New Tools for Understanding Heat and Groundwater Flow in the Northwest Volcanic Aquifer Province, USA

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U.S. Geological Survey
Oregon Water Science Center

USGS
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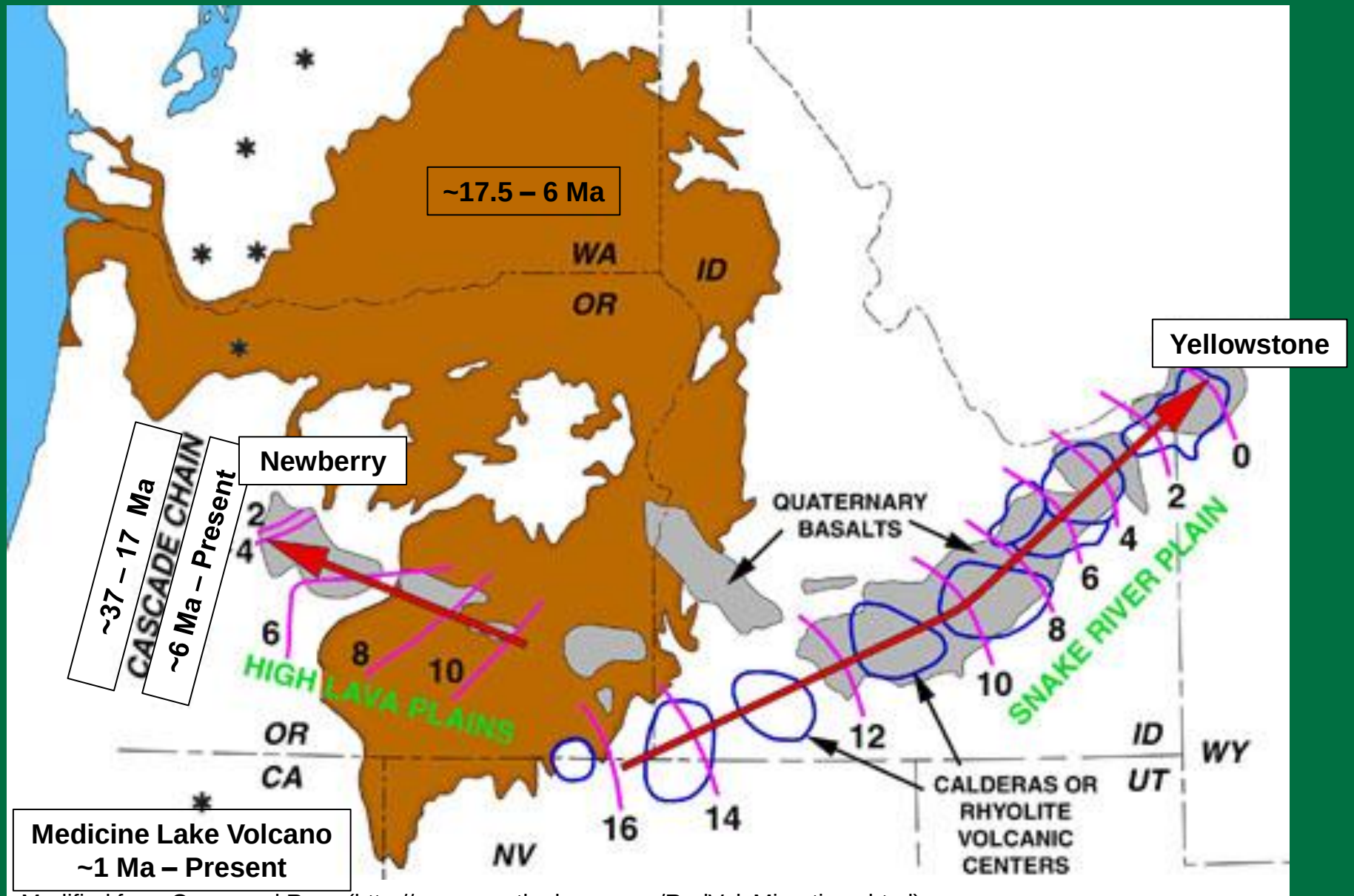
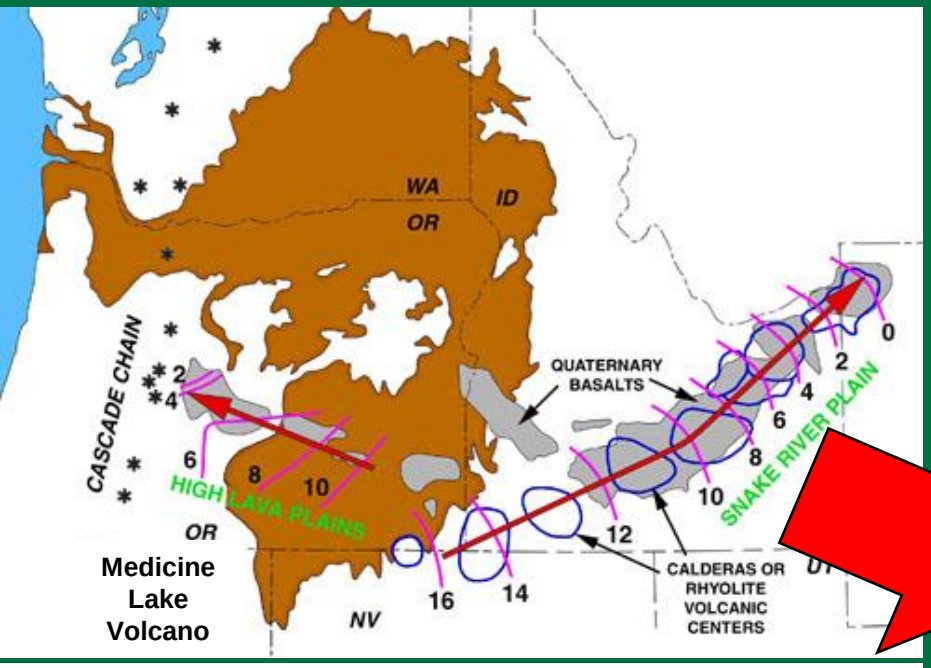
Volcanic History of Northwest



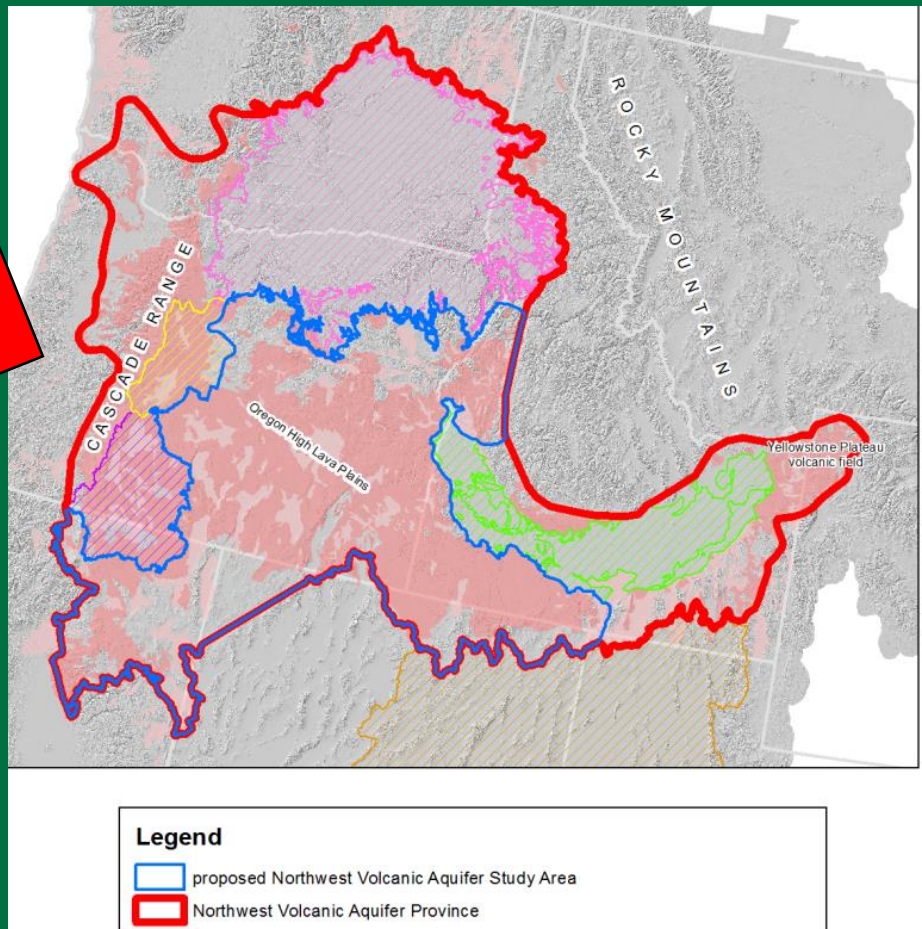
Modified from Camp and Ross (http://www.mantleplumes.org/RadVolcMigrations.html)

Northwest Volcanic Aquifer Province (NVAP)



From Camp and Ross
(http://www.mantleplumes.org/RadVolcMigrations.html)

Regional aquifers in this area are often dominated by volcanic deposits



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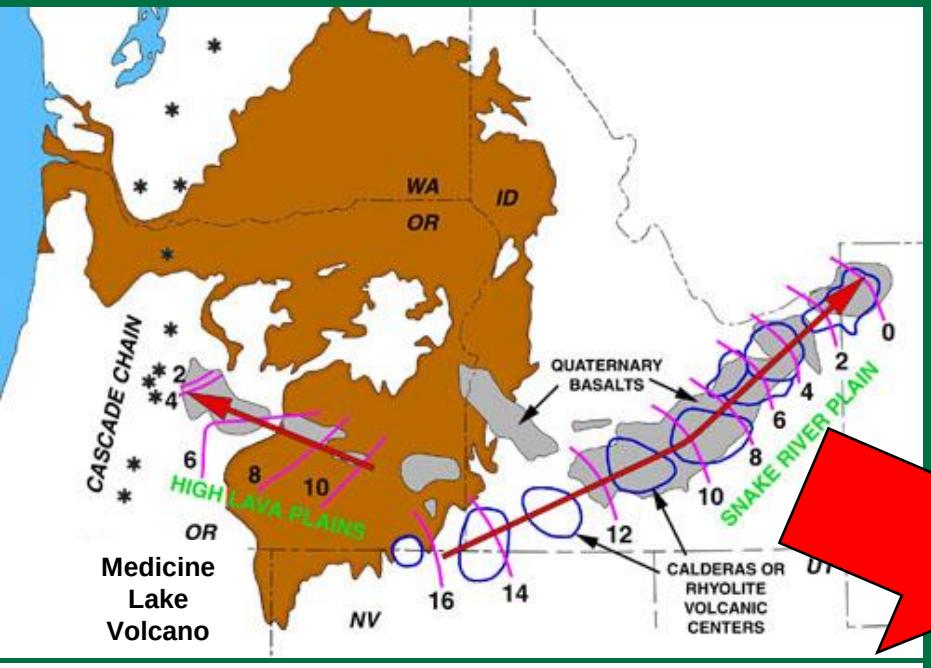
Today: Summarize Aspects of Three Studies



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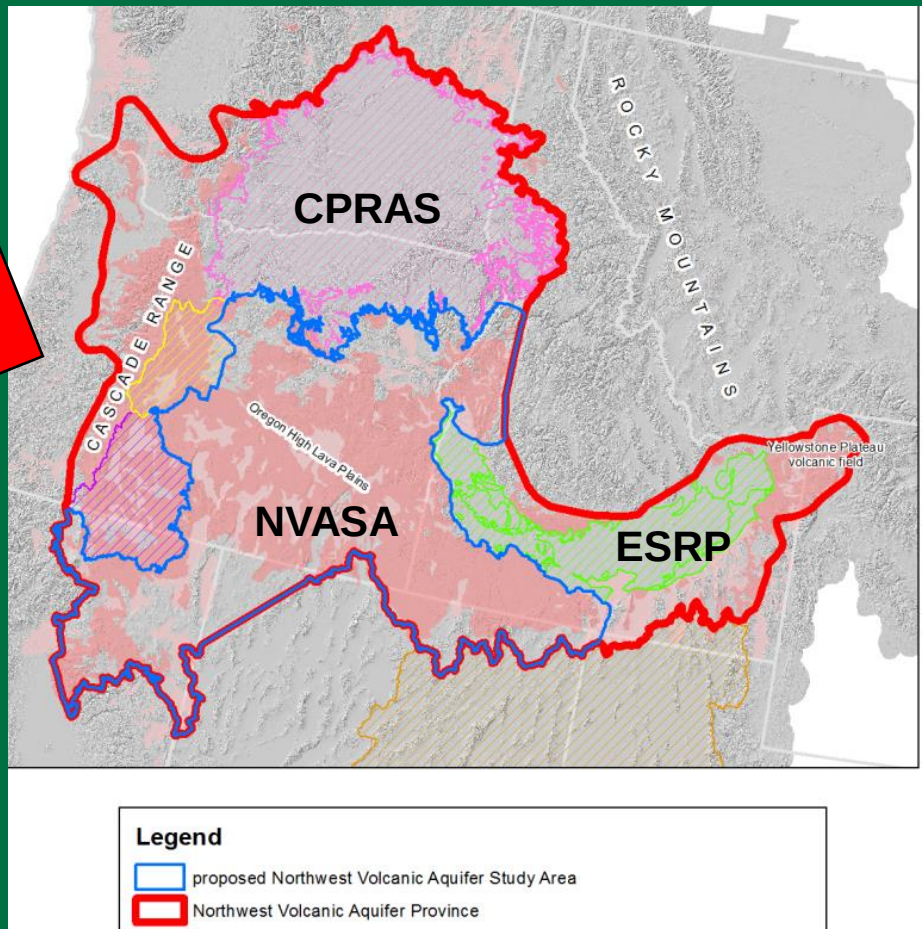

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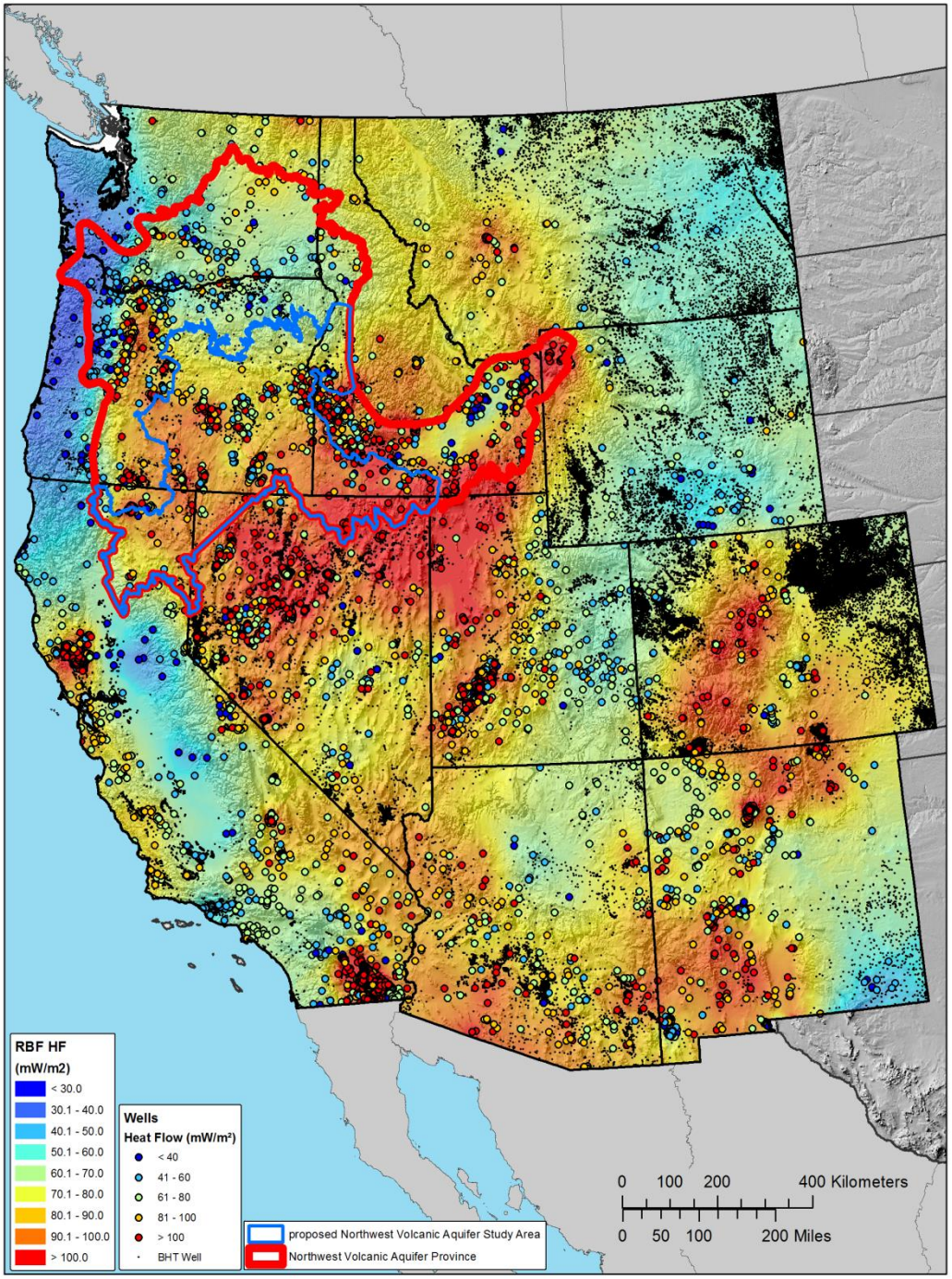
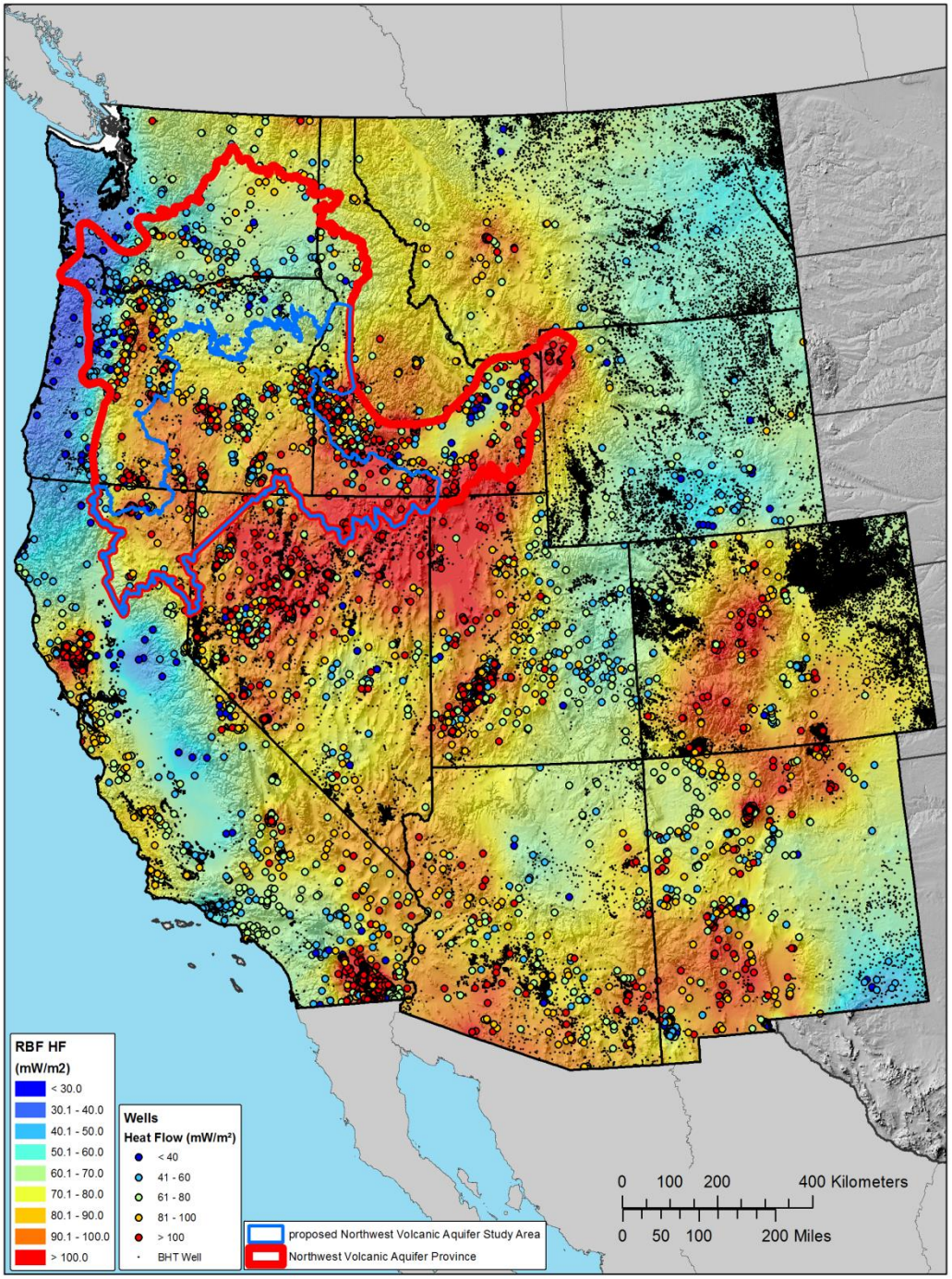
What does heat flow look like in these areas?



Modified from:
Williams and DeAngelo (2011)

USGS

Apparent Low Heat Flow Anomalies



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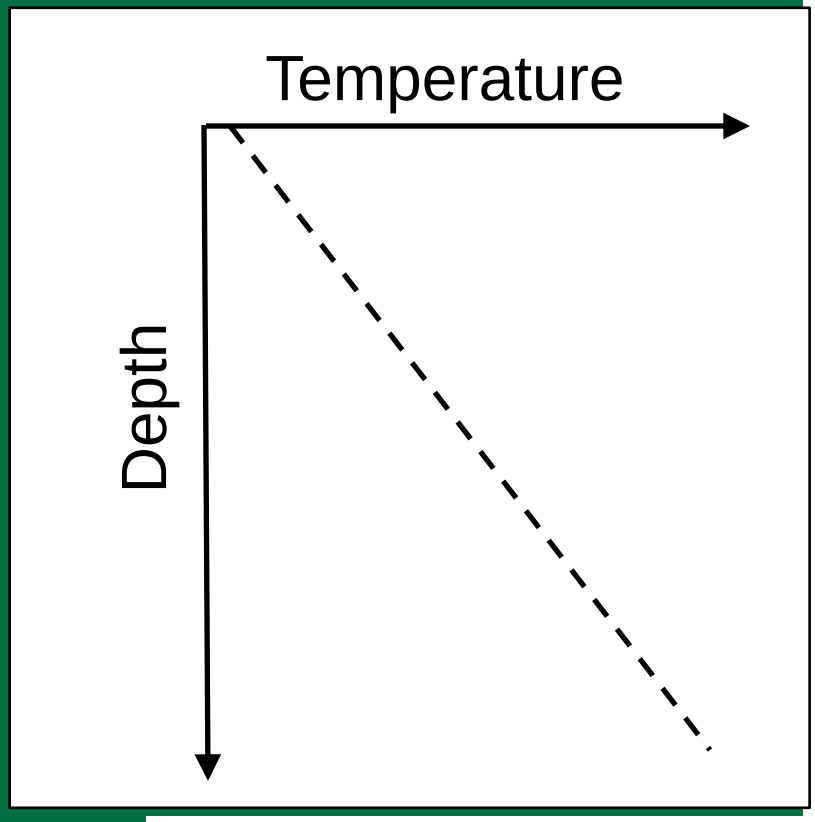
Purely Conductive Heat Flow



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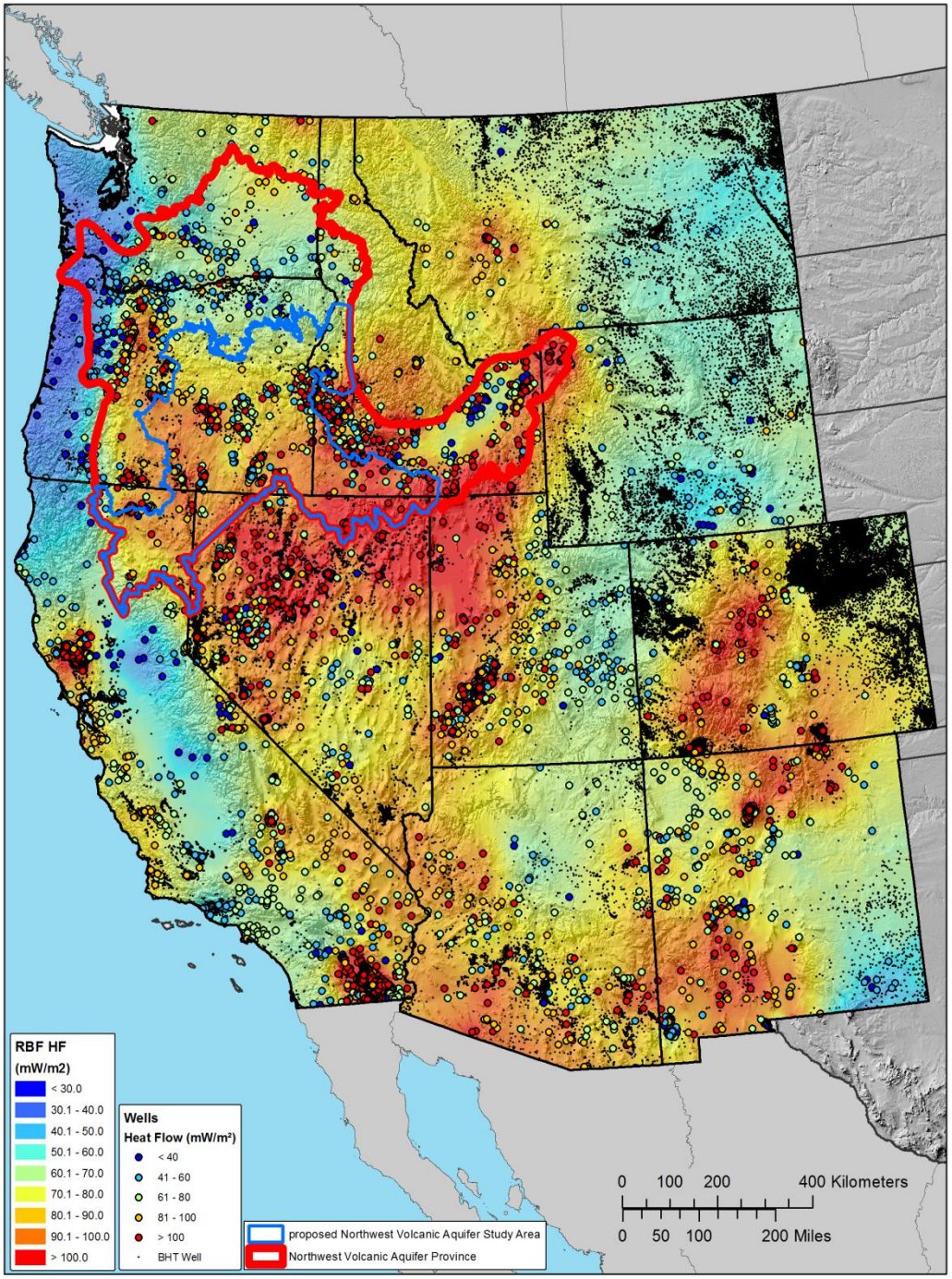

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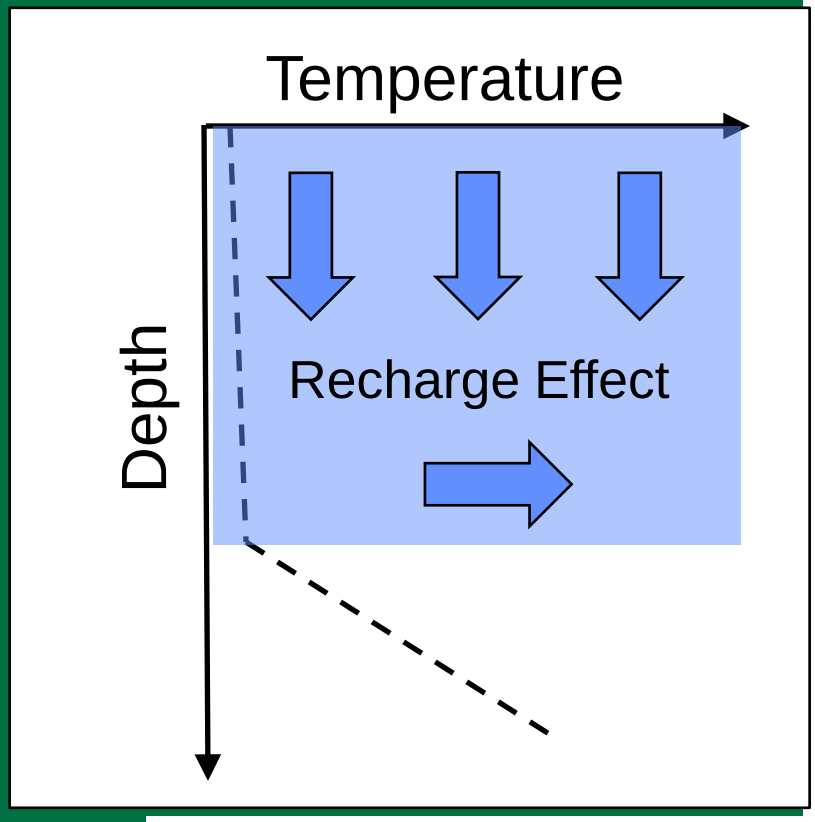
Advection of Heat by Recharge



