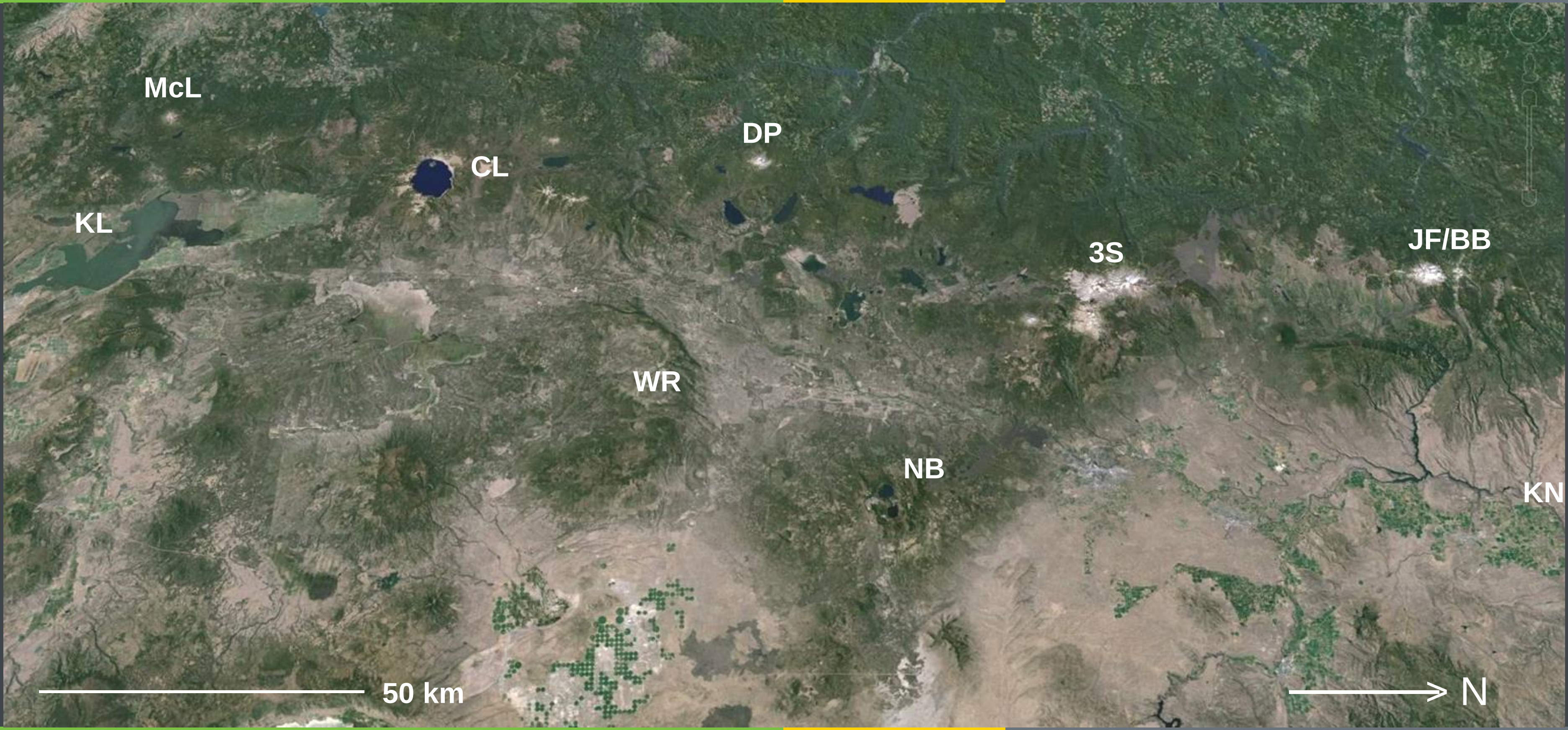
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy



Play Fairway Analysis (PFA): Structurally Controlled Geothermal Systems in the Central Cascades Arc-Backarc Regime, Oregon

Project Officer: Mark Zeigenbein; Total Project Funding: $537,482

May 12, 2015

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Track: Exploration Validation/PFA

Co-I's: Andrew Meigs (OSU); B.Mack Kennedy, Eric Sonnenthal (LBNL); Joseph Moore, (U Utah)

Relevance/Impact of Research

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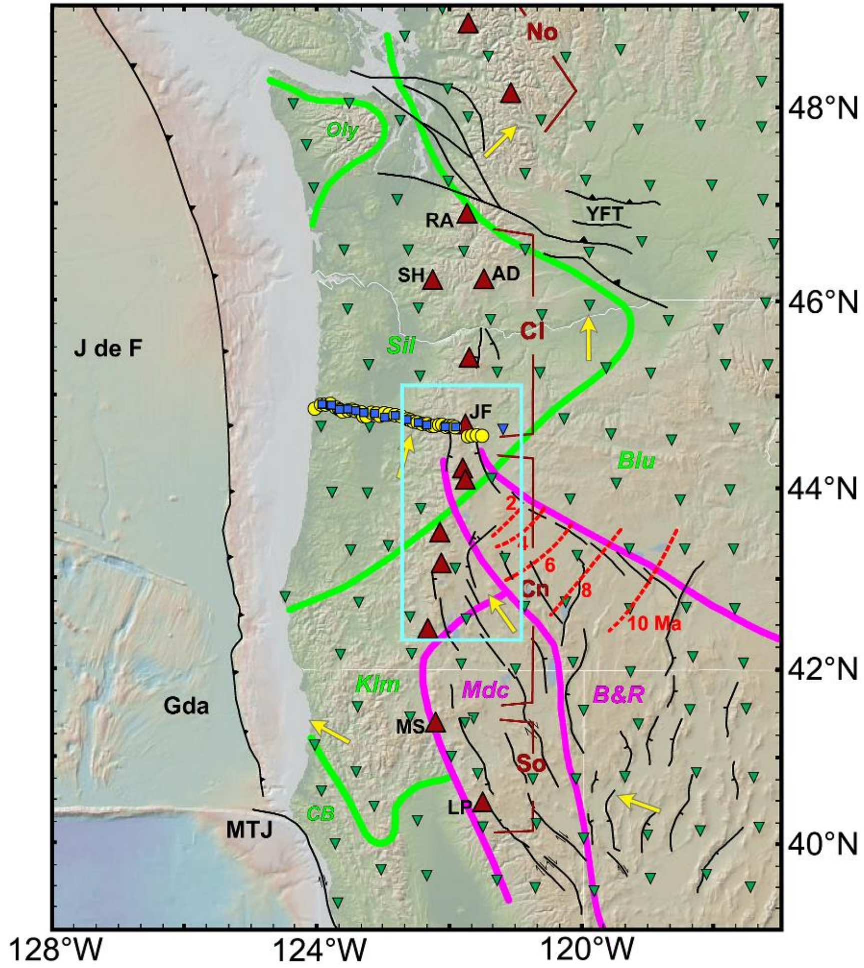
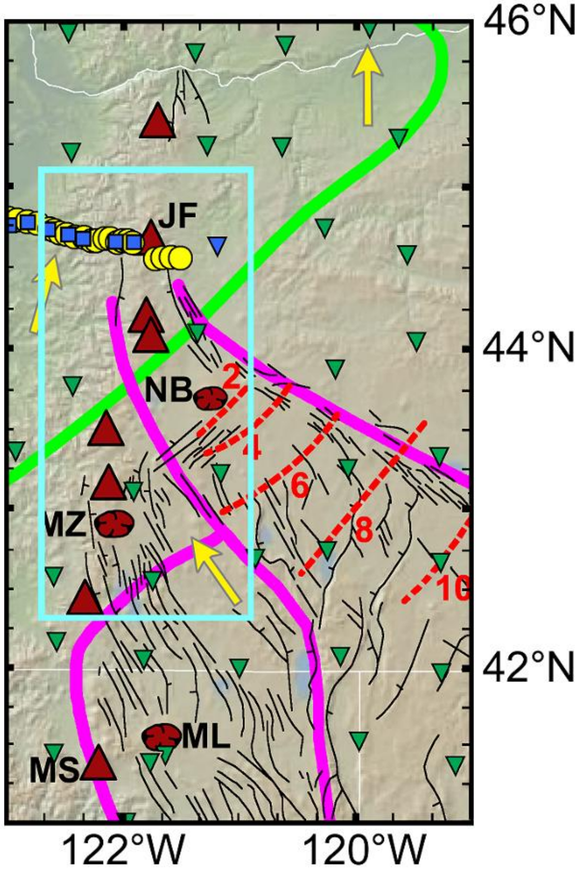
- Principal Objective: Accelerate Near-Term Hydrothermal Growth
  - Lower risks and costs of development and exploration
  - Lower levelized cost of electricity (LCOE) to 6 cents/kWh by 2020
  - Accelerate development of 30 GWe undiscovered hydrothermal resources

- *Challenges/Knowledge Gaps*: Develop a Play Fairway Analysis (PFA) model for Central Cascades, Oregon; overcome dense vegetative cover, rain curtain masking, sparse geoscientific data.
- *Cost Impact*: Improved geothermal costs through new methodologies, new geothermal play model, economies of scale.
- *Innovative Aspects*: Combines MT, structure, geochem; new 3D MT inversion method; new LiDAR-based structure imaging; new subsurface X-T modeling with ToughReact and Geo-T.
- *Meeting GTO goals*: Intended to open an underdeveloped U.S. geothermal province; identify new plays and play types.

