SWNM

May 1, 2021

0.1 Geothermal machine learning analysis: Southwest New Mexico

This notebook is a part of the GeoThermalCloud.jl: Machine Learning framework for Geothermal Exploration.

<img src="../logos/geothermalcloud-small.png" alt="geothermalcloud" width=25% max-width=125px

Machine learning analyses are performed using the **SmartTensors** machine learning framework.

This notebook demonstrates how the **NMFk** module of **SmartTensors** can be applied to perform unsupervised geothermal machine-learning analyses.

More information on how the ML results are interpreted to provide geothermal insights is discussed in our research paper.

0.2 Introduction

Southwest New Mexico (**SWNM**) is a region important for geothermal exploration.

SWNM is broadly divided into four physiographic provinces: - the Colorado Plateau - the Mogollon-Datil Volcanic Field (MDVF) - the Basin and Range, and - the Rio Grande rift.

Each of the **SWNM** physiographic provinces is associated with different types of unique hydrothermal systems with temperatures ranging from low (<90℃) to medium (90-150℃).

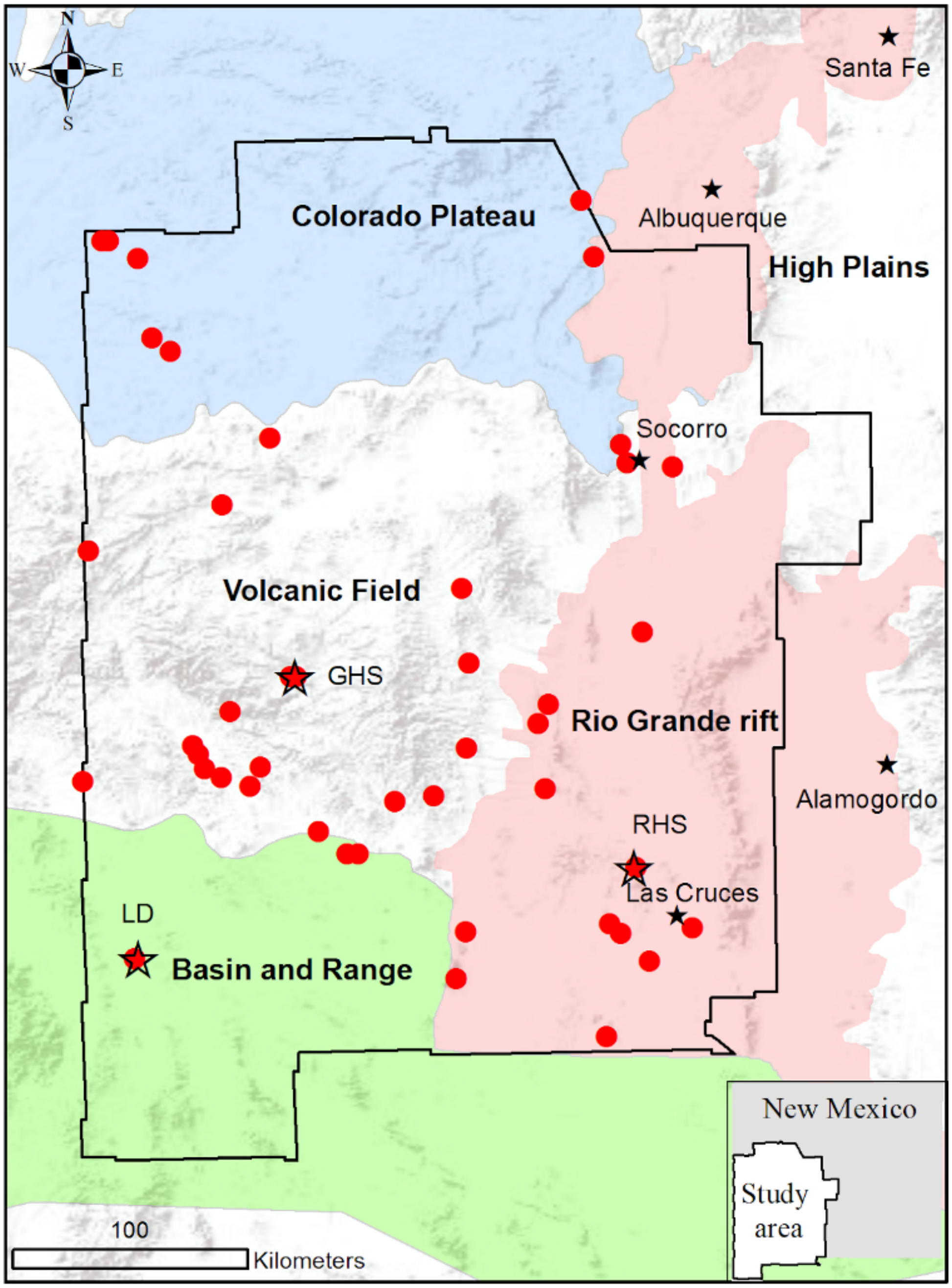
Some of the **SWNM** systems are already utilized for commercial and recreational purposes.

There are already energy-production facilities for both electricity and direct-use heating.

For example, the Basin and Range province has one geothermal power plant (Lightning dock) of gross ~14 MWe power, five greenhouse farms, and numerous medium-temperature wells and springs. There are 14 spas and recreational facilities utilizing the **SWNM** geothermal resources.

Recent Play Fairway Analysis (PFA) Phase I study of **SWNM** conducted at LANL revealed more potential geothermal resources.

The study area and the data collection locations are mapped below.



0.3 GeoThermalCloud installation

If **GeoThermalCloud** is not installed, first execute in the Julia REPL `import Pkg; Pkg.add("GeoThermalCloud"); import Pkg; Pkg.add("NMFk"); Pkg.add("Mads"); Pkg.add("DelimitedFiles"); Pkg.add("JLD"); Pkg.add("Gadfly"); Pkg.add("Cairo"); Pkg.add("Fontconfig")`.

[1]:
```
import GeoThermalCloud
import NMFk
import Mads
```

```julia
import DelimitedFiles
import JLD
import Gadfly
import Cairo
import Fontconfig
```

```
HTML{String}("<script>\n// Immediately-invoked-function-expression to avoid␣
↪global variables.\n(function() {\n    var warning_div = document.
↪getElementById(\"webio-warning-1871911905836905661\");\n    var hide =␣
↪function () {\n        var script = document.
↪getElementById(\"webio-setup-17652940122857074023\");\n        var parent =␣
↪script && script.parentElement;\n        var grandparent = parent && parent.
↪parentElement;\n        if (grandparent) {\n            grandparent.style.
↪display = \"none\";\n        }\n        warning_div.style.display = \"none\";
↪\n    };\n    if (typeof Jupyter !== \"undefined\") {\n        console.
↪log(\"WebIO detected Jupyter notebook environment.\");\n        // Jupyter␣
↪notebook.\n        var extensions = (\n            Jupyter\n            &&␣
↪Jupyter.notebook.config.data\n            && Jupyter.notebook.config.data.
↪load_extensions\n        );\n        if (extensions &&␣
↪extensions[\"webio-jupyter-notebook\"]) {\n            // Extension already␣
↪loaded.\n            console.log(\"Jupyter WebIO nbextension detected; not␣
↪loading ad-hoc.\");\n            hide();\n            return;\n        }\n    ␣
↪} else if (window.location.pathname.includes(\"/lab\")) {\n        // Guessing␣
↪JupyterLa\n        console.log(\"Jupyter Lab detected; make sure the @webio/
↪jupyter-lab-provider labextension is installed.\");\n        hide();\n        ␣
↪return;\n    }\n})();\n\n</script>\n<p\n    ␣
↪id=\"webio-warning-1871911905836905661\"\n    class=\"output_text␣
↪output_stderr\"\n    style=\"padding: 1em; font-weight: bold;\"\n>\n    Unable␣
↪to load WebIO. Please make sure WebIO works for your Jupyter client.\n    For␣
↪troubleshooting, please see <a href=\"https://juliagizmos.github.io/WebIO.jl/
↪latest/providers/ijulia/\">\n    the WebIO/IJulia documentation</a>.\n    <!--␣
↪TODO: link to installation docs. -->\n</p>\n")
```

```
Info: Precompiling NMFk [e40cd9e2-a1df-5d90-a1fa-603fdc3dbdd8]
@ Base loading.jl:1278
```

NMFk: Nonnegative Matrix Factorization + k-means clustering and physics

constraints
====

```
  _    _   _      _    _______   _
 |  \  | | |  \  /  | |  _____| | |  _
 | . \ | | | . \/ . | | |___    | | / /
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 | |  \  | | |    | | | |       | |\ \
 |_|   \_| |_|    |_| |_|       |_| \_\
```

```
NMFk performs unsupervised machine learning based on matrix decomposition
coupled with various constraints.
NMFk provides automatic identification of the optimal number of signals
(features) present in two-dimensional data arrays (matrices).
NMFk offers visualization, pre-, and post-processing capabilities.
```

```
Info: Installing pyqt package to avoid buggy tkagg backend.
@ PyPlot /Users/vvv/.julia/packages/PyPlot/XHEG0/src/init.jl:118
```

0.4 Load and pre-process the data

0.4.1 Setup the working directory containing the SWNM data

[2]:
```
cd(joinpath(GeoThermalCloud.dir, "SWNM"))
```

0.4.2 Load the SWNM data file

[3]:
```
d, h = DelimitedFiles.readdlm("data/Pepin_PCA_Input_Data_LANL.csv", ',';␣
↪header=true);
```

0.4.3 Define names of the data attributes (matrix columns)

[4]:
```
attributes_short = ["Boron"; "Gravity"; "Magnetic"; "Dikes"; "Drainage";␣
↪"FaultInter"; "QuatFaults"; "Seismicity"; "NMFaults"; "Springs"; "Vents";␣
↪"Lithium"; "Precip"; "Air_Temp"; "Silica"; "Subcrop"; "WT_Gradient";␣
↪"WT_Elev"; "Heatflow"; "GS_Elev"; "DTW"; "Crst_Thick"; "Bsmt_Depth"]
attributes_long = uppercasefirst.(lowercase.(["Boron Concentration"; "Gravity␣
↪Anomaly"; "Magnetic Intensity"; "Volcanic Dike Density"; "Drainage Density";␣
↪"Fault Intersection Density"; "Quaternary Fault Density"; "Seismicity";␣
↪"State Map Fault Density"; "Spring Density"; "Volcanic Vent Density";␣
↪"Lithium Concentration"; "Precipitation"; "Air Temperature"; "Silica␣
↪Geothermometer"; "Subcrop Permeability"; "Hydraulic Gradient"; "Watertable␣
↪Elevation"; "Heat flow"; "Groundsurface Elevation"; "Watertable Depth";␣
↪"Crustal Thickness"; "Depth to Basement"]))
attributes_long_new = uppercasefirst.(lowercase.(["Boron"; "Gravity anomaly";␣
↪"Magnetic intensity"; "Volcanic dike density"; "Drainage density"; "Fault␣
↪intersection density"; "Quaternary fault density"; "Seismicity"; "State map␣
↪fault density"; "Spring density"; "Volcanic vent density"; "Lithium";␣
↪"Precipitation"; "Air temperature"; "Silica geothermometer"; "Subcrop␣
↪permeability"; "Hydraulic gradient"; "Watertable elevation"; "Heat flow";␣
↪"Groundsurface elevation"; "Watertable depth"; "Crustal thickness"; "Depth␣
↪to basement"]))
attributes_ordered = ["Boron concentration", "Lithium concentration", "Drainage␣
↪density", "Spring density", "Hydraulic gradient", "Precipitation", "Gravity␣
↪anomaly", "Magnetic intensity", "Seismicity", "Silica geothermometer", "Heat␣
↪flow", "Crustal thickness", "Depth to basement", "Fault intersection␣
↪density", "Quaternary fault density", "State map fault density", "Volcanic␣
↪dike density", "Volcanic vent density"];
```

Short attribute names are used for coding.

Long attribute names are used for plotting and visualization.

0.4.4 Define attributes to remove from analysis

[5]:
```
attributes_remove = uppercasefirst.(lowercase.(["Air Temperature"; "Subcrop␣
↪Permeability"; "Watertable Elevation"; "Groundsurface Elevation";␣
↪"Watertable Depth"]));
```

0.4.5 Define attributes for analysis

[6]:
```
index_remove = indexin(attributes_remove, attributes_long)
attributes_cols = trues(length(attributes_long))
attributes_cols[index_remove] .= false
cols = vec(4:26)[attributes_cols]
attributes = attributes_long[cols .- 3];
print("Attributes used are:")
attributes
```

```
Attributes used are:
```

[6]:
```
18-element Array{String,1}:
 "Boron concentration"
 "Gravity anomaly"
 "Magnetic intensity"
 "Volcanic dike density"
 "Drainage density"
 "Fault intersection density"
 "Quaternary fault density"
 "Seismicity"
 "State map fault density"
 "Spring density"
 "Volcanic vent density"
 "Lithium concentration"
 "Precipitation"
 "Silica geothermometer"
 "Hydraulic gradient"
 "Heat flow"
 "Crustal thickness"
 "Depth to basement"
```

0.4.6 Define names of the data locations

[7]:
```
locations_short = ["Alamos spr";
"Allen spr";
"Apache well";
"Aragon spr";
"Ash spr";
```

```
"B.Iorio well";
"Cliff spr";
"Dent well";
"Derry spr";
"Faywood spr";
"Fed H1 well";
"Freiborn spr";
"Garton well";
"Gila spr 1";
"Gila spr 2";
"Goat spr";
"Jerry well";
"Kennecott well";
"Laguna Pbl";
"Lightning Dock";
"Los Alturas";
"Mangas spr";
"Mimbres spr";
"Ojitos spr";
"Ojo Caliente";
"Ojo Canas";
"Pueblo well";
"Radium spr";
"Rainbow spr";
"Riverside well";
"Sacred spr";
"Socorro Can";
"Spring";
"Spring Can";
"T or C spr";
"Turkey spr";
"Victoria well";
"Warm spr";
"Well 1";
"Well 2";
"Well 3";
"Well 4";
"Well 5";
"Carne well"]

locations_long = ["Alamos Spring";
"Allen Springs";
"Apache Tejo Warm Springs well";
"Aragon Springs";
"Ash Spring";
"B. Iorio 1 well";
"Cliff Warm Spring";
```

```
"Dent windmill well";
"Derry Warm Springs";
"Faywood Hot Springs";
"Federal H 1 well";
"Freiborn Canyon Spring";
"Garton well";
"Gila Hot Springs 1";
"Gila Hot Springs 2";
"Goat Camp Spring";
"Jerry well";
"Kennecott Warm Springs well";
"Laguna Pueblo";
"Lightning Dock";
"Los Alturas Estates";
"Mangas Springs";
"Mimbres Hot Springs";
"Ojitos Springs";
"Ojo Caliente";
"Ojo De las Canas";
"Pueblo windmill well";
"Radium Hot Springs";
"Rainbow Spring";
"Riverside Store well";
"Sacred Spring";
"Socorro Canyon";
"Spring";
"Spring Canyon Warm Spring";
"Truth or Consequences spring";
"Turkey Creek Spring";
"Victoria Land and Cattle Co. well";
"Warm Springs";
"Well 1";
"Well 2";
"Well 3";
"Well 4";
"Well 5";
"Well south of Carne"];
```

Short location names are used for coding.

Long location names are used for plotting and visualization.

0.4.7 Define location coordinates

[8]:

```
dindex = d[:,end] .== 1
rows = convert.(Int32, d[dindex,end-1])
locations = locations_short[rows]
lat = d[dindex, 2]
```

```
lon = d[dindex, 3];
```

0.4.8 Set up directories to store obtained results and figures

[9]:
```
figuredir = "figures-case01"
resultdir = "results-case01";
```

0.4.9 Define a range for the number of signatures to be explored

[10]:
```
nkrange = 2:10;
```

0.4.10 Define and normalize the data matrix

[11]:
```
X = permutedims(d[dindex, cols])
Xu, nmin, nmax = NMFk.normalizematrix_row!(X);
```

0.5 Perform ML analyses

The **NMFk** algorithm factorizes the normalized data matrix `Xu` into `W` and `H` matrices. For more information, check out the **NMFk** website

[12]:
```
W, H, fitquality, robustness, aic = NMFk.execute(Xu, nkrange, 1000;␣
↪resultdir=resultdir, casefilename="nmfk", load=true)
W, H, fitquality, robustness, aic = NMFk.load(nkrange, 1000;␣
↪resultdir=resultdir, casefilename="nmfk");
```

```
Signals:  2 Fit:     32.70151 Silhouette:           1 AIC:    -2276.215
Signals:  3 Fit:      24.6022 Silhouette:   0.9999996 AIC:    -2377.607
Signals:  4 Fit:     18.46274 Silhouette:   0.9999994 AIC:    -2480.975
Signals:  5 Fit:     14.74592 Silhouette:    0.764538 AIC:    -2535.007
Signals:  6 Fit:      12.3538 Silhouette:  -0.1423047 AIC:    -2551.193
Signals:  7 Fit:     10.29325 Silhouette:  -0.0733191 AIC:    -2571.714
Signals:  8 Fit:     8.237522 Silhouette:   0.2518114 AIC:    -2624.163
Signals:  9 Fit:     7.607165 Silhouette: -0.07981342 AIC:    -2563.213
Signals: 10 Fit:     6.023938 Silhouette:  0.02130362 AIC:    -2624.026
Signals:  2 Fit:     32.70151 Silhouette:           1 AIC:    -2276.215
Signals:  3 Fit:      24.6022 Silhouette:   0.9999996 AIC:    -2377.607
Signals:  4 Fit:     18.46274 Silhouette:   0.9999994 AIC:    -2480.975
Signals:  5 Fit:     14.74592 Silhouette:    0.764538 AIC:    -2535.007
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Signals:  7 Fit:     10.29325 Silhouette:  -0.0733191 AIC:    -2571.714
Signals:  8 Fit:     8.237522 Silhouette:   0.2518114 AIC:    -2624.163
Signals:  9 Fit:     7.607165 Silhouette: -0.07981342 AIC:    -2563.213
Signals: 10 Fit:     6.023938 Silhouette:  0.02130362 AIC:    -2624.026
```

```
Info: Results
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkExecute.jl:15
Info: Optimal solution: 5 signals
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkExecute.jl:20
```

```
Signals:  2 Fit:     32.70151 Silhouette:            1 AIC:    -2276.215
Signals:  3 Fit:      24.6022 Silhouette:    0.9999996 AIC:    -2377.607
Signals:  4 Fit:     18.46274 Silhouette:    0.9999994 AIC:    -2480.975
Signals:  5 Fit:     14.74592 Silhouette:     0.764538 AIC:    -2535.007
Signals:  6 Fit:      12.3538 Silhouette:   -0.1423047 AIC:    -2551.193
Signals:  7 Fit:     10.29325 Silhouette:   -0.0733191 AIC:    -2571.714
Signals:  8 Fit:     8.237522 Silhouette:    0.2518114 AIC:    -2624.163
Signals:  9 Fit:     7.607165 Silhouette:  -0.07981342 AIC:    -2563.213
Signals: 10 Fit:     6.023938 Silhouette:   0.02130362 AIC:    -2624.026
```

```
 Info: Optimal solution: 5 signals
 @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkIO.jl:30
```

Here, the **NMFk** results are loaded from a prior ML run.

As seen from the output above, the NMFk analyses identified that the optimal number of geothermal signatures in the dataset **5**. This estimate is based on a criterion that `Silhouette` (`robustness`) of the acceptable solutions is >0.5. However, if a criterion for `Silhouette` is >0.25, the optimal number of signatures is **8**.

It is important to note that our ML methodology can be applied to perform both **classification** and **regression** analyses.

For the case of **regression** (predictive) analyses, the optimal number of signatures is **5**.

Solutions with a number of signatures less than **5** are underfitting.

Solutions with a number of signatures greater than **5** are overfitting and unacceptable.

The solution for `k=8` is also analyzed below because it provides further refinements in the extracted geothermal signatures. It also provides further demonstration of the **classification** capabilities of our ML methodology.

The set of acceptable solutions are defined by the **NMFk** algorithm as follows:

[13]:
```
NMFk.getks(nkrange, robustness[nkrange], 0.5)
```

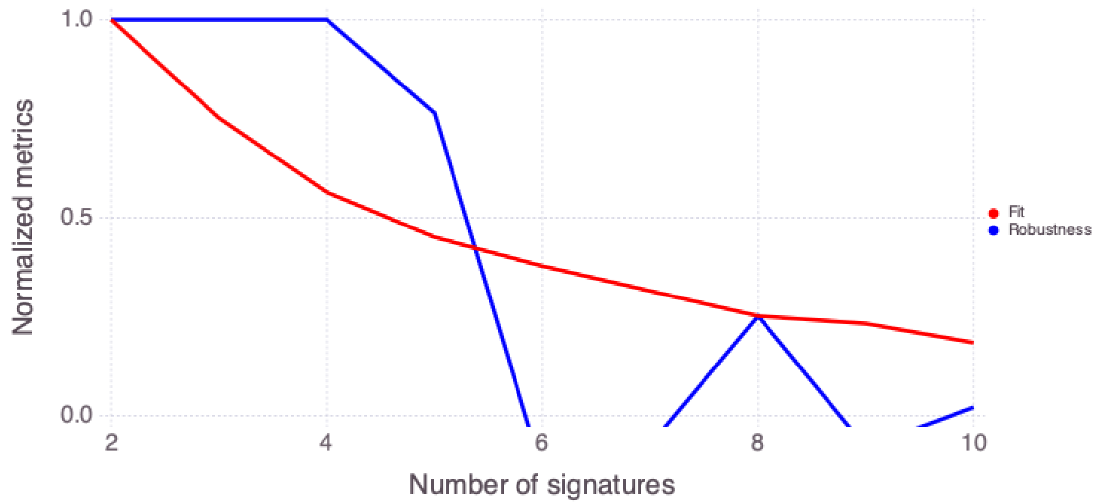
[13]:
```
4-element Array{Int64,1}:
 2
 3
 4
 5
```

The acceptable solutions contain 2, 3, 4, and 5 signatures.

0.5.1 Post-process NMFk results

Number of signatures Below is a plot representing solution quality (fit) and silhouette width (robustness) for different numbers of signatures `k`:

[14]:
```
NMFk.plot_signal_selecton(nkrange, fitquality, robustness; figuredir=figuredir,␣
↪xtitle="Number of signatures")
```



The plot above also demonstrates that the acceptable solutions contain 2, 3, 4, and 5 signatures.

