DIGITAL MAPPING TECHNIQUES 2014

The following was presented at DMT'14
(June 1-4, 2014 - Delaware Geological Survey,
Newark, DE)

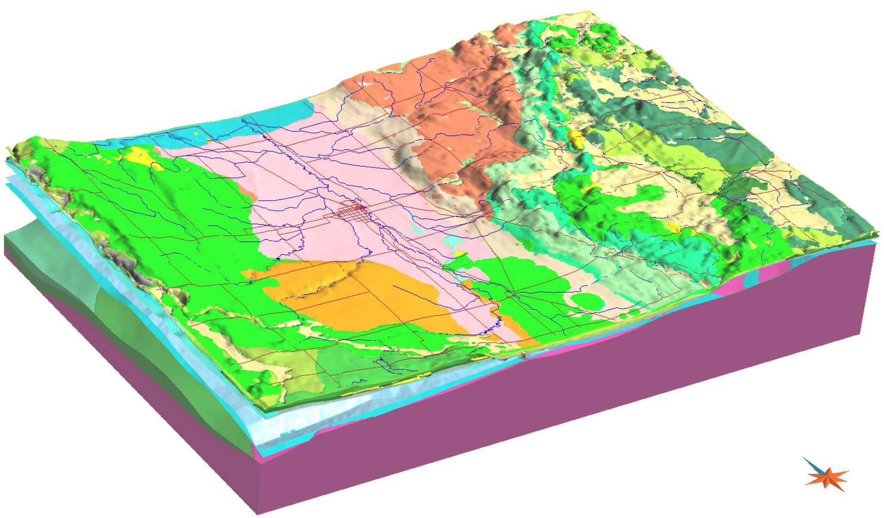
The contents of this document are provisional

See Presentations and Proceedings
from the DMT Meetings (1997-2014)

http://ngmdb.usgs.gov/info/dmt/

Rationale and Methods for Regional 3D Geological Mapping

Harvey Thorleifson, Minnesota Geological Survey



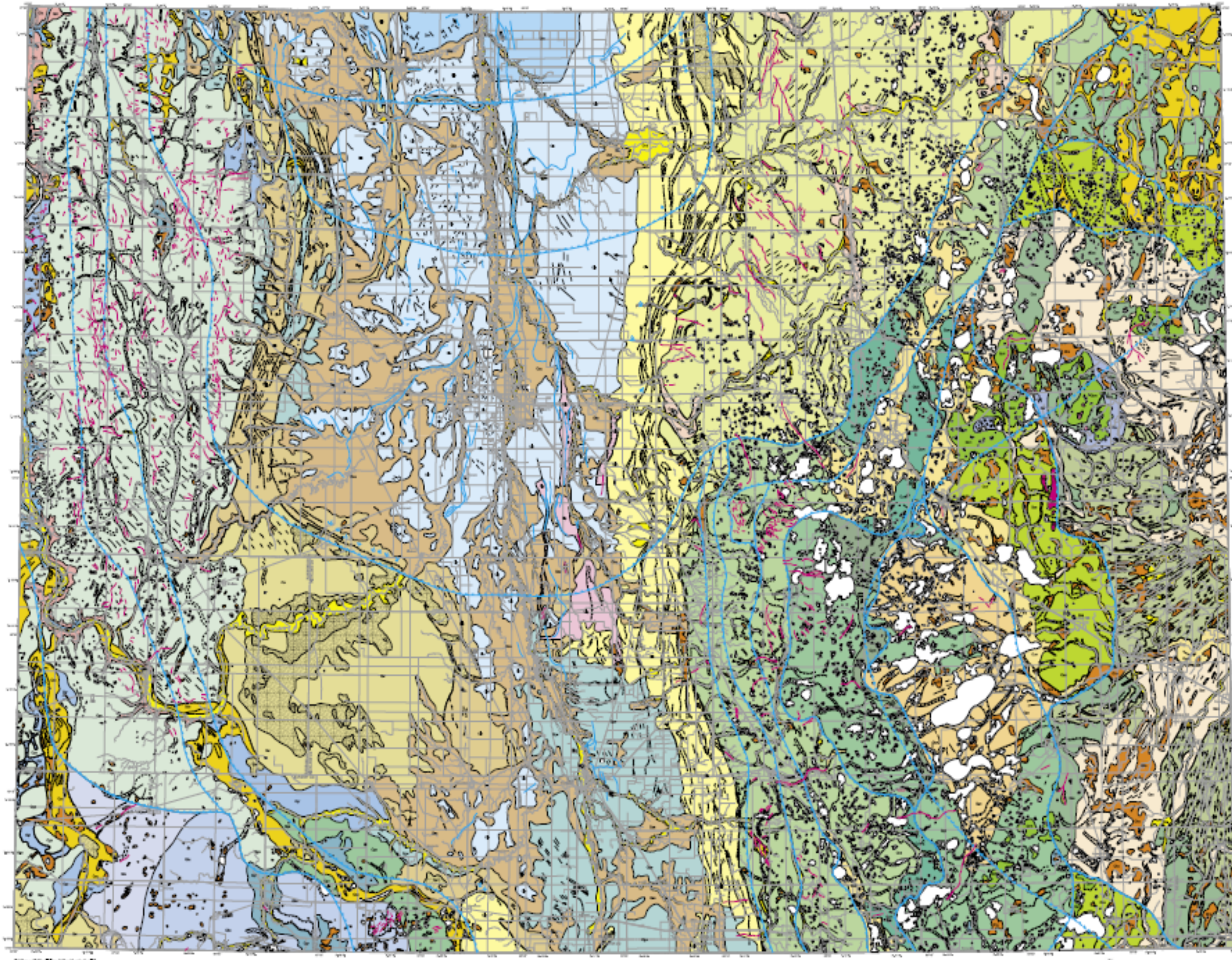
UNIVERSITY OF MINNESOTA
MINNESOTA GEOLOGICAL SURVEY
Harvey Thorleifson, Director