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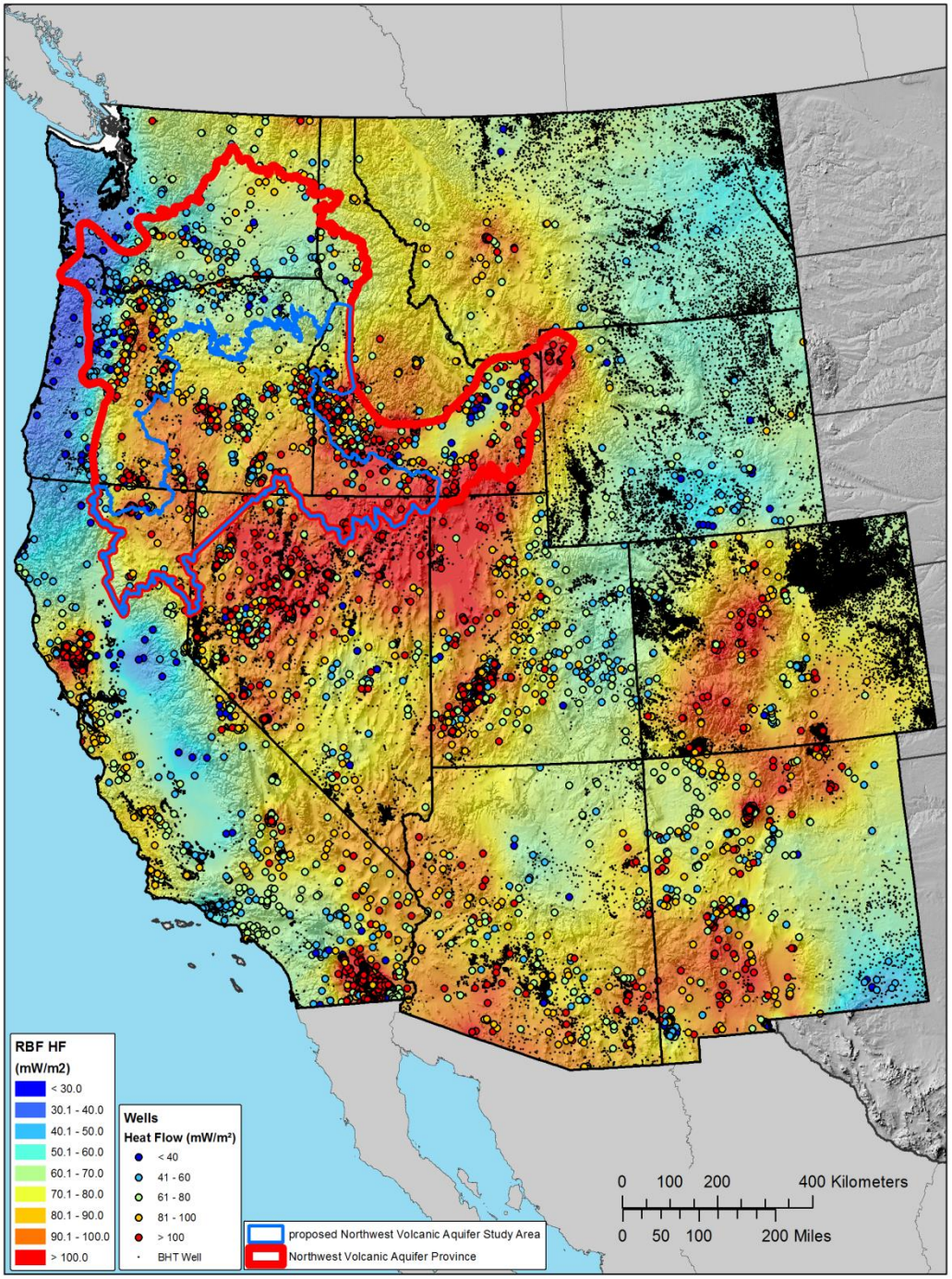

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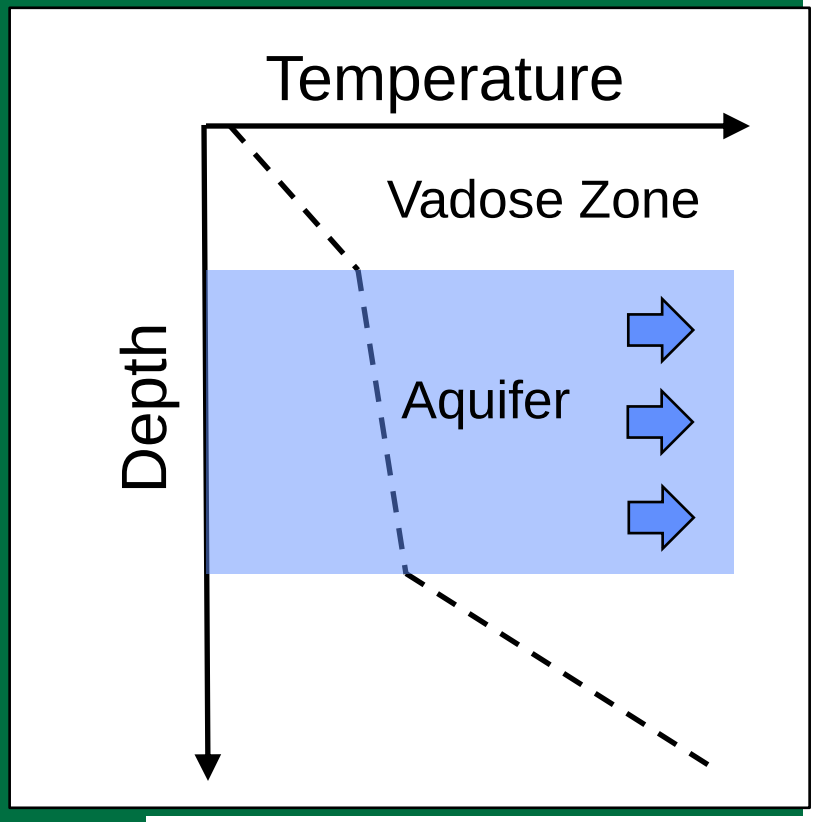
Advection of Heat by Groundwater



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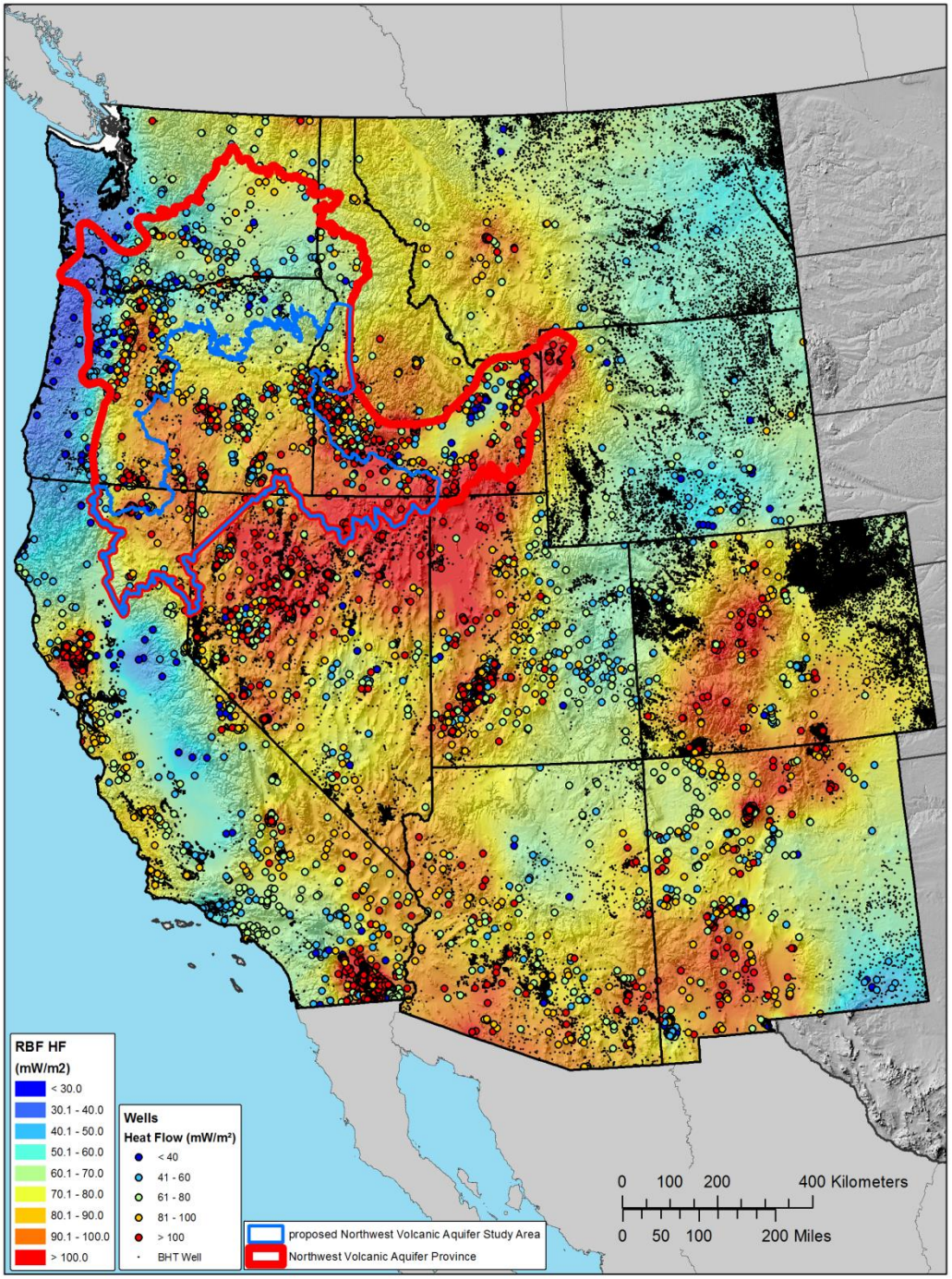

USGS

For the CPRAS, is Groundwater Flow Removing a Significant amount of Heat?

- **If so, what does the resulting heat flow pattern look like?**

<u>Results published so far:</u>

Burns, E.R., Williams, C.F., Ingebritsen, S.E., Voss, C.I., Spane, F.A., and J. DeAngelo (2015) *Understanding Heat and Groundwater Flow through Continental Flood Basalt Provinces: Insights Gained from Alternative Models of Permeability/Depth Relationships for the Columbia Plateau, USA*, Geofluids 15, 120–138, doi: 10.1111/gfl.12095.

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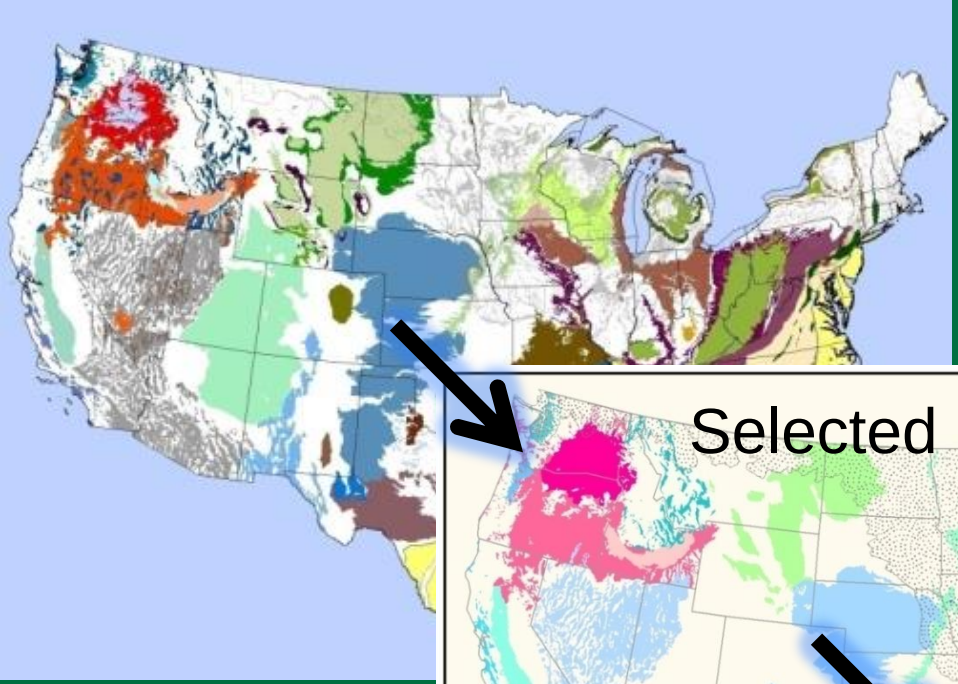
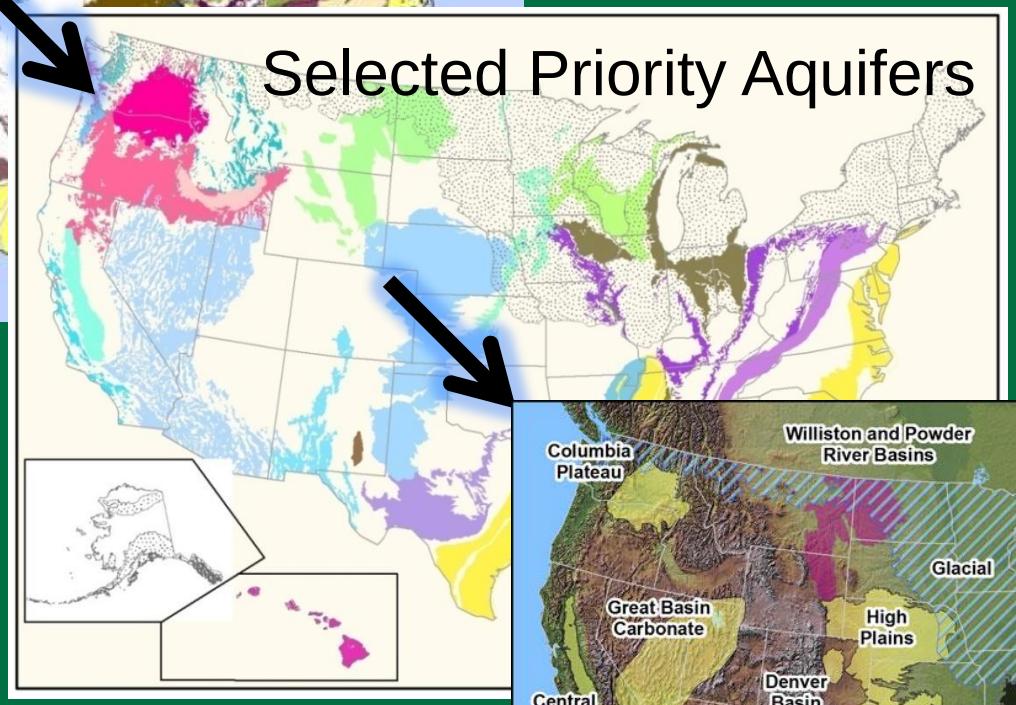
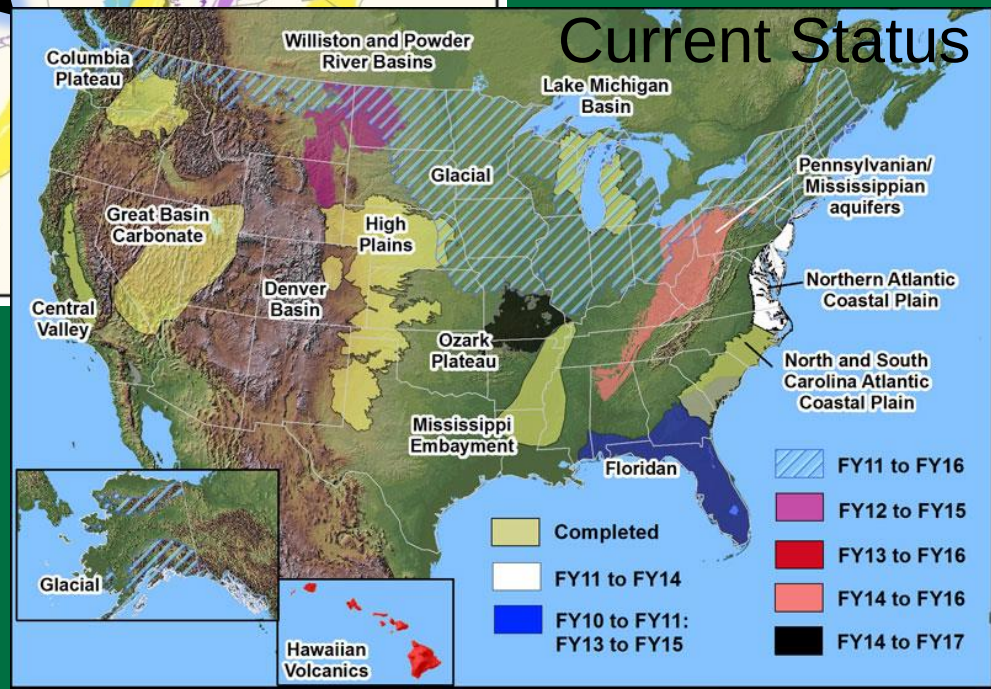
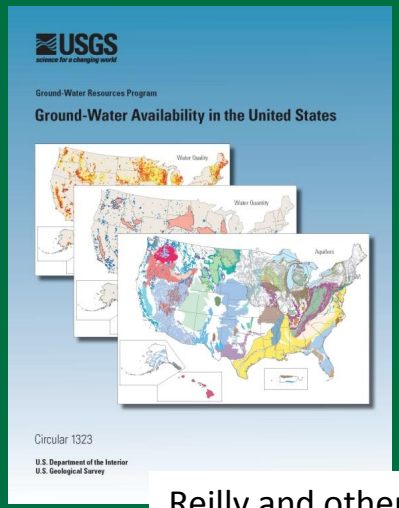
USGS Groundwater Resources Program









Reilly and others, 2008

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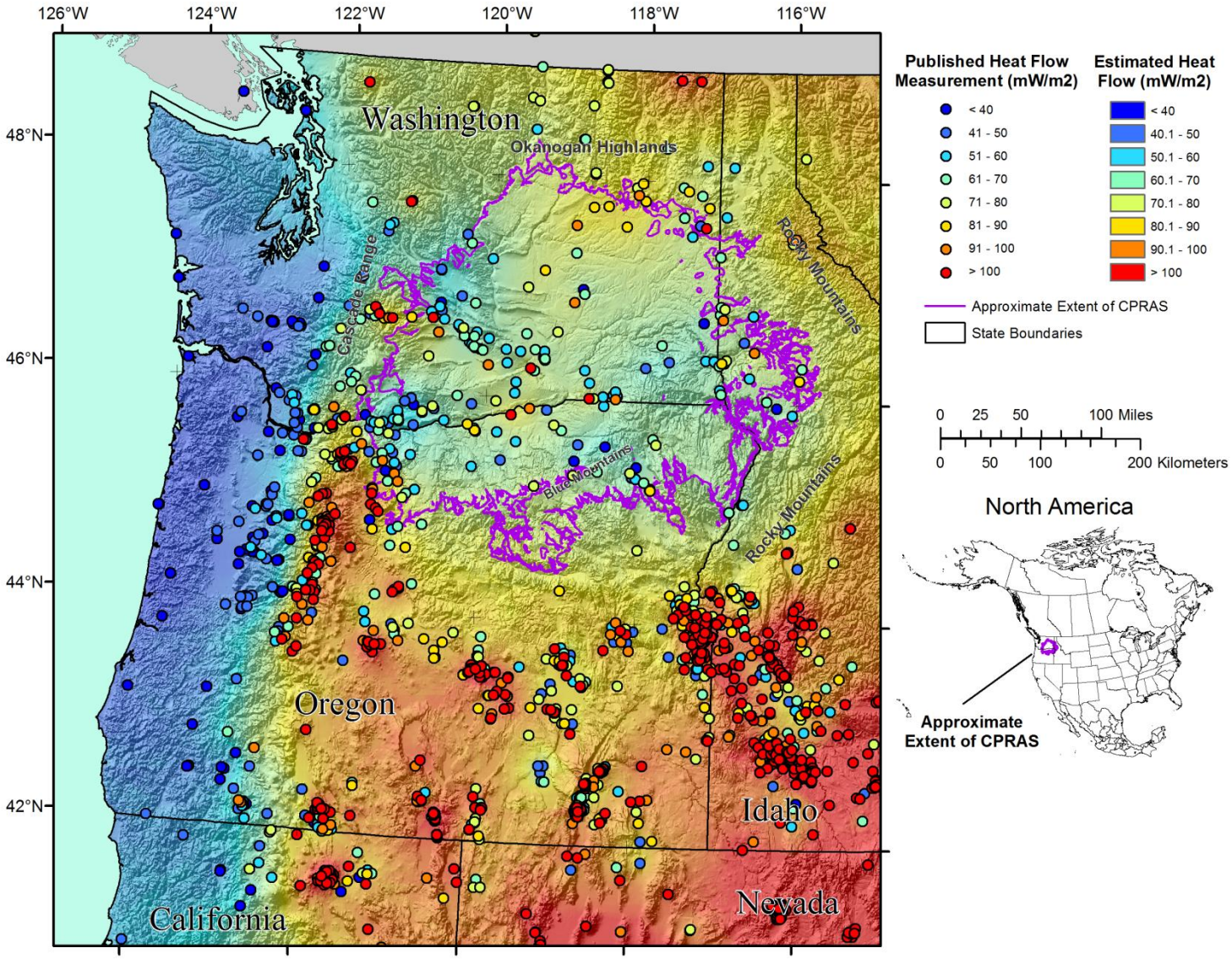
Columbia Plateau Regional Aquifer System



Heat flow map constructed using the methods of Williams and DeAngelo (2008).

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Principle Aquifers = **Columbia River Basalts**

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CRBG Flow size

Largest Lava Flows on Earth!

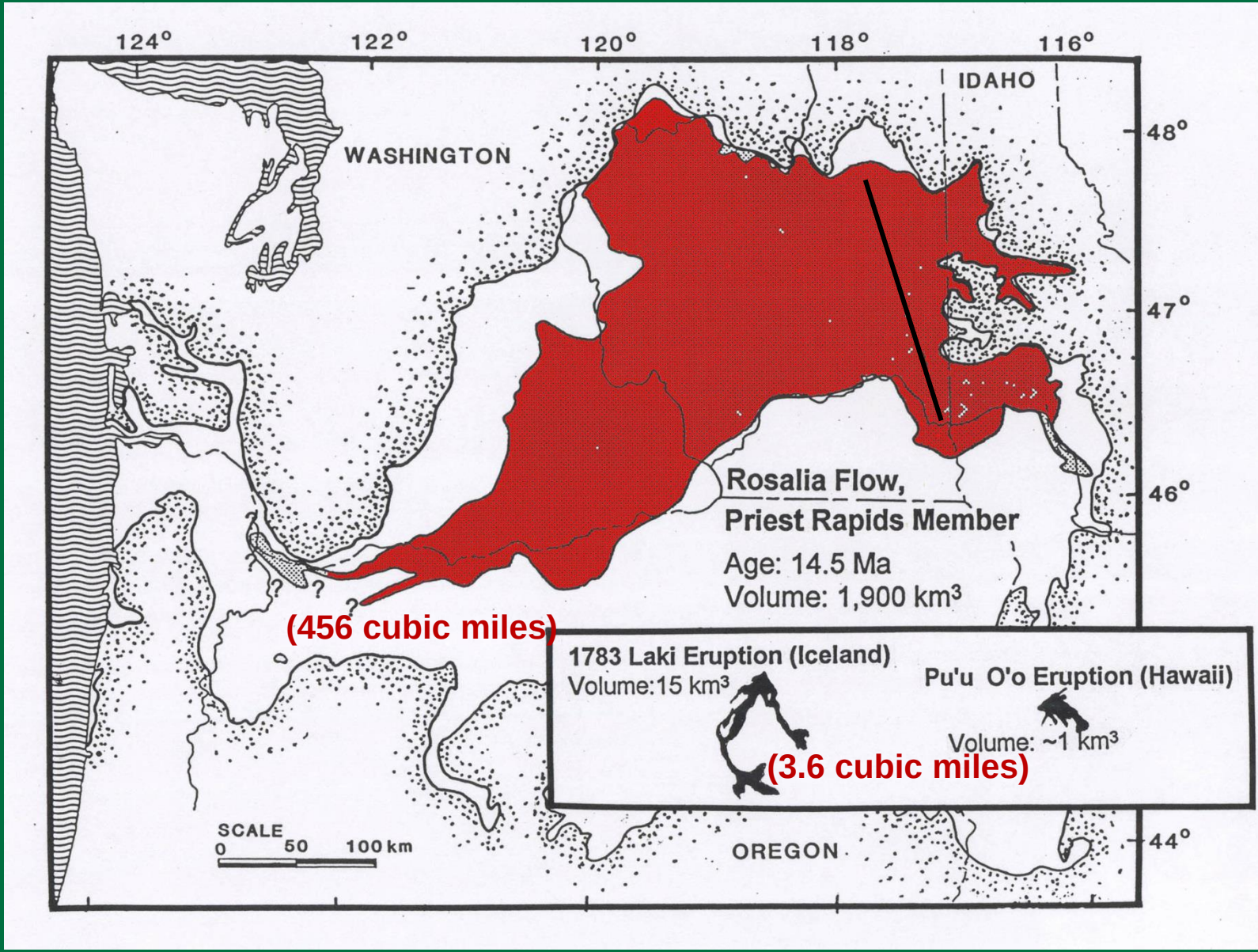

Figure courtesy of Terry Tolan.