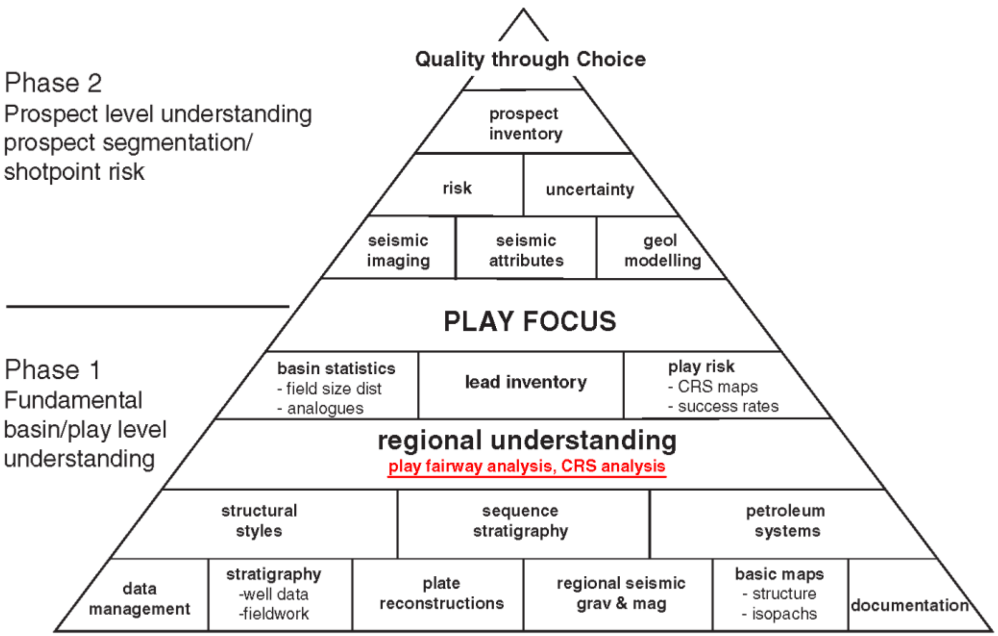
- Central Cascades Rationale: Superposition of andesitic subduction flux and bimodal rifting tectono-magmatism; extensional stress permeability



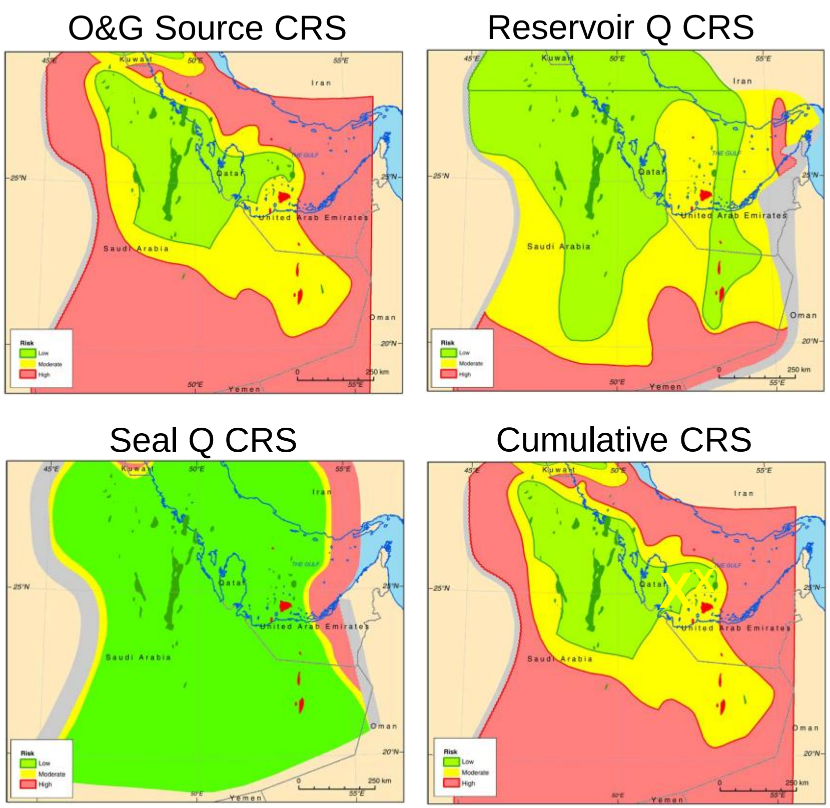


Scientific/Technical Approach

- PFA Approach Summary: Need to identify heat source, access to fluids, pathways to heat up and concentrate fluids, high permeability reservoir, caprock.
- Use MT to image high-T, fluidized upwellings; Use LiDAR and high-res DEM for structural modeling through forest cover; Use Geo-T and ToughReact for subsurface and fluid X-T state.



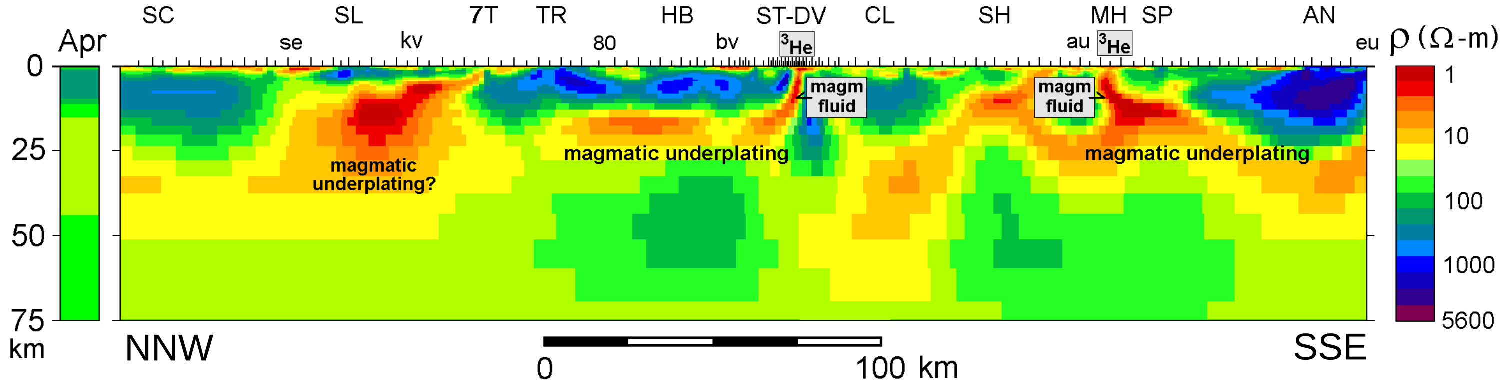
Oil & Gas Exploration Process Triangle (A. Fraser, Geol. Soc. London, 2010)



O&G CRS Analogs (Saudi Pen.)

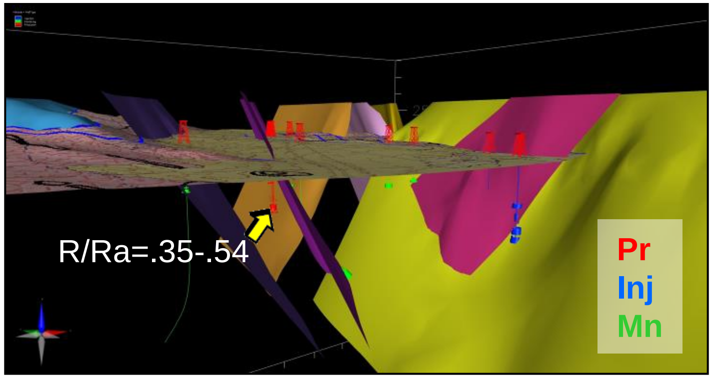
Approach

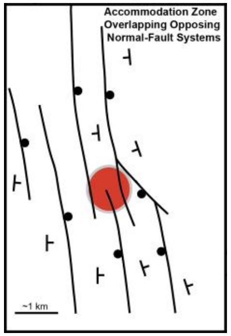
Great Basin Magmatism & McGinness Hills System
Motivation for Method Integration in Cascadia



- Structural setting as accommodation zone
- Deep magmatic connection from elevated R/Ra
- CO_2 flux anomaly along ~NW fault zone

- 3D MT confirms 2D recon
- Connection of prod. to depth
- NW-SE trends at multi-scale

