Applications of a Marine heat flow probe
CFI-JELF proposal

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Goals for Geofluids and Geohazards research program:

Terrestrial projects

Near surface geophysical investigations of fluid migration, fault geometry, “plumbing” of surface features linked to hazards

Marine projects

(Re)Establish a Marine Heat Flow Facility for Canadian Research, continue to investigate hazards on Canada’s west coast, i.e. Queen Charlotte Fault Zone, Cascadia subduction zone

First paragraph of CFI proposal:

"The flow and transfer of heat from the interior of the Earth through the seafloor exerts a fundamental control on:

The occurrence and stability of hydrocarbon and gas hydrate deposits; the patterns of hydrothermal circulation in the ocean crust which in turn impact seismicity and tectonics; the chemical evolution of our oceans; the sustainability of microbial communities in the ocean crust; and the fluxes of fluids and solutes across continental margins, and their impact on coastal water resources."

PGC/NRCan heat flow probe
"Angus"-now retired

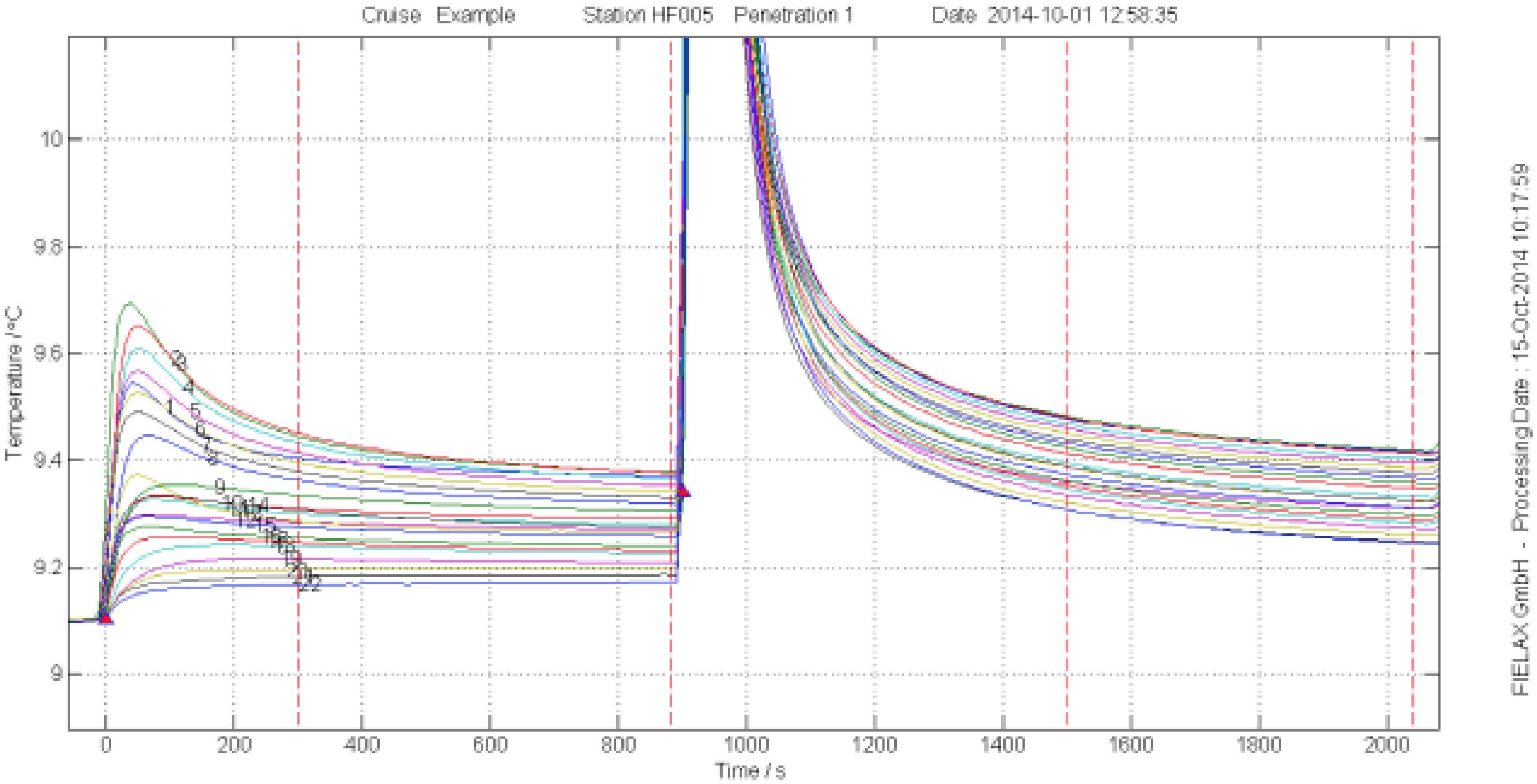
Fielax Probe:
32 measuring channels
Sampling rate: 1 Hz
Depth measurement up to 6000 m
Two axis tilt & vertical acceleration measurements
Internal 1,5 V Al battery for logger supply in autonomous mode
Determination of heat pulse energy

Marine deployment of probe

Over the side of ship with crane, winch system

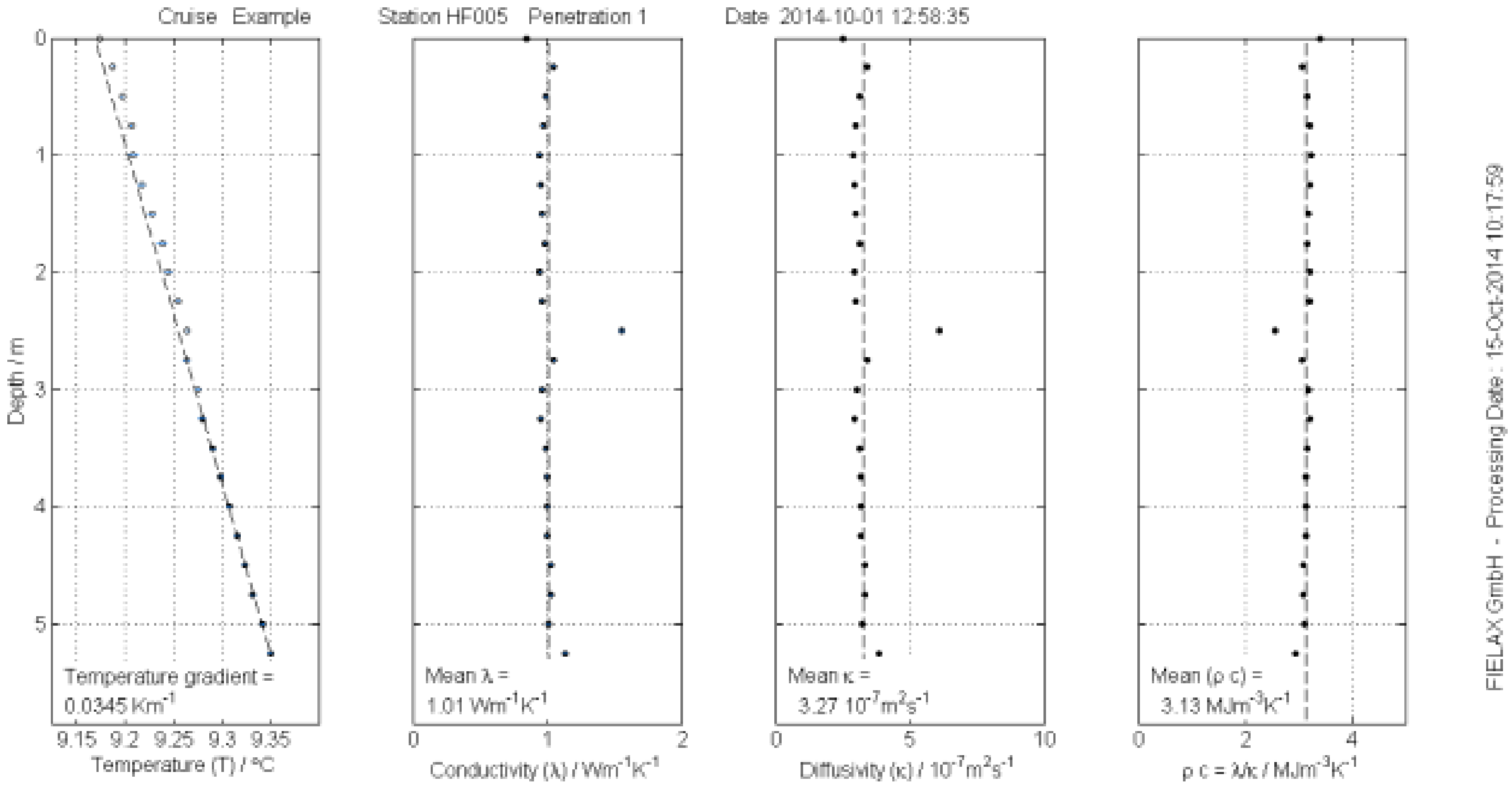
Not to scale!!