Analysis of all the acceptable solutions The ML solutions containing an acceptable number of signatures are further analyzed as follows:

[15]:
```
NMFk.clusterresults(NMFk.getks(nkrange, robustness[nkrange]), W, H, attributes,␣
↪locations; lat=lat, lon=lon, resultdir=resultdir, figuredir=figuredir,␣
↪ordersignal=:Hcount, Hcasefilename="locations", Wcasefilename="attributes");
```

```
  Info: Number of signals: 2
  @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:154

Signal importance (high->low): [1, 2]

  Info: Locations (signals=2)
  @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:158
  Warning: type
Clustering.KmeansResult{Core.Array{Core.Float64,2},Core.Float64,Core.Int64} not
present in workspace; reconstructing
  @ JLD /Users/vvv/.julia/packages/JLD/nQ9iW/src/jld_types.jl:697
  Info: Robust k-means analysis results are loaded from file results-
case01/Hmatrix-2-2_44-1000.jld!
  @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkCluster.jl:67
  Warning: Procedure to find unique signals could not identify a solution …
  @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkCluster.jl:158
  Warning: Procedure to find unique signals could not identify a solution …
  @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkCluster.jl:158
  Warning: type
Clustering.KmeansResult{Core.Array{Core.Float64,2},Core.Float64,Core.Int64} not
```

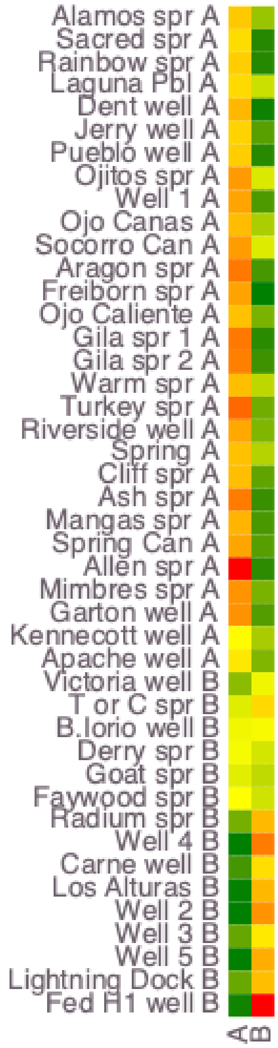
```
present in workspace; reconstructing
 @ JLD /Users/vvv/.julia/packages/JLD/nQ9iW/src/jld_types.jl:697
 Info: Robust k-means analysis results are loaded from file results-
case01/Wmatrix-2-2_18-1000.jld!
 @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkCluster.jl:67
 Info: Signal A -> A Count: 29
 @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:265
 Info: Signal B -> B Count: 15
 @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:265
 Info: Signal A (S1) (k-means clustering)
 @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:282
```

```
29×2 Array{Any,2}:
 "Allen spr"        1.0
 "Turkey spr"       0.884139
 "Aragon spr"       0.849368
 "Gila spr 1"       0.845807
 "Ash spr"          0.839107
 "Gila spr 2"       0.829838
 "Garton well"      0.788626
 "Mimbres spr"      0.7852
 "Ojitos spr"       0.76979
 "Socorro Can"      0.761215
 "Freiborn spr"     0.745613
 "Well 1"           0.743076
 "Spring Can"       0.741828

 "Warm spr"         0.676919
 "Cliff spr"        0.676442
 "Ojo Caliente"     0.670285
 "Spring"           0.669871
 "Alamos spr"       0.64752
 "Pueblo well"      0.63547
 "Rainbow spr"      0.635234
 "Jerry well"       0.622338
 "Laguna Pbl"       0.601675
 "Sacred spr"       0.597838
 "Apache well"      0.563514
 "Kennecott well"   0.510178
```

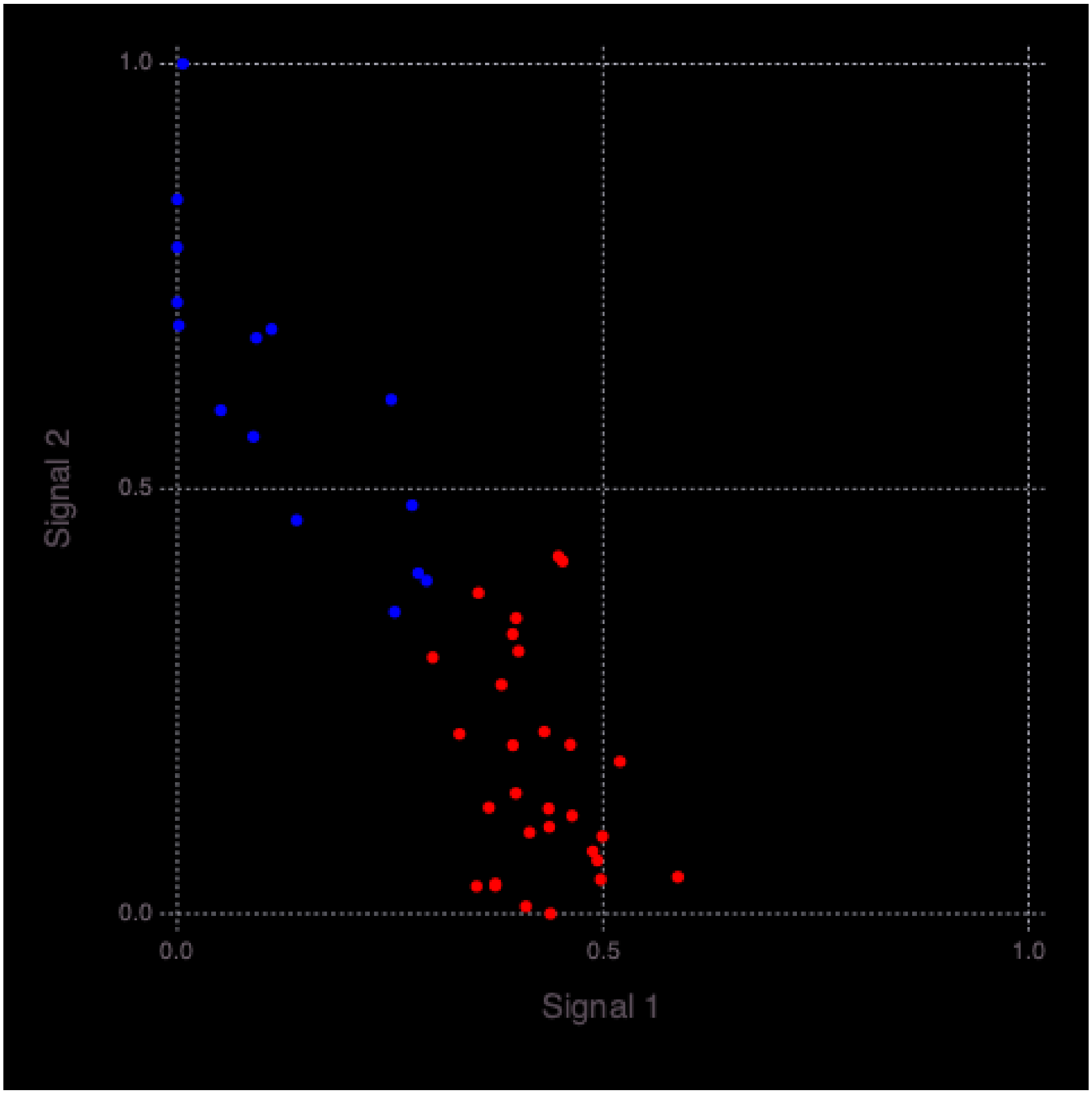
```
15×2 Array{Any,2}:
 "Fed H1 well"      1.0
 "Well 4"           0.840281
 "Well 2"           0.78384
 "Well 5"           0.719246
 "Los Alturas"      0.692025
 "Radium spr"       0.687742
 "Lightning Dock"   0.677317
 "T or C spr"       0.60486
```

```
"Carne well"      0.592351
"Well 3"          0.56113
"B.Iorio well"    0.480433
"Victoria well"   0.462937
"Derry spr"       0.400573
"Faywood spr"     0.391769
"Goat spr"        0.354929
```

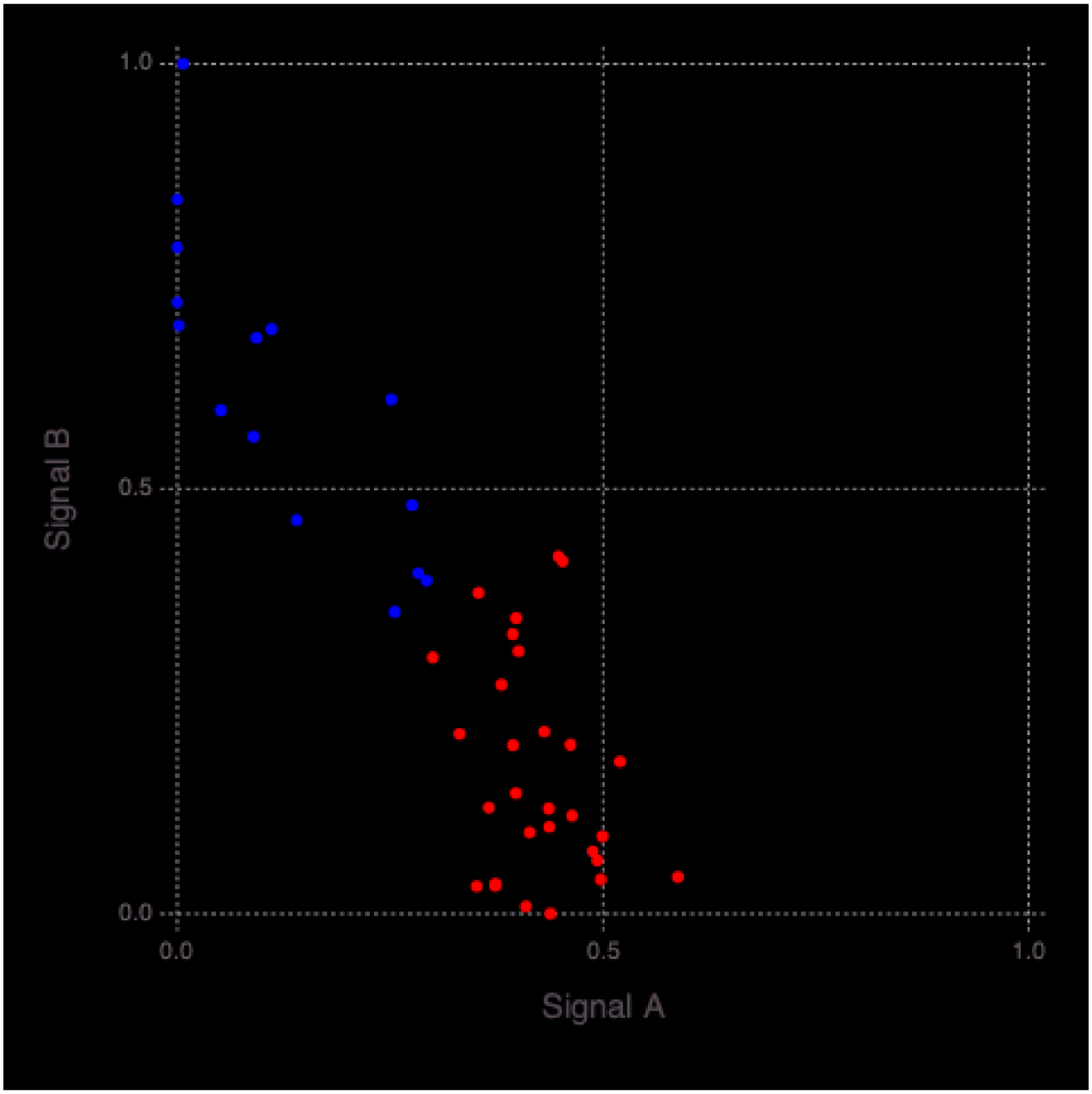

```
Info: Signal B (S2) (k-means clustering)
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:282
```


Alamos spr A
Sacred spr A
Rainbow spr A
Laguna Pbl A
Dent well A
Jerry well A
Pueblo well A
Ojitos spr A
Well 1 A
Ojo Canas A
Socorro Can A
Aragon spr A
Freiborn spr A
Ojo Caliente A
Gila spr 1 A
Gila spr 2 A
Warm spr A
Turkey spr A
Riverside well A
Spring A
Cliff spr A
Ash spr A
Mangas spr A
Spring Can A
Allen spr A
Mimbres spr A
Garton well A
Kennecott well A
Apache well A
Victoria well B
T or C spr B
B.Iorio well B
Derry spr B
Goat spr B
Faywood spr B
Radium spr B
Well 4 B
Carne well B
Los Alturas B
Well 2 B
Well 3 B
Well 5 B
Lightning Dock B
Fed H1 well B
A
B


Alamos spr A
Sacred spr A
Rainbow spr A
Laguna Pbl A
Dent well A
Jerry well A
Pueblo well A
Ojitos spr A
Well 1 A
Ojo Canas A
Socorro Can A
Aragon spr A
Freiborn spr A
Ojo Caliente A
Gila spr 1 A
Gila spr 2 A
Warm spr A
Turkey spr A
Riverside well A
Spring A
Cliff spr A
Ash spr A
Mangas spr A
Spring Can A
Allen spr A
Mimbres spr A
Garton well A
Kennecott well A
Apache well A
Victoria well B
T or C spr B
B.Iorio well B
Derry spr B
Goat spr B
Faywood spr B
Radium spr B
Well 4 B
Carne well B
Los Alturas B
Well 2 B
Well 3 B
Well 5 B
Lightning Dock B
Fed H1 well B
A
B



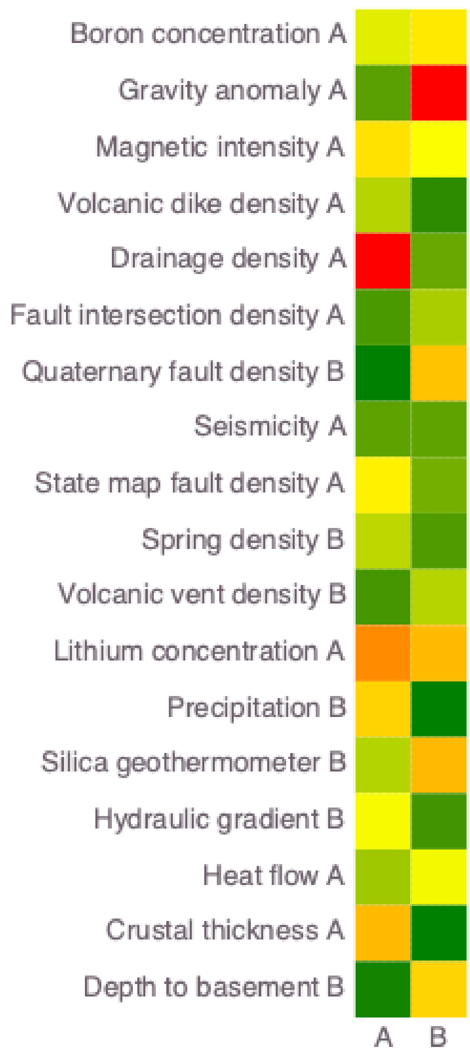
Signal 2
1.0
0.5
0.0
0.0
0.5
1.0
Signal 1




```
11×2 Array{Any,2}:
 "Drainage density"            1.0
 "Lithium concentration"       0.801888
 "Crustal thickness"           0.684456
 "Magnetic intensity"          0.581662
 "State map fault density"     0.539332
 "Boron concentration"         0.431691
 "Volcanic dike density"       0.334325
 "Heat flow"                   0.283606
 "Seismicity"                  0.13724
 "Gravity anomaly"             0.126086
 "Fault intersection density"  0.097643
```

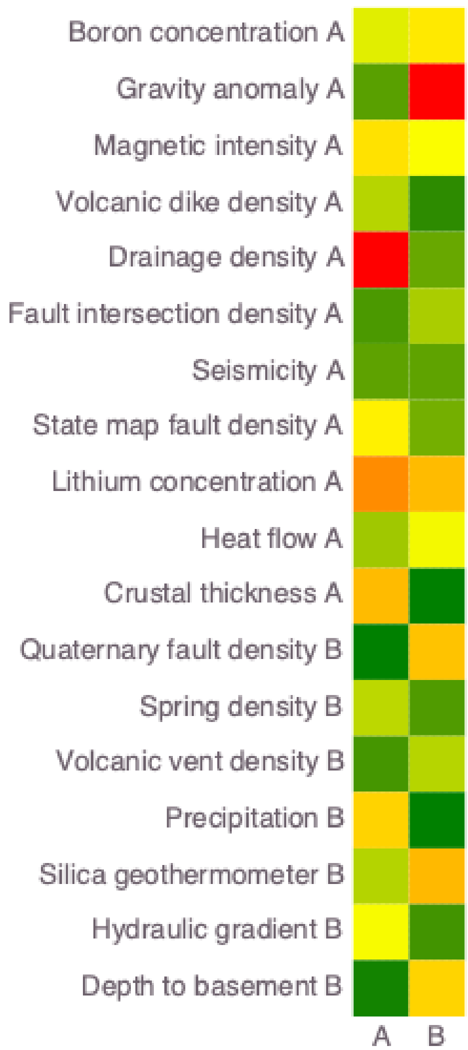
```
7×2 Array{Any,2}:
```

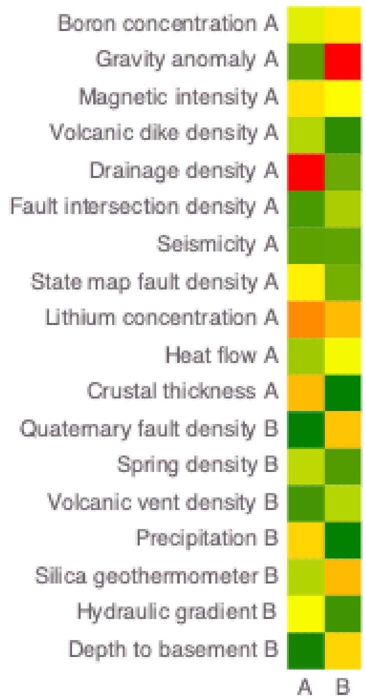
```
"Silica geothermometer"     0.690981
"Quaternary fault density"  0.664186
"Depth to basement"         0.61722
"Volcanic vent density"     0.334398
"Spring density"            0.108699
"Hydraulic gradient"        0.0811159
"Precipitation"             0.0
```

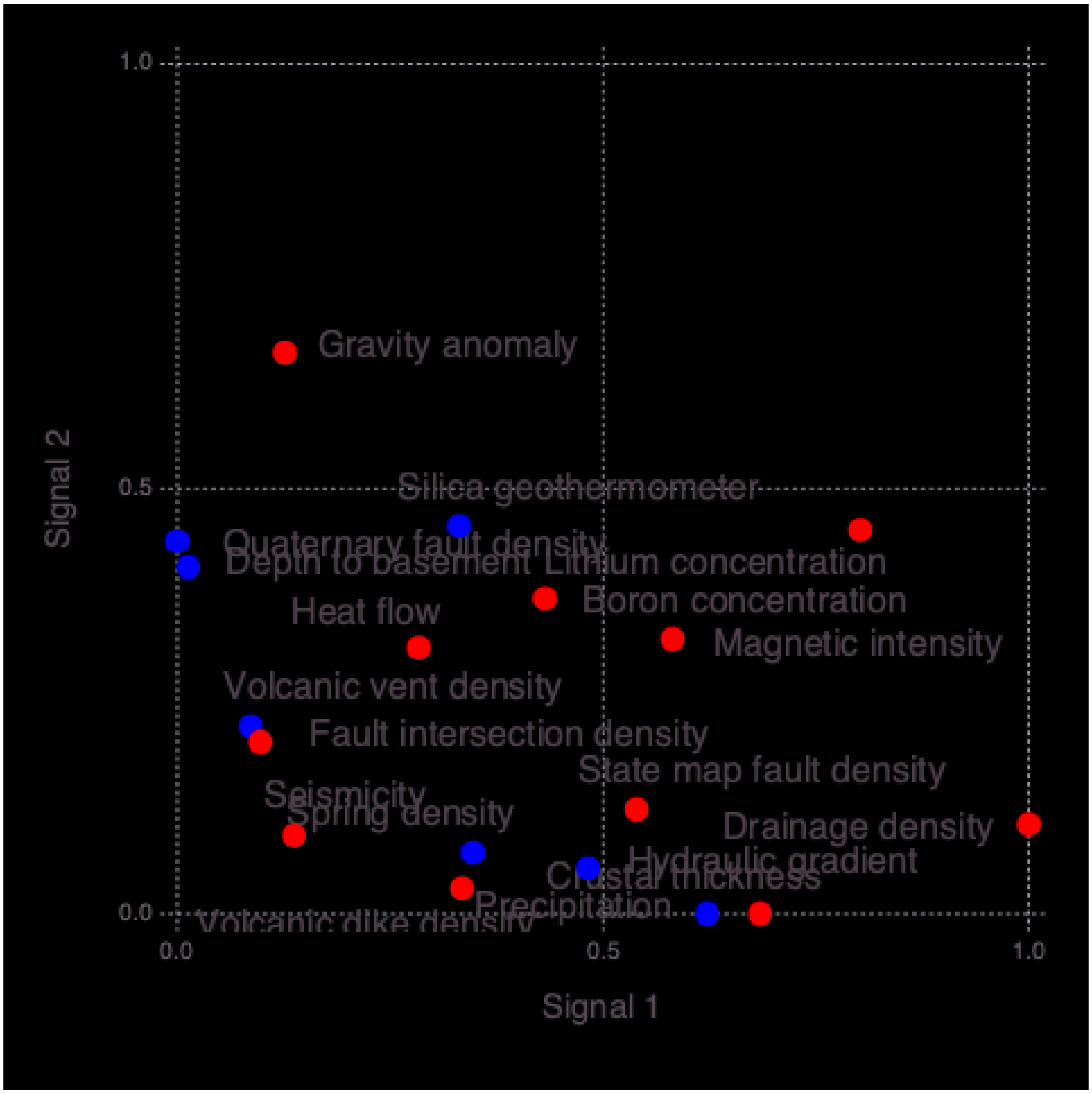


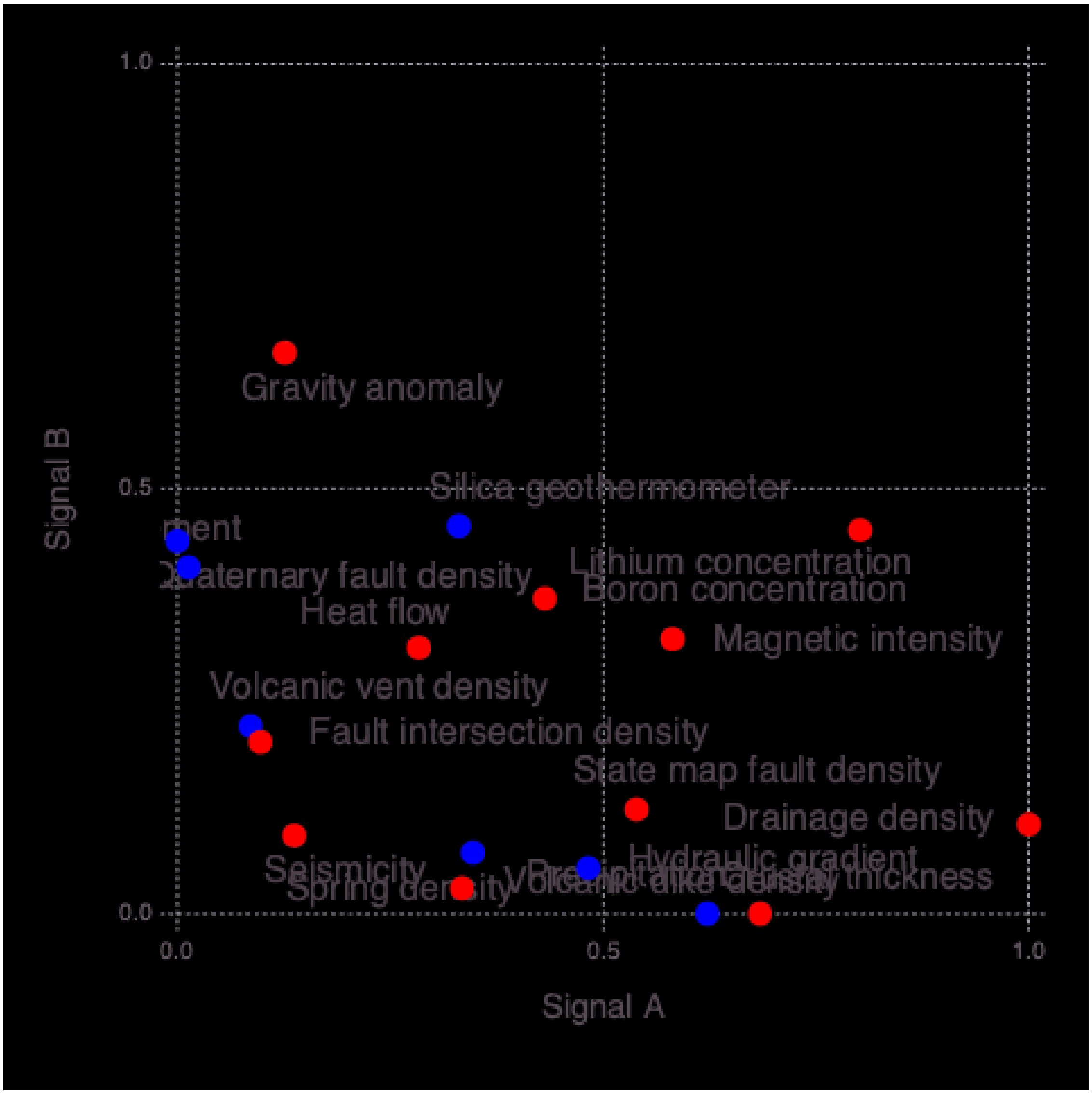

```
Info: Attributes (signals=2)
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:340
Info: Signal A (S1) Count: 11
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:353
```