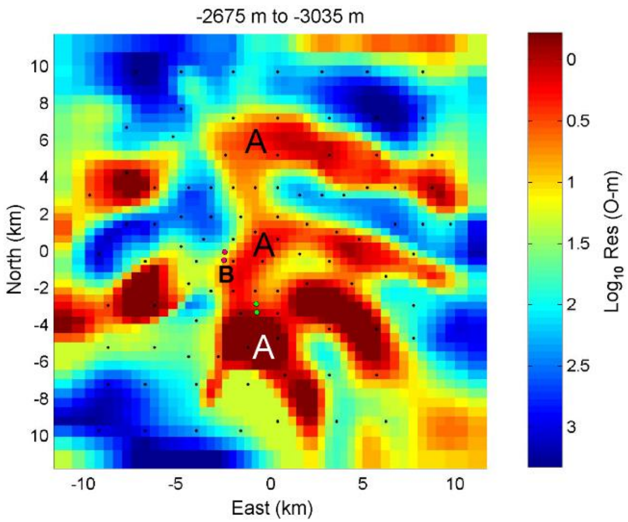




after J. Faulds

⇧ 3D structural perspective view from mapping and wells; ³He R/Ra in production wells

⇦ Purging sample port on well 36-10 for He sampling (L. Owens, Ormat)

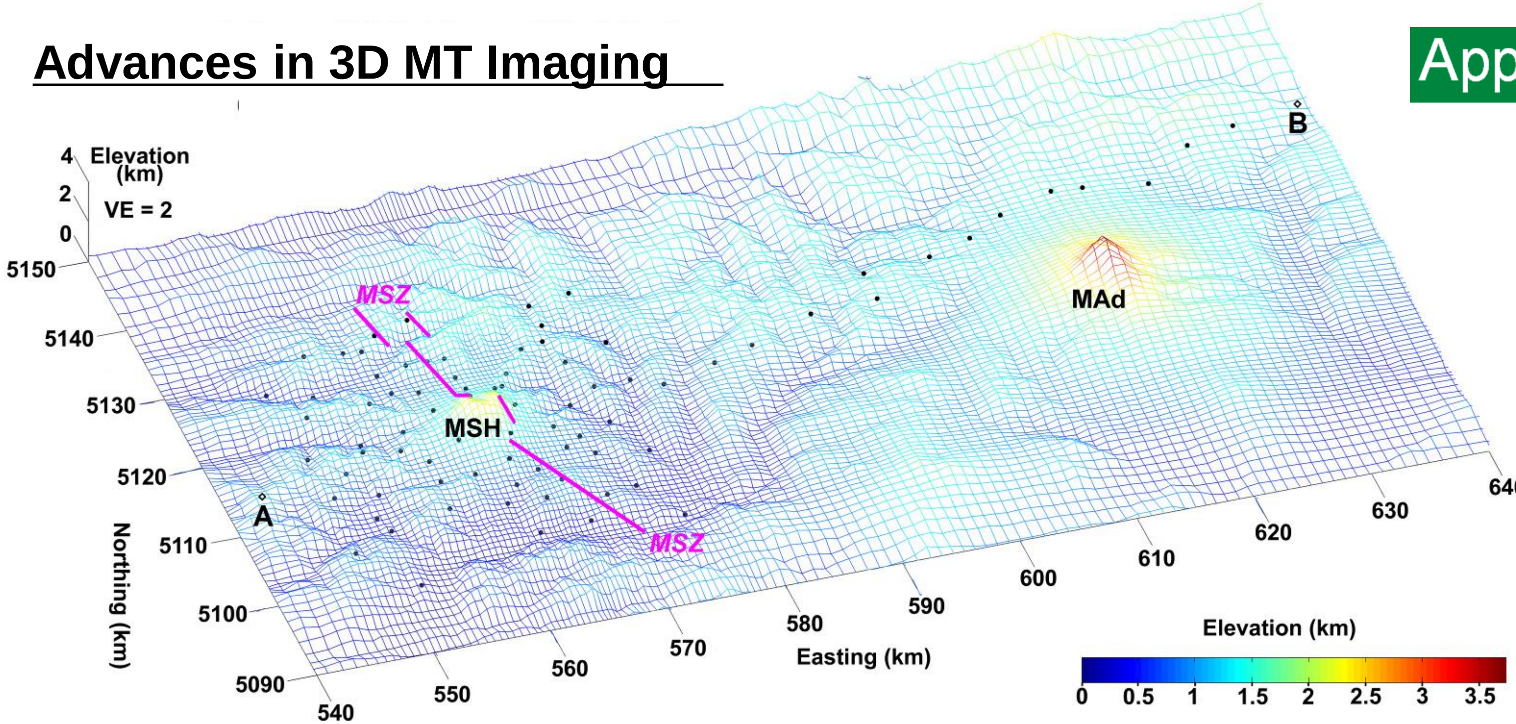


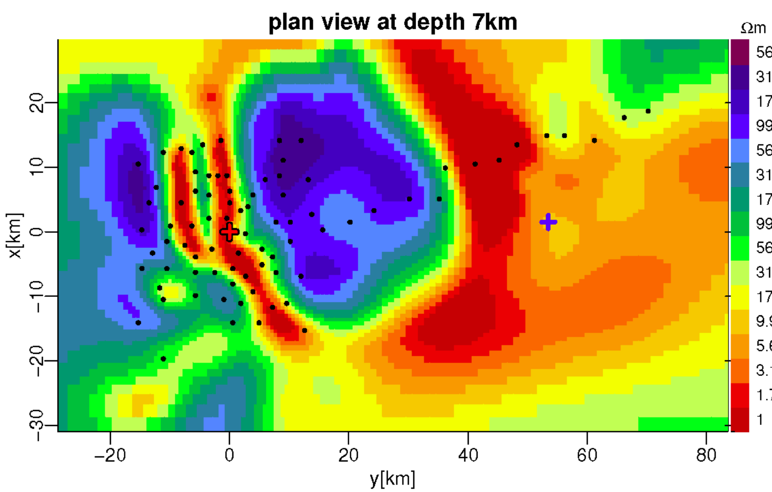
3D MT Resistivity Plan View
B is production, A is deep regional

U.S. DOE contract DE-EE0005514

Advances in 3D MT Imaging

Approach



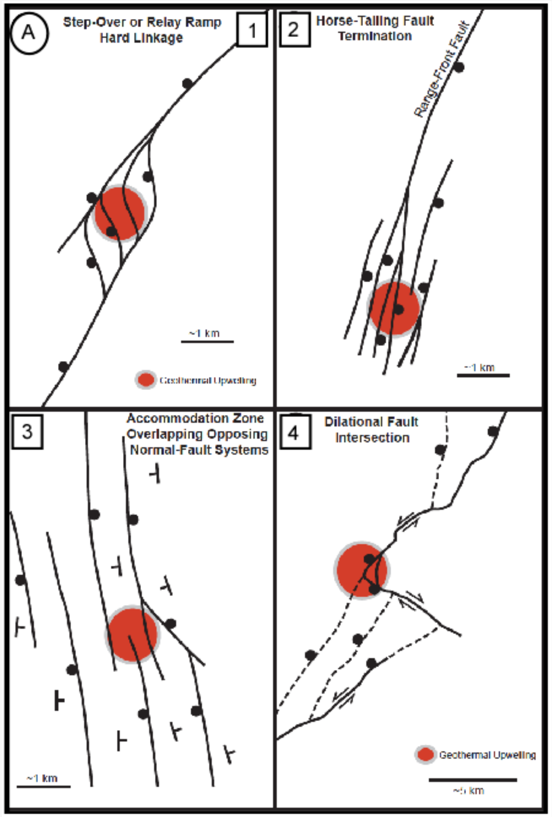


- Stabilized Iterative Earth Resistivity Voxel Estimation
- Non-Linear Step Recast to Data-Space Formulation to Reduce Rank
- Direct Matrix Solutions Used Throughout (Metis, Pardiso, Plasma)
- Can Solve for Tensor Z Static Distortions
- Parallelized on Large RAM, Single-Box Workstations (24-core, 0.5 TB RAM)

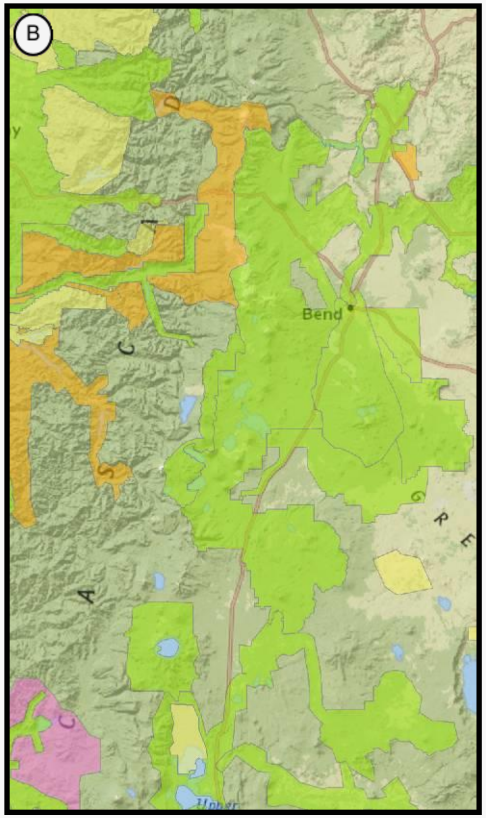
3D MT Inversion using Deformable Edge Finite Elements

Mt St Helens Data (Kordy, Wannamaker, et al., 2015, in revis.)