Example of single measurement-relative temperature vs time



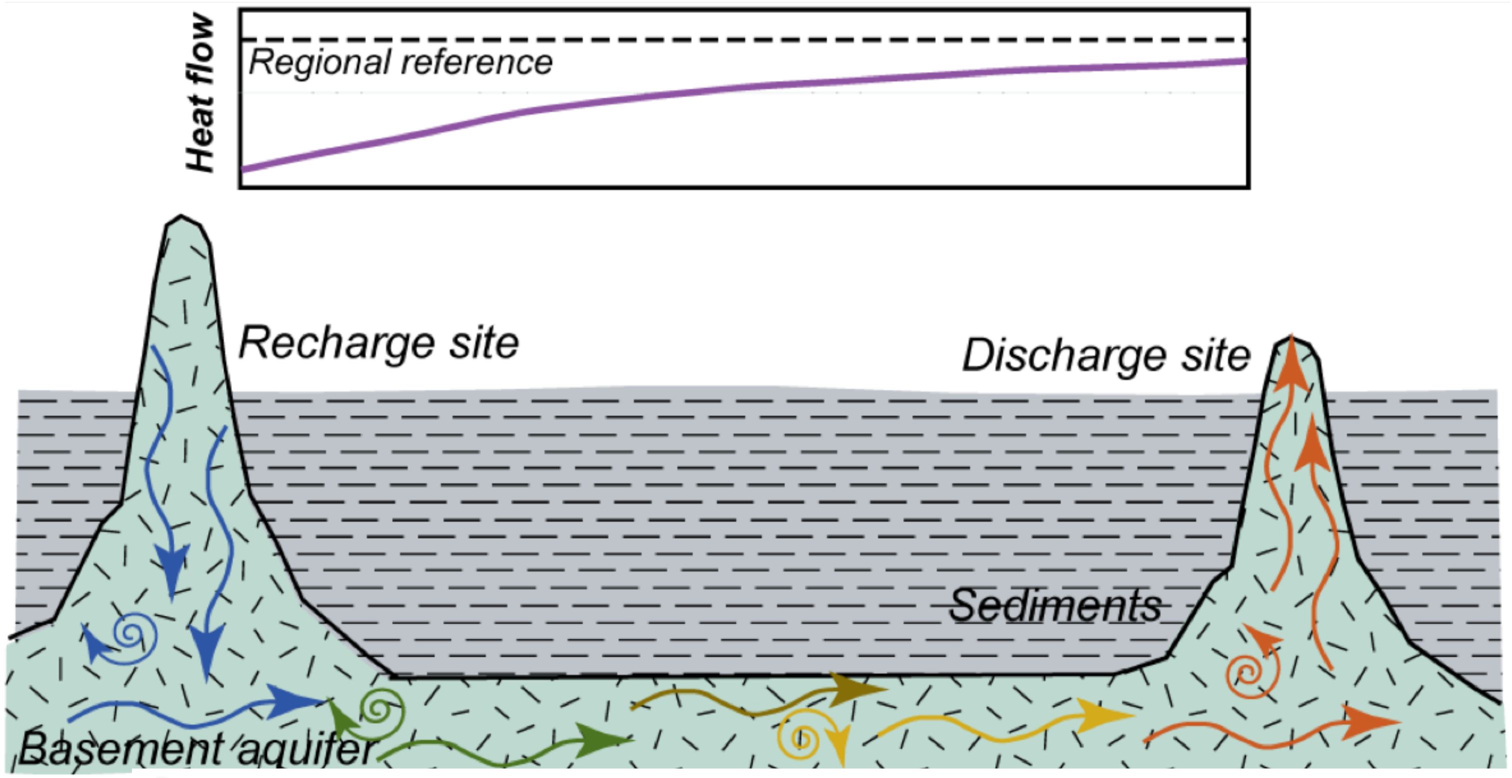
The first decay allows inversion for sediment temperatures, the heat pulse decay for thermal conductivities and diffusivities.

Example of processed results



Depth dependent thermal parameters (in-situ temperatures, thermal conductivities and thermal diffusivities and from those calculated volumetric heat capacities). Dashed lines show the respective mean values. For the temperature (left), the gradient was calculated only from the lowermost sensors (solid symbols).

Ridge-flank hydrothermal circulation is primarily driven by:



…the "hydrothermal siphon"

The magnitude of the driving force depends on: depth of circulation (sediment thickness, aquifer thickness), temperature difference between recharging and discharging fluids, flow rate (coupled system)

modified from *Fisher and Wheat* (2010)

What is the volume of water stored in the upper oceanic crust? The largest aquifer on Earth!

Reservoir	*Storage volume (km^3)*	*Percent of total*
Oceans	1.4 billion	97.2
Glaciers/ice sheets	30 million	2.1
Ocean crust	20-30 million	1-2
Groundwater (continental)	9 million	0.6
Rivers, lakes	100 thousand	0.009
Soil water	70 thousand	0.005
Atmosphere	10 thousand	0.001

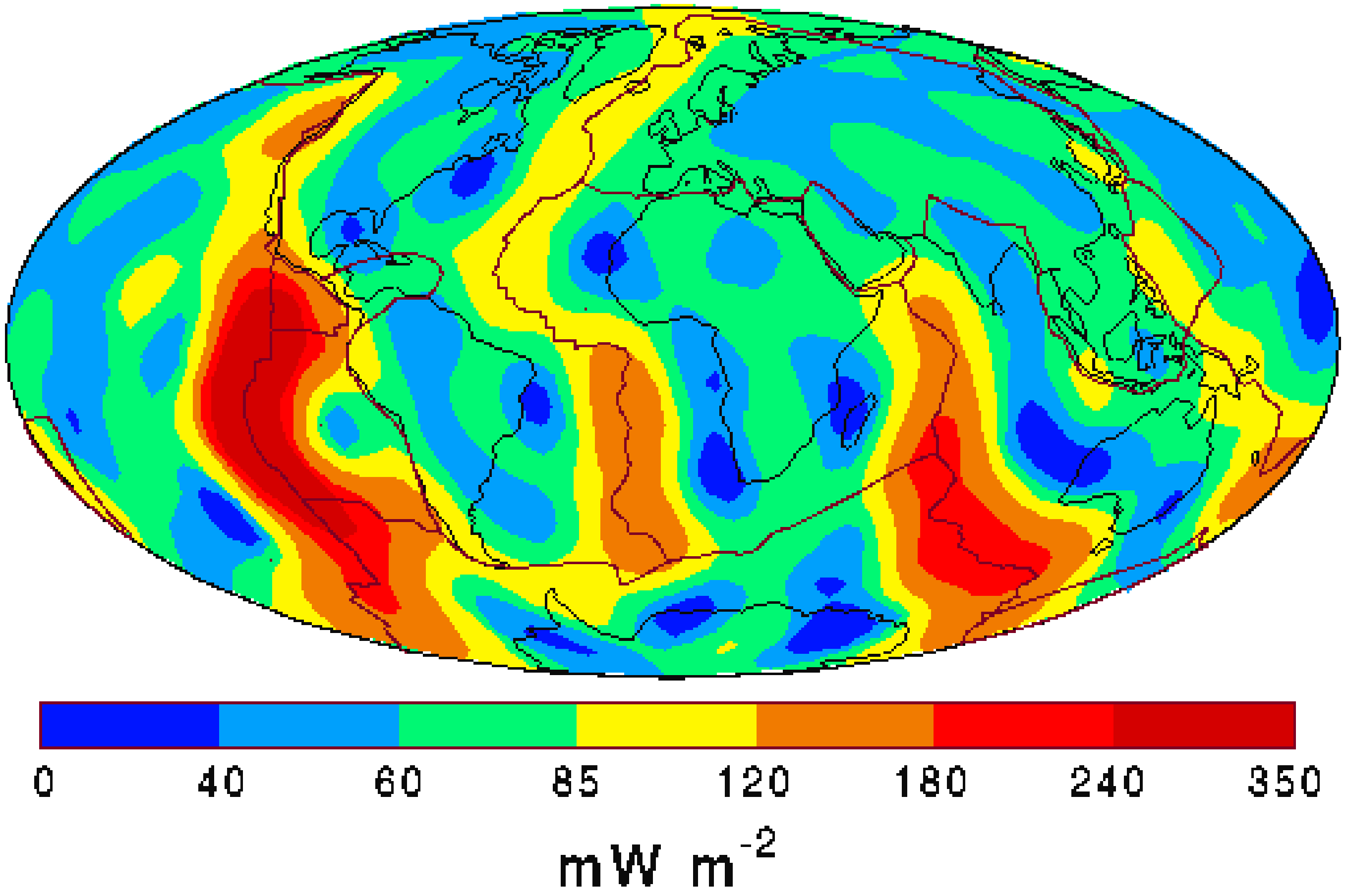
*What is the **rate** of seafloor hydrothermal fluid flow?*

Location/kind	***Volume flux (km^3/yr)***
Rain+snow on land+sea	400,000
Evaporation+transpiration	400,000
River discharge	40,000
Ridge-flank (>1 Ma)	***≥2,000-20,000***
Groundwater discharge	6000
Glacial melting/freezing	6000
Ridge-axis (<1 Ma)	*40*

