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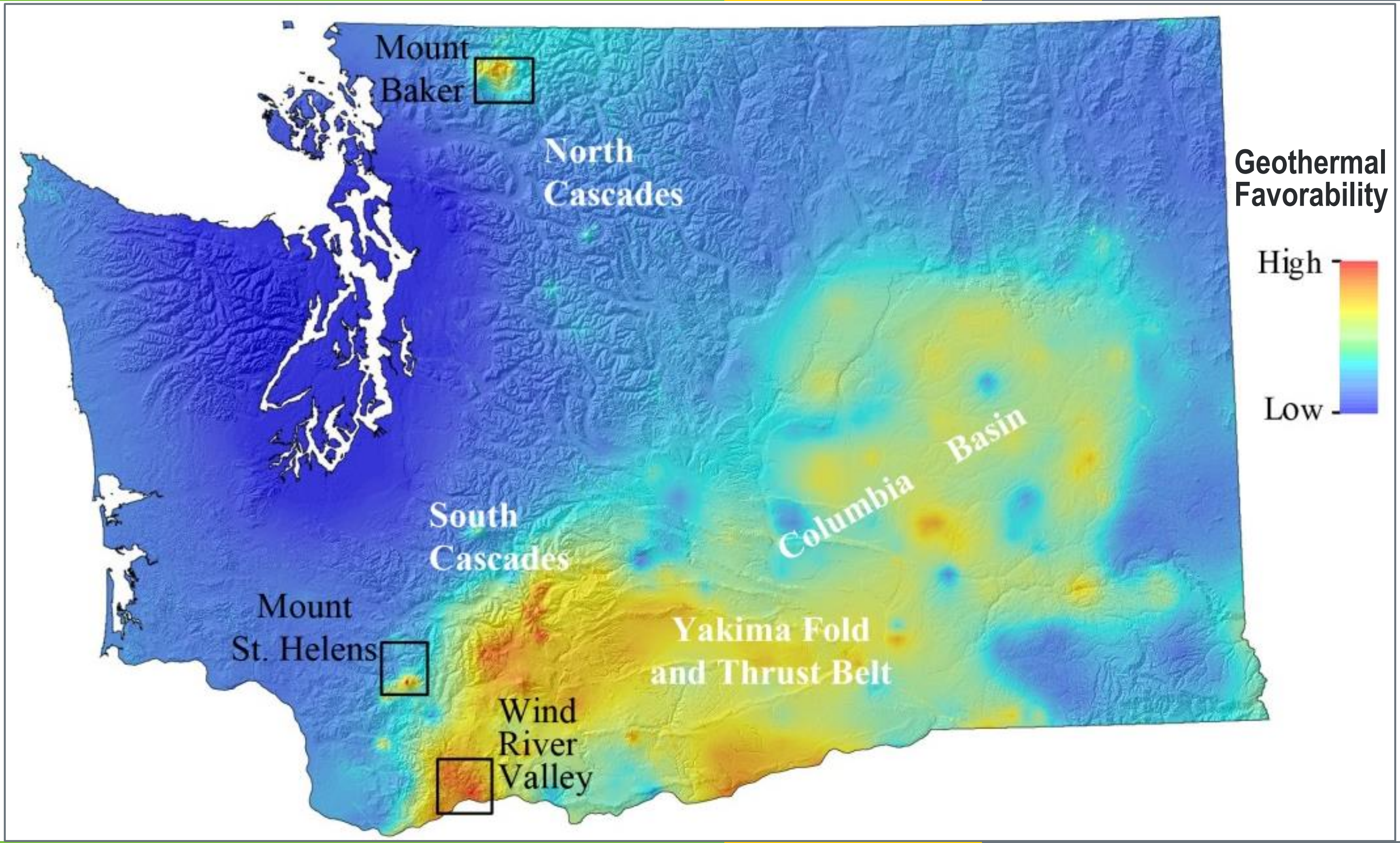


Geothermal Play-Fairway Analysis of Washington State Prospects

Project Officer: Eric Hass
Total Project Funding: $244,536
May 12, 2015

Principal Investigator: Dave Norman
Presenter Name: Corina Forson
Organization: Washington Division of Geology and Earth Resources
Other Participants: AltaRock Energy Inc., Temple University, BOS Technologies, Gifford Pinchot National Forest

Hydrothermal

PROJECT OBJECTIVES

Quantitatively integrate temperature, fault, earthquake, stress/strain, and other geologic and geophysical data into a comprehensive geothermal resource model for three promising plays along the central axis of the magmatic arc of Washington State:

- Mount St. Helens seismic zone
- Wind River valley
- Southeast flank of Mount Baker

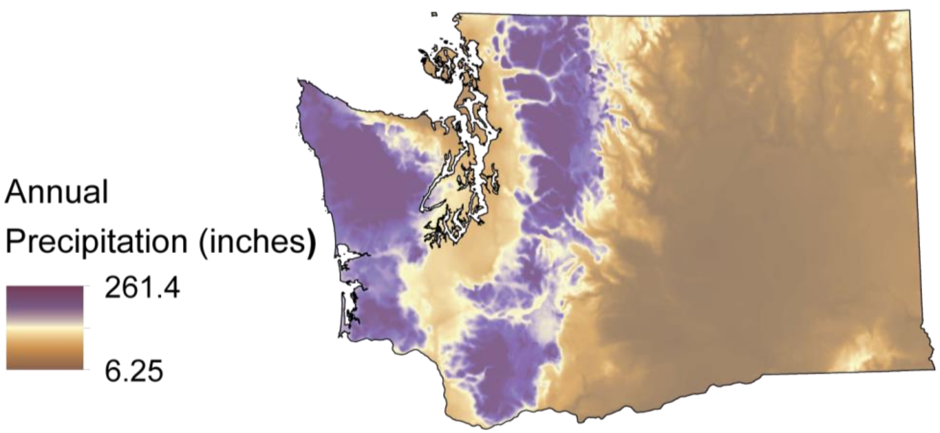
Barriers to geothermal addressed by this study:

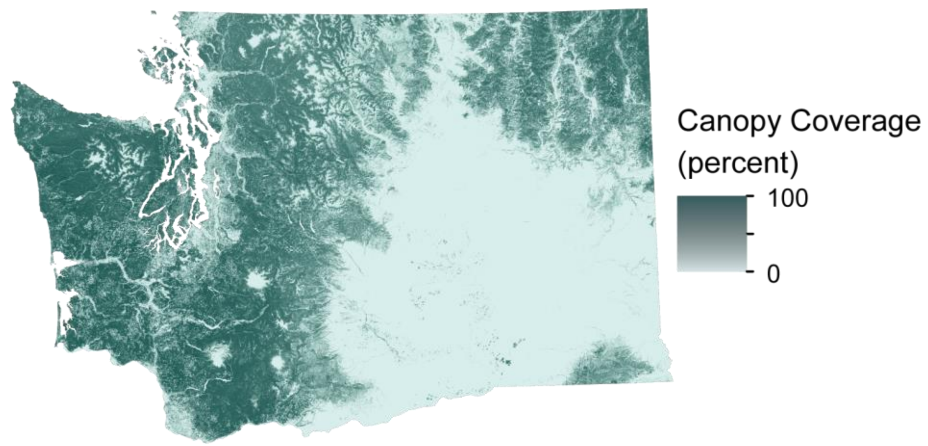
Minimize risk associated with the initial investments in greenfield exploration projects by refining exploration techniques, rigorously analyzing available data, addressing model uncertainty, and sensitivity to input parameters.

