An interactive, literature-integrated digital crust in support of critical minerals assessment

Daven P. Quinn[1], Shanan E. Peters[1], Shivaram Venkataraman[2], Brian Bockelman[3]

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2. Dept. of Computer Science, University of Wisconsin–Madison
3. Morgridge Institute of Research, Madison, WI

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`https://macrostrat.org/map`

DARPA CriticalMAAS Kickoff, August 2023

MACROSTRAT / UW–MADISON TEAM

Department of Geoscience

Project and system design

- Daven Quinn, PI
- Shanan Peters, Co-PI

Department of Computer Science

xDD/Literature data extraction/Entity canonicalization

- Shivaram Venkataraman, Co-PI
- Ian Ross, xDD lead

Morgridge Institute of Research

Infrastructure and software development

- Brian Bockelman, Co-PI
- Cannon Lock
- Brian Aydemir

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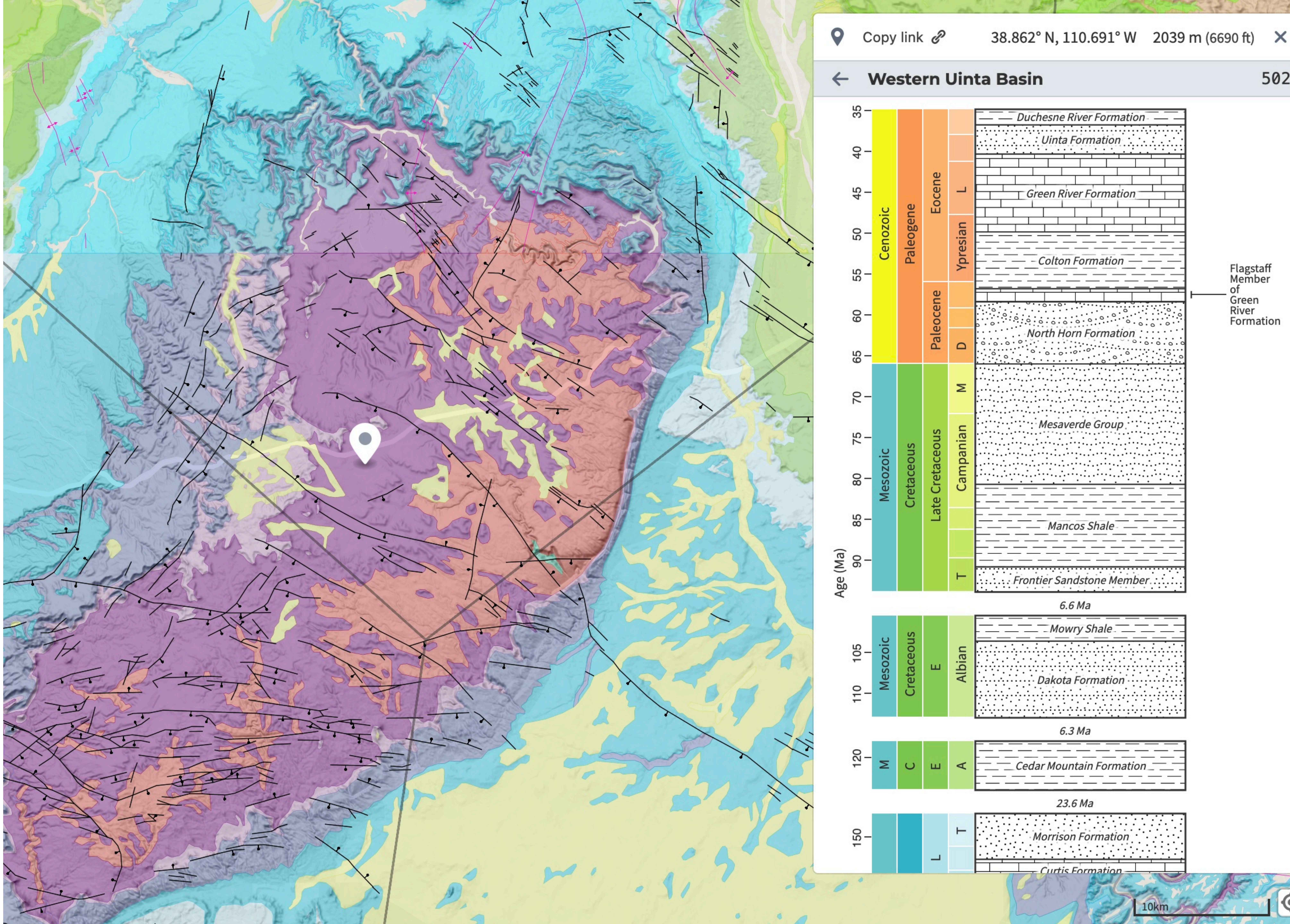
Macrostrat

A quantitative, descriptive data system for geological information

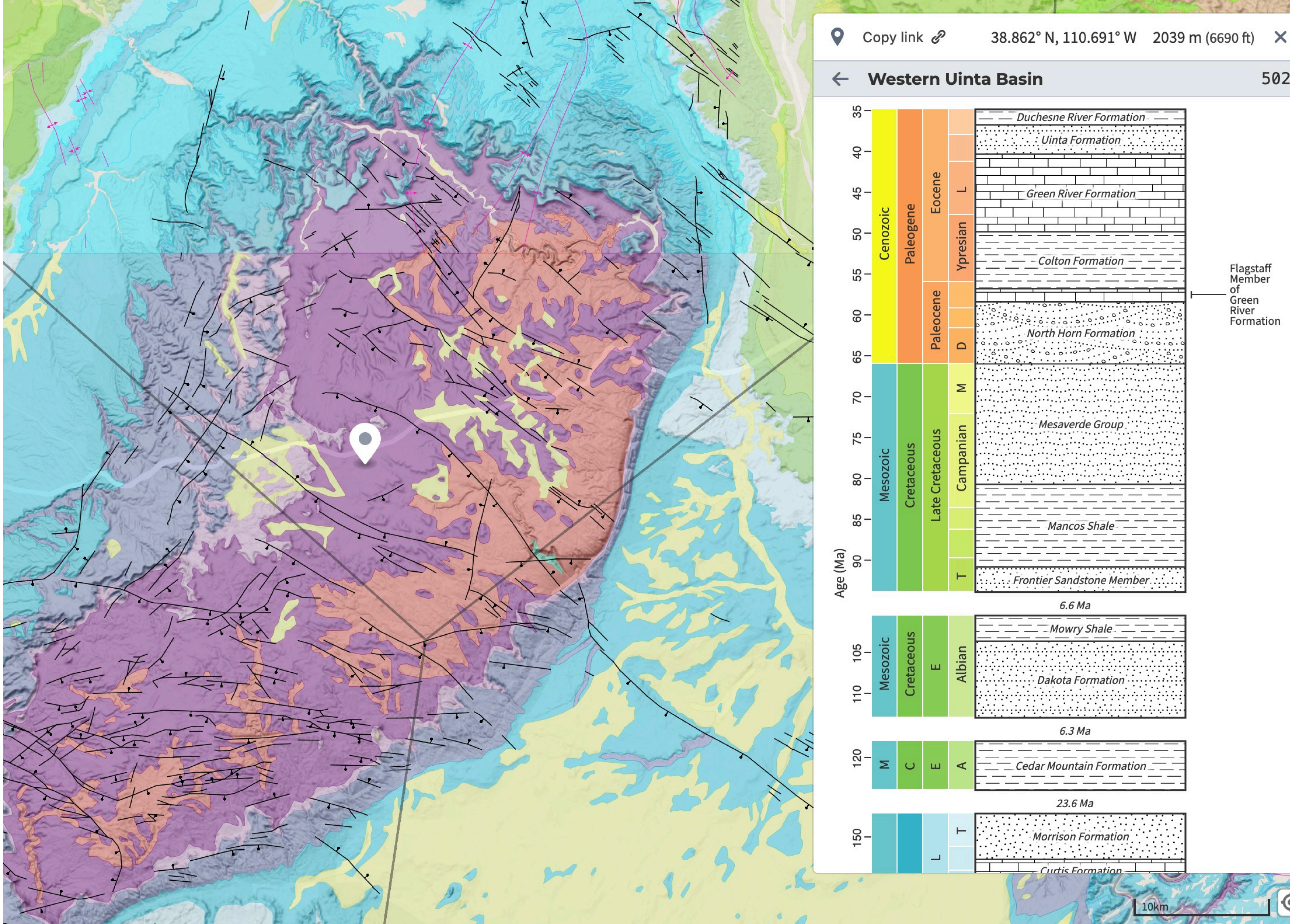


Macrostrat

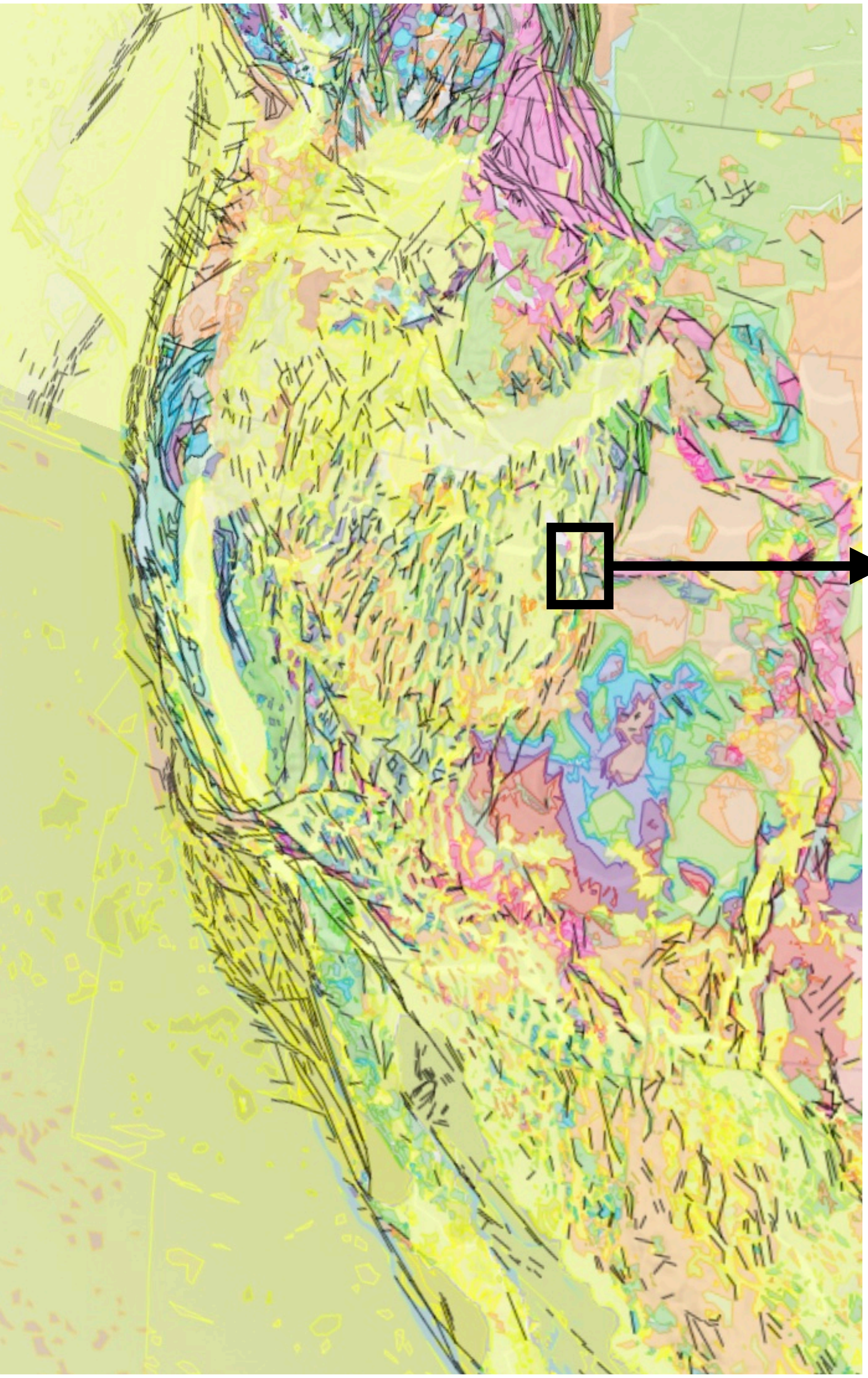
A quantitative, descriptive data system for geological information

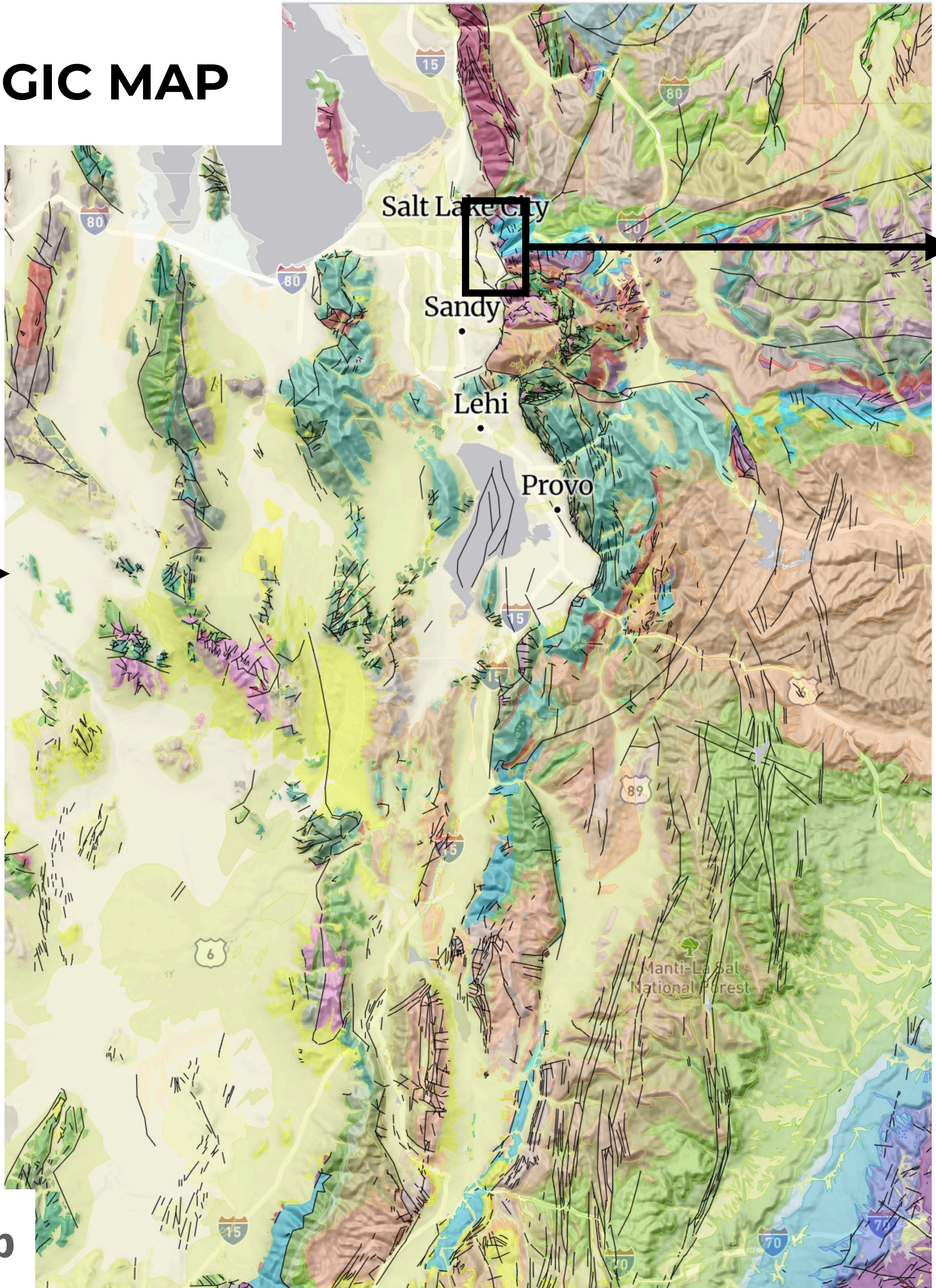
MacroMaas

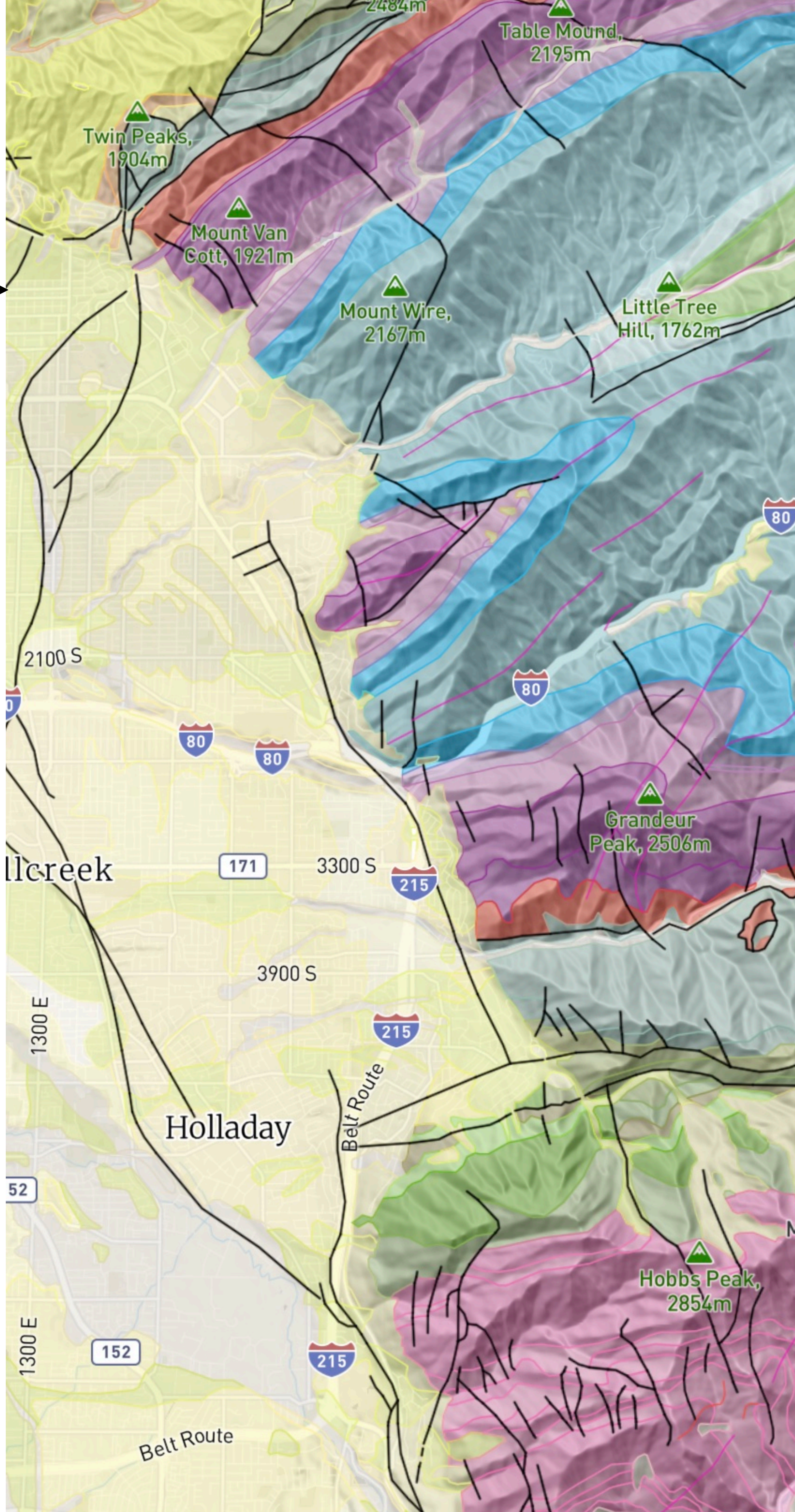
Macrostrat extended for Critical Minerals assessment



MACROSTRAT'S GEOLOGIC MAP







https://macrostrat.org/map

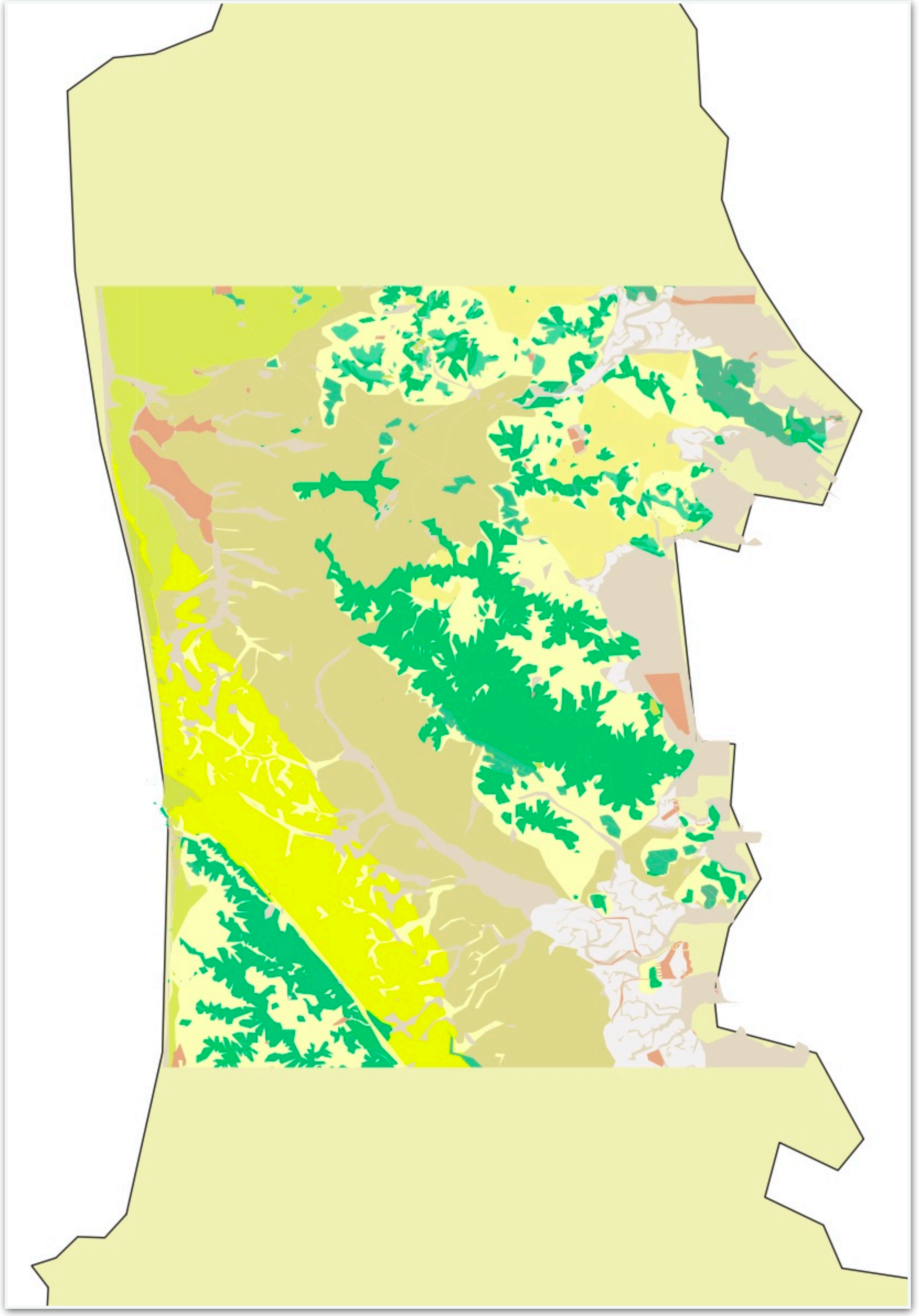
MACROSTRAT'S GEOLOGIC MAP

MORE THAN 300 SOURCES

Most maps are produced by USGS and state surveys

USGS State Map Compilation: ~10% of map polygons

Macrostrat's geologic map: Ingestion and harmonization



‹ Back   Selected Sources   **Options** ^

South San Franciso ^

Preliminary geologic map of the San Francisco South 7.5' quadrangle and part of the Hunters Point 7.5' quadrangle, San Francisco Bay area, California Bonilla, M.G. (1998). *Preliminary geologic map of the San Francisco South 7.5' quadrangle and part of the Hunters Point 7.5' quadrangle, San Francisco Bay area, California*. U.S. Geological Survey Open-File Report 98-354.. Retrieved from http://pubs.usgs.gov/of/1998/of98-354/.