“Recycles” the ocean every 100k-500k yrs

“Recycles” the crustal reservoir every 1k-10k yrs

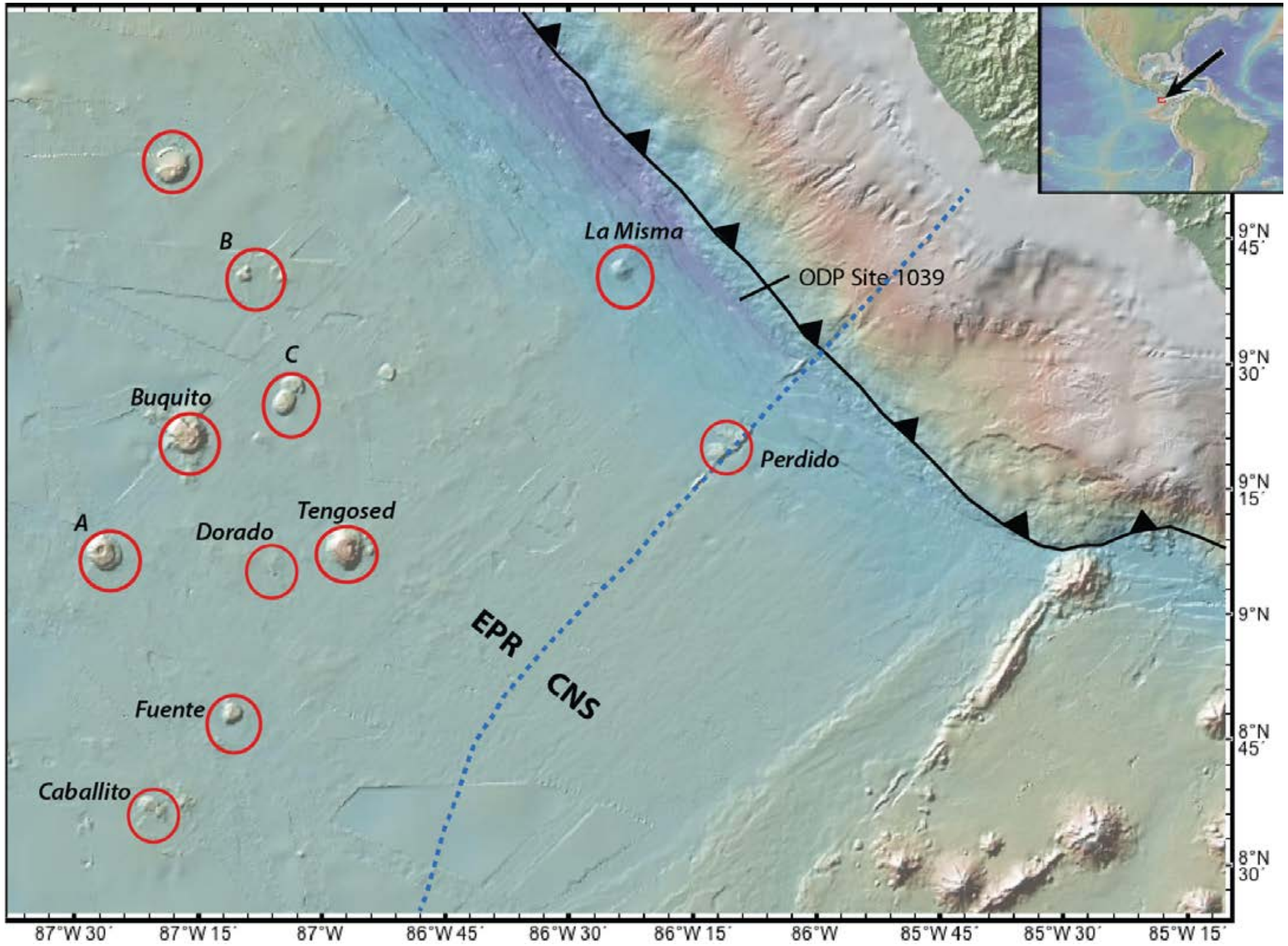
Rate of Earth's heat loss: ~40 Trillion Watts (TW)



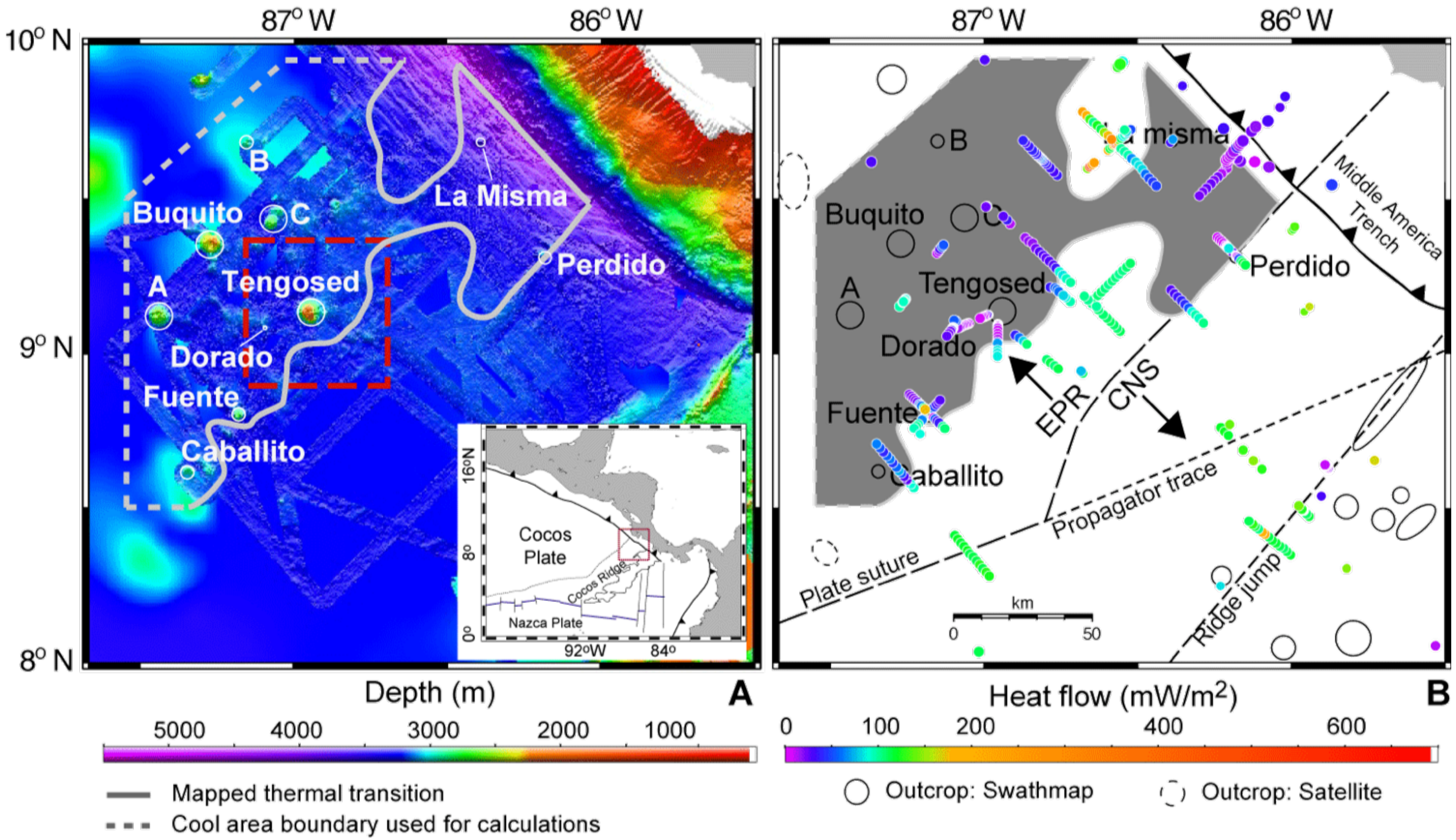
- ~75% of Earth's heat loss occurs through the ocean floor…
  - ~30% of this heat is extracted by hydrothermal fluids (mostly on ridge flanks)

Case study: Lauer et al., 2018

Modeling crustal-scale hydrothermal flows through a seamount network



Heat flow surveys in 2001/2002 identify a large "chilled" region of the seafloor

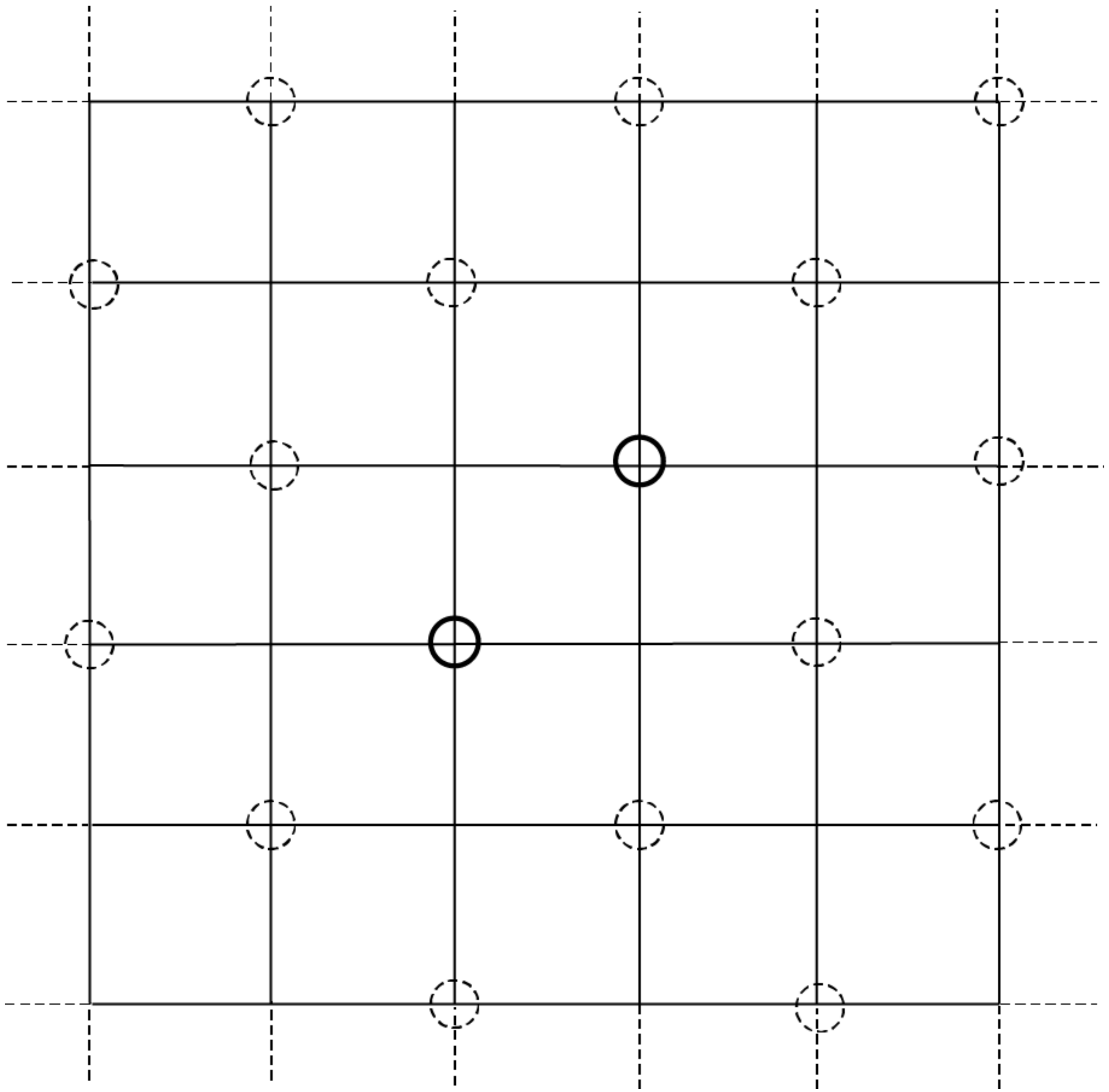


modified from *Hutnak et al.* (2008)