Relevance/Impact of Research

Regional barriers influencing geothermal discovery in Washington:

Massive amounts of precipitation, dense vegetation coverage, and high relief in the western part of the state can mask surface manifestations and dampen the thermal signature of the magmatic heat source, which is conventionally detected through remote sensing. These barriers prevent geothermal resources from being identified and hinder target definition for drilling discovery wells.





Scientific/Technical Approach

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Underlying assumption in heat and permeability modeling: high fracture density promotes a percolating fracture network, porosity to store fluids, and heat exchange area. Active deformation provides the potential to restore permeability and porosity lost to mineral alteration and precipitation.

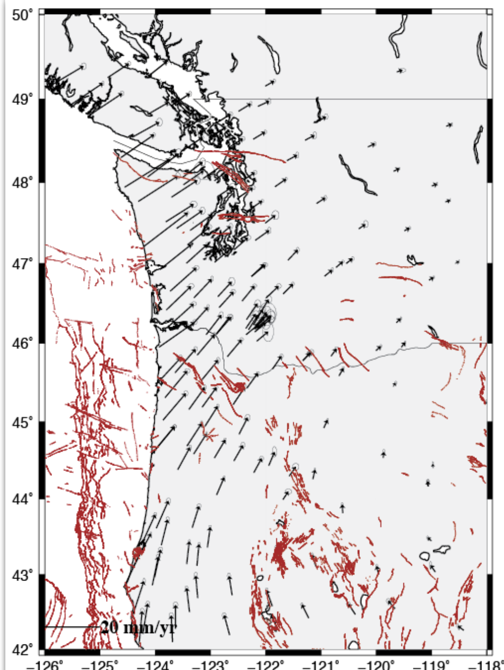
Permeability Layer	Where	Implication	Assumption
displacement/slip tendency	along fault	fault hosted flow	active faulting promotes fault permeability
dilation potential	along fault	fault hosted flow	low normal stress eneables dilation during slip
displacement gradient	along fault	localized fault hosted flow	dU/dx indicates high local strain and intense fracturing
Coulomb Stress/σ3	volume around fault	fractured reservoir extent	favorable stress change = high fracture density
shear and dilational strain	larger scales of earths crust	regional position of reservoir	active crustal deformation promotes fractures and permeability

Understand the local geology

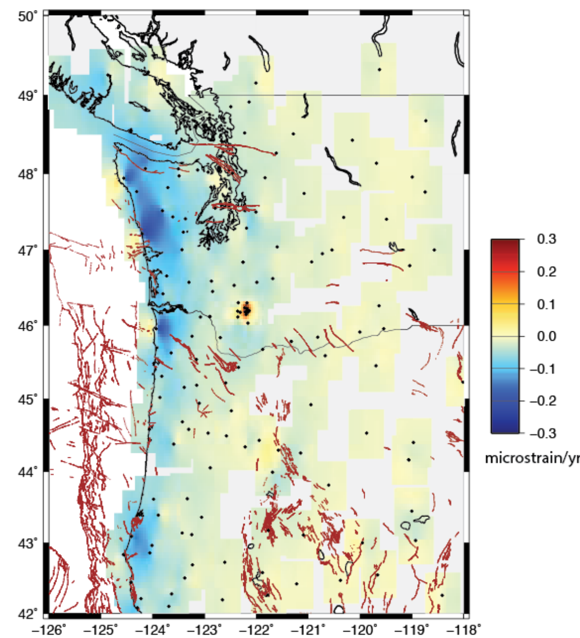
- Mapped faults
- Volcanic vents
- Quaternary intrusives
- Hot springs / fumaroles

Utilize geophysical and geochemical techniques

- Earthquake focal mechanisms
- Fault geometry fit to seismicity
- Derive velocities and infer strain rates from GPS time series
- Geothermometry