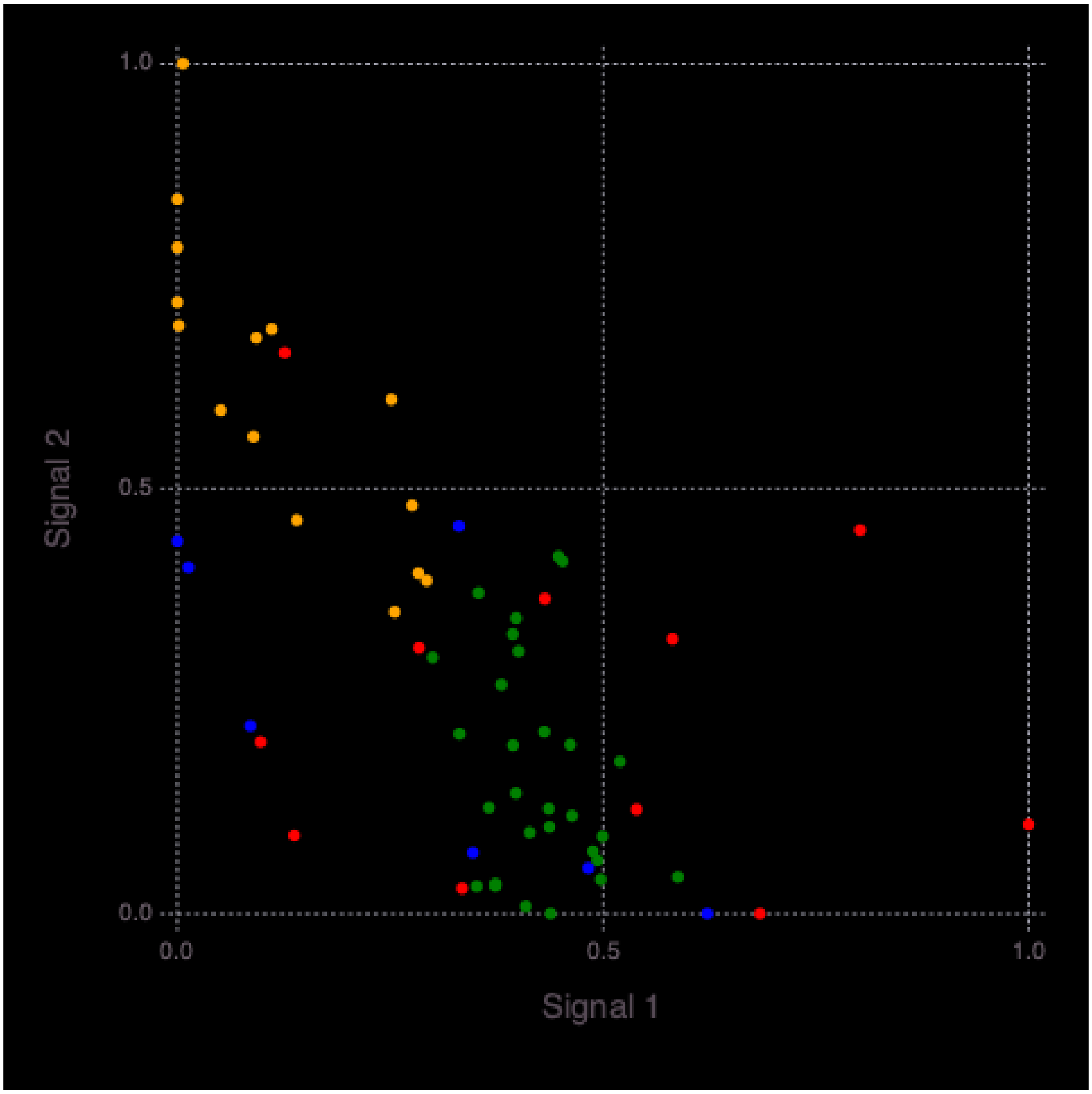
```
Info: Signal B (S2) Count: 7
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:353
Info: Signal A -> A Count: 11
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:363
Info: Signal B -> B Count: 7
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:363
Info: Signal A (remapped k-means clustering)
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:378
Info: Signal B (remapped k-means clustering)
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:378
```

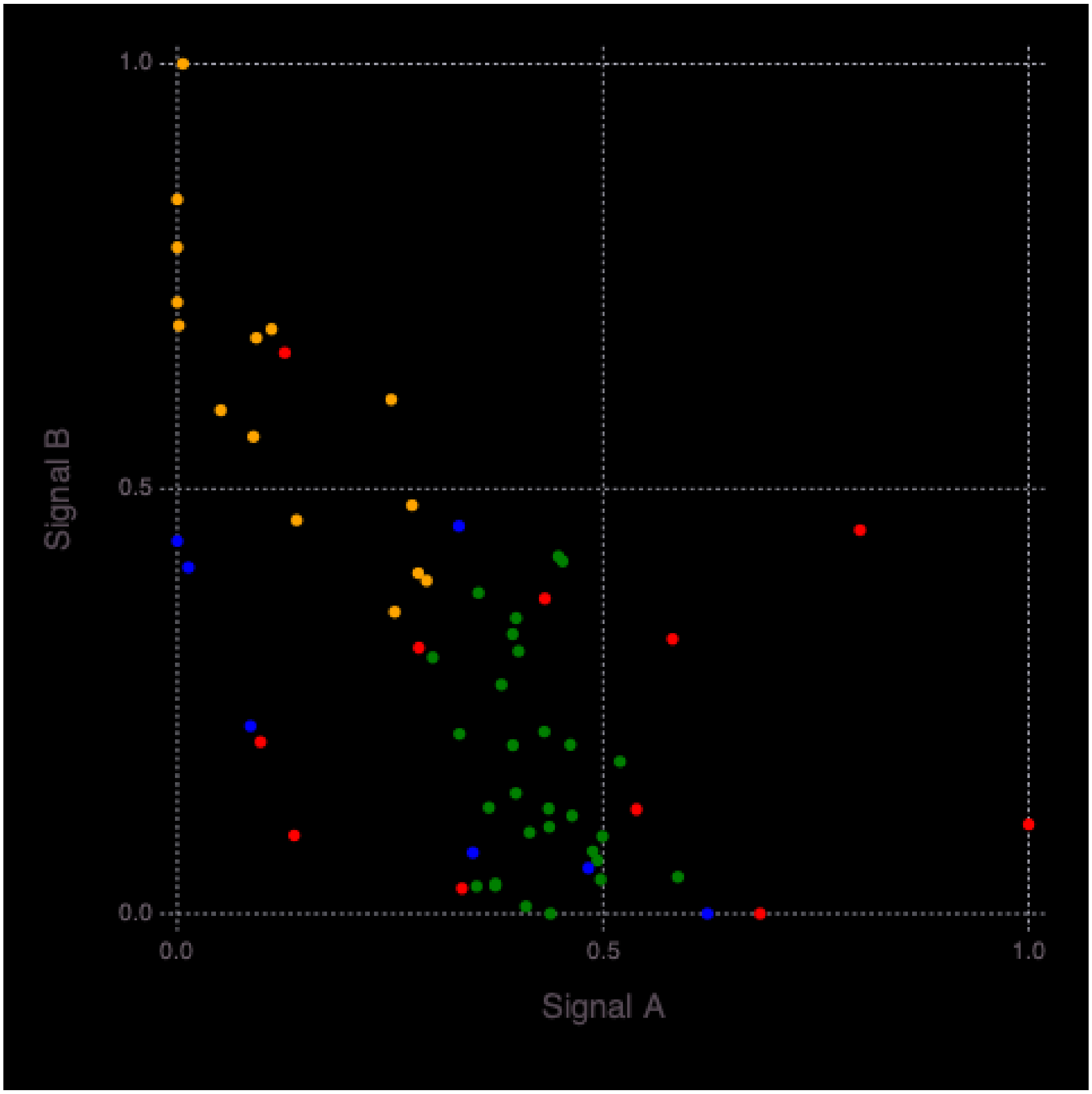



Boron concentration A
Gravity anomaly A
Magnetic intensity A
Volcanic dike density A
Drainage density A
Fault intersection density A
Seismicity A
State map fault density A
Lithium concentration A
Heat flow A
Crustal thickness A
Quaternary fault density B
Spring density B
Volcanic vent density B
Precipitation B
Silica geothermometer B
Hydraulic gradient B
Depth to basement B
A
B


1.0
0.5
0.0
Signal 2
0.0
0.5
1.0
Signal 1
Gravity anomaly
Silica geothermometer
Quaternary fault density
Depth to basement
Lithium concentration
Boron concentration
Heat flow
Magnetic intensity
Volcanic vent density
Fault intersection density
State map fault density
Seismicity
Spring density
Drainage density
Hydraulic gradient
Crustal thickness
Precipitation
Volcanic dike density


Signal B
Signal A
1.0
0.5
0.0
0.0
0.5
1.0
Gravity anomaly
Silica geothermometer
Quaternary fault density
Heat flow
Lithium concentration
Boron concentration
Magnetic intensity
Volcanic vent density
Fault intersection density
State map fault density
Drainage density
Hydraulic gradient
Seismicity
Spring density


1.0
0.5
0.0
Signal 2
0.0
0.5
1.0
Signal 1




```
Signal importance (high->low): [1, 2, 3]

  Info: Number of signals: 3
  @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:154
  Info: Locations (signals=3)
  @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:158
  Warning: type
Clustering.KmeansResult{Core.Array{Core.Float64,2},Core.Float64,Core.Int64} not
present in workspace; reconstructing
  @ JLD /Users/vvv/.julia/packages/JLD/nQ9iW/src/jld_types.jl:697
  Info: Robust k-means analysis results are loaded from file results-
case01/Hmatrix-3-3_44-1000.jld!
  @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkCluster.jl:67
  Warning: Procedure to find unique signals could not identify a solution …
```

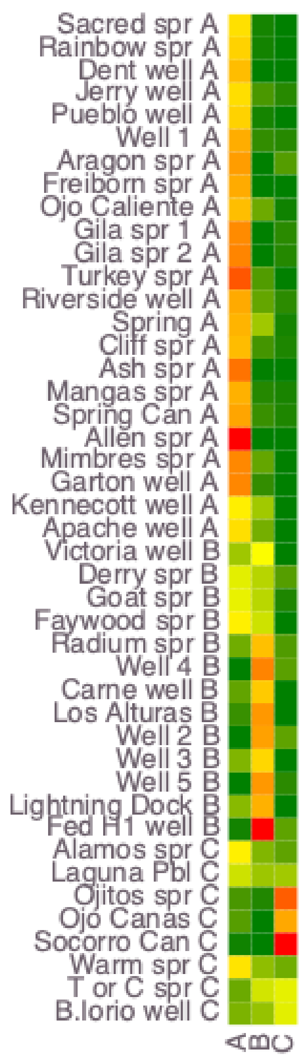
```
 @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkCluster.jl:158
 Warning: Procedure to find unique signals could not identify a solution …
 @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkCluster.jl:158
 Warning: Procedure to find unique signals could not identify a solution …
 @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkCluster.jl:158
 Warning: type
Clustering.KmeansResult{Core.Array{Core.Float64,2},Core.Float64,Core.Int64} not
present in workspace; reconstructing
 @ JLD /Users/vvv/.julia/packages/JLD/nQ9iW/src/jld_types.jl:697
 Info: Robust k-means analysis results are loaded from file results-
case01/Wmatrix-3-3_18-1000.jld!
 @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkCluster.jl:67
```

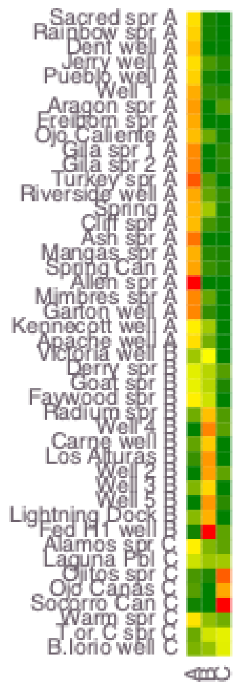
```
23×2 Array{Any,2}:
 "Allen spr"       1.0
 "Turkey spr"      0.916375
 "Ash spr"         0.86
 "Gila spr 2"      0.81917
 "Garton well"     0.814428
 "Mimbres spr"     0.810983
 "Gila spr 1"      0.804735
 "Aragon spr"      0.760672
 "Spring Can"      0.74146
 "Riverside well"  0.729138
 "Freiborn spr"    0.726089
 "Well 1"          0.721013
 "Mangas spr"      0.710025
 "Spring"          0.702419
 "Cliff spr"       0.681147
 "Dent well"       0.67989
 "Ojo Caliente"    0.678069
 "Pueblo well"     0.624881
 "Rainbow spr"     0.623511
 "Jerry well"      0.59157
 "Apache well"     0.58789
 "Sacred spr"      0.586264
 "Kennecott well"  0.545995
```

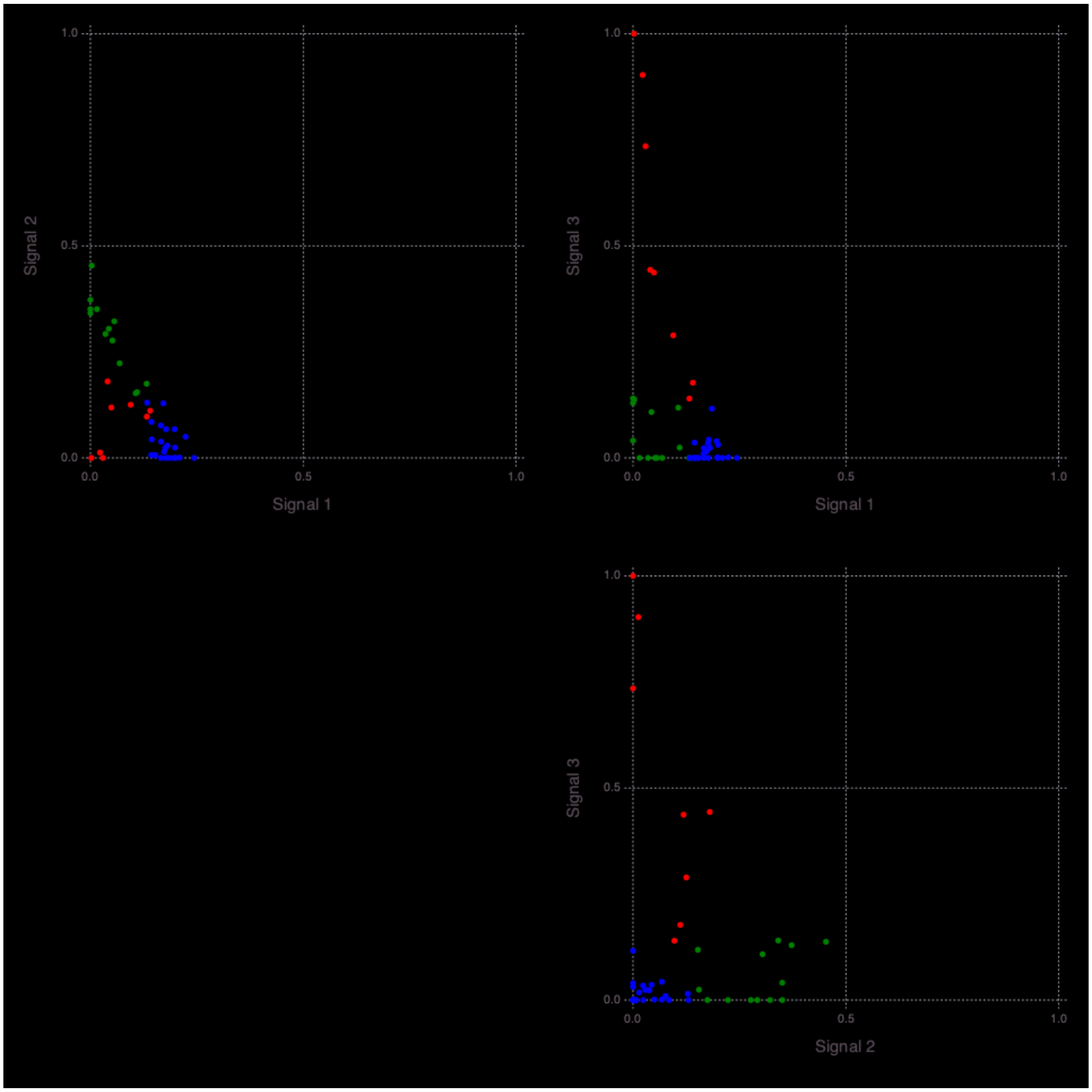
```
13×2 Array{Any,2}:
 "Fed H1 well"     1.0
 "Well 4"          0.821925
 "Well 5"          0.773654
 "Los Alturas"     0.773565
 "Well 2"          0.752558
 "Lightning Dock"  0.71038
 "Radium spr"      0.671286
 "Carne well"      0.644475
 "Well 3"          0.610426
 "Victoria well"   0.492095
```

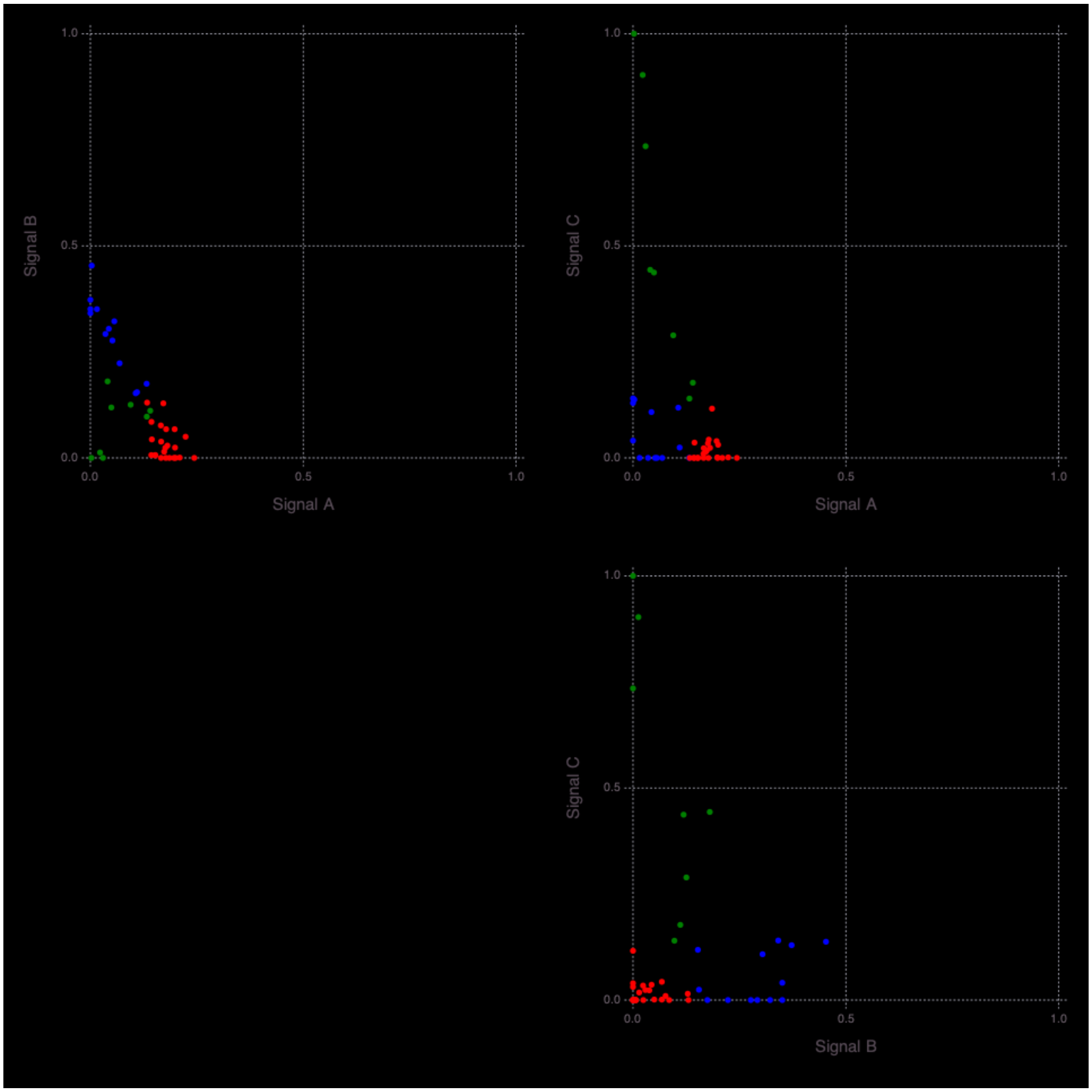
```
 "Faywood spr"      0.385637
 "Goat spr"         0.341865
 "Derry spr"        0.336225

8×2 Array{Any,2}:
 "Socorro Can"   1.0
 "Ojitos spr"    0.902801
 "Ojo Canas"     0.734799
 "T or C spr"    0.443392
 "B.Iorio well"  0.437021
 "Laguna Pbl"    0.288994
 "Warm spr"      0.177227
 "Alamos spr"    0.139853
```

```
Warning: Procedure to find unique signals could not identify a solution …
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkCluster.jl:158
Info: Signal A -> A Count: 23
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:265
Info: Signal B -> B Count: 13
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:265
Info: Signal C -> C Count: 8
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:265
Info: Signal A (S1) (k-means clustering)
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:282
Info: Signal B (S2) (k-means clustering)
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:282
Info: Signal C (S3) (k-means clustering)
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:282
```



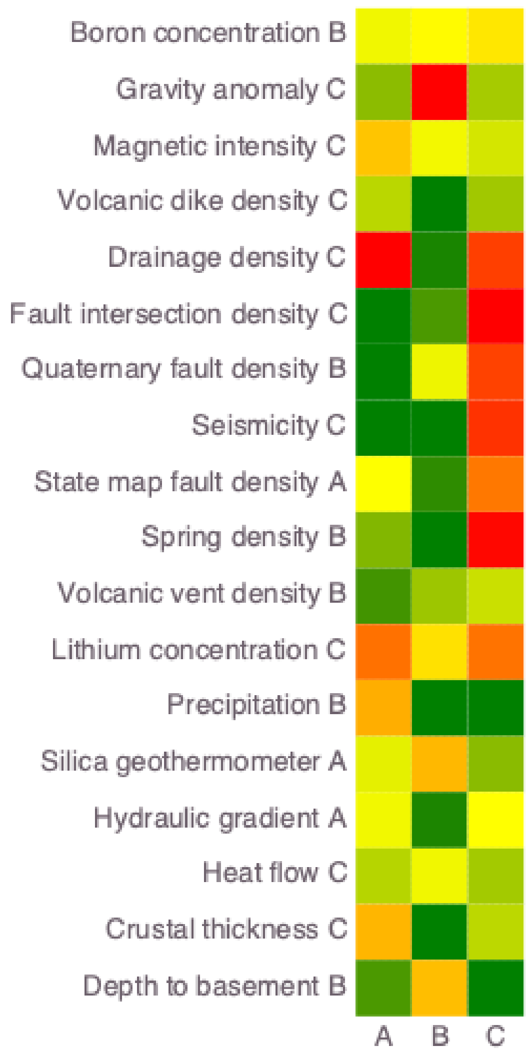

Sacred spr A
Rainbow spr A
Dent well A
Jerry well A
Pueblo well A
Well 1 A
Aragon spr A
Freiborn spr A
Ojo Caliente A
Gila spr 1 A
Gila spr 2 A
Turkey spr A
Riverside well A
Spring A
Cliff spr A
Ash spr A
Mangas spr A
Spring Can A
Allen spr A
Mimbres spr A
Garton well A
Kennecott well A
Apache well A
Victoria well B
Derry spr B
Goat spr B
Faywood spr B
Radium spr B
Well 4 B
Carne well B
Los Alturas B
Well 2 B
Well 3 B
Well 5 B
Lightning Dock B
Fed H1 well B
Alamos spr C
Laguna Pbl C
Ojitos spr C
Ojo Canas C
Socorro Can C
Warm spr C
T or C spr C
B.Iorio well C
A
B
C