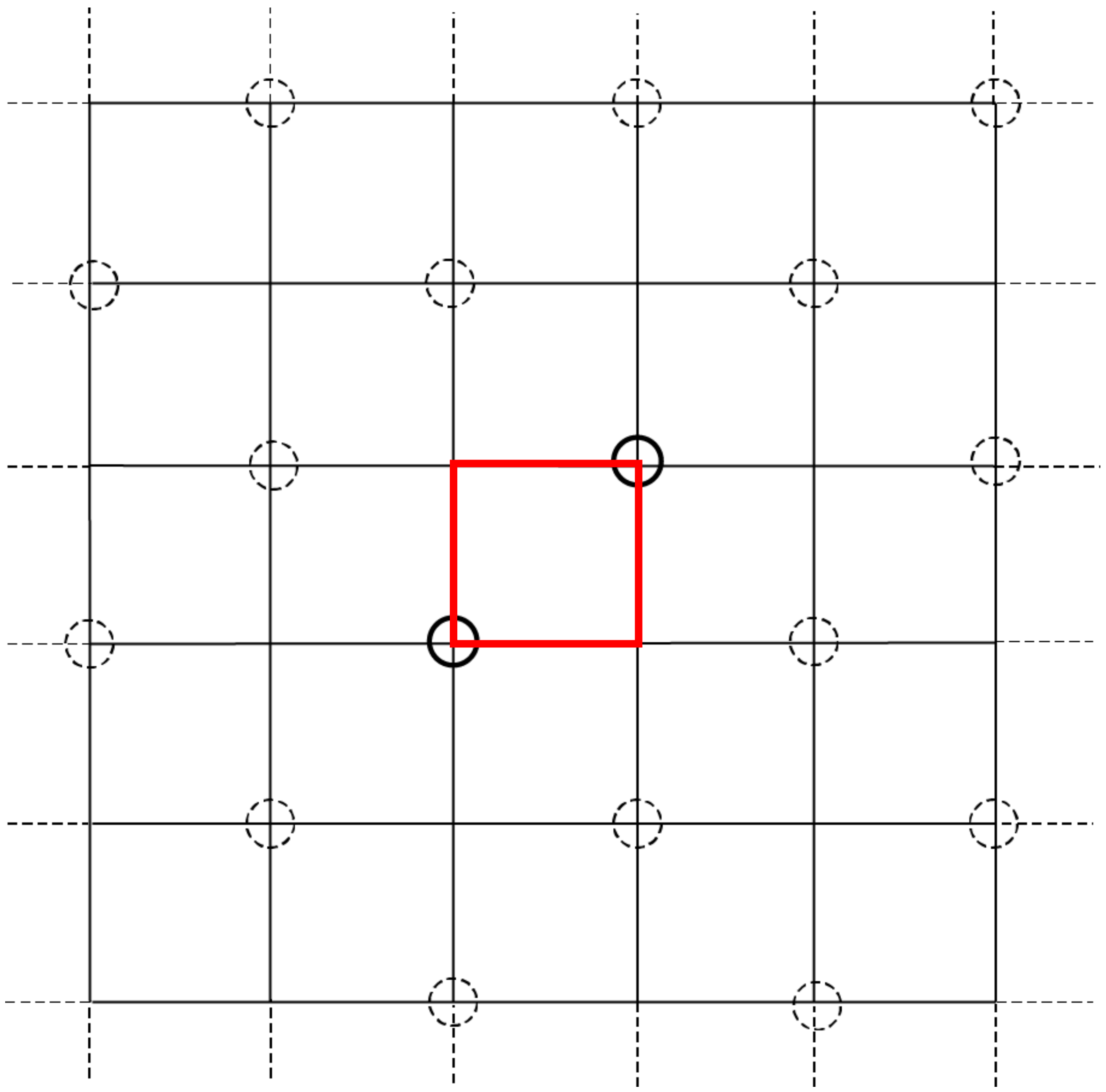
- Eleven (11) outcrops within area the size of Connecticut is missing ~70% of lithospheric heat
- **Mean conductive seafloor heat flux of chilled region is ~30 mW/m²**
- Very high fluid flow rates inferred…but *what rates are required? Is this reasonable?*

Models designed to simulate hydrothermal circulation through a network of seamounts *variable size, geometry, hydraulic parameters*

What parameter space achieves the measured seafloor heat flux around Dorado Outcrop?



One set of simulations illustrate how observations constrain models



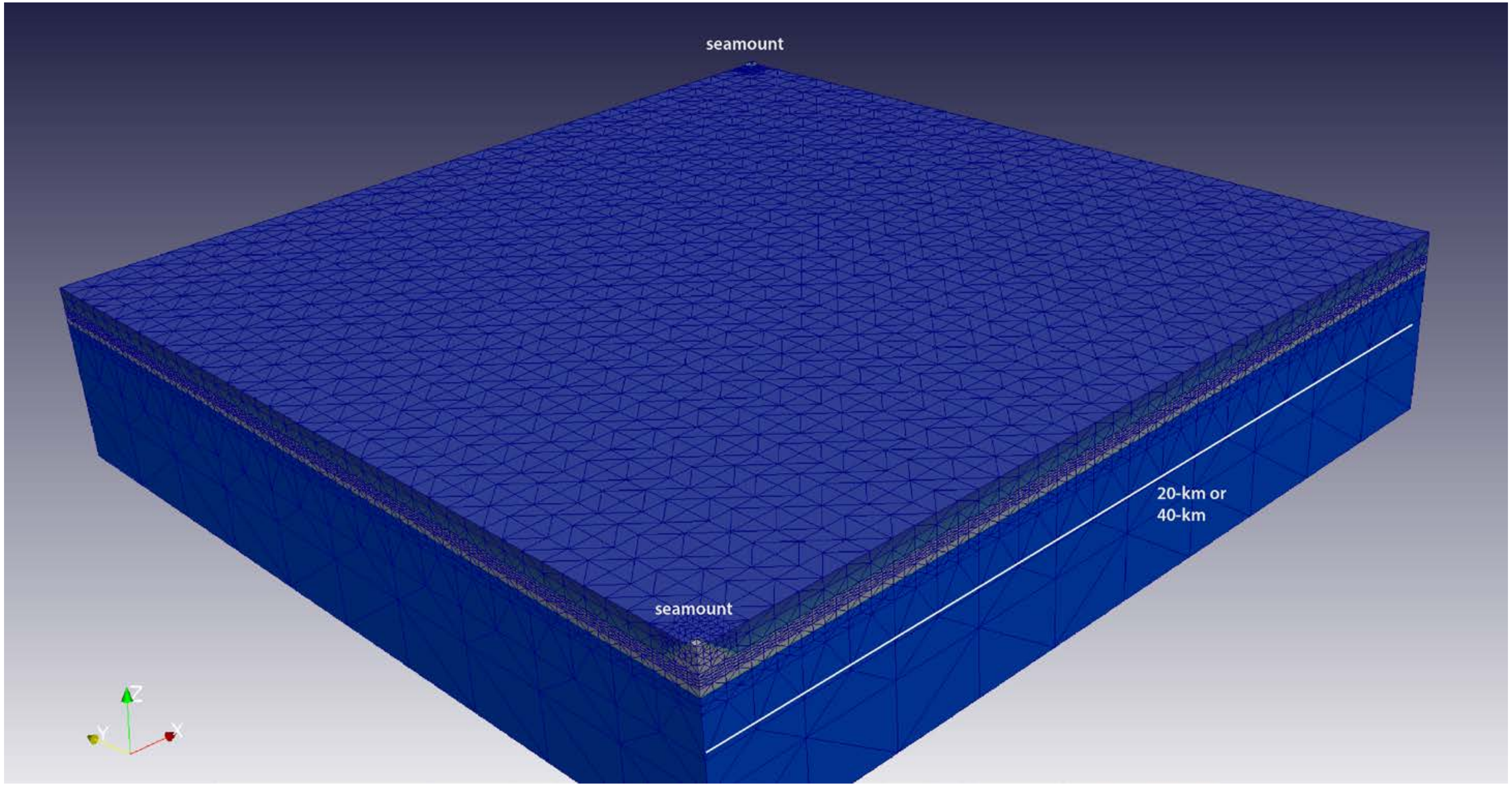
20-km x 20-km square grid, outcrops on opposite corners

Question: *What hydrogeologic conditions are required to advect 70% of the lithospheric heat ?*