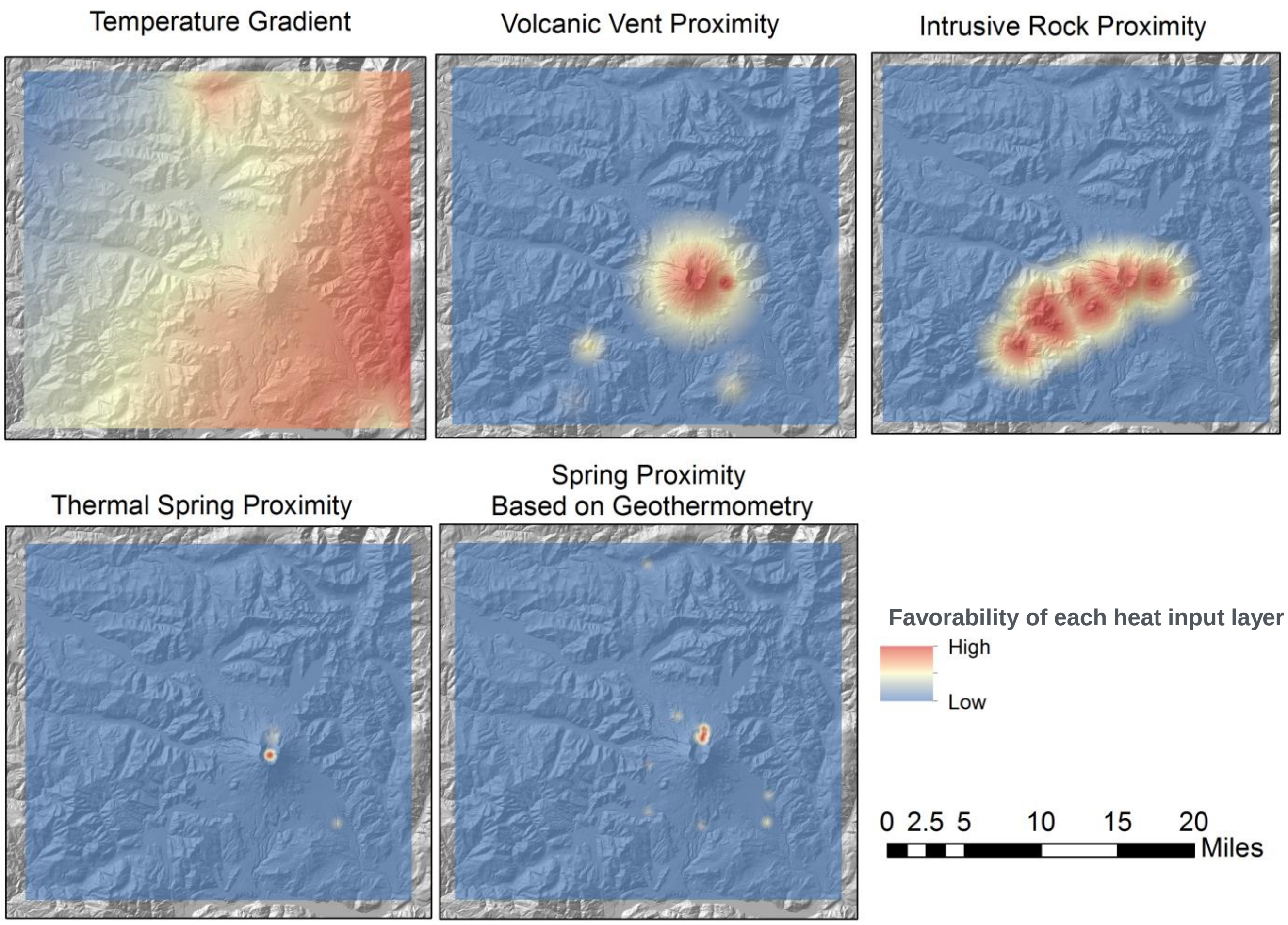


Velocity Vectors with 95% confidence elipses



Dilatational strain rate (microstrain/yr) derived from GPS time series from NSF Earthscope's Plate Boundary Observatory (PBO) by BOS Technologies.

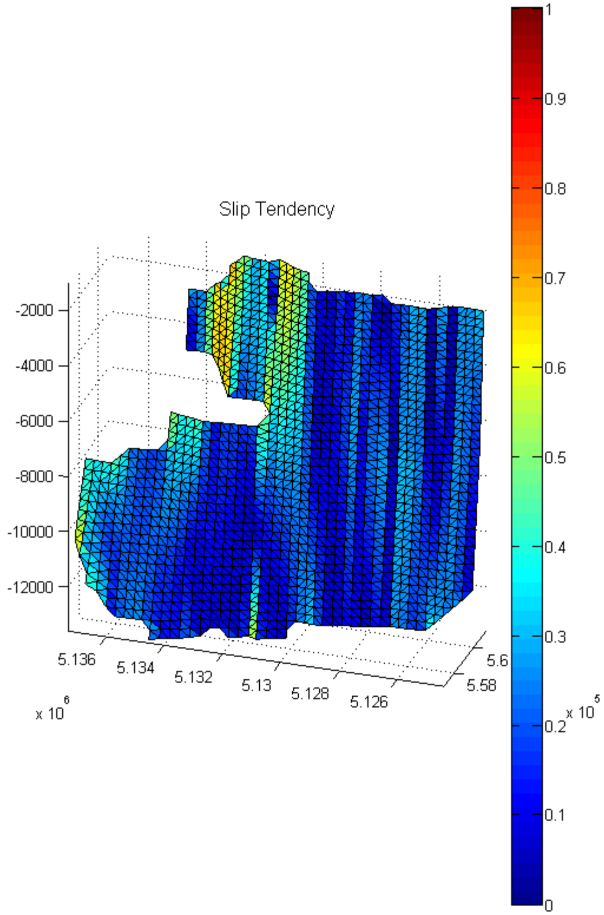
Scientific/Technical Approach

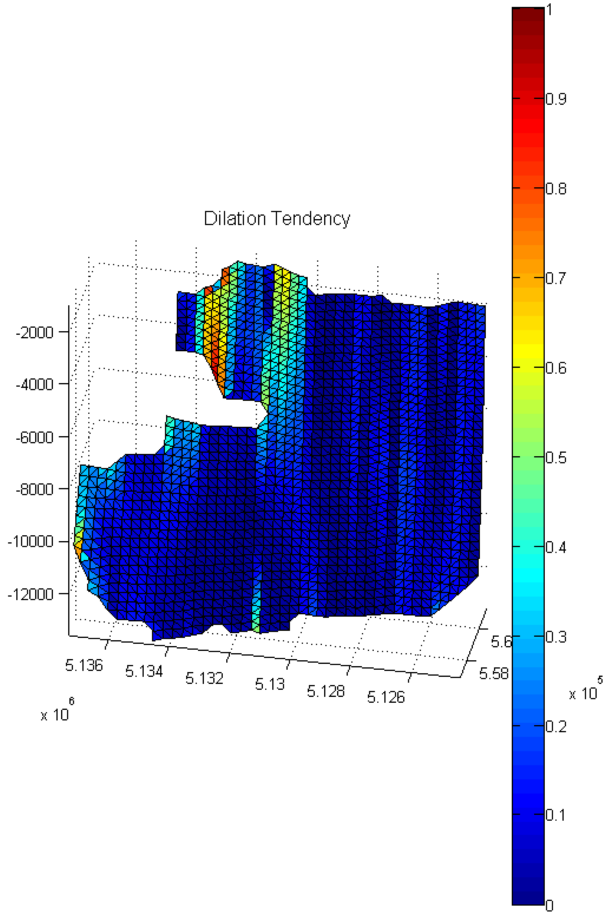


ArcGIS is used to:

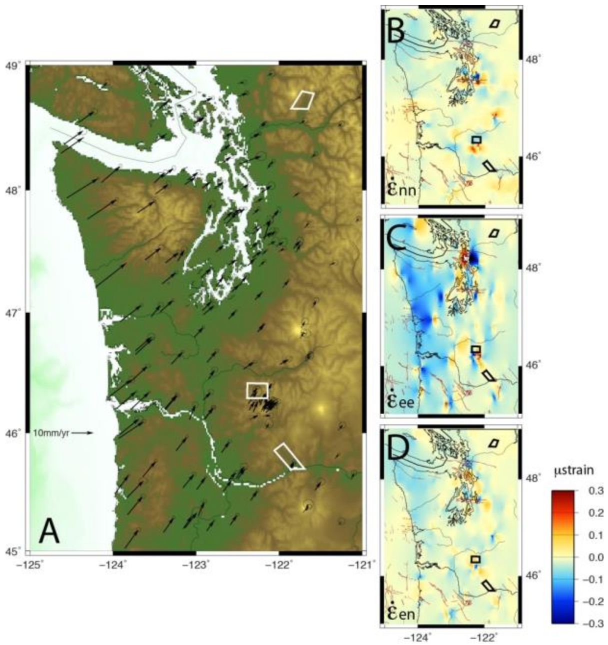
- weight heat inputs by value (temperature, distance, lithology, type, etc.)
- interpolate between points
- combine and normalize the input layers

