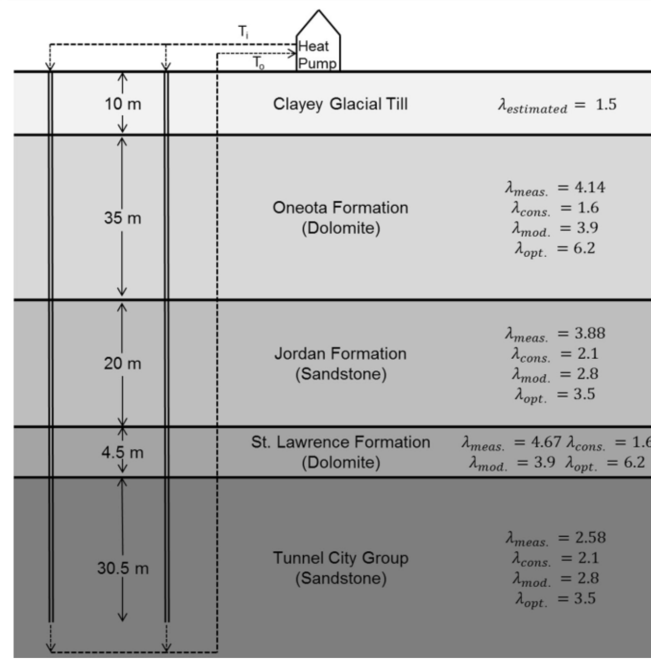
USEPA

Reduce energy consumption by up to:

- 44% compared with air-source heat pumps
- 72% compared with conventional electrical heating and air conditioning

USDOD

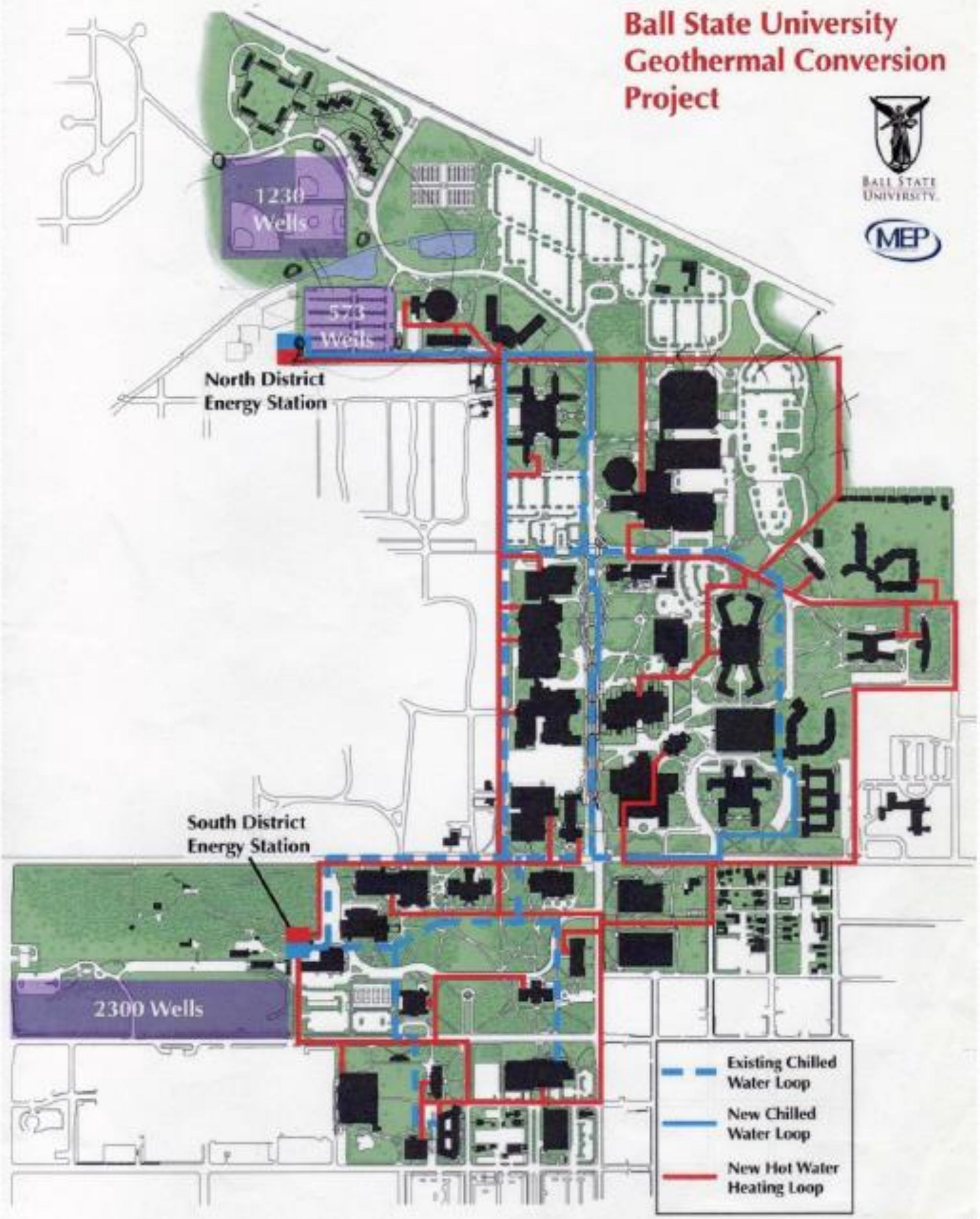
Long-term solution on resource reliance and disaster reduction, such as reducing the number of hydraulic power dams for flood reduction.



Walker et al., 2015

BSU Geothermal Conversion

- Divided into two Phases, Phase I and Phase II
- Both phases are completed and running
- This study concerns the ground temperatures in Phase II since thermal loading began

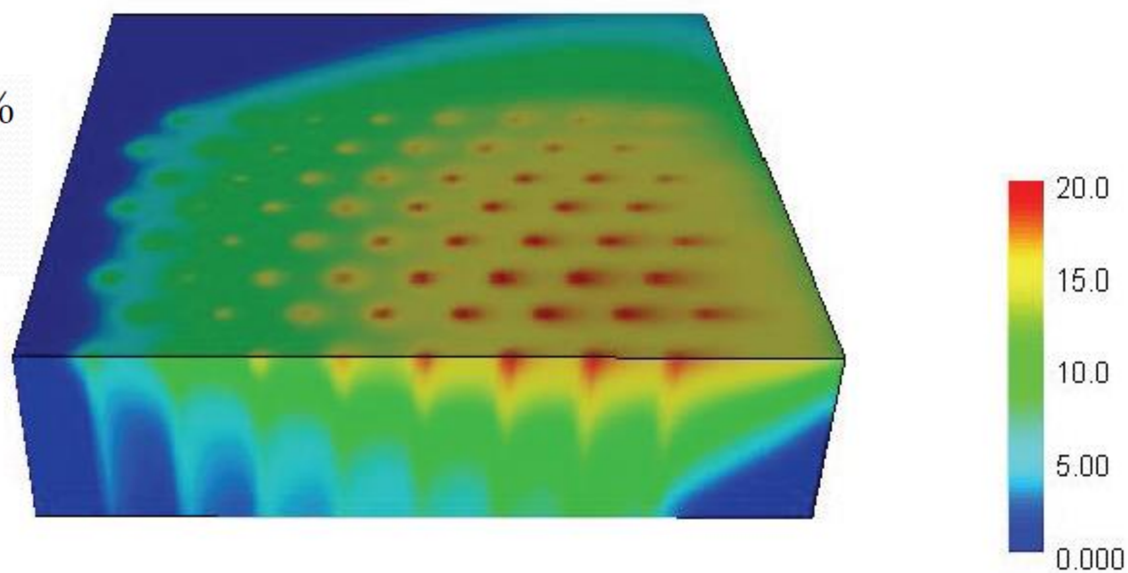


Advection & buoyant convection of thermal plume

- Preliminary data indicate that the BSU is in a thermal excess condition that provides thermal loading to the ground.
- In such conditions, excess thermal load may create a plume of warm buoyant groundwater that advects in the direction of groundwater flow.