Signal 1
Signal 2
Signal 1
Signal 3
Signal 2
Signal 3
0.0
0.5
1.0



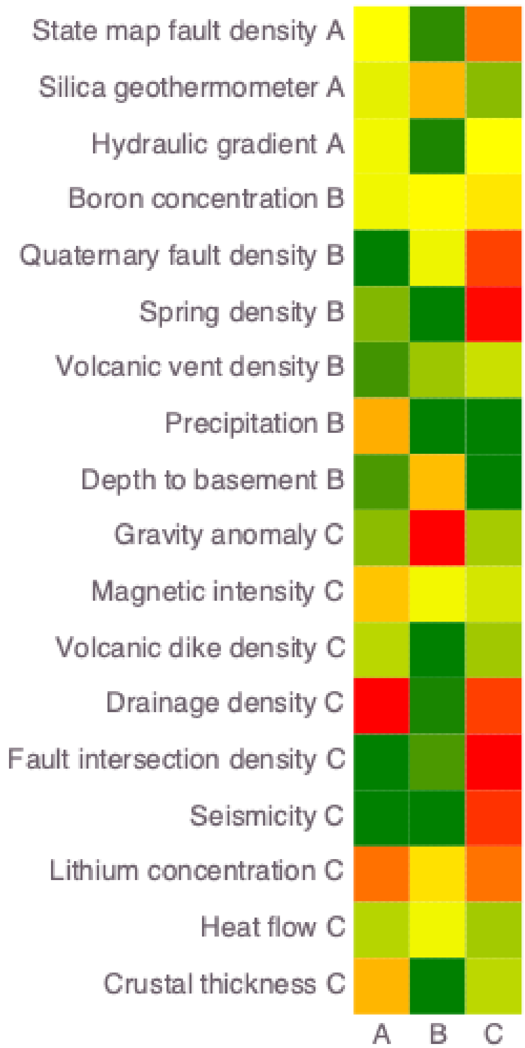

```
3×2 Array{Any,2}:
 "State map fault density"  0.496198
 "Hydraulic gradient"       0.469537
 "Silica geothermometer"    0.439841

6×2 Array{Any,2}:
 "Depth to basement"          0.676939
 "Boron concentration"        0.511079
 "Quaternary fault density"   0.460437
 "Volcanic vent density"      0.27834
 "Spring density"             0.0
 "Precipitation"              0.0

9×2 Array{Any,2}:
```

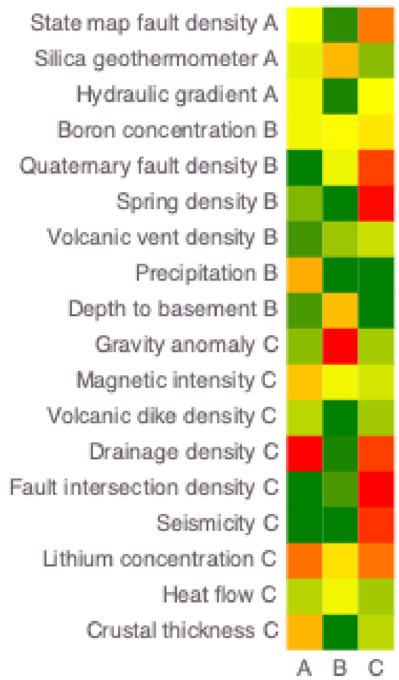
```
"Fault intersection density"  1.0
"Seismicity"                  0.967935
"Drainage density"            0.952827
"Lithium concentration"       0.858236
"Magnetic intensity"          0.403114
"Crustal thickness"           0.346896
"Gravity anomaly"             0.297228
"Heat flow"                   0.290886
"Volcanic dike density"       0.28542
```

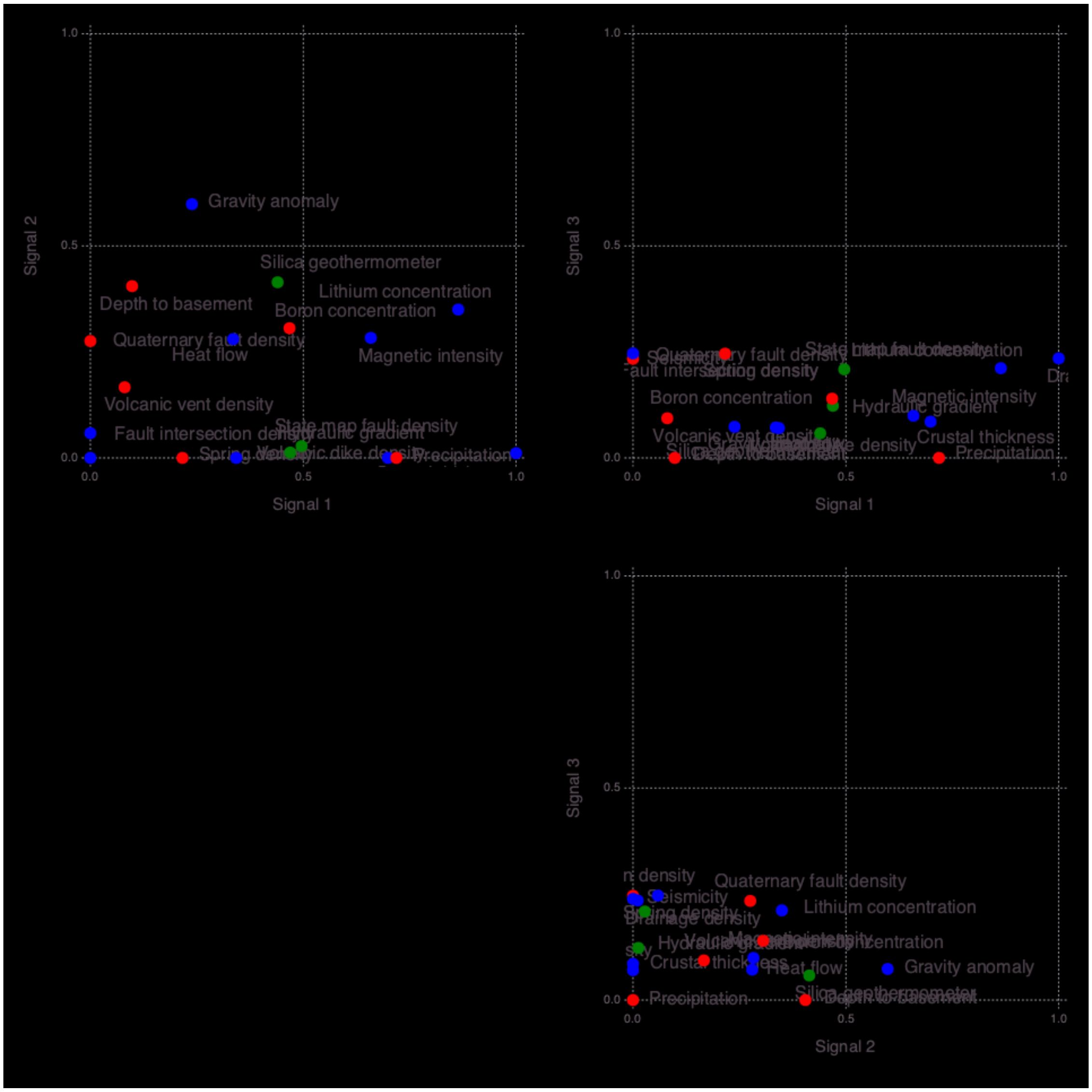


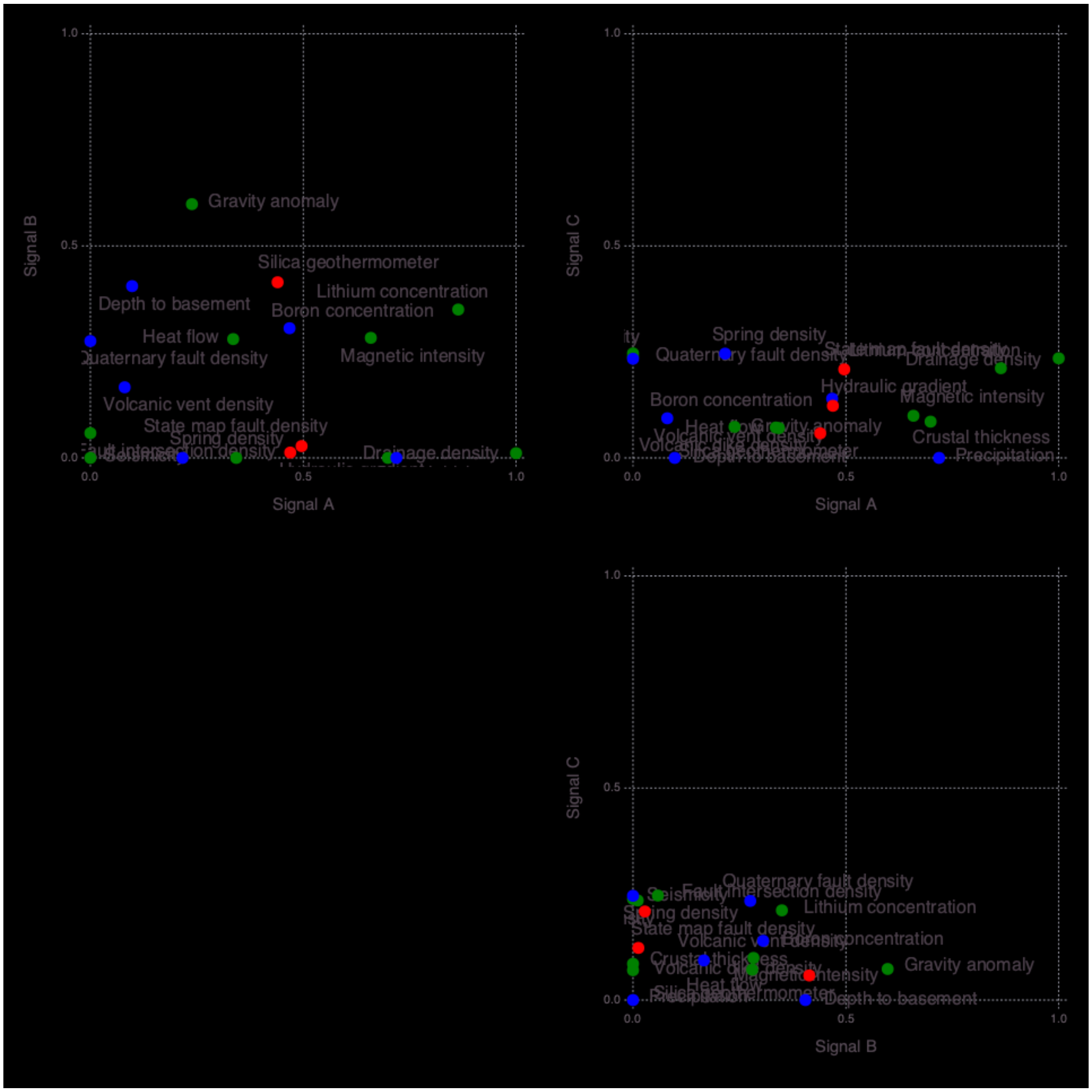

```
Info: Attributes (signals=3)
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:340
```

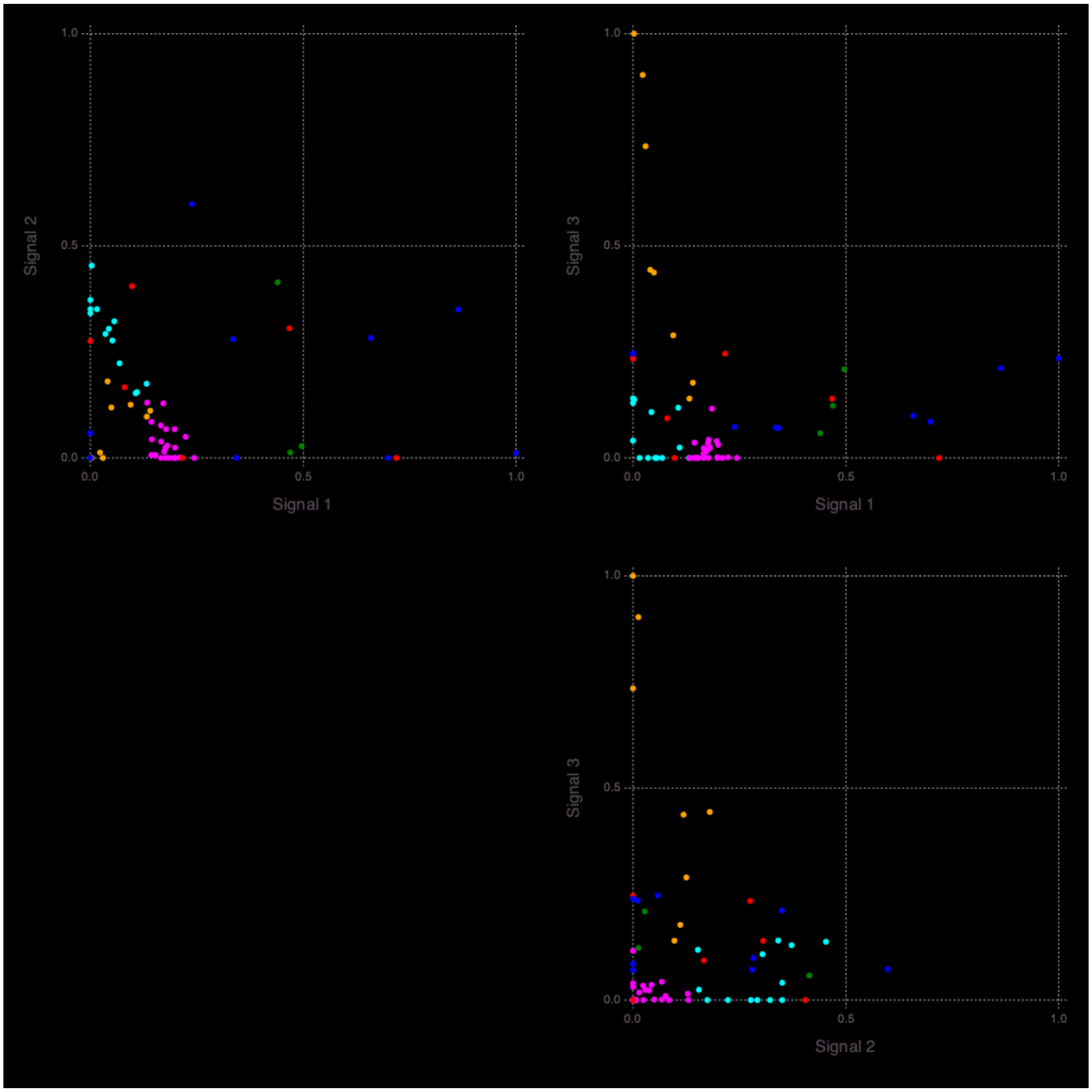
```
Info: Signal A (S3) Count: 9
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:353
Info: Signal B (S2) Count: 6
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:353
Info: Signal C (S1) Count: 3
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:353
Info: Signal C -> A Count: 3
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:363
Info: Signal B -> B Count: 6
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:363
Info: Signal A -> C Count: 9
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:363
Info: Signal A (remapped k-means clustering)
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:378
Info: Signal B (remapped k-means clustering)
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:378
Info: Signal C (remapped k-means clustering)
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:378
```

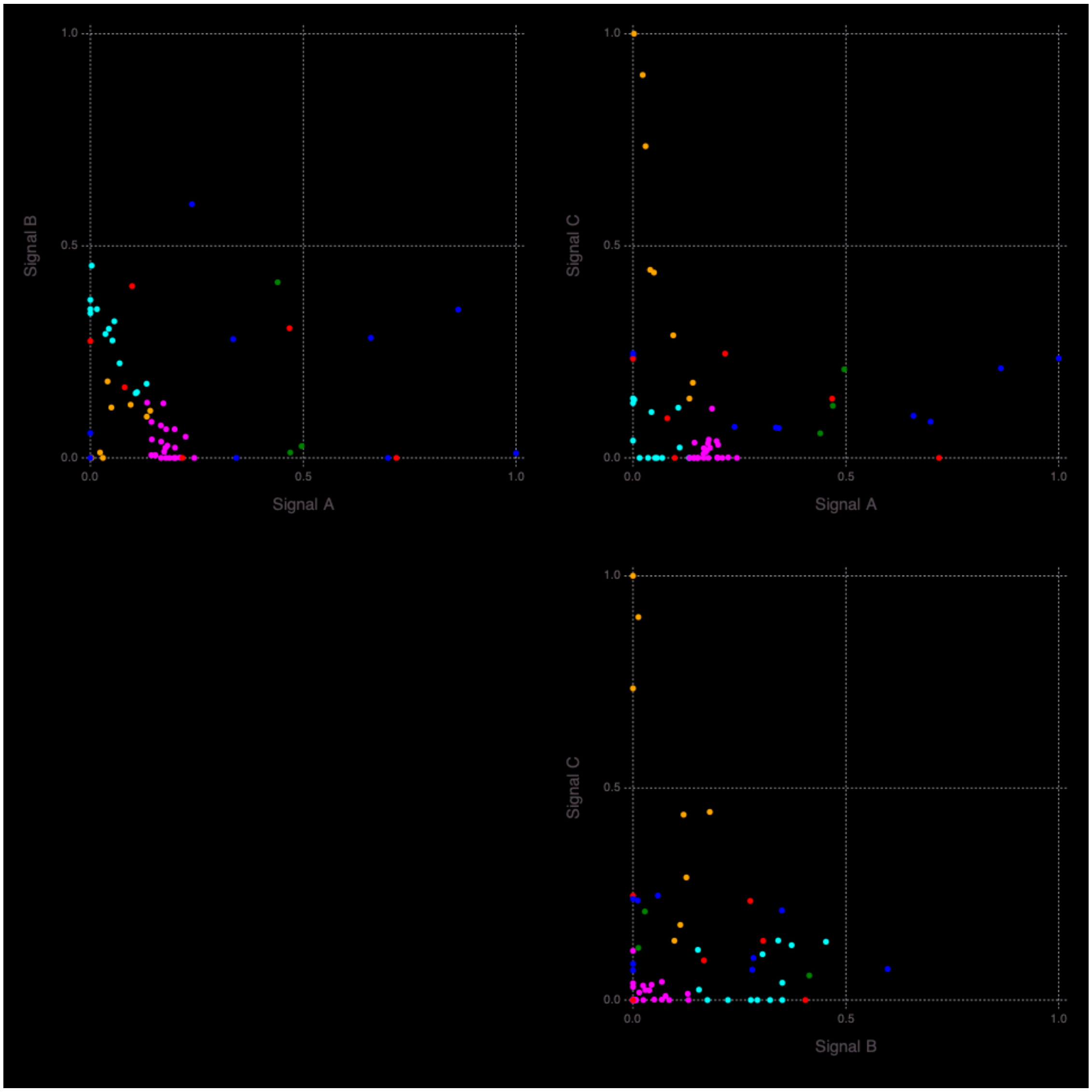

State map fault density A
Silica geothermometer A
Hydraulic gradient A
Boron concentration B
Quaternary fault density B
Spring density B
Volcanic vent density B
Precipitation B
Depth to basement B
Gravity anomaly C
Magnetic intensity C
Volcanic dike density C
Drainage density C
Fault intersection density C
Seismicity C
Lithium concentration C
Heat flow C
Crustal thickness C
A
B
C


State map fault density A
Silica geothermometer A
Hydraulic gradient A
Boron concentration B
Quaternary fault density B
Spring density B
Volcanic vent density B
Precipitation B
Depth to basement B
Gravity anomaly C
Magnetic intensity C
Volcanic dike density C
Drainage density C
Fault intersection density C
Seismicity C
Lithium concentration C
Heat flow C
Crustal thickness C
A
B
C


Signal 2
Signal 1
Gravity anomaly
Silica geothermometer
Lithium concentration
Depth to basement
Boron concentration
Quaternary fault density
Heat flow
Magnetic intensity
Volcanic vent density
State map fault density
Precipitation
Signal 3
Boron concentration
Hydraulic gradient
Magnetic intensity
Crustal thickness
Quaternary fault density
Seismicity
Lithium concentration
Heat flow
Gravity anomaly
Precipitation
1.0
0.5
0.0


Signal A
Signal B
Signal C
Gravity anomaly
Silica geothermometer
Lithium concentration
Depth to basement
Boron concentration
Heat flow
Magnetic intensity
Volcanic vent density
State map fault density
Spring density
Drainage density
Quaternary fault density
Hydraulic gradient
Crustal thickness
Precipitation
Seismicity

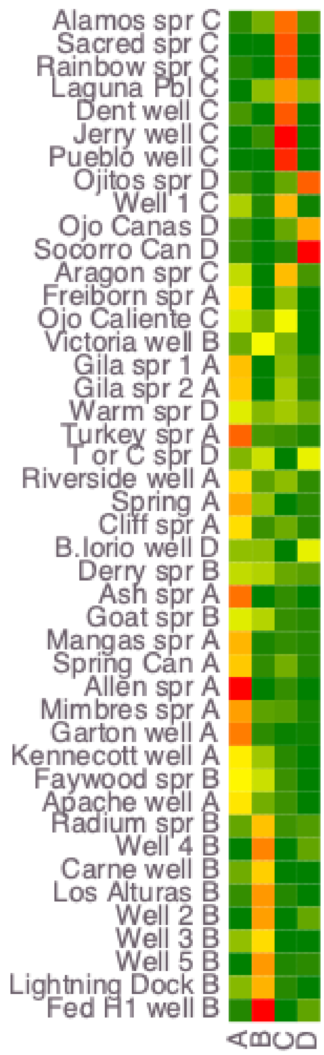

1.0
0.5
0.0
Signal 2
Signal 1
Signal 3
Signal 1
Signal 3
Signal 2



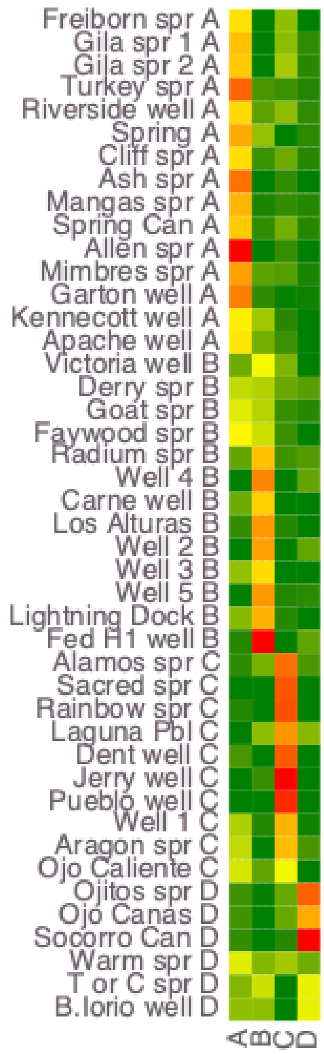

```
Signal importance (high->low): [2, 1, 4, 3]

  Info: Number of signals: 4
  @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:154
  Info: Locations (signals=4)
  @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:158
  Warning: type
Clustering.KmeansResult{Core.Array{Core.Float64,2},Core.Float64,Core.Int64} not
present in workspace; reconstructing
  @ JLD /Users/vvv/.julia/packages/JLD/nQ9iW/src/jld_types.jl:697
  Info: Robust k-means analysis results are loaded from file results-
case01/Hmatrix-4-4_44-1000.jld!
  @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkCluster.jl:67
  Warning: Procedure to find unique signals could not identify a solution …
```

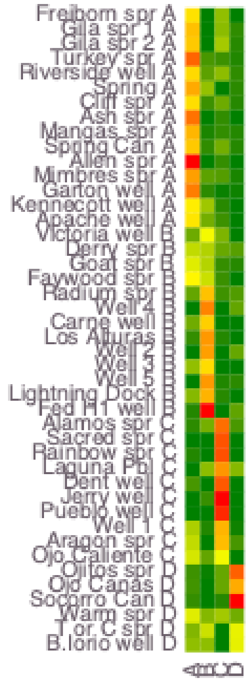
```
 @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkCluster.jl:158
 Warning: Procedure to find unique signals could not identify a solution …
 @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkCluster.jl:158
 Warning: Procedure to find unique signals could not identify a solution …
 @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkCluster.jl:158
 Warning: Procedure to find unique signals could not identify a solution …
 @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkCluster.jl:158
 Warning: type
Clustering.KmeansResult{Core.Array{Core.Float64,2},Core.Float64,Core.Int64} not
present in workspace; reconstructing
 @ JLD /Users/vvv/.julia/packages/JLD/nQ9iW/src/jld_types.jl:697

15×2 Array{Any,2}:
 "Allen spr"        1.0
 "Turkey spr"       0.890671
 "Ash spr"          0.860399
 "Garton well"      0.837981
 "Mimbres spr"      0.756788
 "Spring"           0.727799
 "Mangas spr"       0.697281
 "Gila spr 1"       0.667903
 "Spring Can"       0.647347
 "Gila spr 2"       0.646943
 "Riverside well"   0.602983
 "Cliff spr"        0.592572
 "Freiborn spr"     0.579998
 "Apache well"      0.569518
 "Kennecott well"   0.546961

13×2 Array{Any,2}:
 "Fed H1 well"      1.0
 "Well 4"           0.820447
 "Los Alturas"      0.774358
 "Well 5"           0.771269
 "Well 2"           0.755708
 "Lightning Dock"   0.70557
 "Radium spr"       0.666575
 "Carne well"       0.631706
 "Well 3"           0.596359
 "Victoria well"    0.477645
 "Faywood spr"      0.378783
 "Goat spr"         0.330589
 "Derry spr"        0.324788

10×2 Array{Any,2}:
 "Jerry well"     1.0
 "Pueblo well"    0.978656
 "Rainbow spr"    0.926226
 "Sacred spr"     0.920803
```