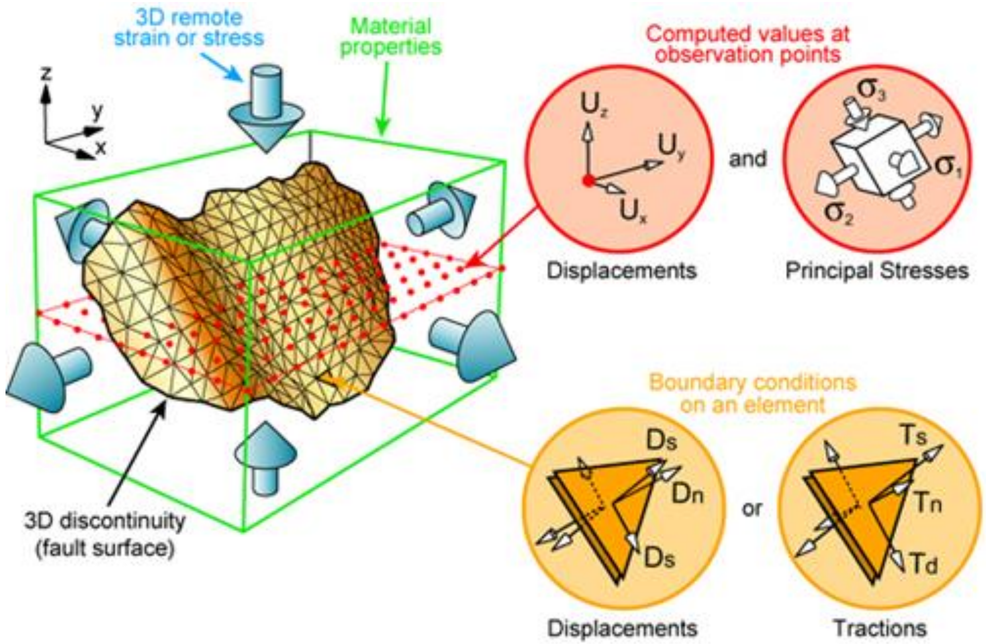
MATLAB is used to model fault geometries from earthquake data, to incorporate mapped faults, and to model the slip and dilation tendency on fault planes in 3D.

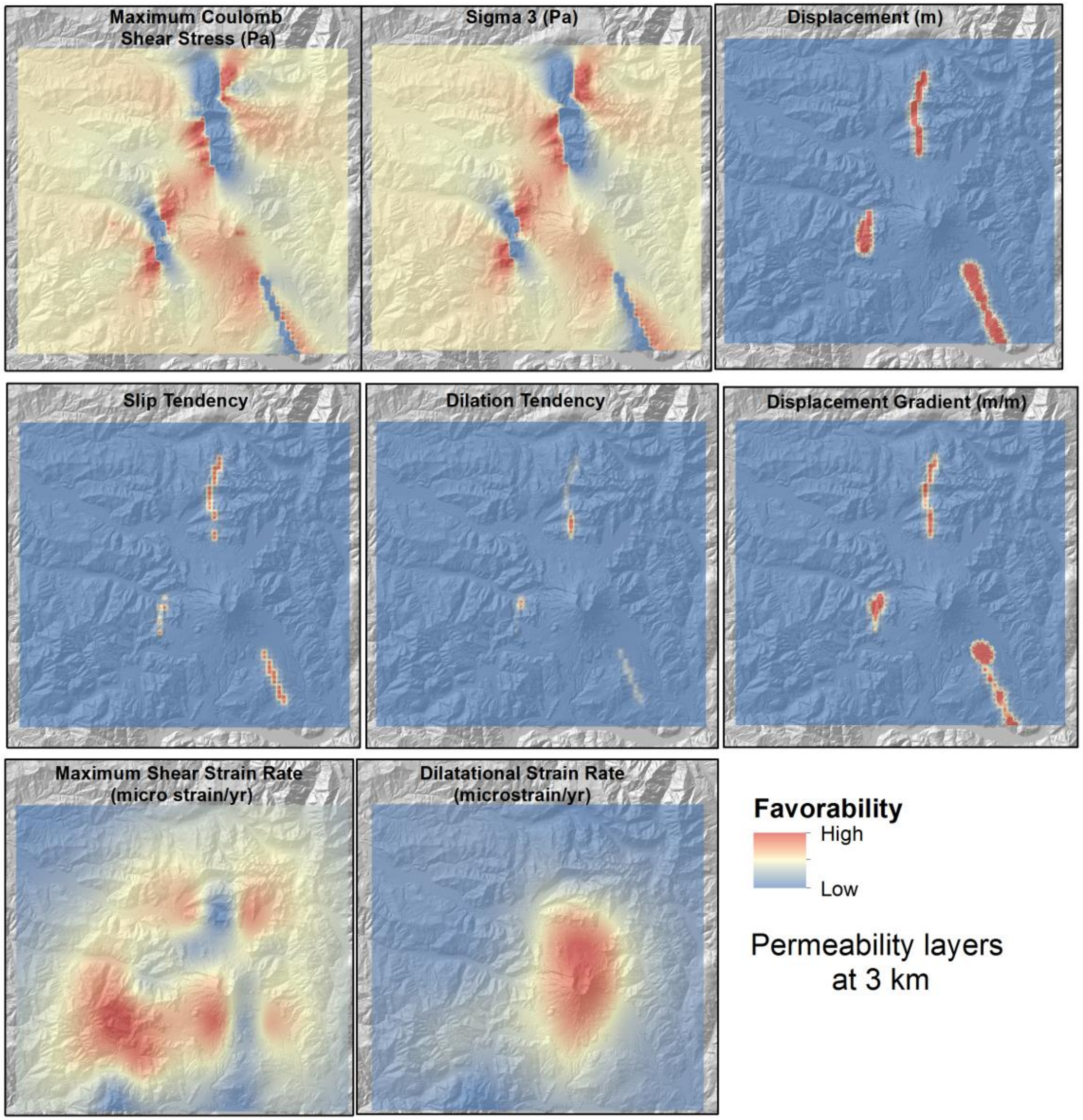




Poly3D software (Thomas, 1993), using boundary conditions derived from GPS strain rates, is used to model fault displacement and displacement gradients to determine where faults are causing proximal damage zones that enhance fault permeability. Maximum Coulomb stress and the least compressive principal stress (σ_3) are used to estimate the fracture density in larger volumes surrounding faults.