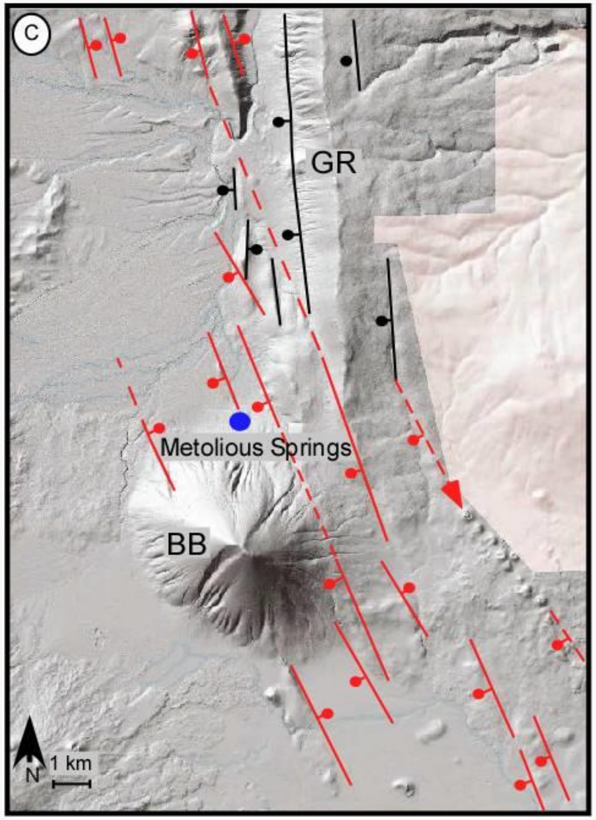
Advances in Structural Geology Analysis



Faulds et al. (2013)



Central Oregon LiDAR Coverage

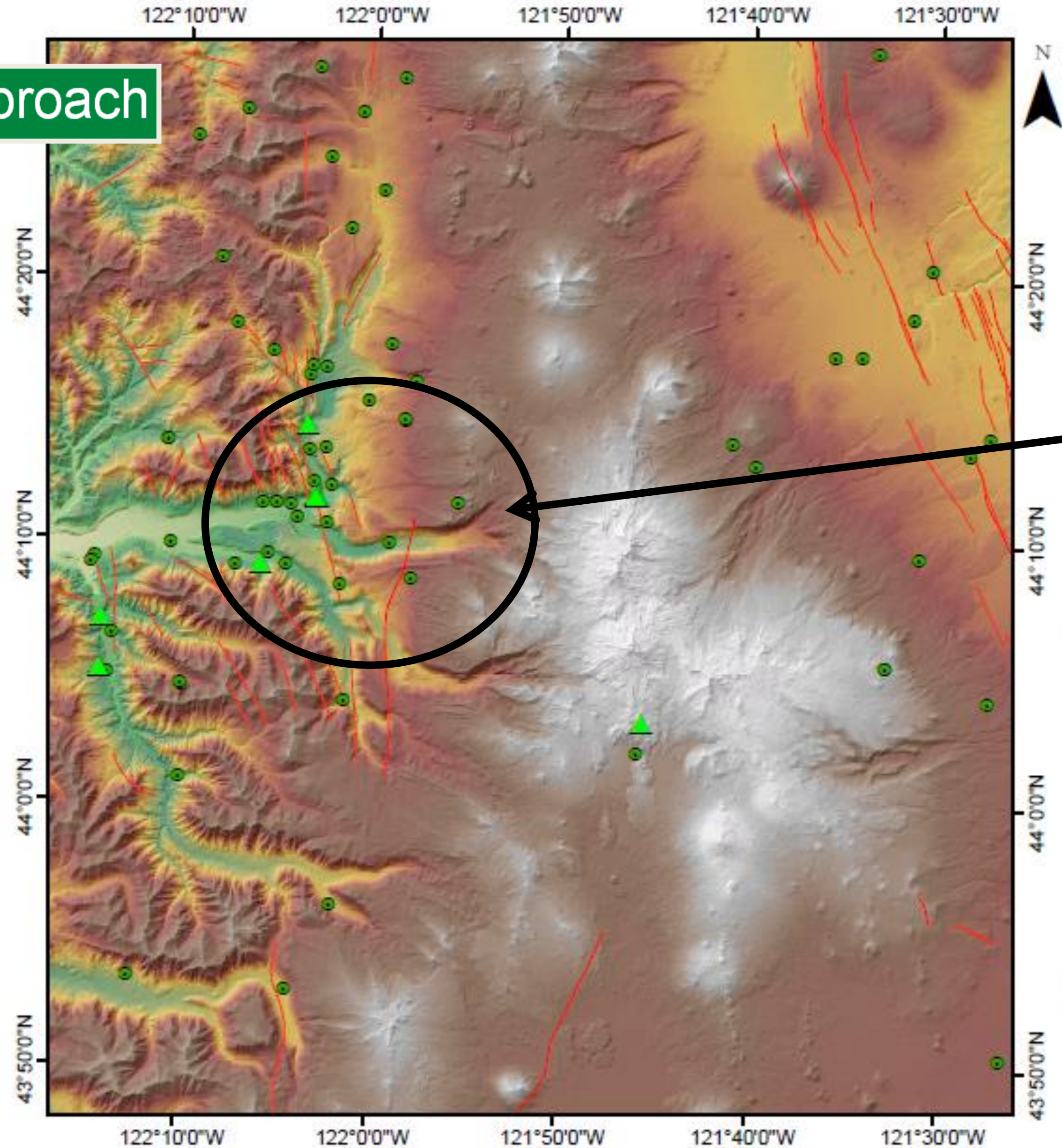


Green Ridge-Black Butte Fault Intersections

Dilatent Structure Examples in Central Cascades from LiDAR Data

- LiDAR reveals lineaments not perceptible previously
- New coverage (orange) includes north-central Cascades graben

Approach



Oregon - Central Cascades
Geothermal Springs
Geochemistry data from
Evans et al. (2004)
Maps compiled Feb 5, 2015

Advances in Major Element And Isotope Geochemistry

Initial Focus Area for Geochemical Evaluation

Map Legend

- GTILO_2_Geothermalspring_database
- GTILO_2_Geothermalwell_database
- orfaults_dd
- ORActiveFaultElement

NED_10m

Value

High : 3426.34

Low : 0

0 5 10 20 Kilometers

1 centimeter = 4,033 meters

Improve Cascades Geochemical System Understanding Through New Tools Geo-T and ToughReact: Apply First to Data-Rich Three Sisters Region

Proposed Milestones at Outset of Project:

Milestone Summary Table							
	Recipient Name:	University of Utah/EGI (Philip E Wannamaker, P.I.)					
	Project Title:	Structurally Controlled Geothermal Systems in the Central Cascadia Arc-BackArc Regime, Oregon					
Task Number	Task Title or Subtask Title (If Applicable)	Milestone Type (Milestone or Go/No-Go Decision Point)	Milestone Number* (Go/No-Go Decision Point Number)	Milestone Description (Go/No-Go Decision Criteria)	Milestone Verification Process (What, How, Who, Where)	Anticipated Date (Months from Start of the Project)	Anticipated Quarter (Quarters from Start of the Project)
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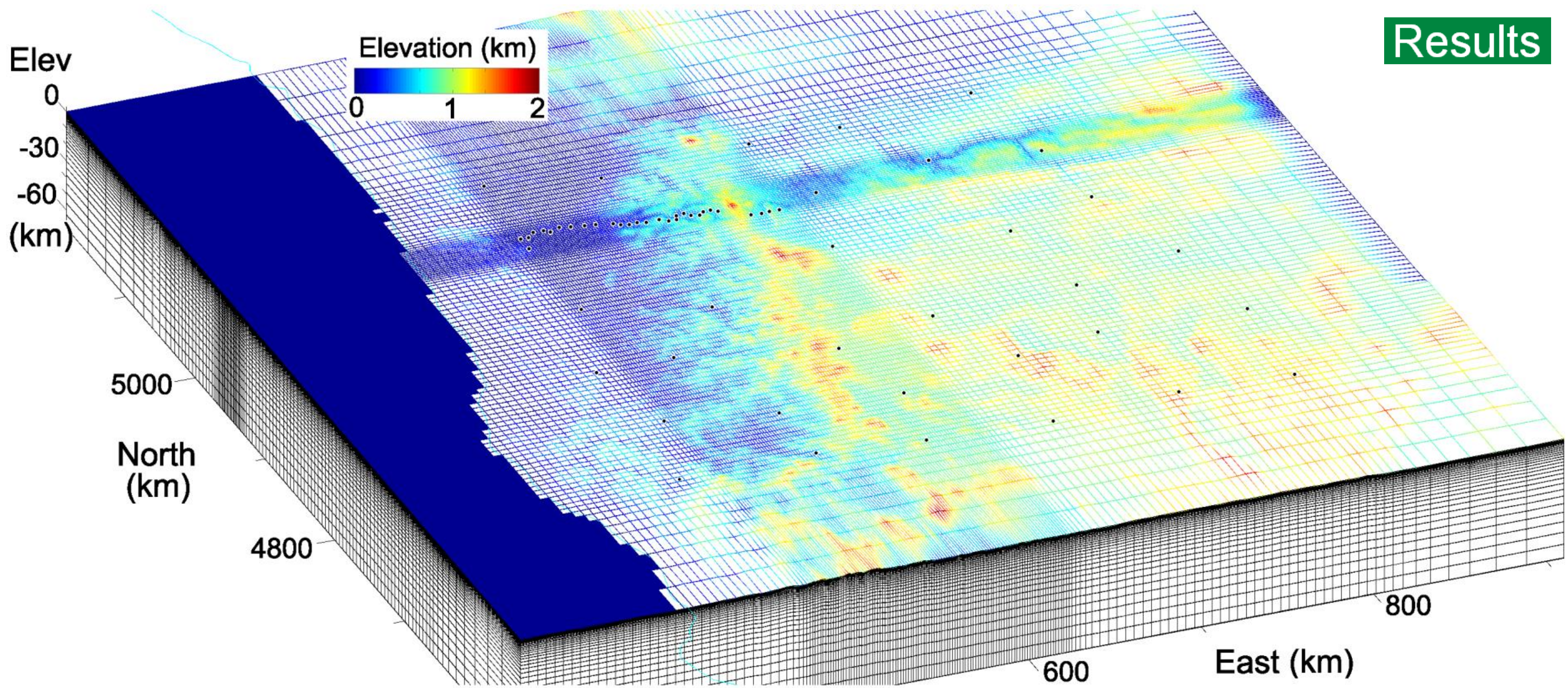
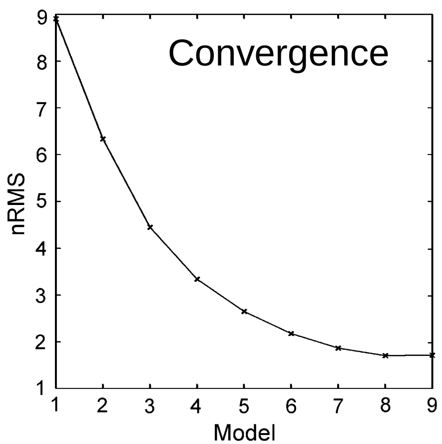
- Project is on time and on budget in each of the stated subtasks above.
- 3D MT inversion shows pertinent conductive geothermal upwellings.
- Improved and new structures from LiDAR, Breitenbush/Belknap maps.
- New fluid subsurface T estimates and fluid history modeling.

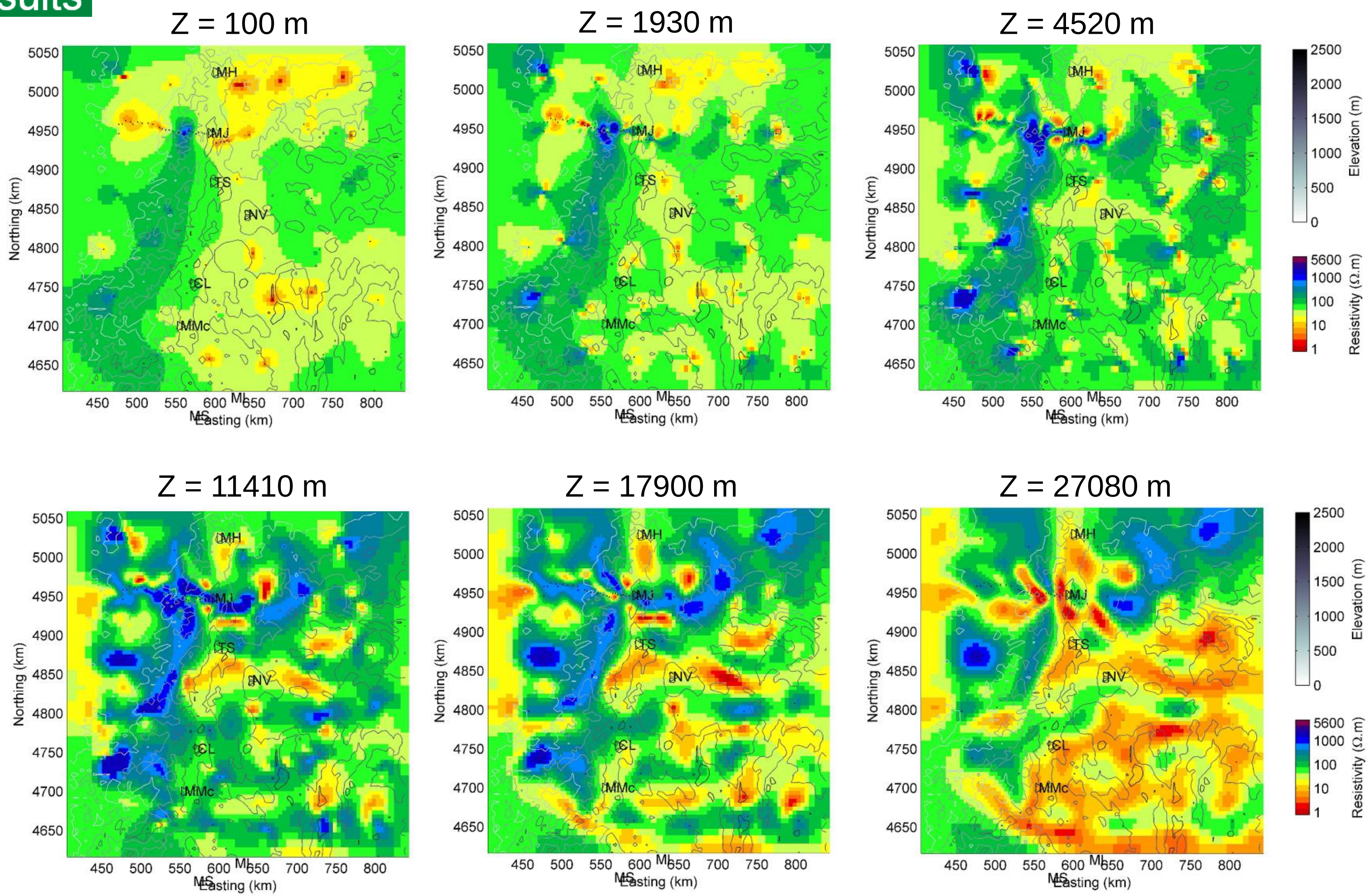
3D MT Inversion Edge Finite Element Mesh (EMSLAB + Earthscope sites)





- 60 MT stations (28 EMSLAB, 32 Earthscope)
- 31 periods (0.11 to 2560 s)
- Sub Rx: min cell = 1.5 km w, max cell 5 km w
- FE mesh: 145 (n) x 231 (e) x 59 (z) cells (10 air)
- Inversion domain: 133 x 214 x 42 = 1,170,134 parameters
- Error floors: 3.5% max{ |Zij| ; |Zxy-Zyx|/2 }, 0.03 tipper
- 33 ohm-m starting model, nRMS = 1.7 after 9 iters
- 31 hours/iter on 24-core w/s with 0.5 TB RAM

