Machine Learning for Geothermal Resource Analysis and Exploration

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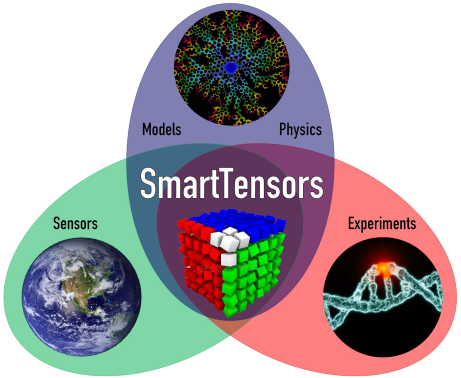
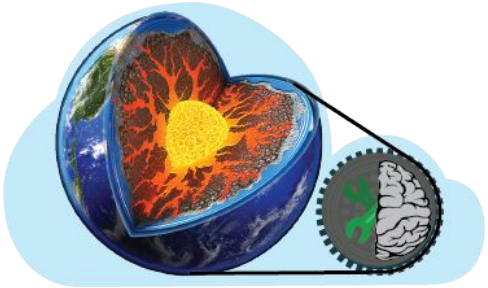
NMF*k*

NTF*k*



GeoThermalCloud



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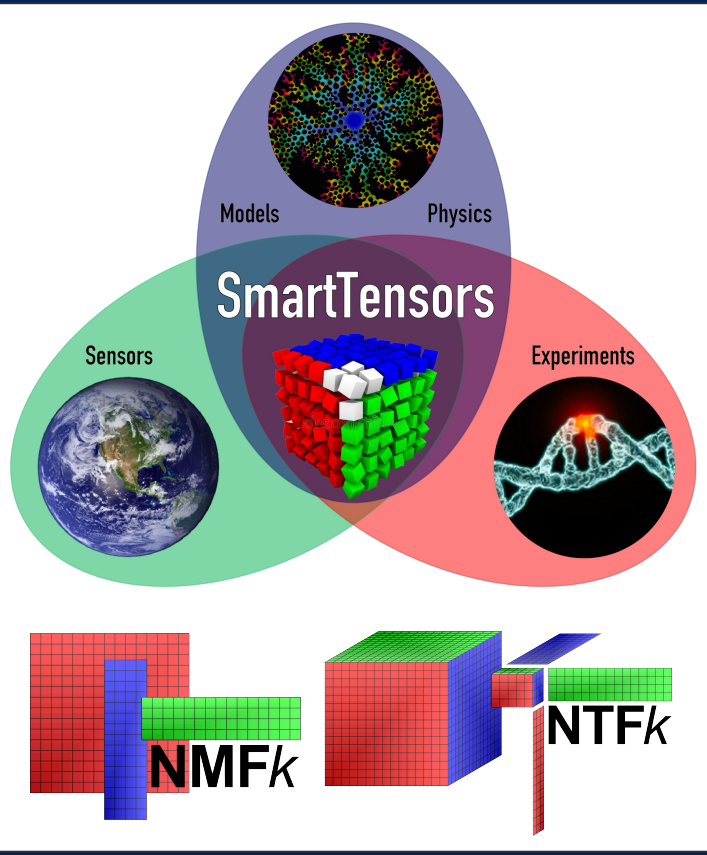
Machine Learning (ML) methods

- **Supervised** ML: learns everything from data
  - ⇒ requires big training datasets
  - ⇒ highly impacted by noise
- **Physics-informed** ML: learns from data but includes preconceived knowledge about the governing processes
  - ⇒ requires smaller training datasets
  - ⇒ produces better predictability with lower uncertainty
  - ⇒ robust to data noise
- **Unsupervised** ML: extracts features from data that can be applied for categorization and prediction
  - ⇒ unbiased analyses not impacted by data labeling, subject-matter-expert opinions, and physics assumptions
  - ⇒ however, physics constraints can be added

SmartTensors

- Novel LANL-patented open-source ML toolbox
- Unsupervised and Physics-Informed Machine Learning (ML)
- Based on matrix/tensor factorization coupled with custom k-means clustering
- Allows for nonnegativity/sparsity/physics constraints:
  - NMFk: Nonnegative **Matrix** Factorization
  - NTFk: Nonnegative **Tensor** Factorization
  - https://github.com/TensorDecompositions
- Capable to efficiently process large datasets (TB's) utilizing GPU's, TPU's & FPGA's
  - Flux.jl, AutoOffLoad.jl, TensorFlow, PyTorch

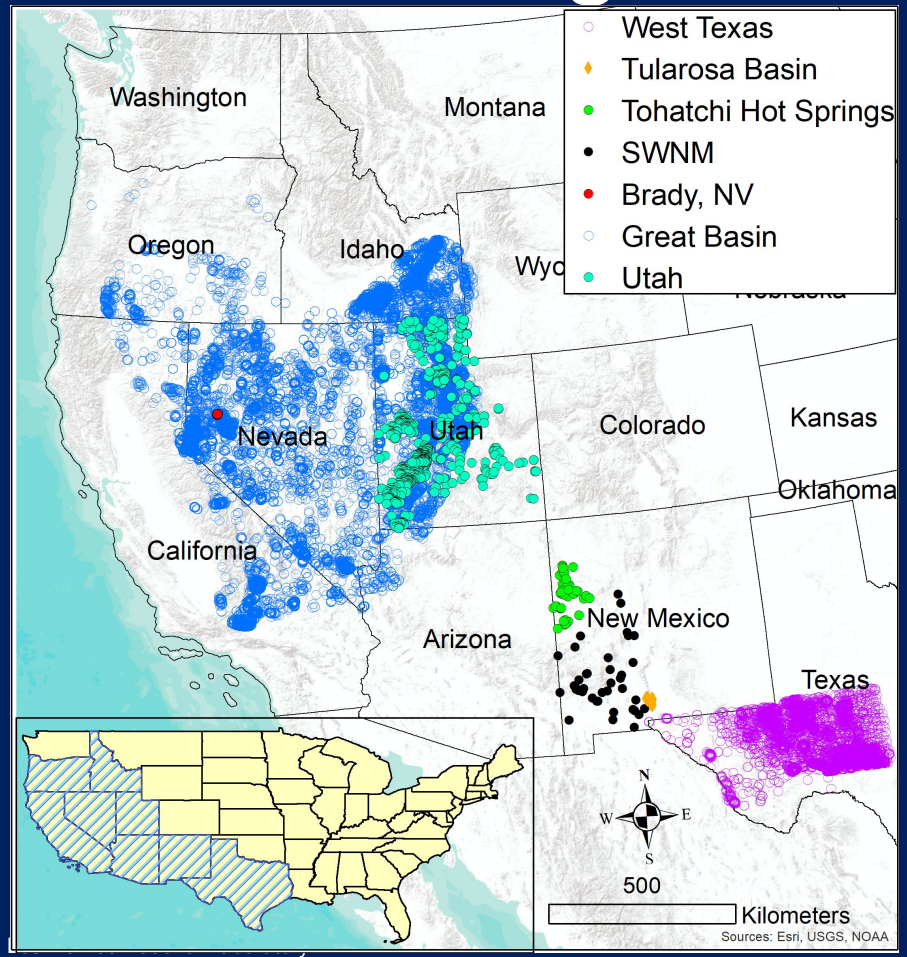


SmartTensors Applications

- **Field Data**:
  - Contamination
  - Climate
  - Geothermal
  - Seismic
  - Oil/gas production
  - CO_2 sequestration
  - **Wildfires** (California 2020)
  - **COVID-19**
- **Lab Data**:
  - X-ray Spectroscopy
  - UV Fluorescence Spectroscopy
  - Microbial population analyses
  - Isotope fractionation