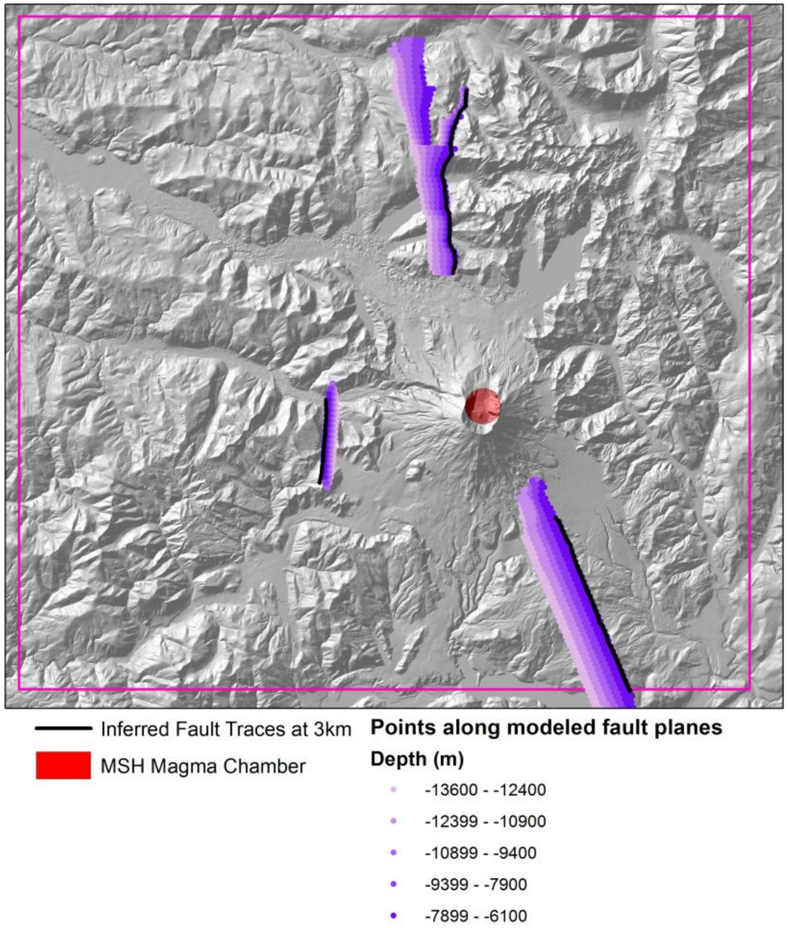






Permeability layers at 3 km

ArcGIS is used to interpolate between points that represent different permeability values calculated in MATLAB and Poly3D



Scientific/Technical Approach

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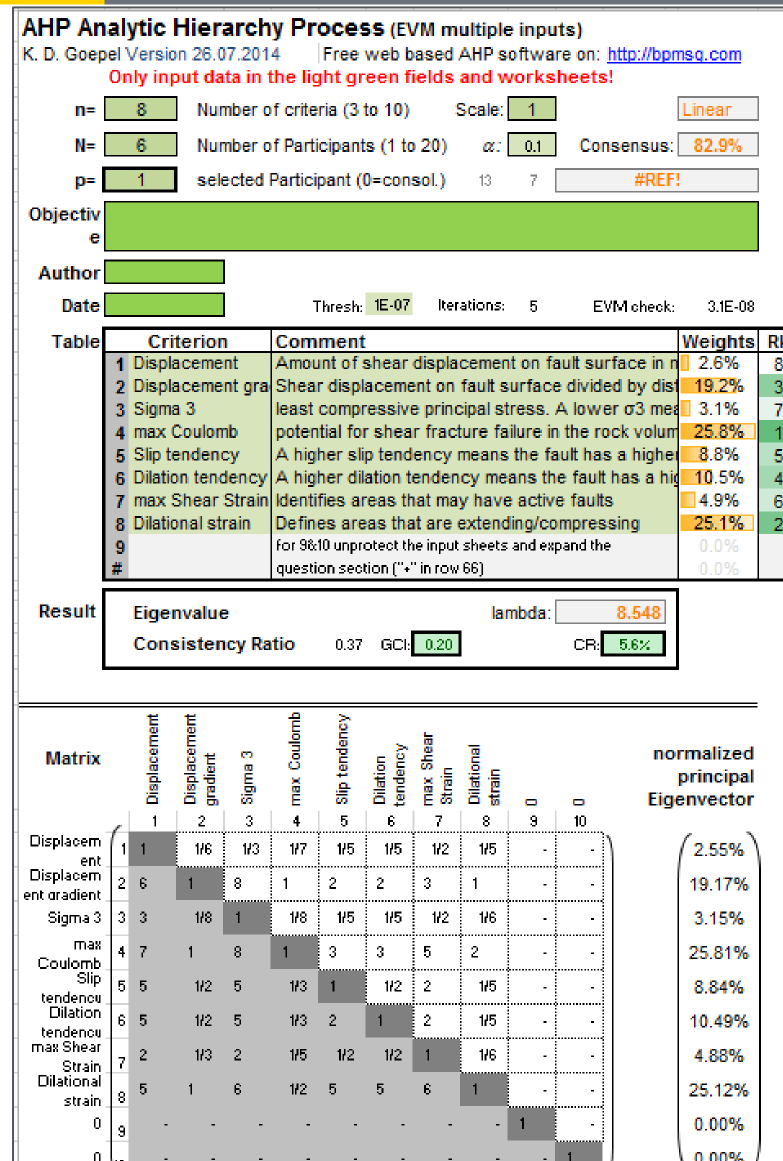
Modeling methods build on other geothermal exploration studies. Favorability layers commonly used include: Hot springs/ fumaroles, hot wells, geothermometry, Quaternary volcanic rocks, Quaternary faults, fault geometry, paleo-surface manifestations (sinter, travertine, tufa, hydrothermal alteration), earthquake epicenters, temperature gradient, heat flow, high rates of crustal strain, and proximity to known geothermal systems

Analytical Hierarchy Process (AHP) is a structured technique for organizing and analyzing complex decisions, based on math and psychology.