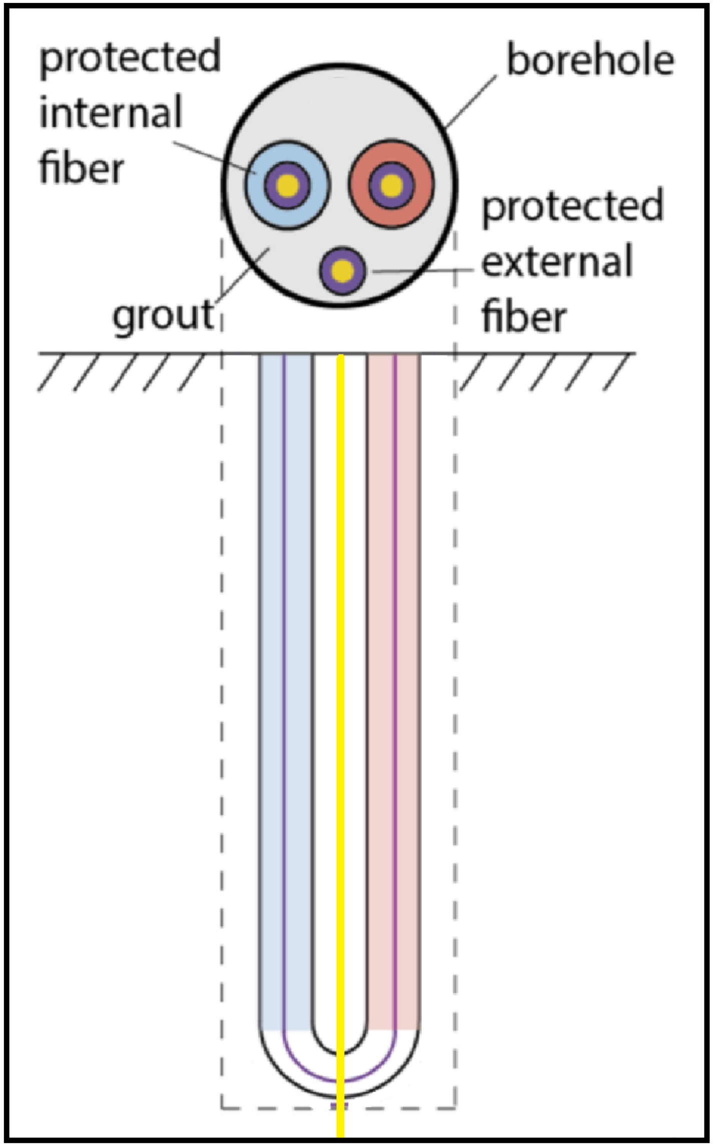
  - Reduce carbon footprint by 50%
  - Save $2 million annually