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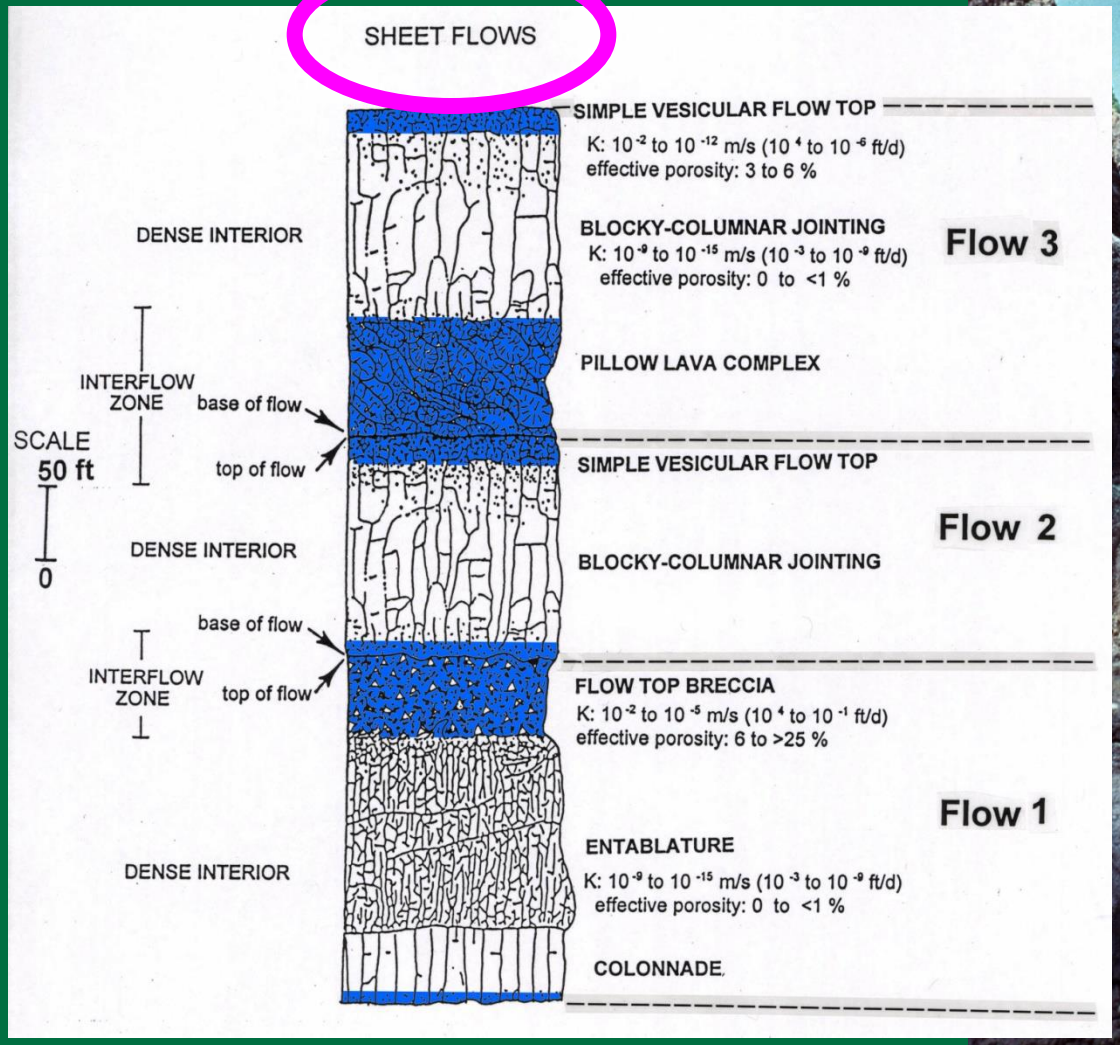
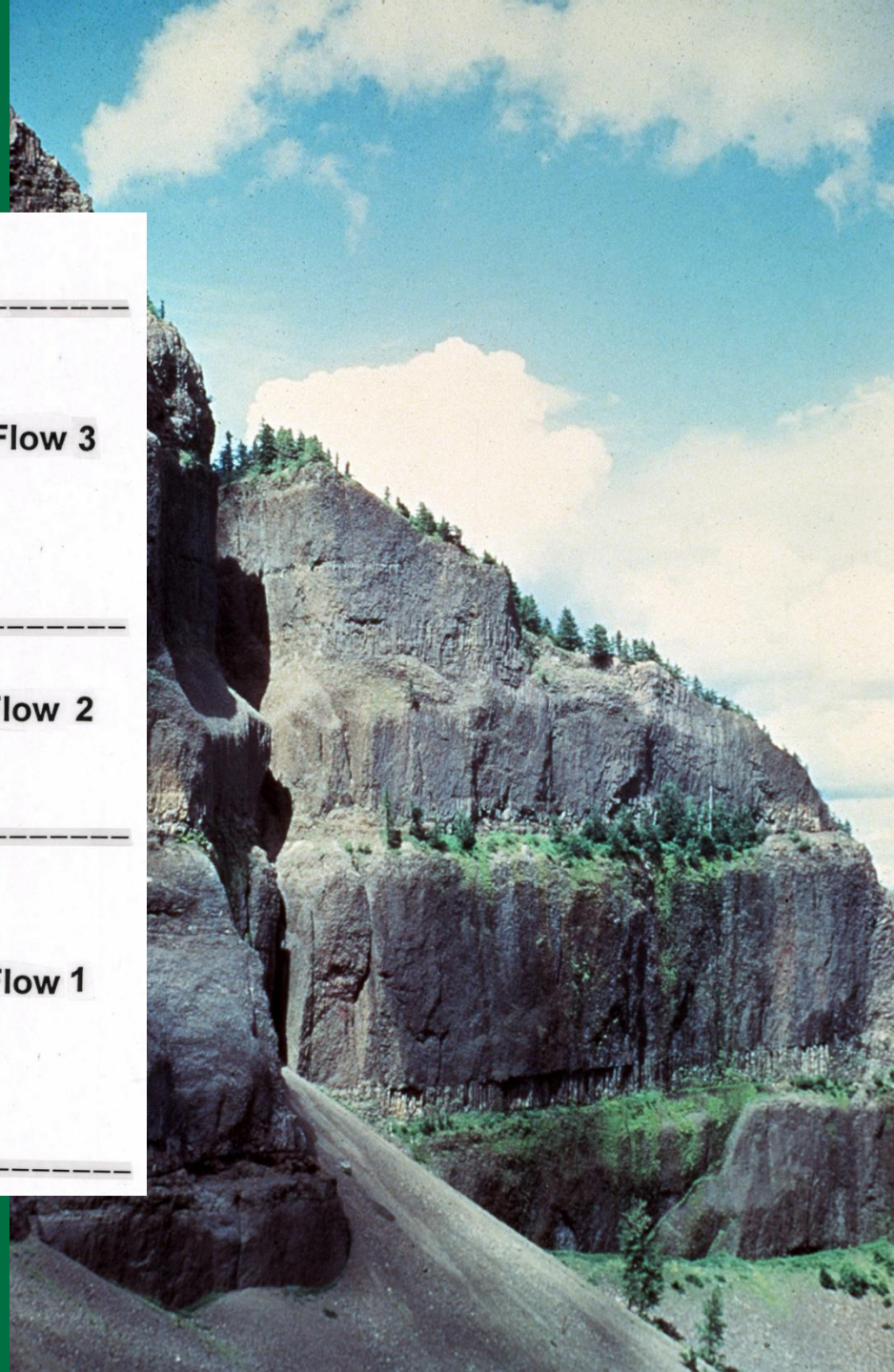
Over 300 flows erupted from17.5 to 6 million years ago

CRBG Lavas





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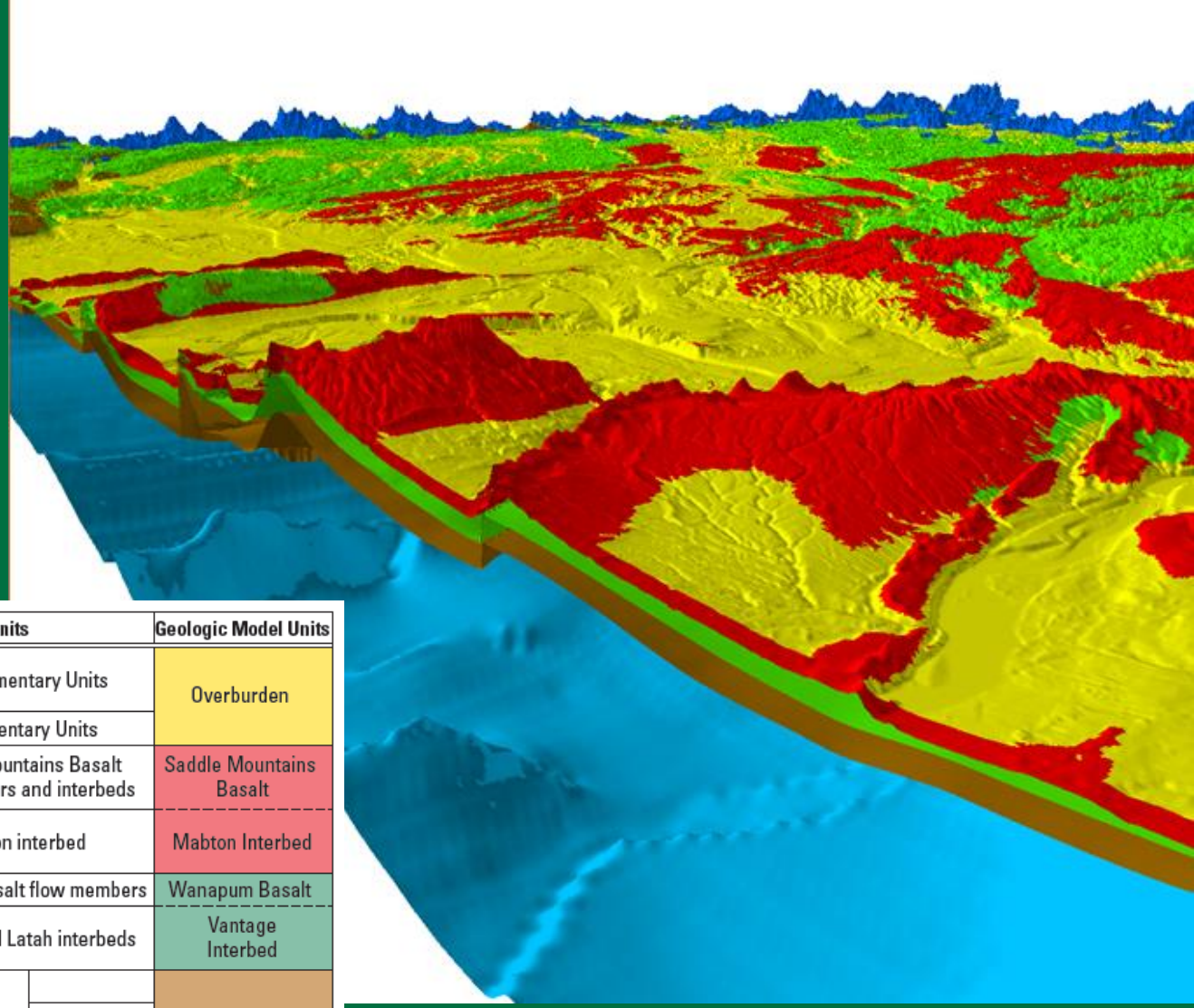
Figures courtesy of Terry Tolan.

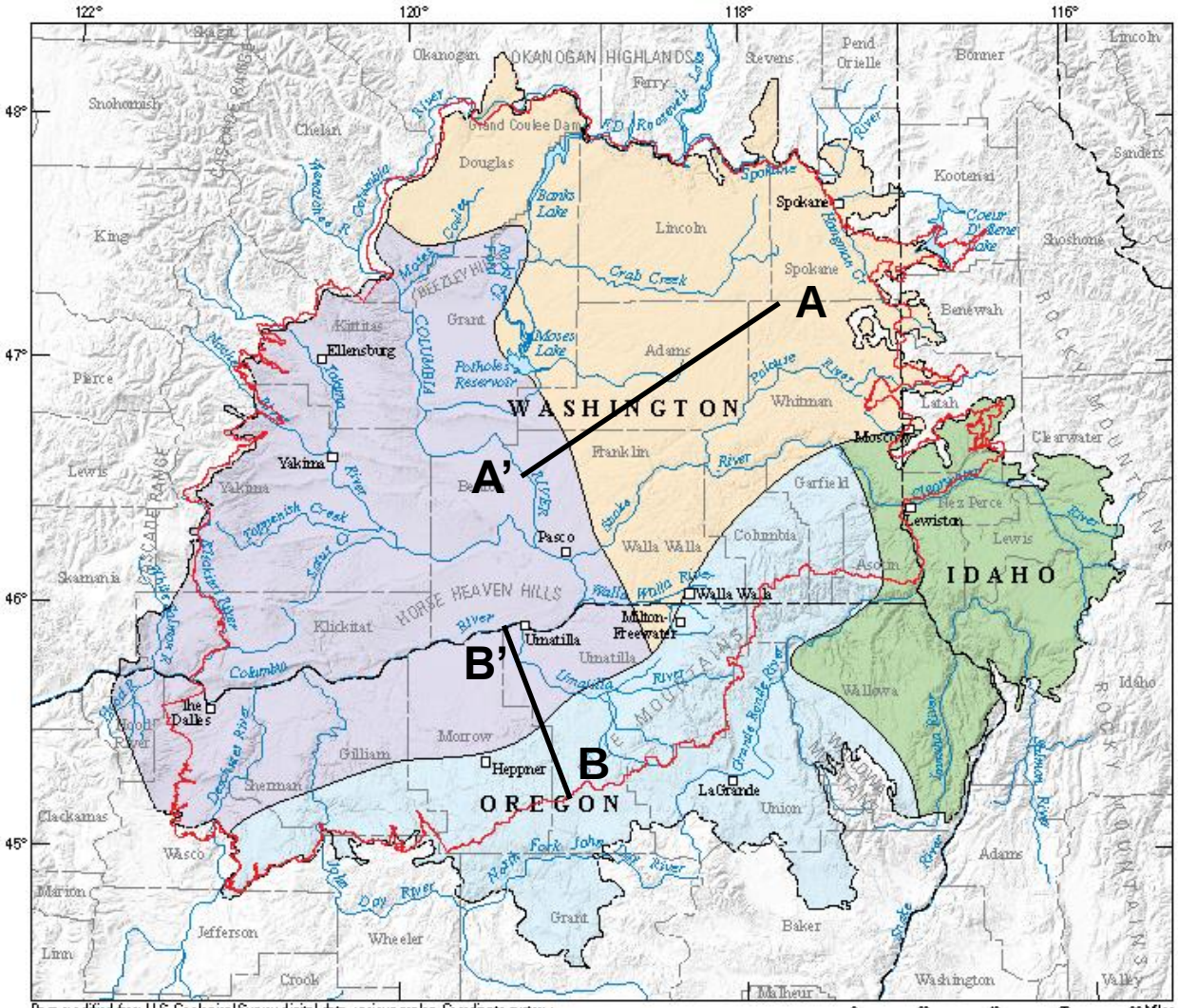


Era	Period	Epoch	Geologic Units			Geologic Model Units
Cenozoic	Quaternary	Holocene	All Quaternary Sedimentary Units			Overburden
		Pleistocene				
	Tertiary	Pliocene	All Pliocene Sedimentary Units			
		Miocene	Columbia River Basalt Group	Saddle Mountains Basalt flow members and interbeds		Saddle Mountains Basalt
				Mabton interbed		Mabton Interbed
				Wanapum Basalt flow members		Wanapum Basalt
				Vantage and Latah interbeds		Vantage Interbed
				Grande Ronde Basalt flow members and interbeds		Grande Ronde Basalt
					Prineville Basalt	
					Picture Gorge Basalt	
				Imnaha Basalt		
		pre-Miocene	pre-Columbia River Basalt Group rocks			Older Bedrock

Note: The Mabton, Vantage, and Latah interbed thicknesses are estimated using regressions.

CRBG Lavas are up to 5 km thick

Type Cross-Sections along Groundwater Flow Paths



Base modified from U.S. Geological Survey digital data, various scales. Coordinate system: State Plane, Washington South, FIPS 4602; Projection: Lambert Conformal Conic. Horizontal datum: North American Datum 1983, Vertical datum: North American Vertical Datum of 1988.

0 20 40 60 80 Miles

0 20 40 60 80 Kilometers

EXPLANATION

Structural region of Columbia Plateau Regional Aquifer System

- Yakima Fold Belt
- Palouse Slope
- Blue Mountains
- Clearwater Embayment
- Study area boundary
- Groundwater-flow model boundary

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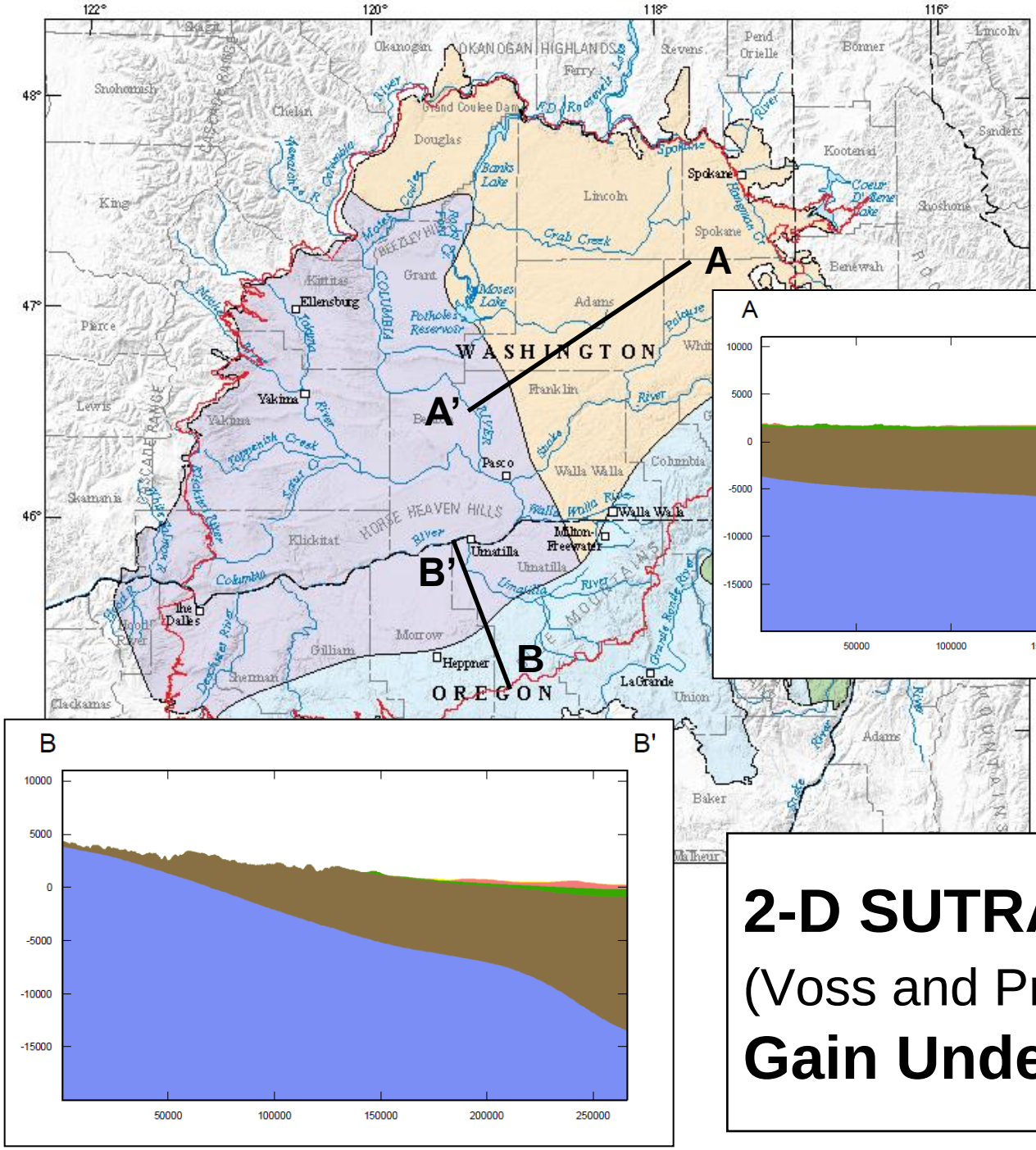
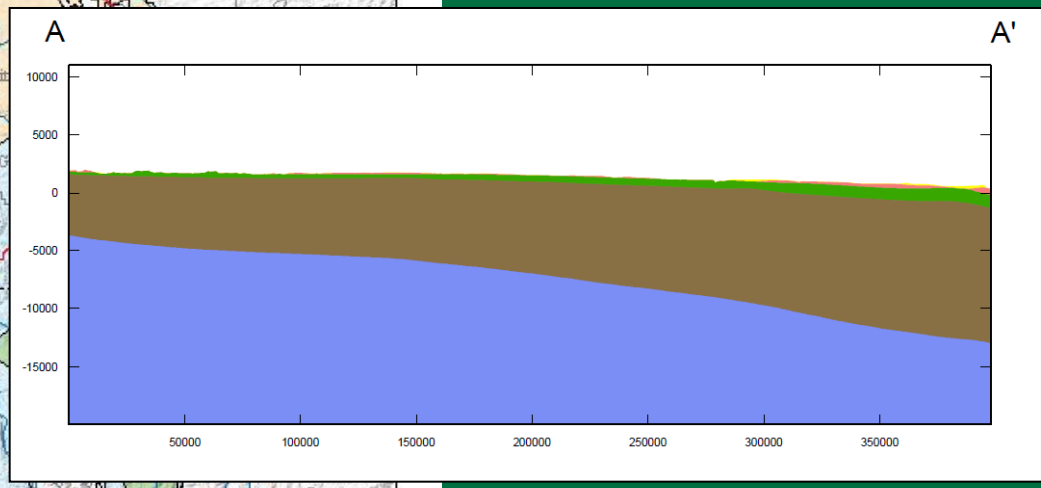
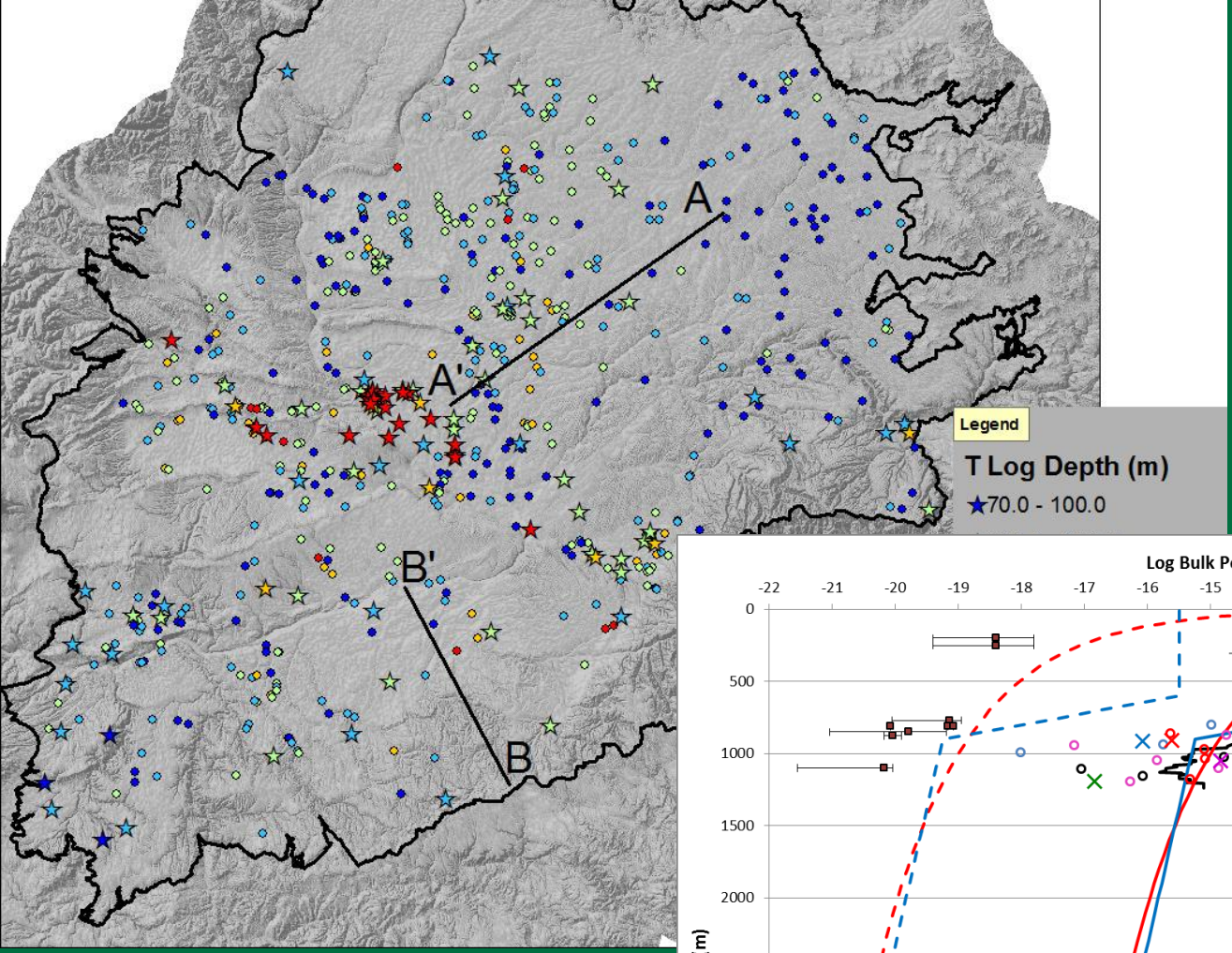


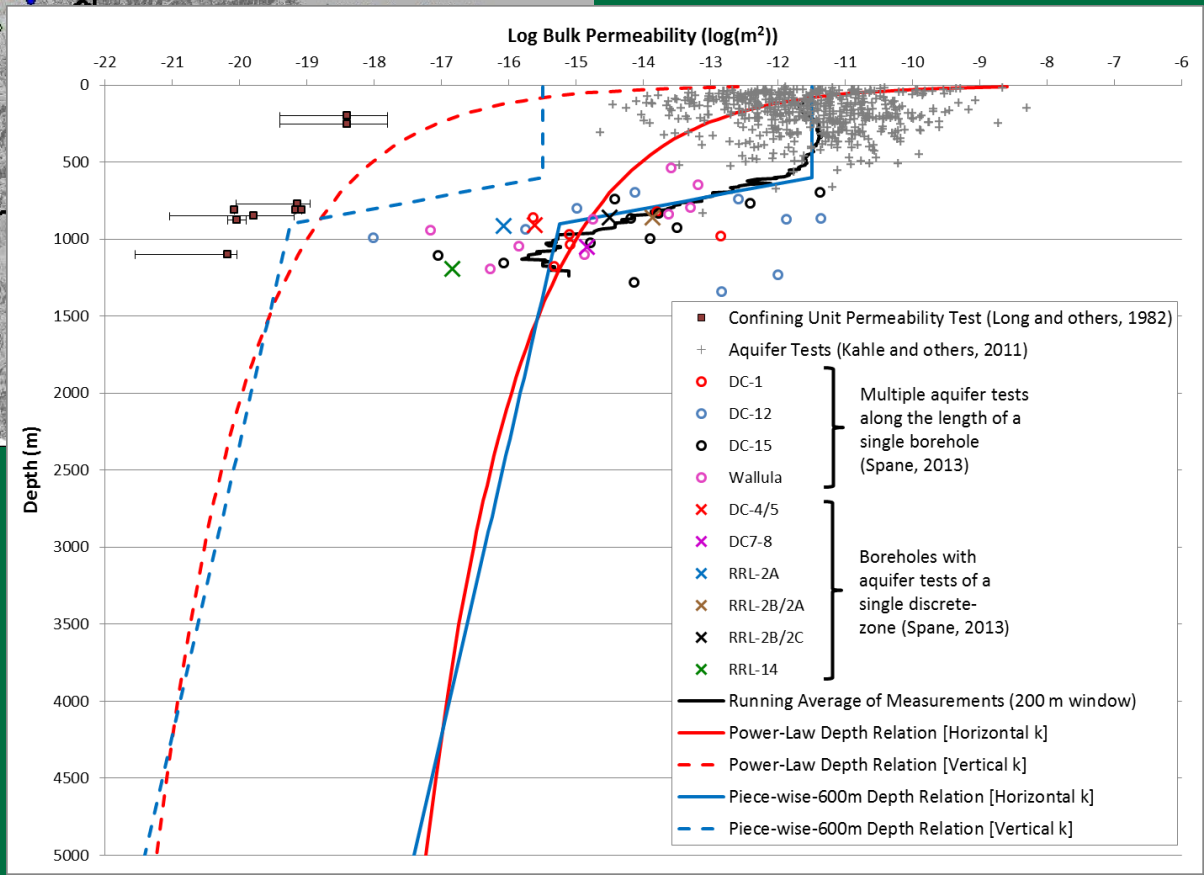


2-D SUTRA Modeling

(Voss and Provost, 2010) **to Gain Understanding**

SUTRA needs Permeability Distribution





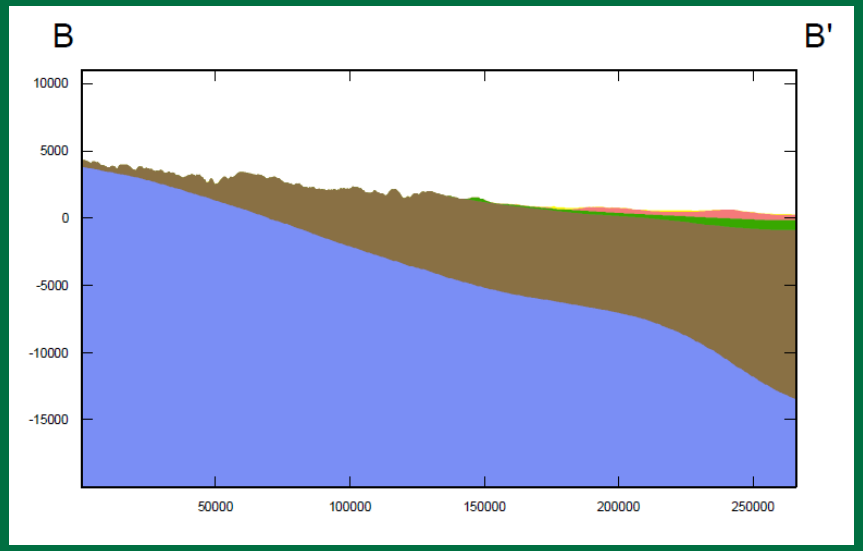
Depth relations from:

Manning and Ingebritsen (1999)