AHP Analytic Hierarchy Process (EVM multiple inputs)

K. D. Goepel Version 26.07.2014 | Free web based AHP software on: http://bpmsg.com

Only input data in the light green fields and worksheets!

n= 8 Number of criteria (3 to 10) Scale: 1 Linear

N= 6 Number of Participants (1 to 20) α: 0.1 Consensus: 82.9%

p= 1 selected Participant (0=consol.) 13 7 #REF!

Objective

Author

Date

Thresh: 1E-07 Iterations: 5 EVM check: 3.1E-08

Table	Criterion	Comment	Weights	Rk
1	Displacement	Amount of shear displacement on fault surface in m	2.6%	8
2	Displacement gra	Shear displacement on fault surface divided by dist	19.2%	3
3	Sigma 3	least compressive principal stress. A lower σ3 mea	3.1%	7
4	max Coulomb	potential for shear fracture failure in the rock volum	25.8%	1
5	Slip tendency	A higher slip tendency means the fault has a higher	8.8%	5
6	Dilation tendency	A higher dilation tendency means the fault has a hig	10.5%	4
7	max Shear Strain	Identifies areas that may have active faults	4.9%	6
8	Dilational strain	Defines areas that are extending/compressing	25.1%	2
9		for 9&10 unprotect the input sheets and expand the	0.0%	
#		question section ("+" in row 66)	0.0%	

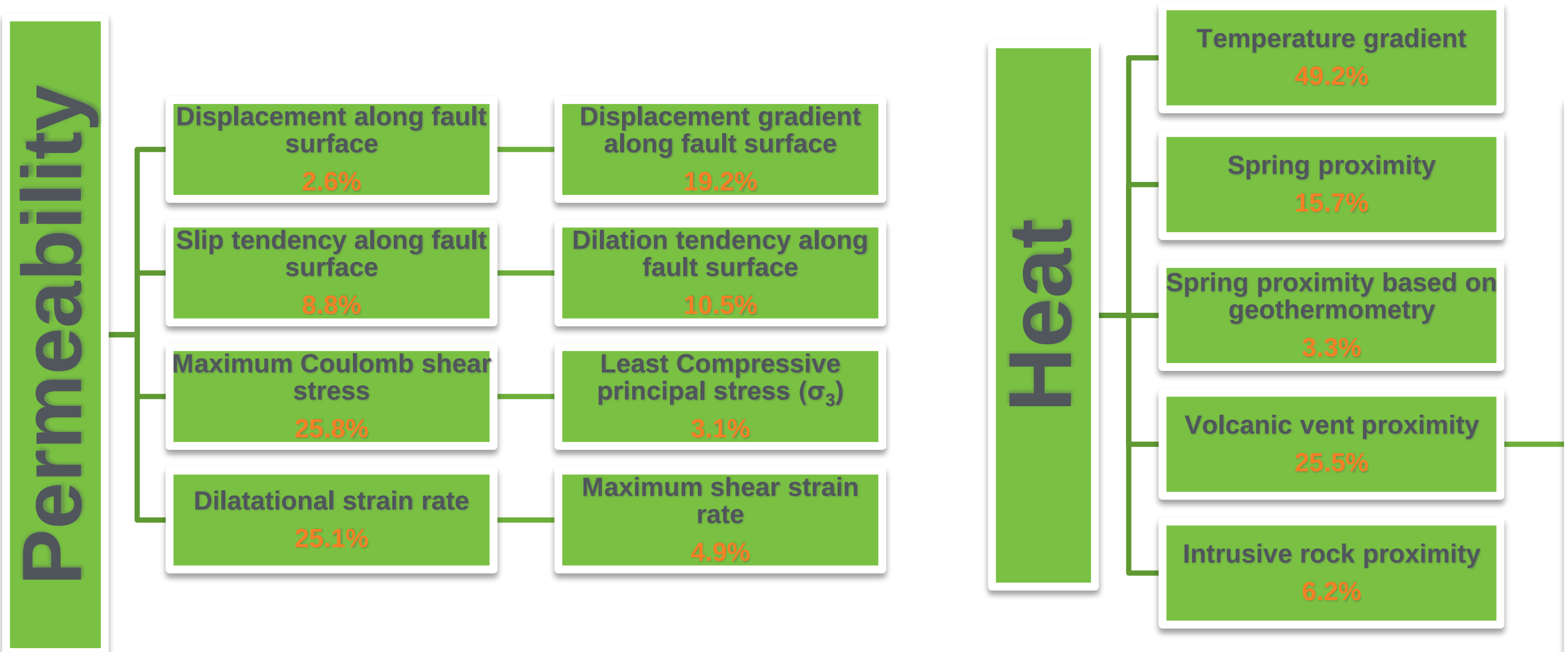
Result

Eigenvalue lambda: 8.548

Consistency Ratio 0.37 GCI: 0.20 CR: 5.6%

Matrix		Displacement 1	Displacement gradient 2	Sigma 3 3	max Coulomb 4	Slip tendency 5	Dilation tendency 6	max Shear Strain 7	Dilational strain 8	0 9	0 10	normalized principal Eigenvector
Displacement	1	1	1/6	1/3	1/7	1/5	1/5	1/2	1/5	-	-	2.55%
Displacement gradient	2	6	1	8	1	2	2	3	1	-	-	19.17%
Sigma 3	3	3	1/8	1	1/8	1/5	1/5	1/2	1/6	-	-	3.15%
max Coulomb	4	7	1	8	1	3	3	5	2	-	-	25.81%
Slip tendency	5	5	1/2	5	1/3	1	1/2	2	1/5	-	-	8.84%
Dilation tendency	6	5	1/2	5	1/3	2	1	2	1/5	-	-	10.49%
max Shear Strain	7	2	1/3	2	1/5	1/2	1/2	1	1/6	-	-	4.88%
Dilational strain	8	5	1	6	1/2	5	5	6	1	-	-	25.12%
0	9	-	-	-	-	-	-	-	-	1	-	0.00%
0	10	-	-	-	-	-	-	-	-	-	1	0.00%