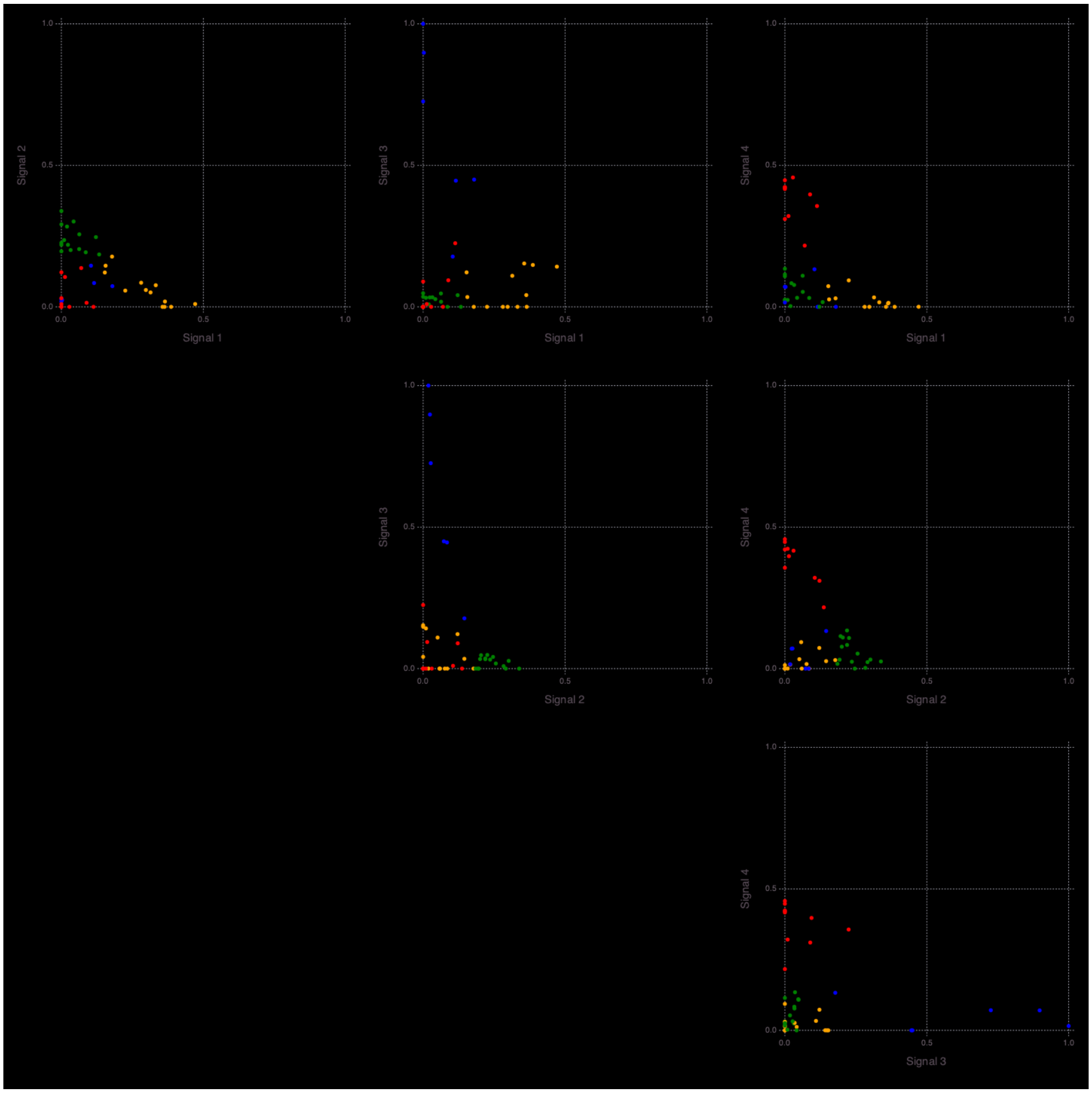
```
 "Dent well"      0.911277
 "Alamos spr"     0.869018
 "Laguna Pbl"     0.779479
 "Well 1"         0.701792
 "Aragon spr"     0.678922
 "Ojo Caliente"   0.473437

6×2 Array{Any,2}:
 "Socorro Can"    1.0
 "Ojitos spr"     0.897681
 "Ojo Canas"      0.725719
 "T or C spr"     0.449617
 "B.Iorio well"   0.445734
 "Warm spr"       0.177576
```

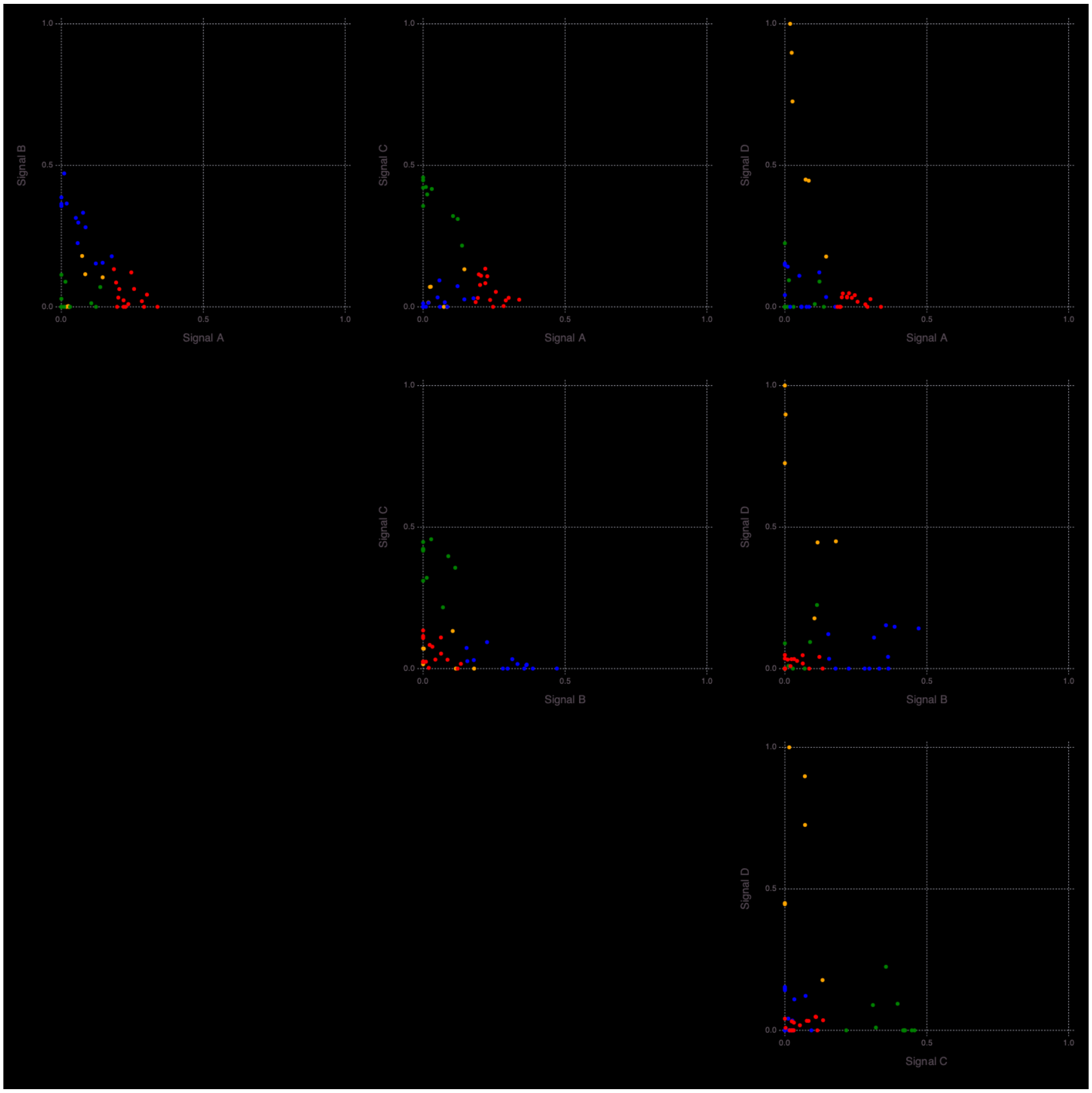


```
  Info: Robust k-means analysis results are loaded from file results-
case01/Wmatrix-4-4_18-1000.jld!
  @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkCluster.jl:67
  Info: Signal A -> A Count: 15
  @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:265
  Info: Signal B -> B Count: 13
  @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:265
  Info: Signal C -> C Count: 10
  @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:265
  Info: Signal D -> D Count: 6
  @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:265
  Info: Signal A (S2) (k-means clustering)
  @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:282
  Info: Signal B (S1) (k-means clustering)
  @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:282
  Info: Signal C (S4) (k-means clustering)
  @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:282
  Info: Signal D (S3) (k-means clustering)
  @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:282
```


Freiborn spr A
Gila spr 1 A
Gila spr 2 A
Turkey spr A
Riverside well A
Spring A
Cliff spr A
Ash spr A
Mangas spr A
Spring Can A
Allen spr A
Mimbres spr A
Garton well A
Kennecott well A
Apache well A
Victoria well B
Derry spr B
Goat spr B
Faywood spr B
Radium spr B
Well 4 B
Carne well B
Los Alturas B
Well 2 B
Well 3 B
Well 5 B
Lightning Dock B
Fed H1 well B
Alamos spr C
Sacred spr C
Rainbow spr C
Laguna Pbl C
Dent well C
Jerry well C
Pueblo well C
Well 1 C
Aragon spr C
Ojo Caliente C
Ojitos spr D
Ojo Canas D
Socorro Can D
Warm spr D
T or C spr D
B.lorio well D
A
B
C
D

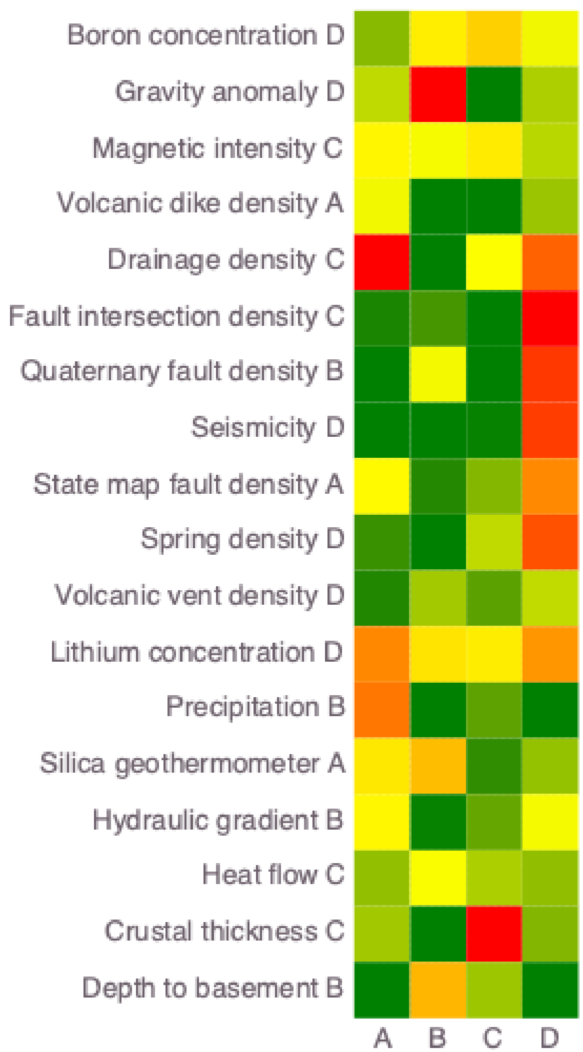

Freiborn spr A
Gila spr 1 A
Gila spr 2 A
Turkey spr A
Riverside well A
Spring A
Cliff spr A
Ash spr A
Mangas spr A
Spring Can A
Allen spr A
Mimbres spr A
Garton well A
Kennecott well A
Apache well A
Victoria well B
Derry spr B
Goat spr B
Faywood spr B
Radium spr B
Well 4 B
Carne well B
Los Alturas B
Well 2 B
Well 3 B
Well 5 B
Lightning Dock B
Fed H1 well B
Alamos spr C
Sacred spr C
Rainbow spr C
Laguna Pbl C
Dent well C
Jerry well C
Pueblo well C
Well 1 C
Aragon spr C
Ojo Caliente C
Ojitos spr D
Ojo Canas D
Socorro Can D
Warm spr D
T or C spr D
B.lorio well D
A
B
C
D


Signal 1
Signal 2
Signal 3
Signal 4



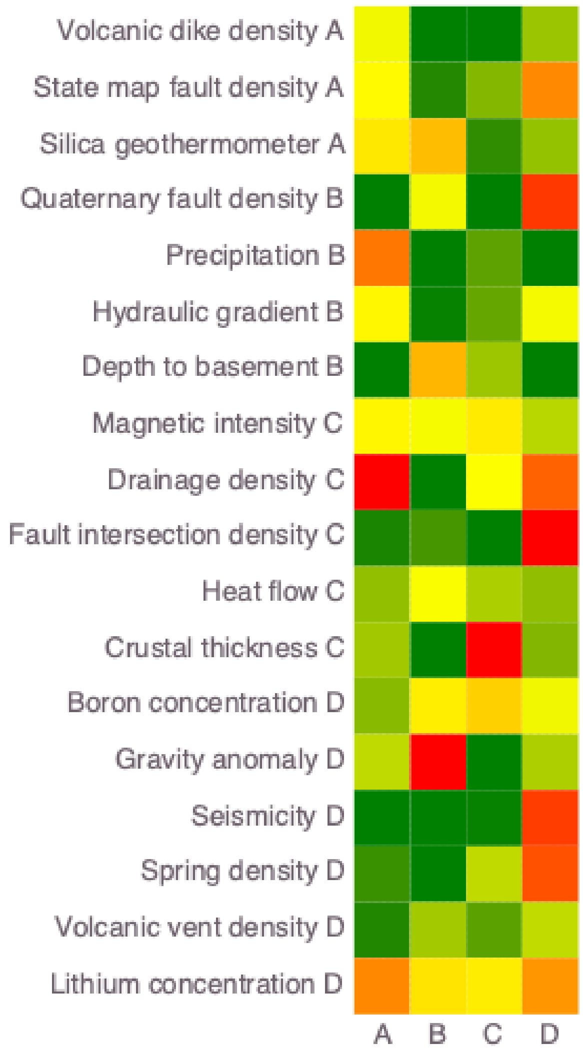

```
3×2 Array{Any,2}:
 "Silica geothermometer"     0.565319
 "State map fault density"   0.516354
 "Volcanic dike density"     0.46948

4×2 Array{Any,2}:
 "Depth to basement"          0.698015
 "Quaternary fault density"   0.473285
 "Hydraulic gradient"         0.00393436
 "Precipitation"              0.0

5×2 Array{Any,2}:
 "Crustal thickness"            1.0
 "Magnetic intensity"           0.556994
```

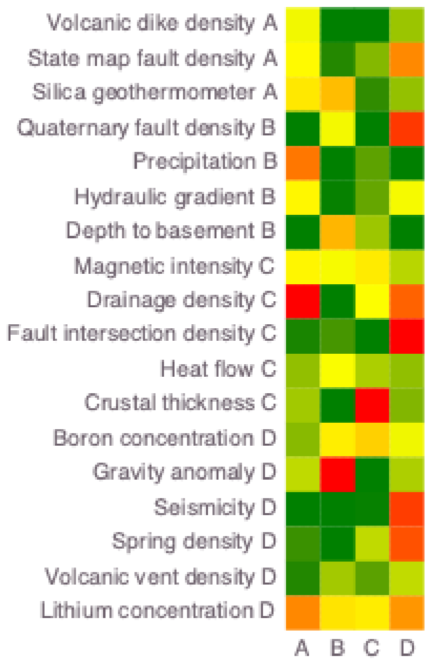
```
 "Drainage density"            0.495465
 "Heat flow"                   0.311164
 "Fault intersection density"  0.0

6×2 Array{Any,2}:
 "Seismicity"             0.95485
 "Spring density"         0.924999
 "Lithium concentration"  0.779688
 "Boron concentration"    0.465497
 "Volcanic vent density"  0.359763
 "Gravity anomaly"        0.313199
```

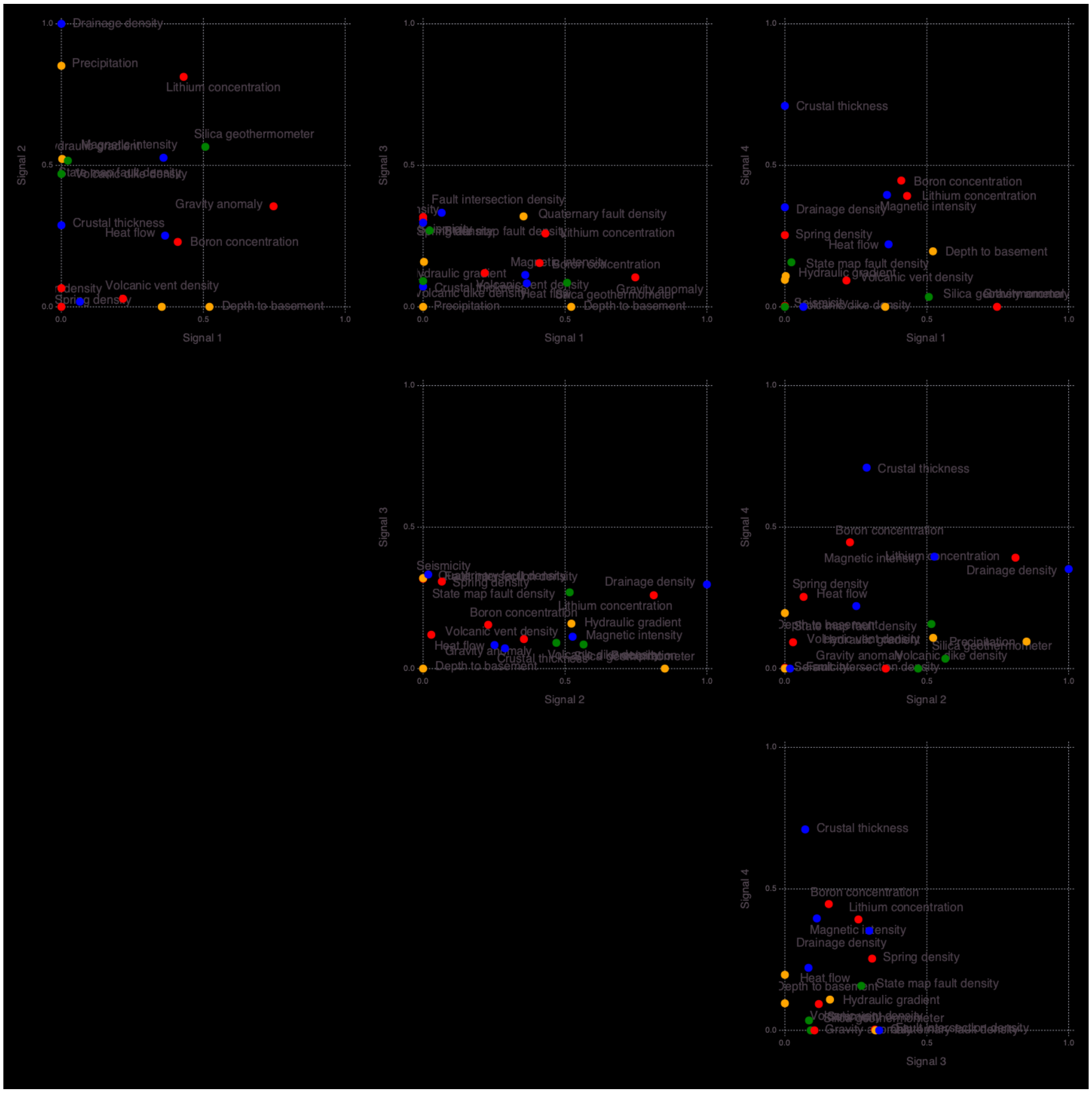



```
Info: Attributes (signals=4)
```

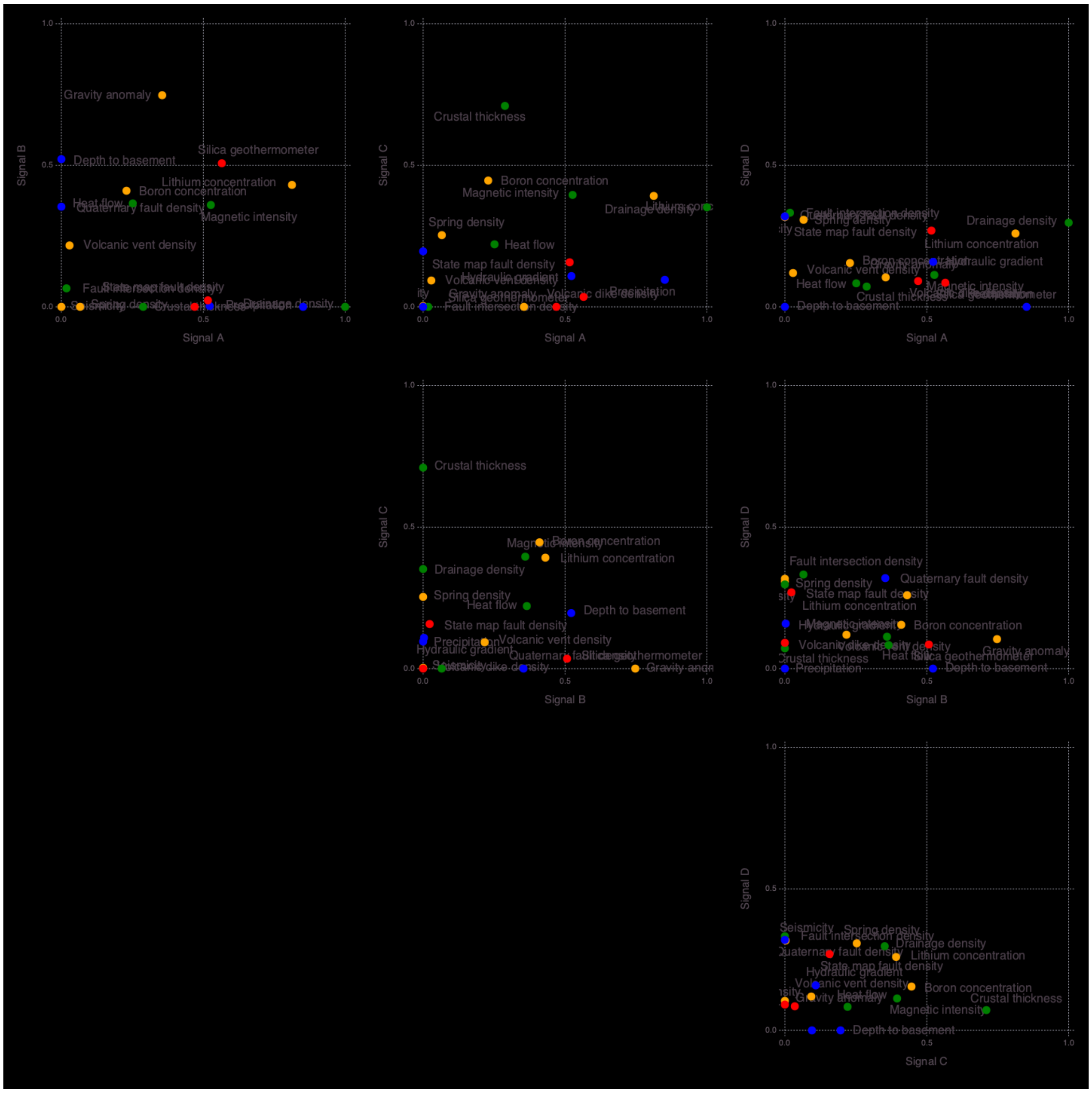
```
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:340
Info: Signal A (S3) Count: 6
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:353
Info: Signal B (S4) Count: 5
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:353
Info: Signal C (S1) Count: 4
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:353
Info: Signal D (S2) Count: 3
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:353
Info: Signal D -> A Count: 3
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:363
Info: Signal C -> B Count: 4
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:363
Info: Signal B -> C Count: 5
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:363
Info: Signal A -> D Count: 6
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:363
Info: Signal A (remapped k-means clustering)
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:378
Info: Signal B (remapped k-means clustering)
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:378
Info: Signal C (remapped k-means clustering)
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:378
Info: Signal D (remapped k-means clustering)
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:378
```