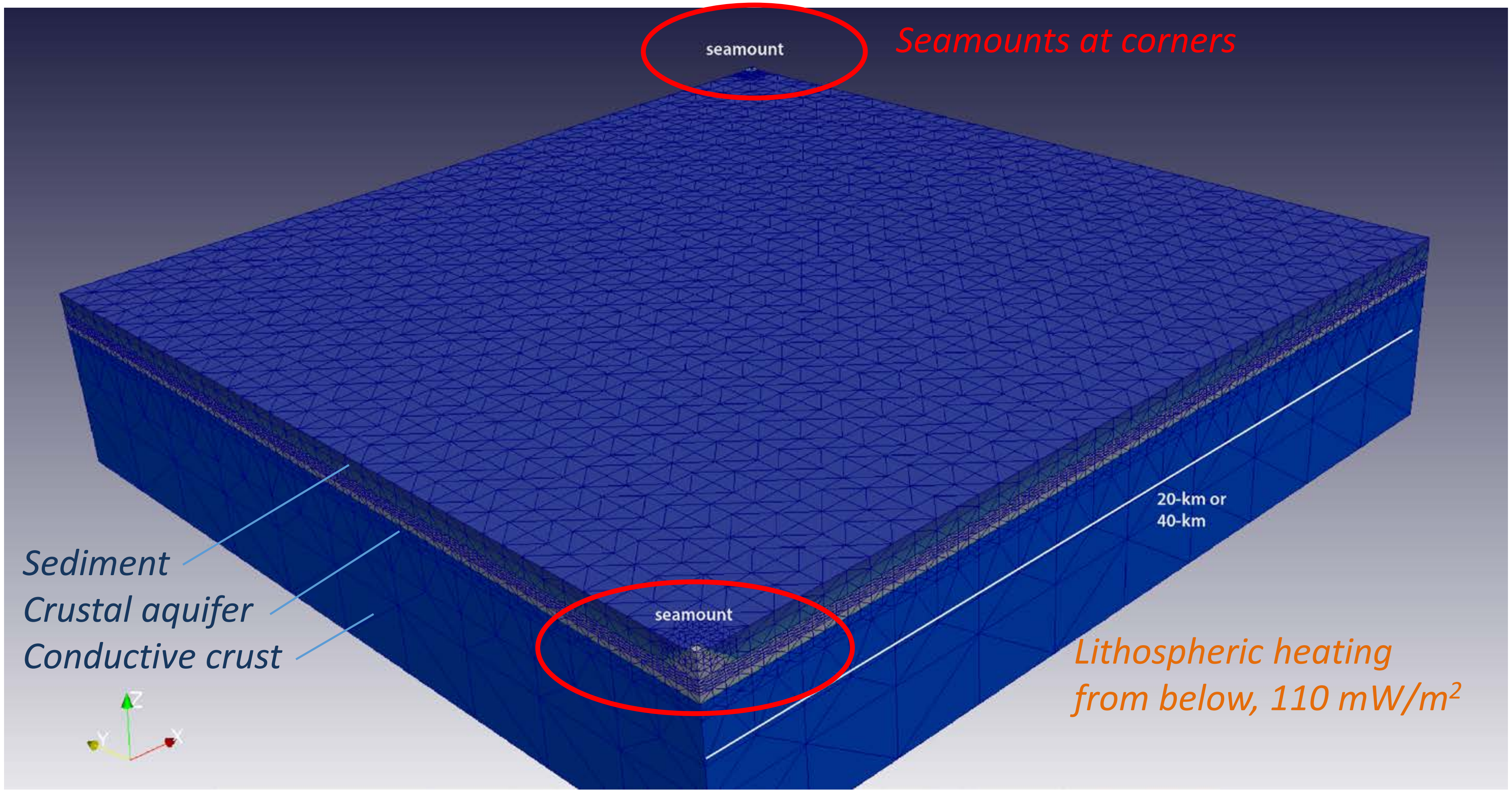
What flow rates occur under these conditions?

How do these flow rates translate into fluxes of solutes, transport of nutrients, etc.?

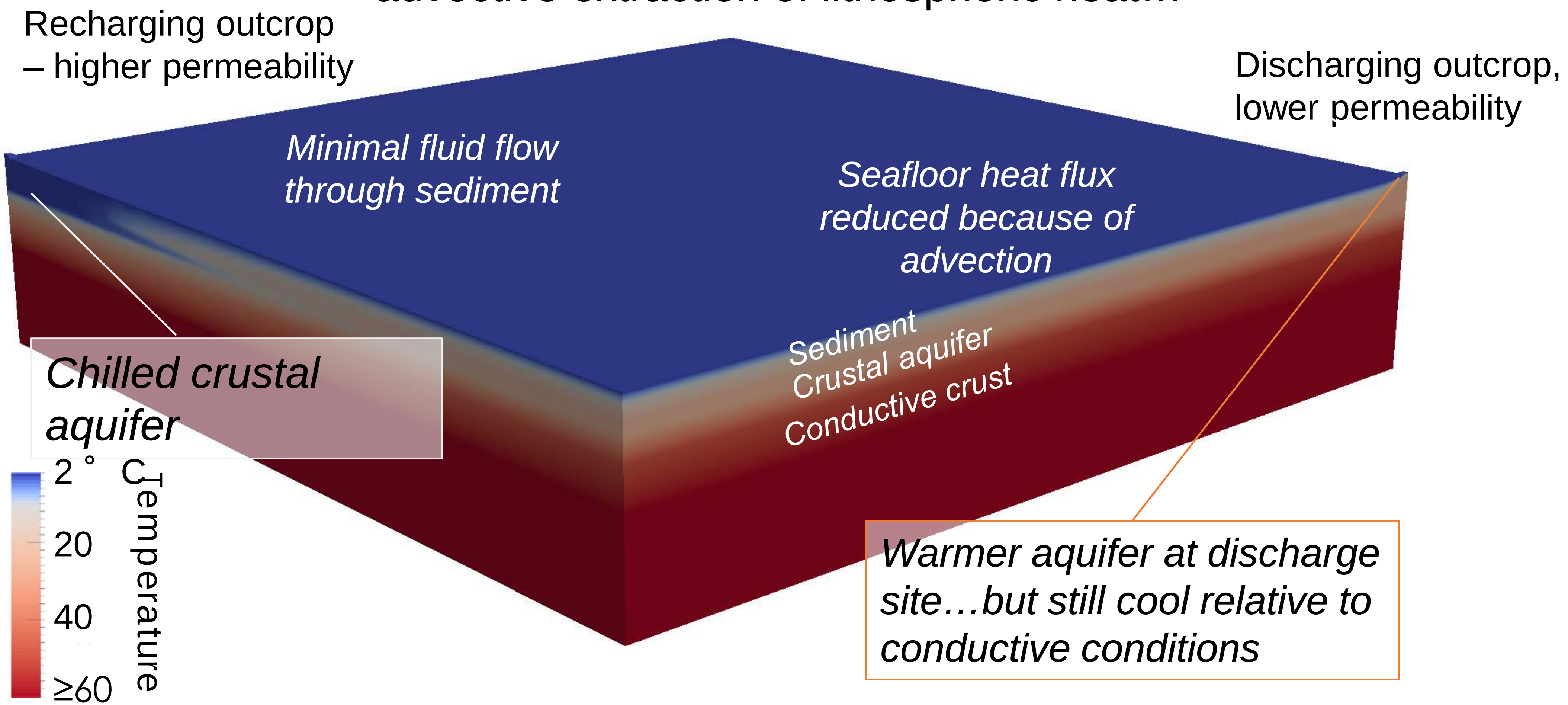
Three-dimensional, finite-element models of coupled fluid-heat flow



Three-dimensional, finite-element models of coupled fluid-heat flow

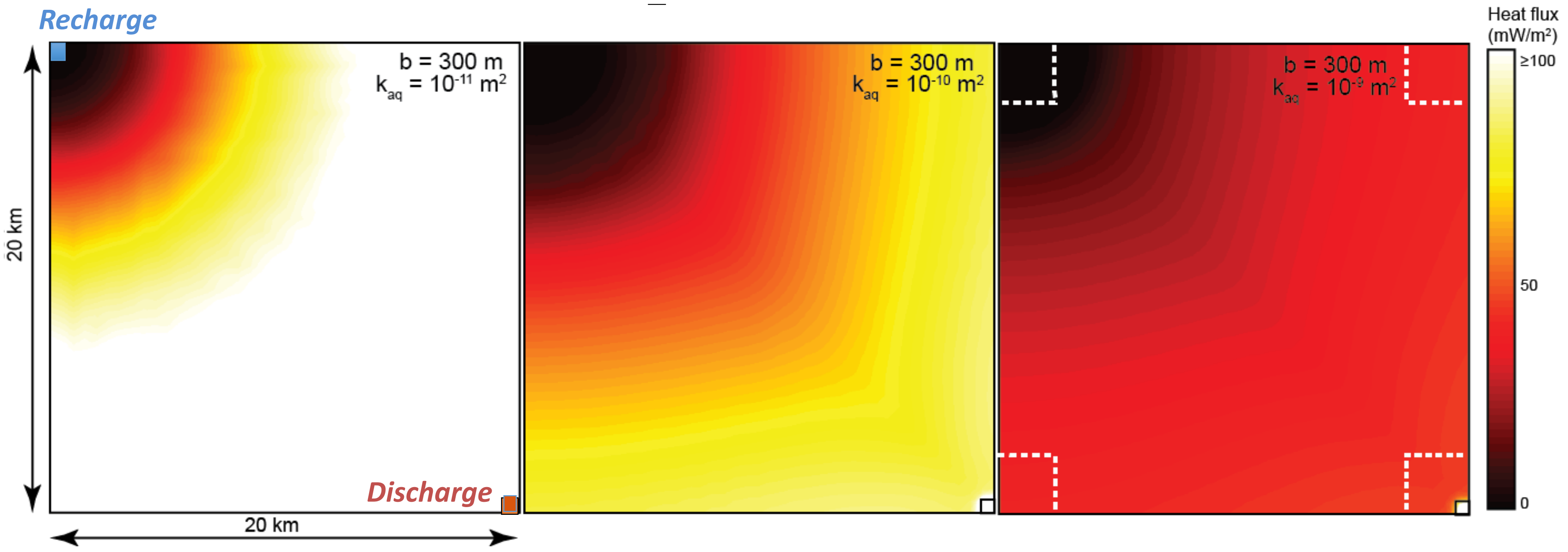


Self-sustaining, ridge-flank hydrothermal siphon with advective extraction of lithospheric heat…



Efficiency of heat extraction scales with aquifer and outcrop permeability

Very high aquifer permeability is required to achieve pattern of seafloor heat flux around Dorado Outcrop: conductive ~ 30%, advective ~70%



As permeability ↑, conductive seafloor heat flux ↓ = more advective heat loss from the crust