- **Operational Data**:
  - LANSCE: Los Alamos Neutron Accelerator
  - Oil/gas production
  - CO_2 sequestration
- **Model Outputs**:
  - Reactive mixing $A + B \rightarrow C$
  - Phase separation of co-polymers
  - Molecular Dynamics of proteins
  - Climate
  - CO_2 sequestration
  - Wildfires

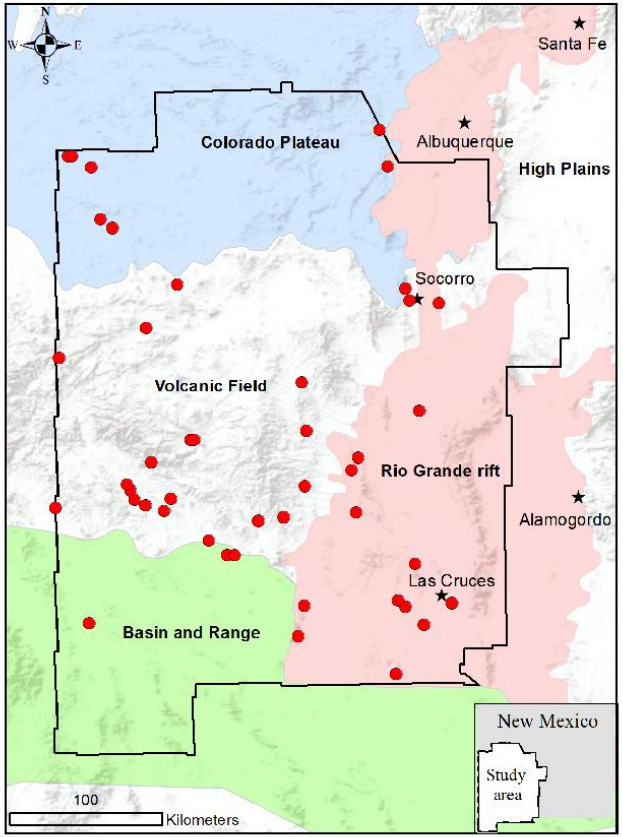
GTcloud: ML geothermal exploration



- **Diverse datasets incorporated and analyzed:**
  - **geochemistry data (Great Basin)**
  - **geothermal, geophysical, geochemistry, and geological data (NV, UT, CA, NM, TX, HI)**
- **Innovative LANL-developed (patented) open-source ML methods (SmartTensors) applied (http://tensors.lanl.gov)**
- **Hidden signatures (signals) and dominant attributes critical for exploration of hidden geothermal resources have been identified (extracted)**

GTcloud: ML geothermal exploration

Southwest NM
(Stanford & GRC, 2020)



GTcloud: ML geothermal exploration

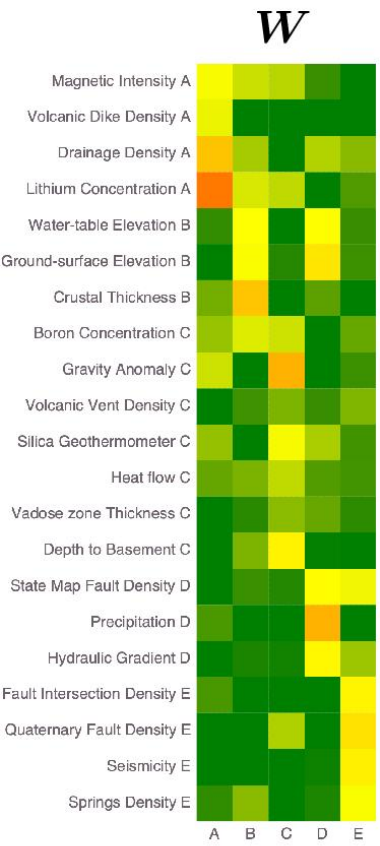
X^T $[44 \times 21]$
[locations × attributes]

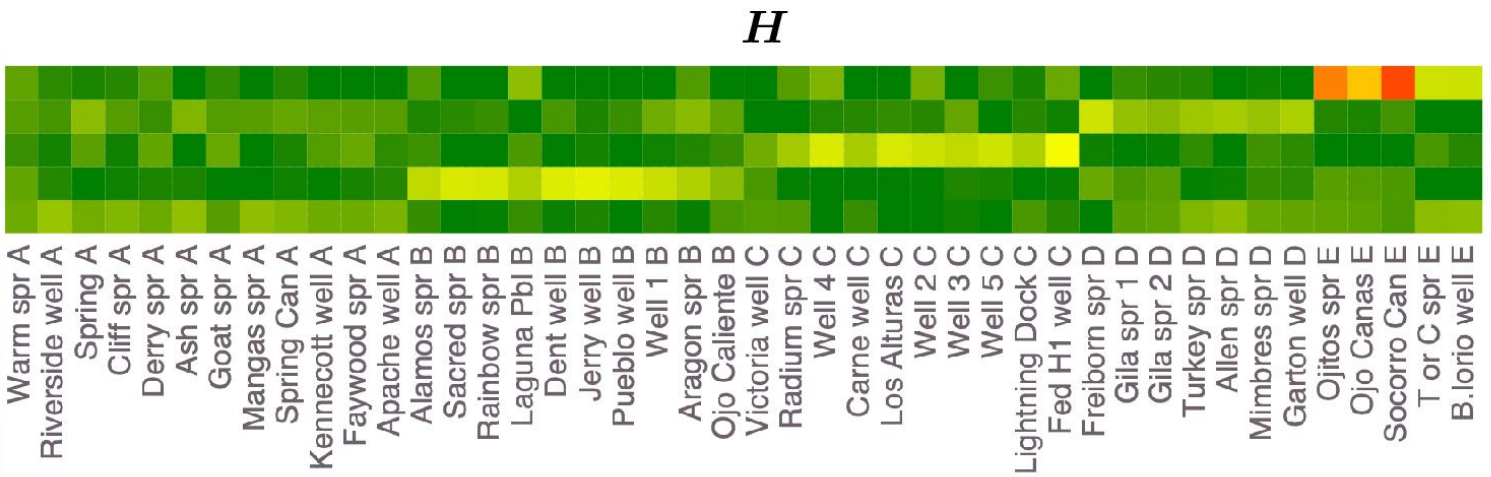
- Boron Concentration
- Gravity Anomaly
- Magnetic Intensity
- Volcanic Dike Density
- Drainage Density
- Fault Intersection Density
- Quaternary Fault Density
- Seismicity
- State Map Fault Density
- Springs Density
- Volcanic Vent Density
- Lithium Concentration
- Precipitation
- Silica Geothermometer Temp
- Hydraulic Gradient
- Watertable Elevation
- Heat flow
- Elevation
- Watertable Depth
- Crustal Thickness
- Depth to Basement