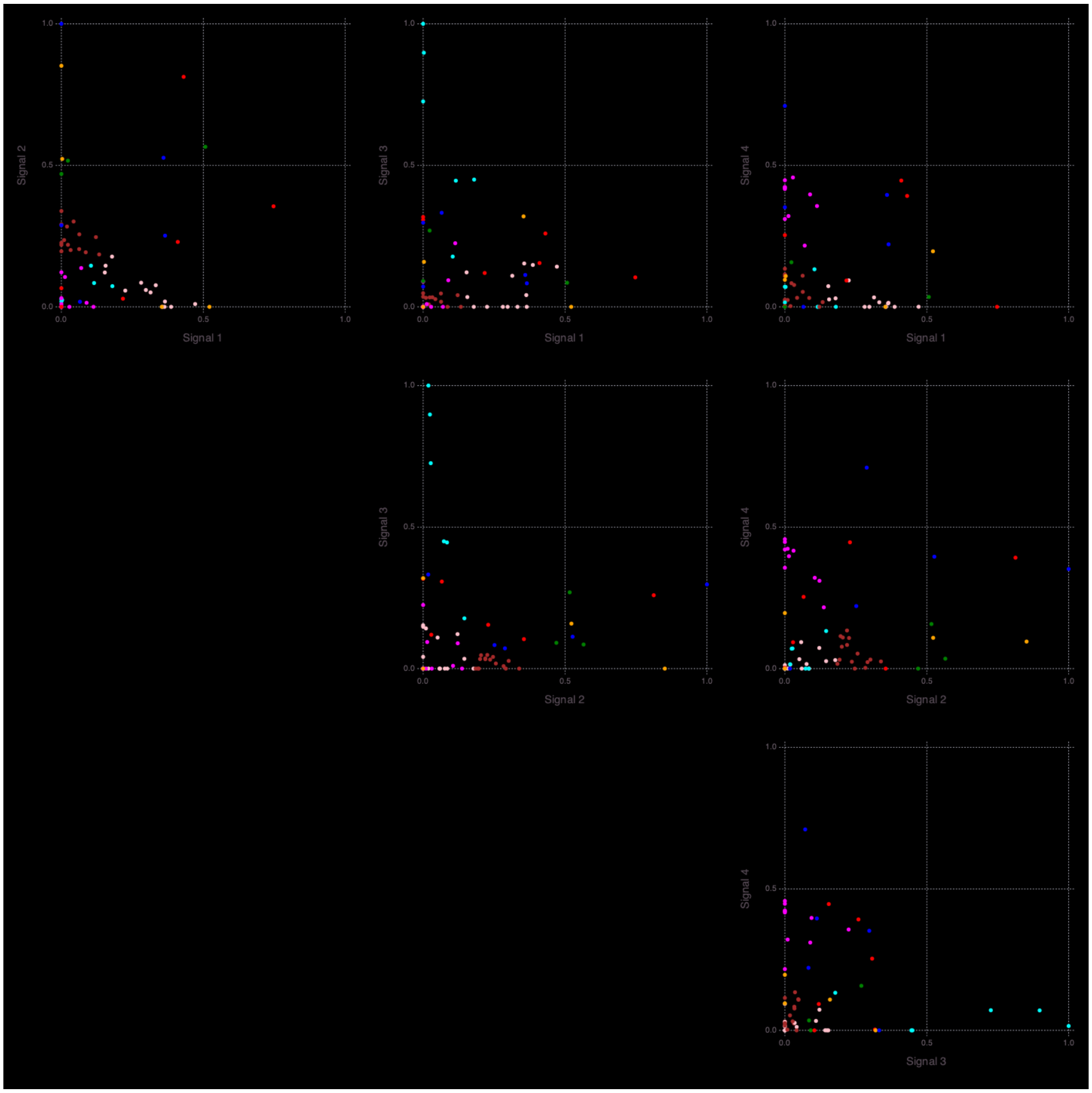

Volcanic dike density A
State map fault density A
Silica geothermometer A
Quaternary fault density B
Precipitation B
Hydraulic gradient B
Depth to basement B
Magnetic intensity C
Drainage density C
Fault intersection density C
Heat flow C
Crustal thickness C
Boron concentration D
Gravity anomaly D
Seismicity D
Spring density D
Volcanic vent density D
Lithium concentration D
A
B
C
D

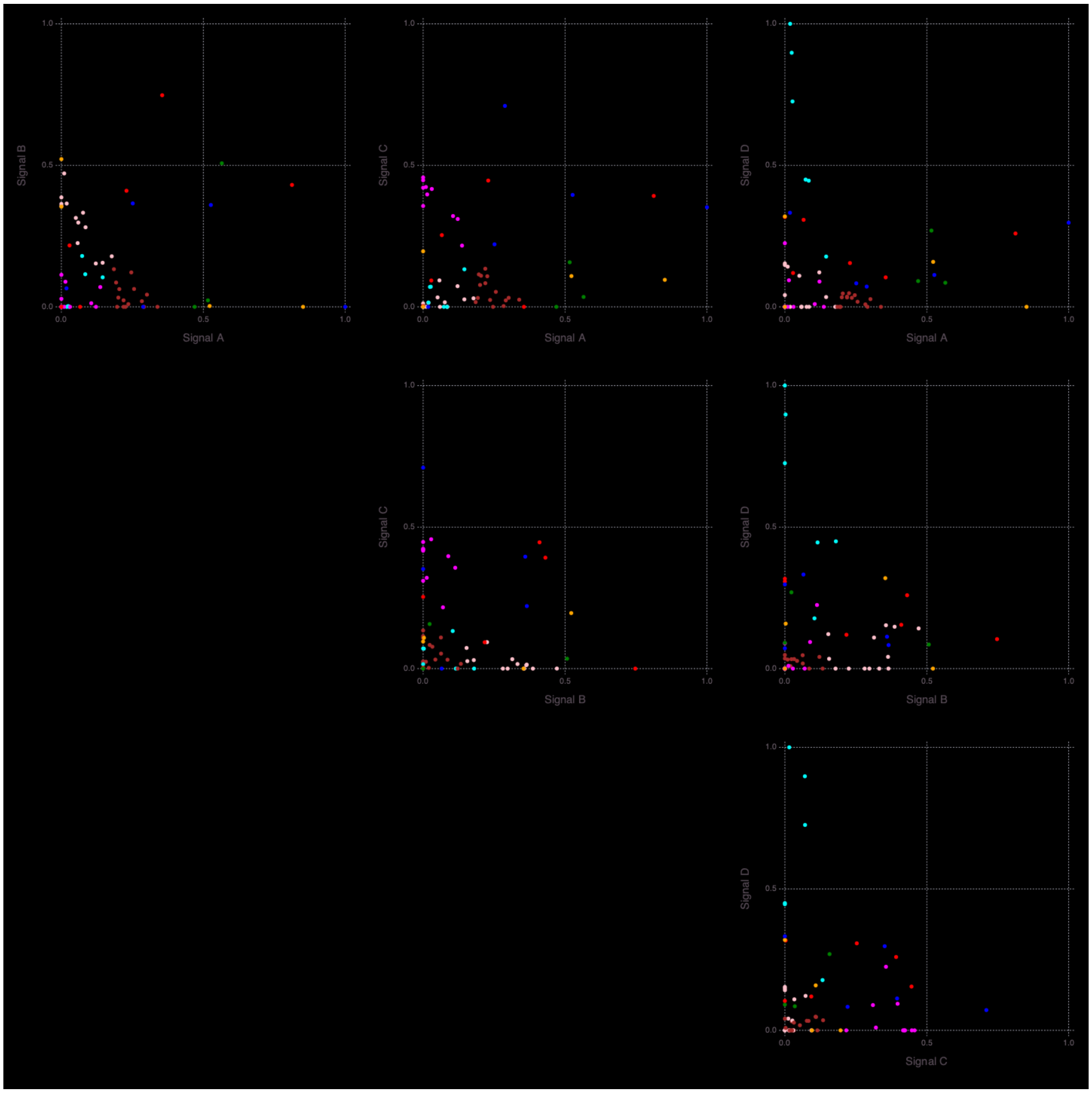

Volcanic dike density A
State map fault density A
Silica geothermometer A
Quaternary fault density B
Precipitation B
Hydraulic gradient B
Depth to basement B
Magnetic intensity C
Drainage density C
Fault intersection density C
Heat flow C
Crustal thickness C
Boron concentration D
Gravity anomaly D
Seismicity D
Spring density D
Volcanic vent density D
Lithium concentration D
A B C D



Signal 1
Signal 2
Signal 3
Signal 4
0.0
0.5
1.0
Drainage density
Precipitation
Lithium concentration
Silica geothermometer
Magnetic intensity
Gravity anomaly
Crustal thickness
Heat flow
Boron concentration
Volcanic vent density
Spring density
Depth to basement
Fault intersection density
Quaternary fault density
Seismicity
State map fault density
Hydraulic gradient
Volcanic dike density

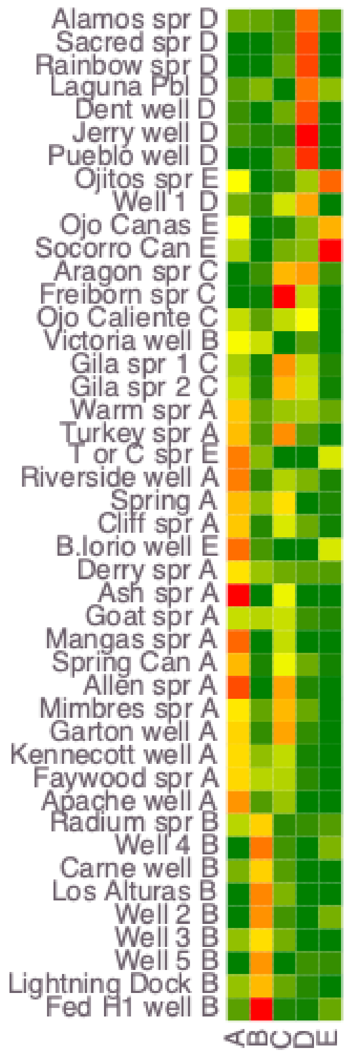

Signal A
Signal B
Signal C
Signal D


Signal 1
Signal 2
Signal 3
Signal 4



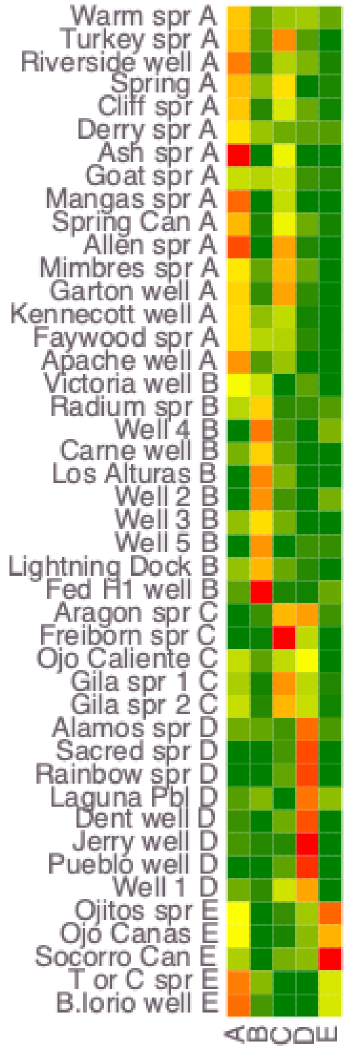

```
Signal importance (high->low): [1, 4, 2, 3, 5]

  Info: Number of signals: 5
  @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:154
  Info: Locations (signals=5)
  @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:158
  Warning: type
Clustering.KmeansResult{Core.Array{Core.Float64,2},Core.Float64,Core.Int64} not
present in workspace; reconstructing
  @ JLD /Users/vvv/.julia/packages/JLD/nQ9iW/src/jld_types.jl:697

16×2 Array{Any,2}:
 "Ash spr"         1.0
 "Allen spr"       0.932476
```

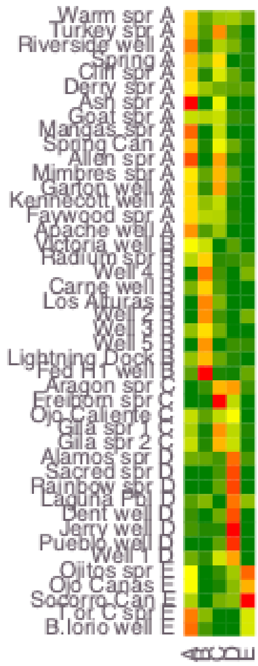
```
 "Mangas spr"      0.883364
 "Riverside well"  0.834285
 "Apache well"     0.782126
 "Spring Can"      0.691235
 "Turkey spr"      0.677725
 "Spring"          0.676908
 "Cliff spr"       0.650192
 "Warm spr"        0.649358
 "Garton well"     0.617193
 "Faywood spr"     0.60702
 "Kennecott well"  0.598779
 "Derry spr"       0.578414
 "Mimbres spr"     0.564978
 "Goat spr"        0.36953

10×2 Array{Any,2}:
 "Fed H1 well"     1.0
 "Well 4"          0.848078
 "Los Alturas"     0.815345
 "Well 2"          0.788889
 "Well 5"          0.777949
 "Lightning Dock"  0.687945
 "Carne well"      0.627357
 "Radium spr"      0.625606
 "Well 3"          0.59283
 "Victoria well"   0.379997

5×2 Array{Any,2}:
 "Freiborn spr"  1.0
 "Gila spr 1"    0.779561
 "Gila spr 2"    0.695982
 "Aragon spr"    0.695158
 "Ojo Caliente"  0.359767

8×2 Array{Any,2}:
 "Jerry well"   1.0
 "Pueblo well"  0.971051
 "Rainbow spr"  0.942867
 "Sacred spr"   0.935706
 "Dent well"    0.927135
 "Alamos spr"   0.872535
 "Laguna Pbl"   0.85495
 "Well 1"       0.738413

5×2 Array{Any,2}:
 "Socorro Can"   1.0
 "Ojitos spr"    0.885484
 "Ojo Canas"     0.707981
 "T or C spr"    0.411346
 "B.Iorio well"  0.409252
```

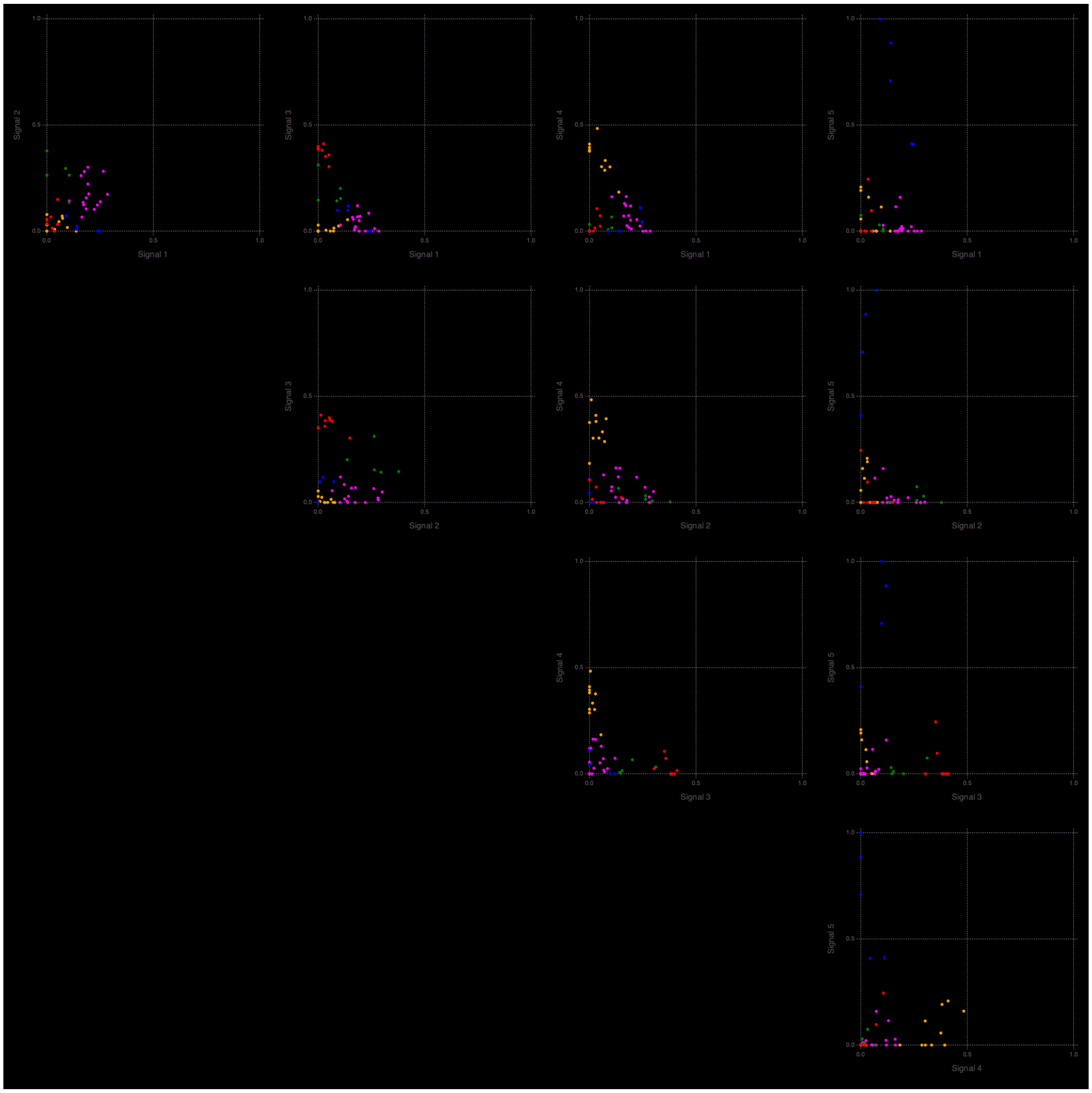


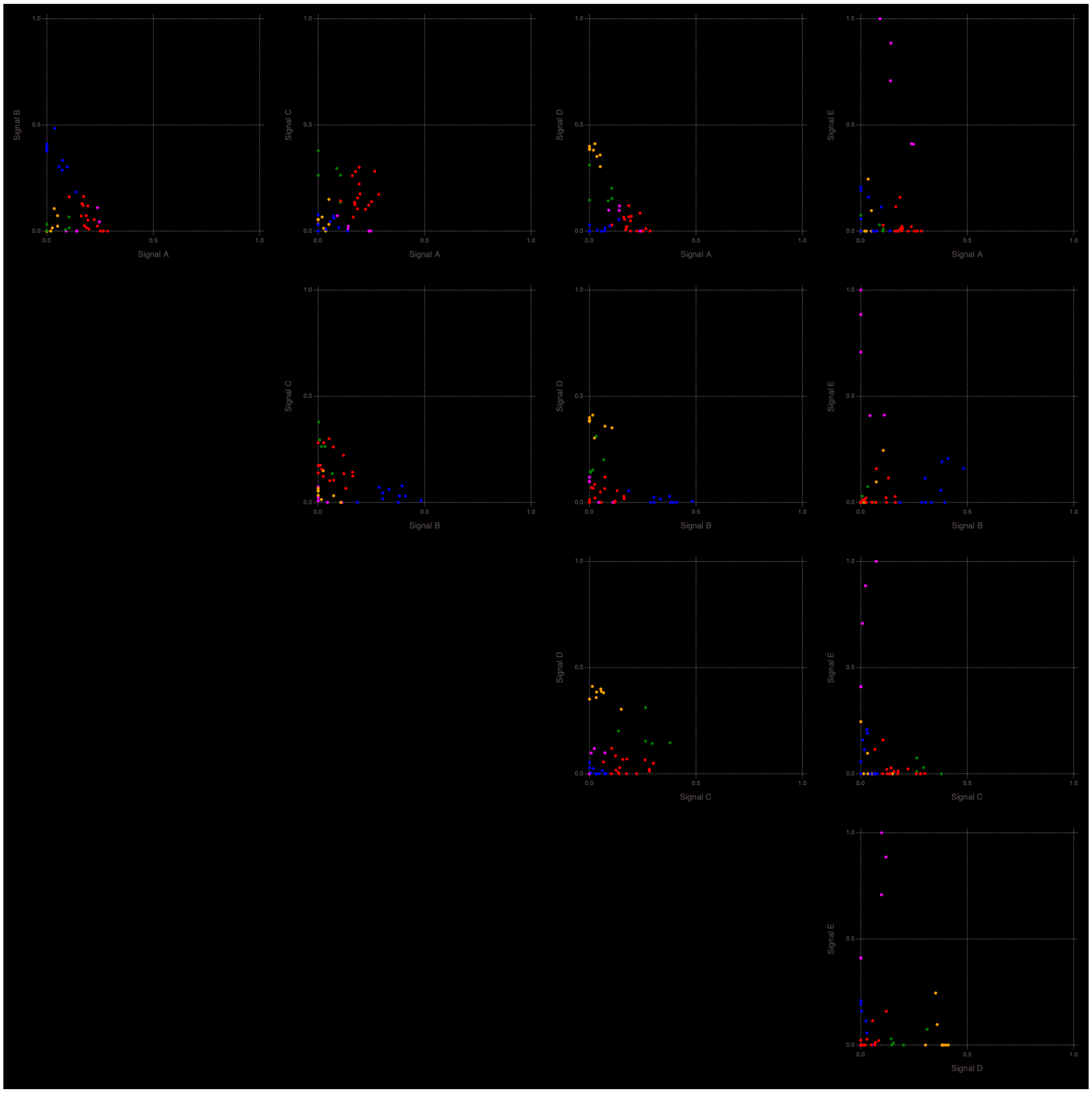

```
 Info: Robust k-means analysis results are loaded from file results-
case01/Hmatrix-5-5_44-1000.jld!
 @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkCluster.jl:67
 Warning: Procedure to find unique signals could not identify a solution …
 @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkCluster.jl:158
 Warning: Procedure to find unique signals could not identify a solution …
 @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkCluster.jl:158
 Warning: Procedure to find unique signals could not identify a solution …
 @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkCluster.jl:158
 Warning: Procedure to find unique signals could not identify a solution …
 @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkCluster.jl:158
 Warning: Procedure to find unique signals could not identify a solution …
 @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkCluster.jl:158
```

```
 Warning: type
Clustering.KmeansResult{Core.Array{Core.Float64,2},Core.Float64,Core.Int64} not
present in workspace; reconstructing
 @ JLD /Users/vvv/.julia/packages/JLD/nQ9iW/src/jld_types.jl:697
 Info: Robust k-means analysis results are loaded from file results-
case01/Wmatrix-5-5_18-1000.jld!
 @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkCluster.jl:67
 Warning: Procedure to find unique signals could not identify a solution …
 @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkCluster.jl:158
 Info: Signal A -> A Count: 16
 @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:265
 Info: Signal B -> B Count: 10
 @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:265
 Info: Signal E -> C Count: 5
 @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:265
 Info: Signal C -> D Count: 8
 @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:265
 Info: Signal D -> E Count: 5
 @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:265
 Info: Signal A (S1) (k-means clustering)
 @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:282
 Info: Signal B (S4) (k-means clustering)
 @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:282
 Info: Signal C (S2) (k-means clustering)
 @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:282
 Info: Signal D (S3) (k-means clustering)
 @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:282
 Info: Signal E (S5) (k-means clustering)
 @ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:282
```


Warm spr A
Turkey spr A
Riverside well A
Spring A
Cliff spr A
Derry spr A
Ash spr A
Goat spr A
Mangas spr A
Spring Can A
Allen spr A
Mimbres spr A
Garton well A
Kennecott well A
Faywood spr A
Apache well A
Victoria well B
Radium spr B
Well 4 B
Carne well B
Los Alturas B
Well 2 B
Well 3 B
Well 5 B
Lightning Dock B
Fed H1 well B
Aragon spr C
Freiborn spr C
Ojo Caliente C
Gila spr 1 C
Gila spr 2 C
Alamos spr D
Sacred spr D
Rainbow spr D
Laguna Pbl D
Dent well D
Jerry well D
Pueblo well D
Well 1 D
Ojitos spr E
Ojo Canas E
Socorro Can E
T or C spr E
B.lorio well E
A
B
C
D
E