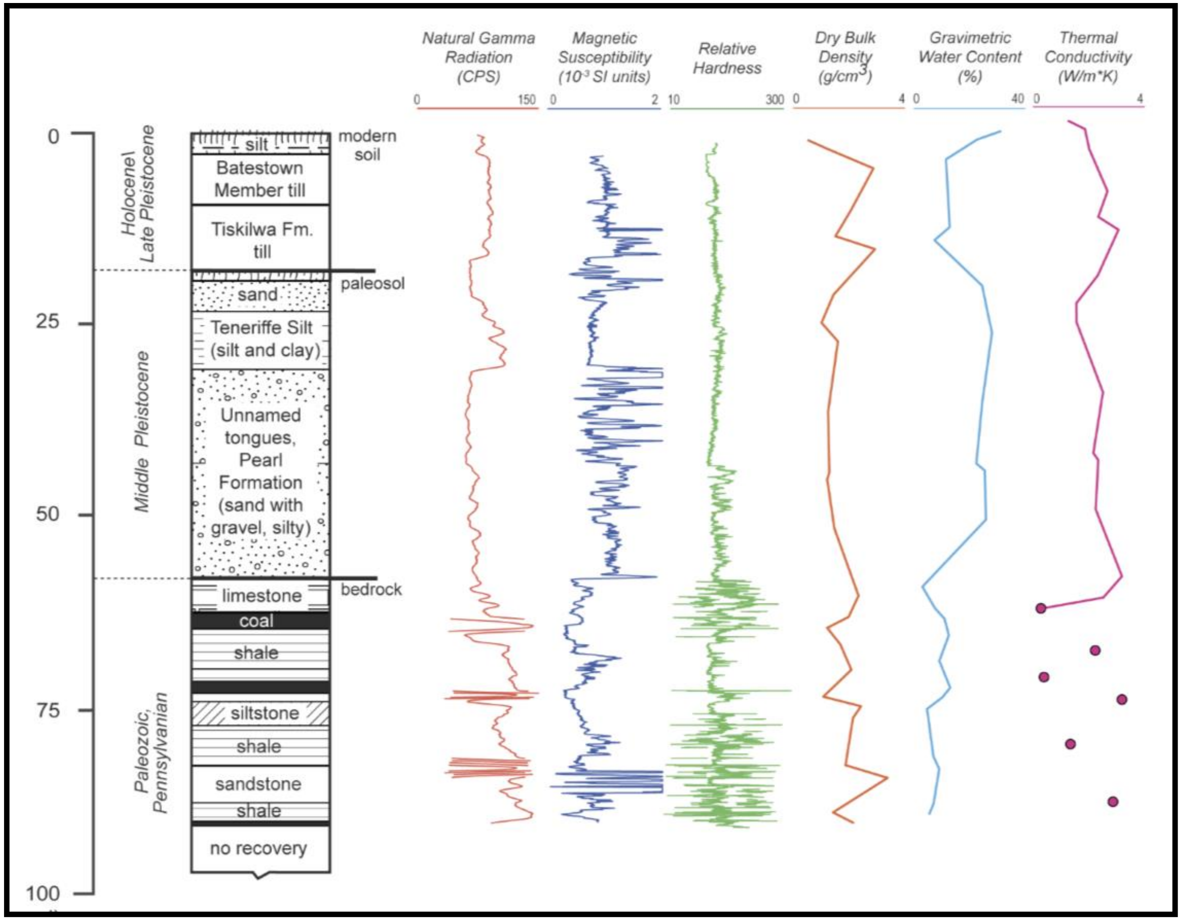
Lowe et al. 2010



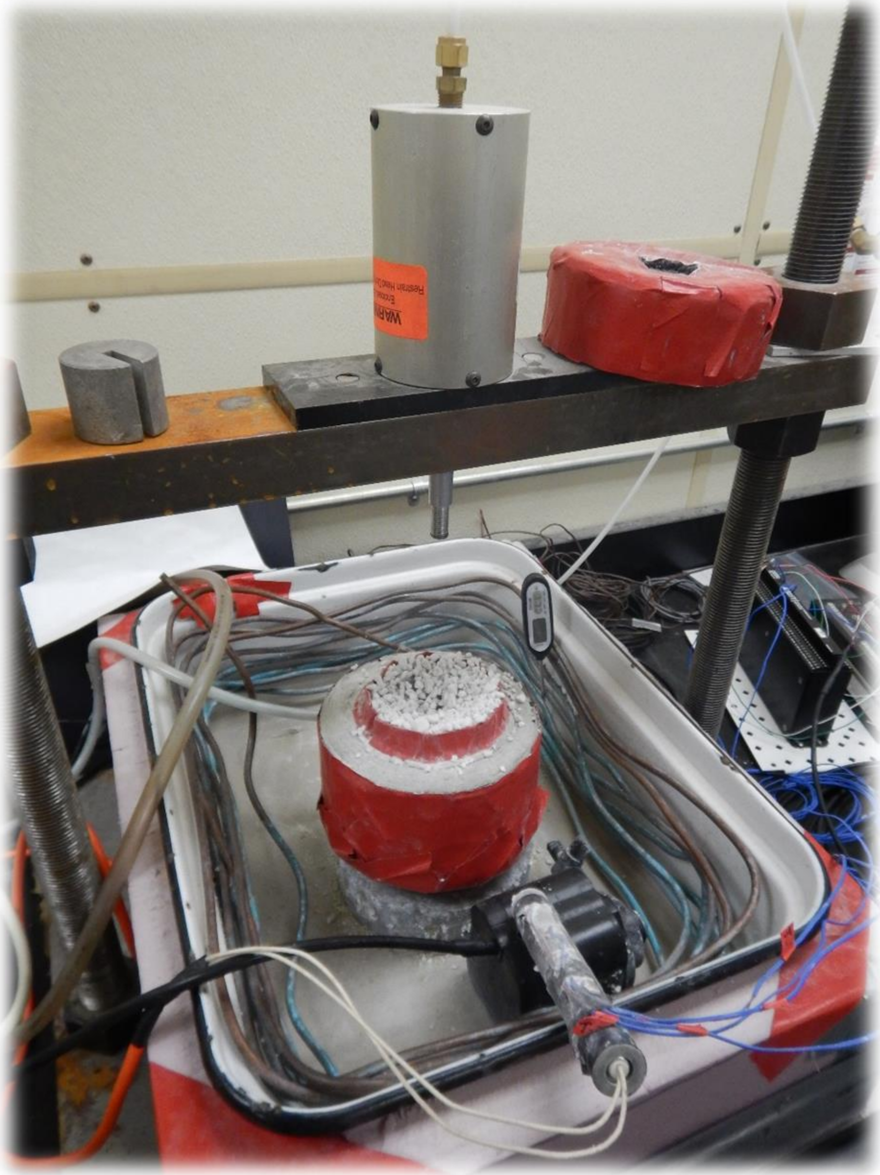
Courtesy of Mike Sukop

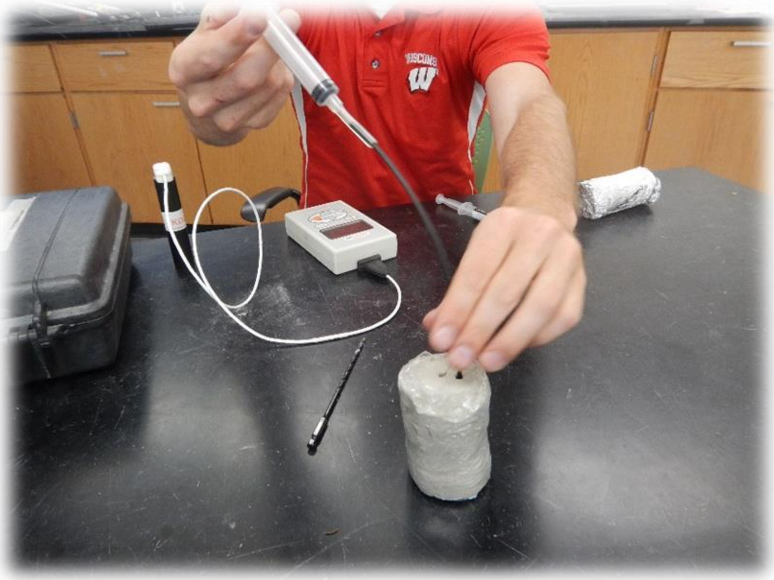
Geothermal Monitoring

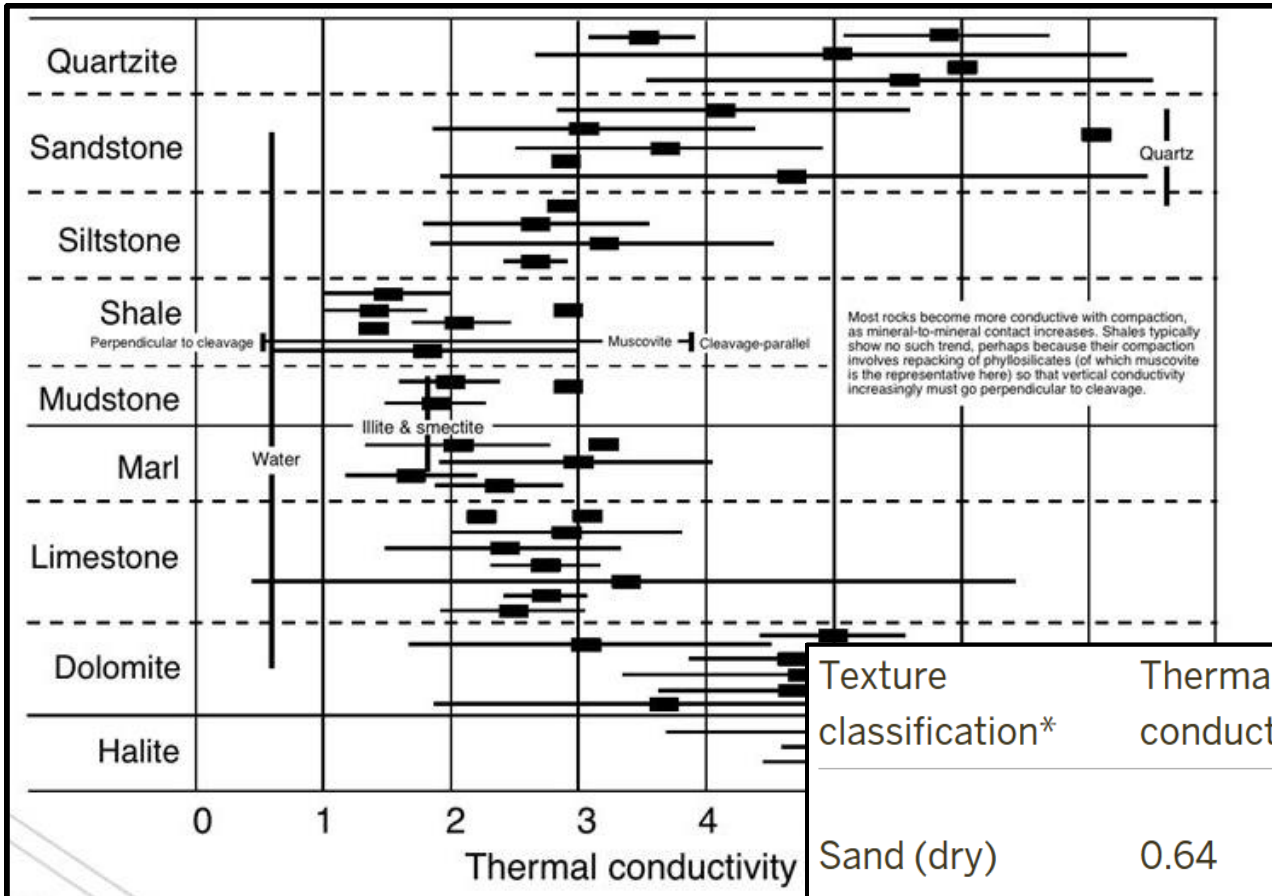




Geothermal Property Analysis







Moisture content ↑
Thermal conductivity ↑

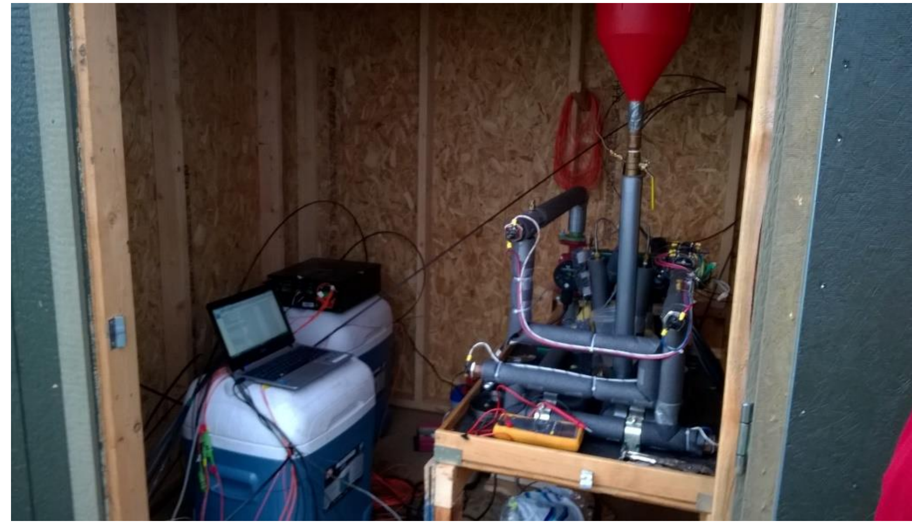
Sandy sediments (←→)
Clayey sediment (→←)

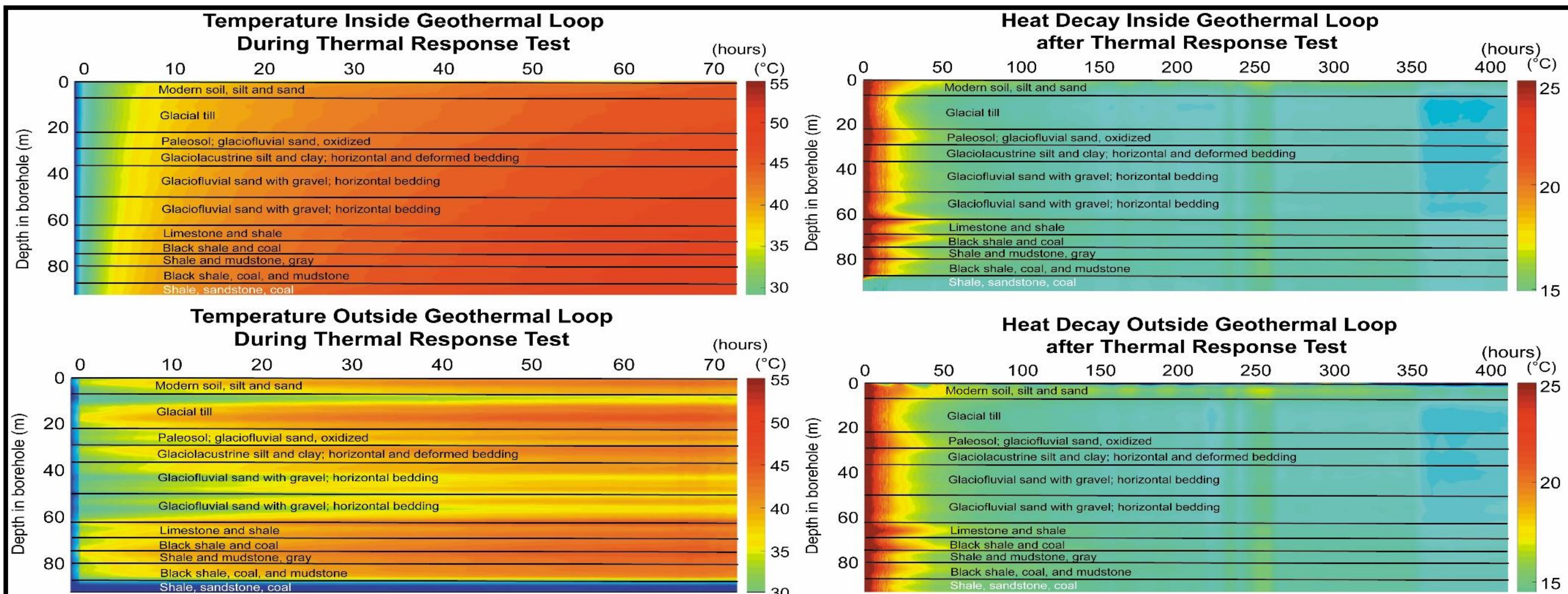
Texture classification*	Thermal conductivity (W/m*K)	Thermal diffusivity D (mm2/s)
Sand (dry)	0.64	0.67
Sand (moist)	1.39	0.73
Silt loam (moist)	1.59	0.70
Silt loam (wet)	1.59	0.56
Clay loam (moist)	1.90	0.57
Clay loam (wet)	2.14	0.61

*Moisture contents are based on degree of saturation (dry: 0-25%, moist: 26-50%, wet: 51-99%)