[Pepin, 2019]

Location	Boron	Gravity	Magnet	Dikes	Drain	Fault	Qfault	Seism	NMFlt	Springs	Vents	Lithium	Precip	Silica	Δh	WT	Qheat	Elev	DTW	Crust	Bsmt
Alamos Spring	-0.2	-203.3	136.2	0.431	7.4	0.000	0.00	0.004	16.2	0.010	0.003	-3.1	264.8	16.5	5.6	5812	4.6	1763	-21.5	38.7	1439
Allen Springs	-3.2	-189.3	184.6	3.625	17.3	0.000	0.01	0.002	15.6	0.003	0.001	-4.0	514.5	24.0	13.9	5994	4.4	1805	-20.1	32.5	51
Apache Tejo Warm Springs well	-1.8	-181.2	15.0	3.807	17.3	0.001	0.03	0.001	0.7	0.003	0.000	-8.6	326.3	52.0	4.7	5261	4.6	1641	34.6	30.7	24
Aragon Springs	1.5	-229.1	-317.7	0.010	19.0	0.000	0.00	0.000	41.1	0.005	0.003	-7.5	387.0	56.5	4.0	6981	4.5	2094	-30.1	38.8	1486
Ash Spring	-2.7	-193.2	66.6	4.914	17.0	0.000	0.00	0.002	9.3	0.003	0.000	-5.0	492.0	29.3	4.1	5712	4.4	1806	71.9	32.2	-92
B. Iorio 1 well	-2.1	-196.5	-48.2	1.936	18.8	0.057	21.02	0.000	9.1	0.003	0.003	-2.6	260.4	59.4	0.9	4240	4.0	1298	7.7	30.9	-188
Cliff Warm Spring	-2.5	-199.1	-47.1	1.290	22.8	0.001	2.58	0.002	11.0	0.002	0.001	-6.9	364.2	64.2	1.8	4546	4.2	1378	-6.7	33.1	-191
Dent windmill well	-2.1	-230.8	89.3	0.000	13.4	0.000	0.00	0.000	0.0	0.005	0.000	-7.3	341.7	19.7	2.4	6600	4.7	2108	94.3	43.5	865
Derry Warm Springs	-1.5	-161.6	197.0	0.659	18.3	0.007	9.16	0.000	15.9	0.002	0.000	-7.5	276.1	37.4	3.0	4183	4.6	1391	130.5	30.0	-120
Faywood Hot Springs	-2.6	-172.1	-49.8	0.939	16.6	0.002	2.81	0.000	1.9	0.003	0.000	-4.8	346.4	67.2	4.2	4910	5.5	1548	49.6	30.0	619
Federal H 1 well	-0.4	-132.0	35.0	0.000	5.8	0.004	20.31	0.001	7.2	0.000	0.015	-5.0	253.8	78.7	2.7	4104	4.9	1315	68.1	27.3	2906
Freiborn Canyon Spring	-2.5	-225.0	-242.0	0.401	13.1	0.000	0.00	0.001	19.8	0.001	0.004	-12.6	538.6	49.8	13.0	7123	4.6	2207	30.9	38.4	1138
Garton well	-3.2	-196.8	35.6	0.150	18.0	0.000	0.00	0.000	28.9	0.002	0.001	-5.0	489.9	70.0	4.3	6165	3.9	2037	146.4	30.9	-266
Gila Hot Springs 1	-1.9	-221.6	-149.3	0.127	24.2	0.000	0.00	0.001	25.5	0.003	0.003	-7.8	422.6	69.9	6.6	5867	4.4	1773	-25.7	34.0	413
Gila Hot Springs 2	-1.8	-222.9	-138.8	0.112	24.7	0.000	0.00	0.001	23.7	0.003	0.003	-6.7	425.9	70.8	3.2	5921	4.6	1811	-1.5	33.9	519
Goat Camp Spring	-2.1	-159.2	-29.7	0.751	10.0	0.001	2.22	0.007	10.6	0.002	0.001	-8.0	344.0	68.9	5.8	4480	4.4	1357	5.8	32.4	19
Jerry well	-0.8	-219.6	172.4	0.111	15.5	0.000	0.00	0.000	6.3	0.004	0.005	-7.9	243.9	13.4	1.0	6360	4.4	1947	6.3	42.3	1190
Kennecott Warm Springs well	-2.4	-178.3	-69.9	1.422	17.8	0.002	1.76	0.000	1.1	0.003	0.000	-6.9	355.0	66.1	4.3	4890	5.0	1520	28.9	30.0	409
Laguna Pueblo	0.4	-204.2	62.5	0.406	8.6	0.004	4.58	0.006	14.6	0.018	0.005	-3.3	259.7	42.9	2.6	5364	4.4	1628	-13.5	37.2	1506
Lightning Dock	-1.0	-168.0	-168.1	0.086	4.6	0.008	8.40	0.002	4.3	0.000	0.000	-3.9	291.5	107.3	0.8	4147	5.0	1278	14.3	29.8	1800
Los Alturas Estates	-1.5	-141.4	-127.5	0.004	7.6	0.003	0.05	0.002	6.6	0.001	0.000	-12.7	265.3	71.9	2.2	3892	6.3	1279	102.9	27.4	4321
Mangas Springs	-2.6	-201.0	-227.1	3.503	20.2	0.000	0.91	0.002	11.5	0.002	0.000	-4.5	393.5	53.6	0.3	4784	4.2	1459	-5.0	32.4	-178
Mimbres Hot Springs	-2.3	-200.6	43.4	0.670	15.4	0.002	1.13	0.000	19.0	0.004	0.000	-3.8	445.9	68.3	9.1	5914	4.9	1834	66.4	31.0	50
Ojitos Springs	-1.6	-202.1	-7.5	1.342	19.6	0.044	19.74	0.037	31.0	0.020	0.005	-4.5	257.5	57.6	7.2	5227	4.5	1594	2.3	33.0	-255
Ojo Caliente	-2.6	-226.5	-168.4	0.000	20.5	0.000	0.00	0.000	8.3	0.004	0.000	-2.9	333.6	48.4	3.5	6263	5.5	1987	74.0	33.8	2415
Ojo De las Canas	-1.7	-188.5	-85.8	0.839	22.3	0.036	12.55	0.036	28.0	0.013	0.003	-6.0	270.5	14.2	4.0	5003	4.5	1585	54.7	31.8	101
Pueblo windmill well	-1.2	-228.8	315.9	0.029	15.2	0.000	0.00	0.000	6.1	0.004	0.003	-12.0	265.8	18.3	2.9	6419	4.3	1963	6.0	42.5	1027
Radium Hot Springs	-0.8	-151.4	-7.8	0.010	8.8	0.013	11.40	0.003	10.6	0.001	0.000	-5.3	264.2	63.6	0.3	3982	5.4	1229	24.4	28.2	1191
Rainbow Spring	-1.7	-227.1	-48.5	0.000	11.0	0.000	0.00	0.001	0.0	0.006	0.000	-7.0	307.8	21.7	3.3	6269	4.7	1955	52.0	43.9	755
Riverside Store well	-1.3	-196.1	-102.9	1.562	22.6	0.000	2.50	0.002	11.7	0.002	0.001	-2.4	356.1	60.8	0.9	4489	4.3	1368	2.8	32.9	-165
Sacred Spring	-1.8	-228.4	-80.4	0.000	10.9	0.000	0.00	0.001	0.0	0.006	0.000	-7.0	298.4	21.2	1.3	6271	4.6	1940	29.7	43.9	742
Socorro Canyon	-1.8	-204.7	-136.5	1.203	21.1	0.051	28.88	0.034	33.8	0.020	0.005	-6.7	284.1	44.6	11.1	5237	5.0	1692	67.7	32.6	-229
Spring	-4.1	-183.5	334.5	0.218	20.1	0.011	1.81	0.000	20.1	0.001	0.006	-6.8	361.9	117.2	5.1	5472	3.8	1759	88.1	31.5	-104
Spring Canyon Warm Spring	-2.1	-194.2	117.3	2.293	21.9	0.000	1.50	0.002	12.7	0.002	0.000	-8.3	361.7	51.6	5.8	4576	4.2	1457	60.2	32.6	-57
Truth or Consequences spring	-1.1	-168.2	-54.3	2.175	18.4	0.064	20.51	0.000	10.3	0.003	0.002	-3.3	265.9	55.3	0.6	4255	4.3	1293	-8.4	31.0	304
Turkey Creek Spring	-3.2	-196.4	54.8	0.984	19.2	0.001	3.69	0.002	28.1	0.002	0.002	-3.7	493.4	81.3	5.8	5478	4.4	1718	7.7	33.6	56
Victoria Land and Cattle Co. well	-1.8	-165.9	-65.4	0.478	6.4	0.003	0.06	0.001	0.9	0.001	0.000	-2.9	253.0	43.0	1.9	4762	4.1	1461	9.6	30.7	2014
Warm Springs	-2.1	-193.3	113.5	0.220	19.0	0.029	2.63	0.000	16.5	0.004	0.003	-2.5	314.6	56.0	5.4	5777	4.3	1797	-1.7	32.7	1252
Well 1	-1.4	-230.7	-31.3	1.190	15.7	0.000	0.75	0.001	22.1	0.004	0.002	-6.6	345.4	49.0	1.7	7382	4.4	2249	1.8	40.0	1961
Well 2	-1.2	-162.5	0.8	0.000	4.5	0.008	24.24	0.003	11.8	0.000	0.006	-10.1	279.5	70.5	1.7	4291	4.8	1355	49.7	27.8	2993
Well 3	-2.5	-140.0	31.7	0.839	2.1	0.001	2.11	0.001	5.0	0.001	0.000	-7.3	369.0	51.0	4.1	4765	4.3	1907	431.7	28.0	3073
Well 4	-1.3	-161.7	-56.1	0.000	3.4	0.008	28.49	0.003	10.6	0.000	0.006	-10.0	274.3	94.0	1.9	4082	4.7	1338	91.3	27.7	3373
Well 5	-1.9	-167.2	-29.9	0.000	2.5	0.008	15.48	0.002	3.1	0.000	0.005	-6.8	243.8	47.0	0.3	3839	4.0	1276	106.1	27.4	5460
Well south of Carne	-2.4	-156.7	-129.6	0.457	4.3	0.000	2.11	0.002	6.0	0.001	0.000	-6.8	269.7	87.1	1.4	4109	4.5	1275	13.5	28.4	2761