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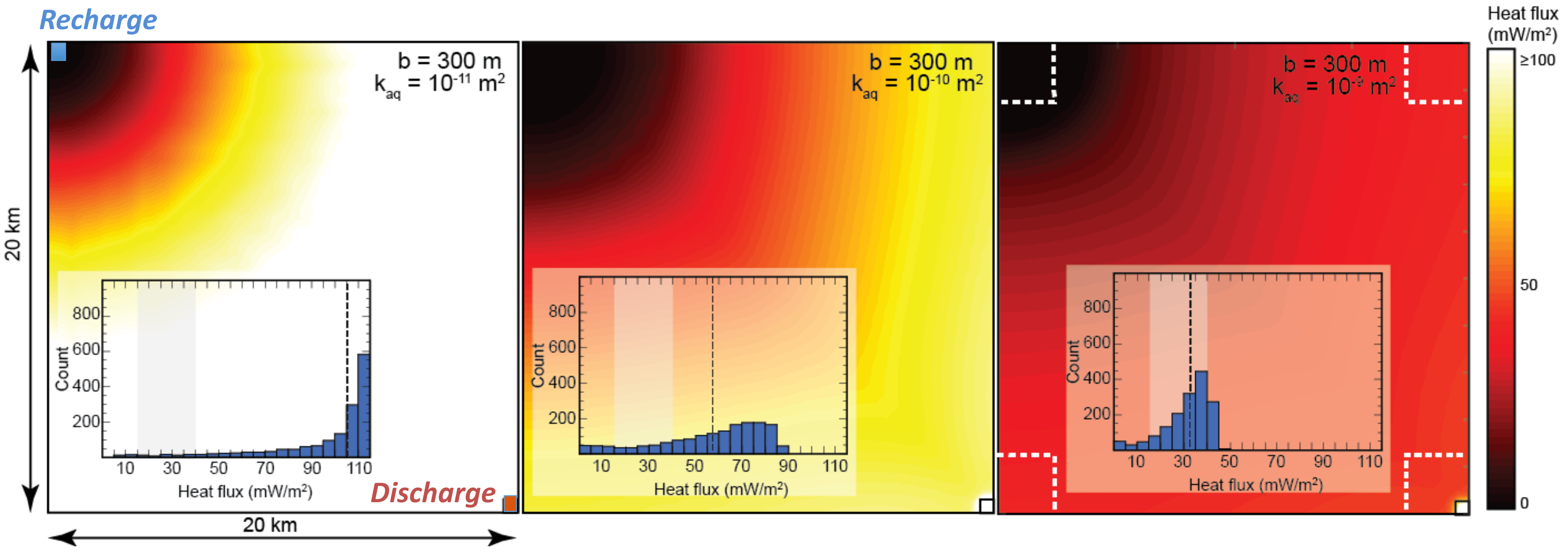
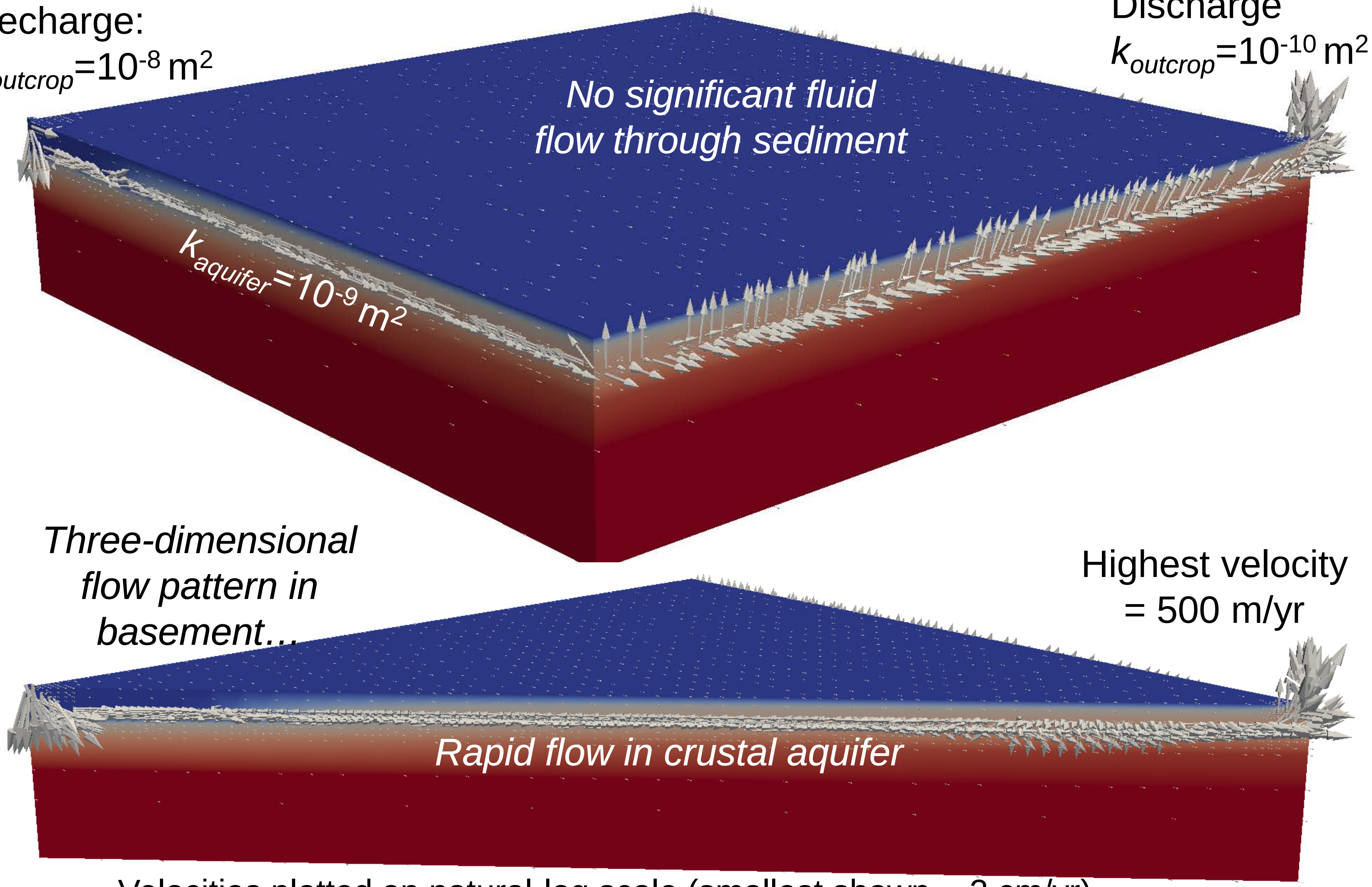


As permeability ↑, conductive seafloor heat flux ↓ = more advective heat loss from the crust