What about bulk density, hardness, mineralogy, cementation, and flowing water?

Distributed Thermal Response Test (DTRT)





Greenhouse gas emissions from powering buildings

1. Heating, ventilation and cooling of buildings ~30% of global GHG

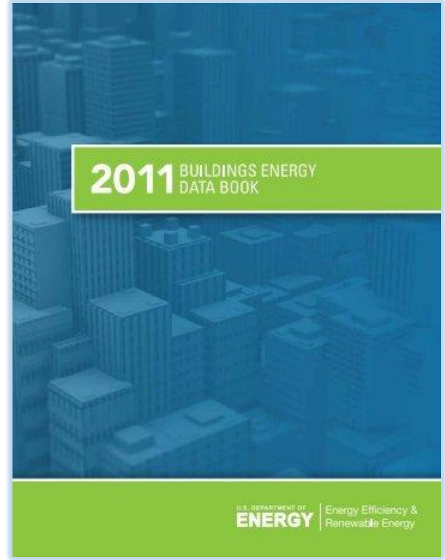
   (*IEA, 2016*)

2. Heating and cooling (USA):
   - 47% of energy demand

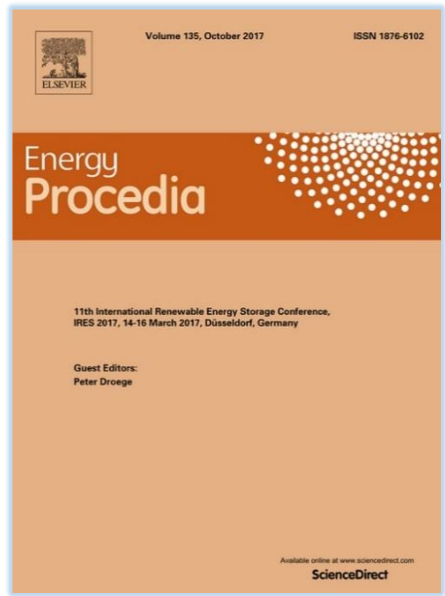
   (*US DOE, 2012*)

3. Energy usage in buildings (China):
   - 20% of total energy in China in 2012
   - 16% of total global energy use in 2012

   (IEA, 2015)

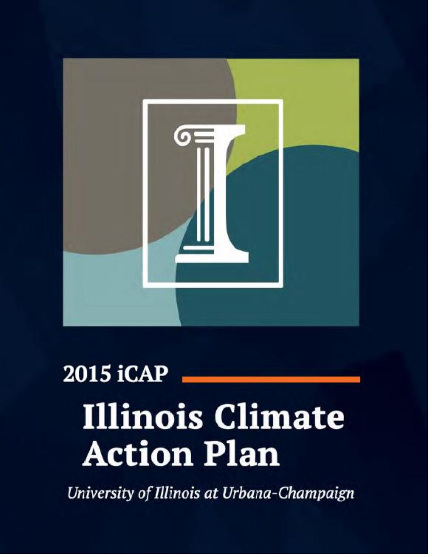


The book is a compendium of statistics on residential and commercial building energy consumption