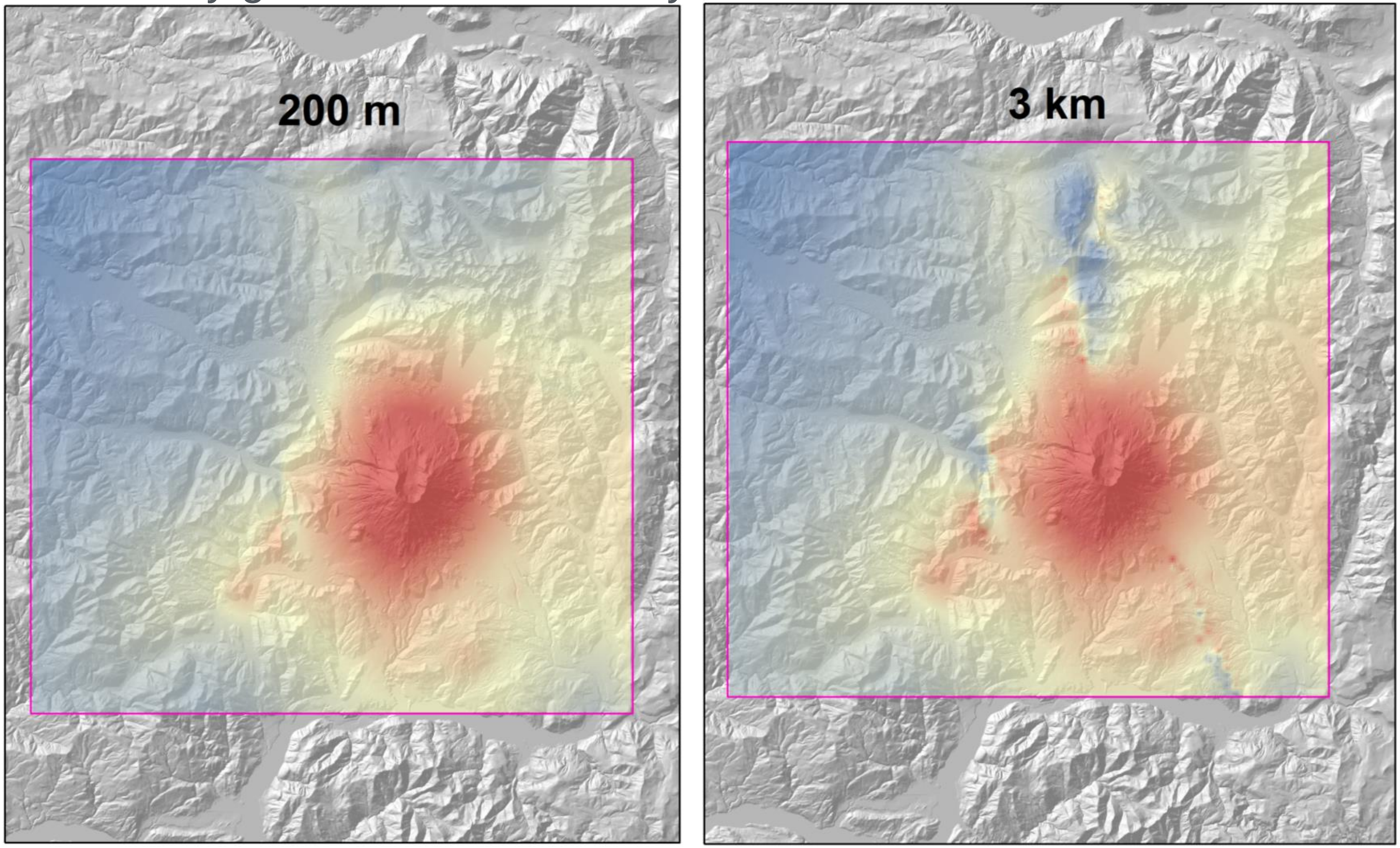
Heat and permeability layers and their respective weights based on AHP for the Mount St. Helens study area



Rock type	weight
rhyolite	7
rhyodacite	6
dacite	5
andesite/ dacite	4
andesite	3
basaltic andesite	2
basalt	1

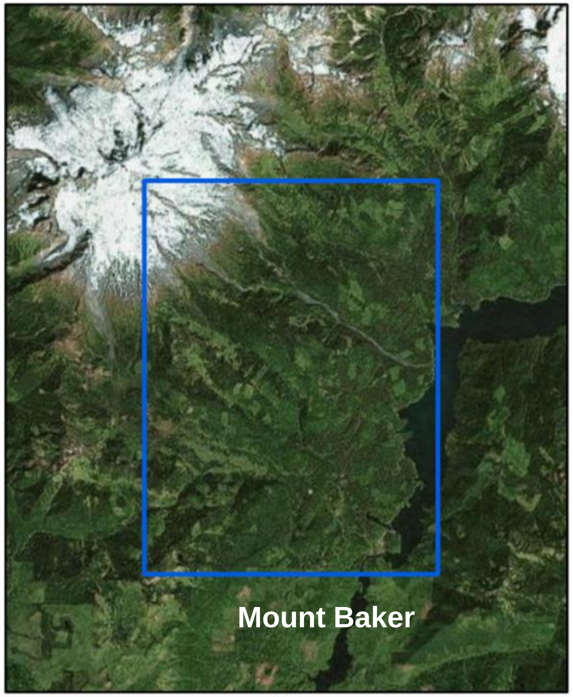
Age	weight
Holocene	7
Pleistocene	6
older	5

Preliminary geothermal favorability of Mount St. Helens seismic zone



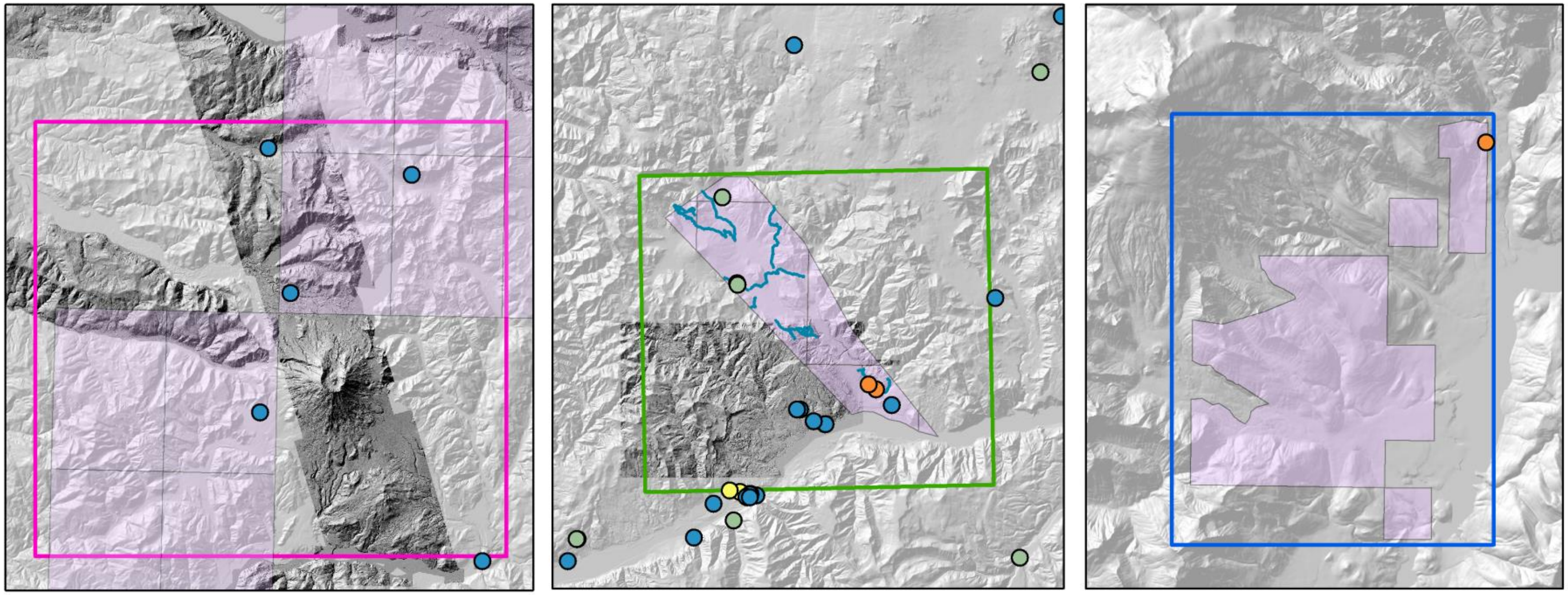
Heat and permeability are weighted evenly in this preliminary analysis