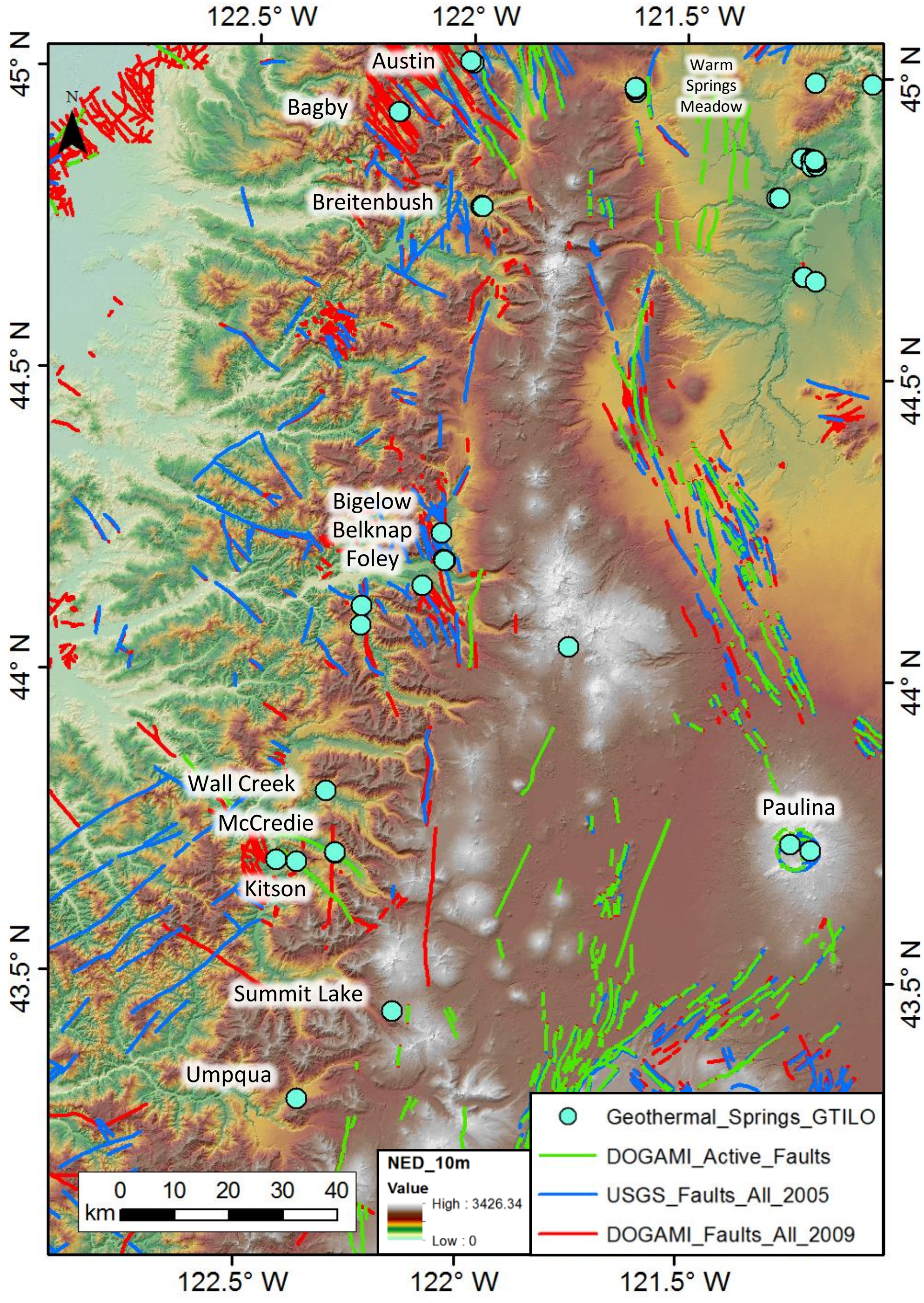
Results



3D MT Inversion Plan Slices (EMSLAB + Earthscope sites)

- <2 km dominated by sediments and shallow alteration
-'Butterfly' conductive upwelling >3 km around Mt Jeff incl. Breitenbush, Kahneeta
- Large-scale, deep E-W conductive trends intersect arc volcanoes

Results



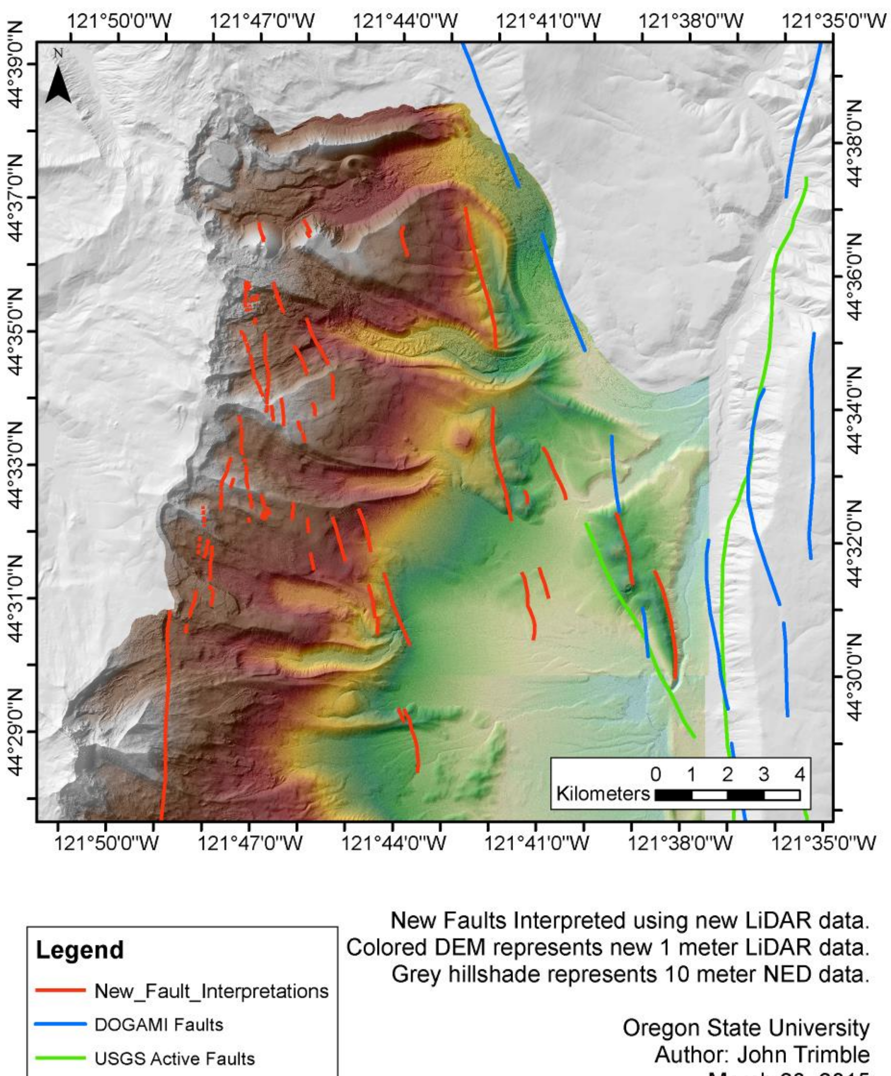
Western and High Cascades (WC, HC)

Hot Springs and Faults, Central Oregon

1. The Mt Jefferson region marks north end of prominent graben.
2. Hot springs are concentrated in the central and eastern parts of the WC.
3. Breitenbush lies in a nexus of N-S and NW-SE trending faults.
4. NNW-trending faults project from WC (Breitenbush, Austin) across HC toward Sisters fault zone.
5. Newly recognized, young NNW-trending faults potentially link WC and Sisters faults across HC.
6. WC-HC structural boundary in McKenzie River area (Foley, Belknap) includes N- and NW-trending faults; cross-cutting ambiguous.

Results

Young Faults in the Cascades Southeast of Mt Jefferson

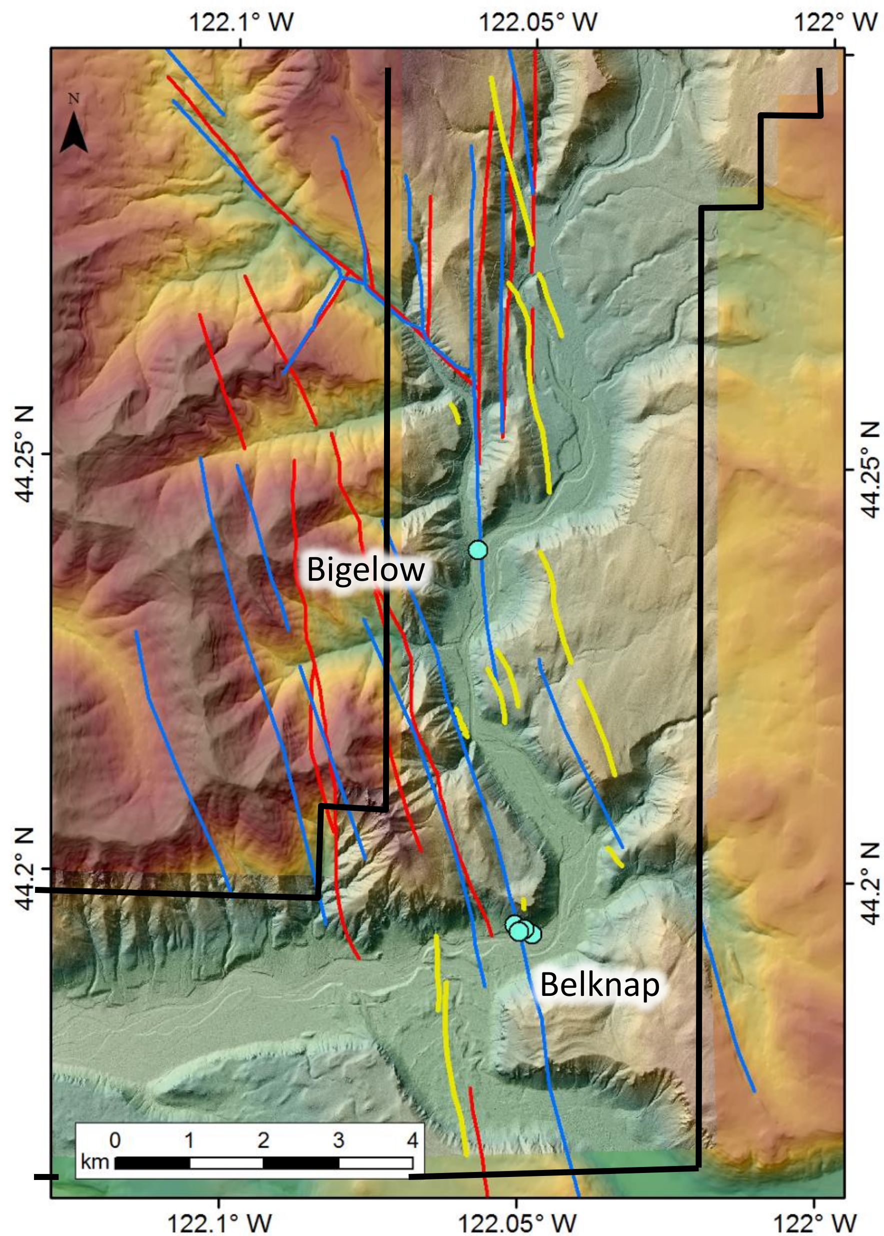


New Faults Interpreted using new LiDAR data.
Colored DEM represents new 1 meter LiDAR data.
Grey hillshade represents 10 meter NED data.