GTcloud: ML geothermal exploration





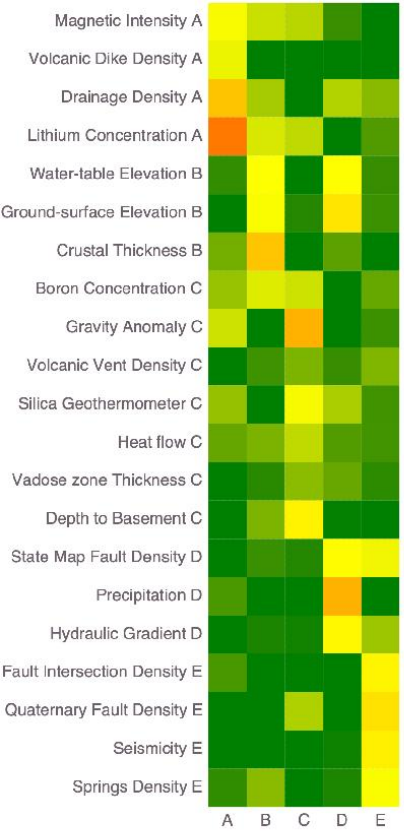
$$X = W \times H$$

5 signatures extracted (A, B, C, D, E)

W: mapping of the **signatures** to geothermal **attributes**

H: mapping of the **signatures** to geothermal **locations**

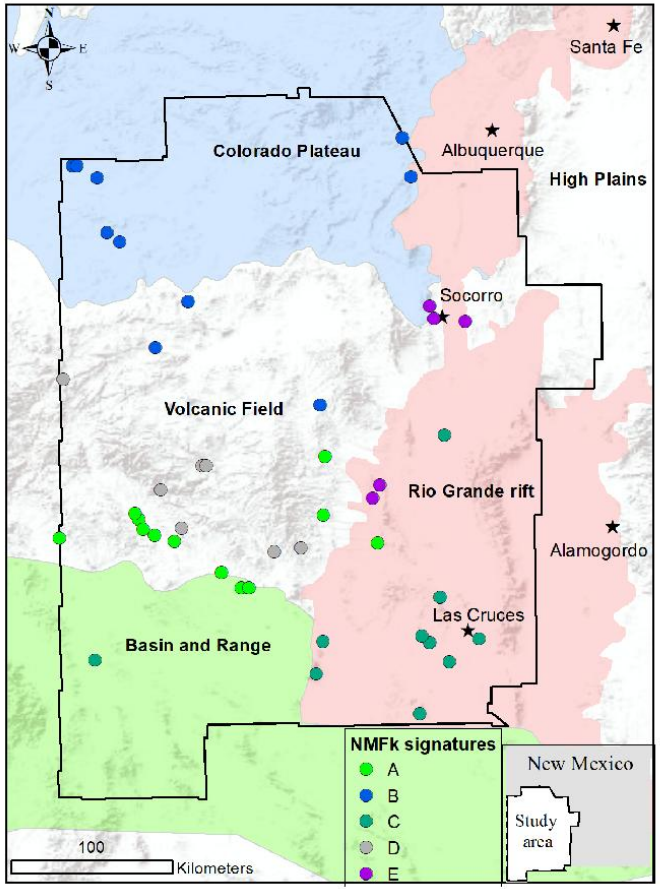
GTcloud: ML geothermal exploration



Physics interpretation:

- **Signature C: Deep heat flow**
  - Volcanic Vent Density
  - Gravity Anomaly
  - Heat flow
  - Silica Geothermometer
  - Watertable Depth
  - Depth to Basement
  - Boron
- **Signature A: Shallow heat flow**
  - Volcanic Dike Density
  - Magnetic Intensity
  - Drainage Density
  - Lithium
- **Signature B: Lateral hydraulics**
  - Water-table Elevation
  - Ground-surface Elevation
  - Crustal Thickness
- **Signature D: Vertical hydraulics**
  - Precipitation
  - Hydraulic Gradient
  - State Map Fault Density
- **Signature E: Tectonics**
  - Seismicity
  - Fault Intersection Density
  - Quaternary Fault Density
  - Springs Density

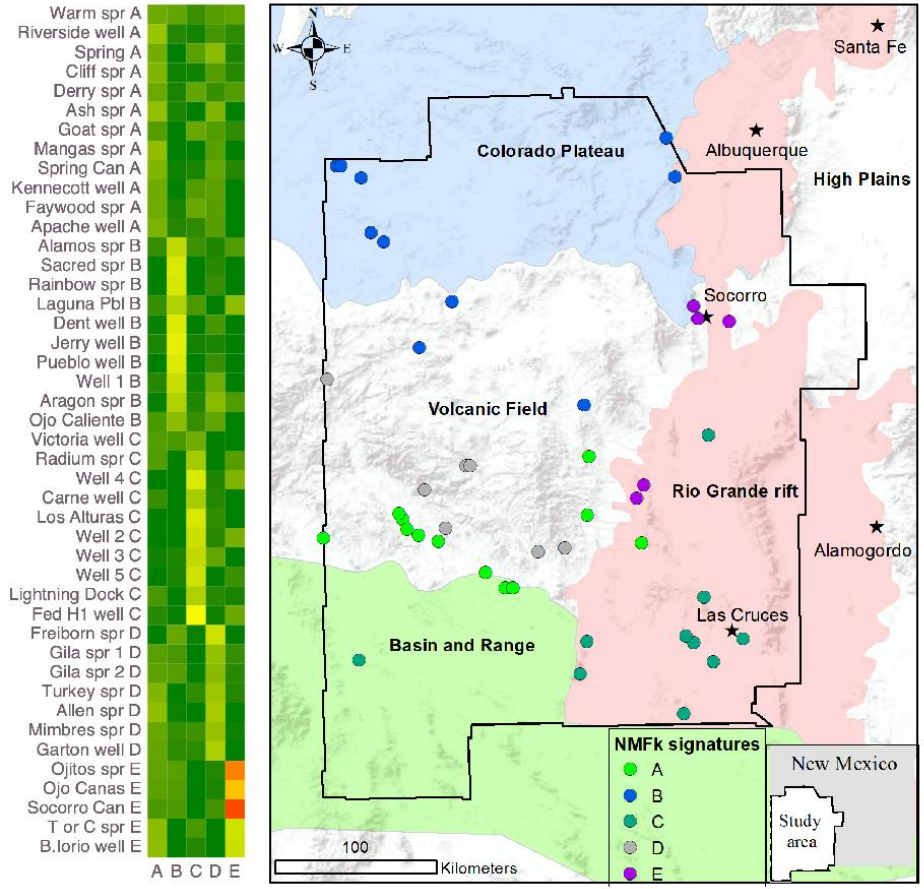
GTcloud: ML geothermal exploration



Province association:

- Signature B: **Colorado Plateau**
- Signature C: **Basin and Range**
- Signature D: **Volcanic Field #1**
- Signature A: **Volcanic Field #2**
- Signature E: **Rift Zone**

GTcloud: ML geothermal exploration



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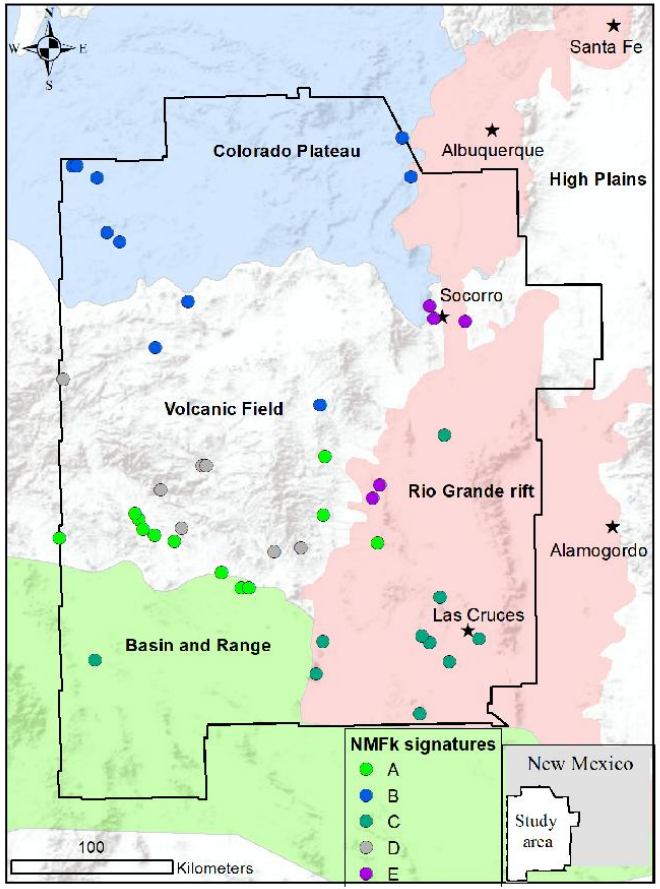
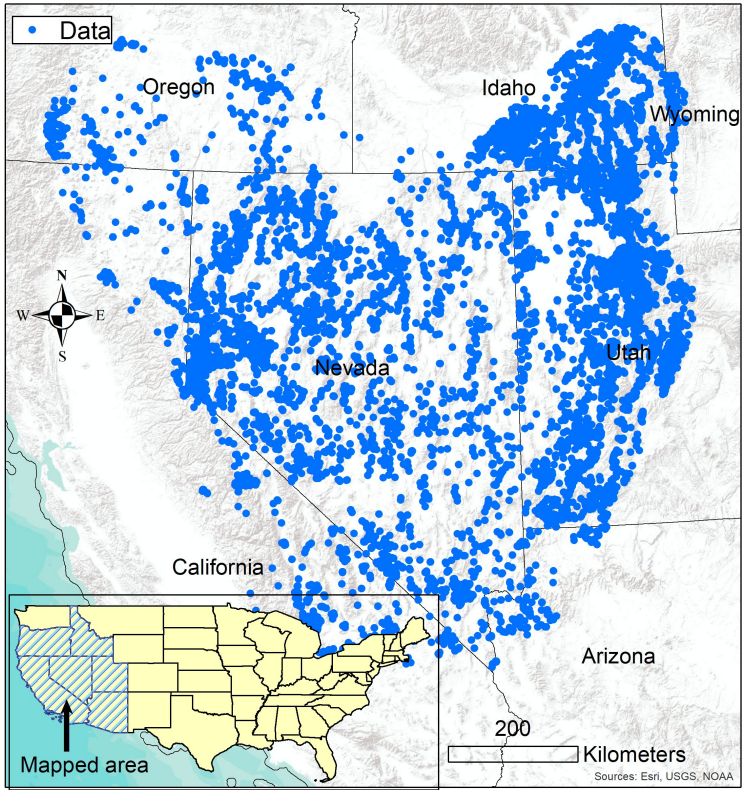