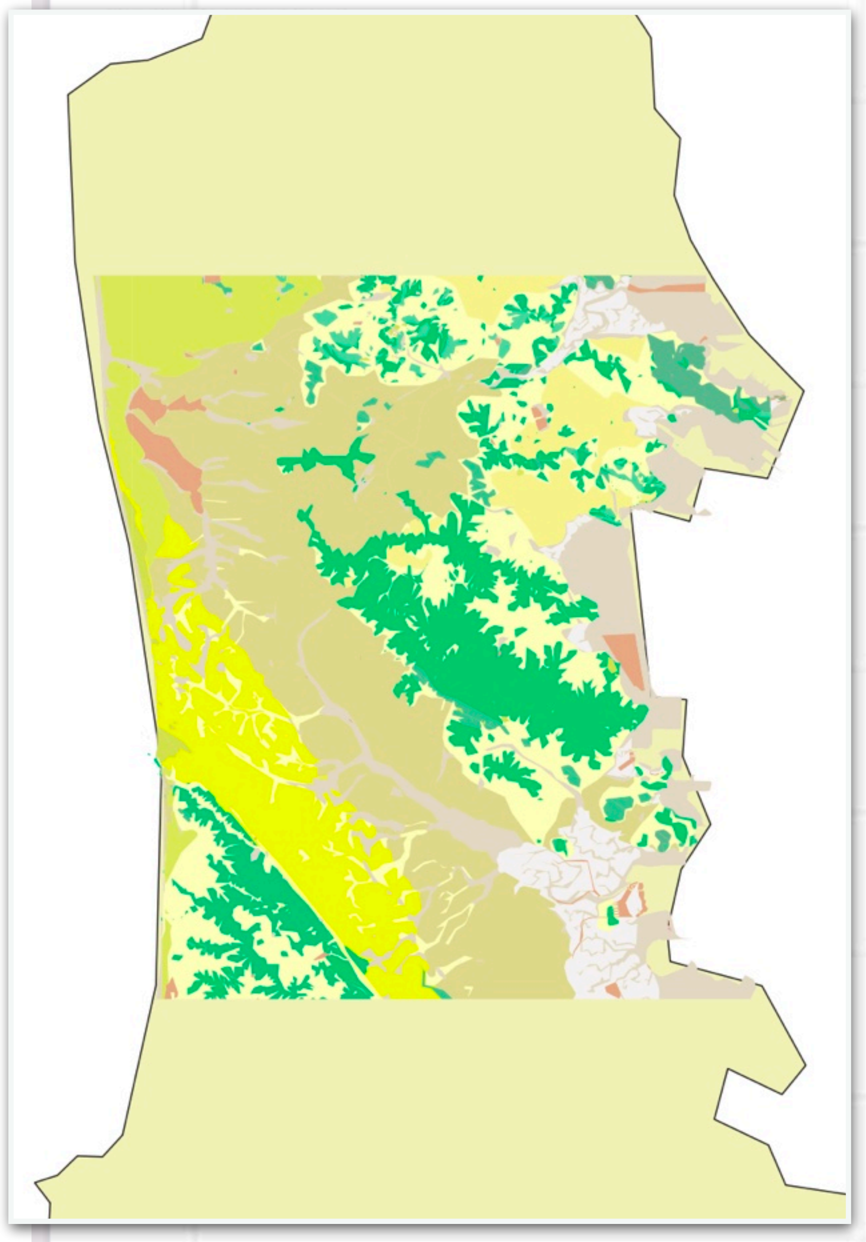
Source ID	88
Scale	large
Features	1441

View map

Starting point: a *vector* geologic map

Macrostrat's geologic map: Ingestion and harmonization

d	ptype	age	early_id	late_id	name
4	Qya	Holocene and late Pleistocene	492	3	Young alluvia
5	Qoa	late to middle Pleistocene	502	492	Old alluvial fl
6	Qyc	Holocene and late Pleistocene	492	3	Young colluv
7	Qya	Holocene and late Pleistocene	492	3	Young alluvia
8	Qyf	Holocene and late Pleistocene	492	3	Young alluvia
9	Tcs	early Pliocene and late Miocene	488	489	Capistrano F
10	Tcs	early Pliocene and late Miocene	488	489	Capistrano F
11	Qls	Holocene and Pleistocene	4	3	Landslide de
		NULL	NULL	NULL	water
		Holocene and Pleistocene	4	3	Landslide de
		Holocene and late Pleistocene	492	3	Young colluv
		Holocene and Pleistocene	4	3	Landslide de
		Cretaceous	33	33	Heterogeneo
		Holocene and late Pleistocene	492	3	Young alluvia
		Holocene and Pleistocene	4	3	Landslide de
		early Pliocene and late Miocene	488	489	Capistrano F
		Holocene and Pleistocene	4	3	Landslide de
21	Qls	Holocene and Pleistocene	4	3	Landslide de



Map ingestion into open-source PostGIS geospatial database

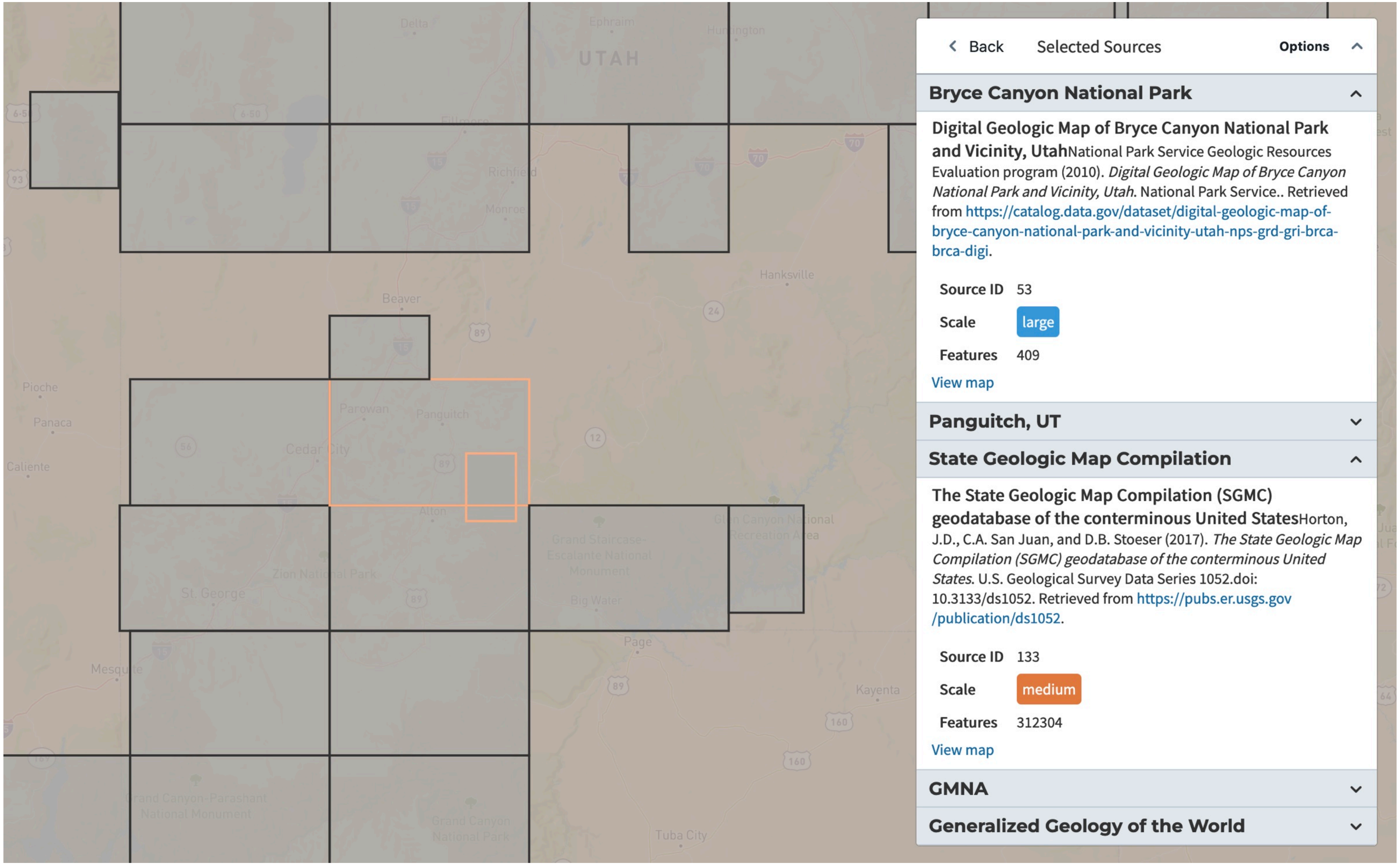
PostgreSQL PostGIS

Attributes are minimally cleaned

Unit names and age ranges are linked to common definitions

Manual ingestion assisted by Python scripts

Geologic map sources are categorized into four scales and composited



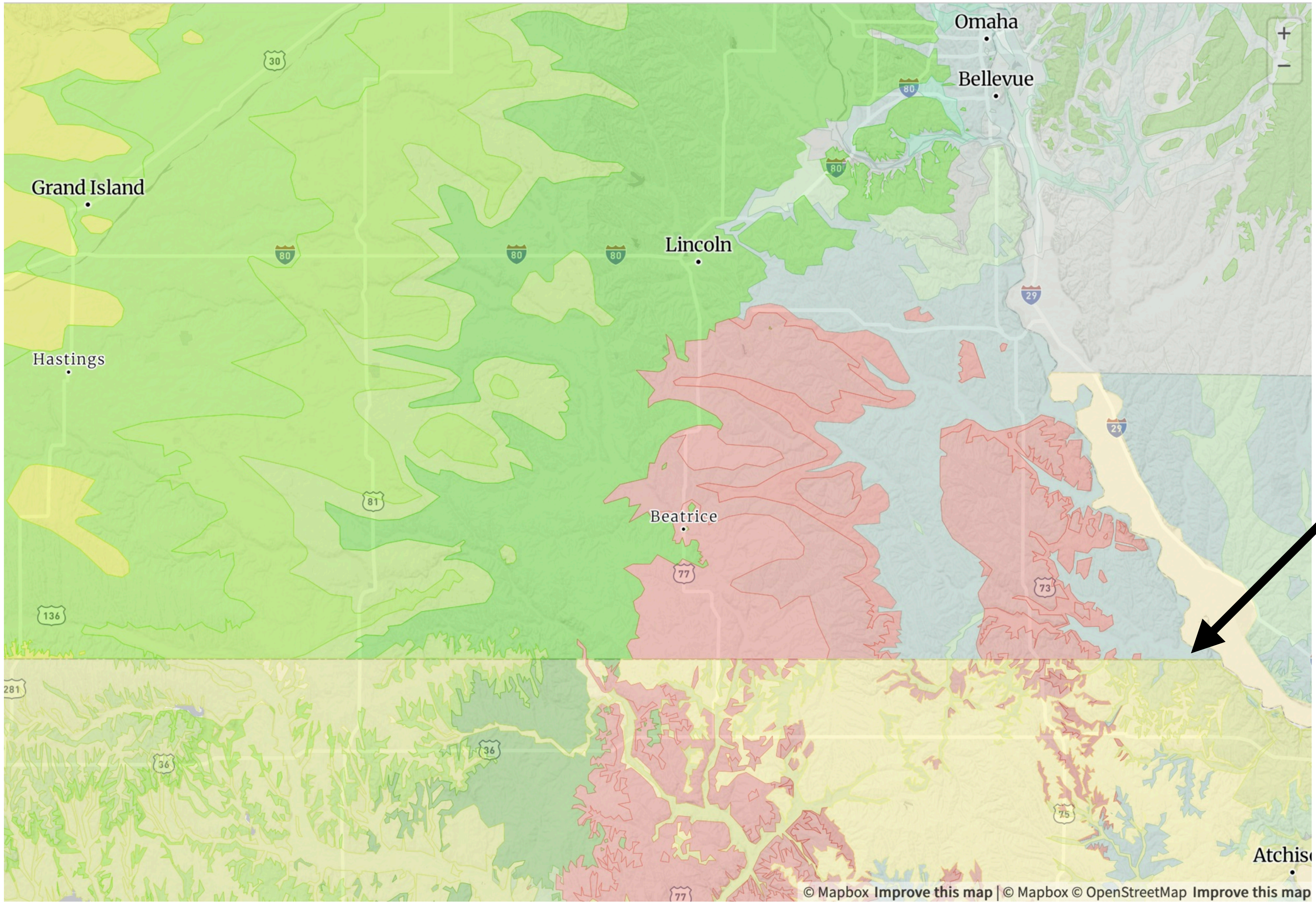
large

medium

small

tiny

Macrostrat's geologic map: Ingestion and harmonization

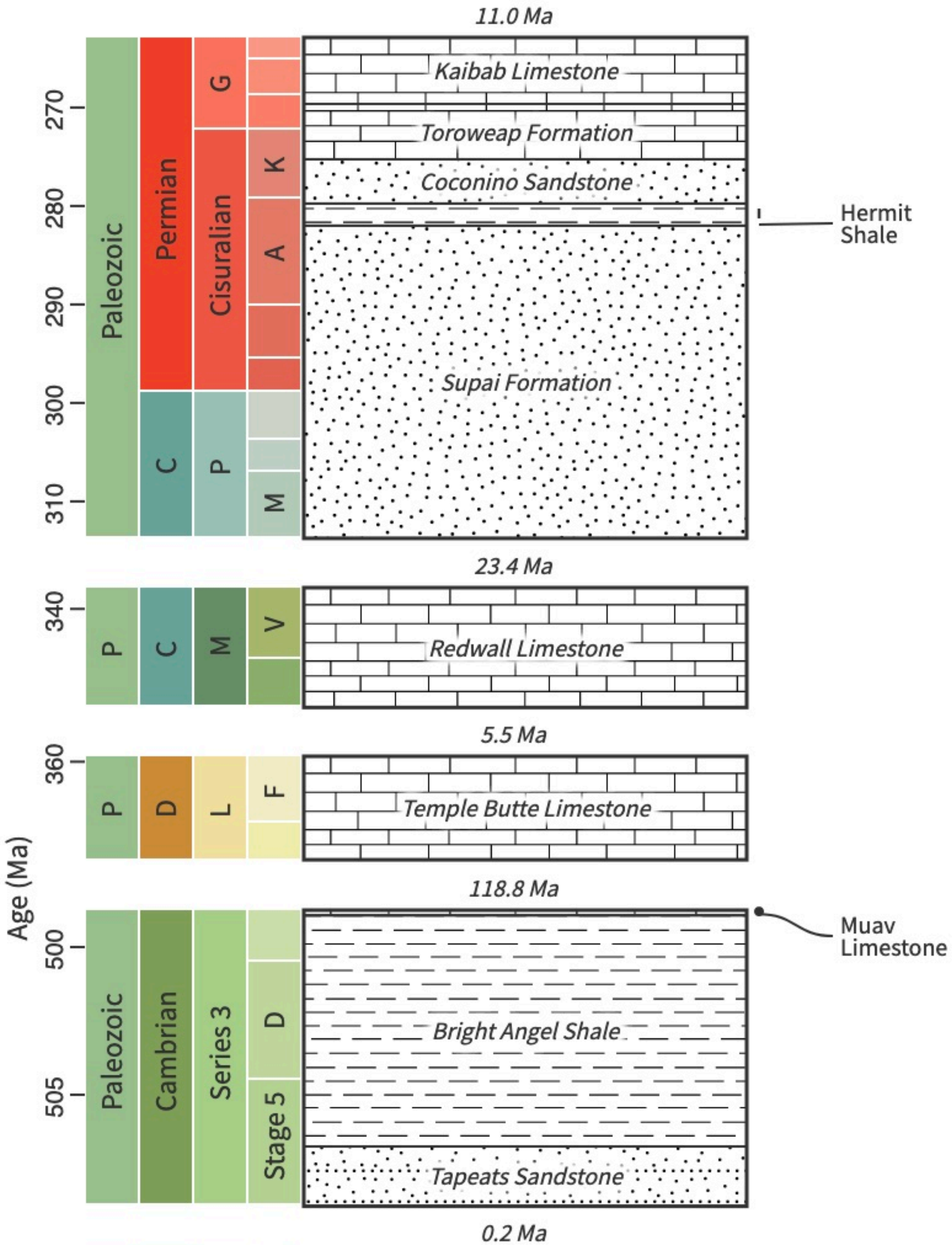


- Maps are composited into a topologically seamless product
- This is computationally intensive

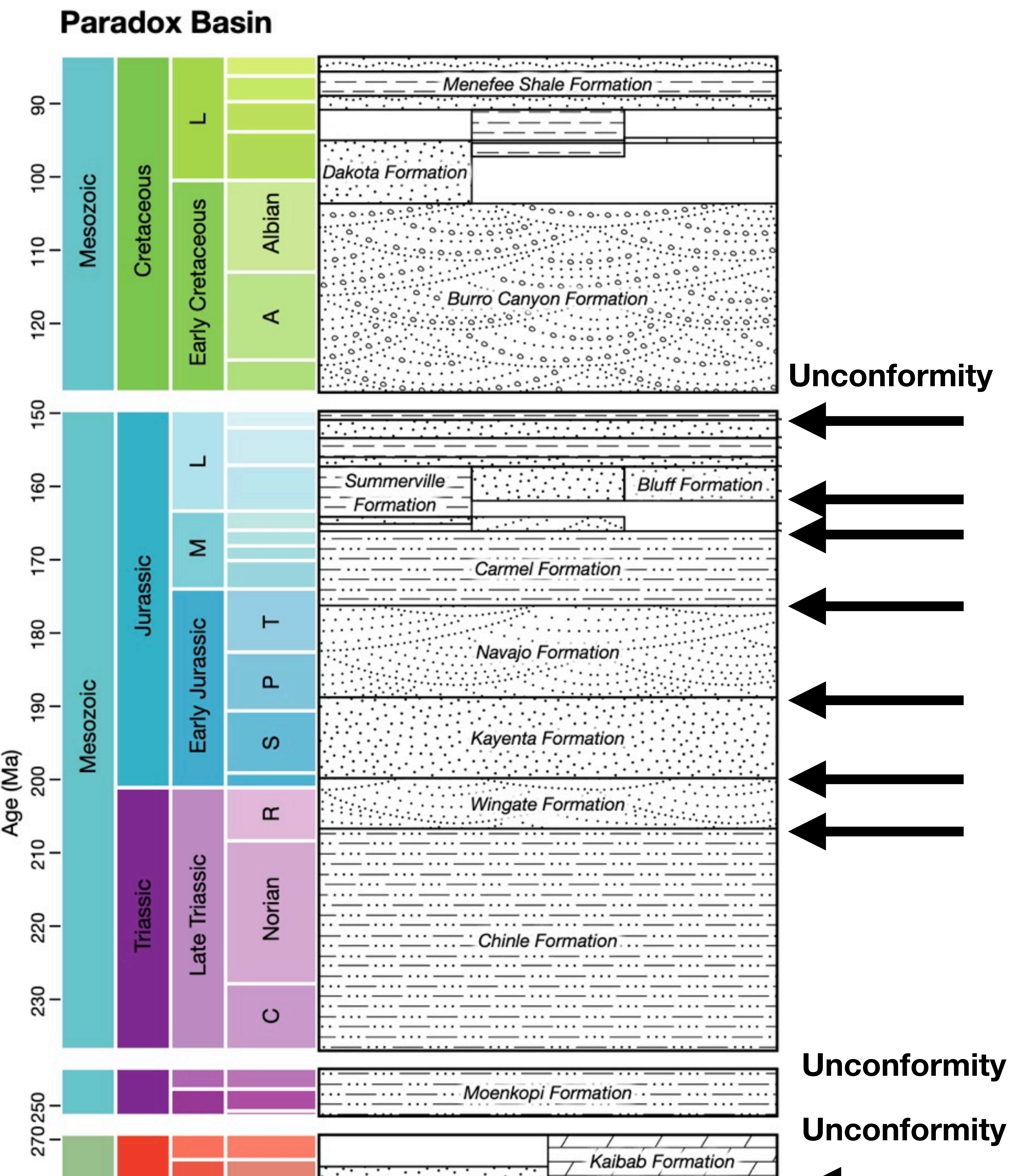
- **NOT seamless map units**
- Source boundaries are often quite apparent

It is not a single map…it is a harmonized "view" of many maps with some standardization

Stratigraphy: another representation of geological framework



Macrostrat stratigraphic column database: continuous time age model



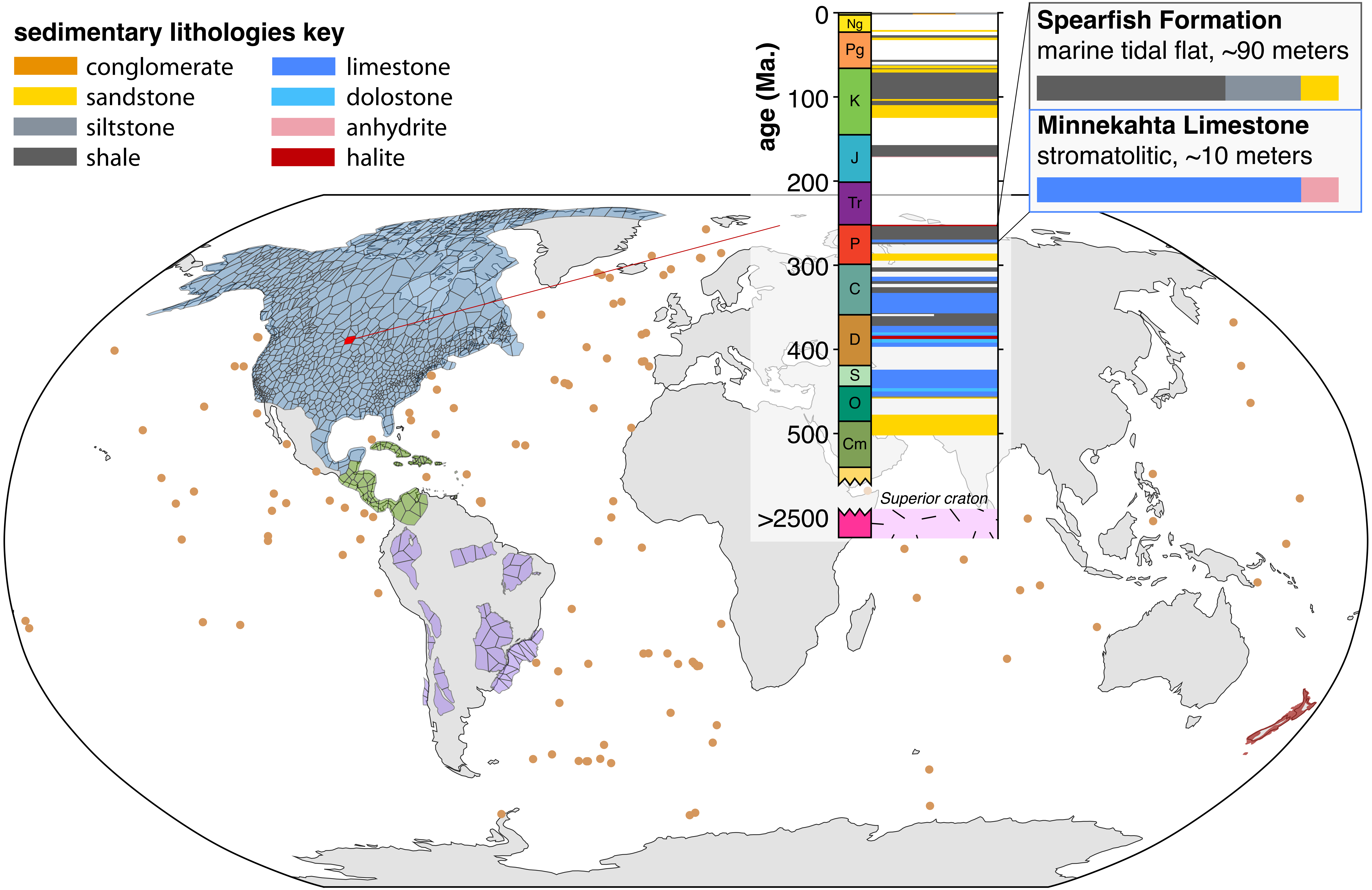
boundaries between units acquire a unique chronostratigraphic identity:

- <u>relative ages</u>: position in a chronostratigraphic bin expressed as a proportion (e.g., 25% through "Middle Cambrian")
- <u>absolute ages</u>: position on a numerical time line (e.g., 511 Ma)

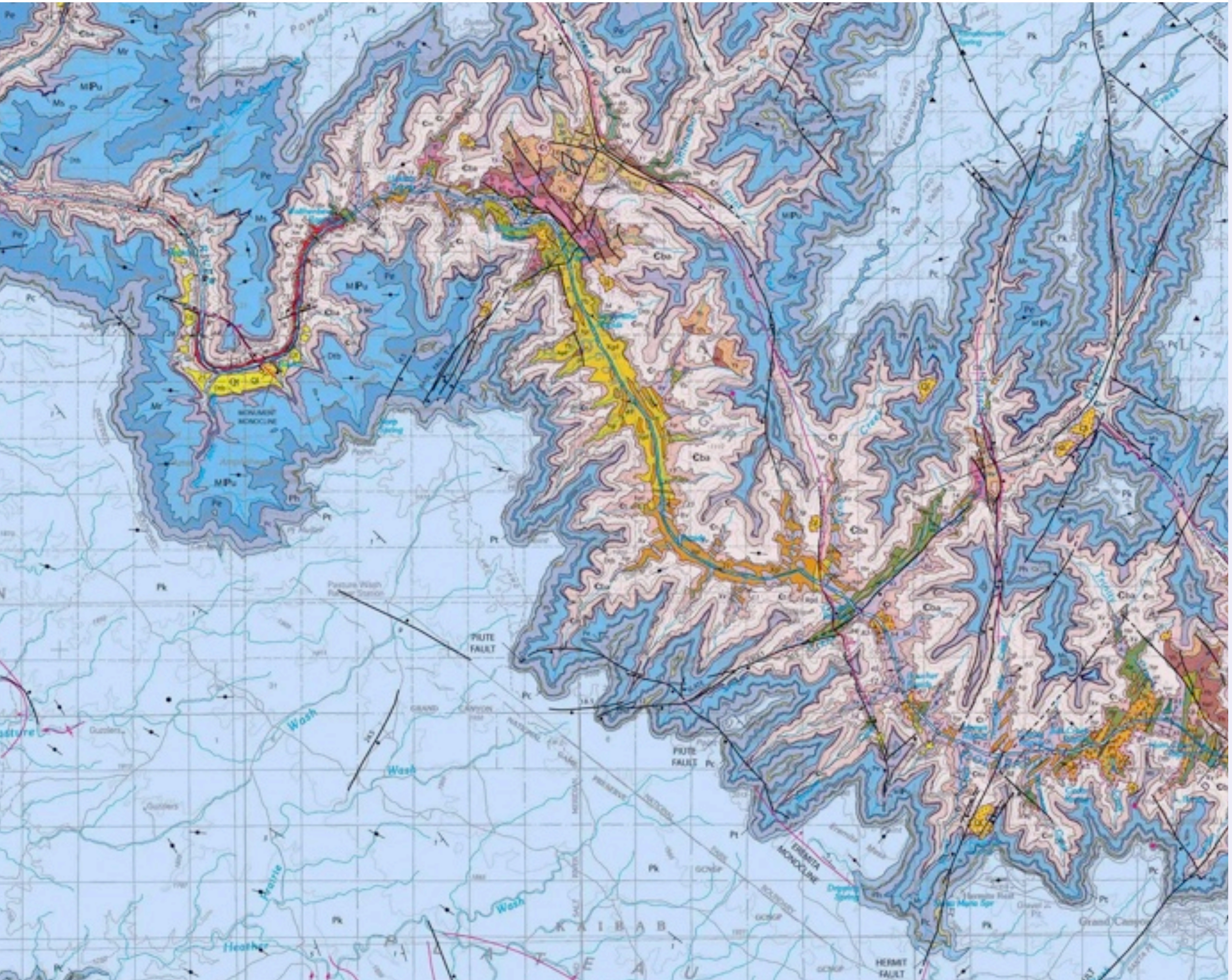
- Interpolating between boundaries produces a high-resolution, continuous record of geologic time