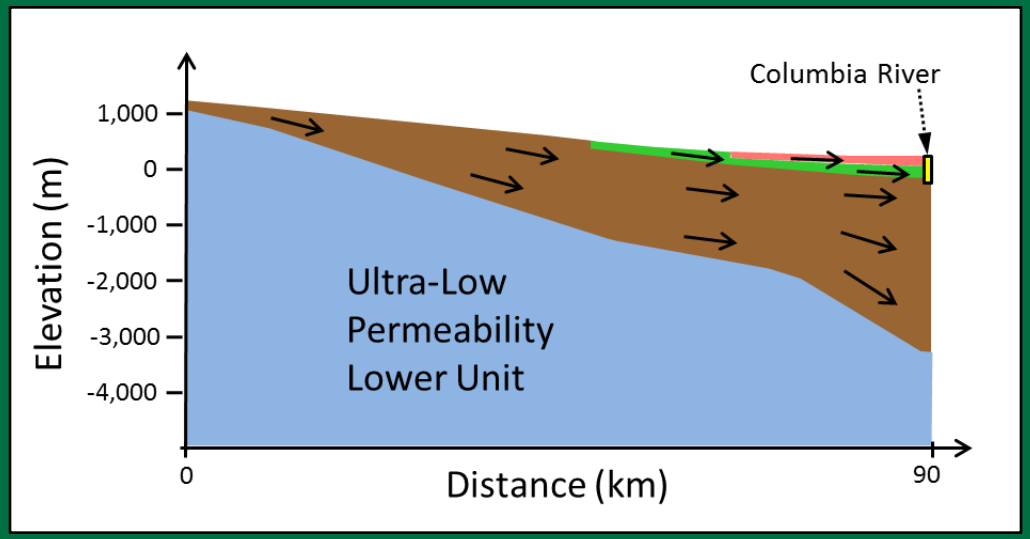
Saar and Manga (2004)

USGS

Cross-Section through 3D digital model



Simplified geometry and permeability distribution



USGS

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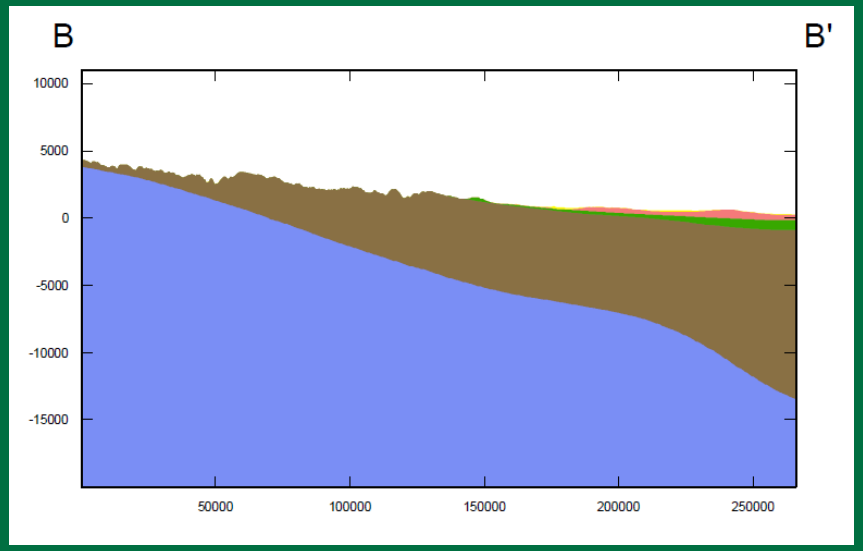
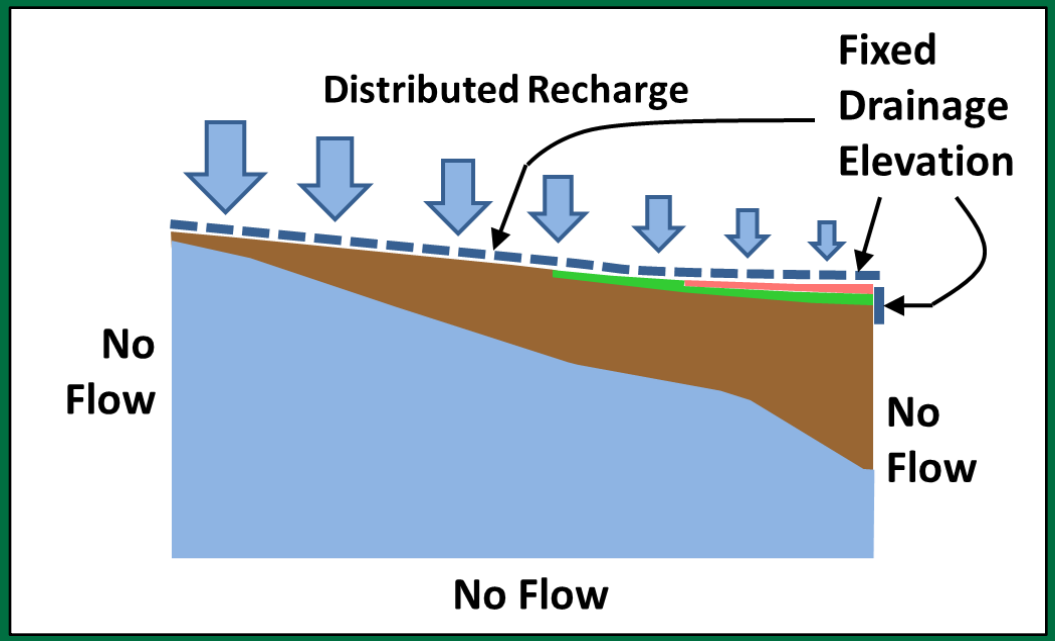


Hydraulic Boundary Conditions



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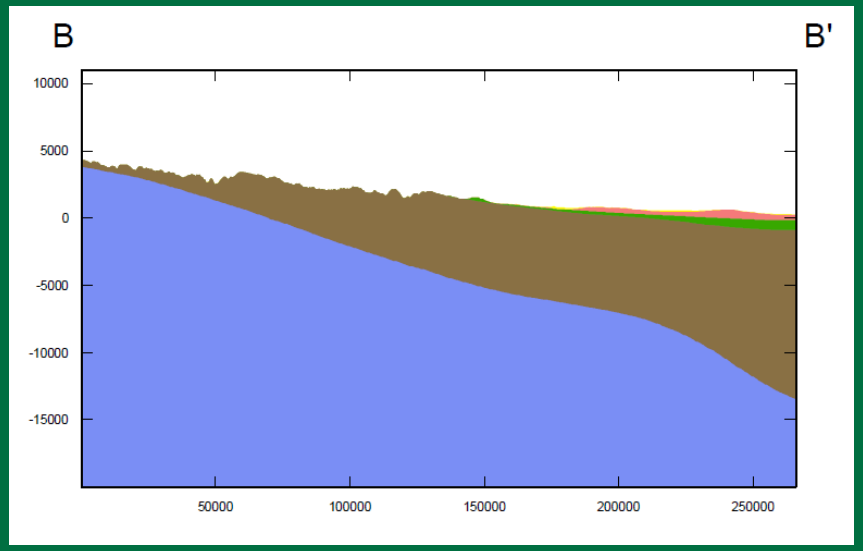
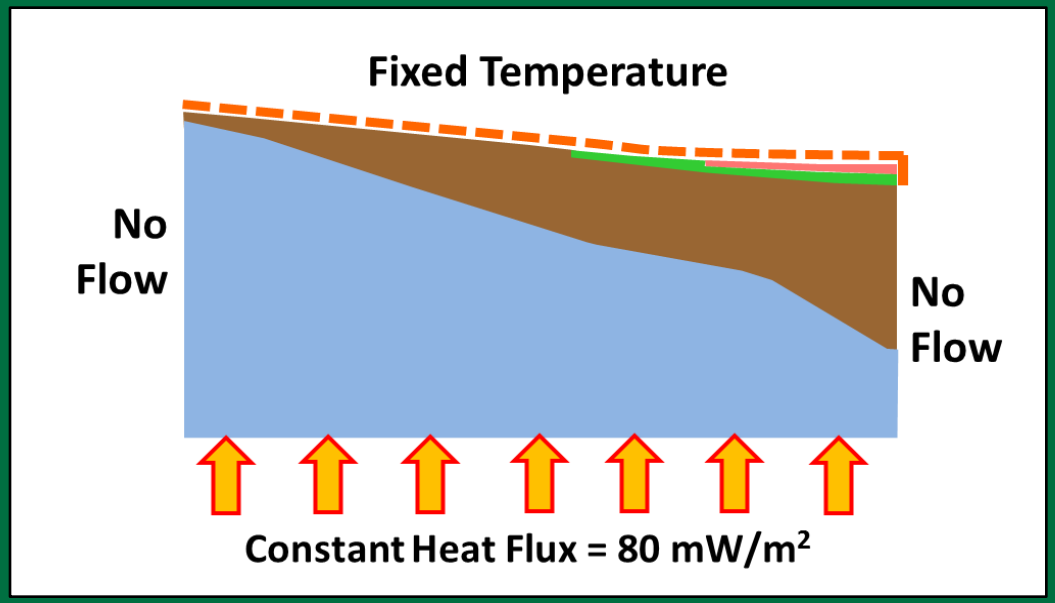
Cross-Section through 3D digital model

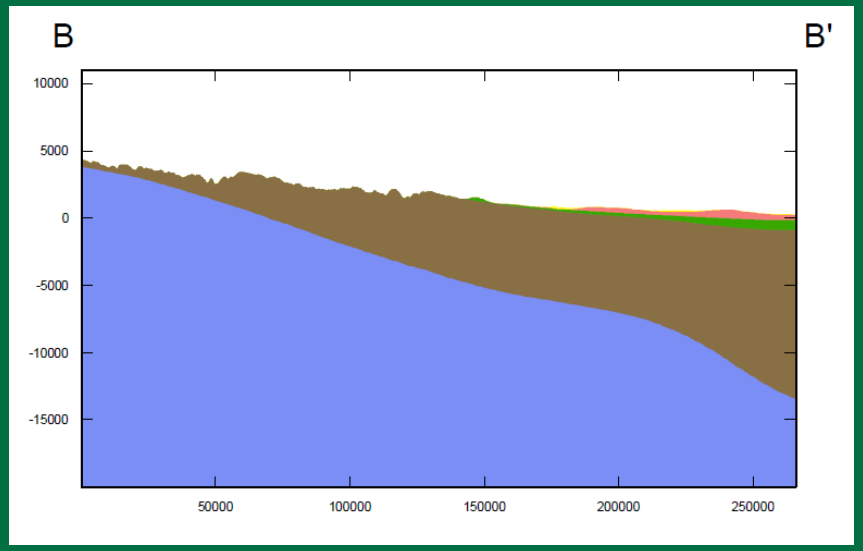


Thermal Boundary Conditions



[Global average heat flow in Tertiary tectonic provinces is approximately 70-80 mW/m^2]

Cross-Section through 3D digital model

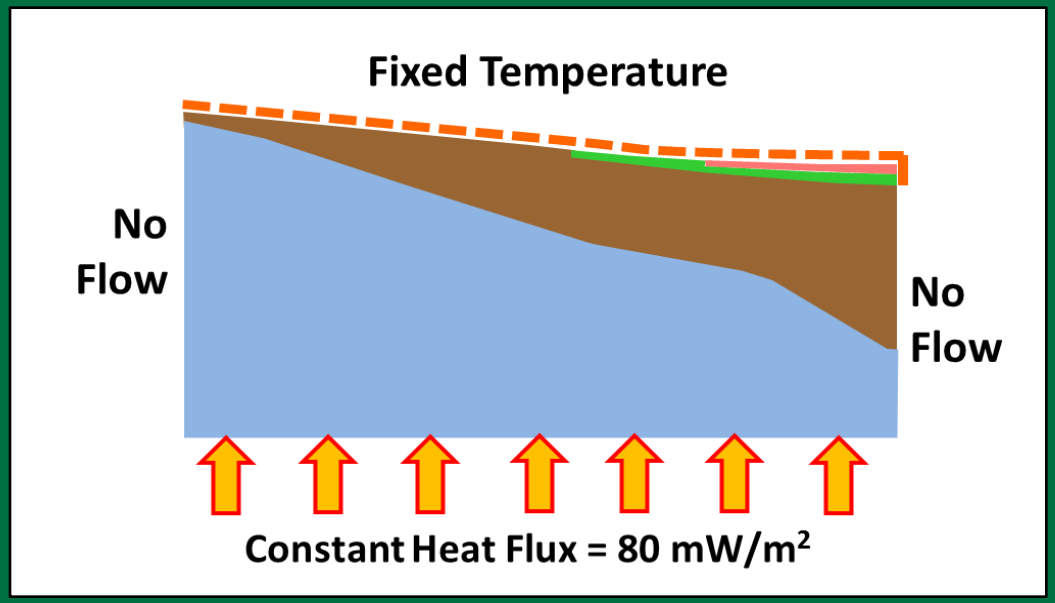


Bulk Thermal Conductivities:

Basalt = 1.59

Pre-Miocene = 2.5

[units = W/m/ºC]



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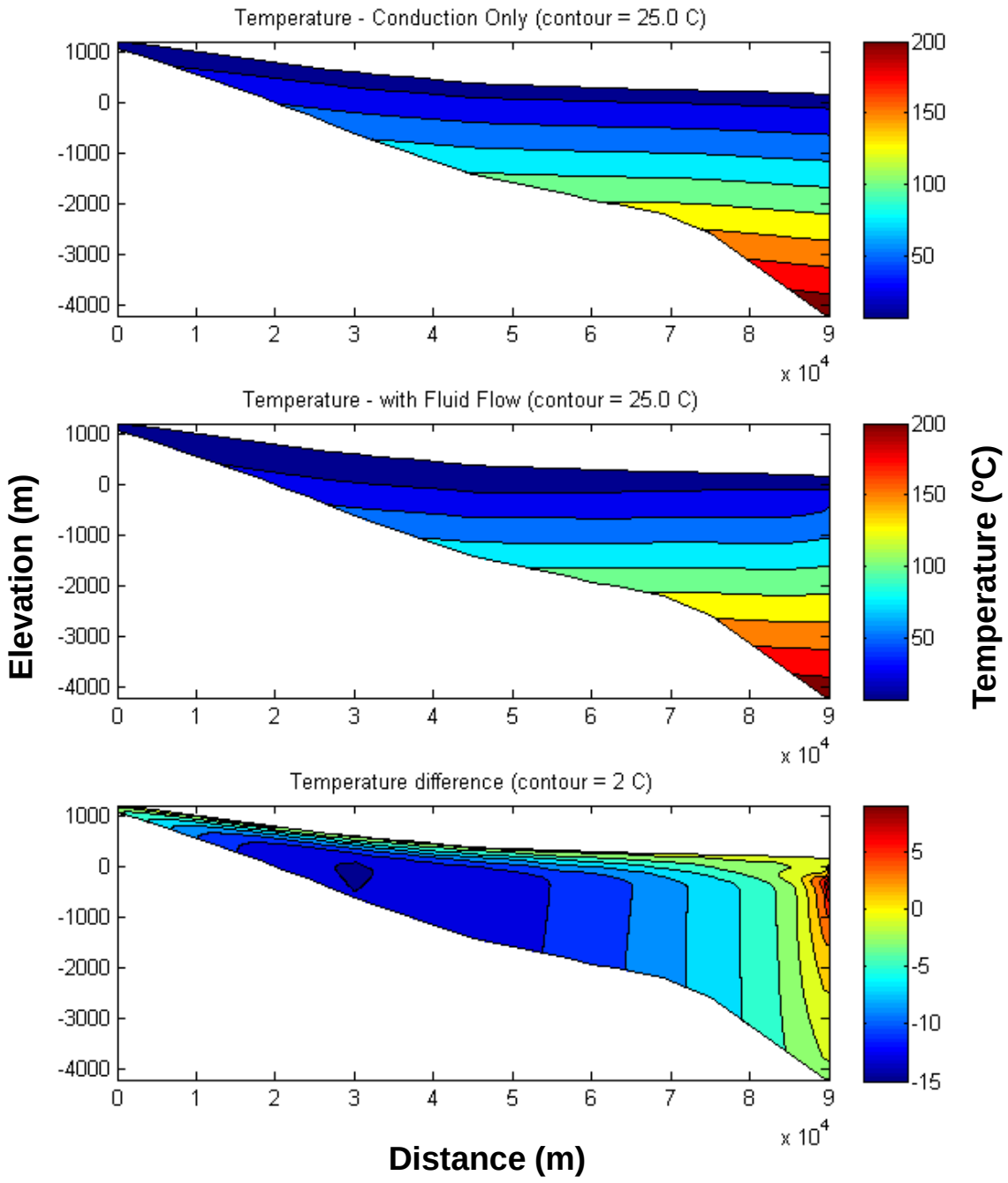
Comparison

Conduction Only

vs.

Combined Groundwater and Heat Flow



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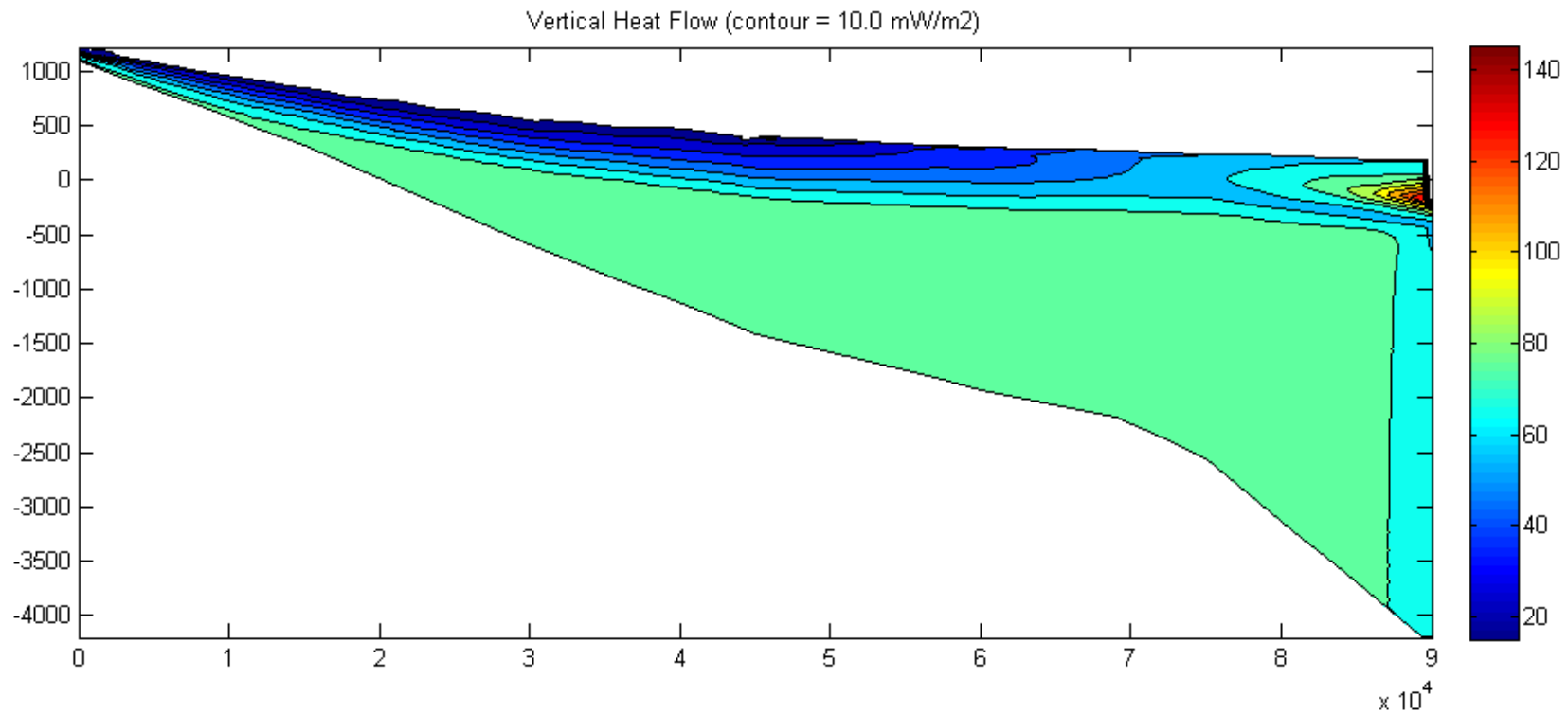
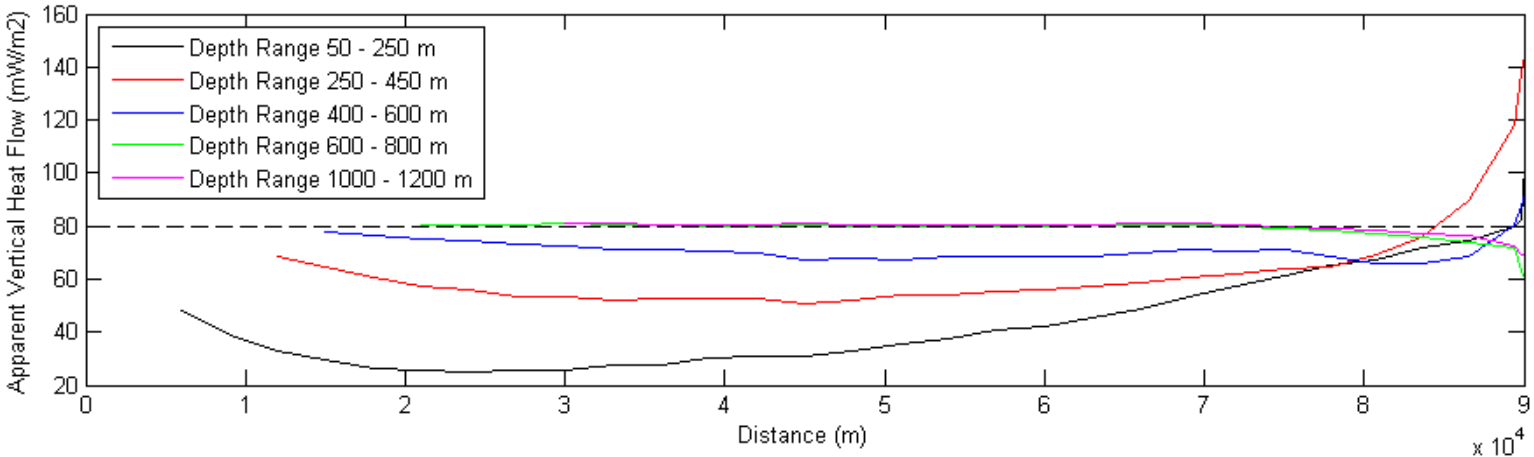
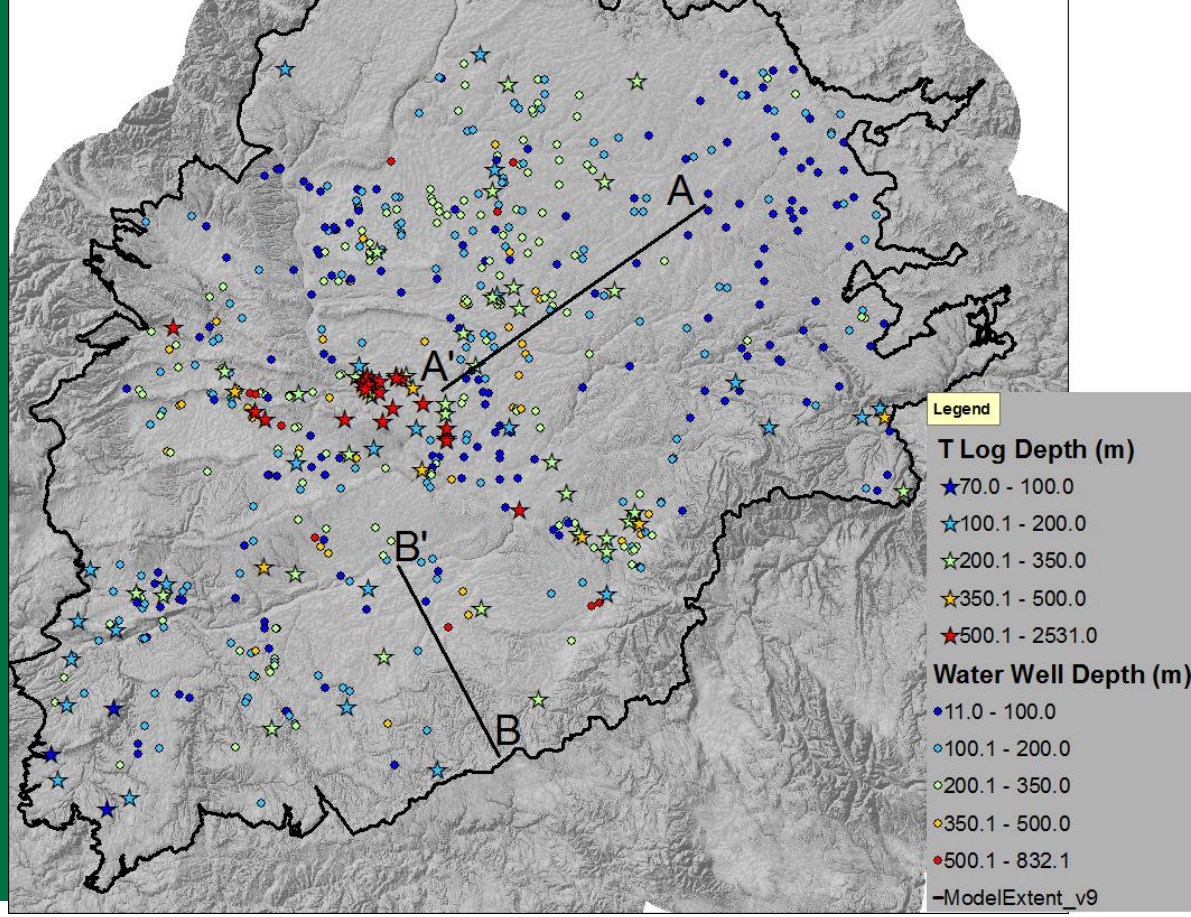
Simulated Vertical Heat Flow

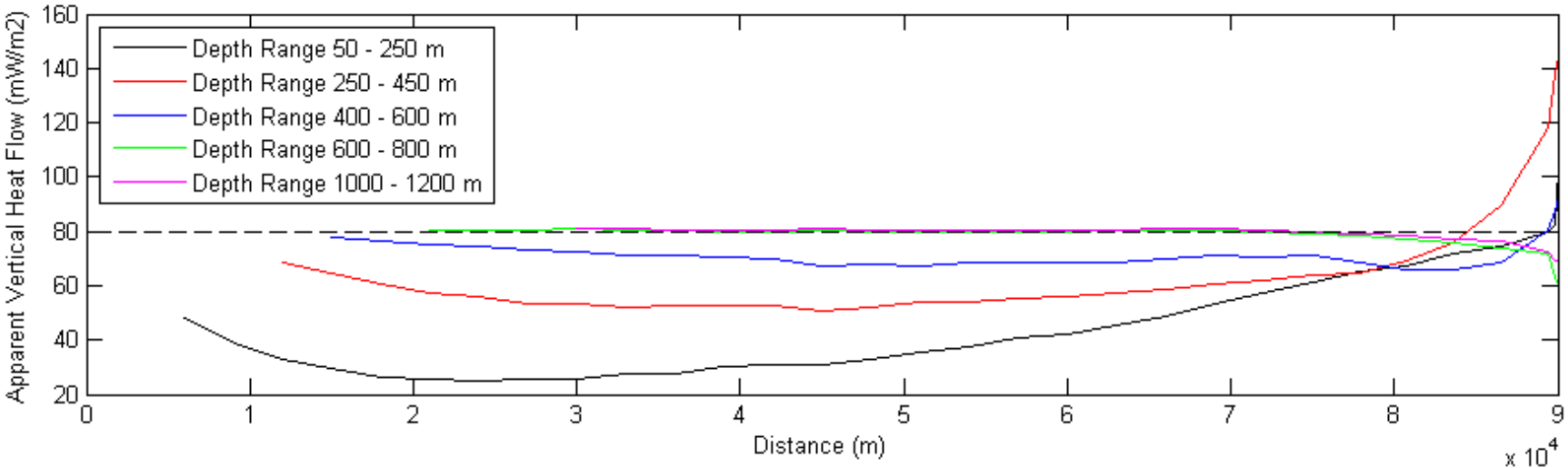




Some statistics…

- Of 120 wells with T profile data
  - 95 above 450 m
  - 43 in range 150-300 m
  - 20 below 600 m