Physics/province association:

- Signature B:
  Colorado Plateau ⇔ Lateral hydraulics
- Signature C:
  Basin and Range ⇔ Deep heat flow
- Signature D:
  Volcanic Field #1 ⇔ Vertical hydraulics
- Signature A:
  Volcanic Field #2 ⇔ Shallow heat flow
- Signature E:
  Rift Zone ⇔ Tectonics

GTcloud: Great Basin



Study area with 14,258 data points

- **Geochemical data are easier to collect compared to geophysical and well-logging data**
- **Geochemistry provides critical inference during early stage of geothermal exploration**
- **Geochemistry can be applied to infer reservoir temperatures, geothermal conditions, reservoir boundaries, and heat source type (e.g., meteoric, magmatic, mixed)**
- **Geochemistry also represents water / rock interaction**

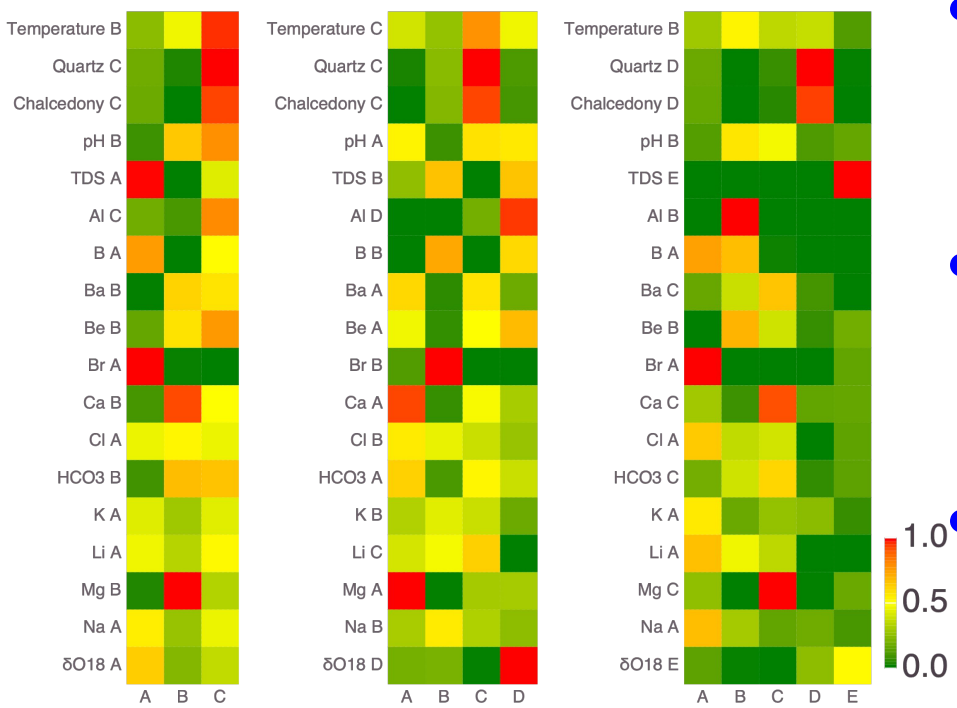
GTcloud: Great Basin Data Attributes

Attribute	Minimum	Mean	Maximum	Missing (%)
Groundwater temperature (℃)	0.1	23.7	275	2.6
Quartz geothermometer (℃)	-50.8	81.0	273	39.1
Chalcedony geothermometer (℃)	-81.6	50.3	271	39.1
pH	1	7.5	11.7	35.0
TDS (total dissolved solid) (PPM)	0	5770	329000	87.8
Al^{3+} (PPM)	0	7.3	6400	90.5
B^{+} (PPM)	0	3.1	590	61.7
Ba^{2+} (PPM)	0	0.1	27.4	82.4
Be^{2+} (PPM)	0	0	0.7	88.5
Br^{-} (PPM)	0	2.0	84	86.4
Ca^{2+} (PPM)	0	97.0	2570	33.6
Cl^{-} (PPM)	0	2870	240000	29.2
HCO_3^{-} (PPM)	0	278	37000	76.1
K^{+} (PPM)	0	101	13000	40.8
Li^{+} (PPM)	0	4.95	970	80.3
Mg^{2+} (PPM)	0	86.8	8500	34.8
Na^{+} (PPM)	0	1960	160000	38.2
$\delta^{18}O$ (‰)	-19.2	-14.6	7.8	89.7

- 18 data attributes
- 14,258 locations
- Matrix size: 14,258 x 18
- Dataset is sparse
- Dataset is normalized (bringing attribute values to a common scale)

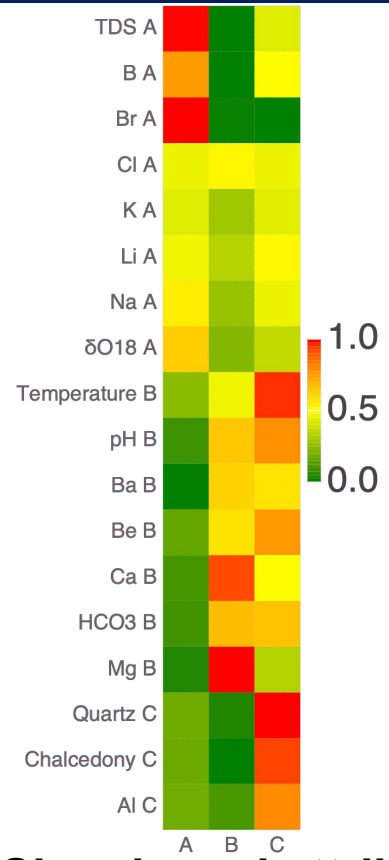
GTcloud: Extracted Great Basin Geothermal Signatures

Three signals **Four signals** **Five signals**



- **Three signals:** low- (A), medium- (B), and high-temperature (C) resources
- **Four signals:** low- (B), medium- (A,D), (A) and high-temperature (C) resources
- **Five signals:** low- (E), medium- (A,C,D), and high-temperature (B) resources