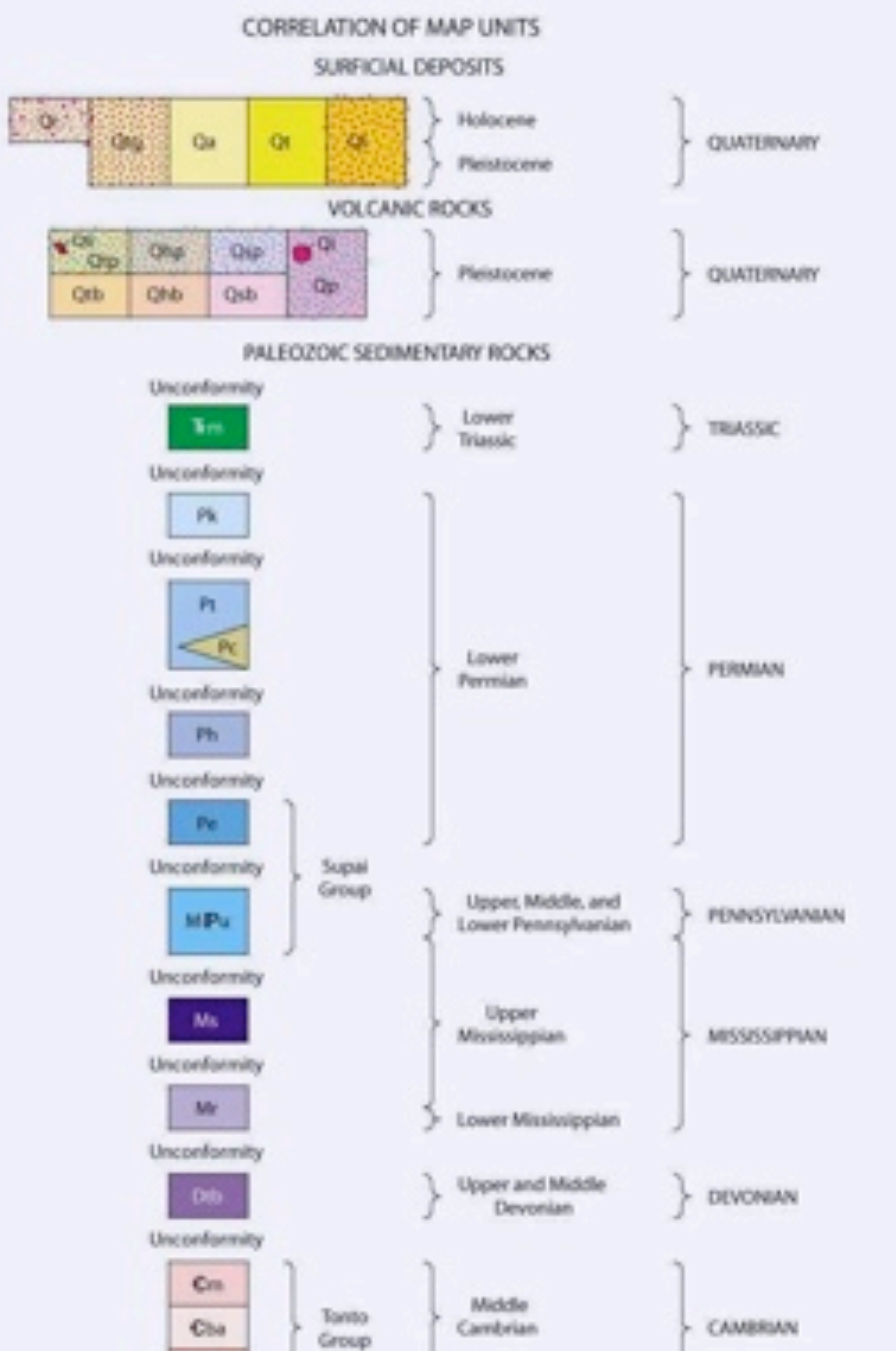
Macrostrat column database

Comprehensive and harmonized (at least within North America)

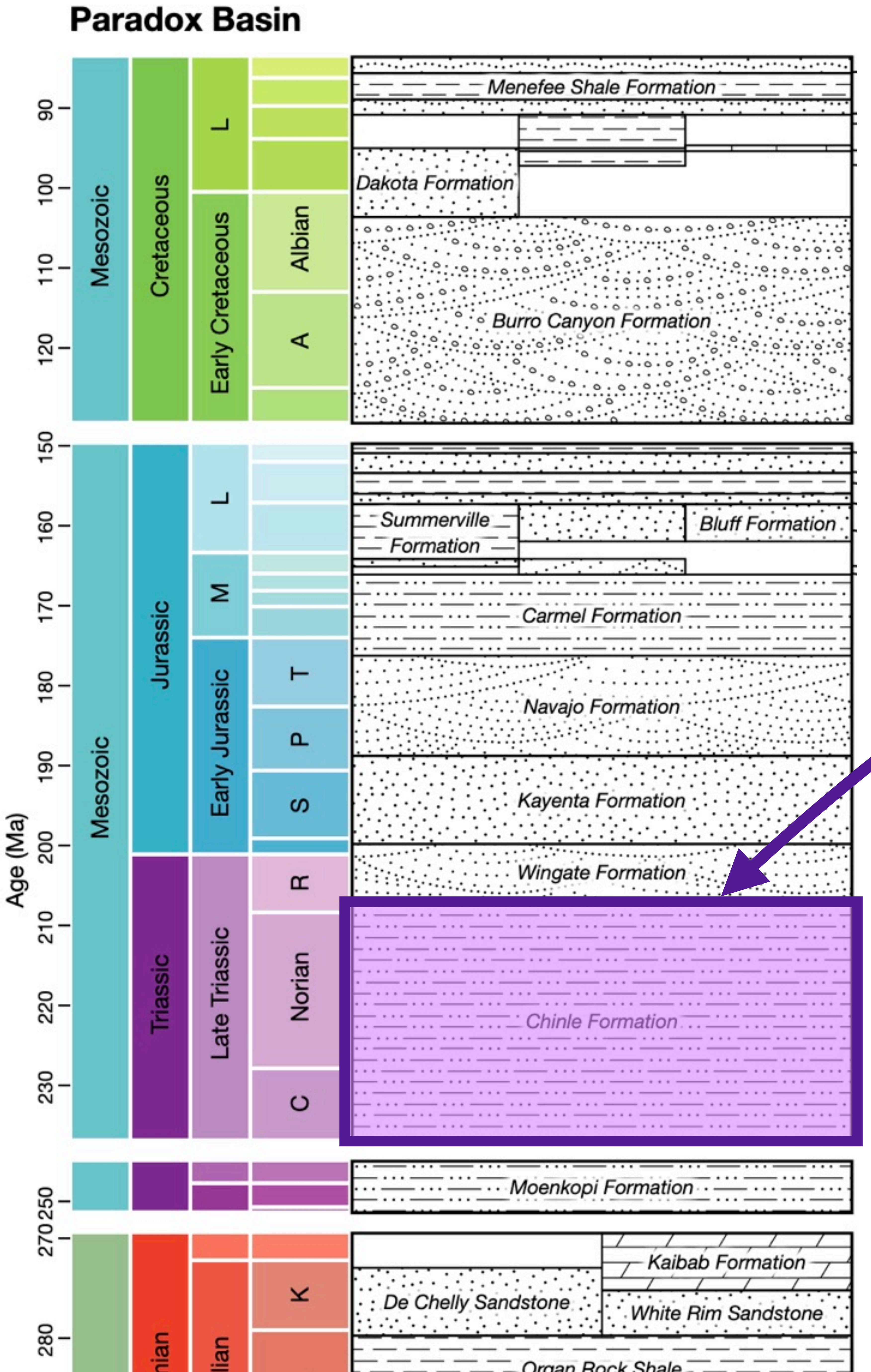


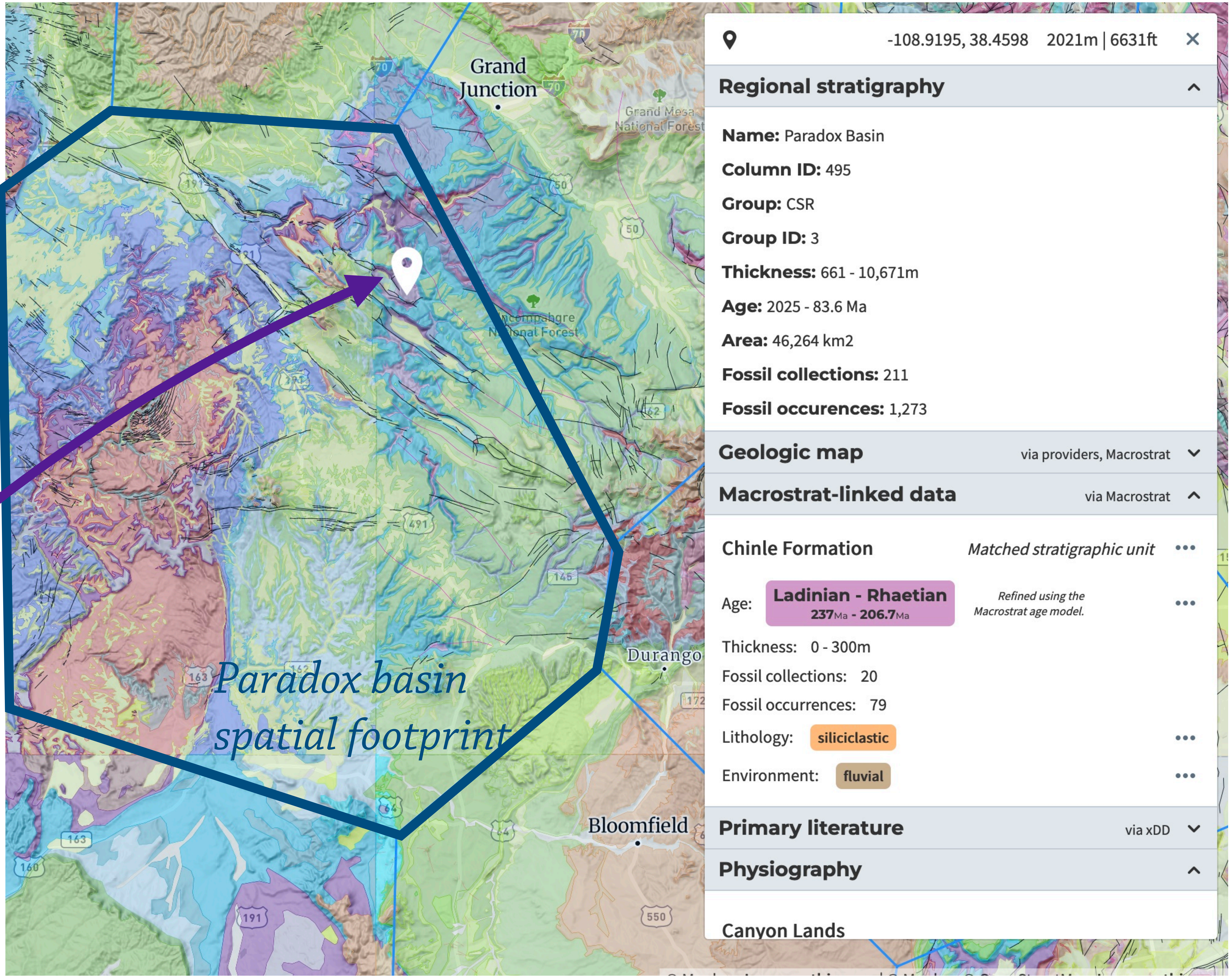
Geologic maps have a stratigraphic representation



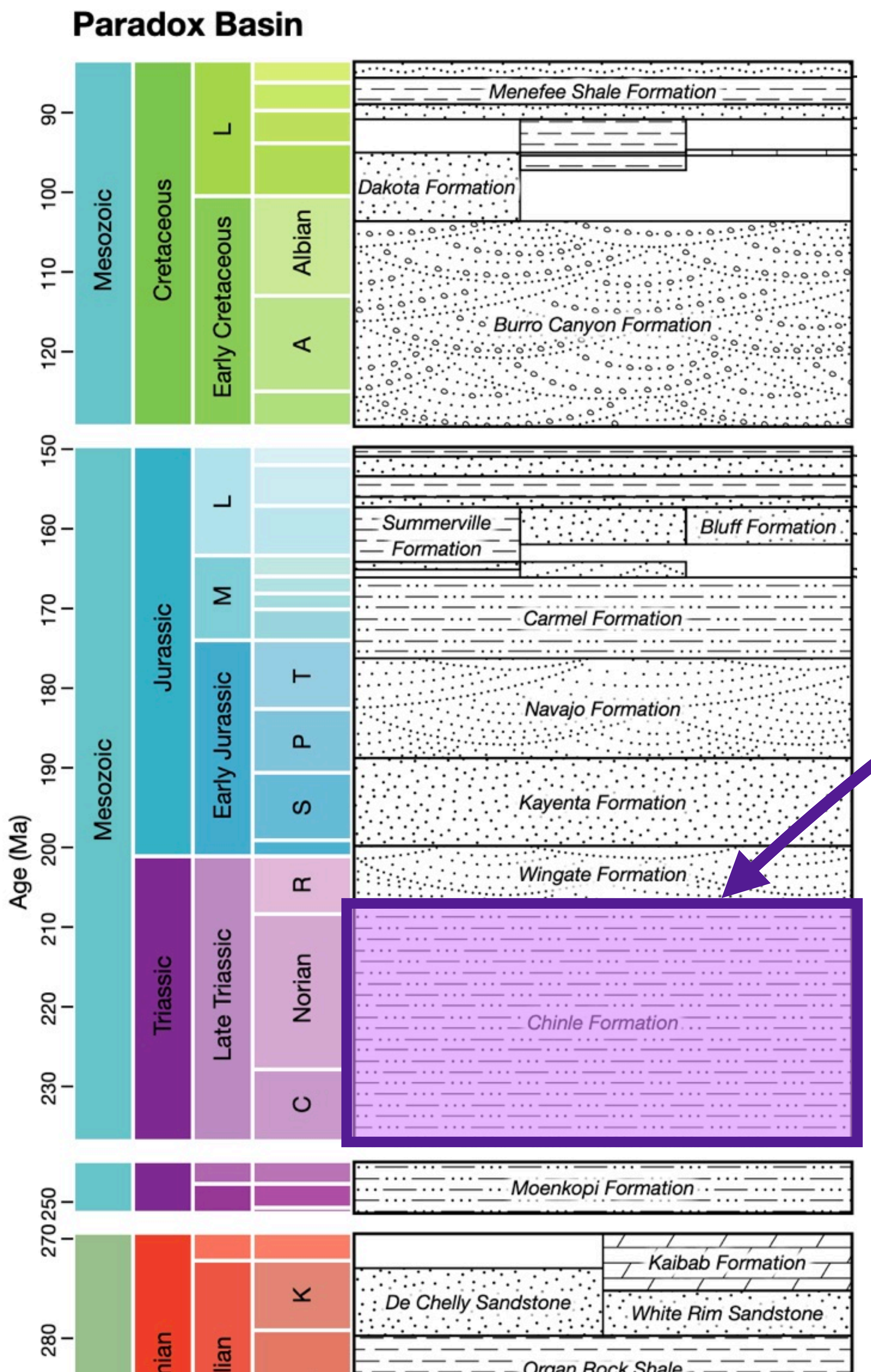


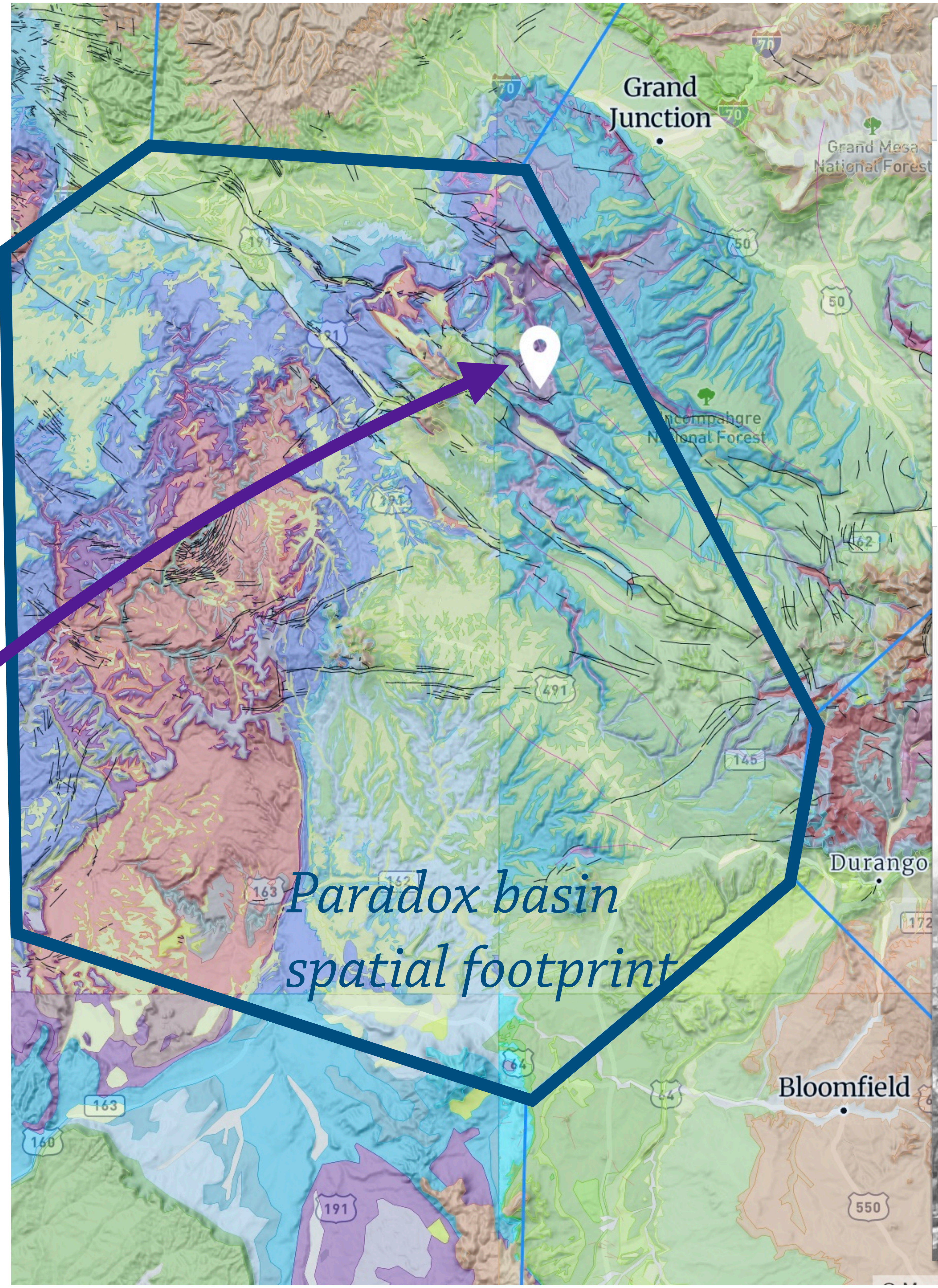
Map harmonization: Linking columns to maps