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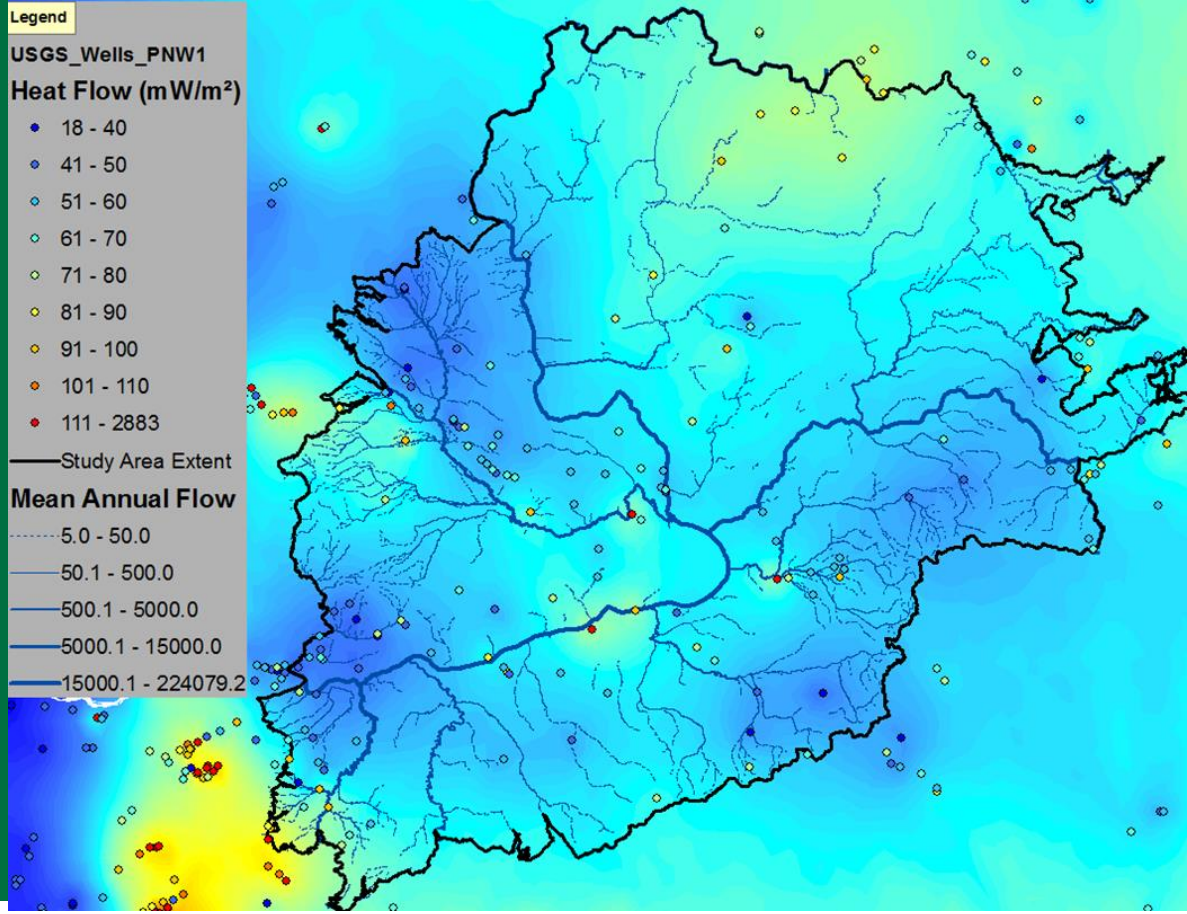

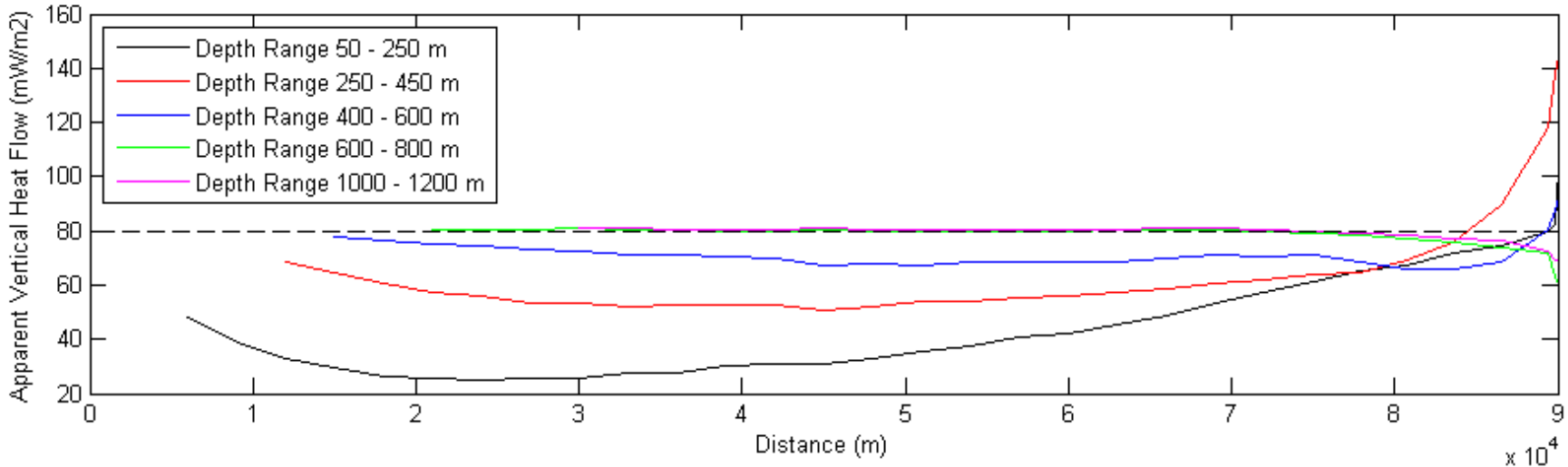

Primary Conclusion

- **Groundwater flow can explain anomalously low heat flow estimates made from shallow (<600 m) data**

Results published:

Burns, E.R., Williams, C.F., Ingebritsen, S.E., Voss, C.I., Spane, F.A., and J. DeAngelo (2015) *Understanding Heat and Groundwater Flow through Continental Flood Basalt Provinces: Insights Gained from Alternative Models of Permeability/Depth Relationships for the Columbia Plateau, USA*, Geofluids 15, 120–138, doi: 10.1111/gfl.12095.

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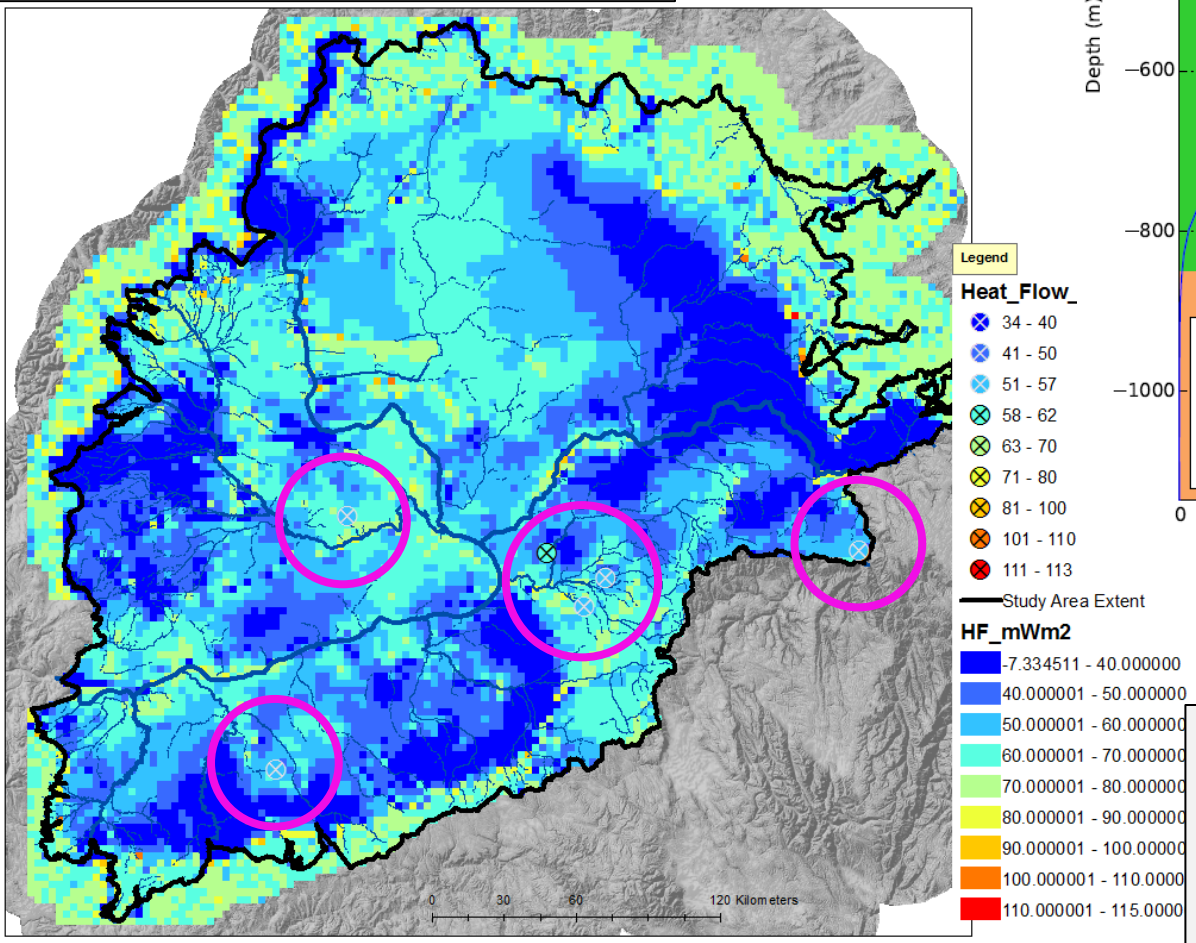
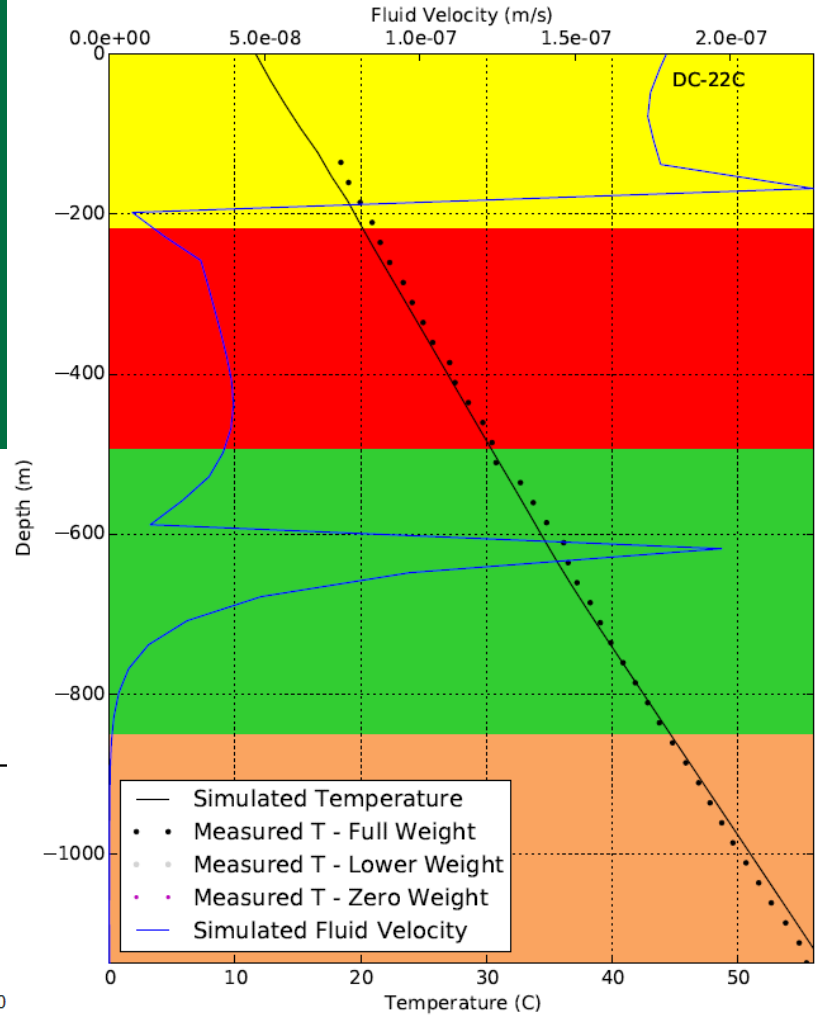
Ongoing Work—3D Maps using SUTRA

- Re-analysis of data

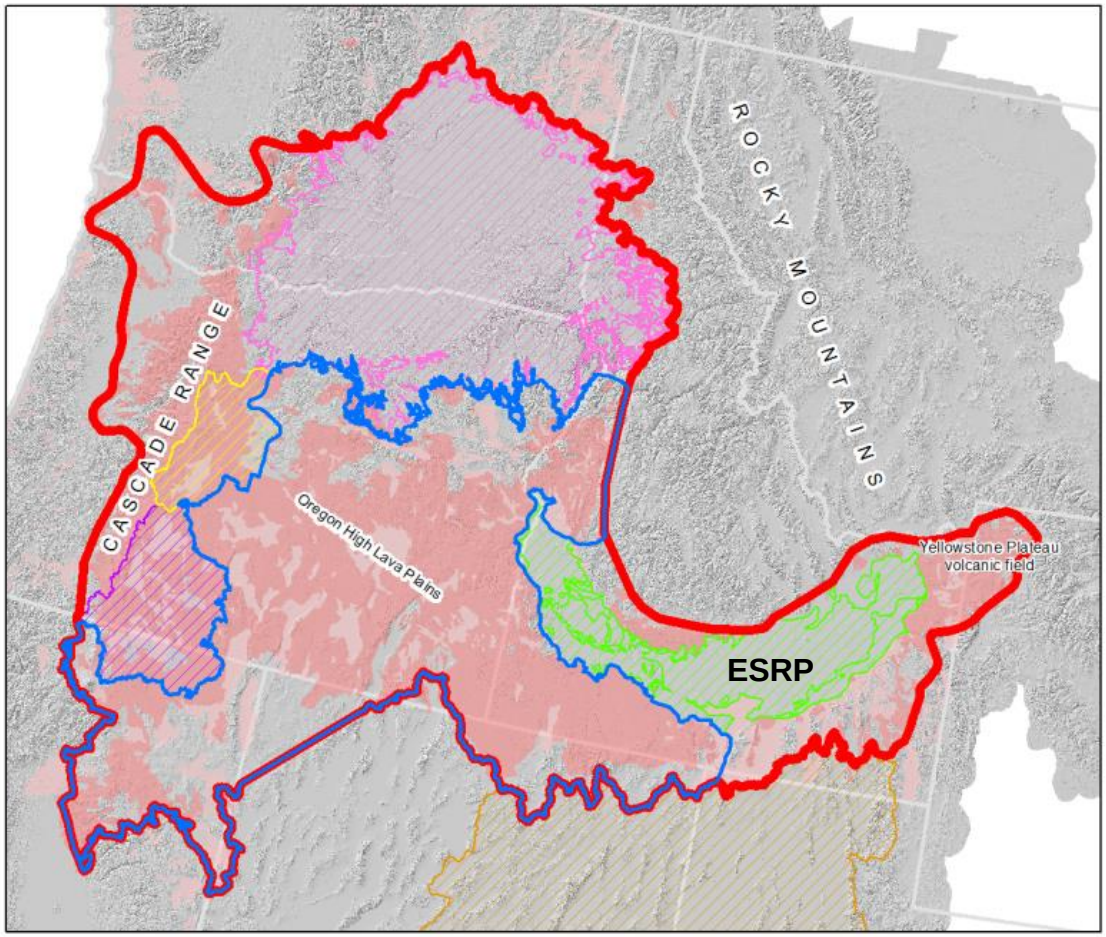
Provisional (and very preliminary) data, subject to revision.





Simulated Heat Flow at 250 m Depth

Demonstration of Use of a Simple Analytic Solution



Legend

- proposed Northwest Volcanic Aquifer Study Area
- Northwest Volcanic Aquifer Province
- Great Basin Carbonate-Alluvial Aquifer study area (Heilweil and Brooks, 2011)
- Upper Deschutes Basin (Gannett and Lite, 2004)
- Upper Klamath Basin (Gannett and others, 2012)
- Columbia Plateau Regional Aquifer System (Kahle and others, 2011)
- Snake River Plain Regional Aquifer System (Lindholm, 1986)
- Pacific Northwest basaltic-rock aquifers (Reilly and others, 2008)
- Pacific Northwest basin-fill aquifers (Reilly and others, 2008)

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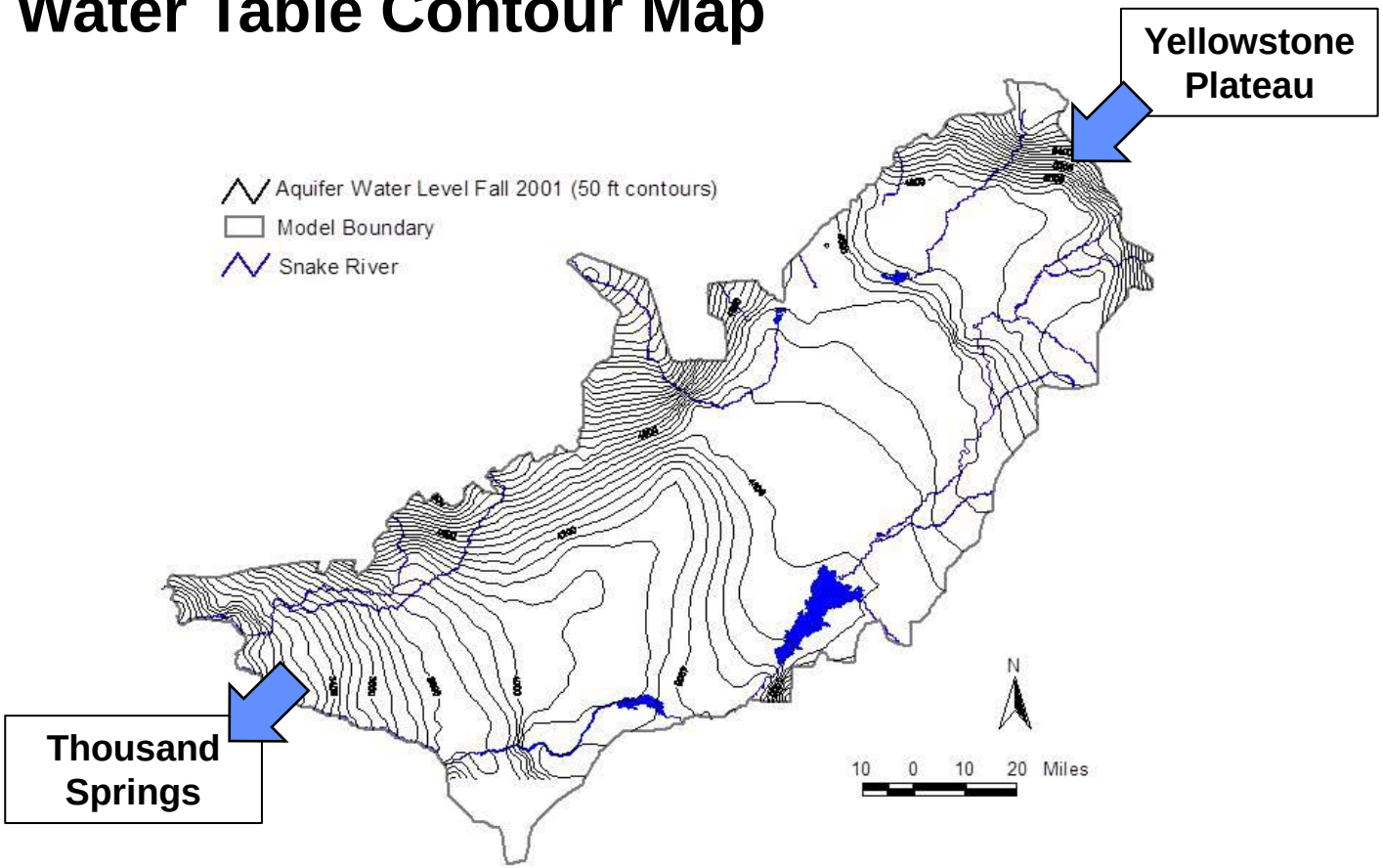
Groundwater Flow Direction under the Eastern Snake River Plain

Water Table Contour Map



Modified from IDWR (2013)

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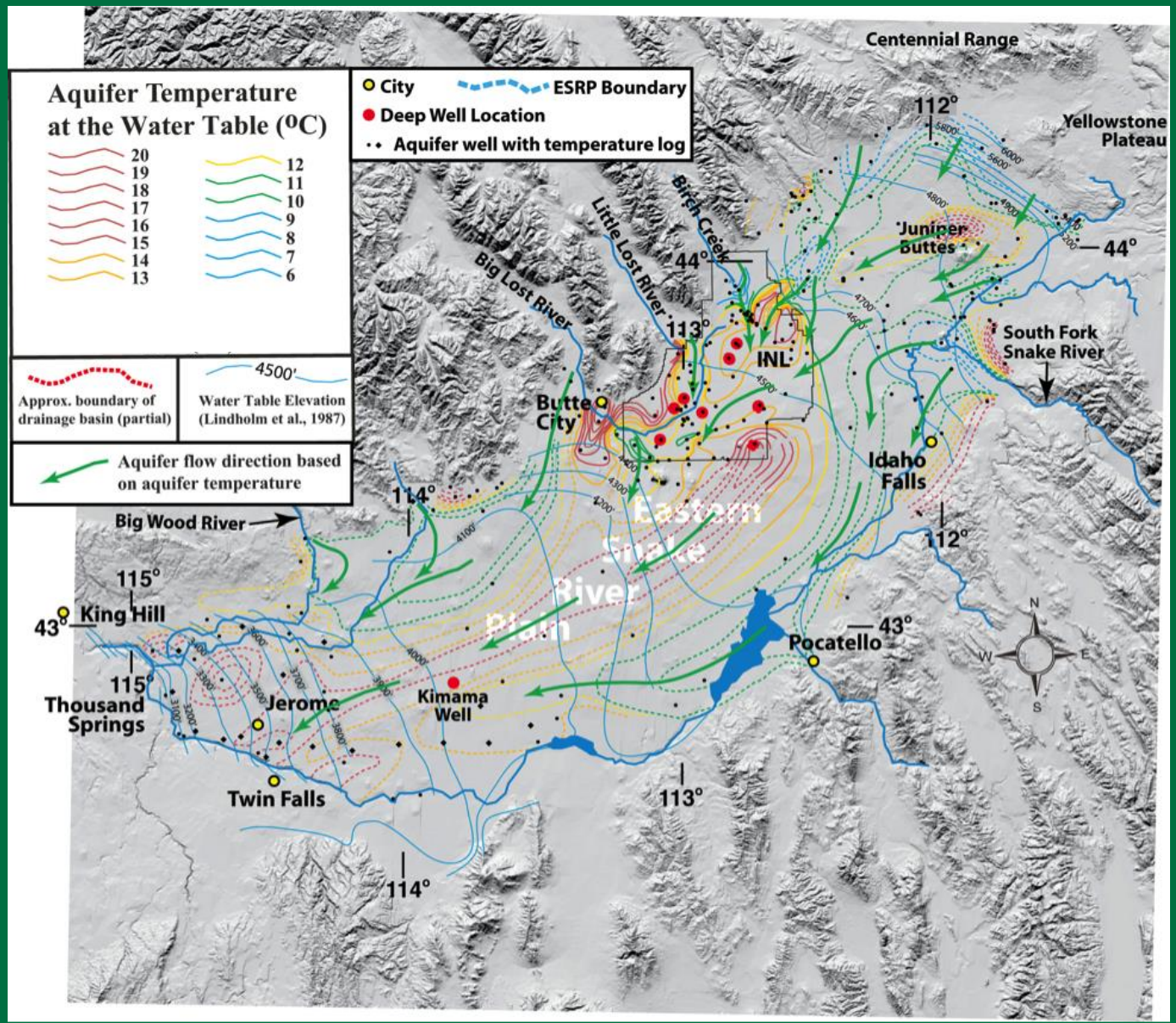
Water Table Temperature



Reproduced with permission:
McLing and others (in press)

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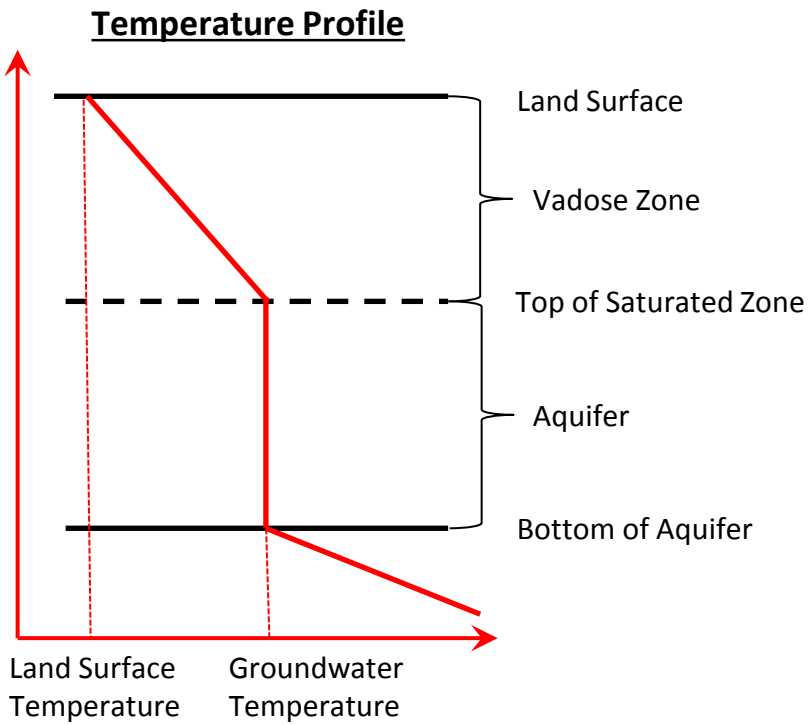
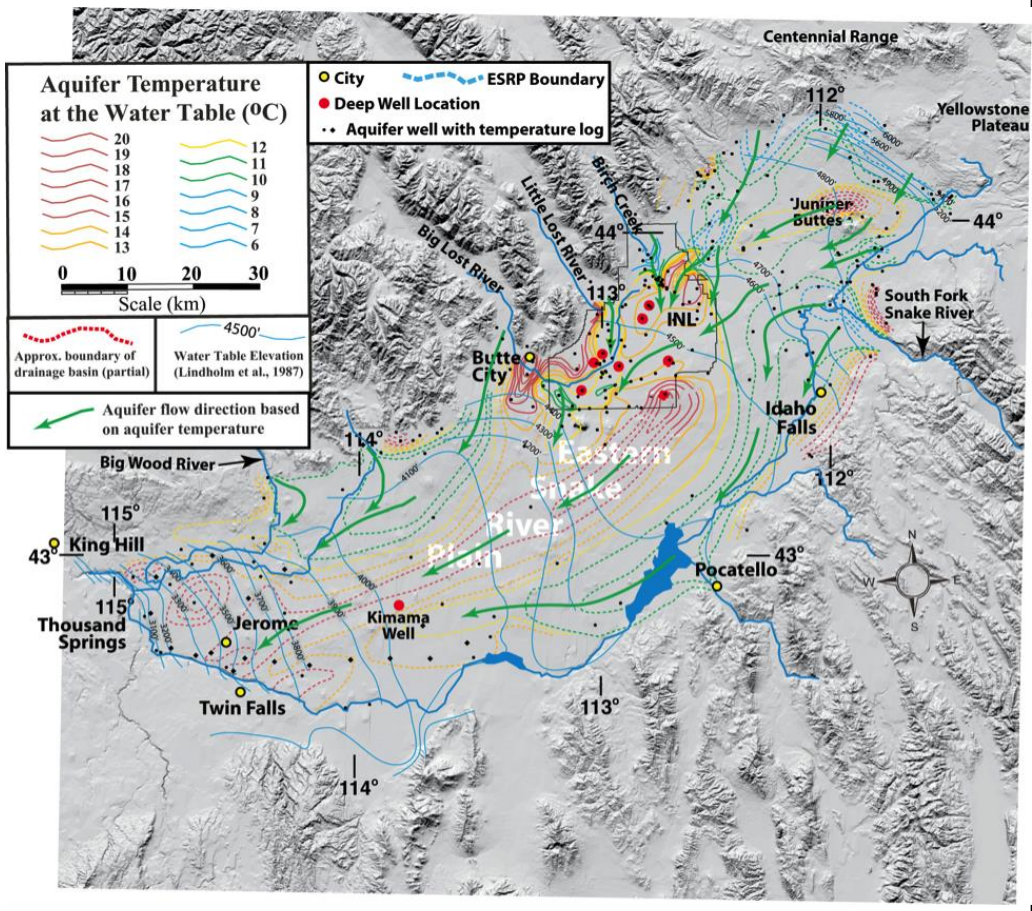
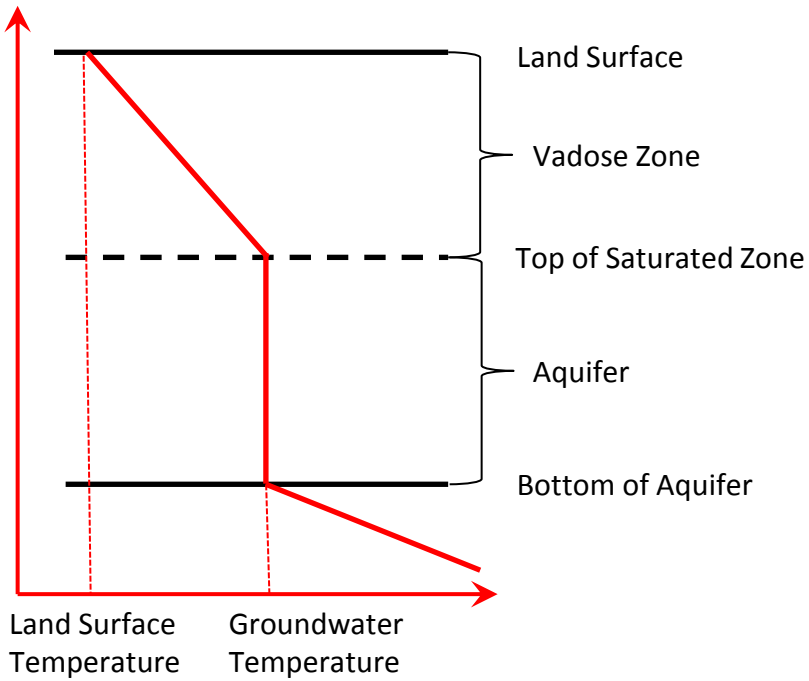
Analytic Solution for Well-Mixed Aquifer