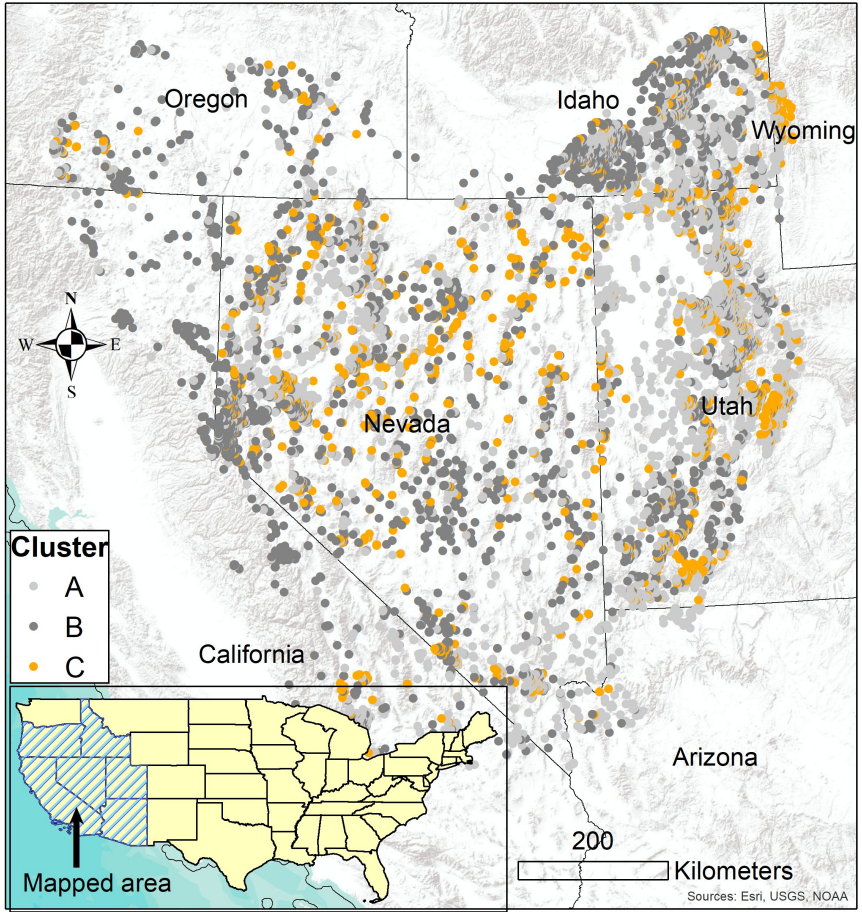
GTcloud: Significance of Great Basin Signatures



Signals and attributes

- **A: Low-temperature resource**
  - **TDS, B, Br**
- **B: Medium-temperature resource**
  - **Cl, pH, Ba, Ca, HCO3, Mg**
- **C: High-temperature resource**
  - **pH, Be, HCO_3, Quartz and Chalcedony geothermometers, Al**

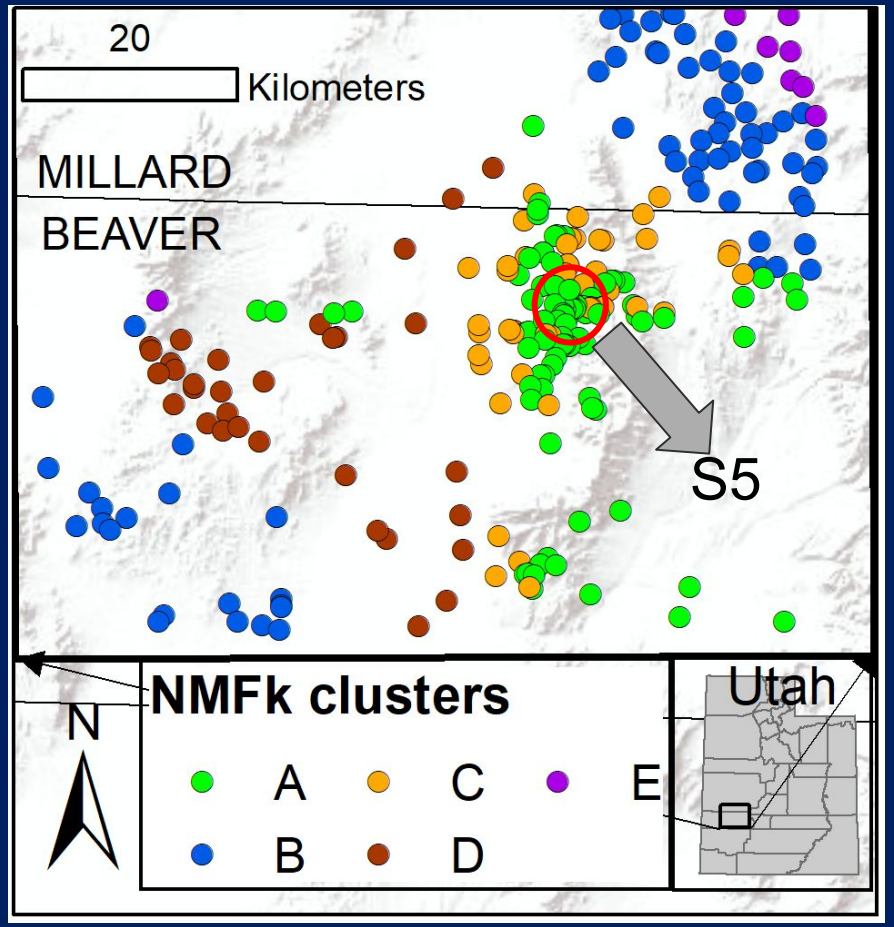
GTcloud: Spatial Distribution of Great Basin Signatures

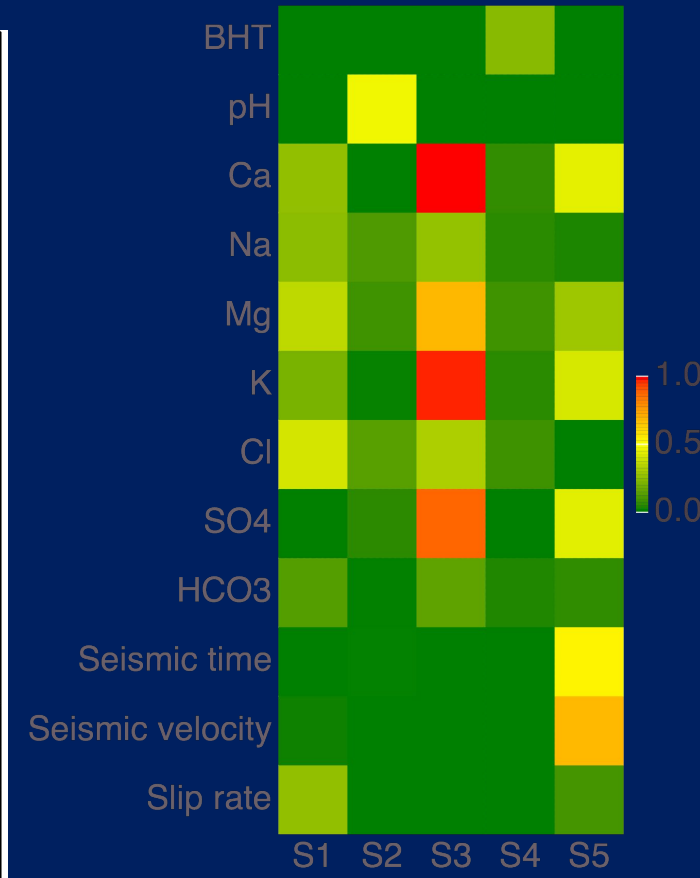


- ML also estimates the spatial distribution of hidden geothermal signatures
- Spatial distribution of the signatures represents spatial extent of different hidden geothermal resources
  - C: high-temperature
  - B: medium-temperature
  - A: low-temperature

GTcloud: ML geothermal exploration

Utah Forge
(GRC, 2020)