Geological Sequestration

The ISGS has completed several projects to study storing CO_2 deep underground



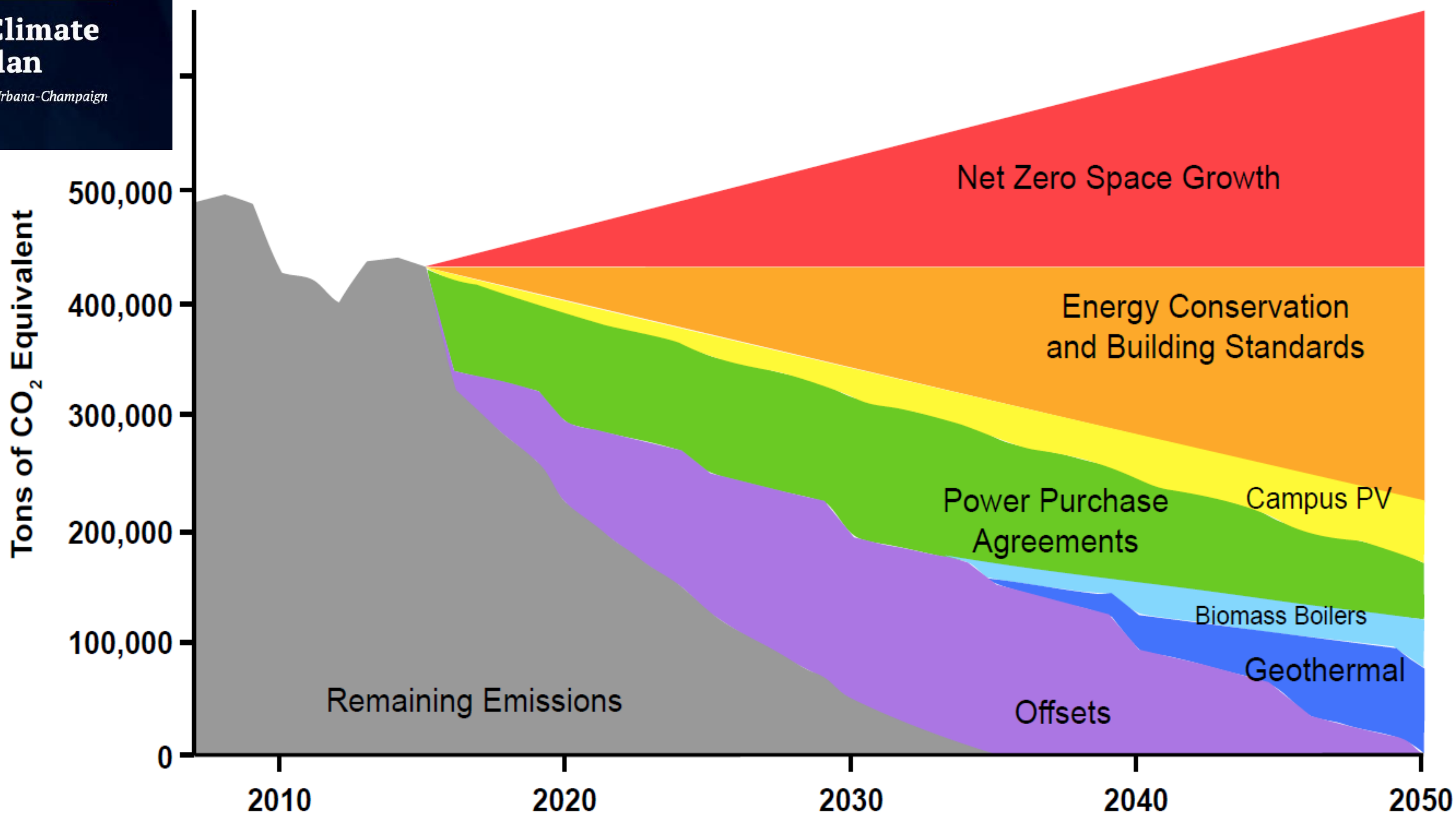
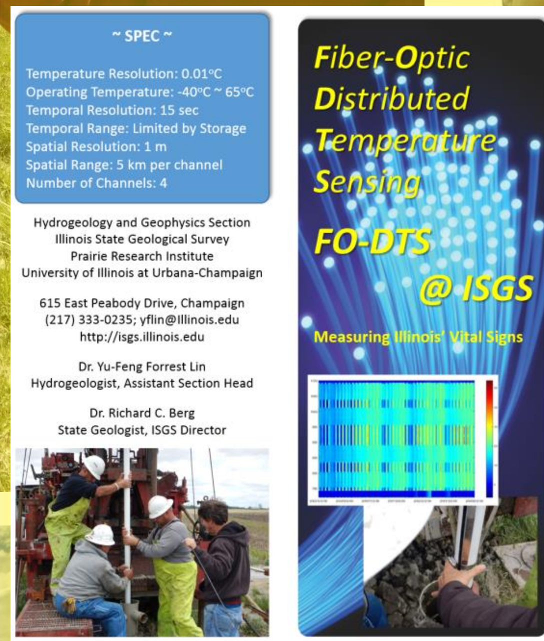


Figure 3: 2015 iCAP Wedge Diagram showing only energy emissions projected, with potential clean energy scenario



~ SPEC ~

Temperature Resolution: 0.01°C
Operating Temperature: -40°C ~ 65°C
Temporal Resolution: 15 sec
Temporal Range: Limited by Storage
Spatial Resolution: 1 m
Spatial Range: 5 km per channel
Number of Channels: 4

Hydrogeology and Geophysics Section
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State Geologist, ISGS Director

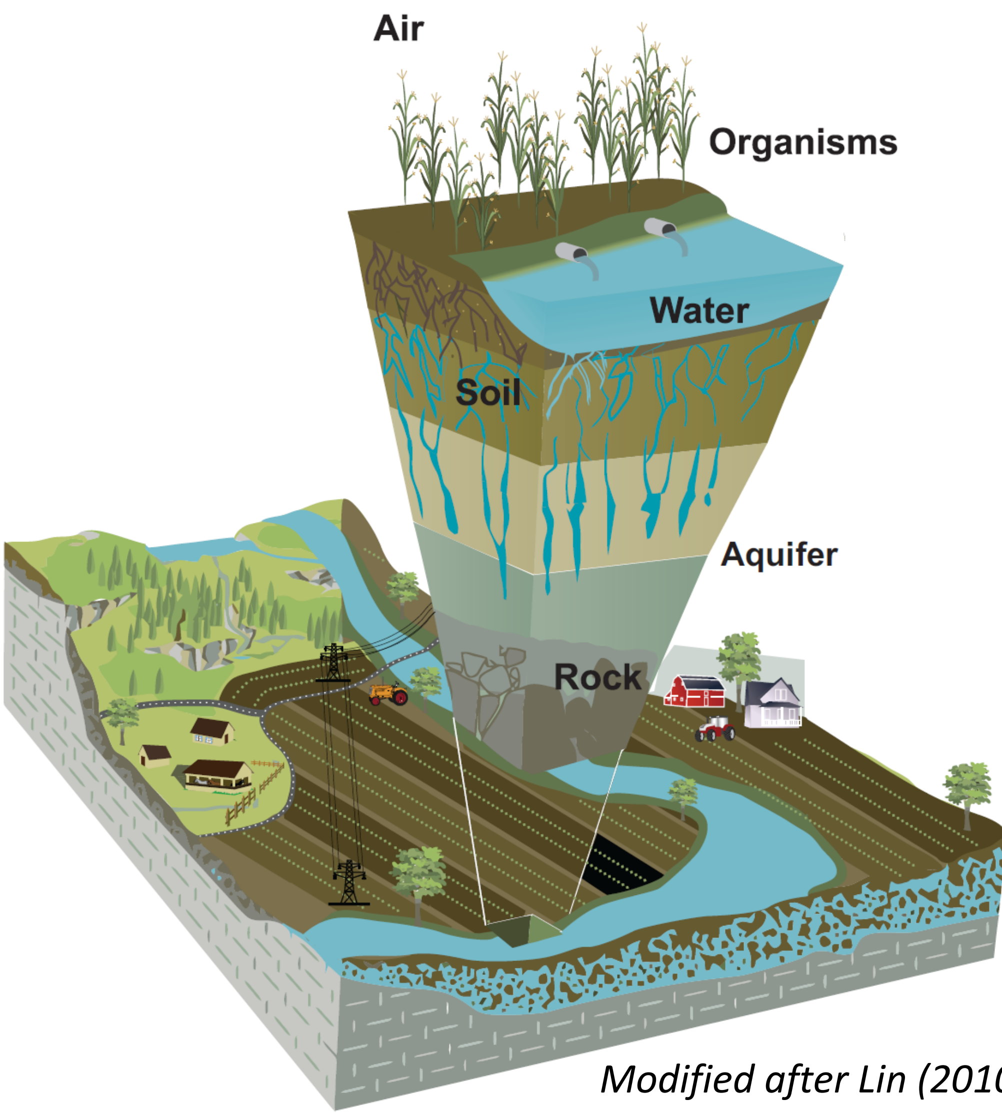
Fiber-**O**ptic **D**istributed **T**emperature **S**ensing