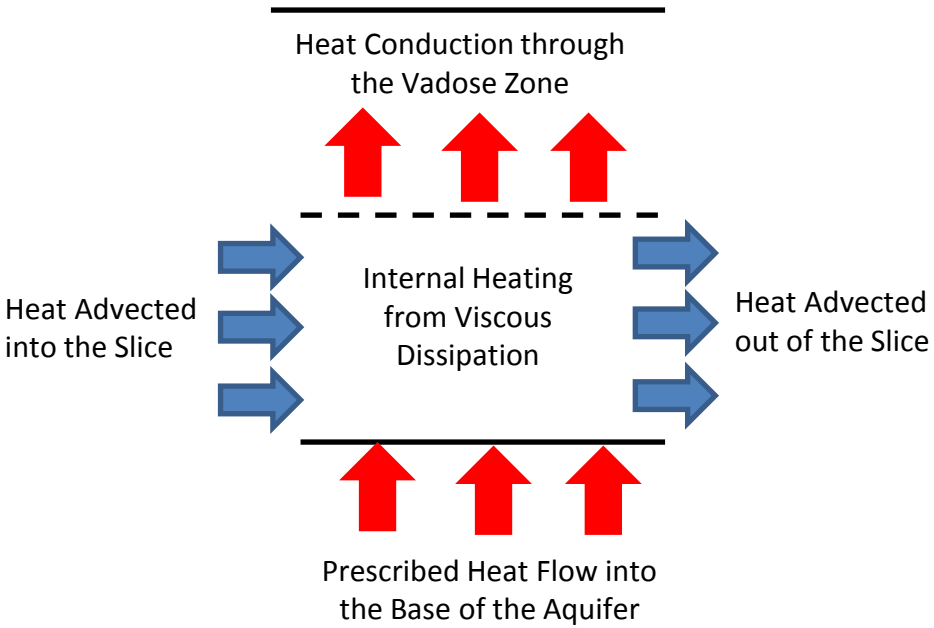


Physics considered

Temperature Profile



Heat Flow Budget for a Slice of Aquifer



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Developed Analytic Solution for…

- Linearly varying:
  - Land surface temperature
  - Hydraulic head
- Constant:
  - Depth to water
  - Vadose zone thermal conductivity
  - Heat flow into the bottom of the aquifer
  - Groundwater flow rate

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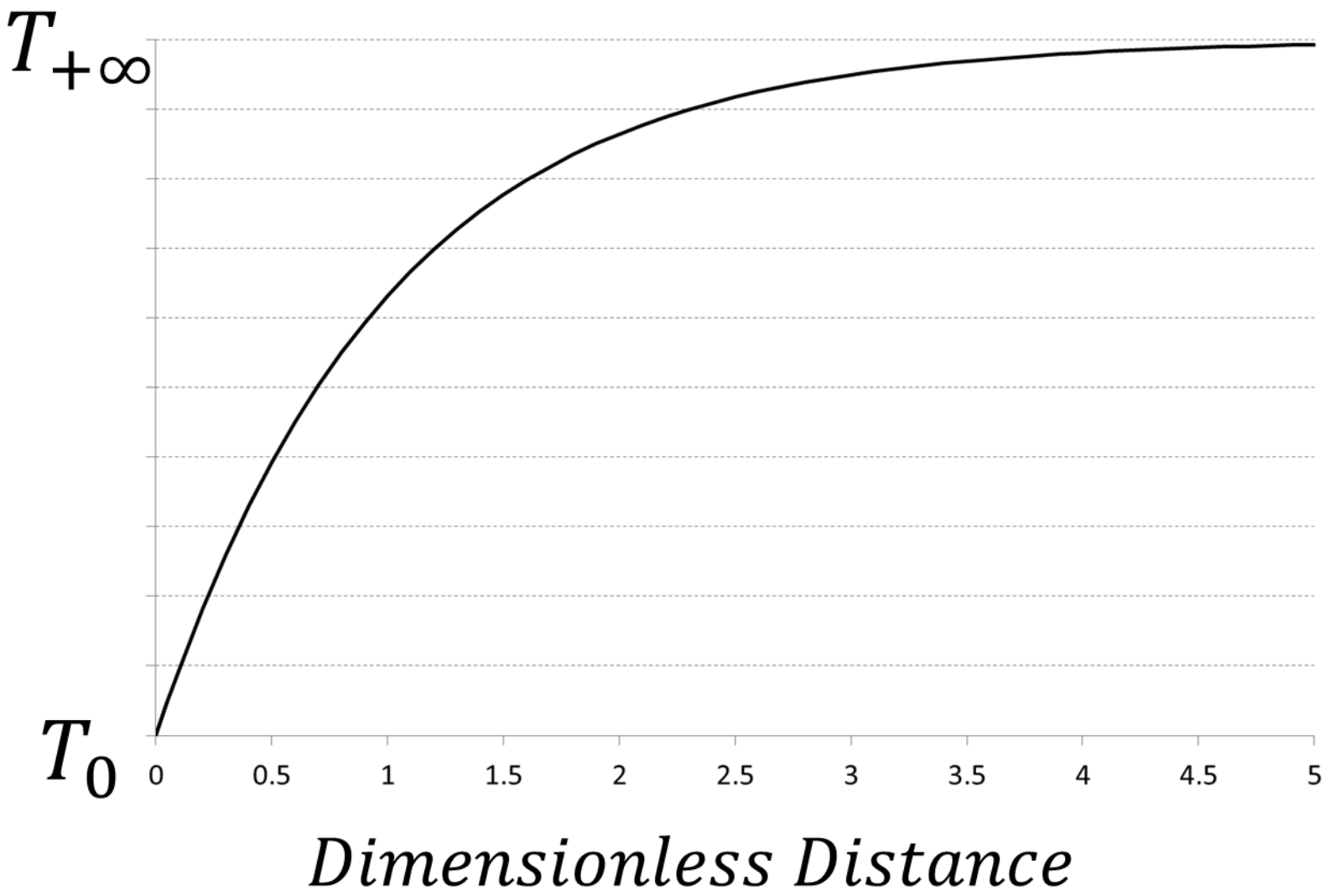
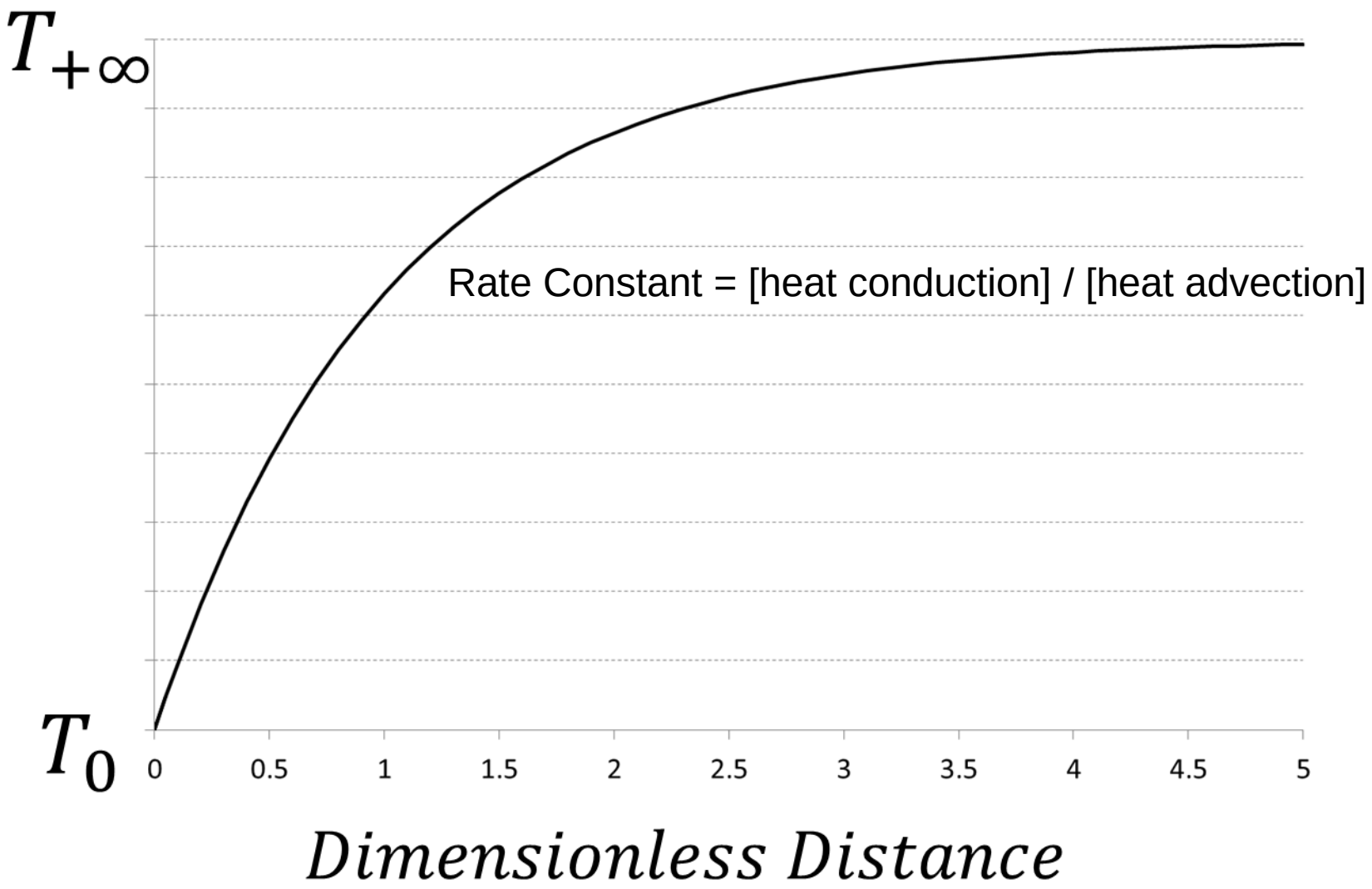
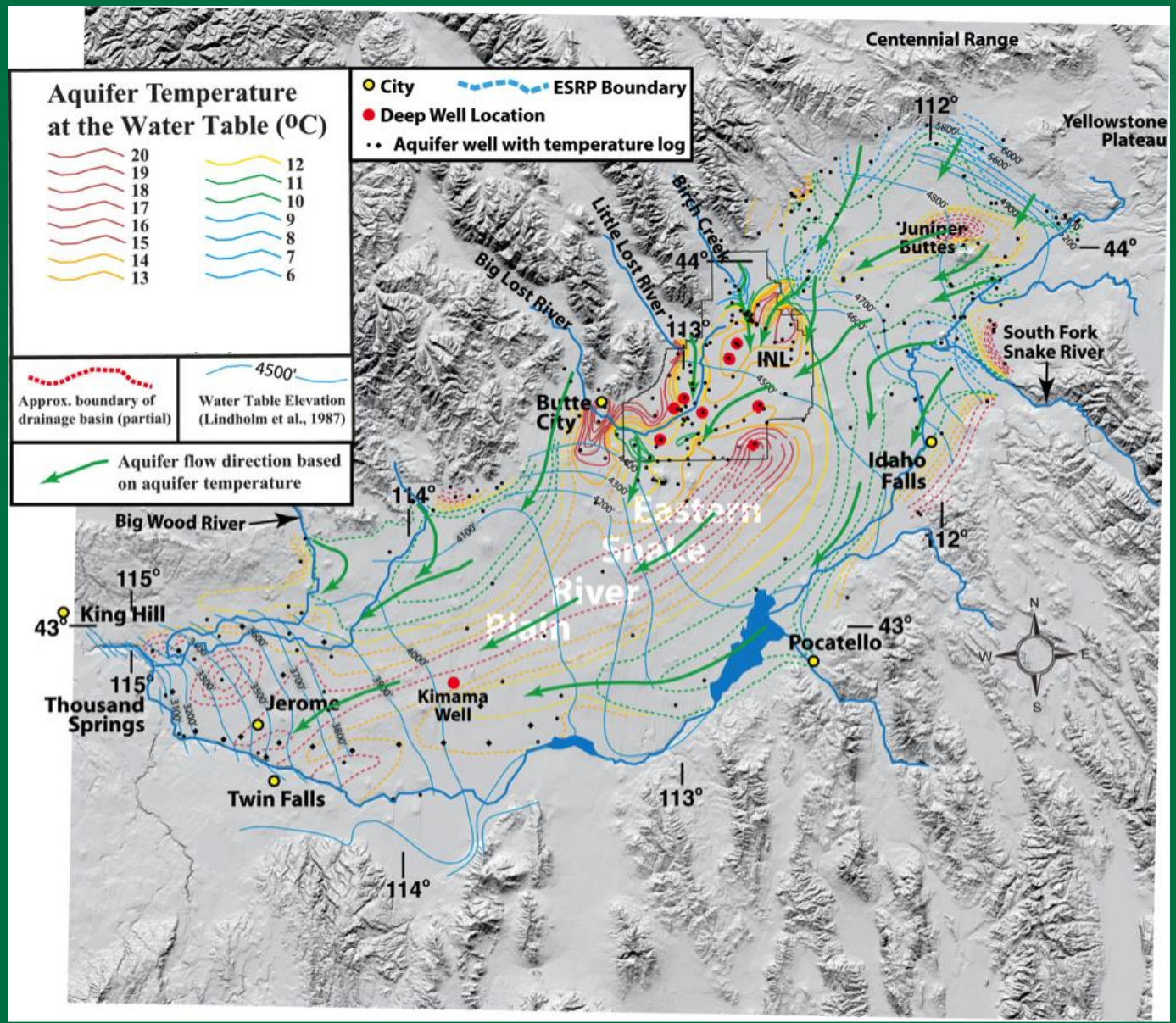
Thermal Perturbations Decay Exponentially



Thermal Perturbations Decay Exponentially



Water Table Temperature



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McLing and others (in press)

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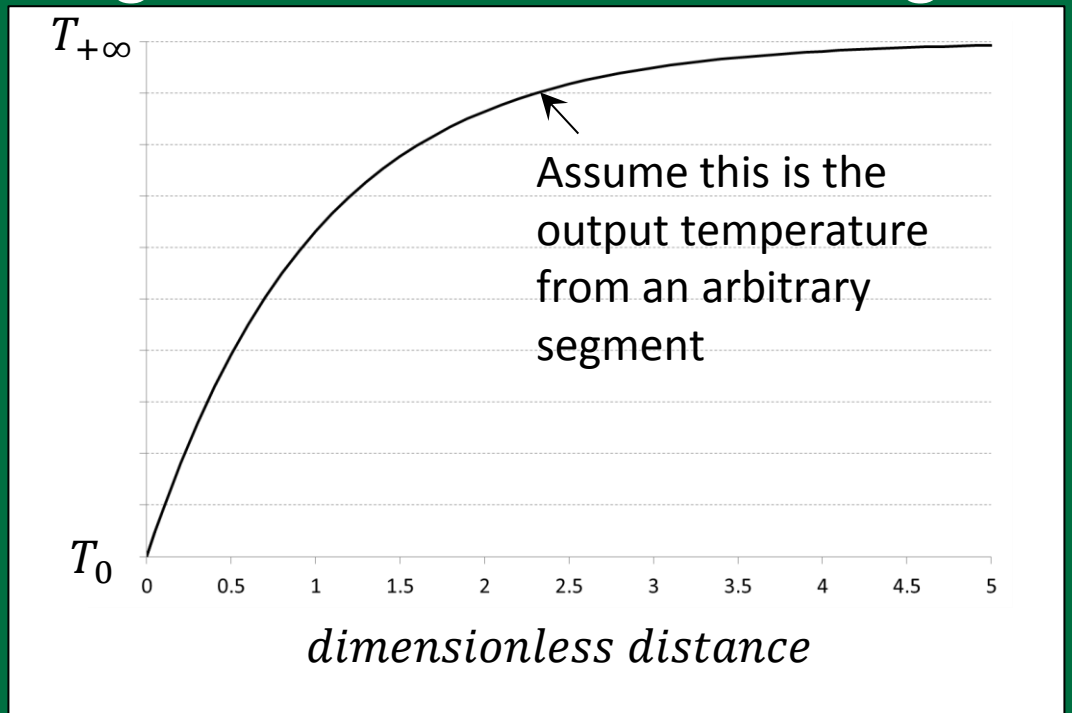
More Complex Problems Solved Piece-wise

- Each variable defined for each segment
  - Flow rate and groundwater temperature leaving once segment is input to the "downstream" segment
- Also, additional recharge and discharge can be simulated assuming instantaneous mixing



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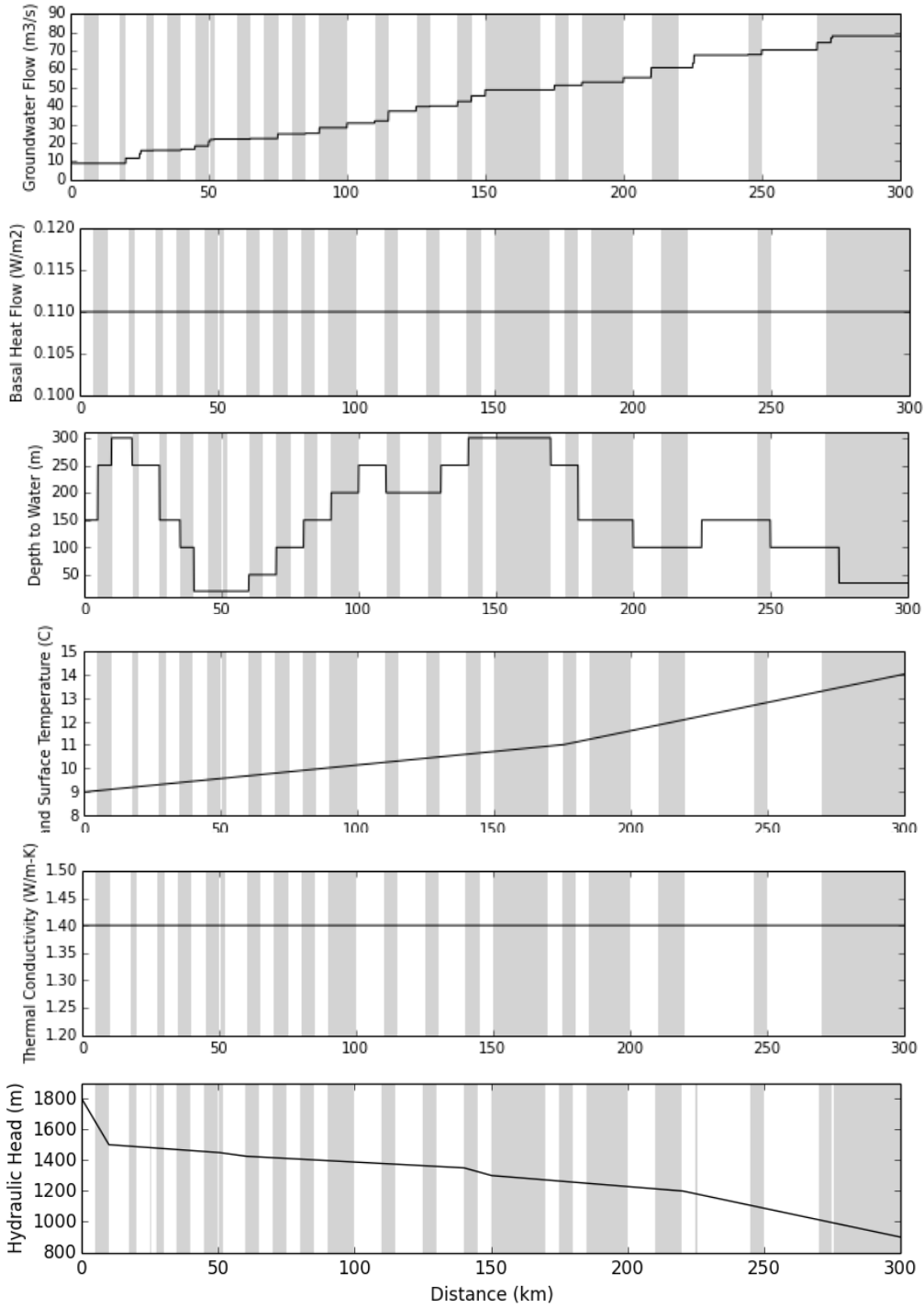
Input for the ESRP Aquifer



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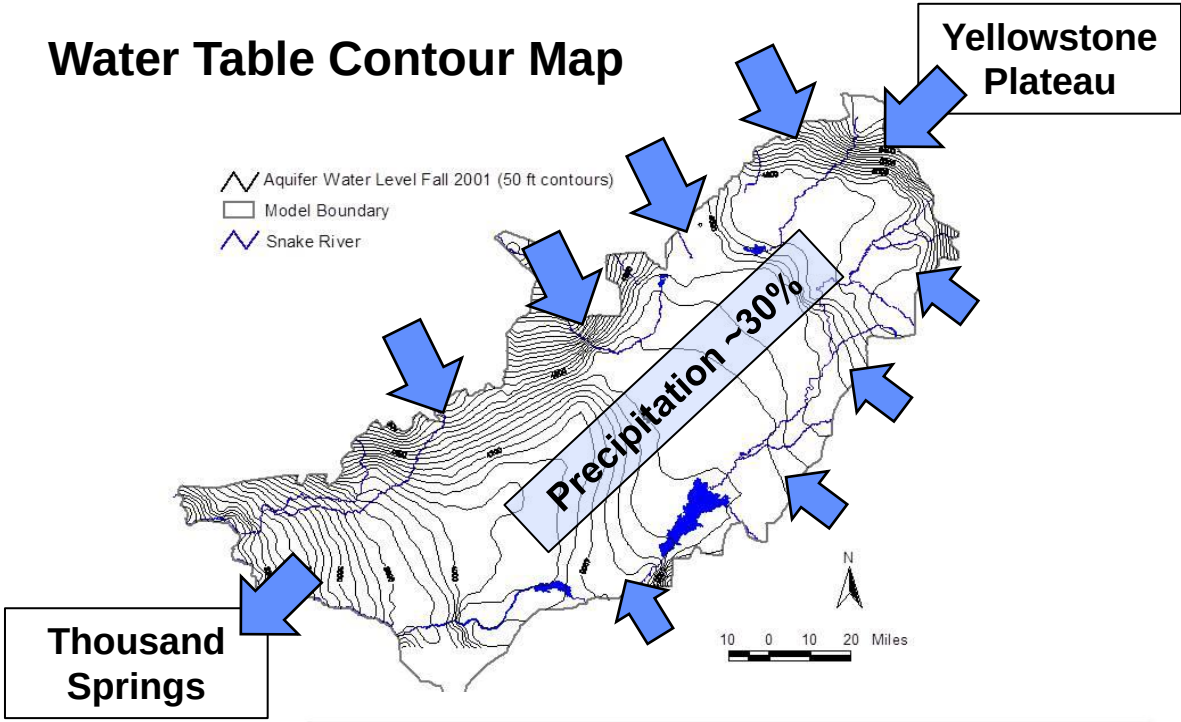
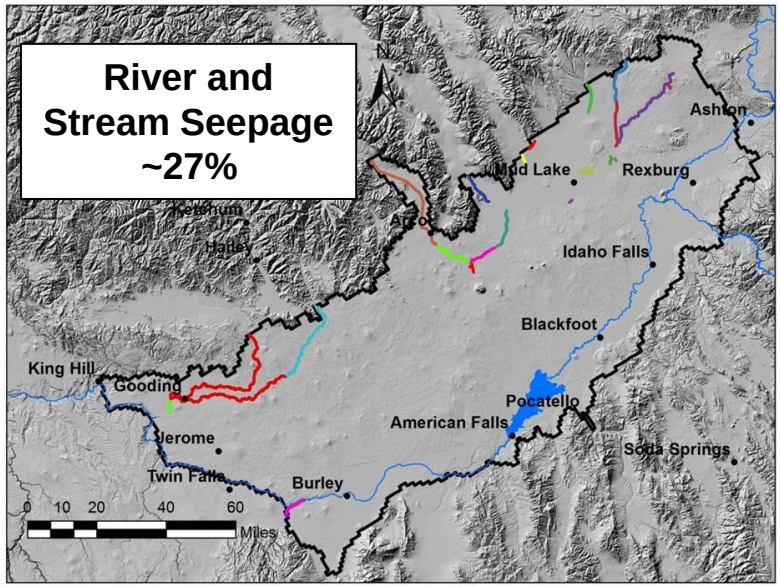
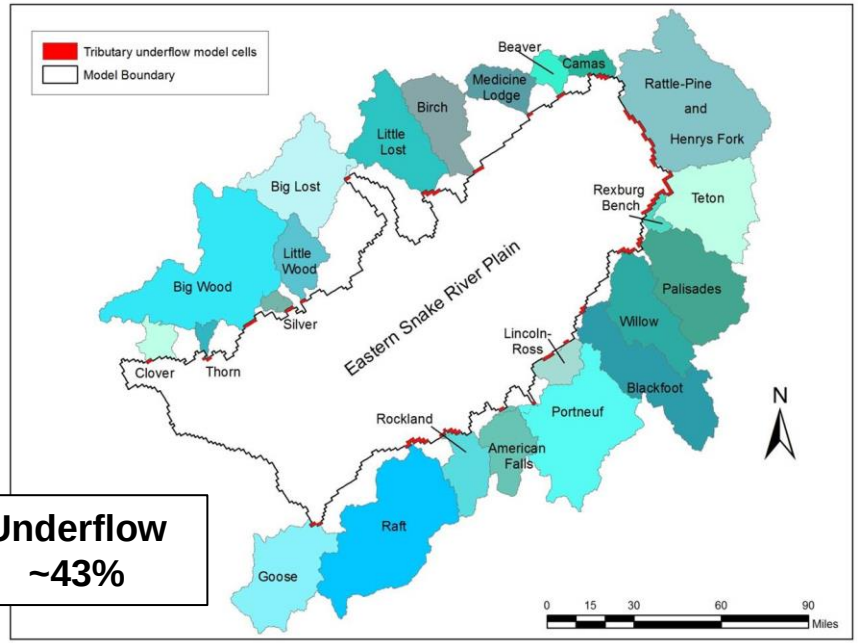
ESRP – Pre-Development Water Budget

Modified from IDWR (2013)