Future Directions



Milestone	Status & Expected Completion Date
3.2 & 3.3	Use workflow and data processing techniques developed for MSH in the Wind River and Mount Baker play-fairway studies. Expected completion: May 2015 and July 2015
3.4	Uncertainty and risk modeling for all three plays. Expected completion: August 2015
3.5	Metadata in multiple formats for all data deliverables. Expected completion: August 2015
4	Technical reporting and data delivery. Expected completion: October 2015

Future Directions



Gradient Wells

Degrees C/km

- 0.2 - 50
- 51 - 100
- 101 - 150
- 151 - 200
- 201 - 250
- Magnetic survey
- Mapped at 24k

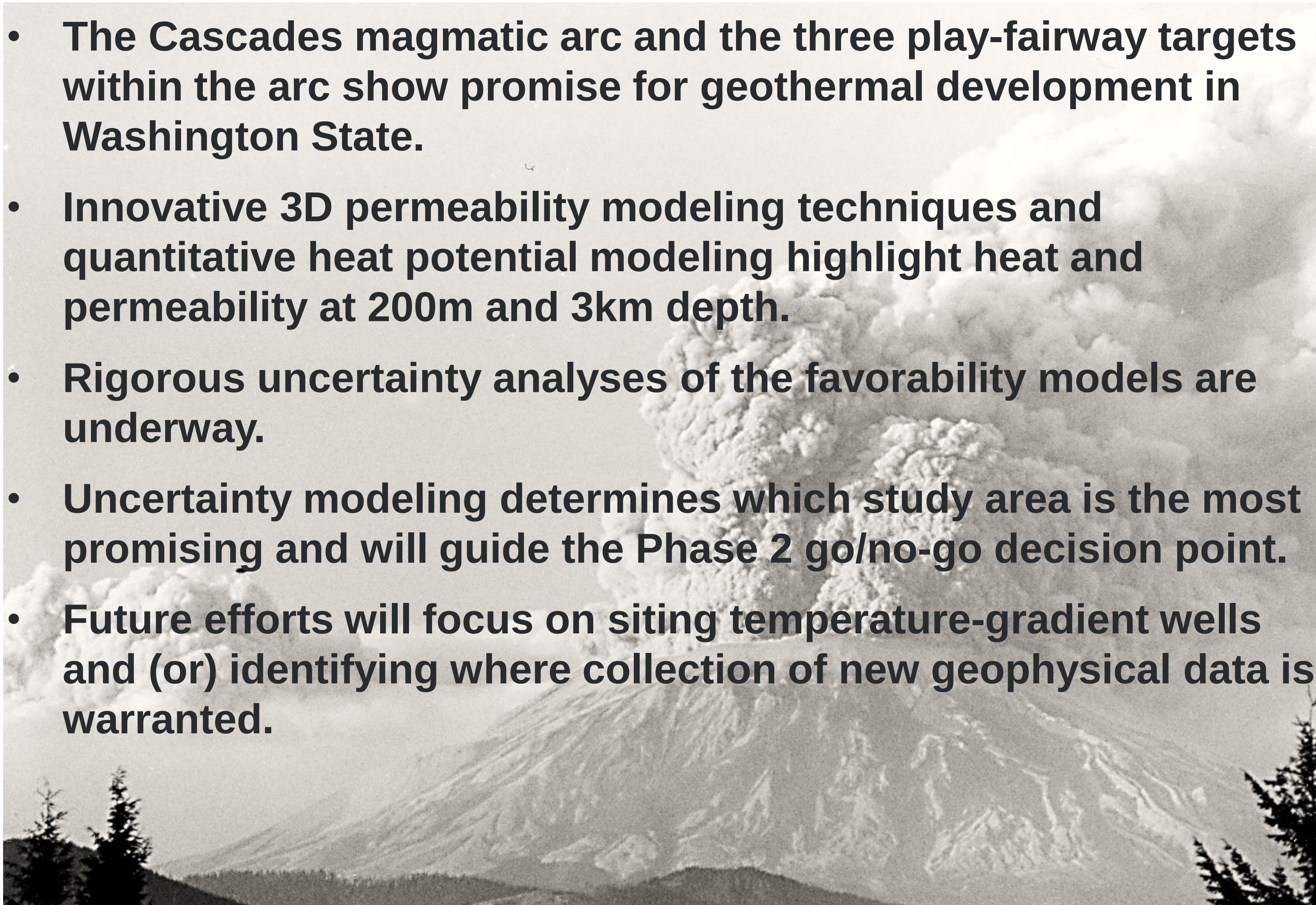
LIDAR

Temperature-gradient wells

High-resolution geophysical surveys

Detailed geologic mapping

Summary



- **The Cascades magmatic arc and the three play-fairway targets within the arc show promise for geothermal development in Washington State.**
- **Innovative 3D permeability modeling techniques and quantitative heat potential modeling highlight heat and permeability at 200m and 3km depth.**
- **Rigorous uncertainty analyses of the favorability models are underway.**
- **Uncertainty modeling determines which study area is the most promising and will guide the Phase 2 go/no-go decision point.**
- **Future efforts will focus on siting temperature-gradient wells and (or) identifying where collection of new geophysical data is warranted.**