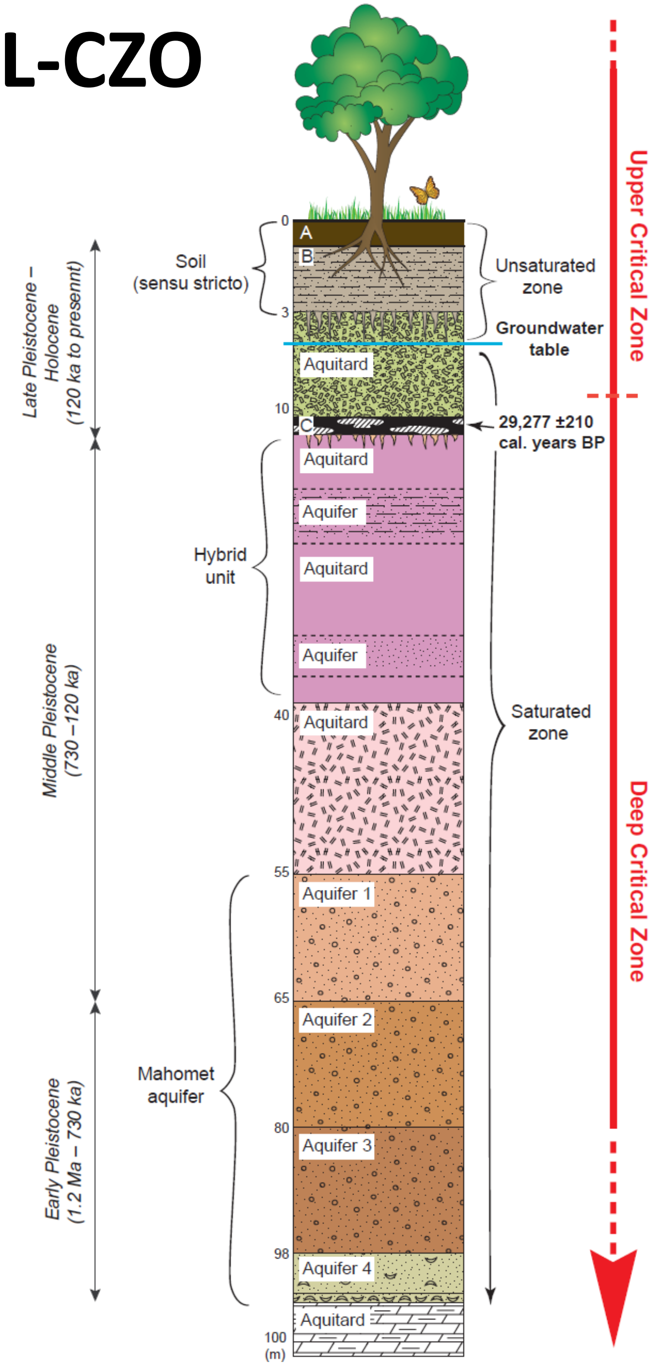
FO-DTS @ ISGS

Measuring Illinois' Vital Signs

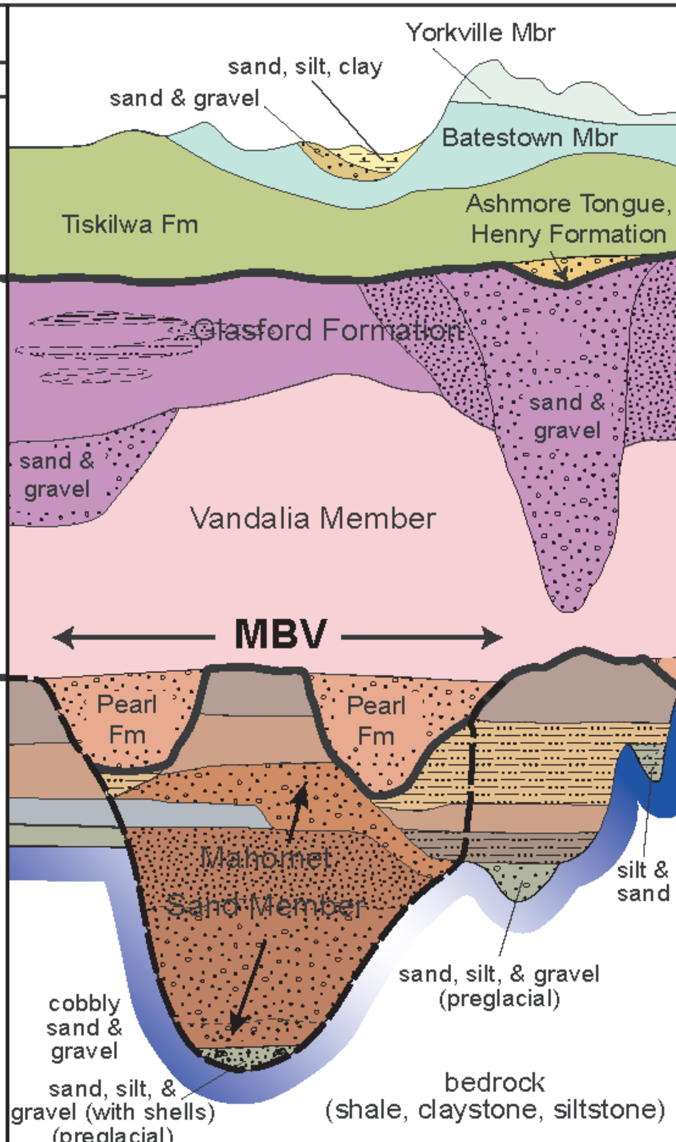
Upper Sangamon River Basin @ IML-CZO

including the modern soil, glacial sediment, the unsaturated zone, the saturated zone, and bedrock.