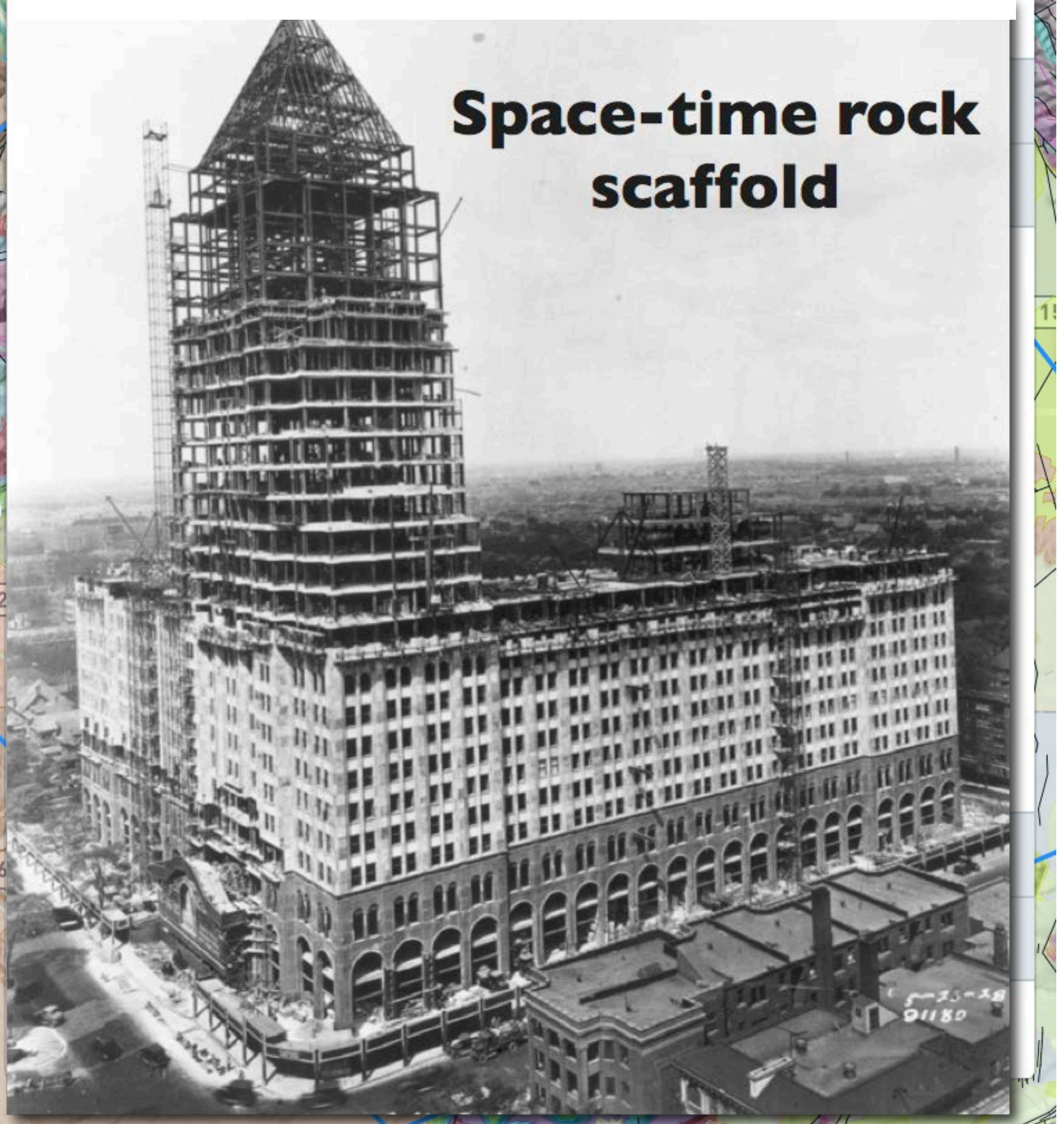


Map harmonization: Linking columns to maps





A space-time "scaffold" for the Earth's crust



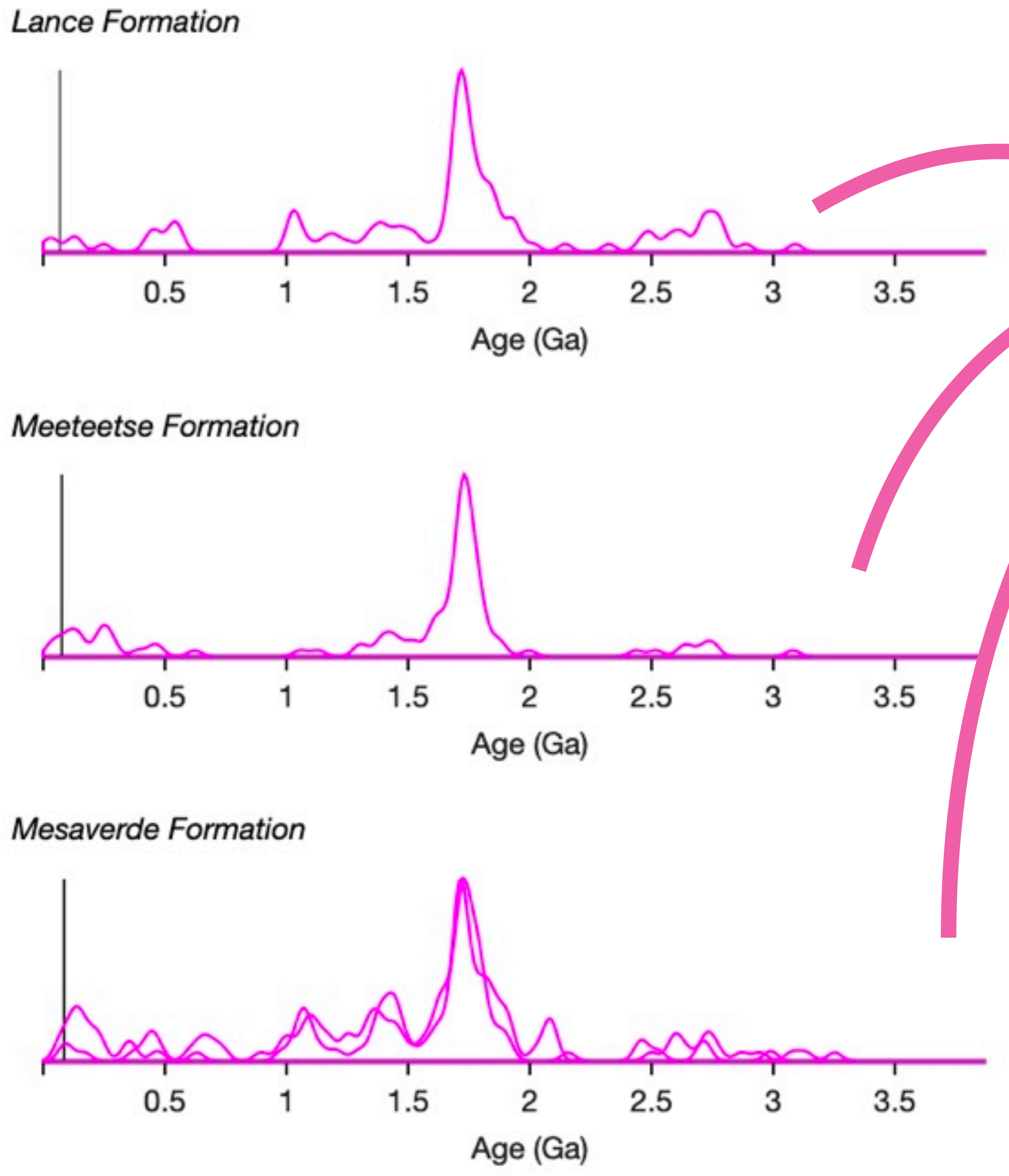
COLUMNS + MAPS + GEOCHRONOLOGY

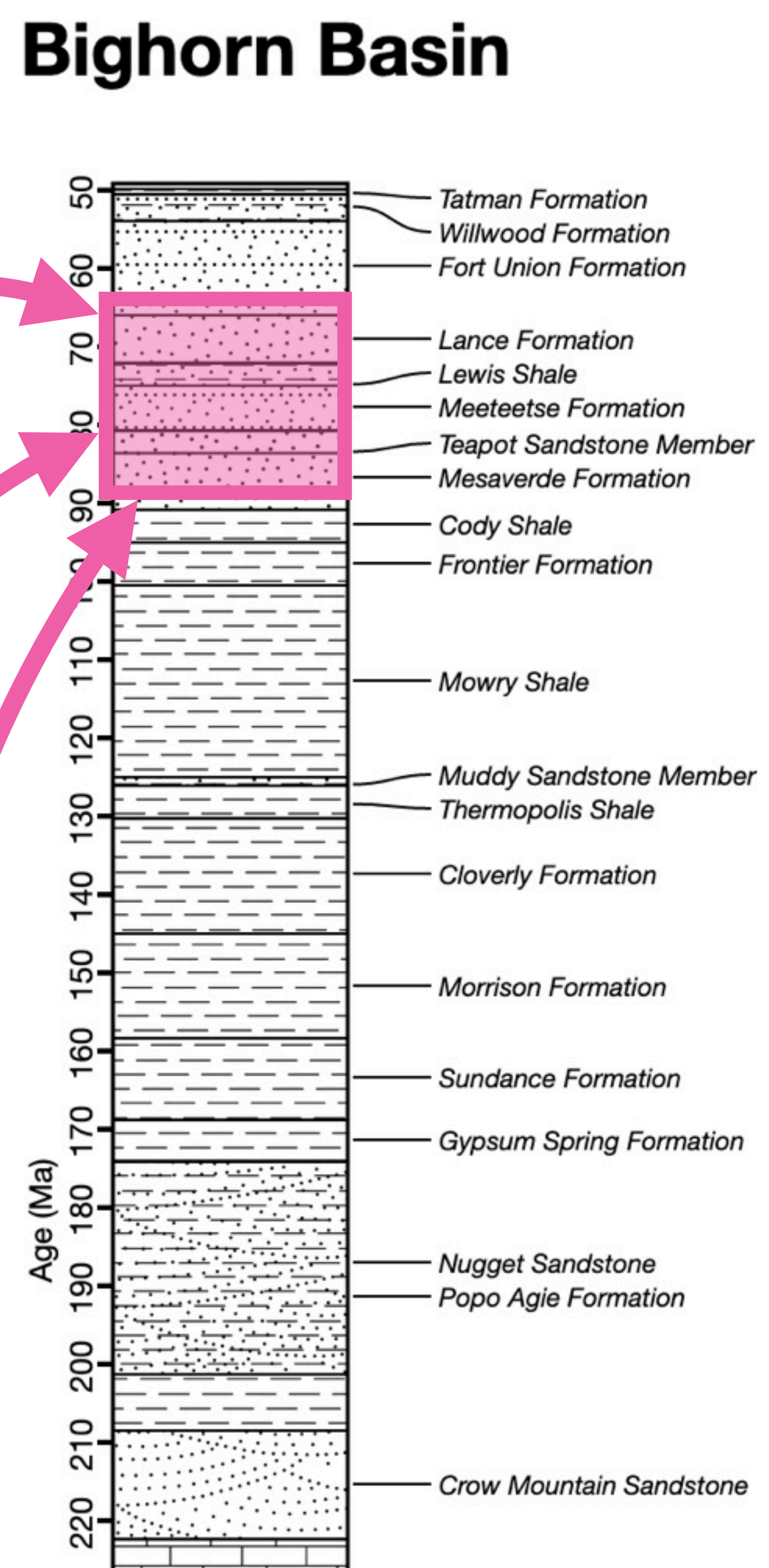
RESEARCH ARTICLE | JUNE 24, 2021

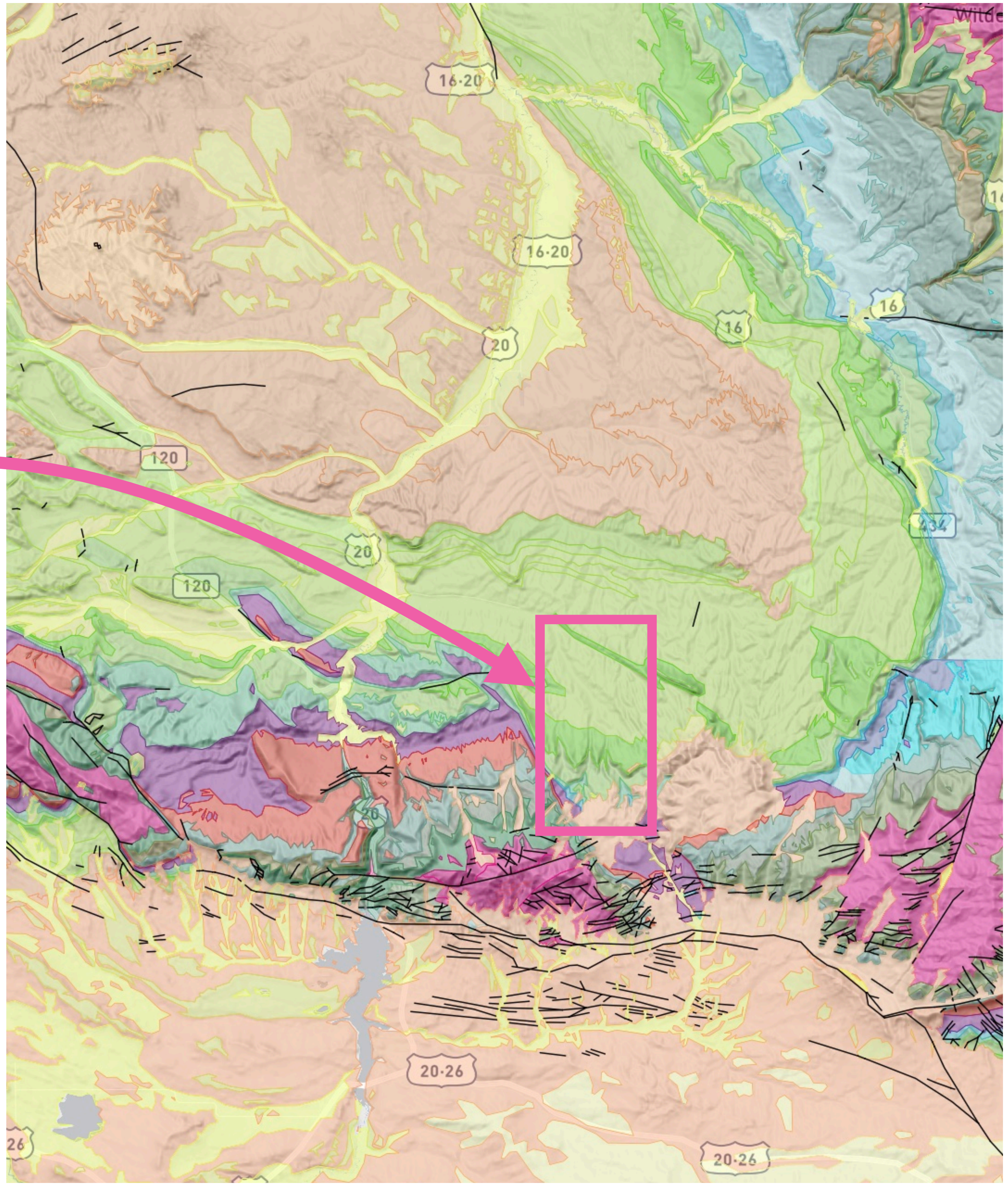
Igneous rock area and age in continental crust

Shanan E. Peters; Craig R. Walton; Jon M. Husson; Daven P. Quinn; Oliver Shorttle; C. Brenhin Keller; Robert R. Gaines

Geology (2021) 49 (10): 1235–1239.

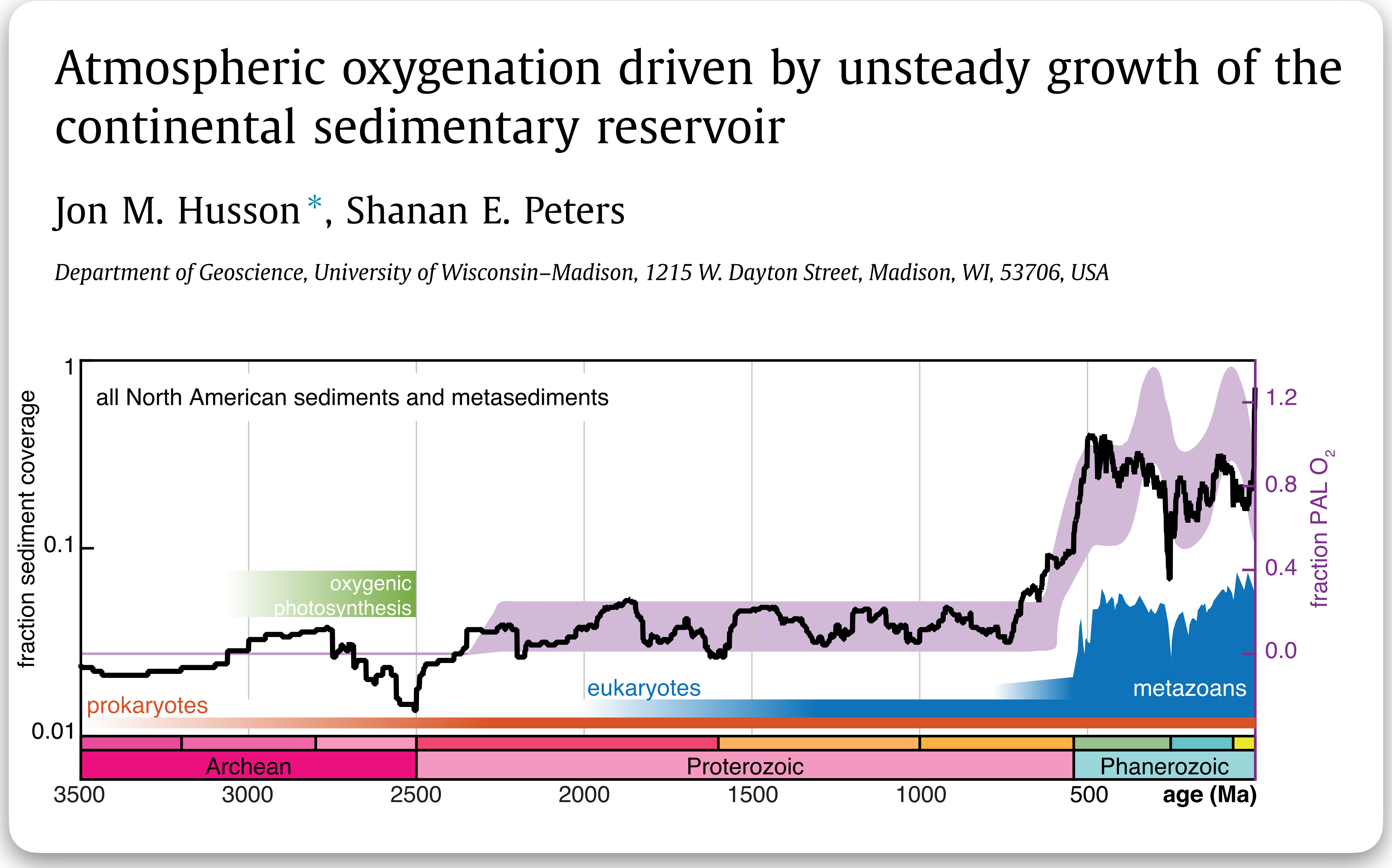






MACROSTRAT'S ORIGINAL GOAL

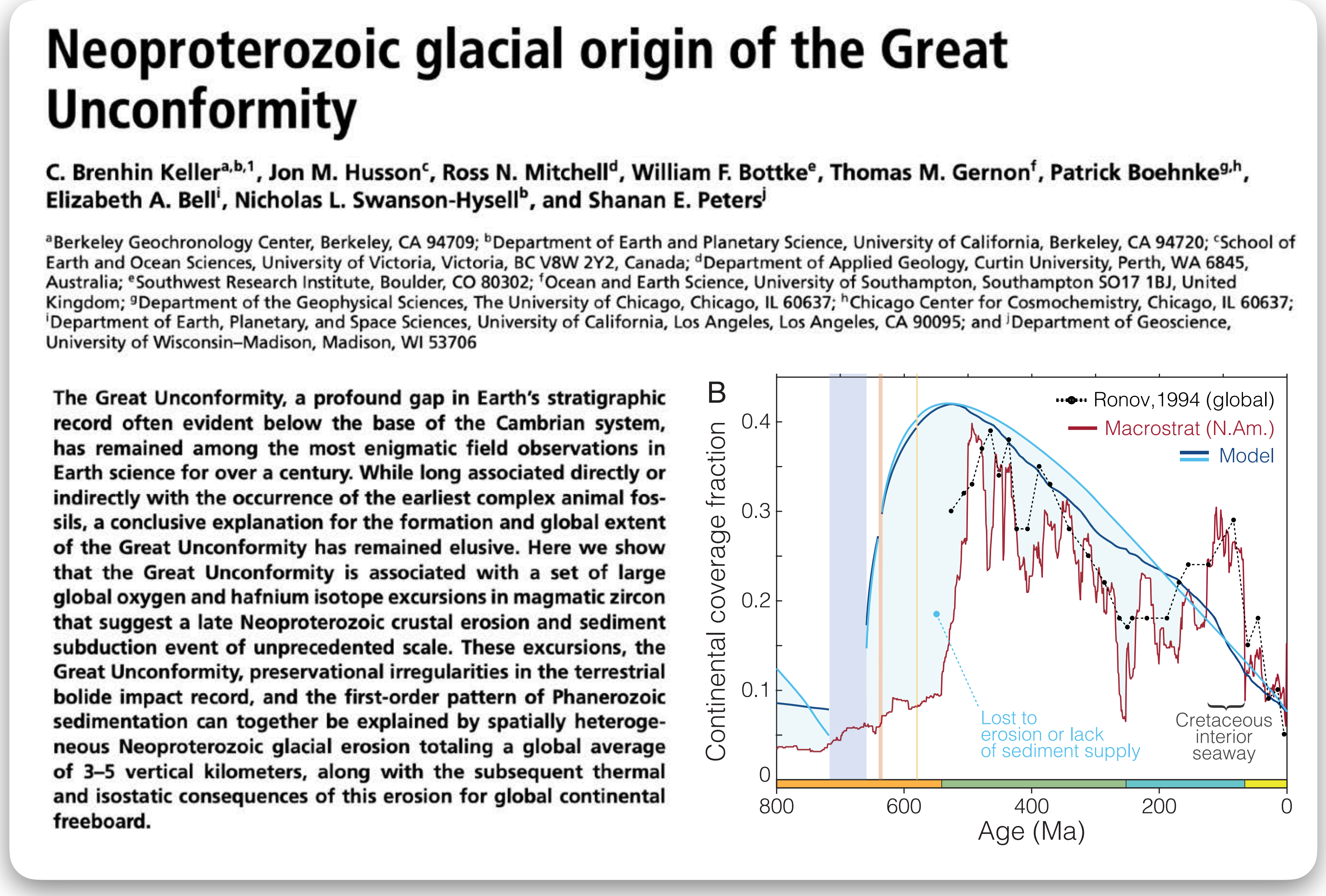
ANSWER "BIG" SCIENCE QUESTIONS ABOUT THE EVOLUTION OF THE EARTH



Atmospheric oxygenation driven by unsteady growth of the continental sedimentary reservoir

Jon M. Husson *, Shanan E. Peters

Department of Geoscience, University of Wisconsin–Madison, 1215 W. Dayton Street, Madison, WI, 53706, USA

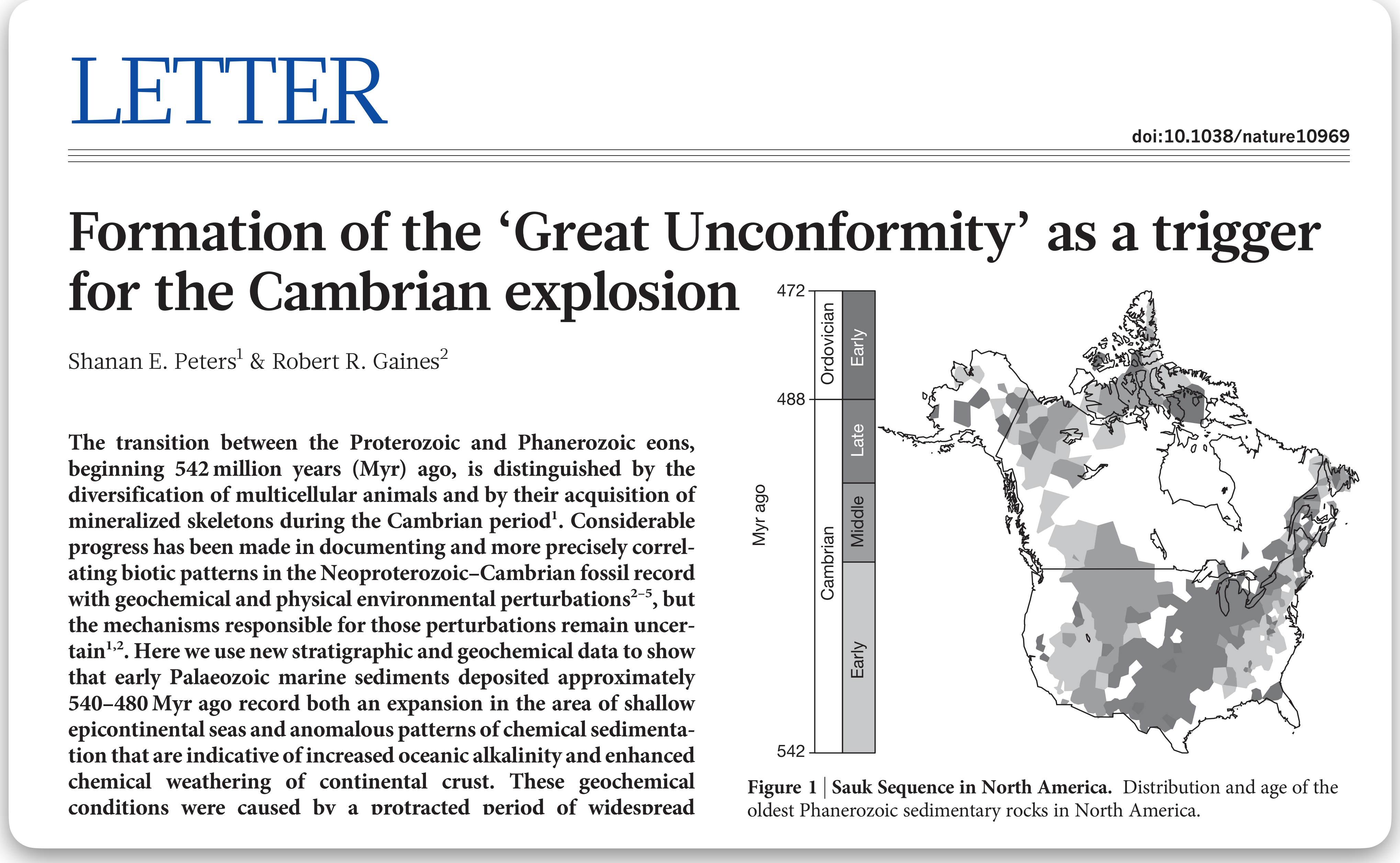


Neoproterozoic glacial origin of the Great Unconformity

C. Brenhin Keller[a,b,1], Jon M. Husson[c], Ross N. Mitchell[d], William F. Bottke[e], Thomas M. Gernon[f], Patrick Boehnke[g,h], Elizabeth A. Bell[i], Nicholas L. Swanson-Hysell[b], and Shanan E. Peters[j]

[a]Berkeley Geochronology Center, Berkeley, CA 94709; [b]Department of Earth and Planetary Science, University of California, Berkeley, CA 94720; [c]School of Earth and Ocean Sciences, University of Victoria, Victoria, BC V8W 2Y2, Canada; [d]Department of Applied Geology, Curtin University, Perth, WA 6845, Australia; [e]Southwest Research Institute, Boulder, CO 80302; [f]Ocean and Earth Science, University of Southampton, Southampton SO17 1BJ, United Kingdom; [g]Department of the Geophysical Sciences, The University of Chicago, Chicago, IL 60637; [h]Chicago Center for Cosmochemistry, Chicago, IL 60637; [i]Department of Earth, Planetary, and Space Sciences, University of California, Los Angeles, Los Angeles, CA 90095; and [j]Department of Geoscience, University of Wisconsin–Madison, Madison, WI 53706

The Great Unconformity, a profound gap in Earth's stratigraphic record often evident below the base of the Cambrian system, has remained among the most enigmatic field observations in Earth science for over a century. While long associated directly or indirectly with the occurrence of the earliest complex animal fossils, a conclusive explanation for the formation and global extent of the Great Unconformity has remained elusive. Here we show that the Great Unconformity is associated with a set of large global oxygen and hafnium isotope excursions in magmatic zircon that suggest a late Neoproterozoic crustal erosion and sediment subduction event of unprecedented scale. These excursions, the Great Unconformity, preservational irregularities in the terrestrial bolide impact record, and the first-order pattern of Phanerozoic sedimentation can together be explained by spatially heterogeneous Neoproterozoic glacial erosion totaling a global average of 3–5 vertical kilometers, along with the subsequent thermal and isostatic consequences of this erosion for global continental freeboard.



LETTER

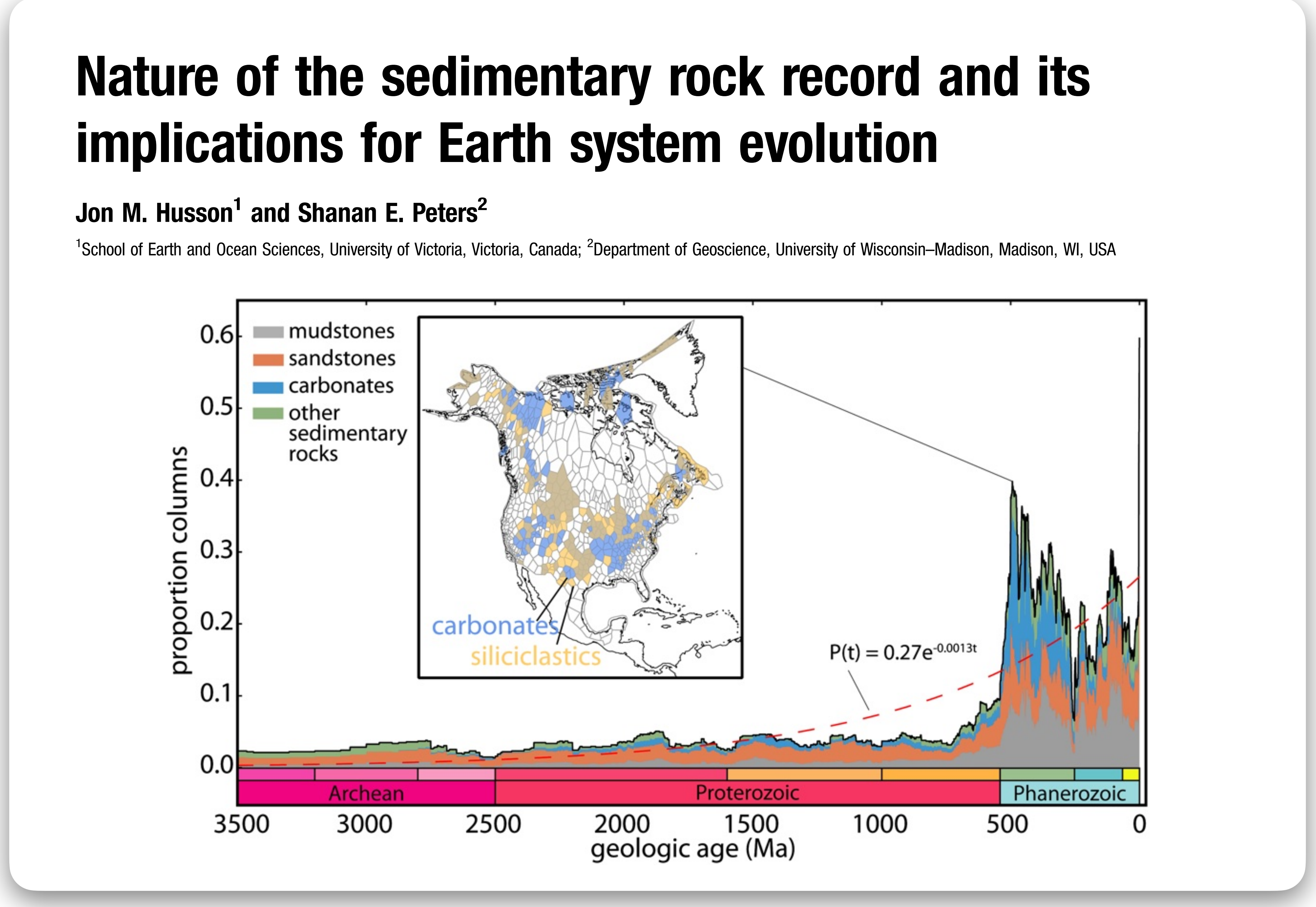
doi:10.1038/nature10969

Formation of the 'Great Unconformity' as a trigger for the Cambrian explosion

Shanan E. Peters[1] & Robert R. Gaines[2]

The transition between the Proterozoic and Phanerozoic eons, beginning 542 million years (Myr) ago, is distinguished by the diversification of multicellular animals and by their acquisition of mineralized skeletons during the Cambrian period[1]. Considerable progress has been made in documenting and more precisely correlating biotic patterns in the Neoproterozoic–Cambrian fossil record with geochemical and physical environmental perturbations[2–5], but the mechanisms responsible for those perturbations remain uncertain[1,2]. Here we use new stratigraphic and geochemical data to show that early Palaeozoic marine sediments deposited approximately 540–480 Myr ago record both an expansion in the area of shallow epicontinental seas and anomalous patterns of chemical sedimentation that are indicative of increased oceanic alkalinity and enhanced chemical weathering of continental crust. These geochemical conditions were caused by a protracted period of widespread

Figure 1 | **Sauk Sequence in North America.** Distribution and age of the oldest Phanerozoic sedimentary rocks in North America.