Patterns of subseafloor hydrothermal circulation between outcrops

Recharge:
$k_{outcrop}$=10^{-8} m^2

Discharge
$k_{outcrop}$=10^{-10} m^2

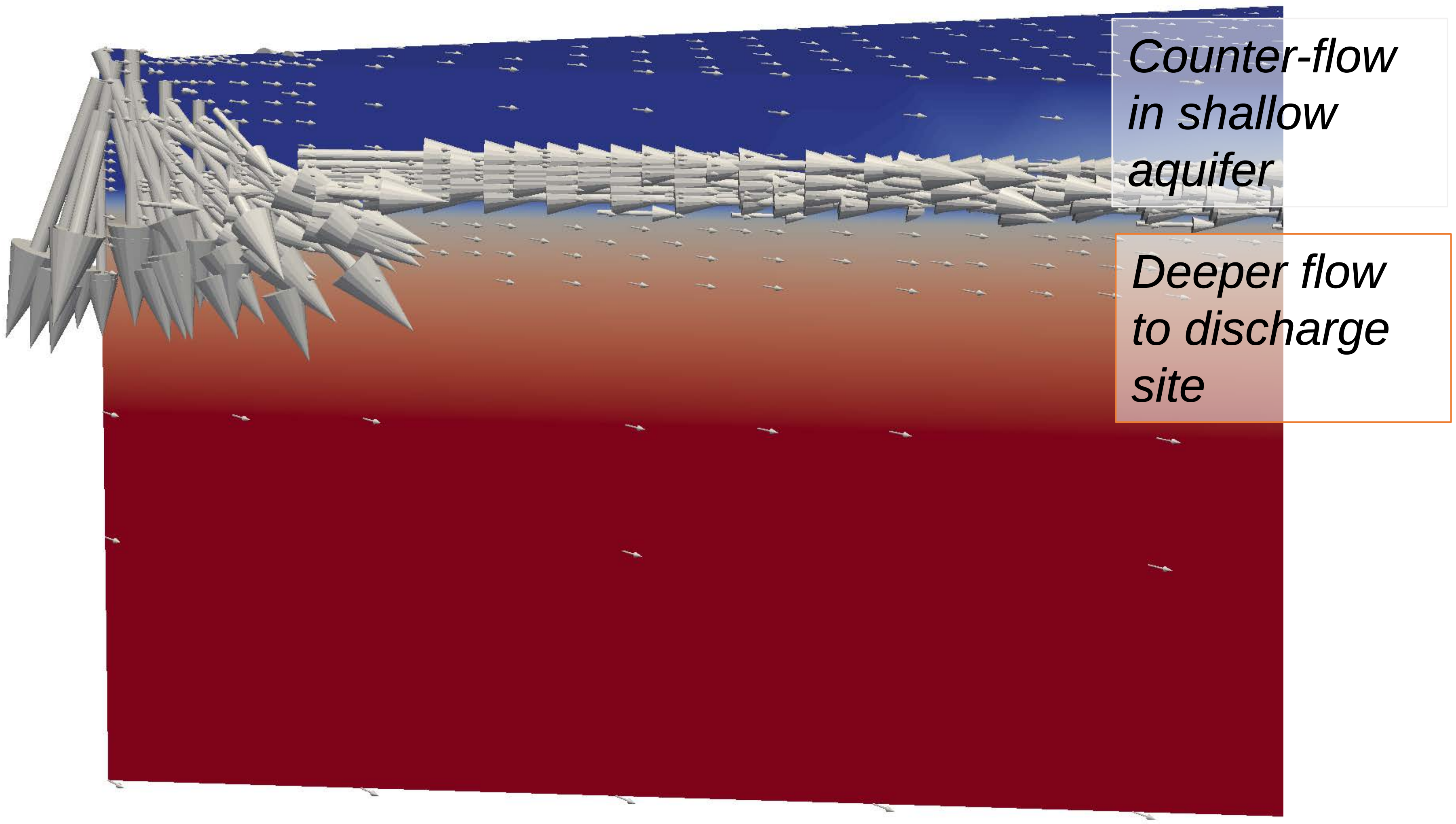


Three-dimensional flow pattern in basement…

Highest velocity = 500 m/yr

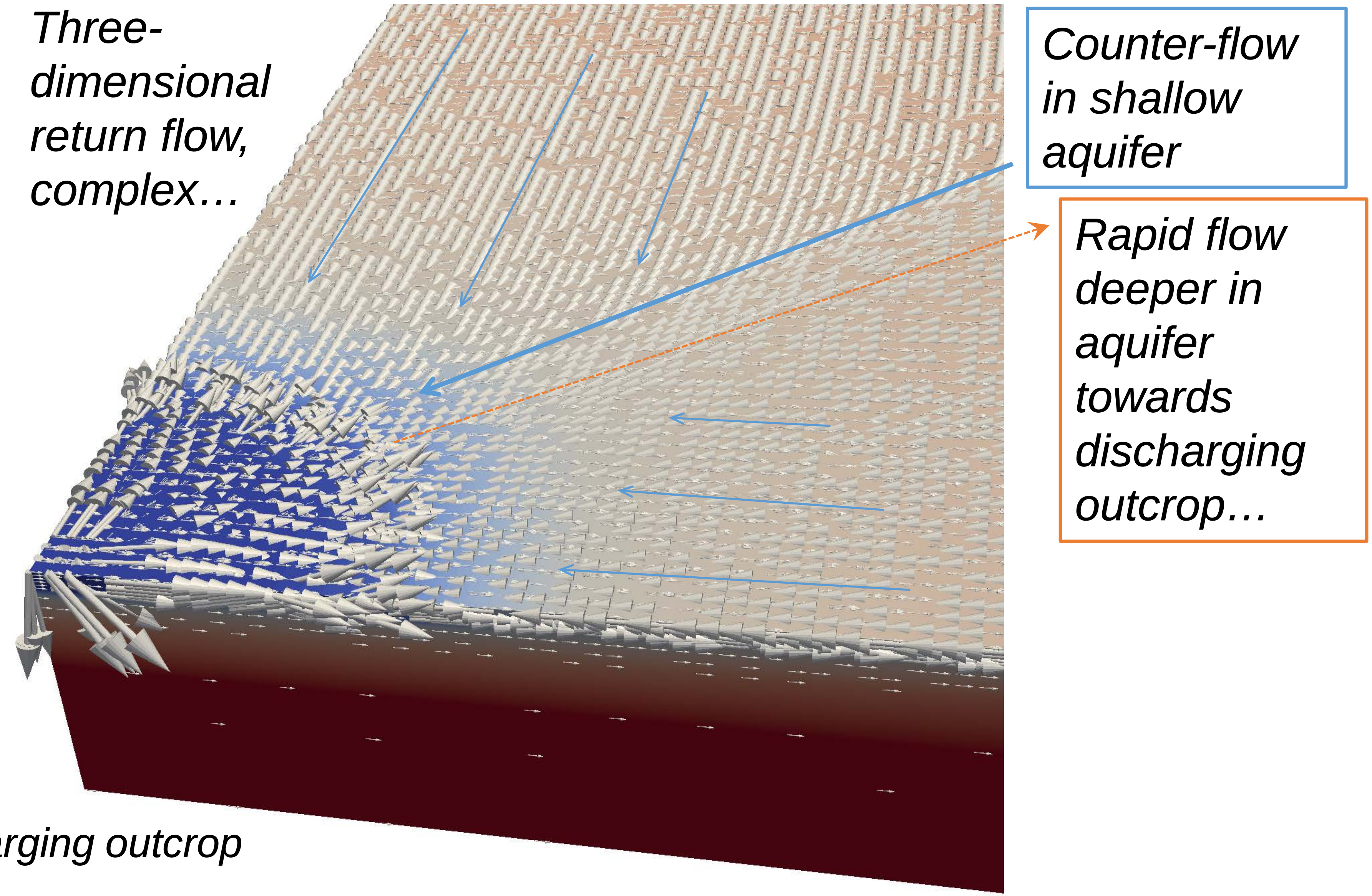
Velocities plotted on natural-log scale (smallest shown ~ 2 cm/yr)

Detailed cross-section of recharging outcrop (on grid diagonal)…



…rapid inflow, strong lateral flow (no local return with small outcrop)

Detailed cross-section of recharging outcrop (sediment removed)



Getting back to the original questions

What hydrogeologic conditions are required to advect 70% of the lithospheric heat ?

Very high aquifer and outcrop permeability (details vary with number of outcrops, distribution, etc.)

What flow rates occur under these conditions?

Specific discharge up to 500 m/day, volume flow rate
Q = 1000-3000 L/s for a discharging outcrop
[consistent with hypothesis from *Hutnak et al.* (2008)]

How do these flow rates translate into fluxes of solutes, transport of nutrients, etc.?

Simple examples, **$F_s = Q \times [S]$**
= 50 to 150 mmol/s/outcrop of DOC and NO_3
= 1.5 to 4.5 Mmol/yr/outcrop

…this is only an input, need to know how solutes might be used by microbial ecosystems…

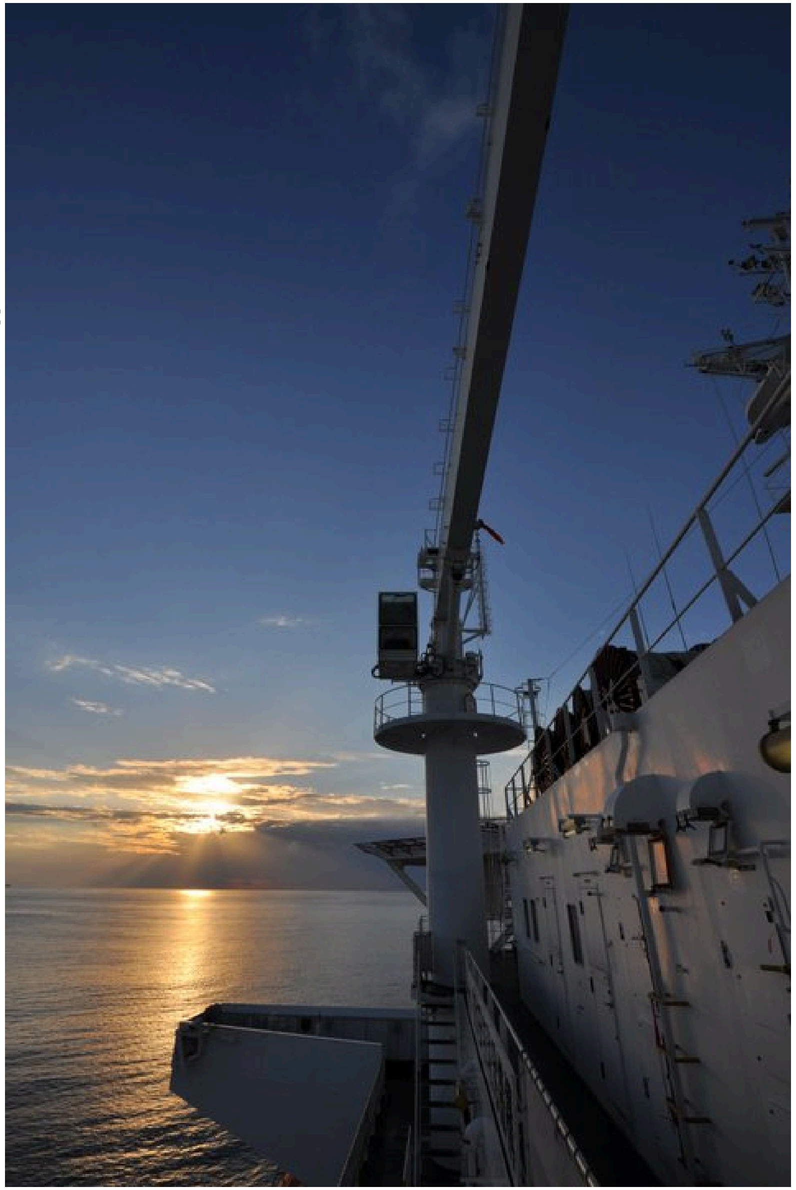
Summary and next steps

1. Removing 70% of lithospheric heat via advection requires rapid flow rates and high aquifer permeability (10^{-9} m^2) ***Testable hypothesis!***

2. Fluid flow rate needed to extract this much heat within a field of outcrops is ≥1000 to 3000 L/s per outcrop
(could be more if basement temperatures are lower)
Being tested at Dorado Outcrop!

3. Next steps include incorporation of biogeochemistry in reactive transport models of the ocean crust…but this requires additional geologic complexity (layering, heterogeneity, etc.)