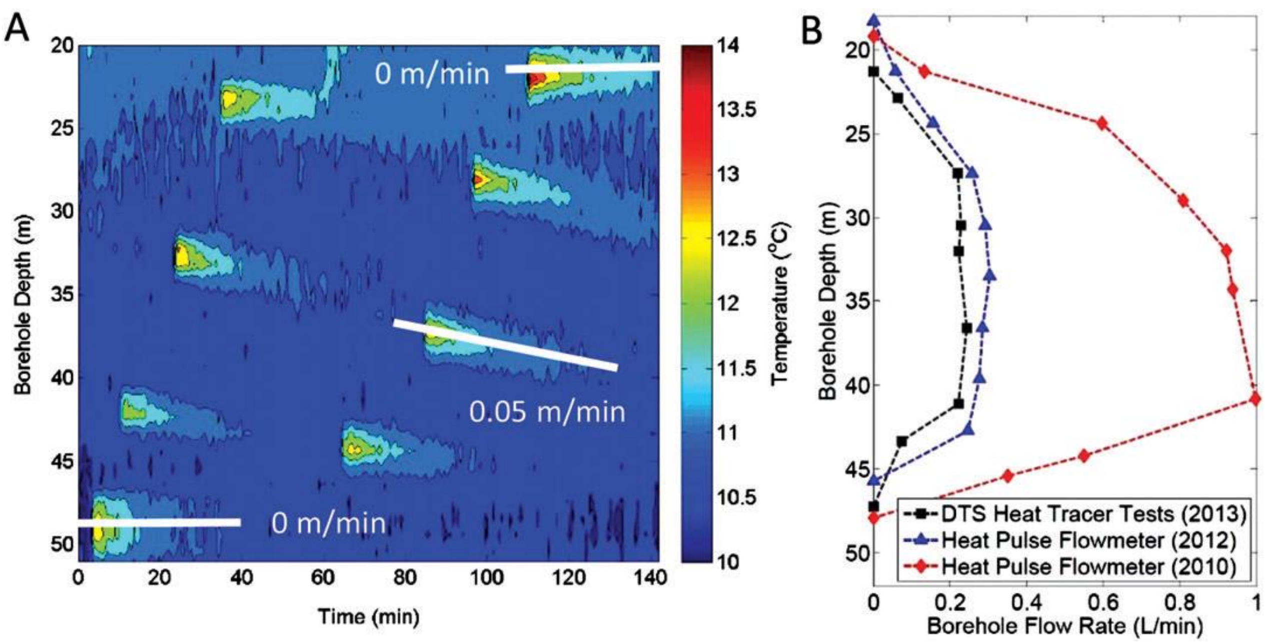
Modified after Lin (2010) and Akob and Küsel (2011)



Age (ka)	Episode	Thickness	Sediment Record/Depositional Environment
12,000 – 25,000	Wisconsin Episode	15 to 30 meters	Till and ice-marginal sediments deposited under and adjacent to glaciers; proglacial meltwater sediments deposited in rivers and and lakes; windblown silt (loess); postglacial stream, lake, wind, and slope deposits. Includes buried organic-rich sediment and peat, and the formation of the modern soil.
125,000 – 200,000	Illinois Episode	25 to 45 meters	Till and ice-marginal sediments deposited under and adjacent to glaciers; proglacial meltwater sediments deposited in rivers and and lakes; windblown silt (loess); nonglacial stream, lake, wind, and slope deposits. Includes soils that formed in these deposits and sediments that accumulated during interglacial periods.
425,000 – 1,600,000 and older	Pre-Illinoian Episode	20 to 60 meters	Till and ice-marginal sediments deposited under and adjacent to glaciers; proglacial meltwater sediments deposited in rivers and and lakes; windblown silt (loess); nonglacial stream, lake, wind, and slope deposits. Includes the soils that formed these deposits, sediments that accumulated during inter-glacial periods, and residium formed on preglacial sediment and bedrock.

Fracture Flow Detection in Tuscola, IL, 2016-2017

3. Current and Future Related Projects
Fracture Flow Detection in Madison, WI, 2013



Sellwood et al., 2015

Fiber-Optic Distributed Temperature Sensing (FO-DTS)

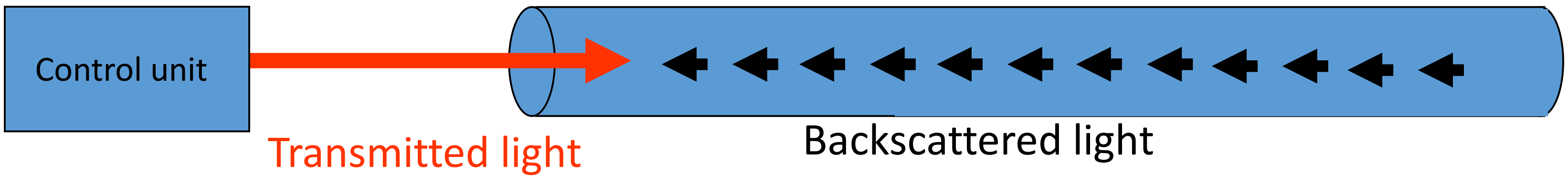
Strengths:

- High spatial resolution (~0.5 to 1 m)
- High precision (0.01° C)
- Large scale (10's of km possible)
- Continuous measurement (in time and space)
- Continuous data download (no retrieval/disturbance)
- Long-term installation possible
- Mobility

Limitations:

- Fiber is glass – can be damaged
- Deployment can be labor-intensive
- DTS systems are costly ($15-100K) but getting cheaper
- Require calibration and field verification with conventional measurements

Measurement Physics (1/3)

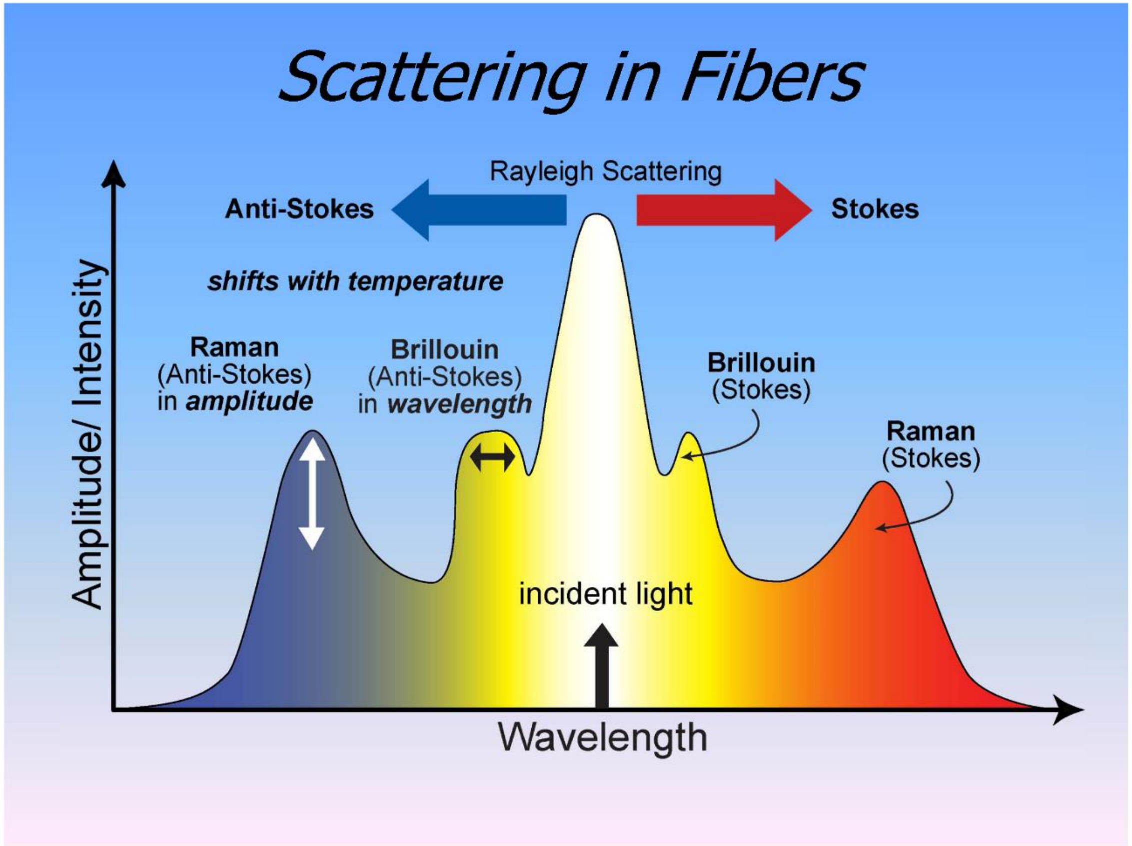


- Control unit transmits laser light down cable
- Cable acts as a “light pipe”
- Light scatters back to the control unit by several mechanisms (Rayleigh, Brillouin, Raman)