Nature of the sedimentary rock record and its implications for Earth system evolution

Jon M. Husson[1] and Shanan E. Peters[2]

[1]School of Earth and Ocean Sciences, University of Victoria, Victoria, Canada; [2]Department of Geoscience, University of Wisconsin–Madison, Madison, WI, USA

Macrostrat – A platform for geological exploration

Public, web-based "application programming interface" (API)

`https://macrostrat.org/api/v2`

1,534 columns

9,162 packages

35,478 units

1,245,645 measurements

2,540,323 geologic map polygons

51,212 stratigraphic names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{
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  "section_id": 4229,
  "col_id": 515,
  "project_id": 1,
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  "unit_name": "Mesaverde Fm",
  "strat_name_id": 1281,
  "Mbr": "",
  "Fm": "Mesaverde",
  "Gp": "",
  "SGp": "",
  "t_age": 80.725,
  "b_age": 90.825,
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```

Macrostrat – A platform for geological exploration

https://macrostrat.org/map

Macrostrat – A platform for geological exploration

Web interface

https://macrostrat.org/map

Field trip area: Harper's Ferry

https://macrostrat.org/map

Macrostrat – A platform for geological exploration

Map filtering

`https://macrostrat.org/map`

Macrostrat – A platform for geological exploration

https://macrostrat.org/map

Macrostrat API – provides mapping data to other projects

Rockd – *our own app!*

`https://rockd.org`

Mancos

Flyover Country

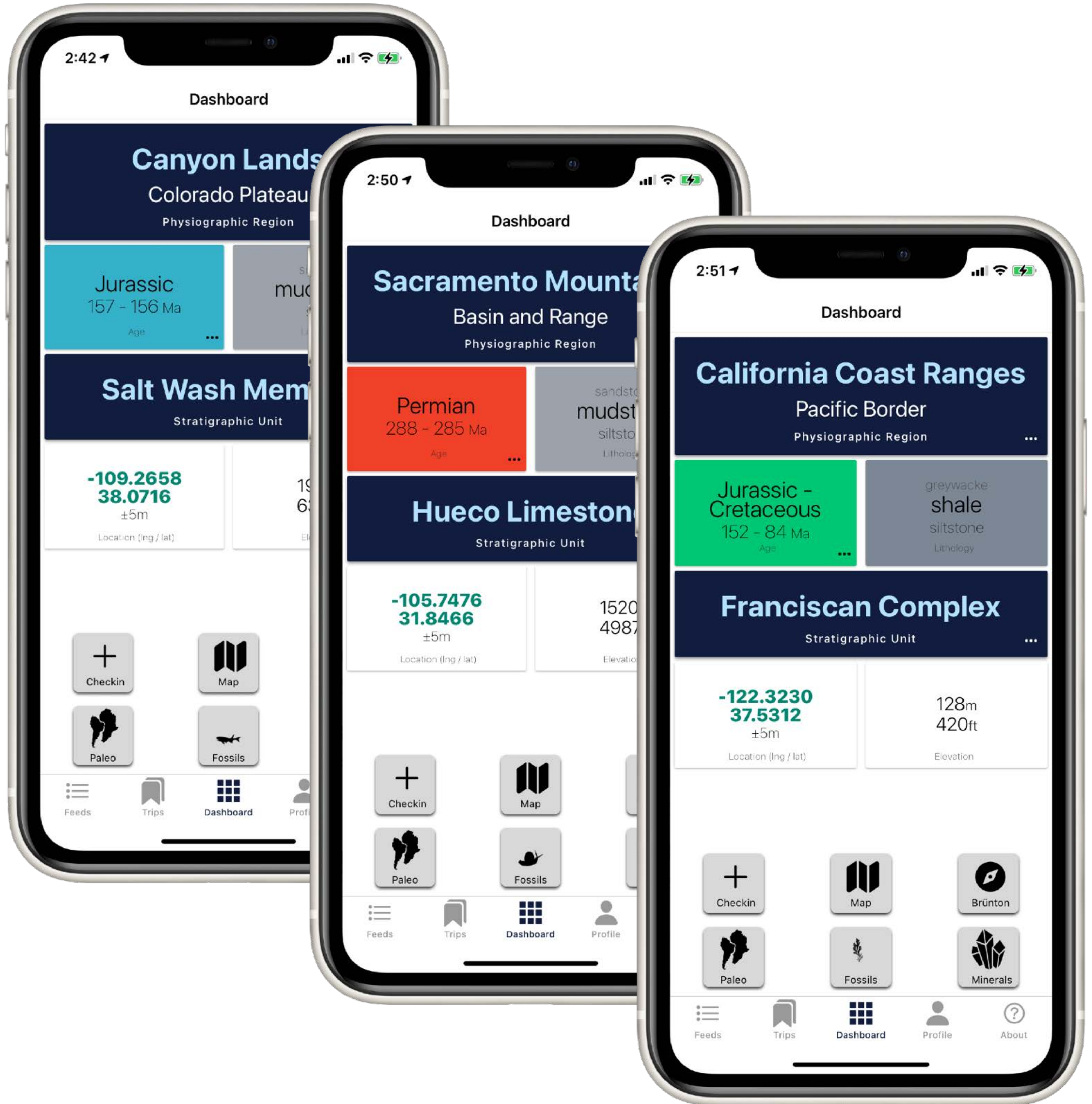
StraboSpot

...and many more!

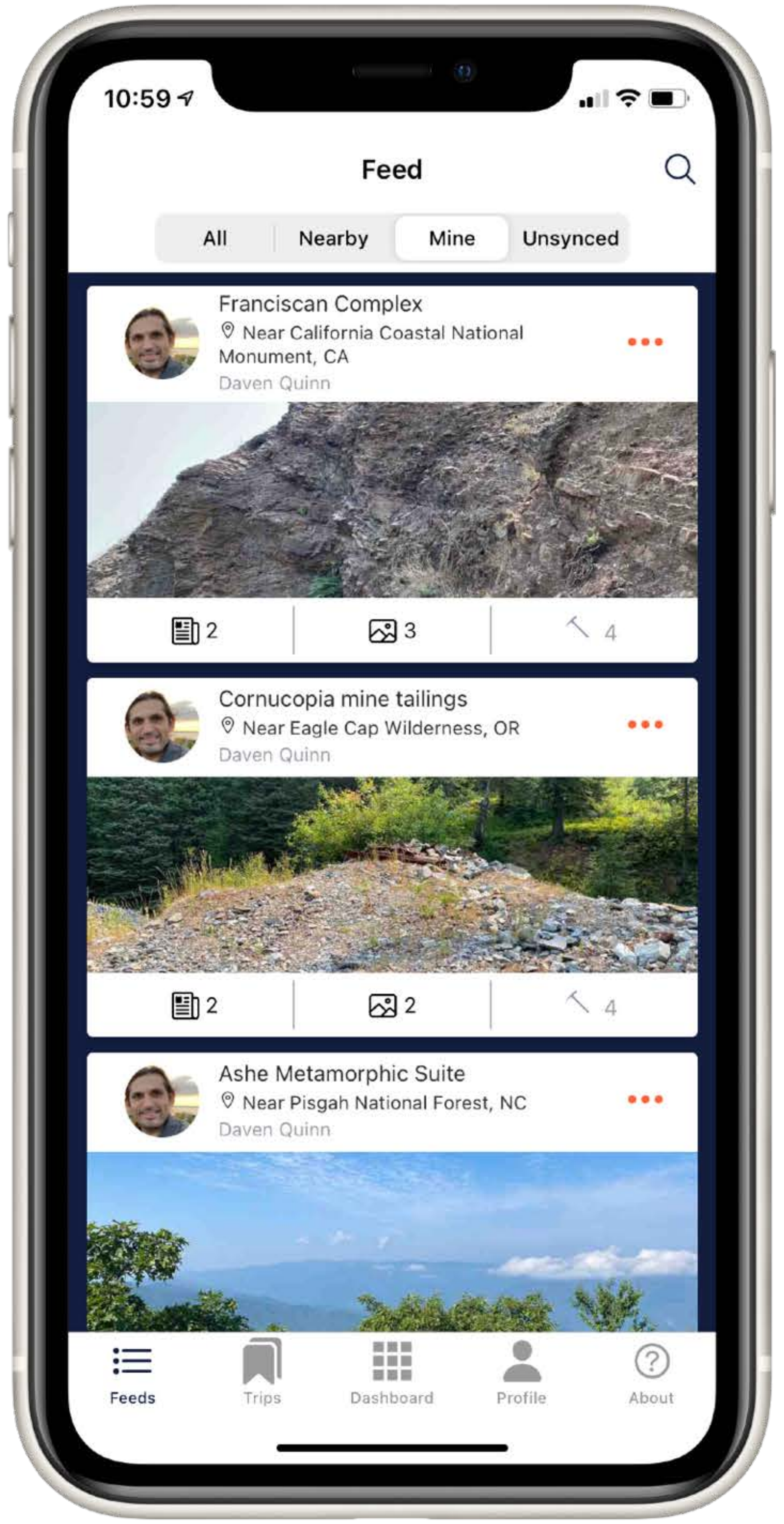
Rockd

https://rockd.org

EXPLORE THE GEOLOGY AROUND YOU



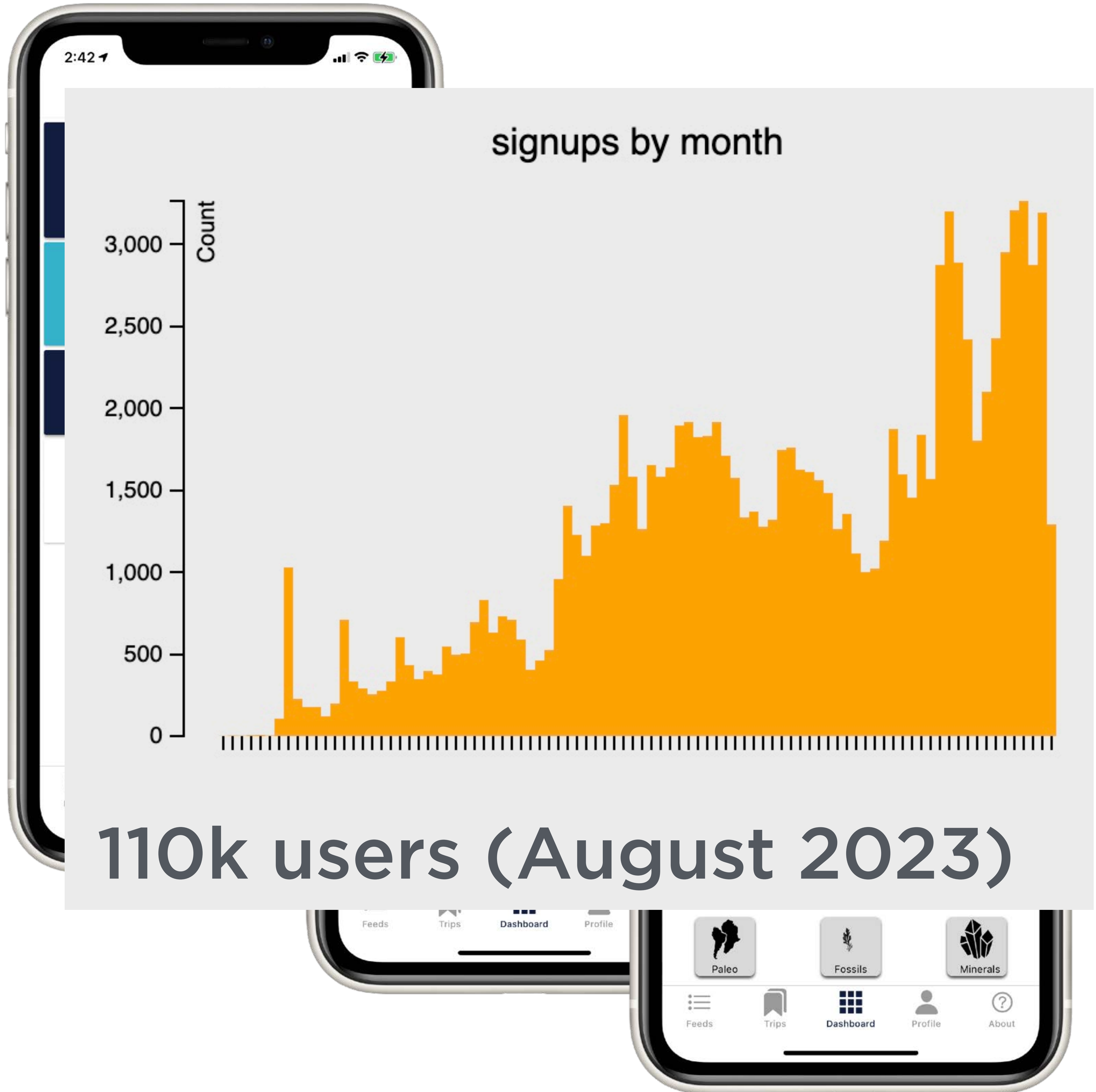
COLLECT AND VIEW LOCAL OBSERVATIONS



Rockd

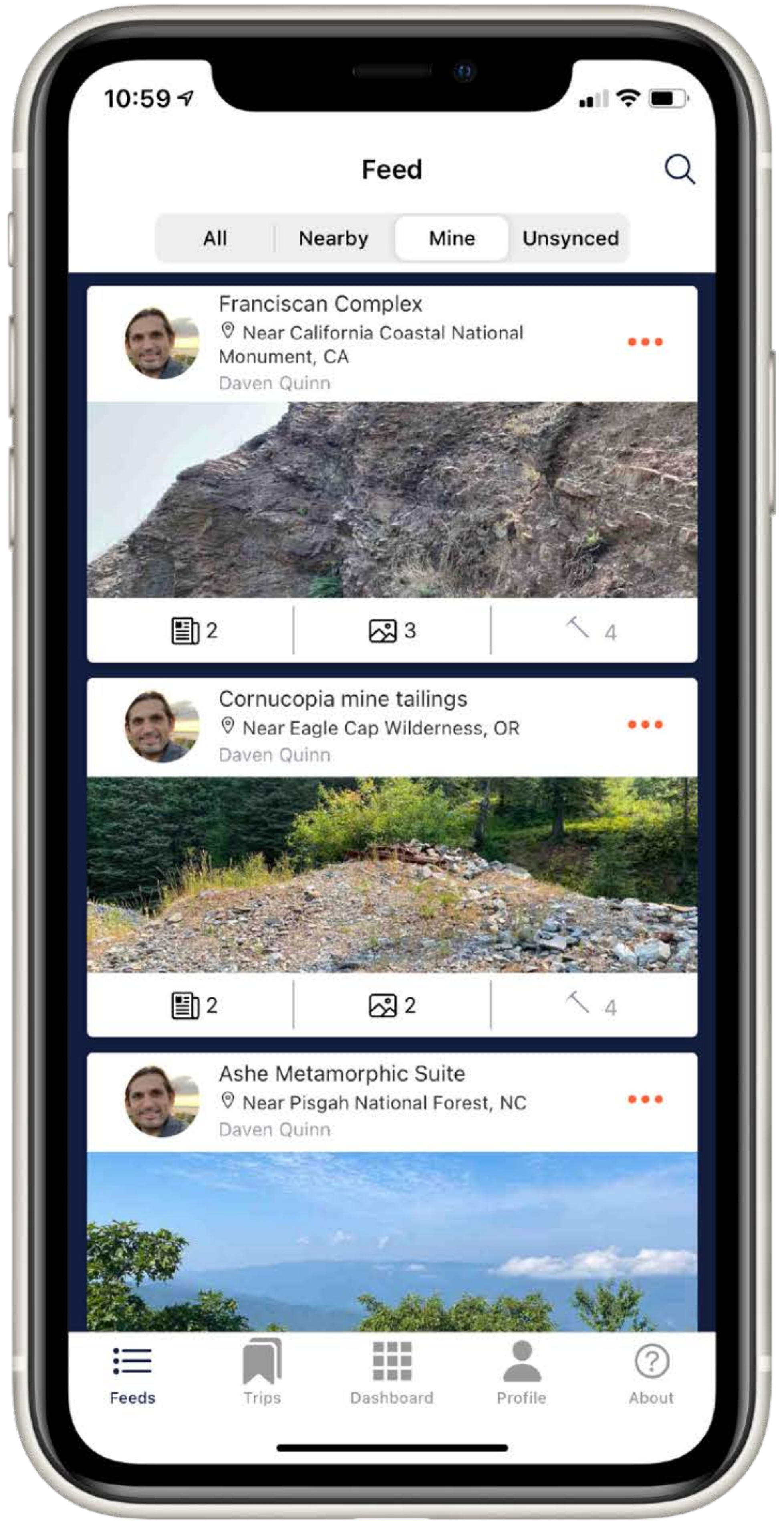
https://rockd.org

EXPLORE THE GEOLOGY AROUND YOU



110k users (August 2023)

COLLECT AND VIEW LOCAL OBSERVATIONS



Macrostrat system architecture

Geologic maps

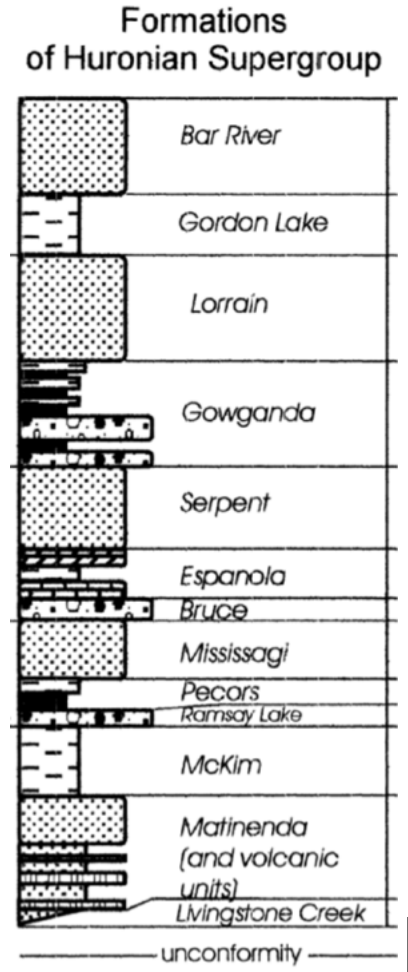
from

National agencies

State surveys

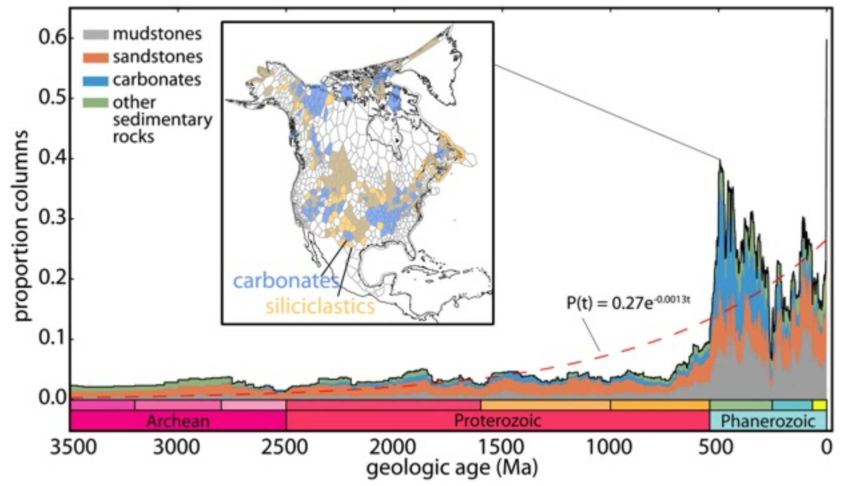
Academic curators

...and other sources

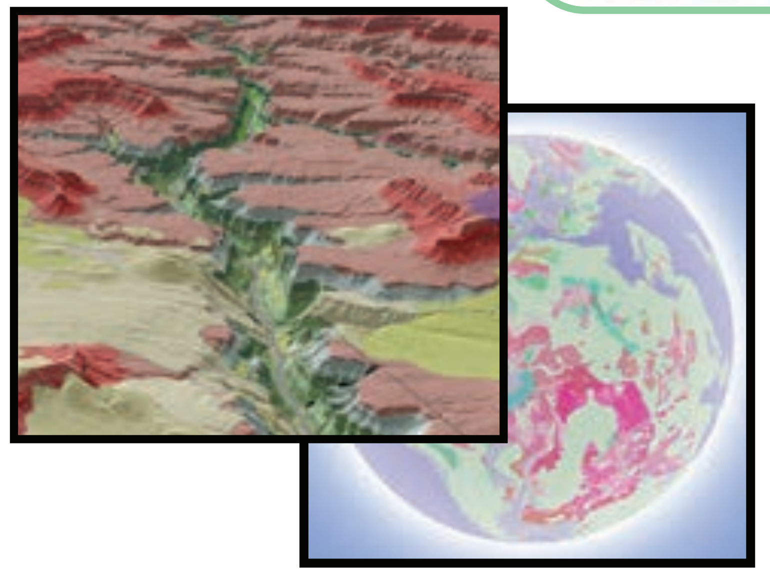


Stratigraphic columns

Global, integrative science



Apps + web viewers



PostGIS relational geodatabase

Tile server

Macrostrat software platform

Ingestion + harmonization

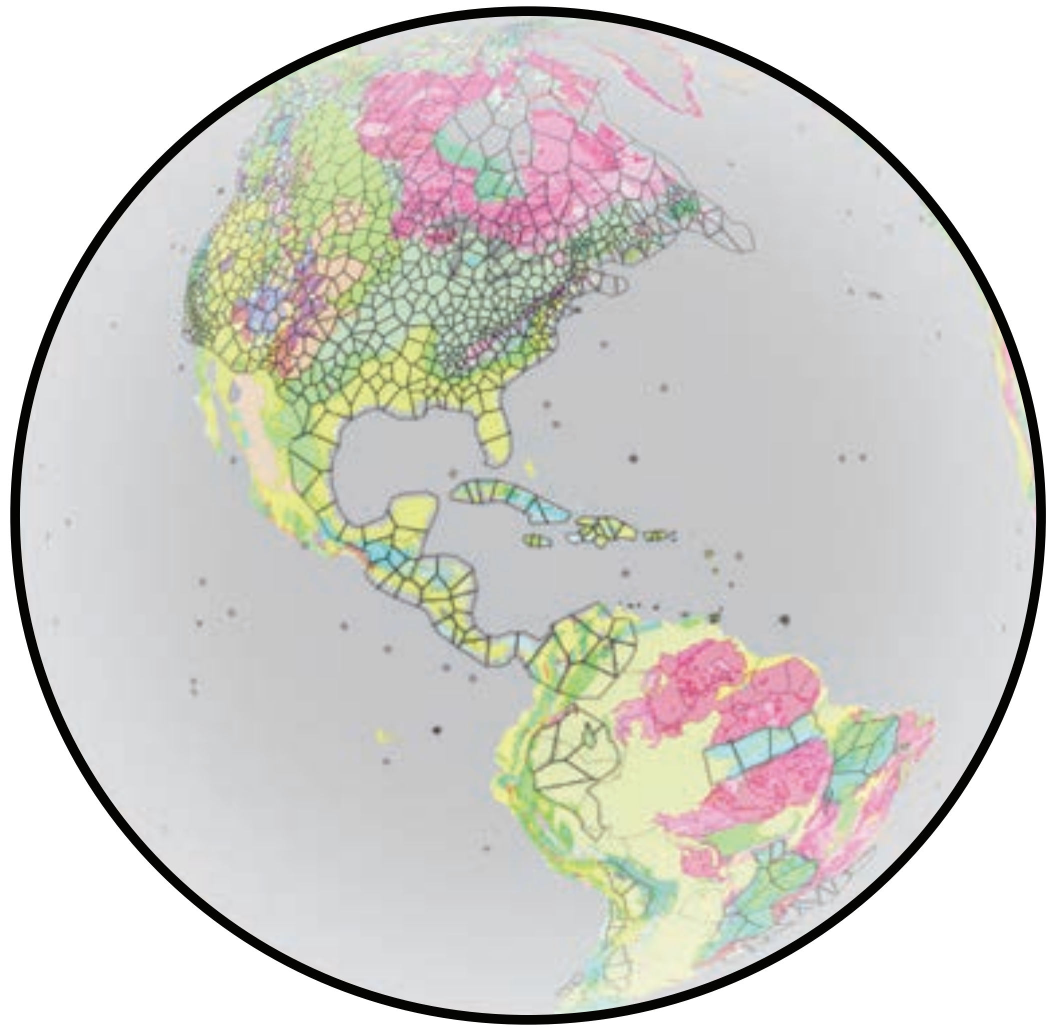
Partially automated

Open APIs

Automated

GIS platforms

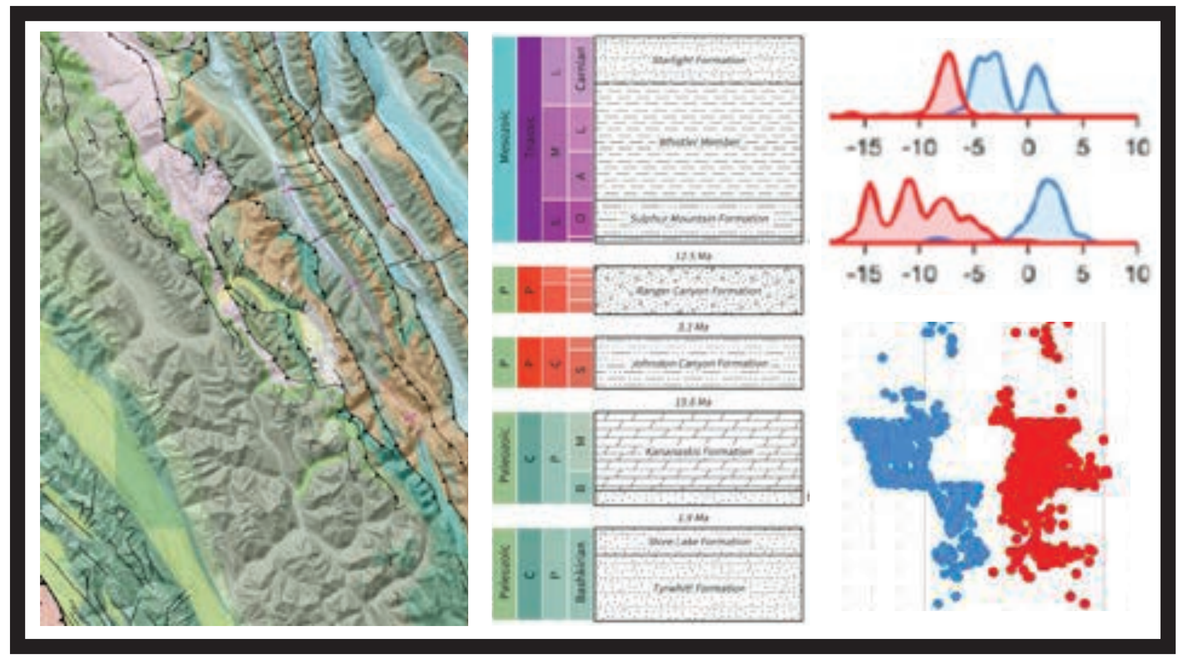
Macrostrat



- Software infrastructure that adds context to geologic datasets
- APIs to serve harmonized geologic information to other systems
- Human-computer interfaces for geological data visualization