Water Table Contour Map



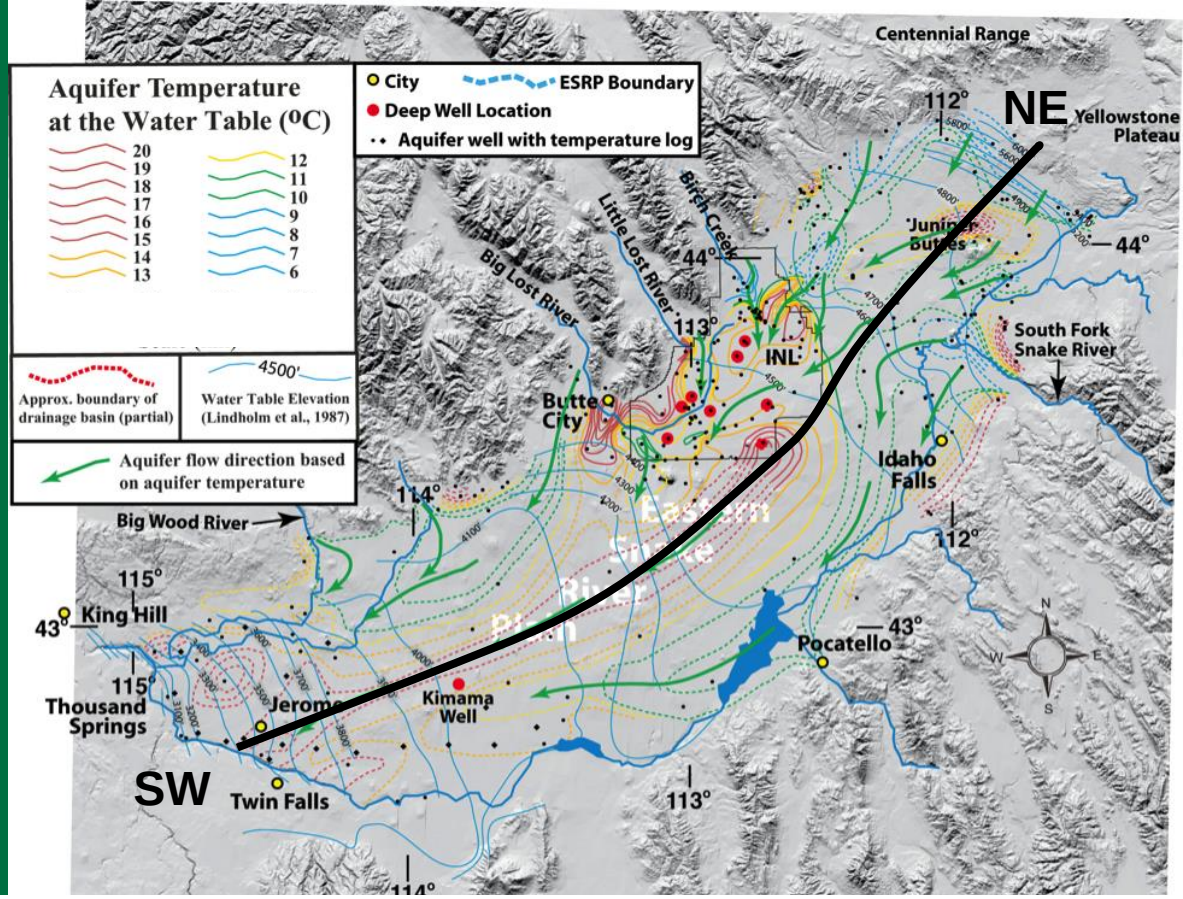




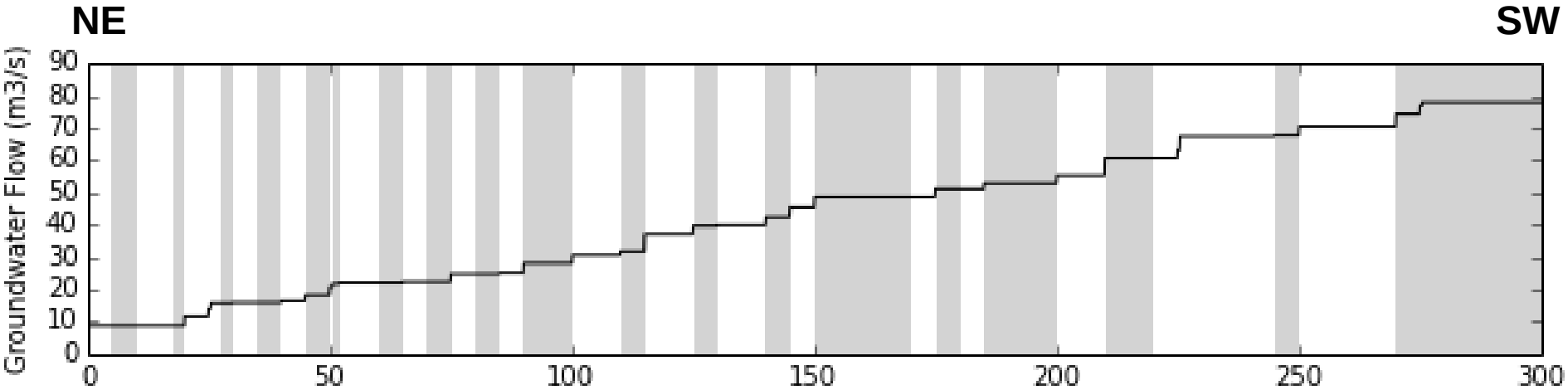
Underflow ~43%

McLing and others (in press)

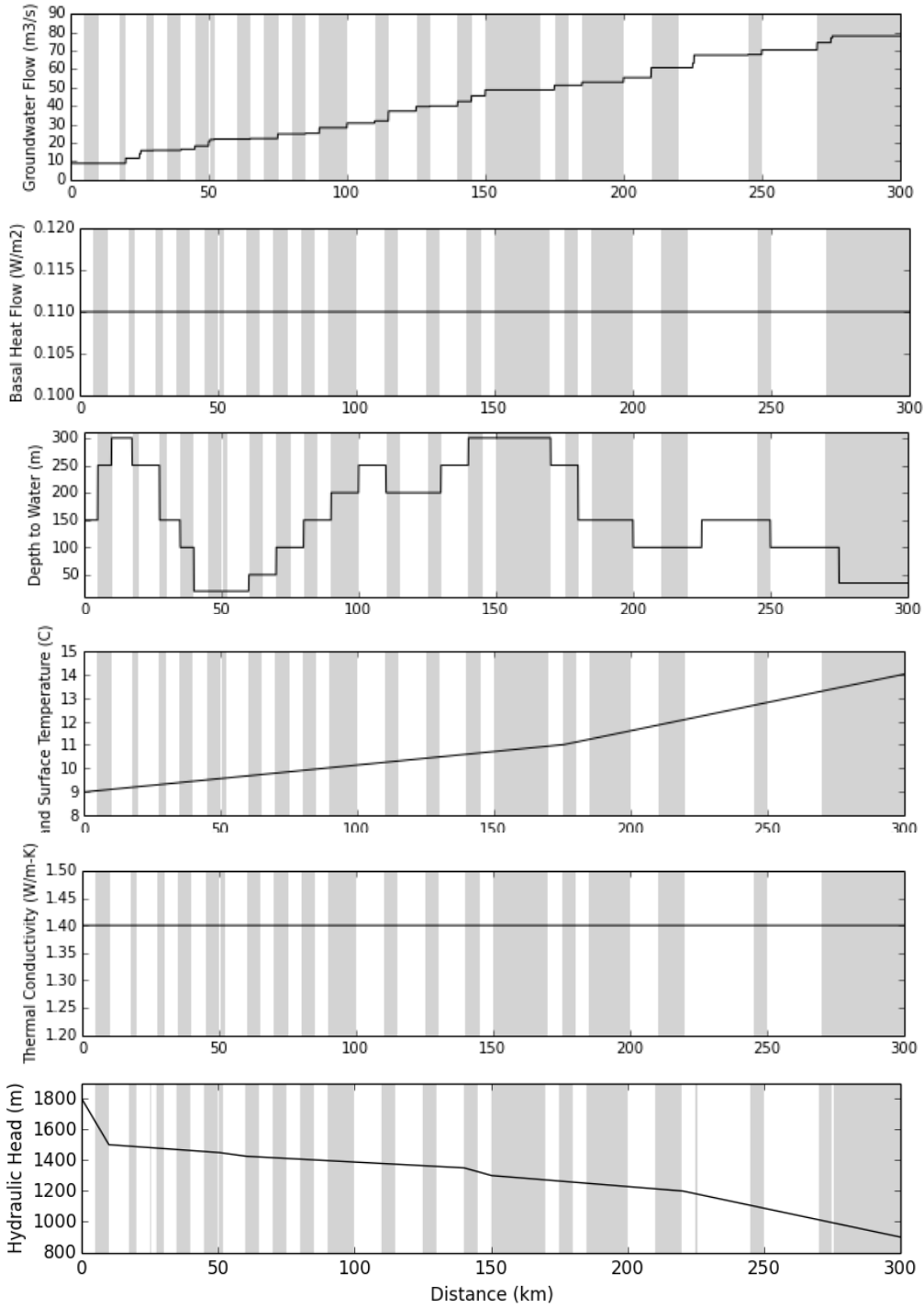
Sum Recharge along Flowpath



Burns and others (in review)



Input for the ESRP Aquifer



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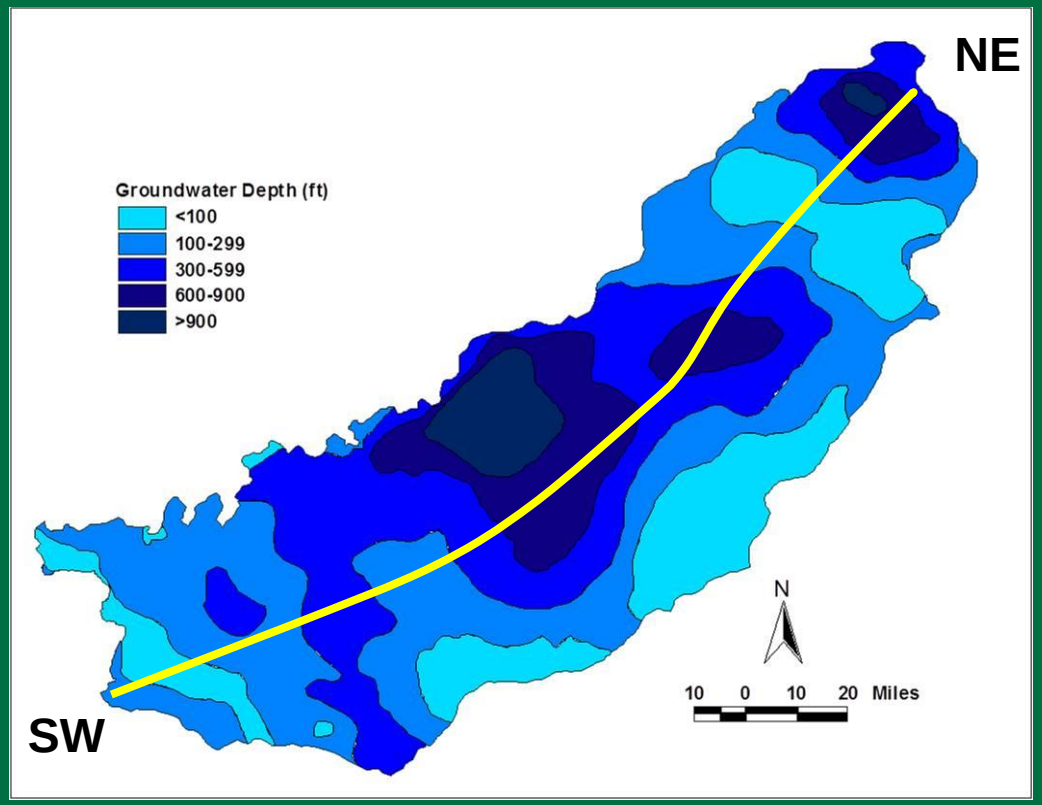
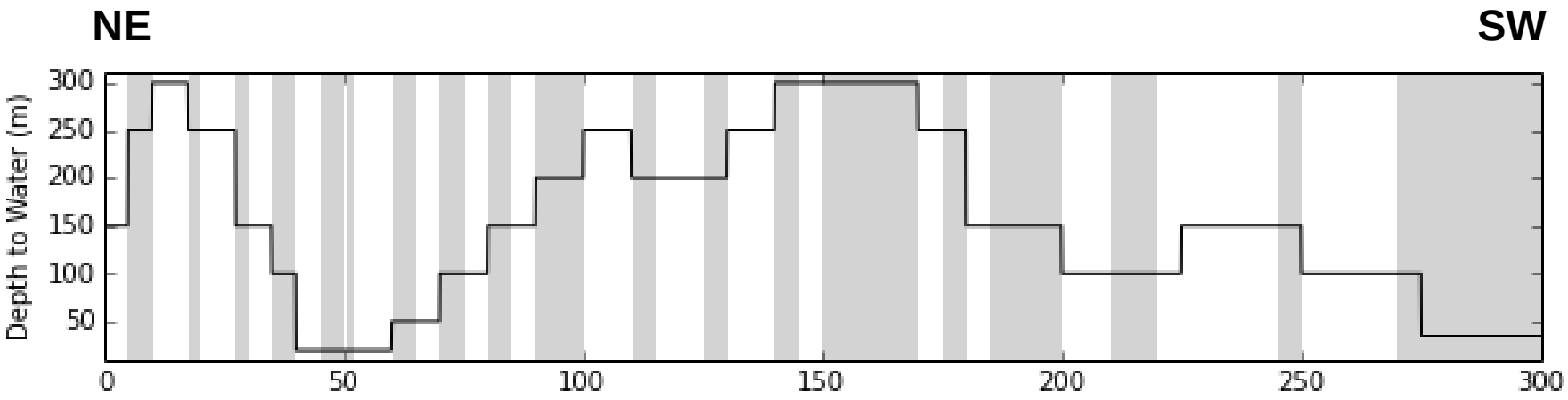
Modified from IDWR (2013)

Depth to Water



Burns and others (in press)



Basal Heat Flow = 110 mW/m^2 (Blackwell and Steele, 1992)

Land Surface Temperature Estimated from the Boundary Condition of Brott and others (1981)

Calibrated and compared to tabulated values of Brott and others (1981)

Head Distribution from Water Table Map (IDWR, 2013)

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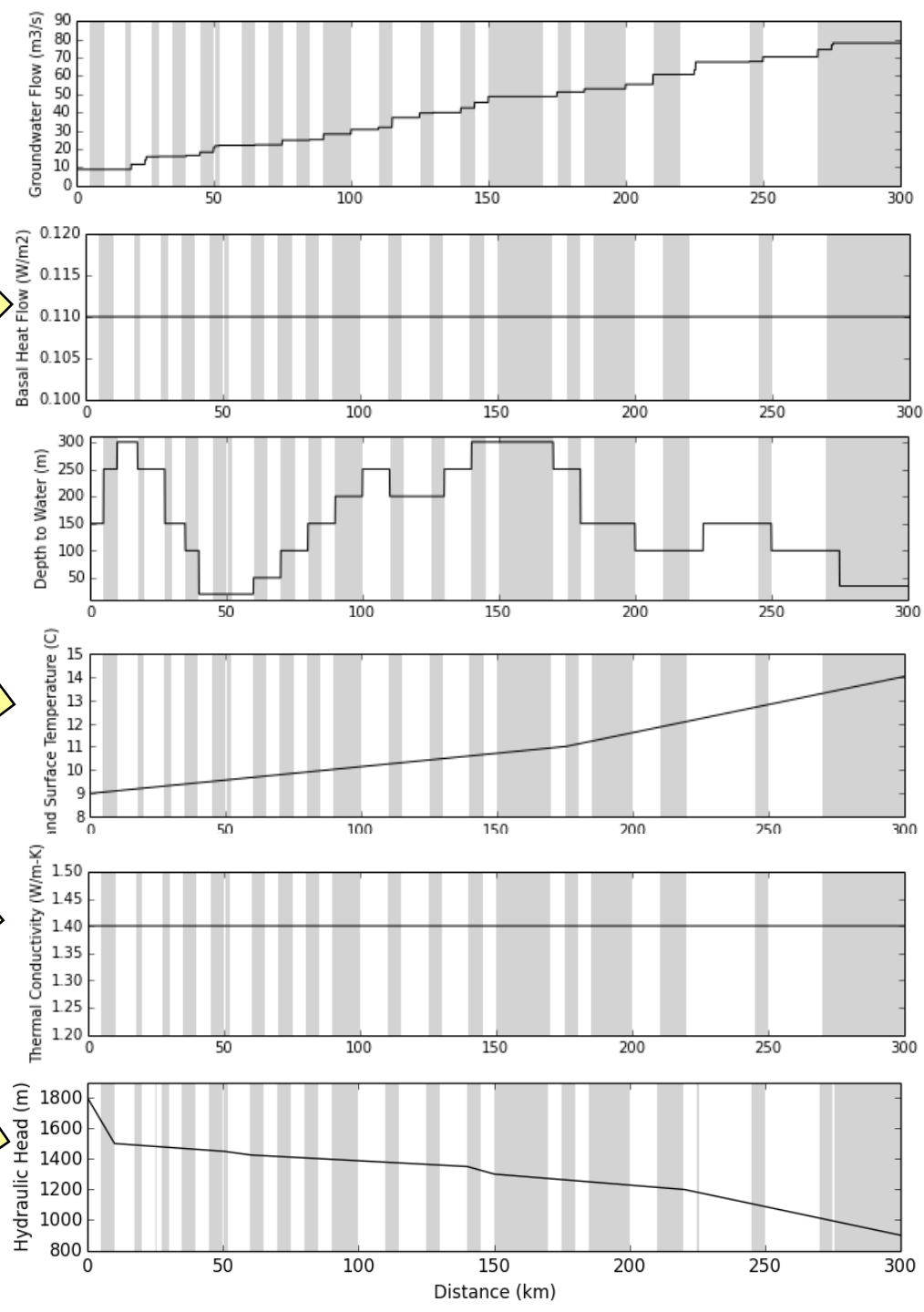
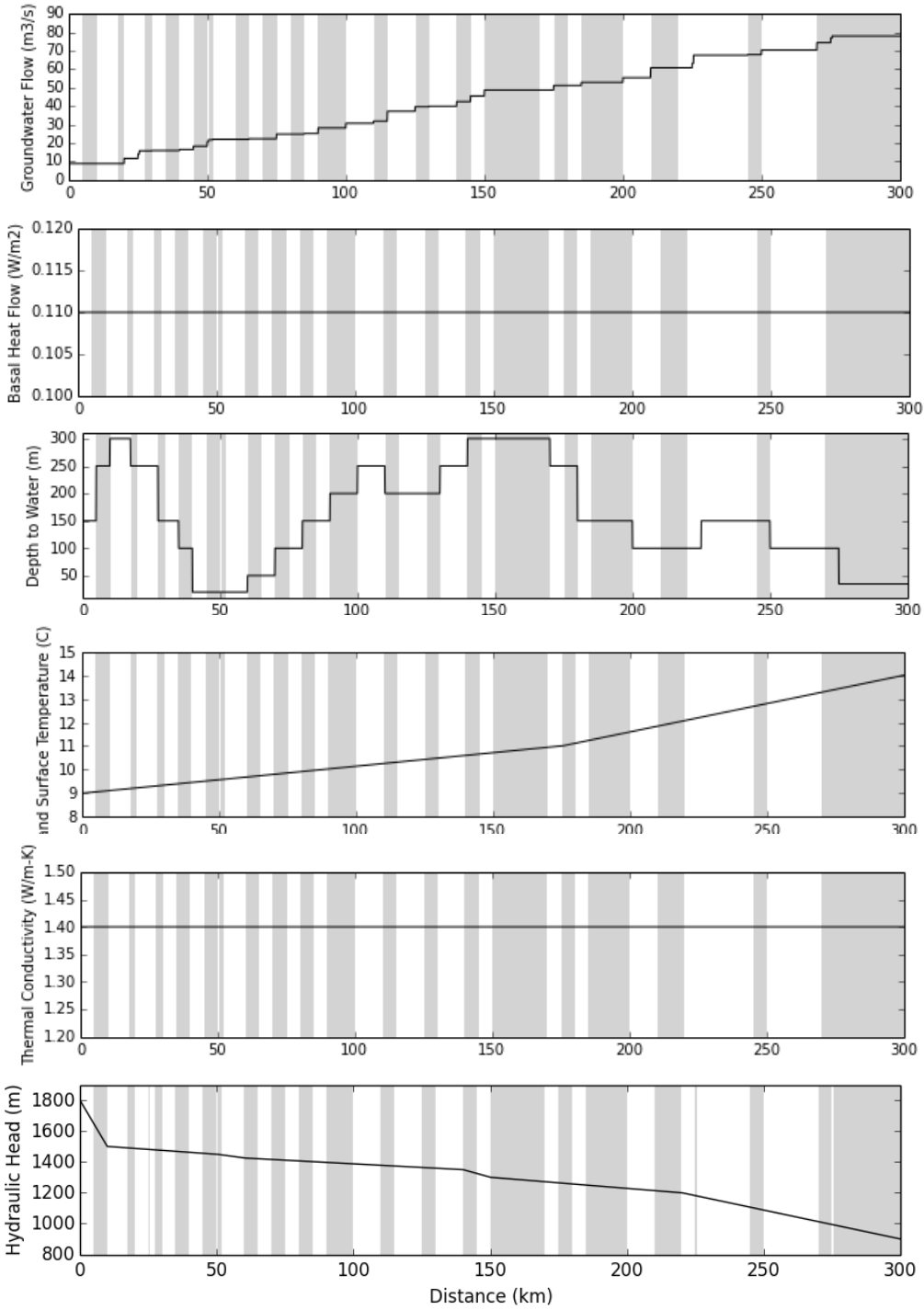


Gray Bands Show Segments



Burns and others (in review)

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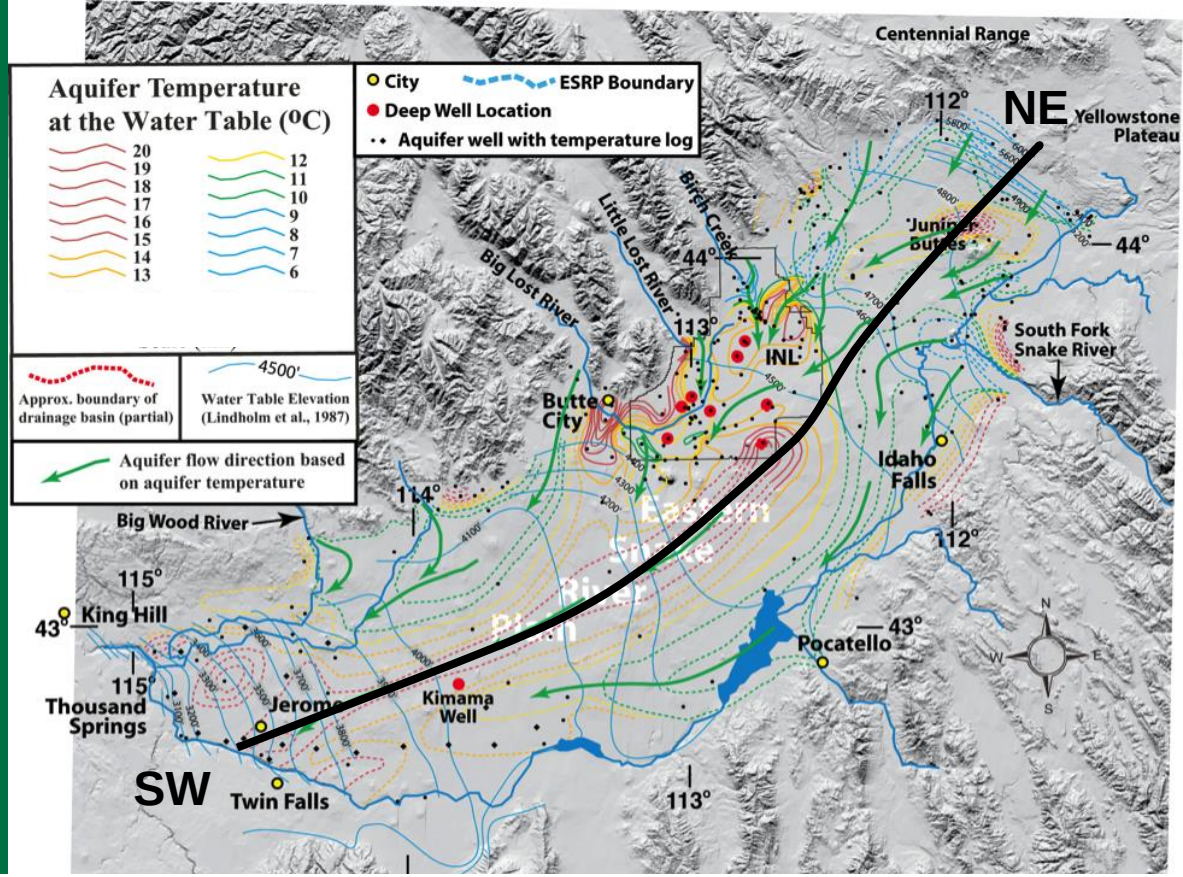
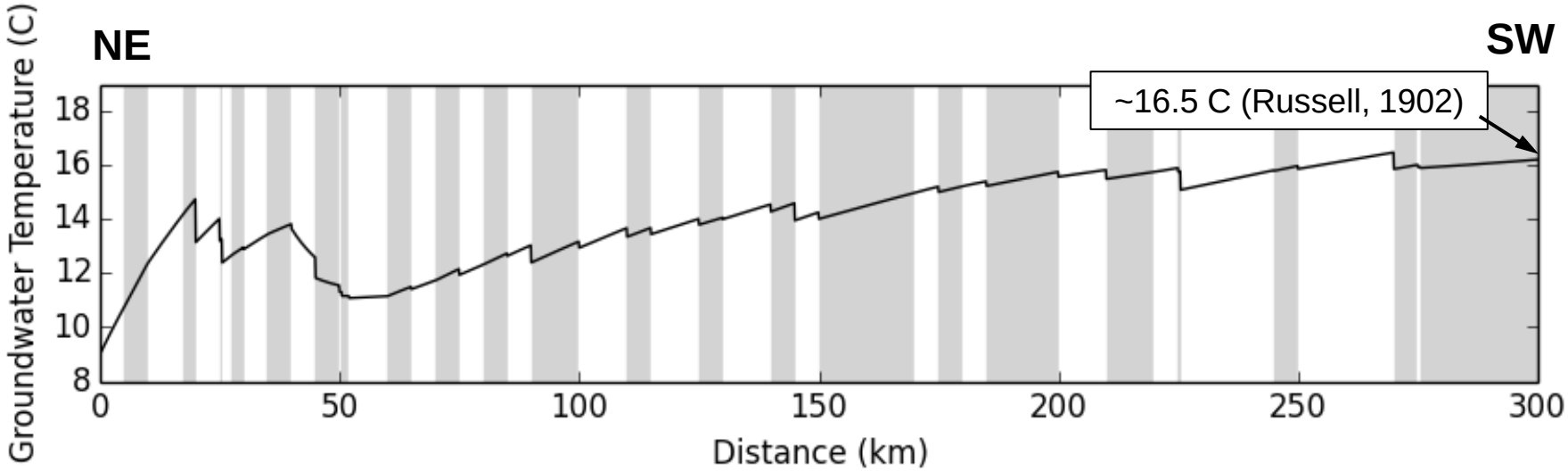
McLing and others (in press)

Results of Simulation

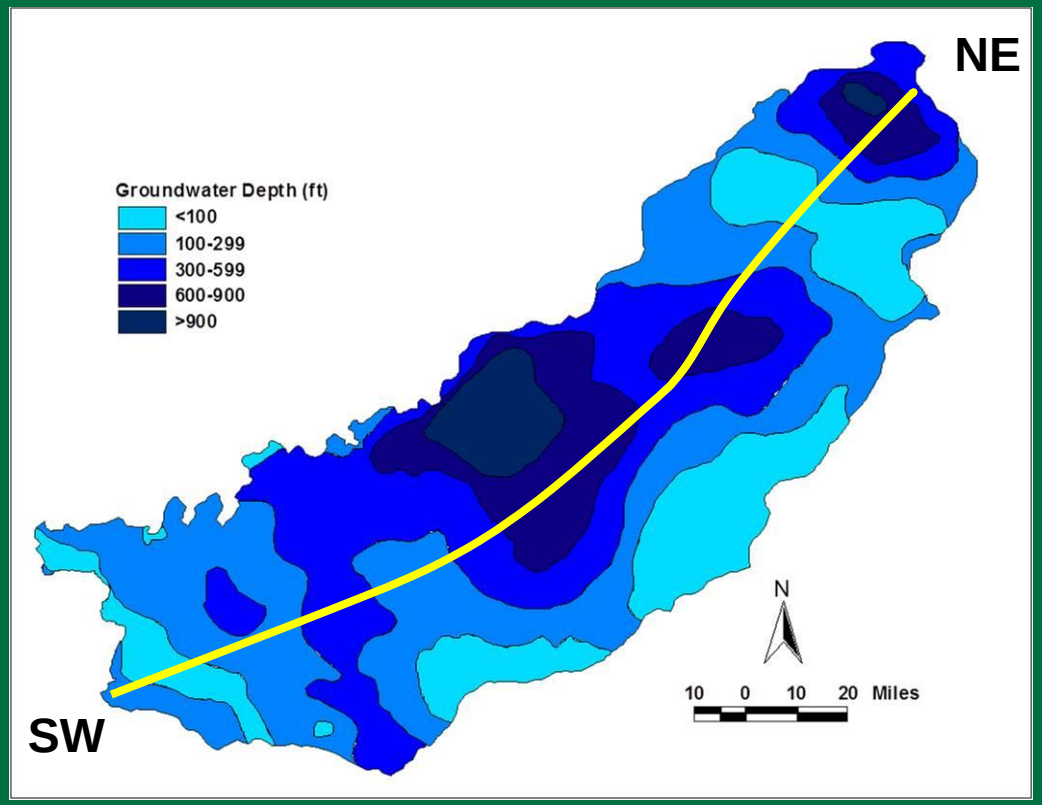


Burns and others (in press)