From USGS-OGW/BG

Measurement Physics (2/3)

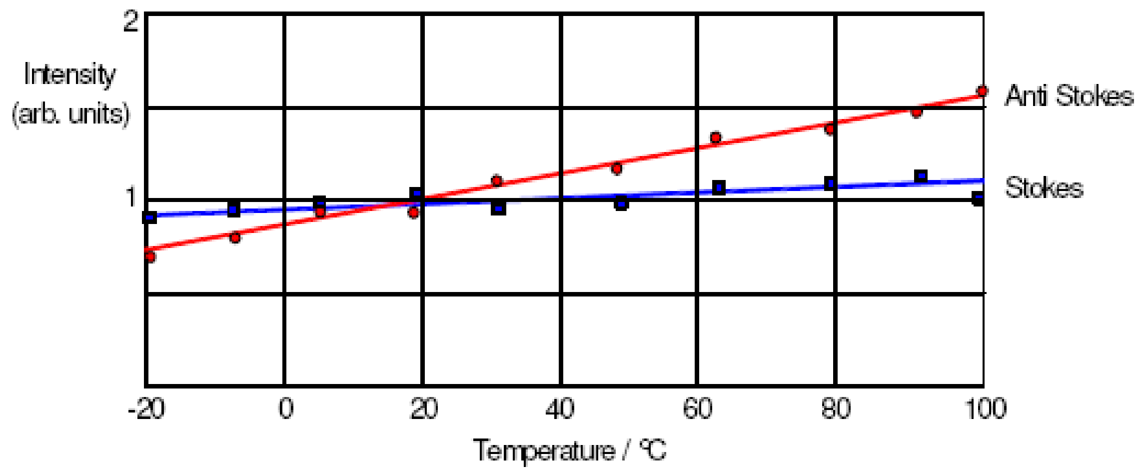
- **Rayleigh scatter** –frequency of incident light
- **Raman** (scatter a function of electron vibrational state): Intensity of anti-stokes depends on temperature
- **Brillouin** (scatter from variations in glass density): Wavelength of anti-stokes depends on temperature (intensity depends on strain)



From NSF-CTEMPs

Measurement Physics (3/3)

- Raman anti-stokes is highly sensitive to temperature
- Raman stokes is less sensitive
- Measurement principle: Infer temperature from ratio of Stokes:Anti-stokes



From Lios Operating Manual

Measurement physics

- **Rayleigh scatter** –frequency of incident light
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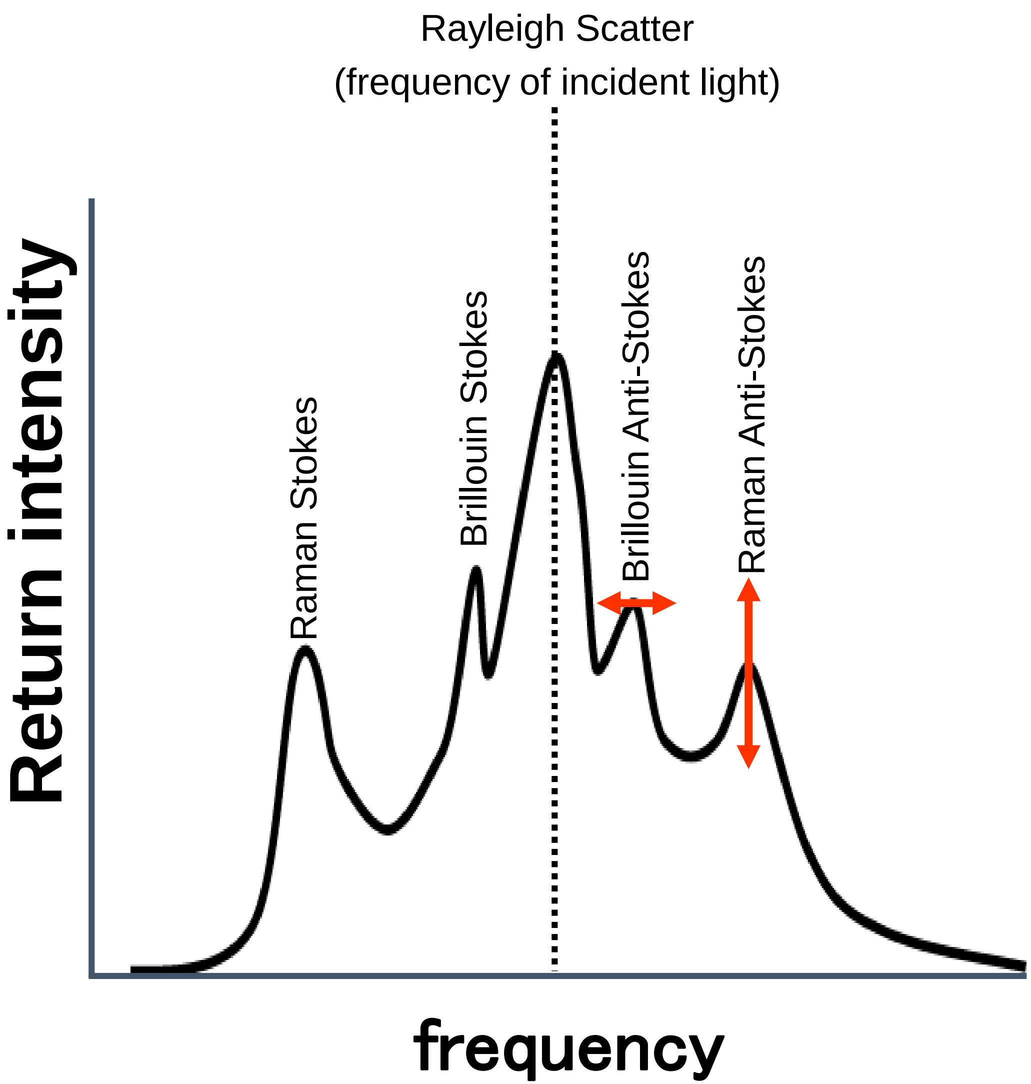

Measurement physics

Raman-based DTS – going from backscatter to temperature (See PDF of Lee LFW article)

$$R(T) = \frac{I_{stokes}}{I_{anti-stokes}} = \left(\frac{\lambda_{stokes}}{\lambda_{anti-stokes}}\right)^4 \exp\left(-\frac{hc\upsilon'}{kT}\right)$$

Where,

- $\lambda_{anti\text{-}stokes}$ and λ_{stokes} are the anti-stokes and stokes wavelengths
- ν' the wavenumber separation from the pump wave length
- h is Planck's constant
- c is the velocity of light
- k is the Boltzman constant
- T is the absolute temperature of the fiber core

Measurement physics

Calculating absolute temperature at a location (See PDF of Lee LFW article)

$$T = \left[\frac{1}{\theta} - \frac{k}{hc\upsilon'} \ln\left(-\frac{R(T)}{R(\theta)} \right) \right]$$

Where,

- θ is the temperature for a reference section of fiber
- $R(\theta)$ is the intensity ratio (Stokes/Anti-stokes) for the reference section of fiber

Notes:

- Instruments have software to do all of this work for you
- May have to calibrate measurements outside software – need for conventional measurements
- Instrument output (options): Stokes, Antistokes, temperature