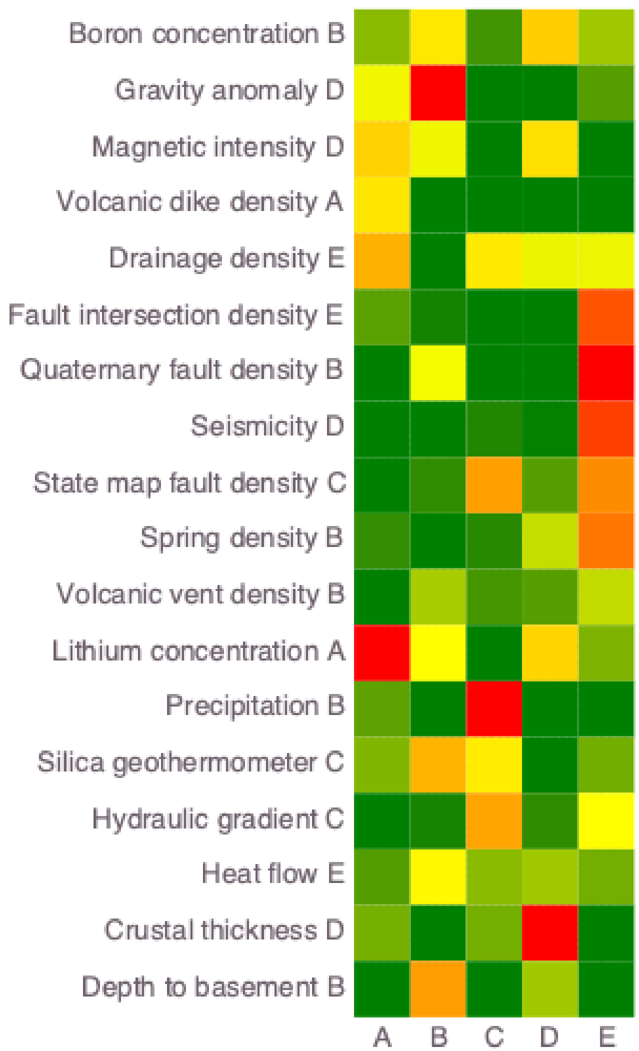

Warm spr A
Turkey spr A
Riverside well A
Spring A
Cliff spr A
Derry spr A
Ash spr A
Goat spr A
Mangas spr A
Spring Can A
Allen spr A
Mimbres spr A
Garton well A
Kennecott well A
Faywood spr A
Apache well A
Victoria well B
Radium spr B
Well 4 B
Carne well B
Los Alturas B
Well 2 B
Well 3 B
Well 5 B
Lightning Dock B
Fed H1 well B
Aragon spr C
Freiborn spr C
Ojo Caliente C
Gila spr 1 C
Gila spr 2 C
Alamos spr D
Sacred spr D
Rainbow spr D
Laguna Pbl D
Dent well D
Jerry well D
Pueblo well D
Well 1 D
Ojitos spr E
Ojo Canas E
Socorro Can E
Tor. C spr E
B.Iorio well E
A
B
C
D
E


Signal 1
Signal 2
Signal 3
Signal 4
Signal 5

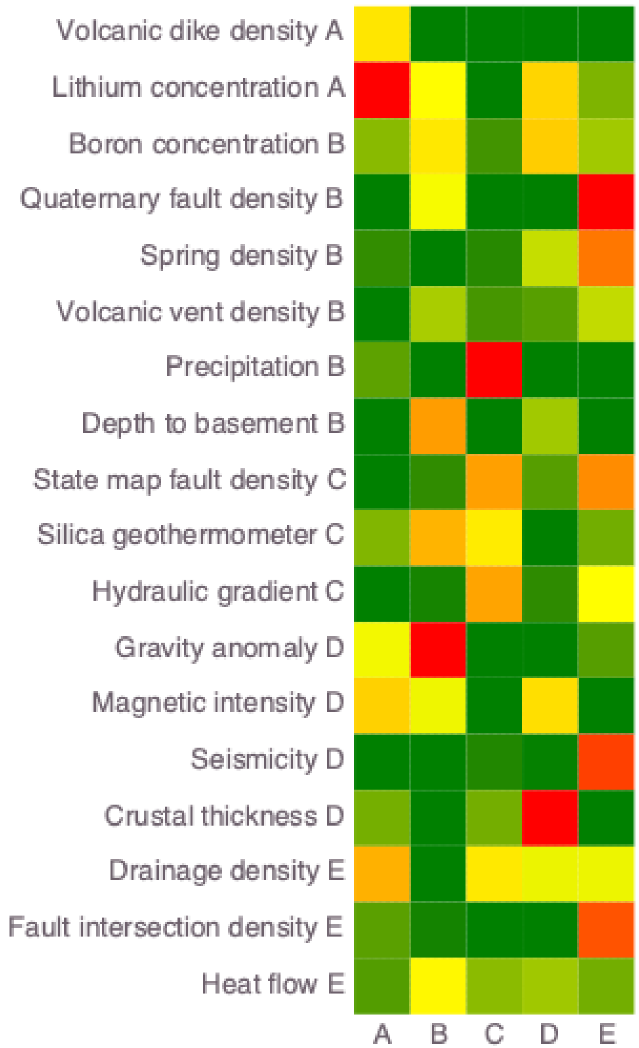


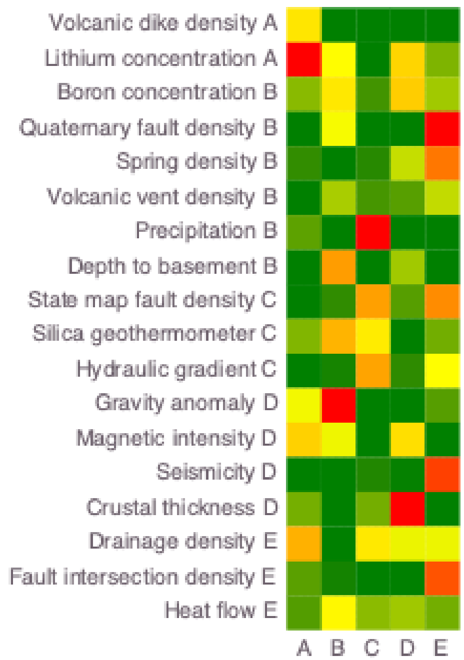
```
2×2 Array{Any,2}:
 "Lithium concentration"  1.0
 "Volcanic dike density"  0.56854

6×2 Array{Any,2}:
 "Depth to basement"           0.760709
 "Boron concentration"         0.565134
 "Quaternary fault density"    0.481084
 "Volcanic vent density"       0.303895
 "Spring density"              0.0
 "Precipitation"               0.0

3×2 Array{Any,2}:
 "State map fault density"  0.755023
```

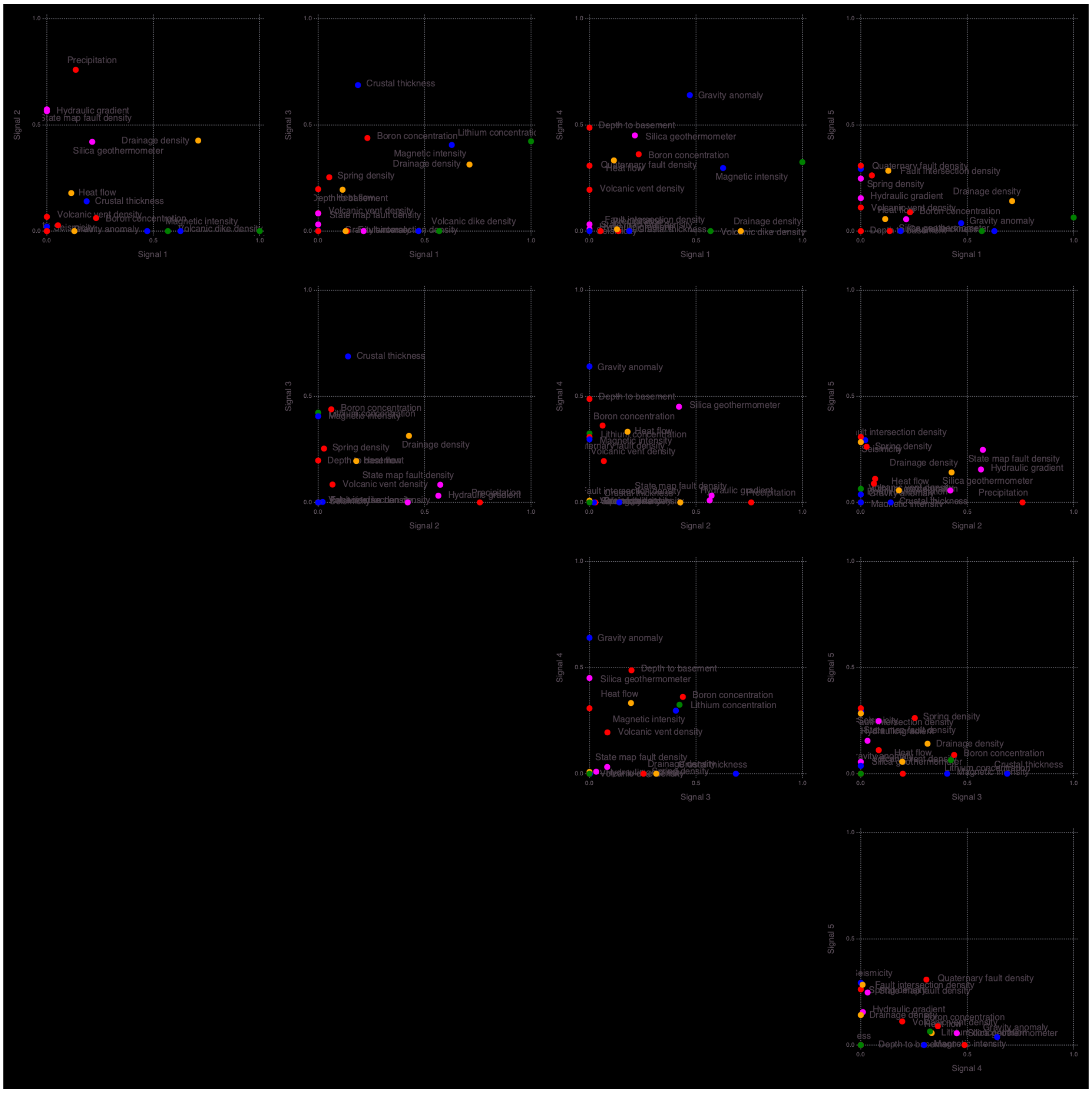
```
 "Hydraulic gradient"       0.743237
 "Silica geothermometer"    0.553526

4×2 Array{Any,2}:
 "Crustal thickness"   1.0
 "Magnetic intensity"  0.590051
 "Seismicity"          0.0030882
 "Gravity anomaly"     0.0

3×2 Array{Any,2}:
 "Fault intersection density"  0.921753
 "Drainage density"            0.458627
 "Heat flow"                   0.183895
```

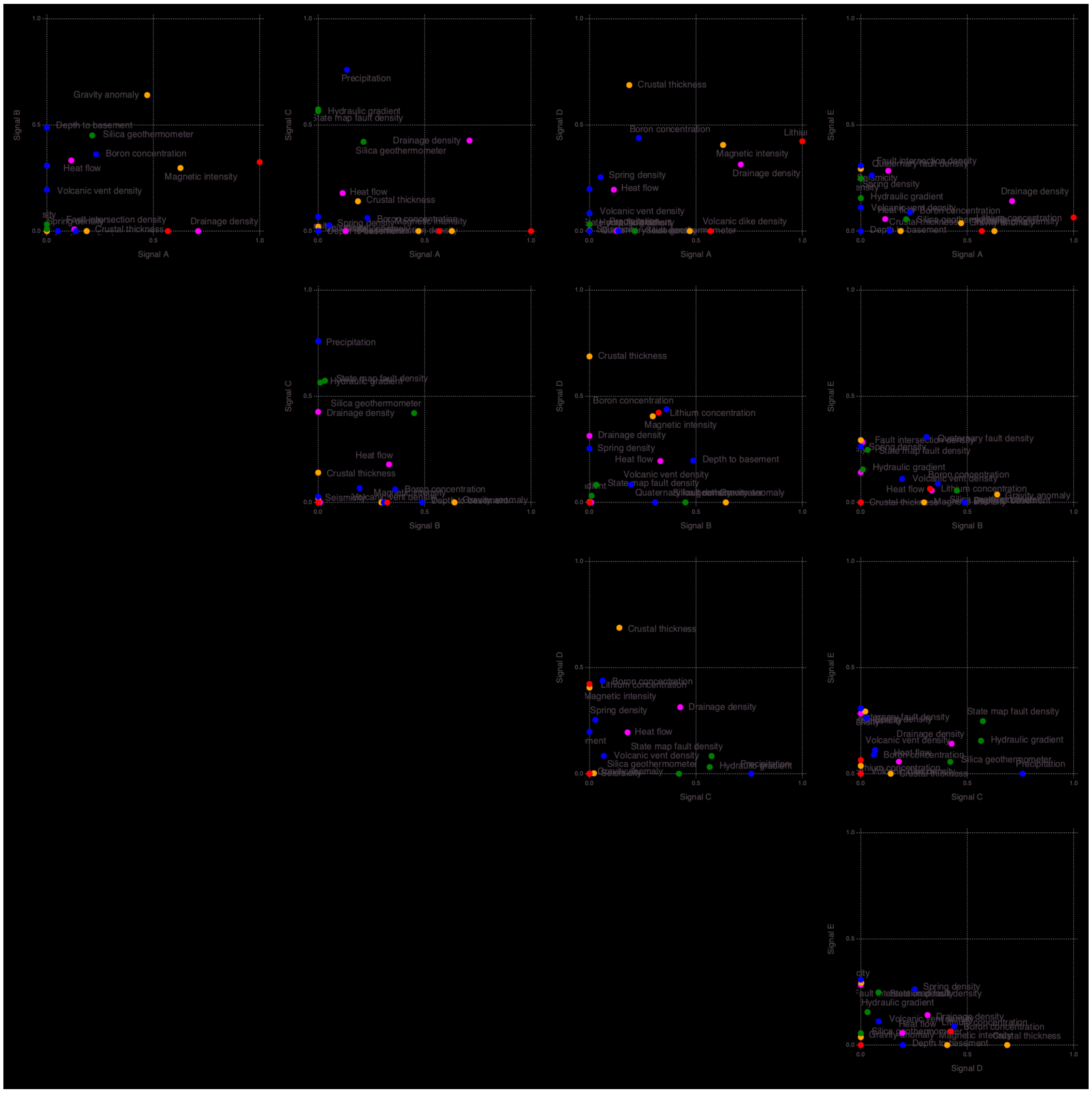


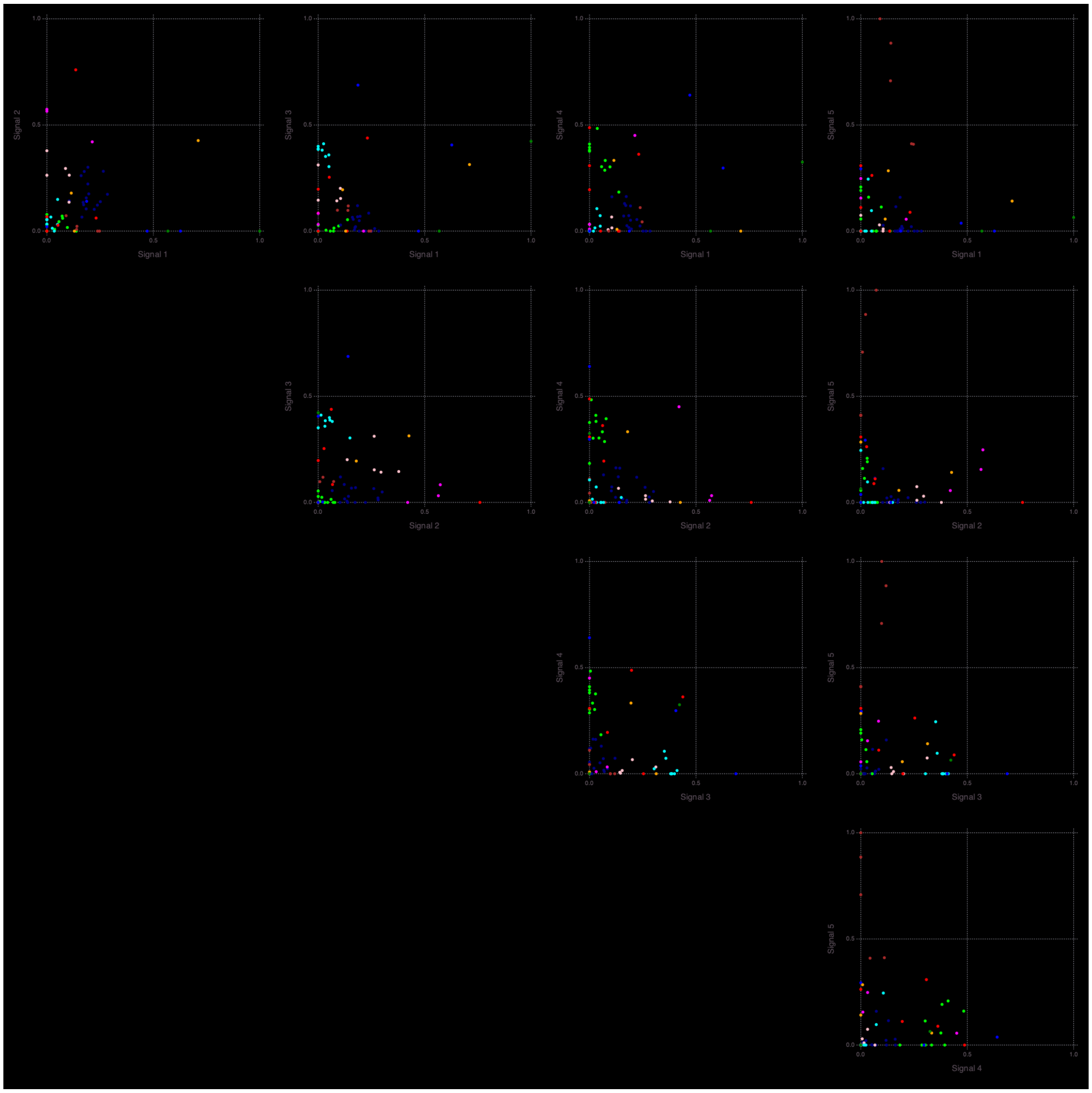
```
Info: Attributes (signals=5)
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:340
Info: Signal A (S4) Count: 6
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:353
Info: Signal B (S3) Count: 4
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:353
Info: Signal C (S5) Count: 3
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:353
Info: Signal D (S2) Count: 3
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:353
Info: Signal E (S1) Count: 2
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:353
Info: Signal E -> A Count: 2
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:363
Info: Signal A -> B Count: 6
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:363
Info: Signal D -> C Count: 3
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:363
Info: Signal B -> D Count: 4
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:363
Info: Signal C -> E Count: 3
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:363
Info: Signal A (remapped k-means clustering)
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:378
Info: Signal B (remapped k-means clustering)
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:378
Info: Signal C (remapped k-means clustering)
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:378
Info: Signal D (remapped k-means clustering)
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:378
Info: Signal E (remapped k-means clustering)
@ NMFk /Users/vvv/.julia/dev/NMFk/src/NMFkPostprocess.jl:378
```

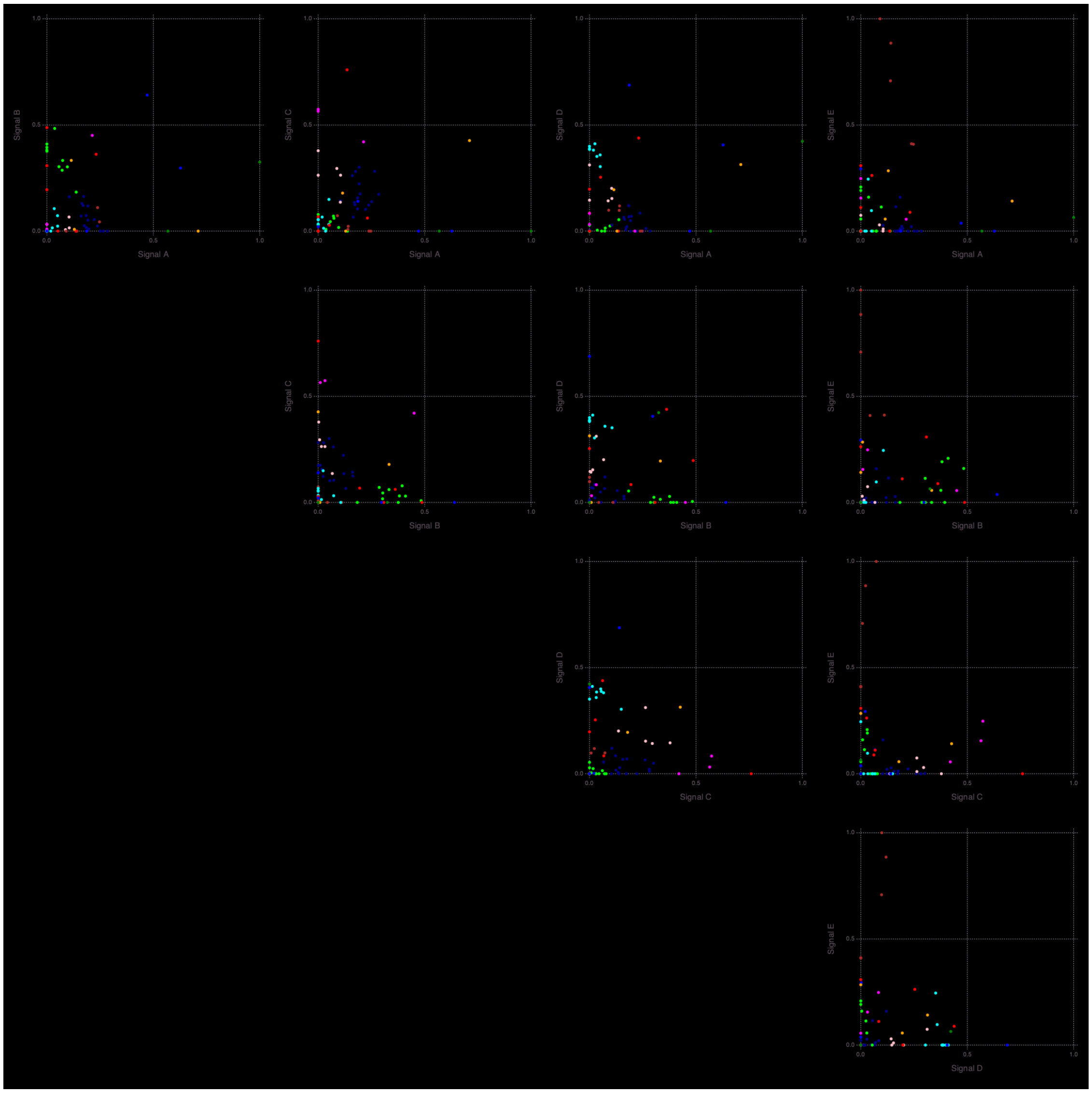

Volcanic dike density A
Lithium concentration A
Boron concentration B
Quaternary fault density B
Spring density B
Volcanic vent density B
Precipitation B
Depth to basement B
State map fault density C
Silica geothermometer C
Hydraulic gradient C
Gravity anomaly D
Magnetic intensity D
Seismicity D
Crustal thickness D
Drainage density E
Fault intersection density E
Heat flow E
A
B
C
D
E


Volcanic dike density A
Lithium concentration A
Boron concentration B
Quaternary fault density B
Spring density B
Volcanic vent density B
Precipitation B
Depth to basement B
State map fault density C
Silica geothermometer C
Hydraulic gradient C
Gravity anomaly D
Magnetic intensity D
Seismicity D
Crustal thickness D
Drainage density E
Fault intersection density E
Heat flow E
A
B
C
D
E




Signal A
Signal B
Signal C
Signal D
Signal E


Signal 1
Signal 2
Signal 3
Signal 4
Signal 5



Analysis of the 5-signature solution The results for a solution with **5** signatures presented above will be further discussed here.