Oregon State University
Author: John Trimble
March 20, 2015

>20 new scarp segments identified southeast of Mt Jefferson. Identification not possible in prior 10 m NED data.

Faults in the Belknap Hotspring Area

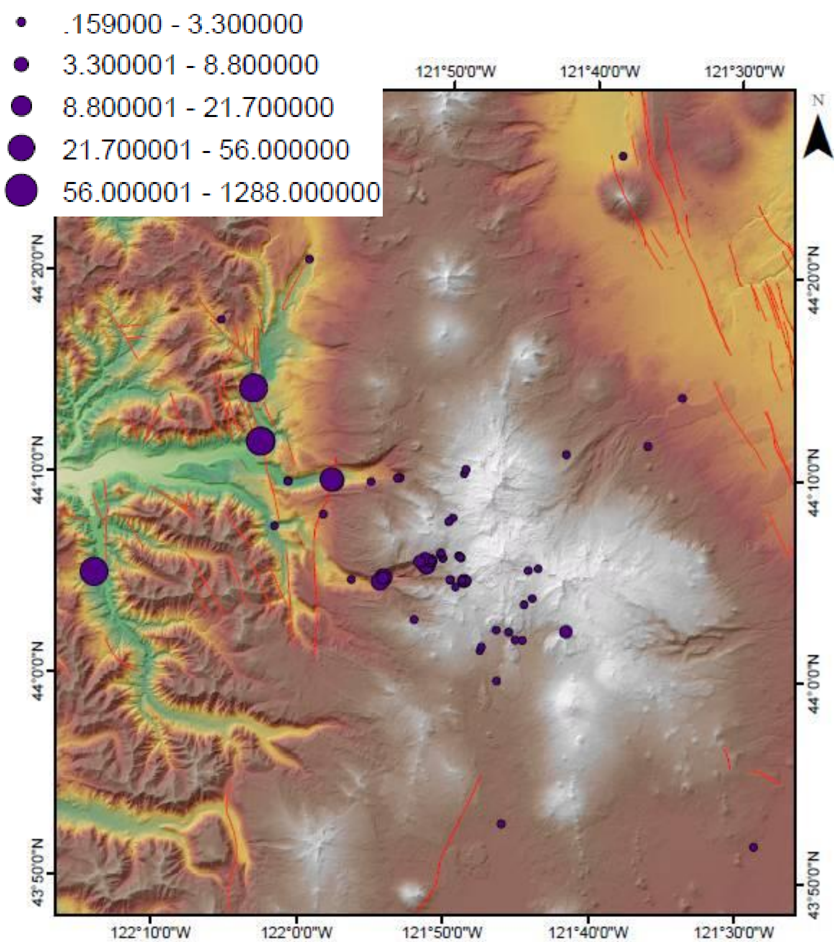


LiDAR (black box) reveals unrecognized faults (yellow).

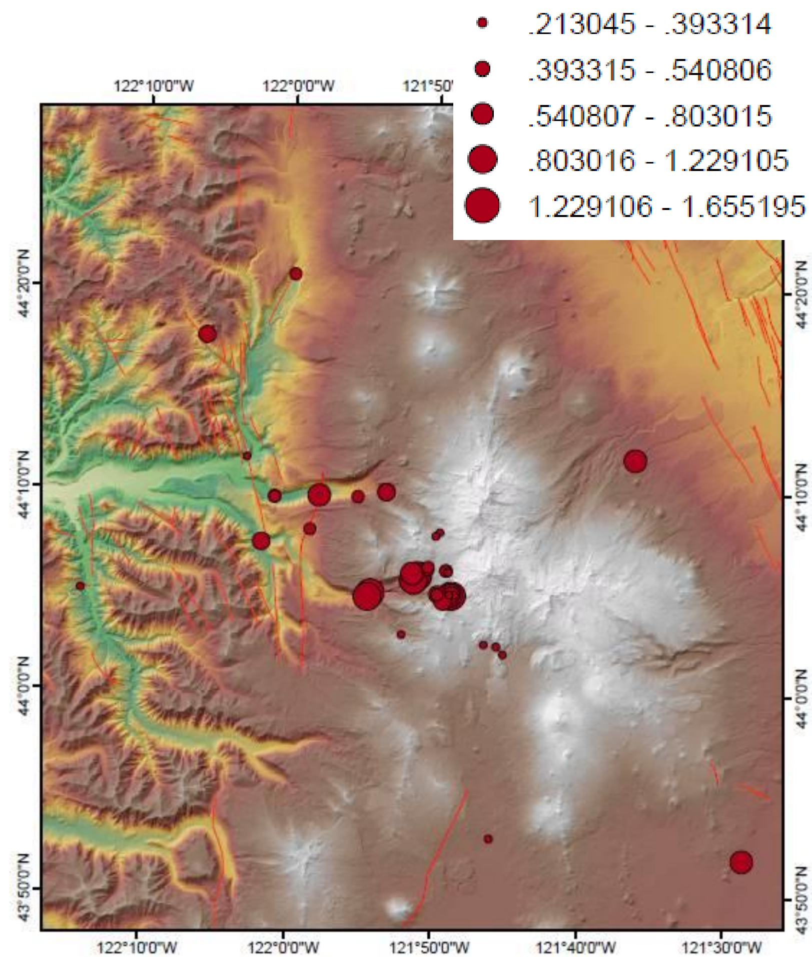
Results

Central Cascades Bi-Modal Fluid Chemistry
Three Sisters Region (Thermal and Cold Springs)
Data: Evans et al., 2004

Chloride (mg/L)



Alkalinity (mg/L)

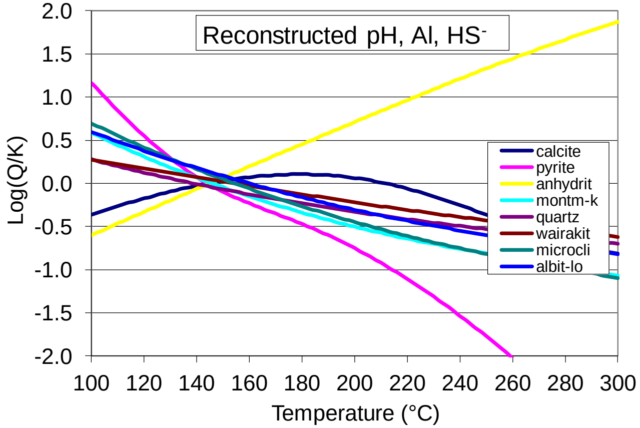


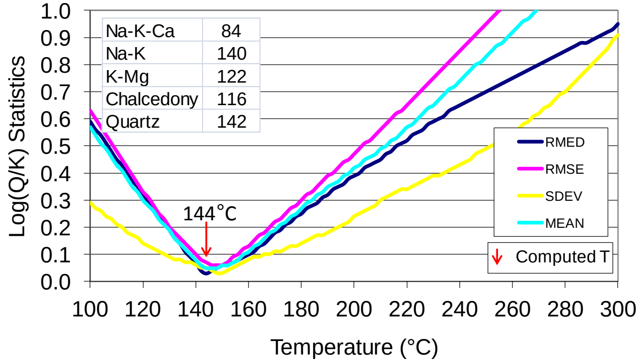
Chloride content and alkalinity tend to increase westward past Three Sisters

Results

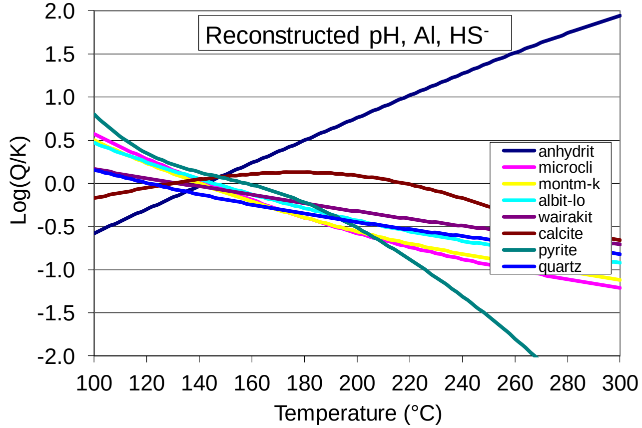
Three Sisters Region: Thermal Springs (high chloride)
Multi-Component Geothermometry (Geo-T)