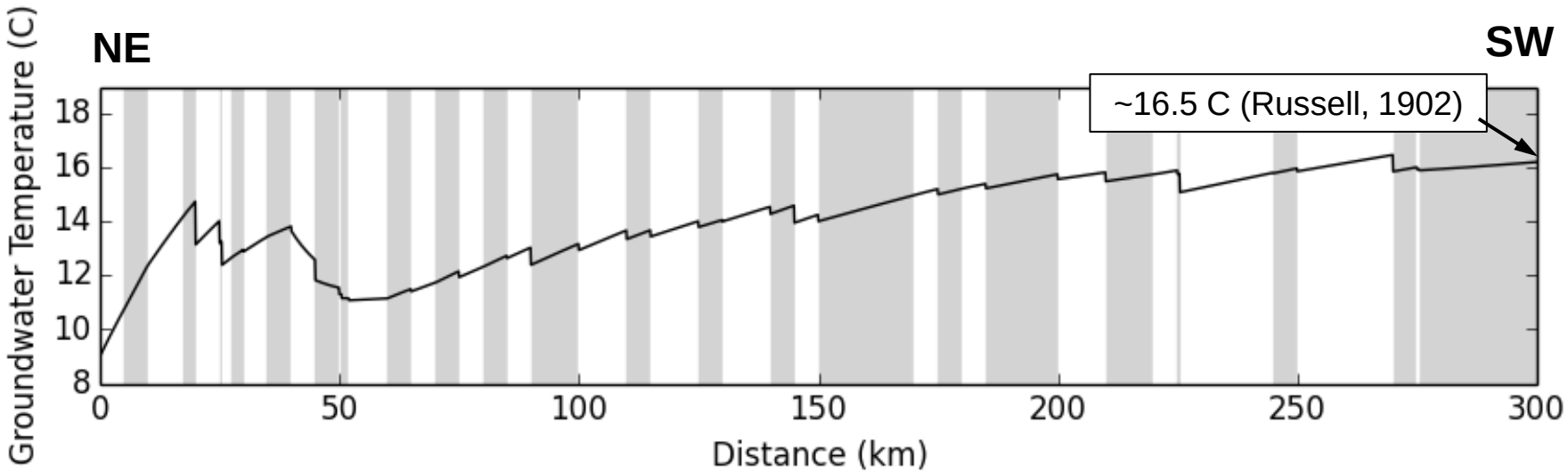


Modified from IDWR (2013)

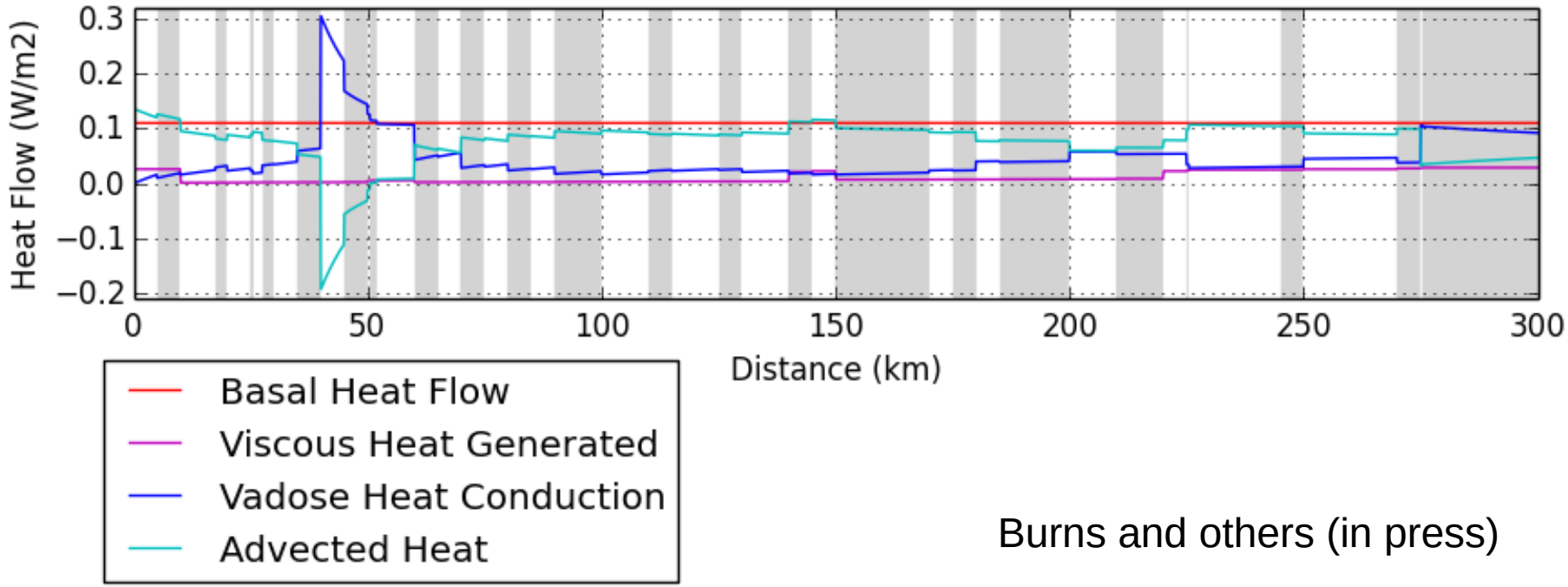
Why the dip?



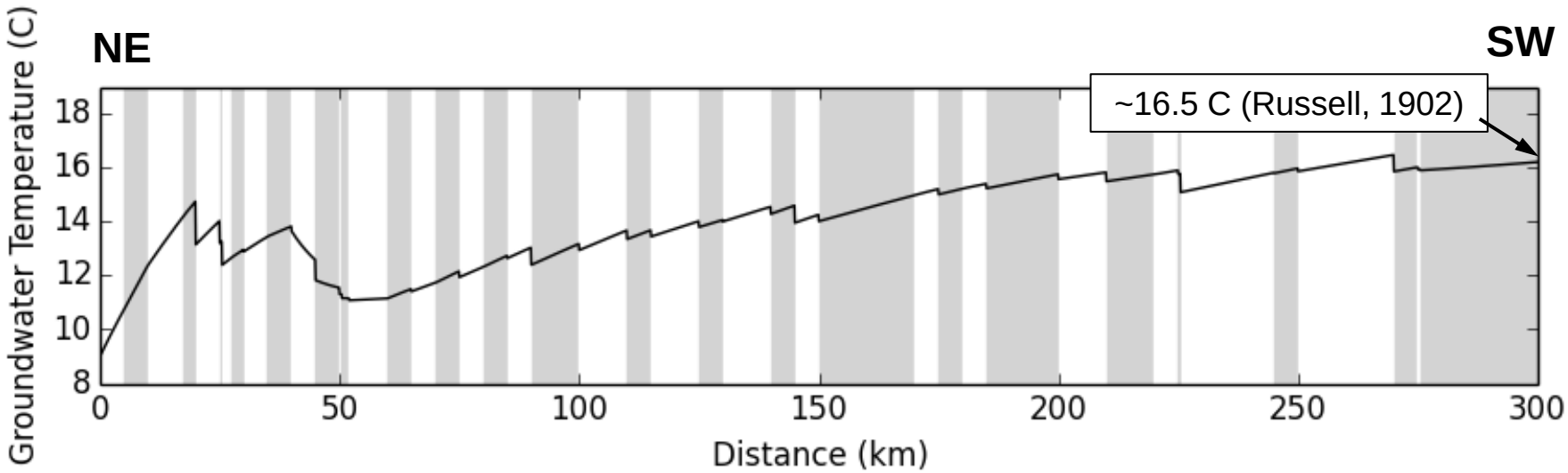
Burns and others (in press)



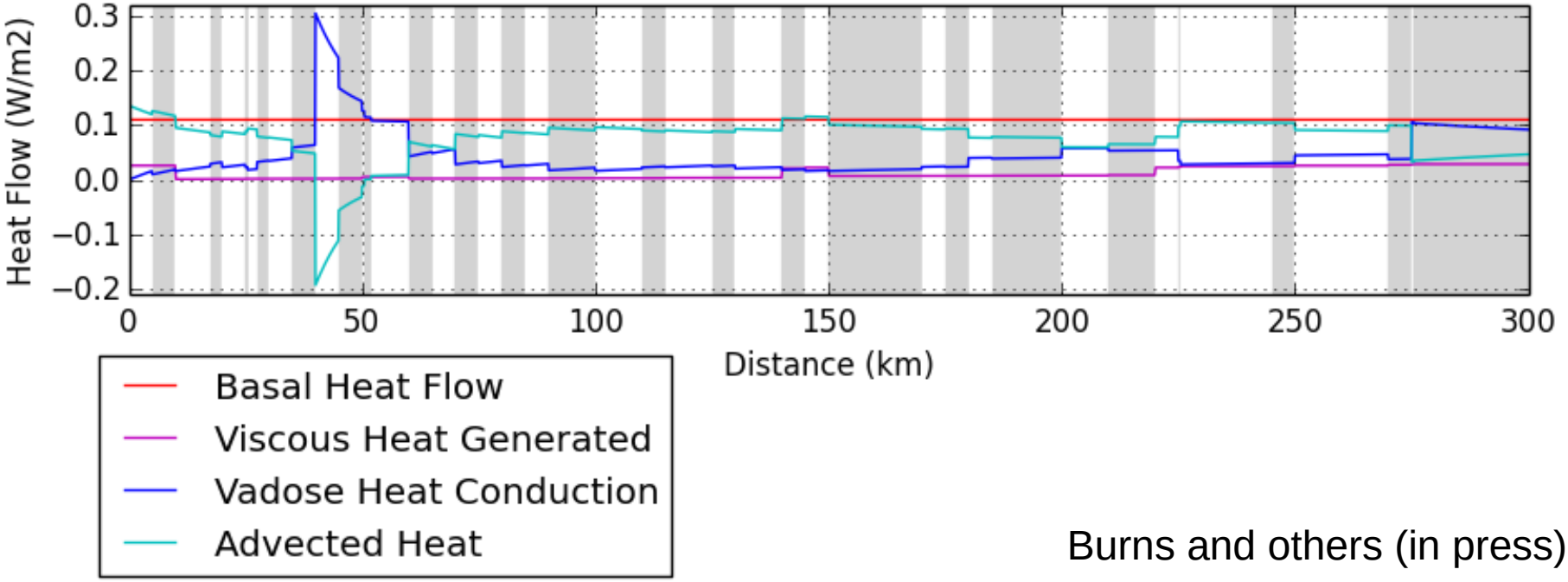
Heat Exits via Thin Vadose Zone



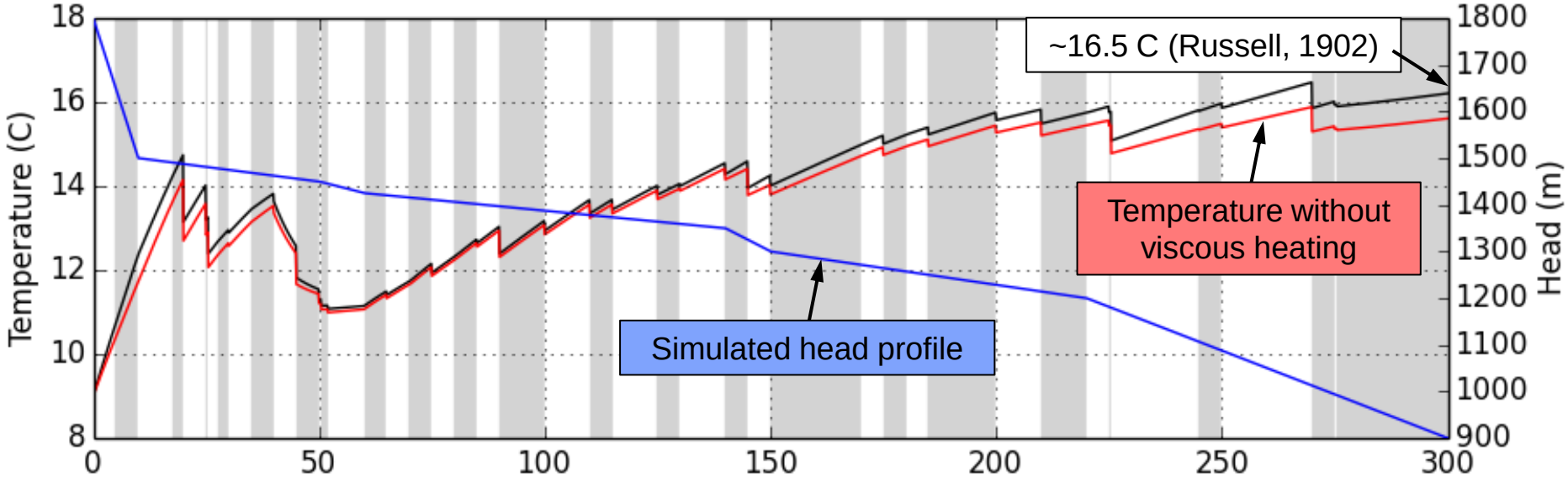
Burns and others (in press)



Viscous Heat Production is Simulated



Burns and others (in press)



Last notes on this tool…

- The Python script will be freely available and is easy to use
  - Input for each parameter is a comma-separated list of values
  - Runs in a few seconds
  - This allows quick evaluation of important physical processes
- The ESRP example shown took about 4 hours to construct by extracting the information from the literature

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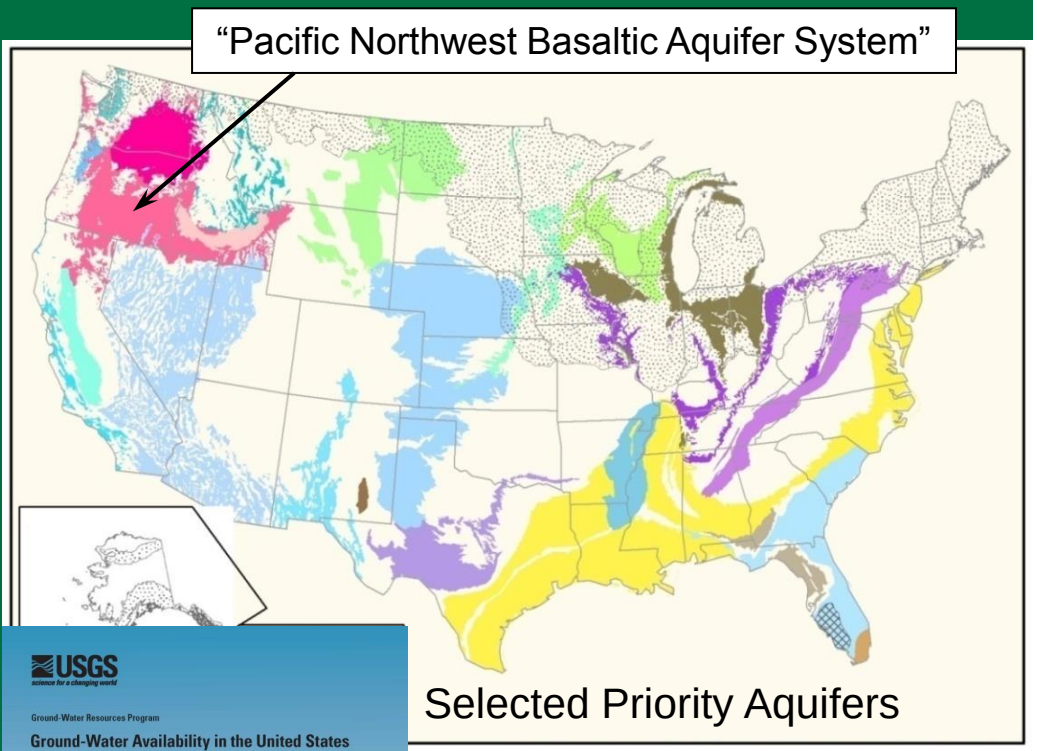
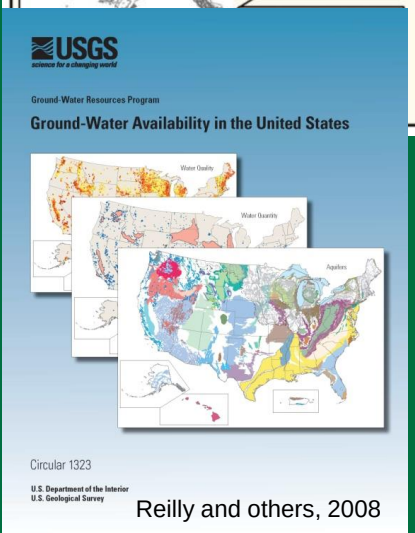
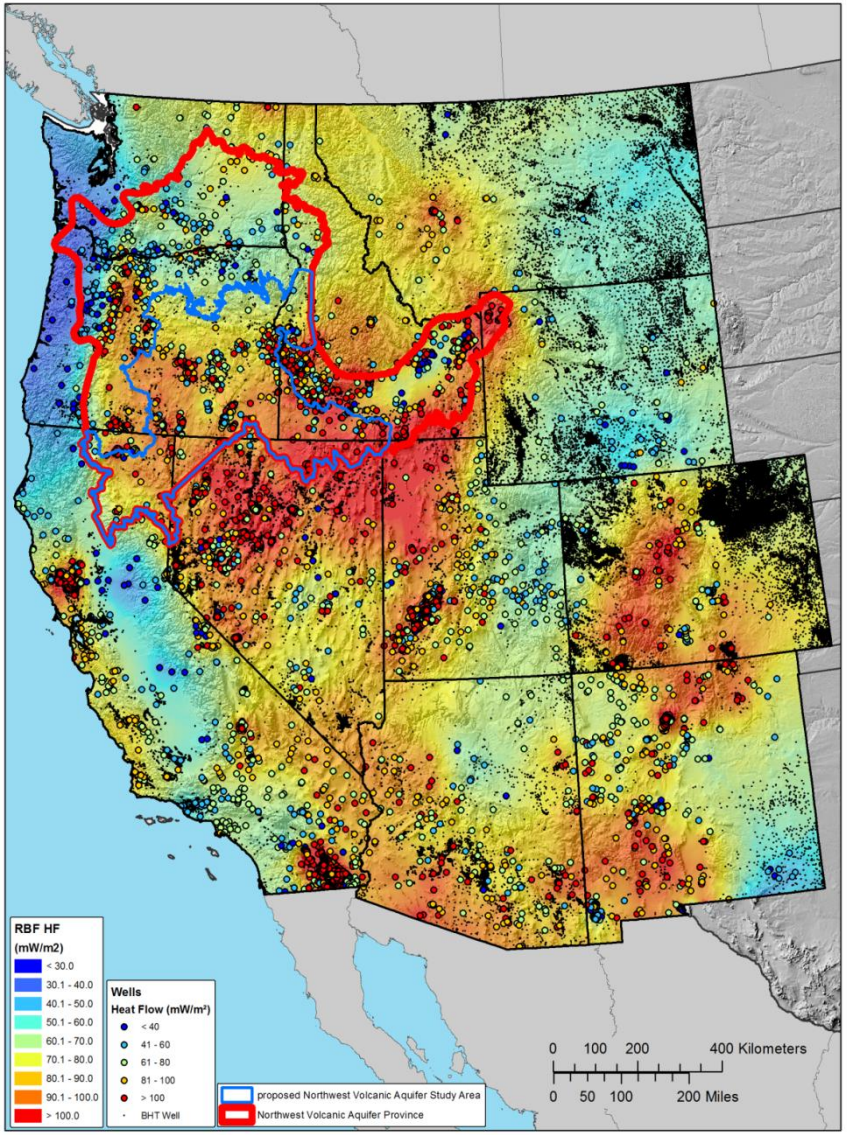
New Northwest Volcanic Aquifer Study Area (NVASA)

Approach with Intent: Joint Geothermal-Groundwater Study

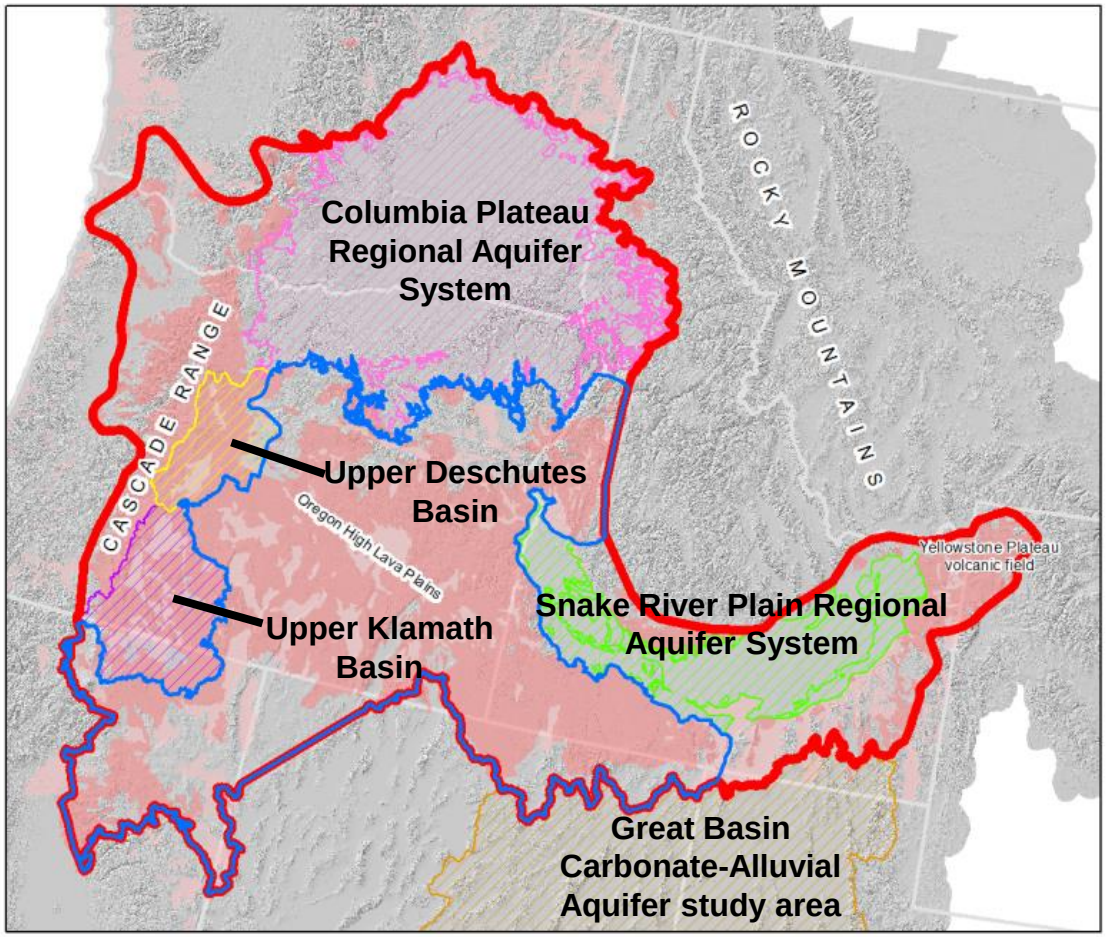




Reilly and others, 2008



Removing Previous Major Groundwater Flow Simulation Studies within the NVAP yields the NVASA



Legend

- proposed Northwest Volcanic Aquifer Study Area
- Northwest Volcanic Aquifer Province
- Great Basin Carbonate-Alluvial Aquifer study area (Heilweil and Brooks, 2011)
- Upper Deschutes Basin (Gannett and Lite, 2004)
- Upper Klamath Basin (Gannett and others, 2012)
- Columbia Plateau Regional Aquifer System (Kahle and others, 2011)
- Snake River Plain Regional Aquifer System (Lindholm, 1986)
- Pacific Northwest basaltic-rock aquifers (Reilly and others, 2008)
- Pacific Northwest basin-fill aquifers (Reilly and others, 2008)

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Play-Fairway Studies also Surround the NVASA

- Hope to gain insight into heat flow in the NVASA from proximal studies

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(Initial) Major Components of the Study

- Construct a geologic framework that is appropriate for use as the foundation for both a hydrogeologic framework and a geothermal resource framework
- Estimate distributed groundwater recharge
  - Available resources
- Construct hydrogeologic framework
  - Distribution of hydrologic properties
  - Conceptual models of groundwater flow in different subareas
  - Etc.

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(Initial) Major Components of the Study

- Construct geothermal framework
  - Distribution of thermal properties
  - Account for groundwater influence
  - Conceptual models of heat flow in different subareas
  - Etc.
- Create a geothermal database for the study
- Synthesize all of the above to create improved geothermal resource maps
  - Identify subareas for future play-fairway analyses?

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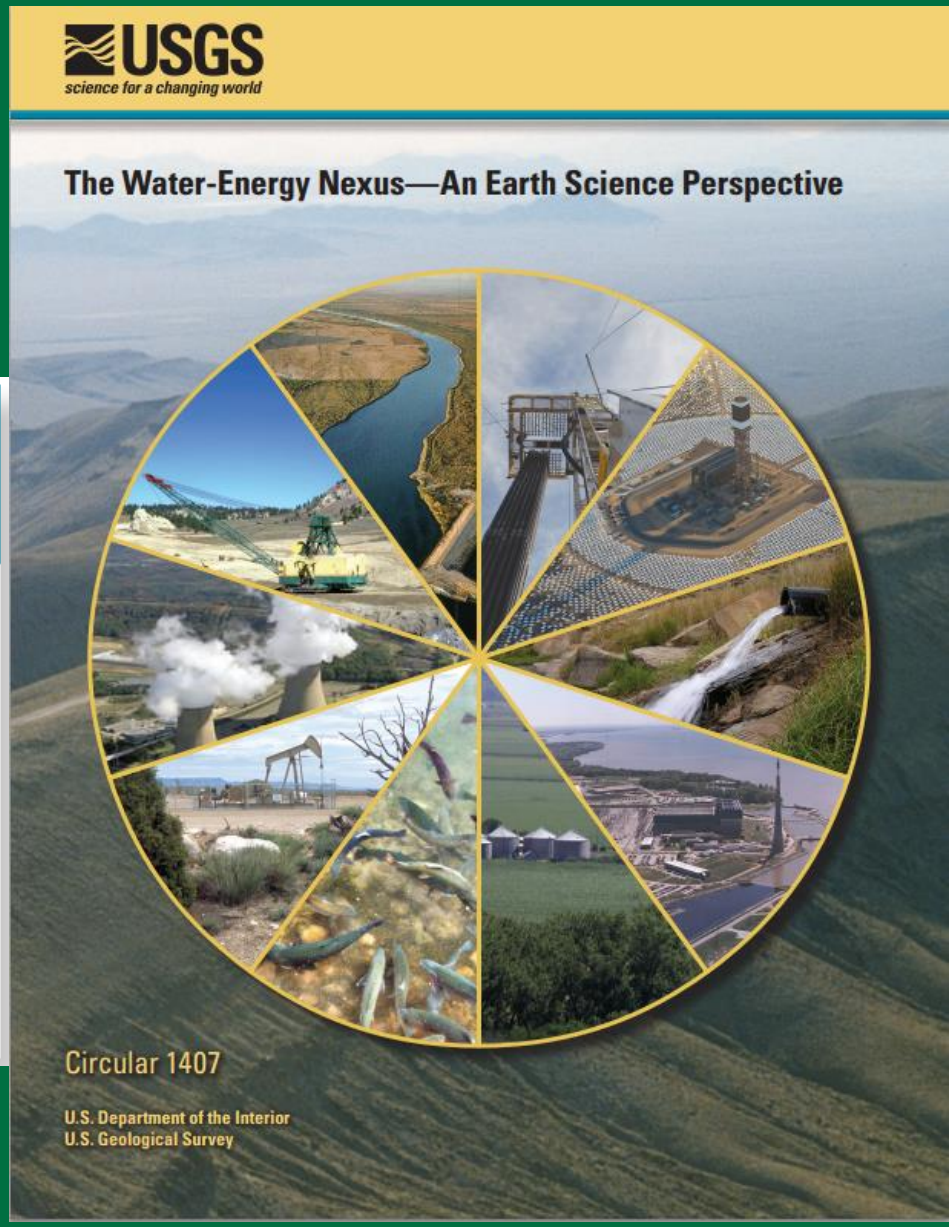
In closing… a recent publication…

Priorities for Assessing Geothermal Resources

- Identify untapped traditional hydrothermal fields.
- Develop a fundamental understanding of the way in which geothermal systems function, including water and energy balances and their relation to seismic activity.
- Identify favorable sites for enhanced geothermal system power plants and determine the water requirements and potential seismic hazards.



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Healy and other (2015)