The geothermal attributes are clustered into **5** groups:

[16]:
```
Mads.display("results-case01/attributes-5-groups.txt")
```

```
Signal A
Lithium concentration          1.0
Volcanic dike density          0.569

Signal B
```

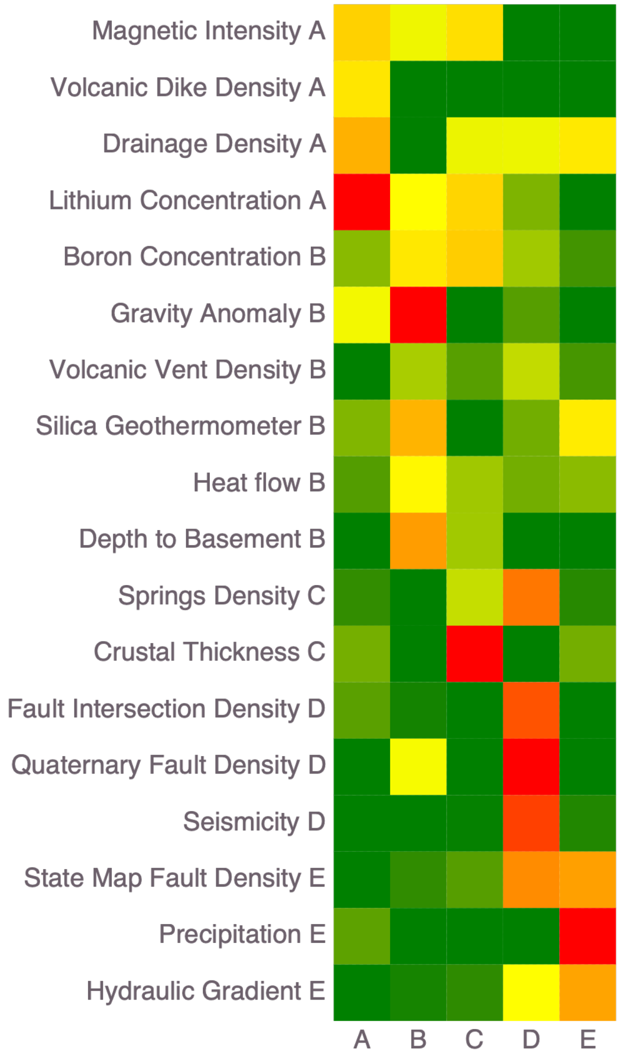
Depth to basement	0.761
Boron concentration	0.565
Quaternary fault density	0.481
Volcanic vent density	0.304
Spring density	0.0
Precipitation	0.0

Signal C	
State map fault density	0.755
Hydraulic gradient	0.743
Silica geothermometer	0.554

Signal D	
Crustal thickness	1.0
Magnetic intensity	0.59
Seismicity	0.00309
Gravity anomaly	0.0

Signal E	
Fault intersection density	0.922
Drainage density	0.459
Heat flow	0.184

This grouping is based on analyses of the attribute matrix `W`:



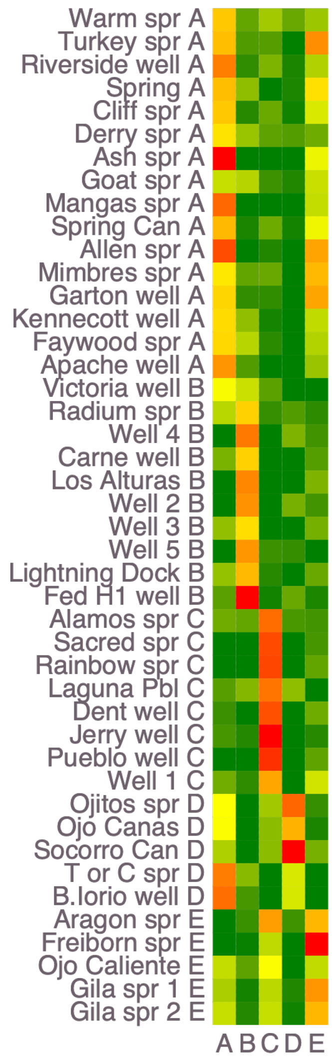
The well locations are also clustered into **5** groups:

[17]:
```
Mads.display("results-case01/locations-5-groups.txt")
```

```
Signal A (S1)
Ash spr         1.0
Allen spr       0.932
Mangas spr      0.883
Riverside well  0.834
Apache well     0.782
Spring Can      0.691
Turkey spr      0.678
Spring          0.677
Cliff spr       0.65
Warm spr        0.649
Garton well     0.617
```

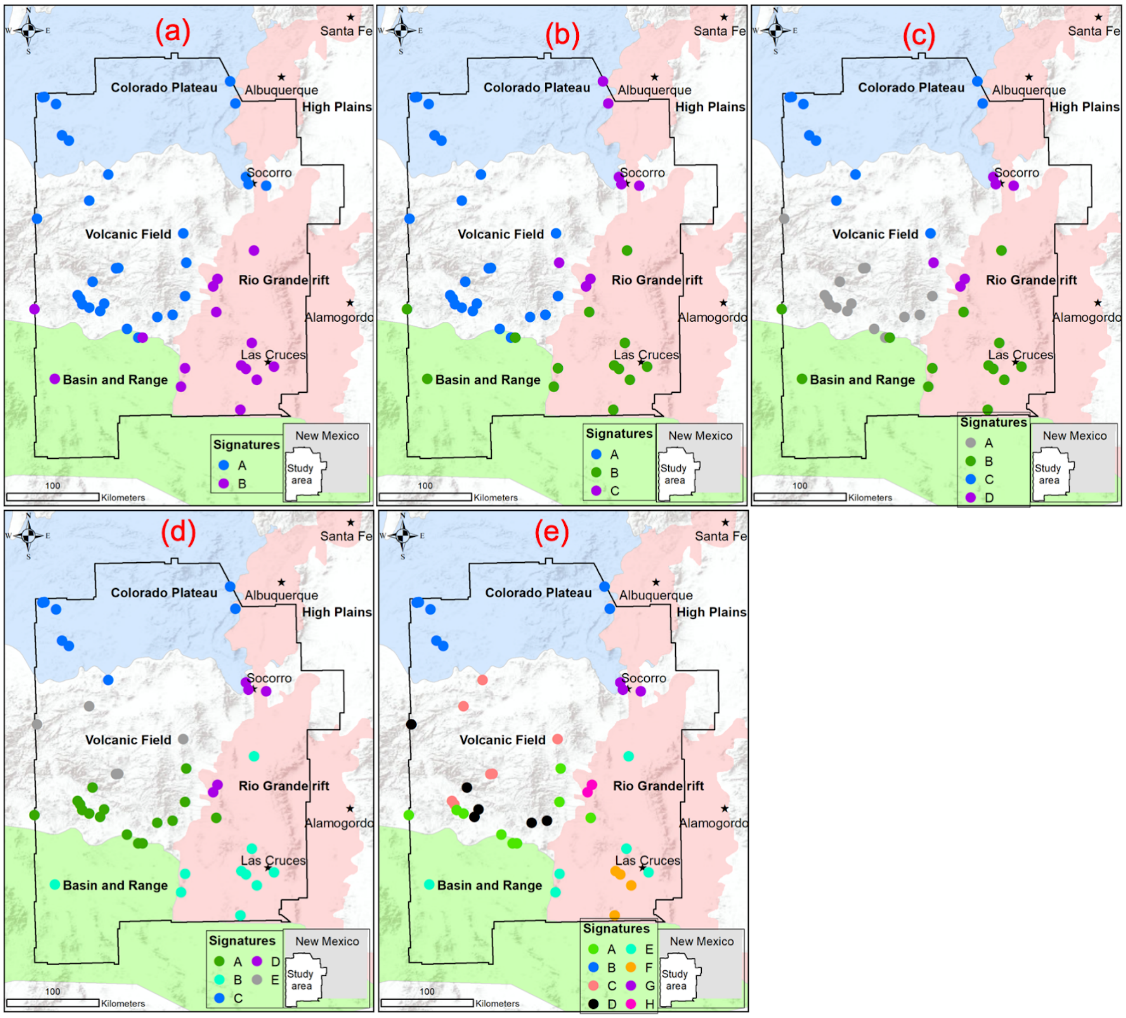
```
Faywood spr     0.607
Kennecott well  0.599
Derry spr       0.578
Mimbres spr     0.565
Goat spr        0.37

Signal B (S4)
Fed H1 well     1.0
Well 4          0.848
Los Alturas     0.815
Well 2          0.789
Well 5          0.778
Lightning Dock  0.688
Carne well      0.627
Radium spr      0.626
Well 3          0.593
Victoria well   0.38

Signal C (S2)
Freiborn spr    1.0
Gila spr 1      0.78
Gila spr 2      0.696
Aragon spr      0.695
Ojo Caliente    0.36

Signal D (S3)
Jerry well      1.0
Pueblo well     0.971
Rainbow spr     0.943
Sacred spr      0.936
Dent well       0.927
Alamos spr      0.873
Laguna Pbl      0.855
Well 1          0.738

Signal E (S5)
Socorro Can     1.0
Ojitos spr      0.885
Ojo Canas       0.708
T or C spr      0.411
B.Iorio well    0.409
```

This grouping is based on analyses of the location matrix `H`:



The map ../figures-case01/locations-5-map.html provides interactive visualization of the extracted location groups (the html file can also be opened within any browser).

Comparison of the ML solutions against the SWNM physiographic provinces The spatial association of the extracted signatures with the four physiographic provinces in SWNM is summarized in the figure below:



The solutions for k=2, 3, and 4 provide a higher-level classification of the geothermal locations, while the k=8 solution allow us to further refine the geothermal signatures and their association to the physiographic provinces. The solution for k=5 provides the best classification of the geothermal locations.

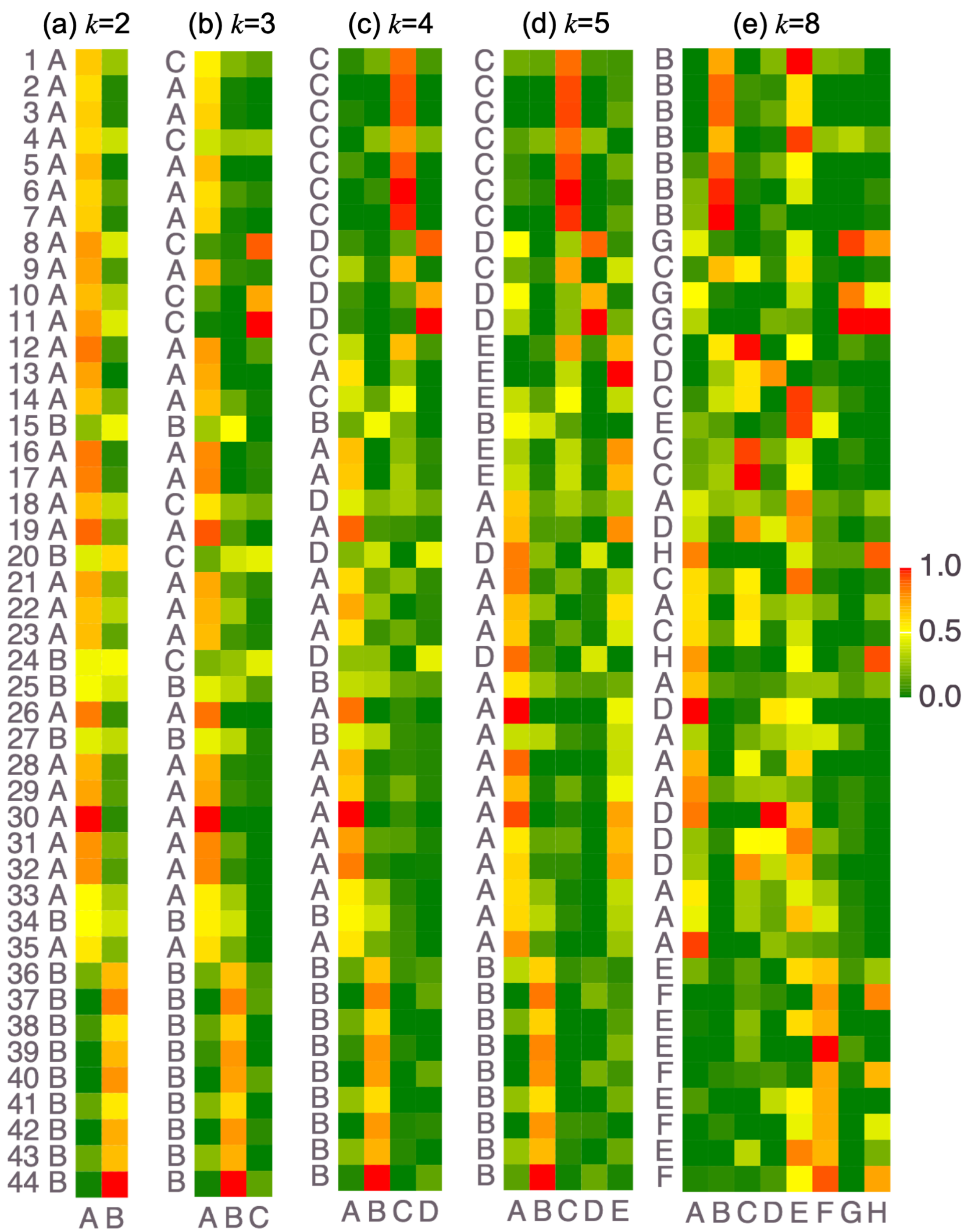
Based on the figure above, it is clear that our ML algorithm was able to blindly identify the physiographic provinces associated with analyzed hydrogeothermal systems without providing any information about their spatial location (coordinates).

Further observations based on the figure above are:

- The solution for k=2 separates the Colorado Plateau and the Volcanic Field (Signature A) from the Basin and Range and the Rift zone (Signature B) provinces (Figure a).
- The k=3 solution combines the Colorado Plateau and the Volcanic Field in Signature A; however, Signatures B and C separate the Basin and Range and the Rio Grande Rift provinces, respectively (Figure b).
- Signature A of the k=4 solution (Figure c) represents the Volcanic Field. Signature B captures the Basin and Range province. Signature C coincides with the Colorado Plateau. Signature D encompasses the Rio Grande Rift zone (Figure c).

- The k=5 solution (Figure d) regroups the four signatures of the k=4 solution into five signatures. Signatures A and E cover MDVF; Signatures B, C, and D capture the remaining three provinces: the Basin and Range, the Colorado Plateau, and the Rio Grande Rift provinces, respectively.
- In the k=8 solution (Figure e), Signature B captures the Colorado Plateau province. Signatures G and H encompass two separate areas in the Rio Grande Rift zone (Figure e). Three of the signatures (A, C, D) are associated with the Volcanic Field capture spatial variability within this province. Two signatures (E and F) represent the spatial variability in the Basin and Range province.

Description of location matrices (`W`) The plot below shows location matrices (`W`) of the extracted signatures for all the accepted solutions together. From left to right, the number of signatures increases. The matrices are color-coded to show high (red) and low (green) associations between the locations and signatures. Like the maps above, this figure below demonstrates how the signatures get transformed and modified as the number of signatures increases. The transitions of the signatures show the consistencies of the obtained results.



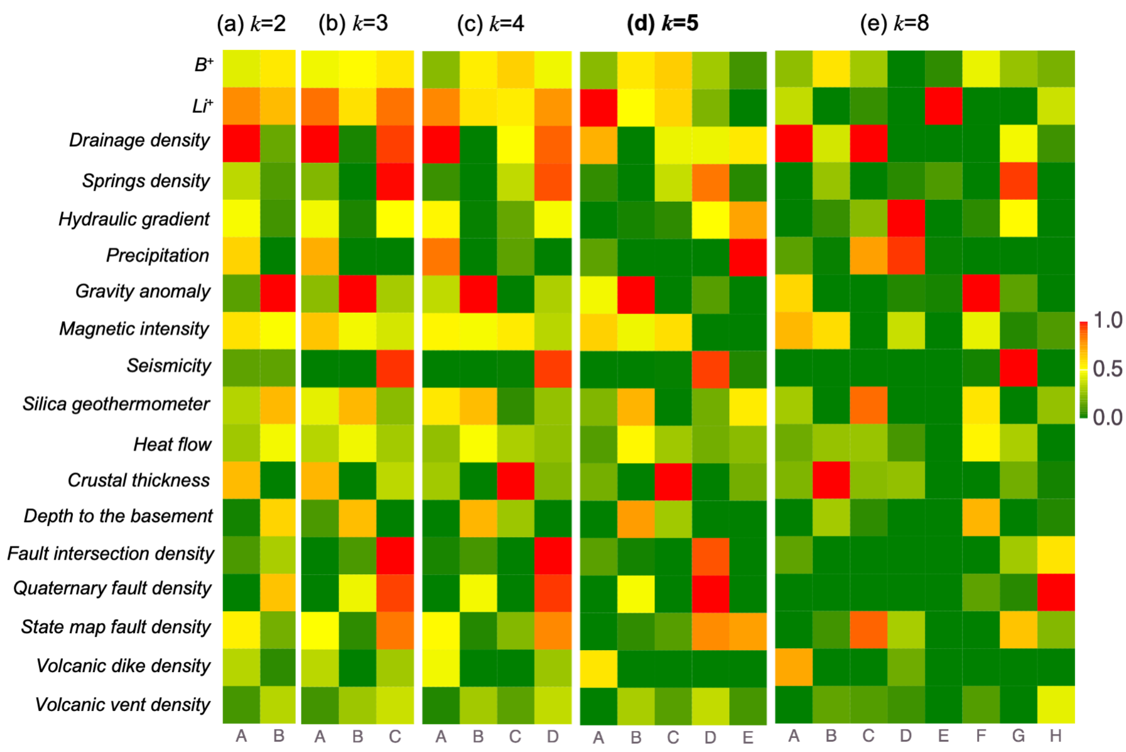
Further observations based on the figure above are (note that these observations are consistent with the observations provided above regarding the physiographic provinces):

- The k=2 solution subdivides the SWNM into two subregions.
- Signatures A and B of the k=3 solution are split up into Signatures A, B, and C of the k=4 solution; however, Signature C of the k=3 solution and Signature D of the k=4 solution share very similar properties.
- Signatures A, B, C, and D of both the k=4 and 5 solutions possess similar properties; however,

the k=5 solution got a completely new signature (Signature E).

- The k=8 solution regrouped the signatures of the k=5 solution. Signature A of the k=5 solution possesses similar properties to Signatures A and D of the k=8 solution. Signature B of the k=5 solution shares similar properties to Signatures E and F of the k=8 solution. Signature C of the k=5 solution has similar properties to both Signatures B and C of the k=8 solution. Signature D of the k=5 solution and both Signatures G and H of the k=8 solution share similar properties.
- It is critical to mention that although the 44 locations in the `W` matrices are labeled to be associated with a given geothermal signature (i.e., a certain region; A, B, etc.), it does not mean the locations are associated with only one signature as seen by the color-coding in the figure.
- Instead, it means that those locations predominantly dominate commensurate signatures with contributions from other signatures too.

Description of attribute matrices (`H`) The plot below shows attribute matrices of all the accepted solutions. The number of signatures increases from left to right. The figure demonstrates how each attribute contributes to the extracted signature. The matrices are color-coded to show high (red) and low (green) associations between the attributes and signatures. Also, this plot shows how the signatures get transformed and modified as the number of signatures increases. As above, the transitions of the signatures show the consistencies of the obtained ML results.

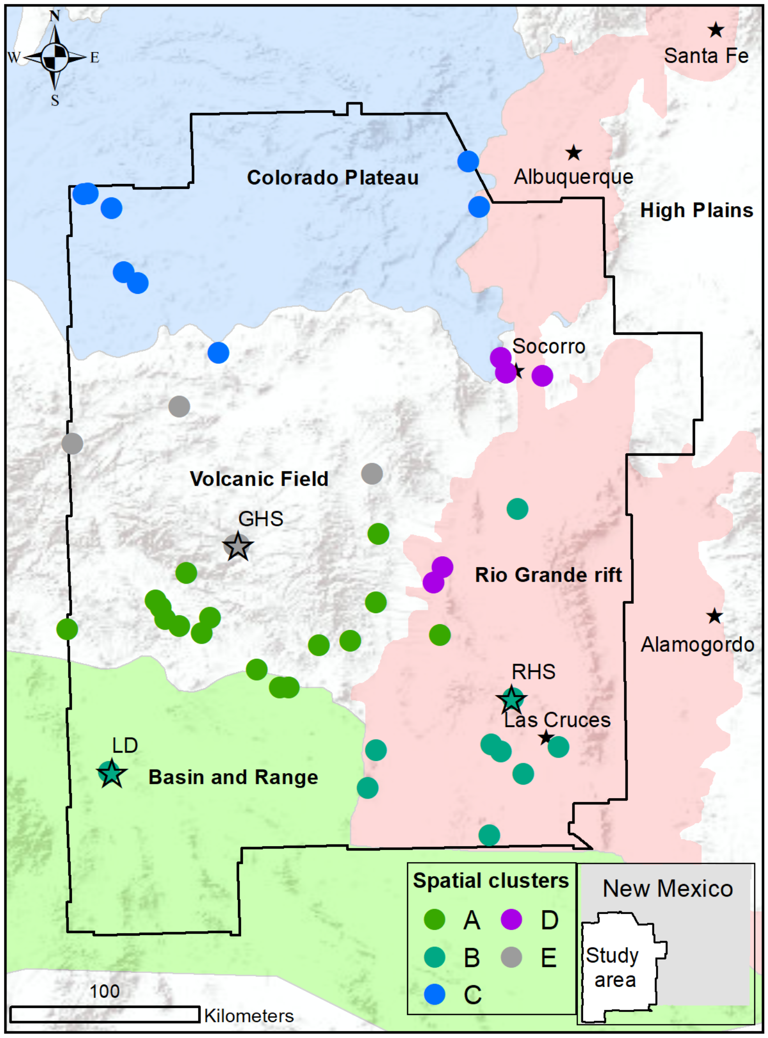


Further observations based on the figure above are:

- Signatures A, B, and C of the k=3 solution have similar properties to Signatures A, B, and both C and D of the k=4 solution, respectively.

- Signatures of A, B, C, and D of the k=4 solution possess similar properties to signatures both A and E, B, C, and D of the k=5 solution, respectively.
- Signatures A, B, C, D, and E of the k=5 solution share similar properties to both A and E, F, B, both G and H, and both C and D of the k=8 solution, respectively.

Optimal geothermal signatures charecterizing SWNM region The figure below shows the map of the optimal signatures. The k=5 solution best characterizes the spatial associations and geothermal attributes of the SWNM.



Signatures and their relationships to resource types, geothermal attributes, physical processes and physiographic provinces ccccc

Signature	Resource type	() Physical Significance * 0.16Dominant at- tributes	Physiographci province

|A|Low temperature|

Gravity anomaly Magnetic intensity Volcanic dike density Drainage density Li+ concentration

|Shallow heat flow|Southern MDVF| |B|Medium temperature|

B+ and Li+ concentrations Gravity anomaly Magnetic intensity Quaternary fault density Silica geothermometer Heat flow Depth to the basement

|Deep heat flow|Southern Rio Grande rift| |C|Low temperature|

B+ and Li+ concentrations Magnetic intensity Drainage density Crustal thickness

|Deep heat source|Colorado Plateau| |D|Low temperature|

Drainage density Fault intersection density Seismicity State map fault density Spring density Hydraulic gradient

|Tectonics|Northern Rio Grande Rift | |E|Medium temperature|

Drainage density State map fault density Precipitation Silica geothermometer Hydraulic gradient

|Vertical hydraulics|Northern MDVF|

Geothermal resource assessment

- The extracted signatures characterize low- and medium-temperature hydrothermal systems.
- The signatures are characterized by unique geothermal attributes which are automatically identified by our ML analyses.

Medium-temperature hydrothermal systems

- Two of the signatures (B and E) represent medium-temperature hydrothermal systems
- The medium-temperature signatures (B and E) fall in the Southern Rio Grande Rift and the Northern MDVF zones.
  - The dominant attributes of the Southern Rio Grande Rift zone are B+ and Li+ concentrations, Gravity anomaly, Magnetic intensity, Quaternary fault density, Silica geothermometer, Heat flow, Depth to the basement.
  - The dominant attributes of the Northern MDVF are Drainage density, State map fault density, Precipitation, Silica geothermometer, Hydraulic gradient.

Low-temperature hydrothermal systems

- Three of the signatures (A, C, and D) represent low-temperature hydrothermal systems.
- The low-temperature signatures (A, C, and D) fall in the Southern MDVF, Colorado Plateau, and Northern Rio Grande Rift zones.

For more details, please look at our paper titled: "Discovering Hidden Geothermal Signatures using Unsupervised Machine Learning."