MacroMAAS (Macrostrat for Mineral Assessment with AI Support)

+ Make it modular + scalable!
+ Ingest candidate geologic datasets provided by AI pipelines
+ Include contextual data sources relevant to critical minerals assessment
+ Add interfaces for feedback/correction of candidate datasets




MacroMAAS
Proposed system architecture
Macrostrat
Literature extractions
Predictive mineral maps
New data sources
USGS
Measurements
Raster maps
Geophysics
TA1-2
PostGIS relational geodatabase
Tile server
Macrostrat software platform
TA3
Ingestion + harmonization
~~Partially automated~~
Fully automated
Feedback
"Human in the loop"
Expert feedback interfaces
GIS platforms
esri
QGIS

Ingestion of AI-generated candidate map datasets (TA1 output)

Planned

d	ptype	age	early_id	late_id	name
4	Qya	Holocene and late Pleistocene	492	3	Young alluvia
5	Qoa	late to middle Pleistocene	502	492	Old alluvial fl
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		Holocene and late Pleistocene	492	3	Young alluvia
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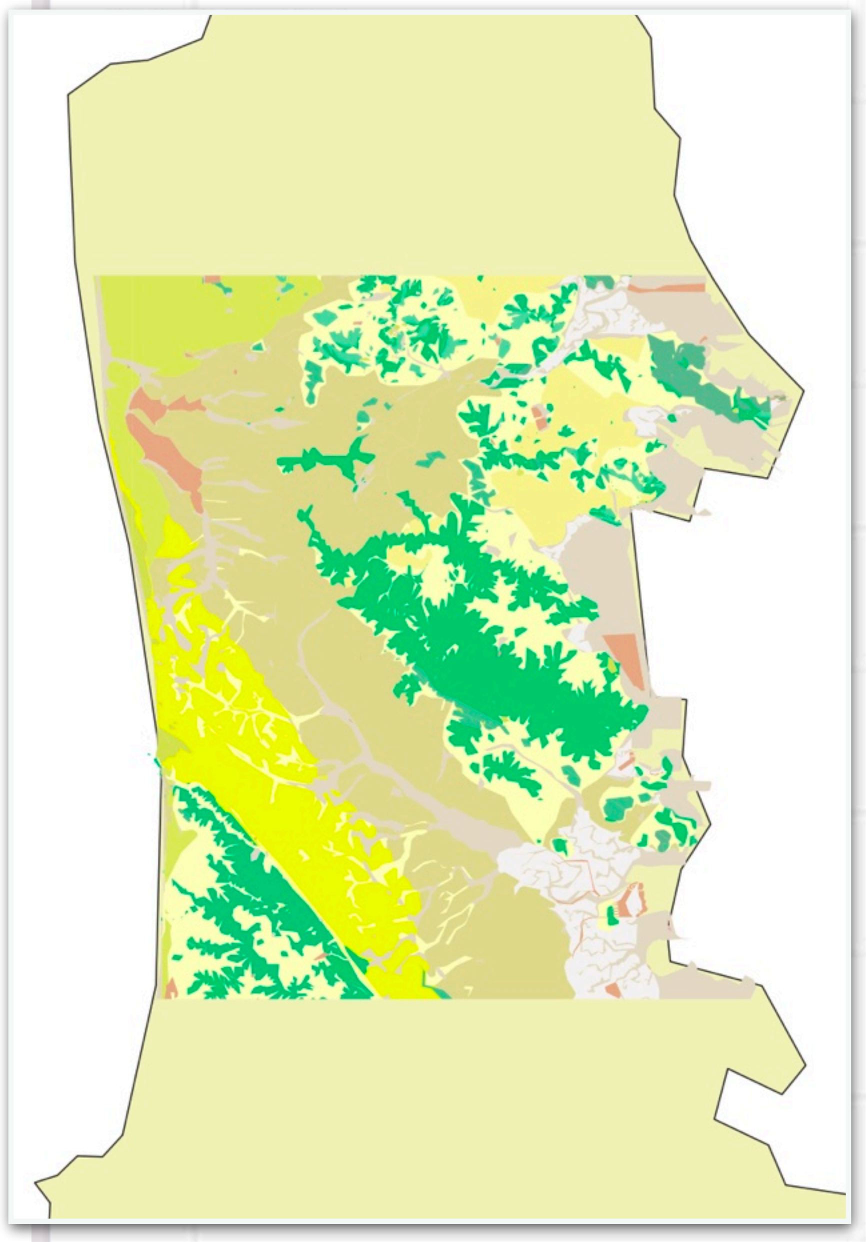
21	Qls	Holocene and Pleistocene	4	3	Landslide de



Map ingestion into open-source PostGIS geospatial database

PostgreSQL PostGIS

- Attributes are minimally cleaned
- **Unit names and age ranges are linked to common definitions**

~~Manual ingestion assisted by Python scripts~~

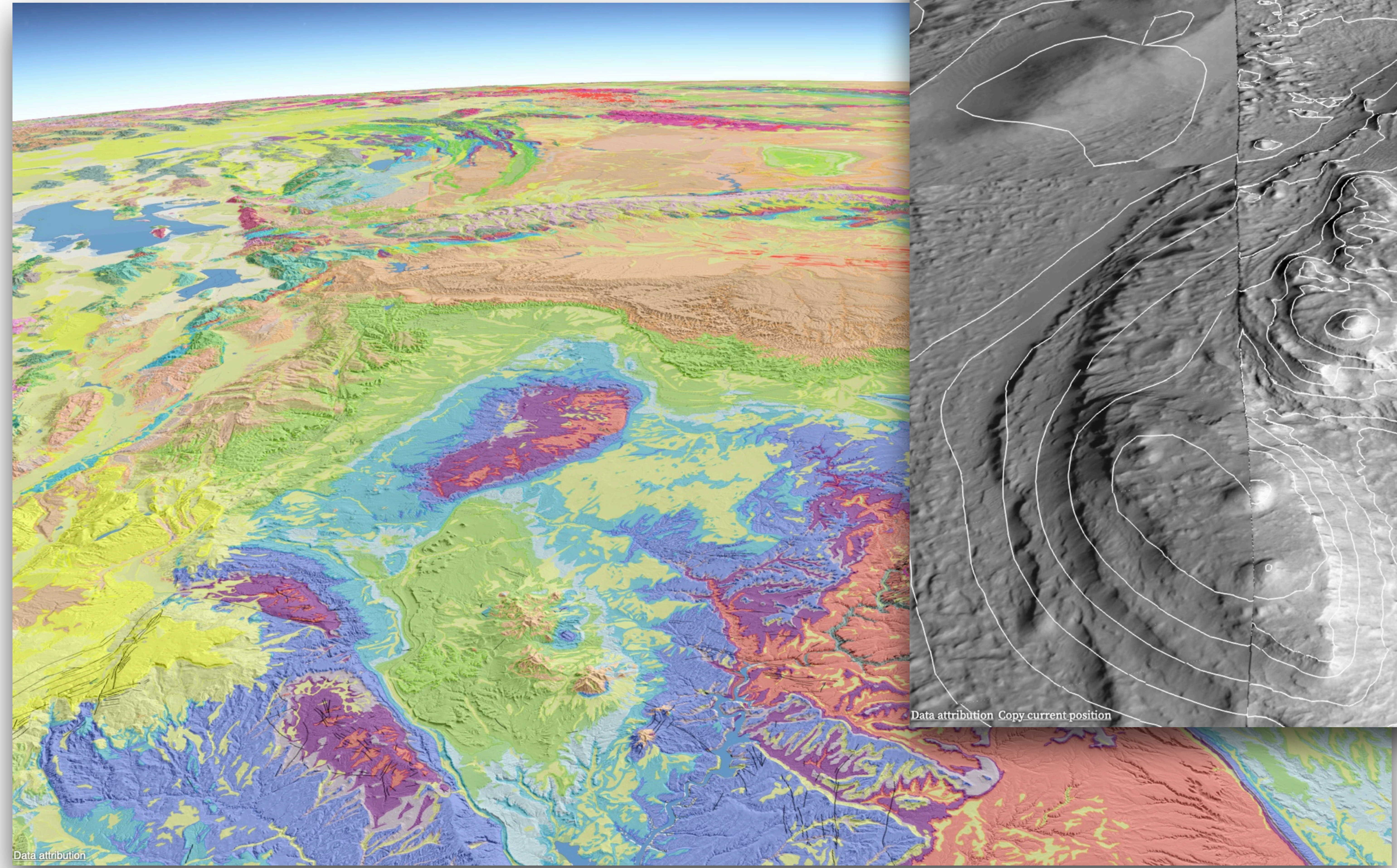
Automated "best-effort" ingestion

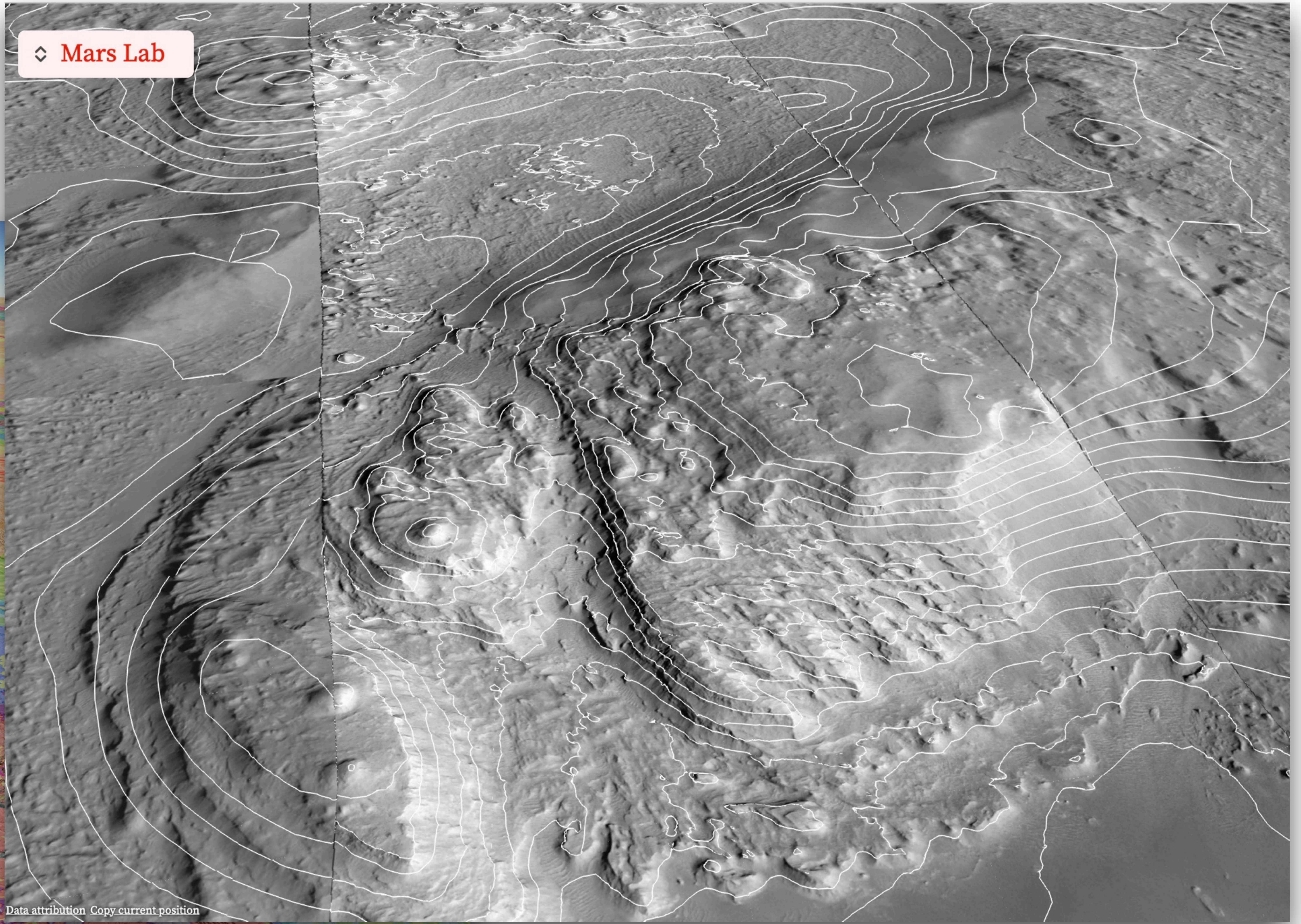
Integrating new contextual data sources

Prototype capability

A dynamic tile server for raster datasets

https://argyre.geoscience.wisc.edu/app/





In collaboration with

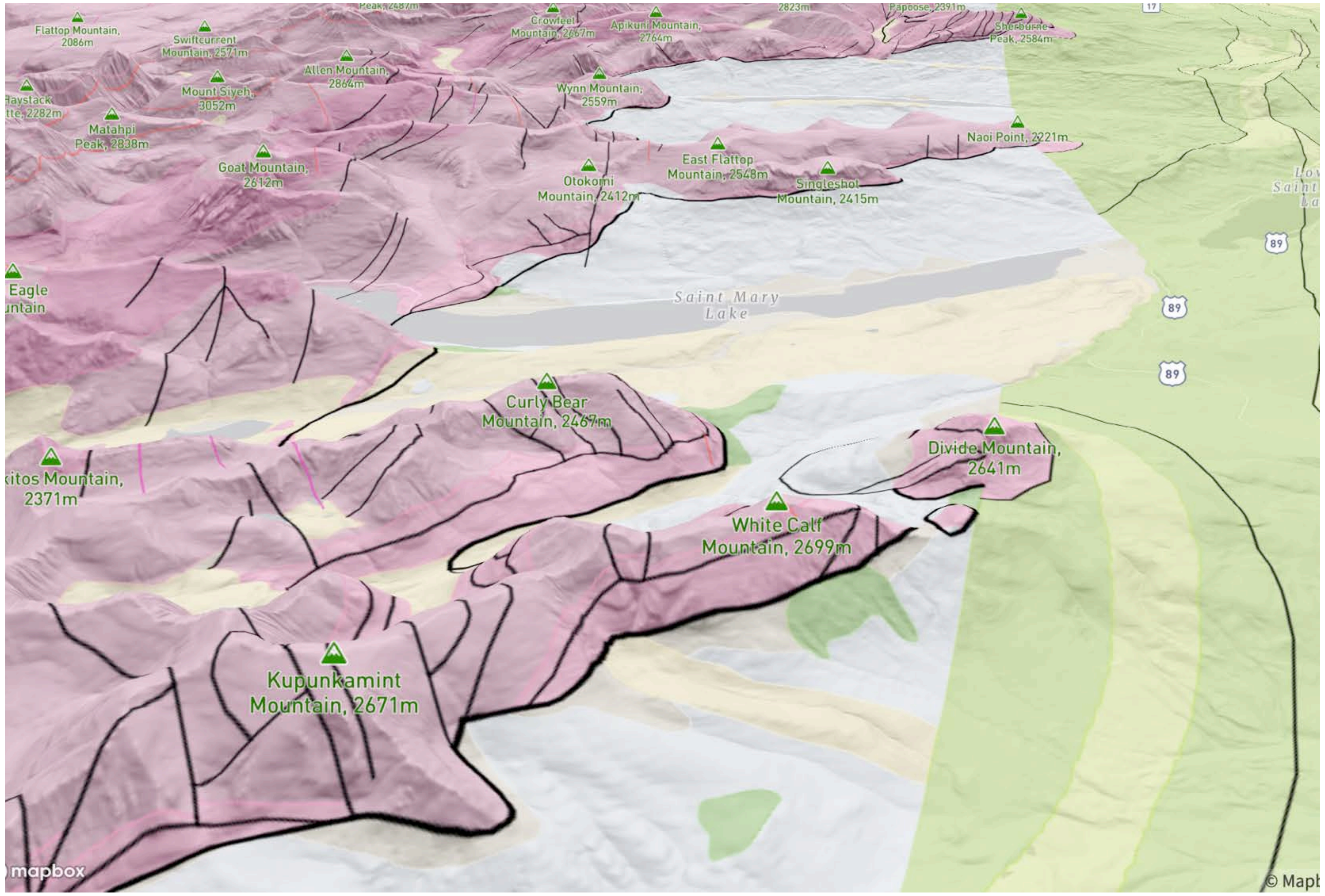
Jet Propulsion Laboratory
California Institute of Technology

Integrating new contextual data sources

Prototype capability

A dynamic tile server for raster datasets

Macrostrat web interface showing raster geologic map

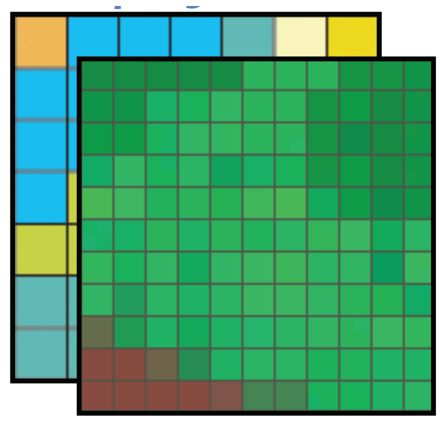


Vectorized version of same map

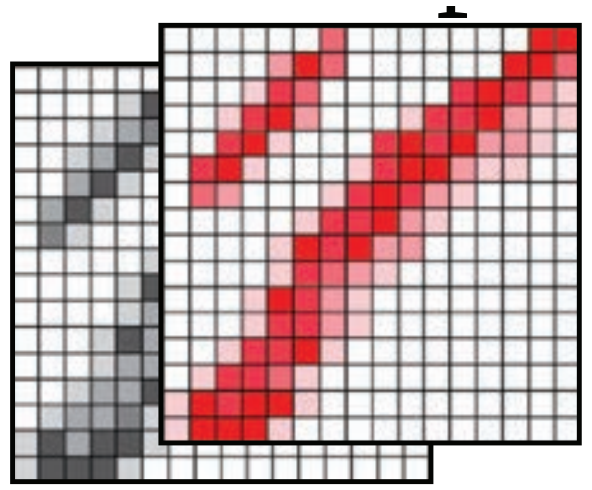
Critical for surfacing

Geologic basemaps

Geophysical evidence layers



Predictive mineral maps

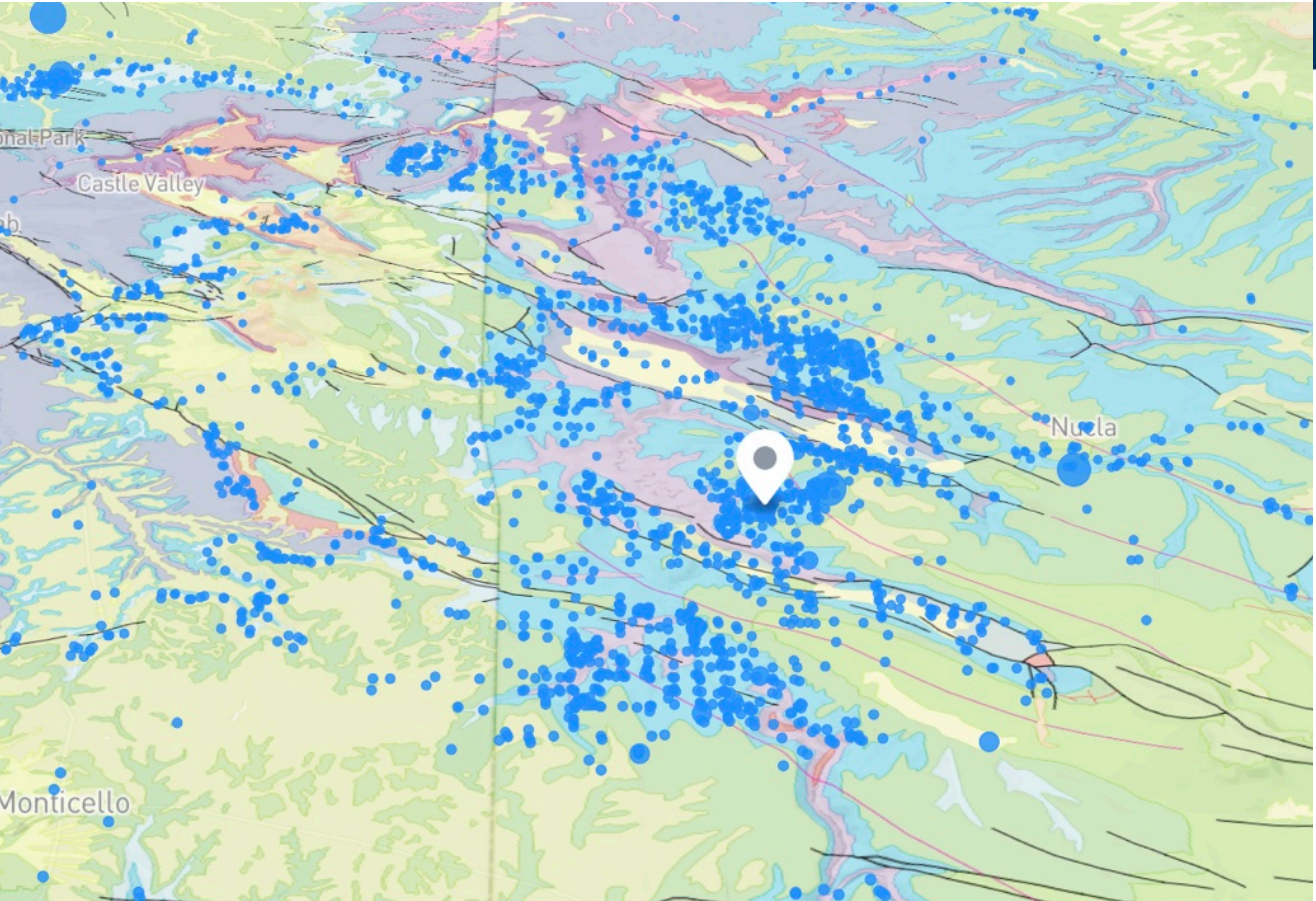


Integrating new contextual data sources

Prototype capability

A flexible system for integrating/representing station-based data

Site data from Mineral Resources Data System



USGS
science for a changing world

Mineral Resources / Online Spatial Data / Mineral Resource Data System (MRDS)

Club #3 Mine

Unknown in Montrose county in Colorado, United States with commodities Uranium, Vanadium

Map | XML | JSON | KML | D

Geologic information

Identification information	
Deposit ID	10305115
MAS/MILS ID	0080850689
Record type	Site
Current site name	Club #3 Mine