4. Looking for land based opportunities/collaborations, potential borehole deployment configurations, preparing **NSERC** Ship time proposal for heat flow mapping campaign along the Queen Charlotte Fault, Cascadia subduction zone



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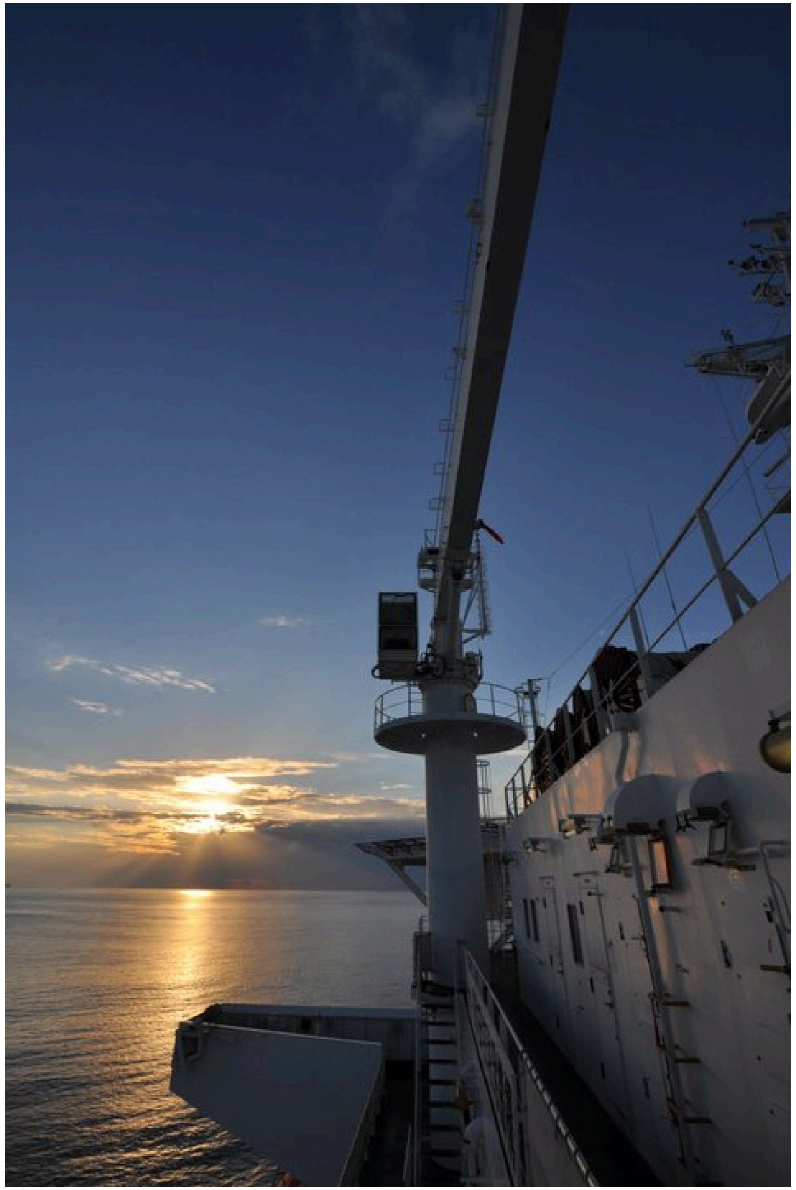
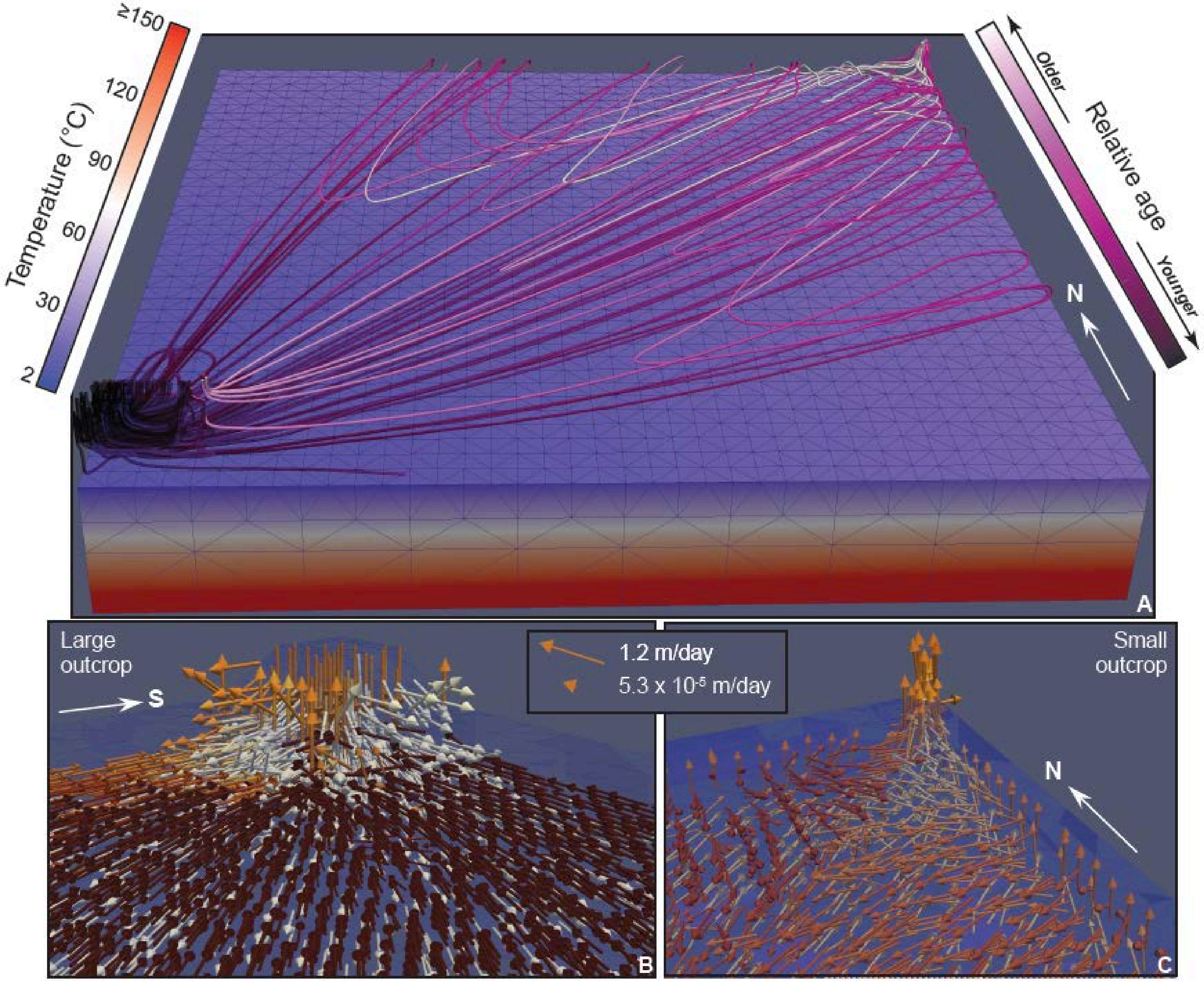
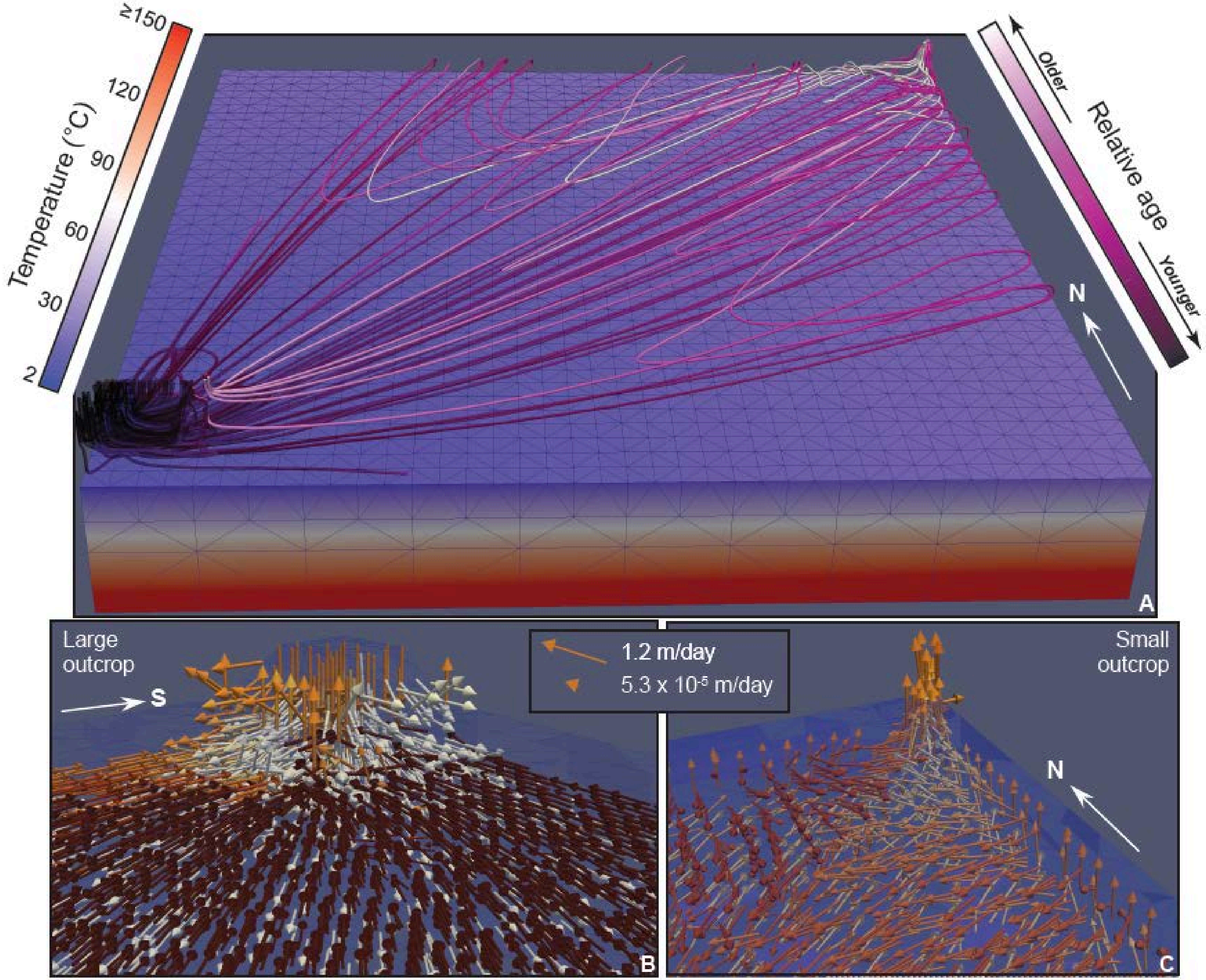




≥150
120
90
60
30
2
Temperature (°C)
Older
Relative age
Younger
N
A
Large outcrop
S
1.2 m/day
5.3 x 10-5 m/day
B
Small outcrop
N
C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