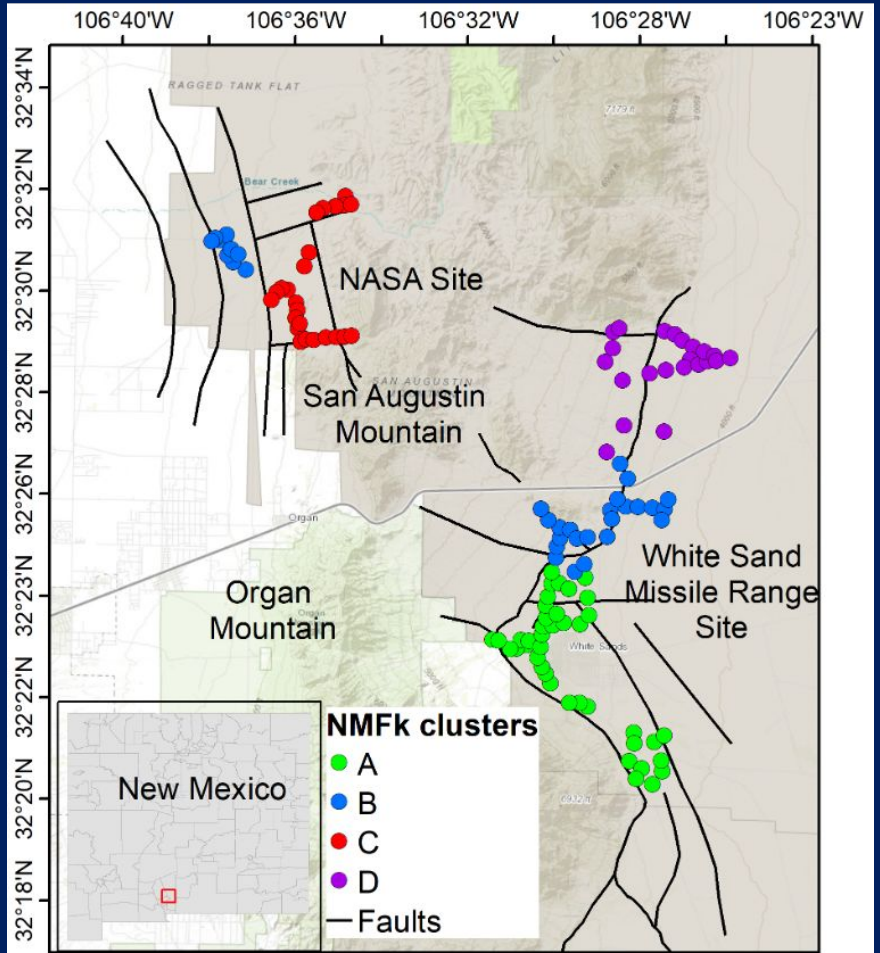


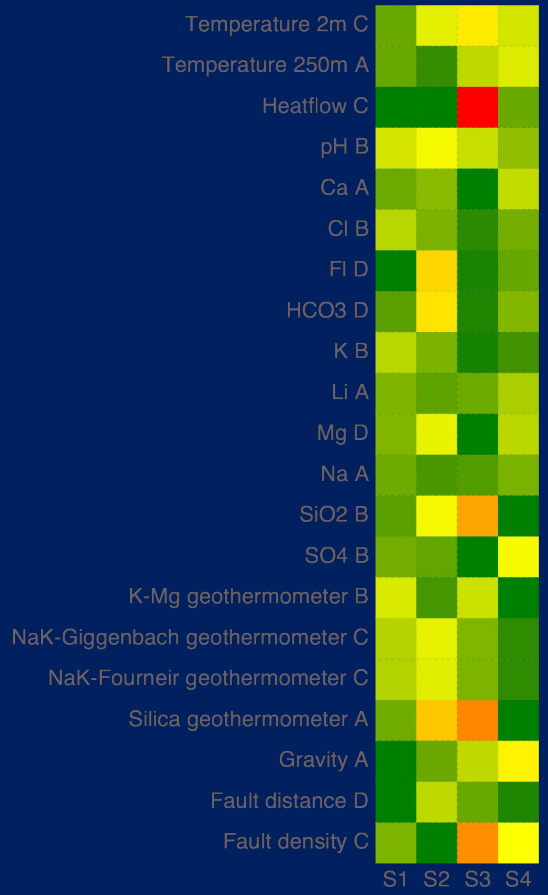
Hidden signals

GTcloud: ML geothermal exploration

Tularosa Basin

(GRC, 2020)

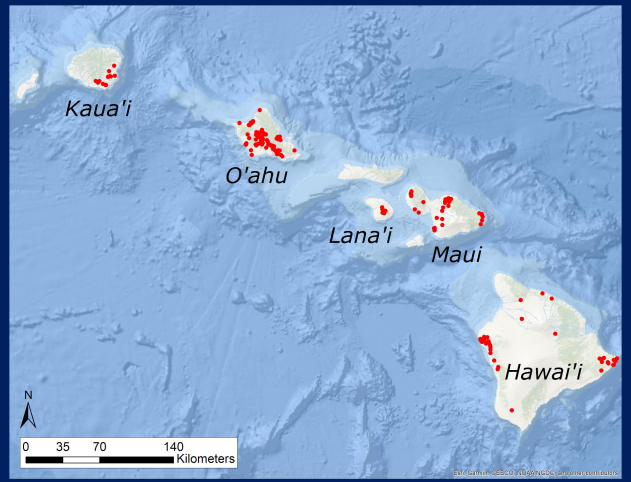




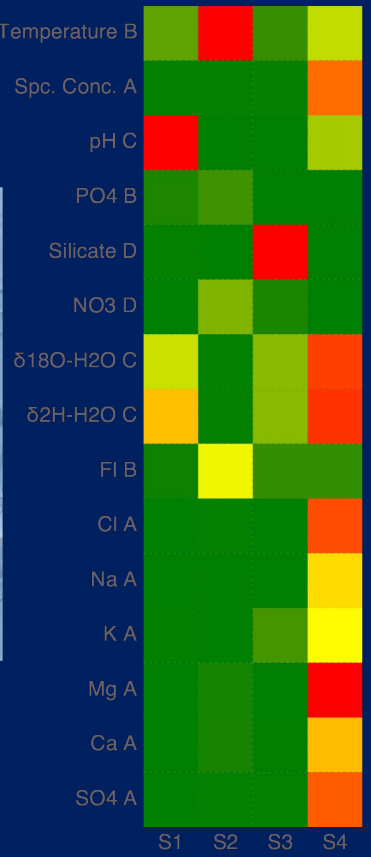
Hidden signals

GTcloud: ML geothermal exploration

Hawaii Islands
(GRC, 2020)



Sampling locations



Hidden signals @ Oahu Island

- geophysical, geological, and geochemistry datasets processed
- Hawaii islands analyzed simultaneously and jointly
- dominant attributes associated with each island discovered

Summary

- **SmartTensors**: Novel LANL-patented open-source ML toolbox for unsupervised and Physics-Informed Machine Learning
- **SmartTensors** have been used to solve various real-world problems
- **SmartTensors** examples, tests, notebooks, papers, presentations, applications:
  - http://madsjulia.github.io/Mads.jl/Examples/blind_source_separation_http://tensors.lanl.gov
  - http://tensordecompositions.github.io
  - https://github.com/TensorDecomositions
  - https://hub.docker.com/u/montyvesselinov