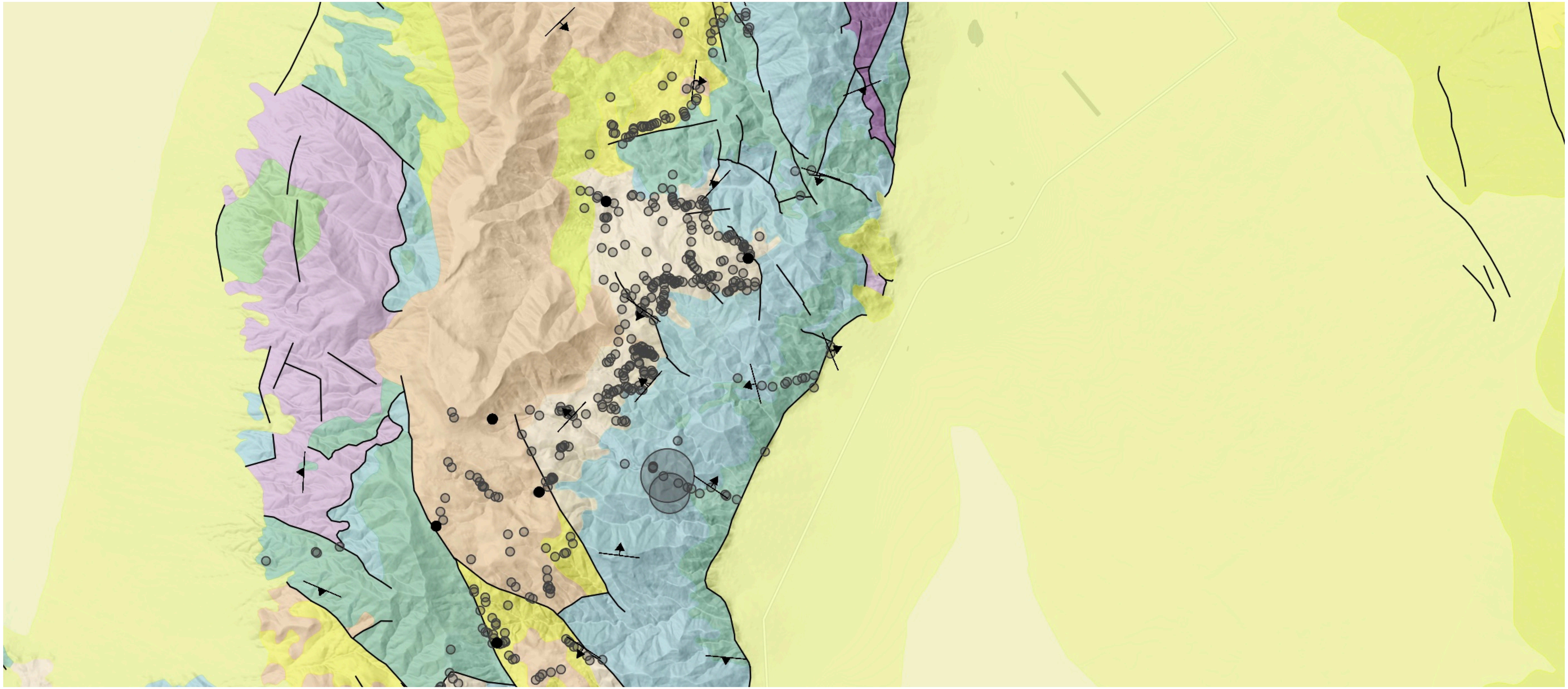
Geographic coordinates	
Point of reference	Main Entrance
Geographic coordinates:	-108.78288, 38.39079 (WGS84)
Elevation	1701
Location accuracy	10 *(meters)*
Political divisions (FIPS codes)	
Montrose (county)	

Integrating new contextual data sources

Prototype capability

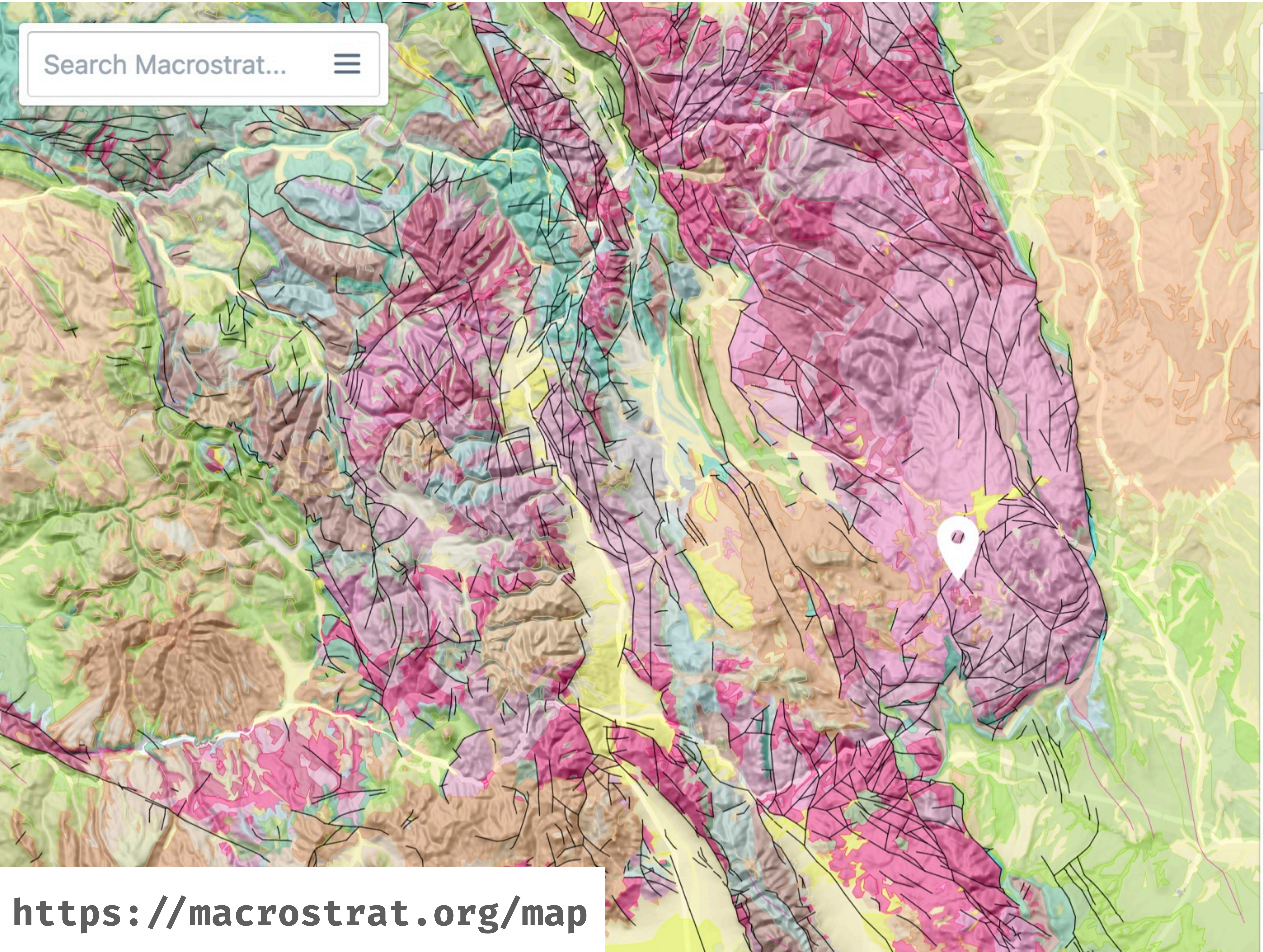
A flexible system for integrating/representing station-based data

Structural data from StraboSpot



Integrating contextual data from the geologic literature

Established capability



-105.2245, 38.7848 2737m | 8980ft

Primary literature via xDD

Robinson, Charles Sherwood, Geology and ore deposits of the Whitepine area, Tomichi mining district, Gunnison County, Colorado.

Nash, J. Thomas, Supergene uranium deposits in brecciated zones of Laramide upthrusts; concepts and applications.

Young, E. J., Felsic-mafic ratios and silica saturation ratios; their rationale and use as petrographic and petrologic indicators.

Hills, F. A., Dickinson, K. A., Silver Plume Granite; possible source of uranium in sandstone uranium deposits, Tallahassee Creek and High Park areas, Fremont and Teller counties, Colorado.

Finch, Warren Irvin, Stratigraphic distribution of uranium clusters in the Rocky Mountain and Intermontane Basins Uranium Province.

Braddock, William A., Cole, James C., Preliminary geologic map of the Greeley 1 degree by 2 degrees Quadrangle, Colorado and Wyoming.

Snyder, George L., Preliminary geologic map of the central Laramie Mountains, Albany and Platte counties, Wyoming.

McCallum, M. E., Burch, A. L., Uranium and thorium in Precambrian crystalline rocks of the Medicine Bow Mountains, north-central Colorado.

Stuckless, J. S., Hedge, C. E., Wenner, D. B., Nkomo, I. T., Isotopic studies

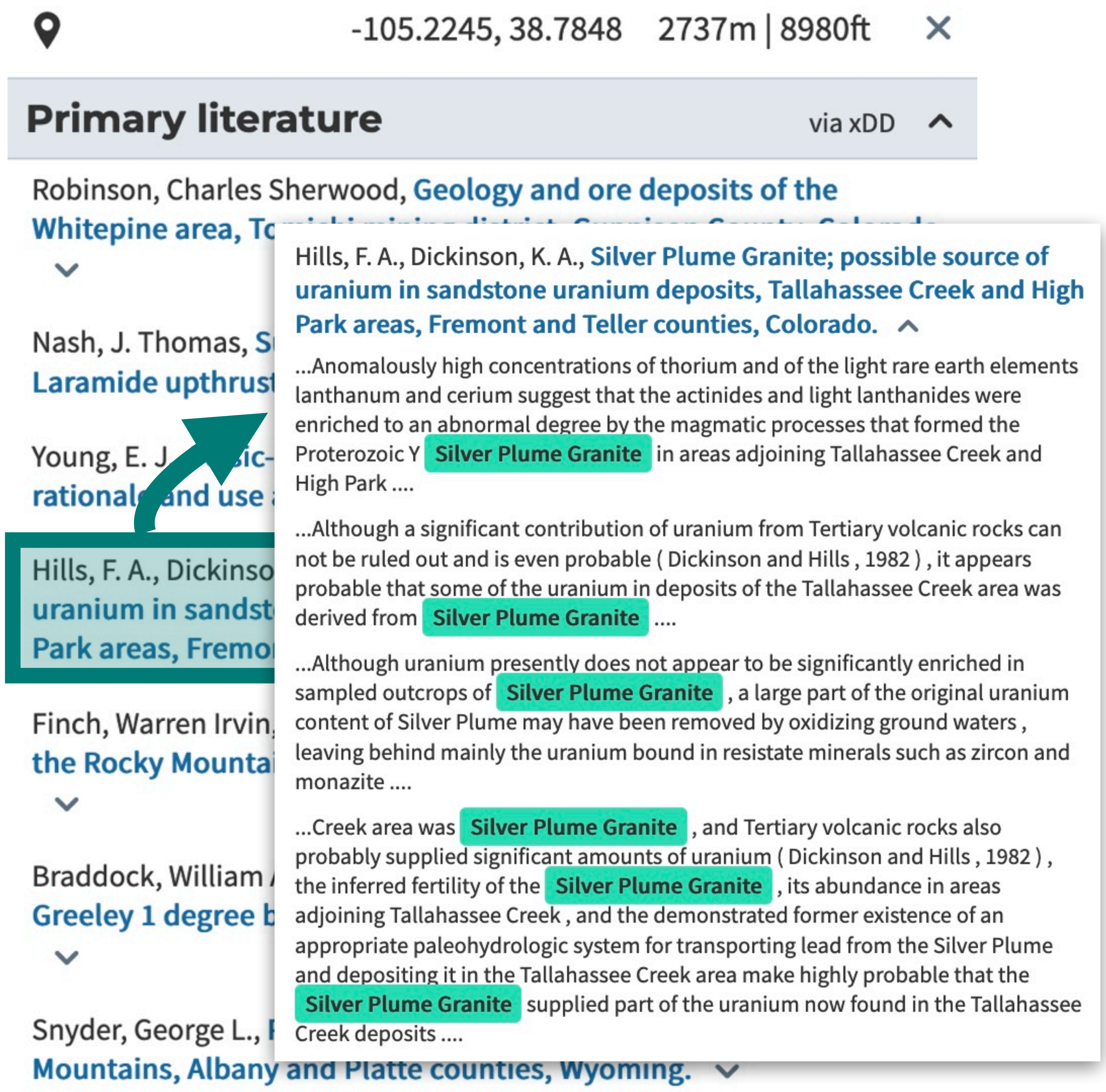
https://macrostrat.org/map

Integrating contextual data from the geologic literature

Established capability

xDD: Integrating contextual data from the geologic literature

Established capability



Macrostrat is linked to the xDD (formerly, GeoDeepDive) machine reading library, data infrastructure, and API

16,909,371 documents

108,486 added this month

25,112 added this week

3,683 added in the last 24 hours

https://xdd.wisc.edu

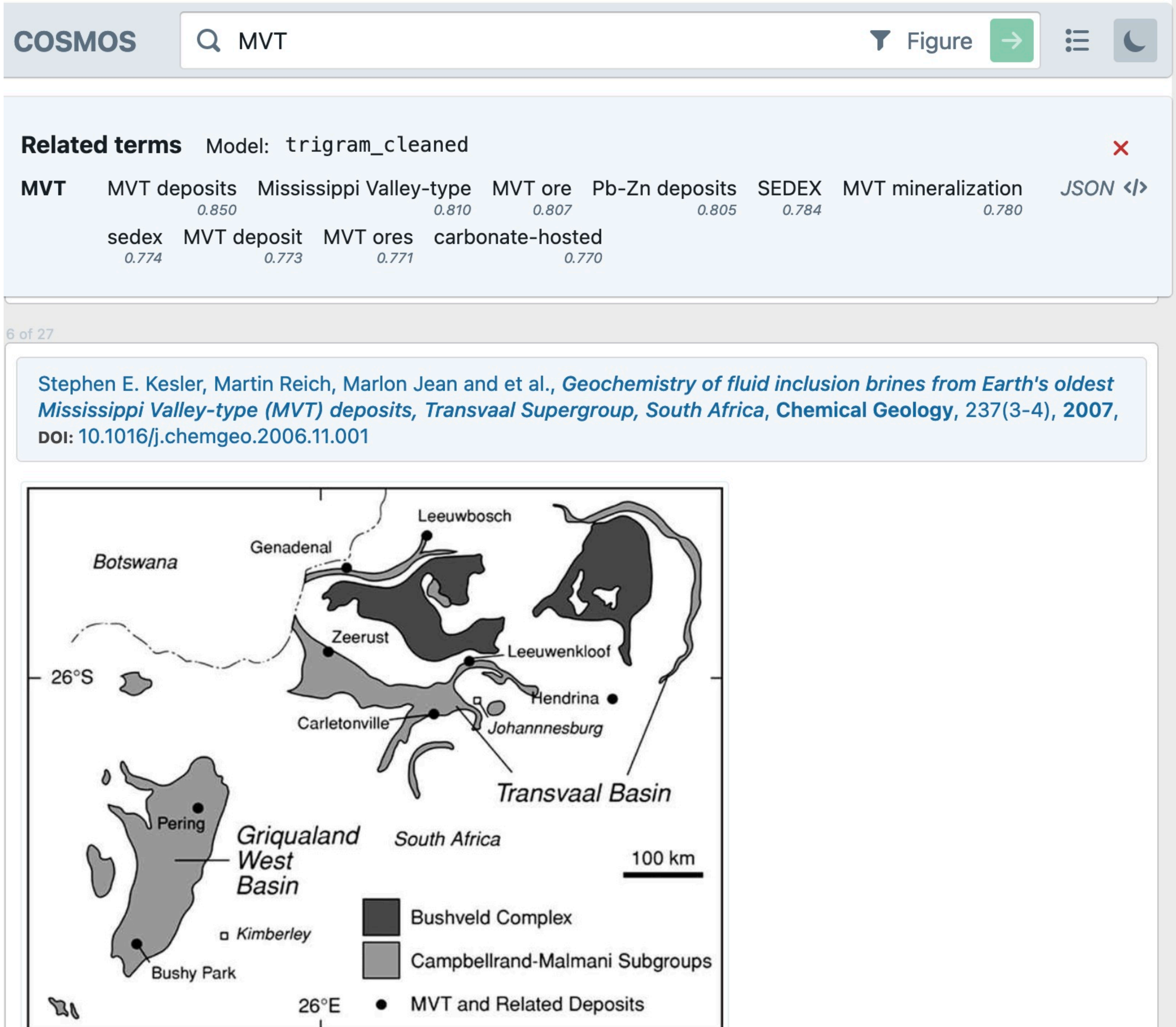
xDD + COSMOS

Established capability

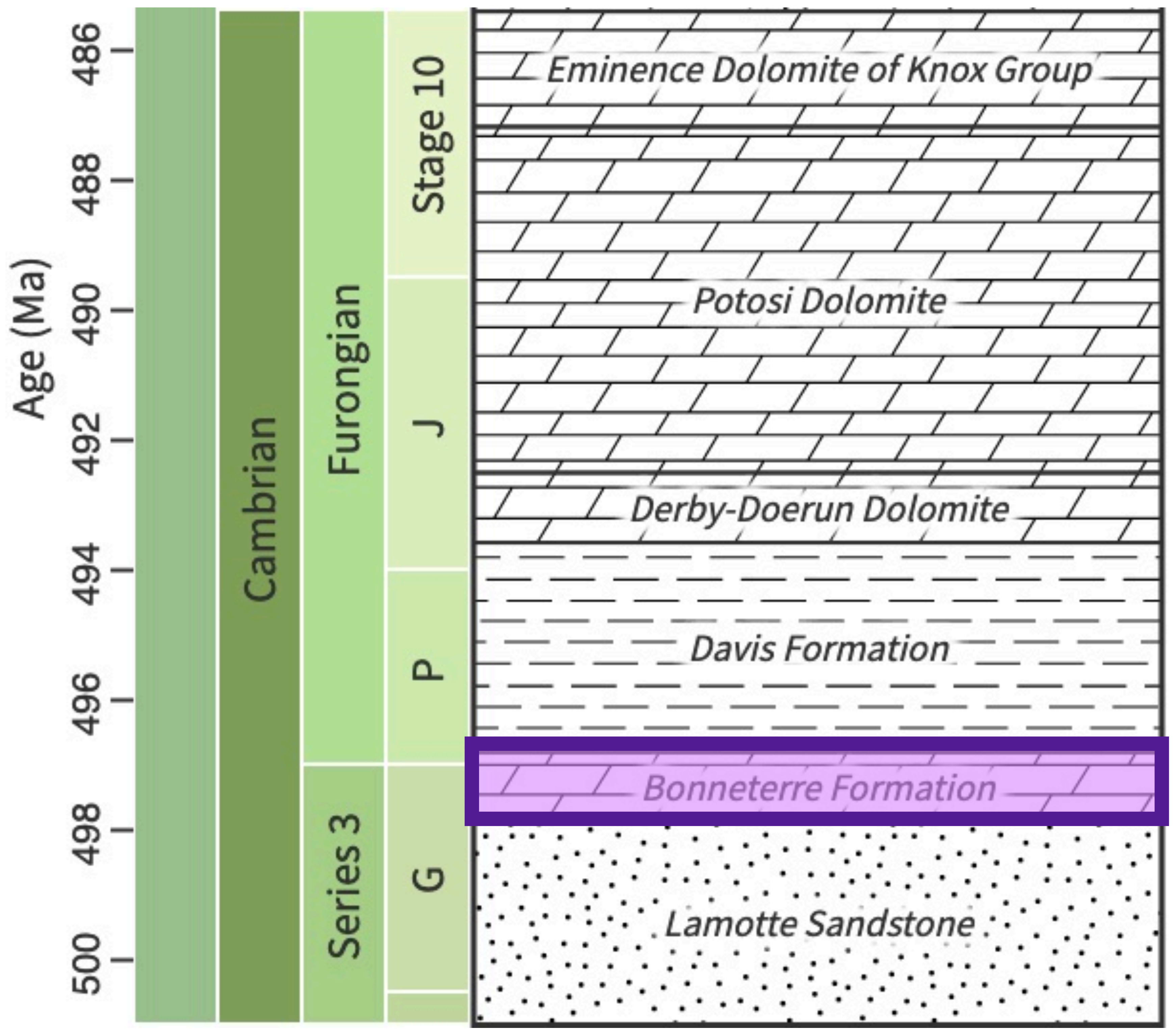
Surface relevant information from the geologic literature

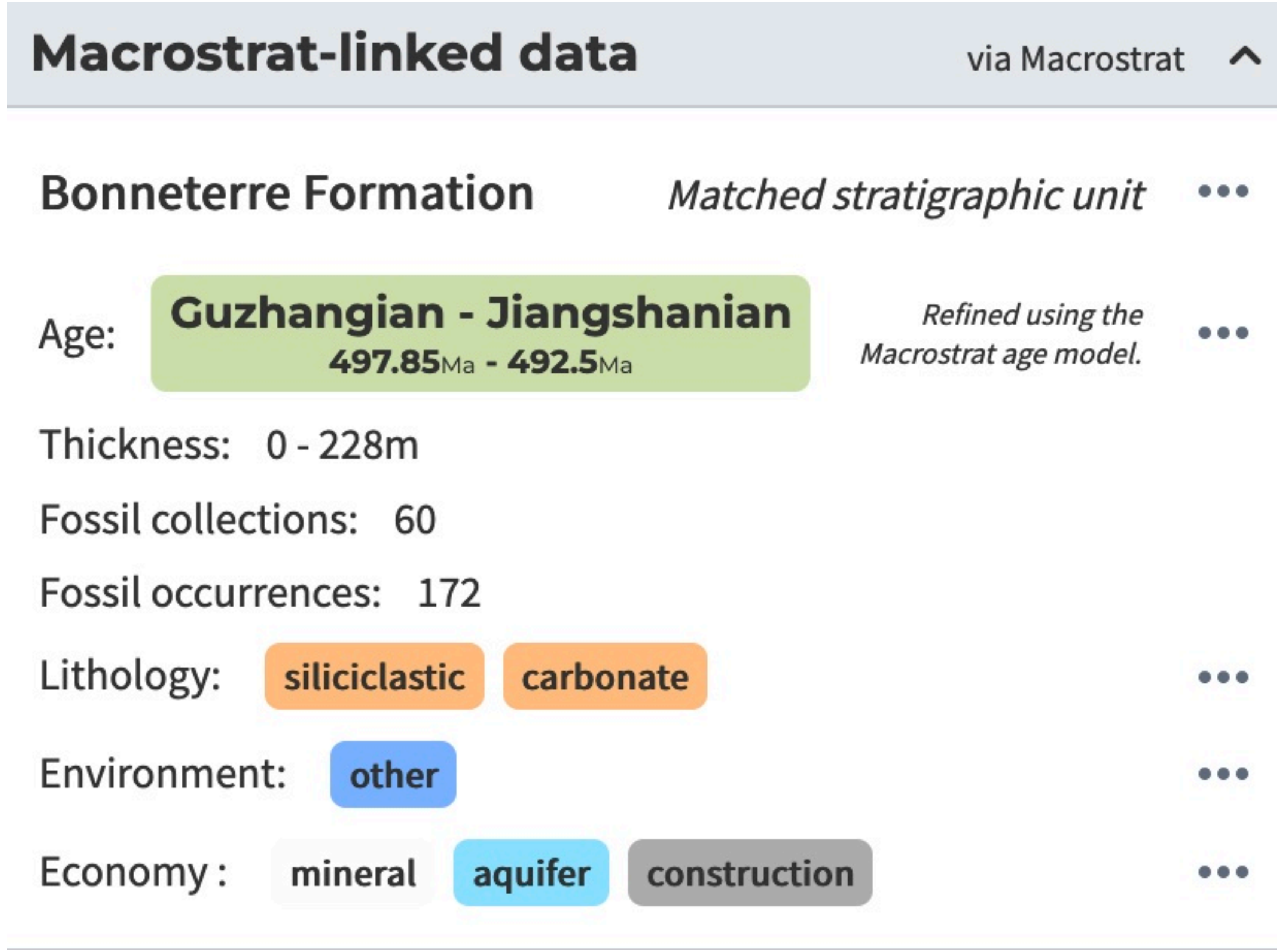
Example: Mississippi Valley-type ore deposits