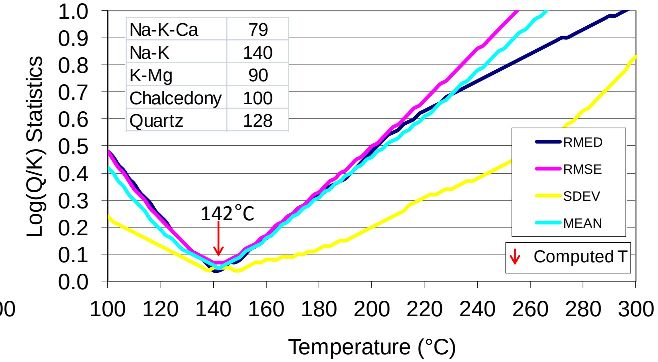
Belknap (no dilution)



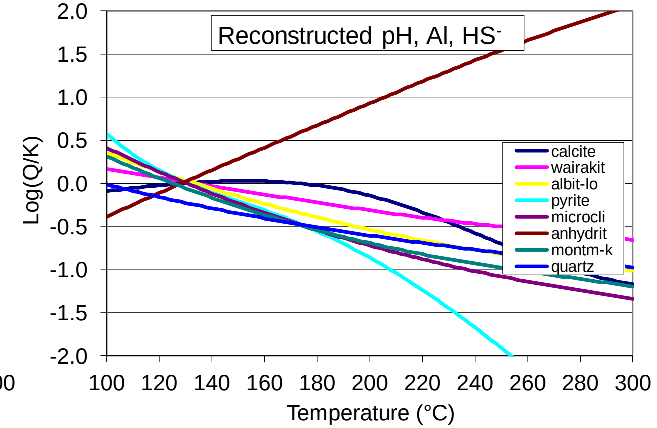


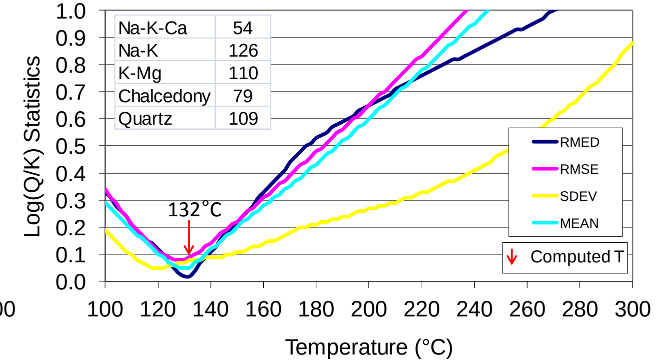
Bigelow (1% dilution)





Terwilliger (26% dilution)





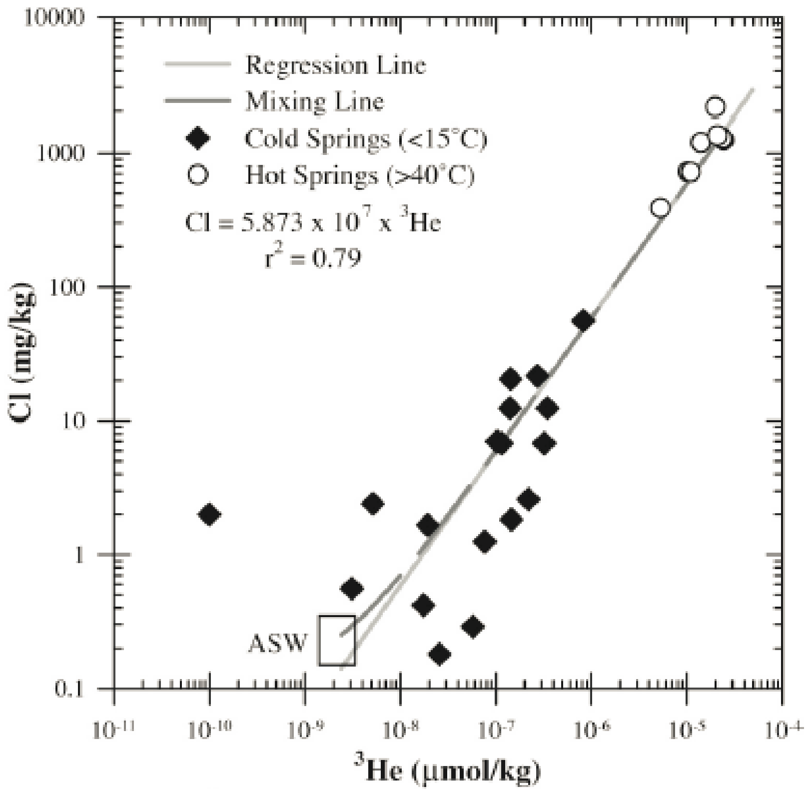
Convergence at T ~ 130-140 C

Simultaneous regression
Solve for Al and dilution factor
HS set with pyrite equilibrium

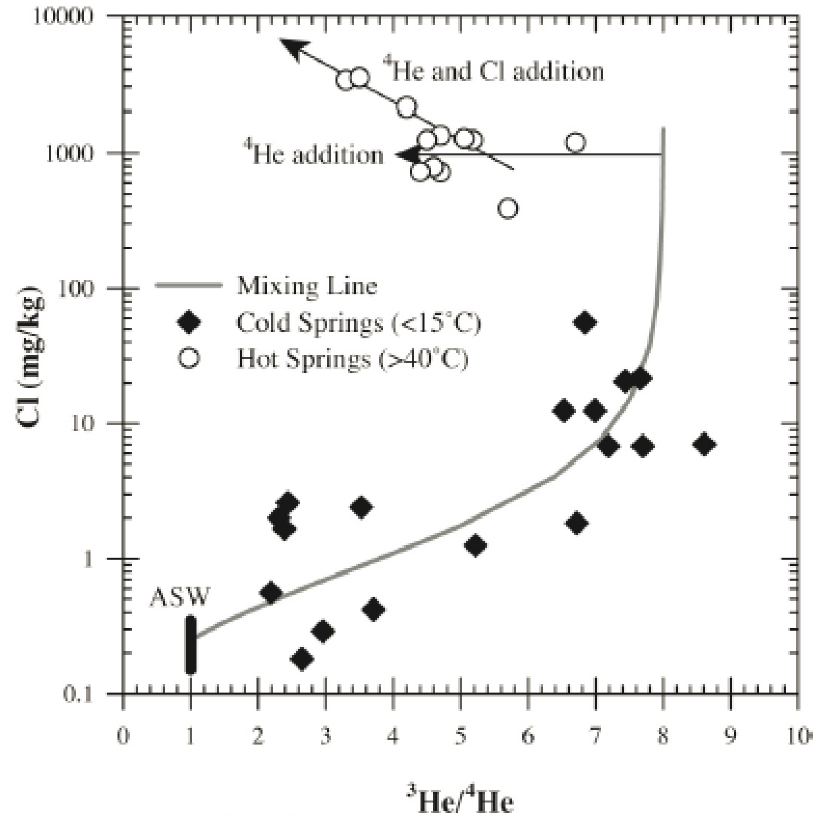
Geo-T: http://esd.lbl.gov/research/projects/geot/

Results

Helium – Chloride Co-Variations:
Oregon Cascade Thermal Springs and Three Sisters Area Cold springs



Strong correlation between concentration of magmatic ^3He and Chloride



Lack of similar correlation with $^3He/^4He$ ratios suggests Cl-rich fluids, which contain more ^4He, are more evolved or passed through different lithology

Future Directions

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- Our strategy is intended to provide focus for followup exploration and development in this area of possible high geothermal potential. Table presents project year plan going forward.
- Future activities for FY2015:
  - Complete cataloging of possible geothermally-relevant low-resistivity upwellings.
  - ID of new faulting esp. to south in area, dilatency analysis for permeability potential.
  - Spring chemistry modeling esp. to south in area, interp. of ultimate fluid sources.
  - Derivation of characteristic geothermal model(s) for Central Cascadia.
  - Presentation of possible play areas for followup assessment.
  - Identification of data needs and next steps in this region of sparse knowledge.

Summary

- Central Cascades should have high geothermal potential given confluence of subduction arc and extensional magmatism.
- Integration of MT resistivity, structural analysis and fluid geochemistry constitutes methodology for prioritizing exploration and play ranking.
- Low-resistivity upwellings resolved using new MT inversion capability may point toward shallower high temperatures and fluids.
- New LiDAR and high-res DEM data are allowing identification of hidden recent faulting, NW cross-arc trends, and structural setting for dilatency assessment.
- State-of-the-art geochemical modeling allows equilibrium or reaction-based subsurface fluid temperature estimates with rigor beyond standard geothermometry.
- PFA will move southward from Mt Jefferson-Three Sisters area as project progresses.
- Central Cascades suffers from data sparseness which needs to be addressed going forward.