- Surface source data for TA1-3
- Datasets filtering on arbitrary criteria can be created on demand (ex. *dolomite*)



https://xdd.wisc.edu/set_visualizer/sets/dolomites?query=MVT&type=Figure





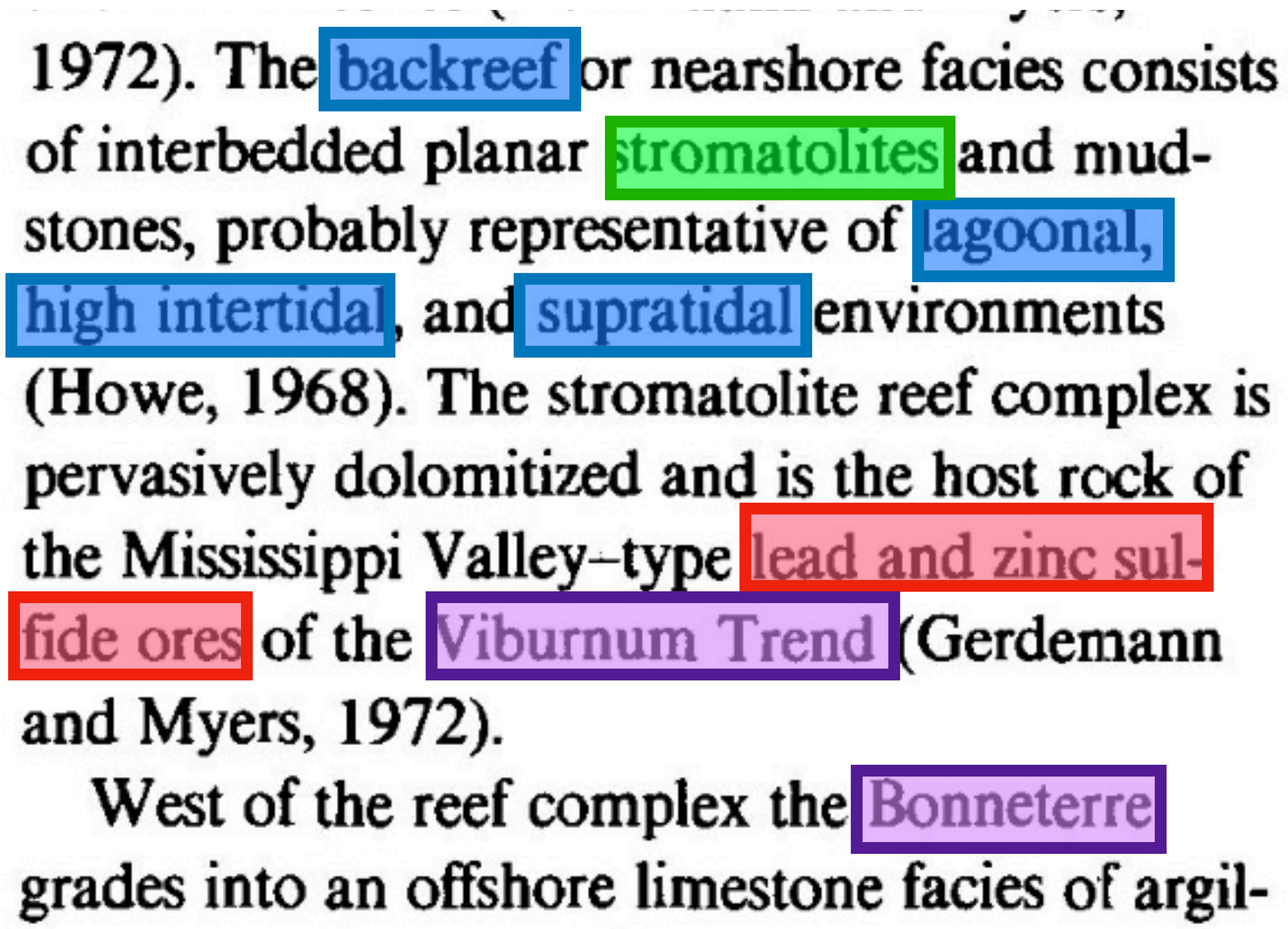
xDD + COSMOS

Planned capability

IMPROVE MACROSTRAT GEOLOGIC ENTITIES

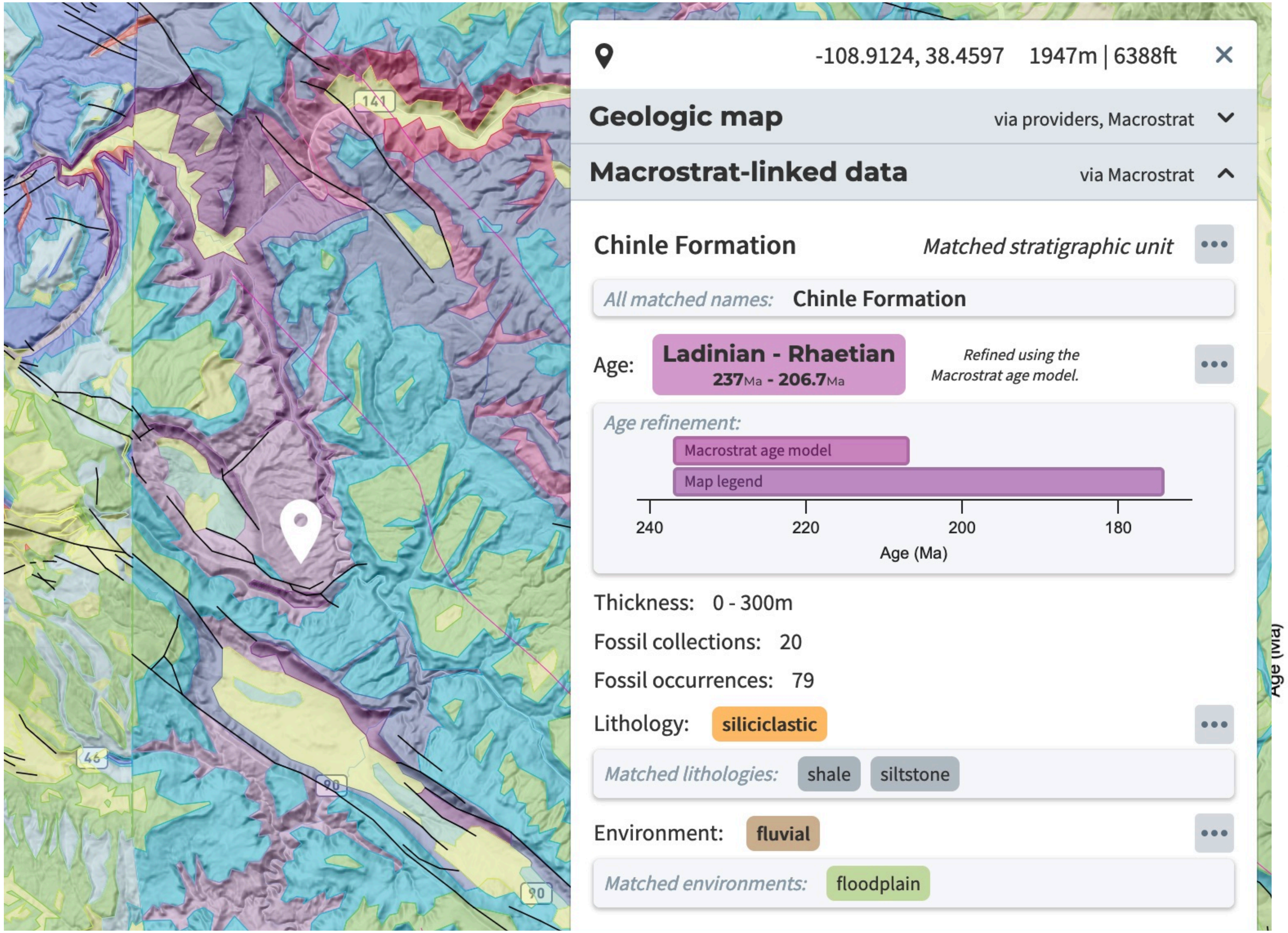
Improve the quality of structured geological information by "canonicalizing" literature mentions

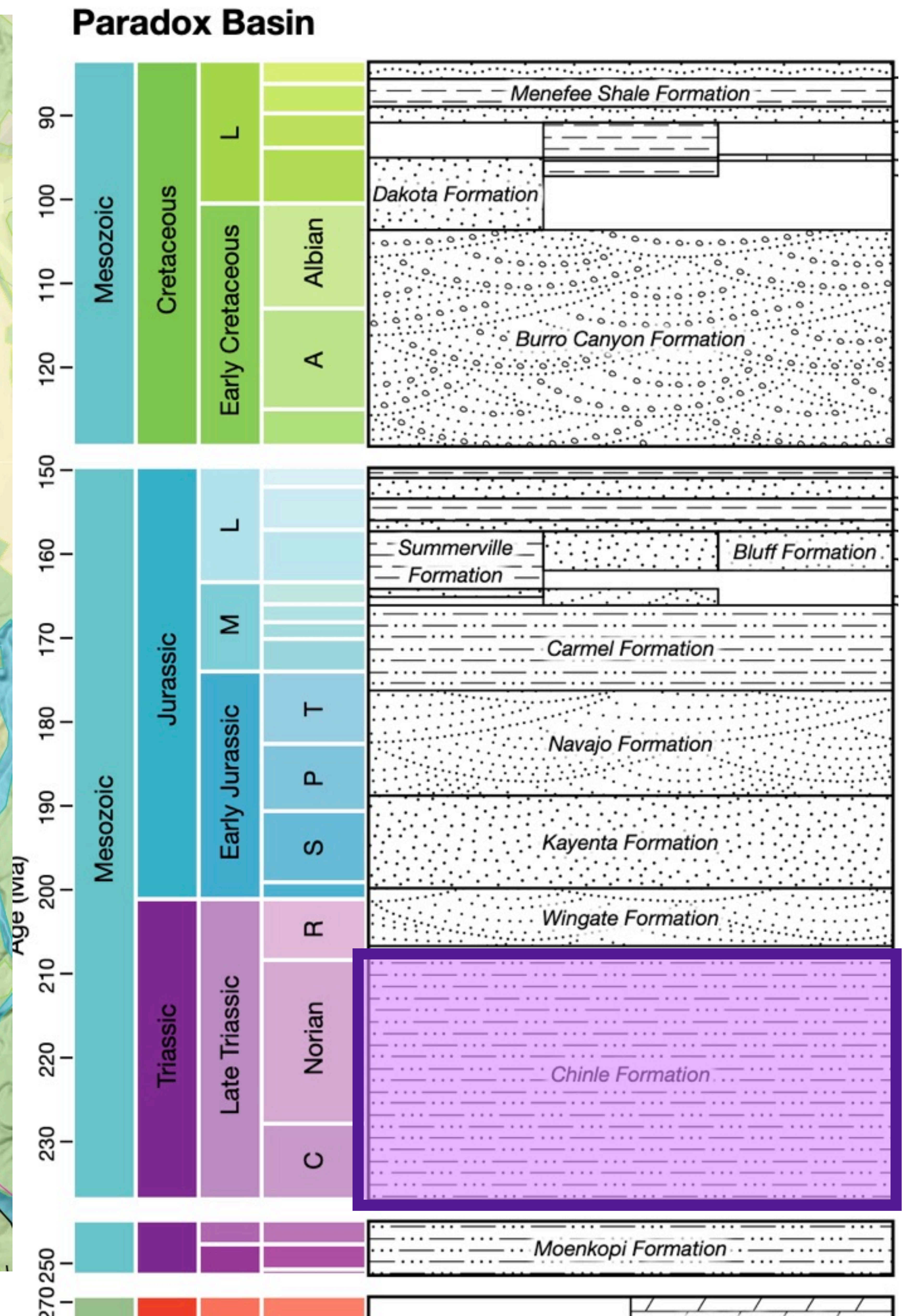
Regional epigenetic dolomitization in the Bonneterre Dolomite (Cambrian), southeastern Missouri


1972). The backreef or nearshore facies consists of interbedded planar stromatolites and mudstones, probably representative of lagoonal, high intertidal, and supratidal environments (Howe, 1968). The stromatolite reef complex is pervasively dolomitized and is the host rock of the Mississippi Valley–type lead and zinc sulfide ores of the Viburnum Trend (Gerdemann and Myers, 1972).

West of the reef complex the Bonneterre grades into an offshore limestone facies of argil-

FEEDBACK AND ASSESSMENT TOOLS BASED ON MACROSTRAT WEB INTERFACES

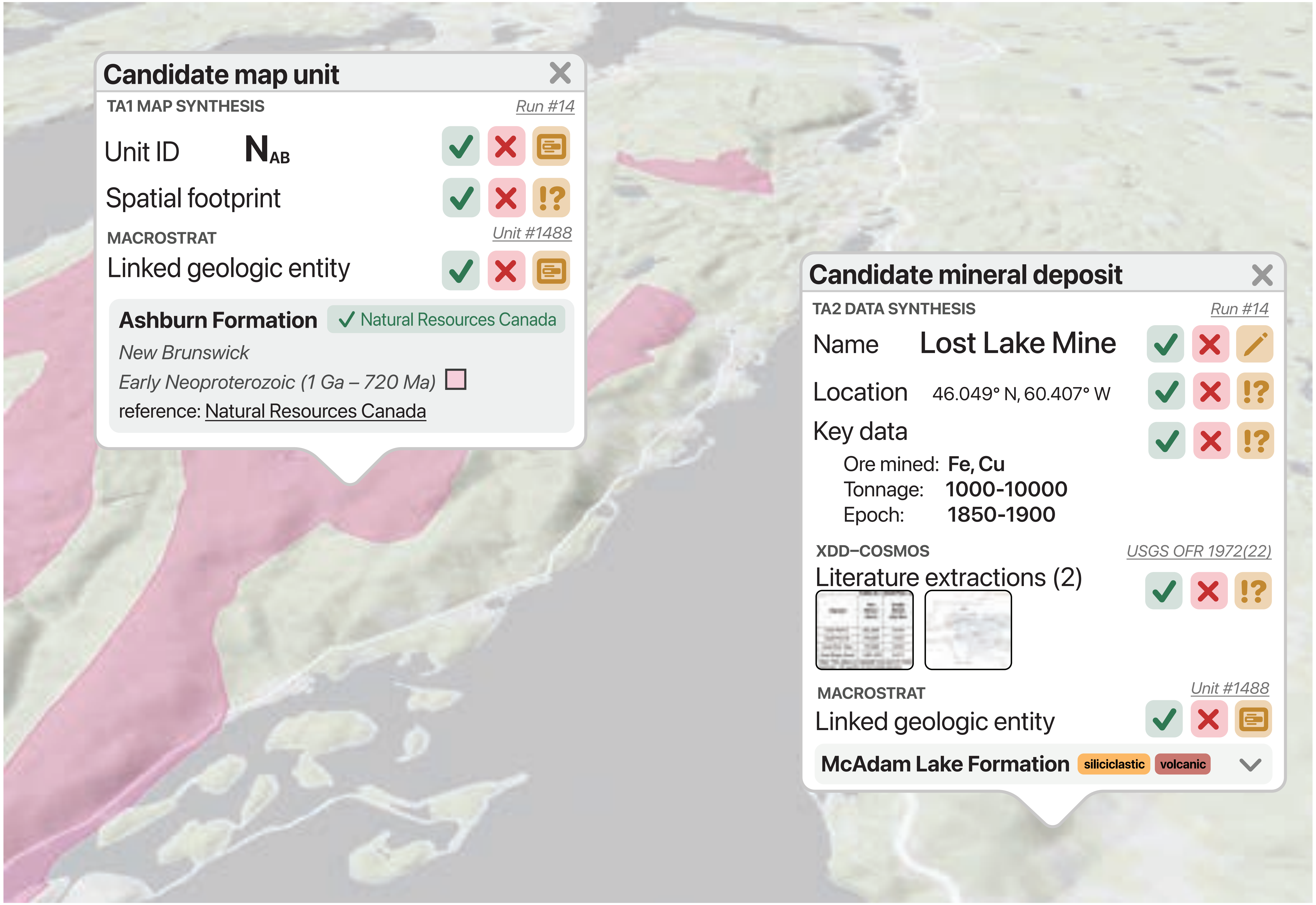




Map assessment widgets

for evaluation of TA1-3 outputs in geologic context

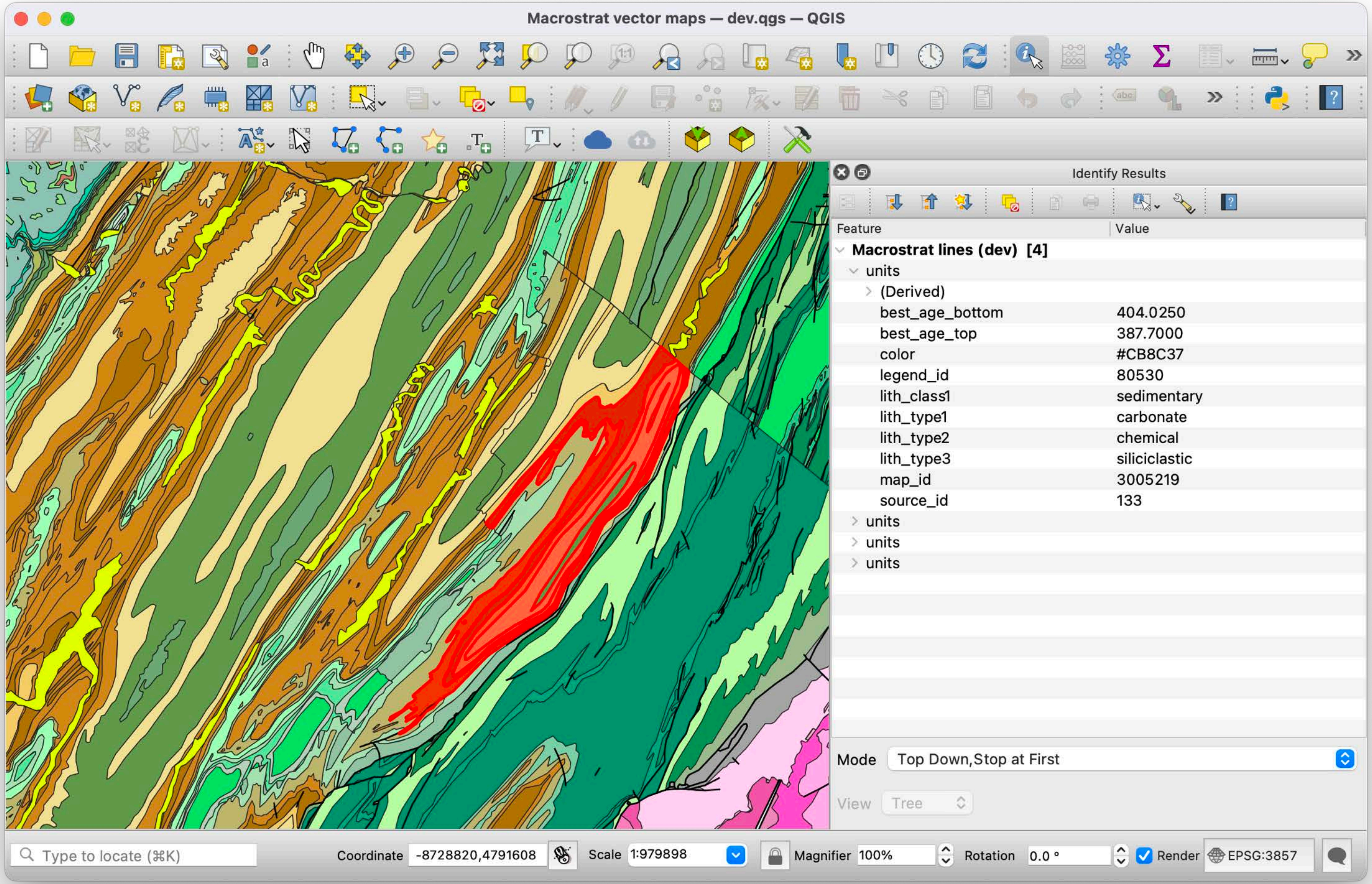
Will sit within Macrostrat web interface and benefit from context



Planned

Expert feedback/correction interfaces: Compatibility with GIS tools

Prototype capability



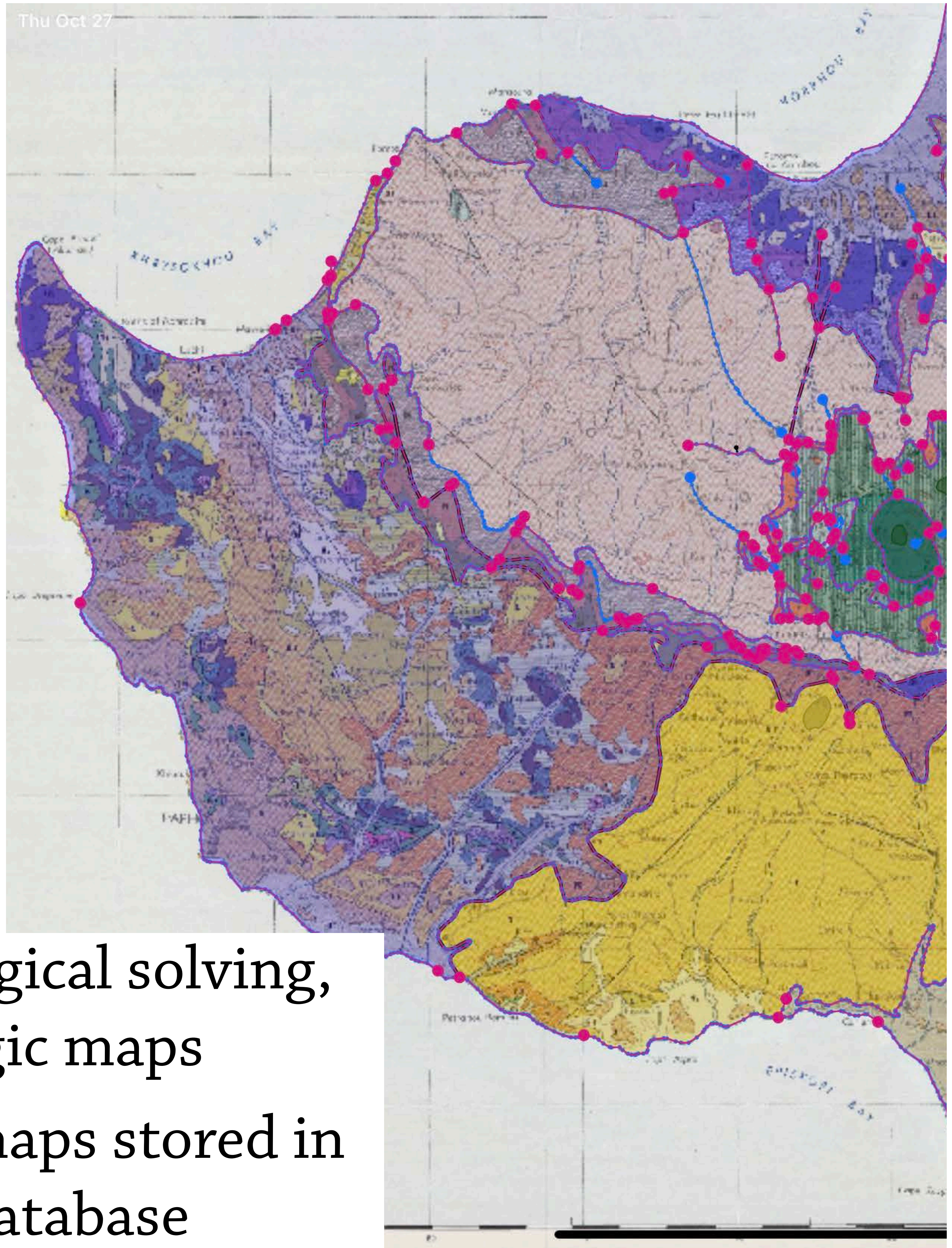
- Macrostrat works well with standard GIS tools (especially QGIS)
- Compatibility will be maintained for CriticalMAAS outputs

Expert feedback/correction interfaces: Rapid geologic map capture/correction

Integrate with Mapboard GIS iPad app

https://mapboard-gis.app

Planned



- Fluid drawing, topological solving, and revision of geologic maps
- Works directly with maps stored in Macrostrat PostGIS database

Expert feedback/correction interfaces: Data entry tools for geologic columns

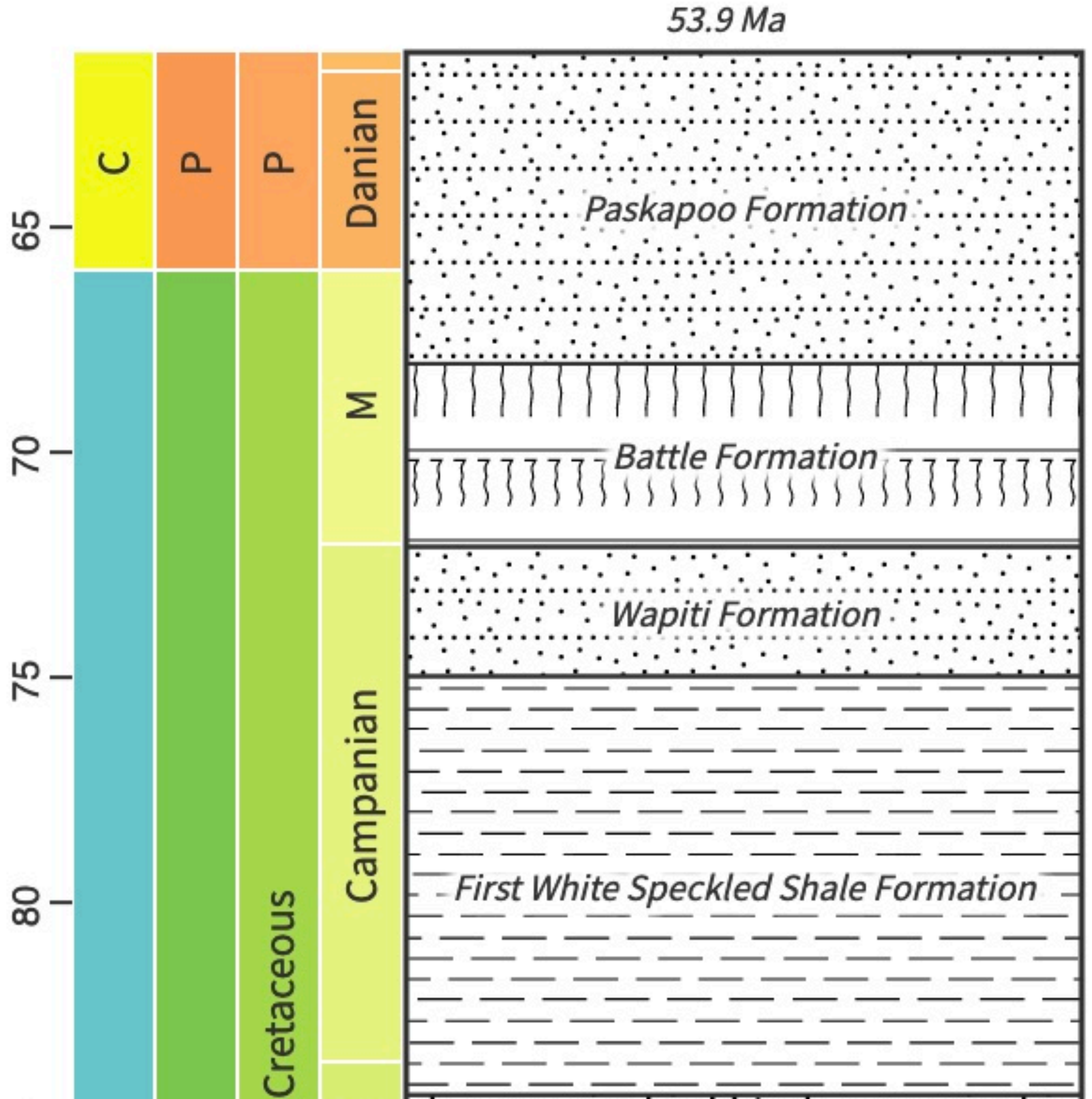
Allows correction of the time-stratigraphic component of geologic maps

Prototype

Projects > Column Groups > **Column**

Sections for Column: Swan Hills

Unit view | Section View | Reorder Units



+ Add Section

Section #9560

ID	Strat Name	Liths	Envs	Interval	Thickness
37335	unnamed	GR... SAND	fluvial indet.	Holocene	0
37334	unnamed	GRAVEL S... TI...	glacial indet.	Pleistocene	0

+ Add Section

Section #9561

ID	Strat Name	Liths	Envs	Interval	Thickness
37333	unnamed	GR... CONGLOMERATE	inferred marine	Messinian - Pliocene	0

+ Add Section

Section #9562

ID	Strat Name	Liths	Envs	Interval	Thickn
37332	Paskapoo Fm	S... SANDSTONE C..	non-marine	Maastrichtian - Paleocene	30
37331	Battle Fm	CLAY	non-marine	Maastrichtian	3
37330	Wapiti Fm	S... SANDSTONE C..	non-marine	Campanian - Maastrichtian	350
37329	First White Speckled Shale Fm	SHALE	inferred marine	Santonian - Campanian	100
37328	Badheart Fm	SANDSTONE IRONSTONE	marine	Santonian	50
37327	First White Speckled Shale Fm	SHALE	inferred marine	Coniacian - Santonian	100

Thanks! Any questions?