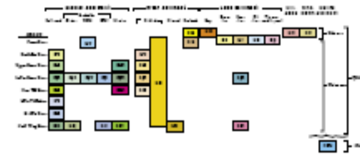
SUPPORTED IN PART BY THE DEPARTMENT OF INTERIOR, BUREAU OF RECLAMATION

DRAFT MAP: FARGO-MOORHEAD AREA
SURFICIAL GEOLOGY UNITS AND
GEOMORPHIC FEATURES

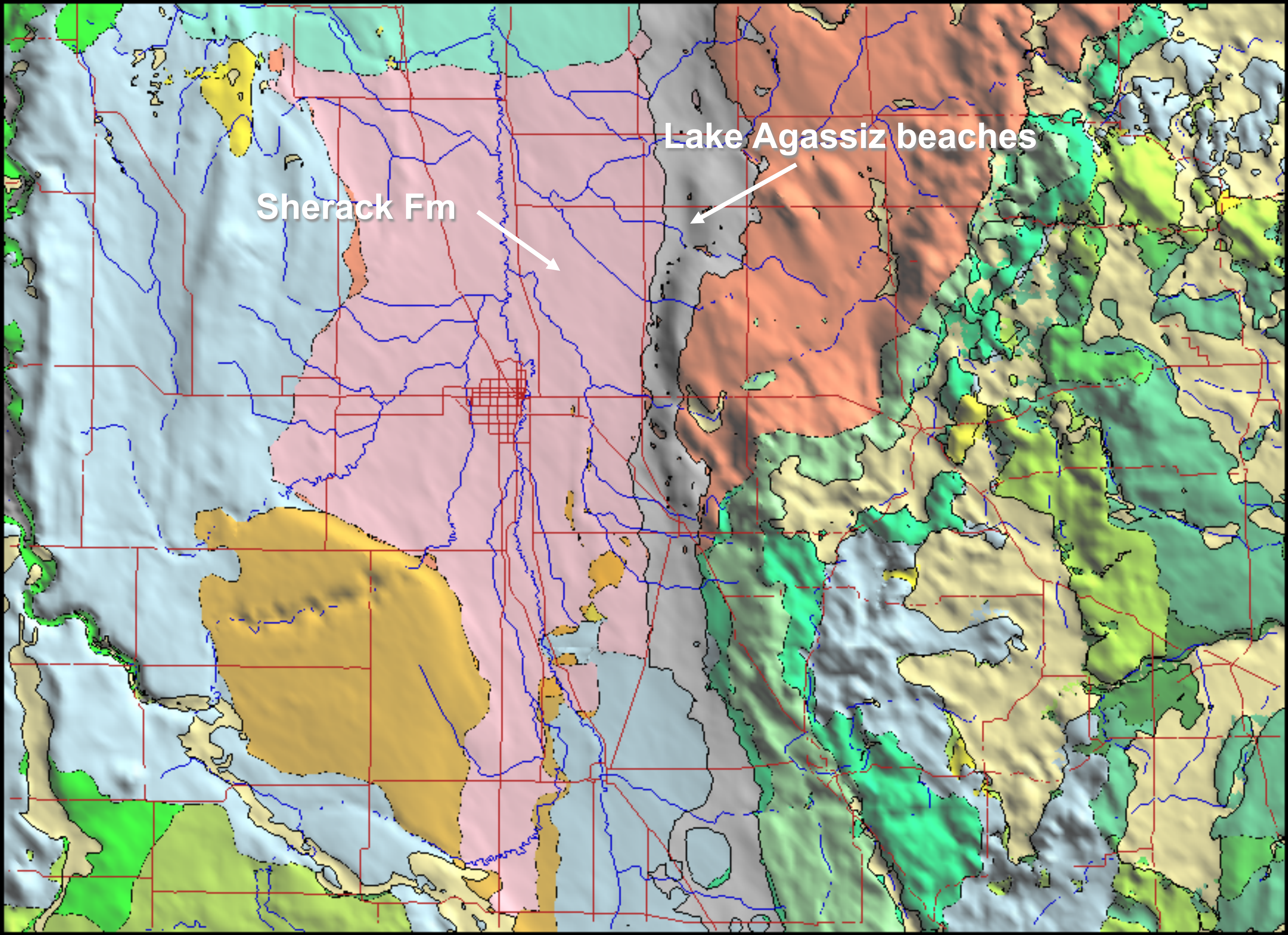
SURFICIAL GEOLOGY OF THE FARGO-MOORHEAD AREA

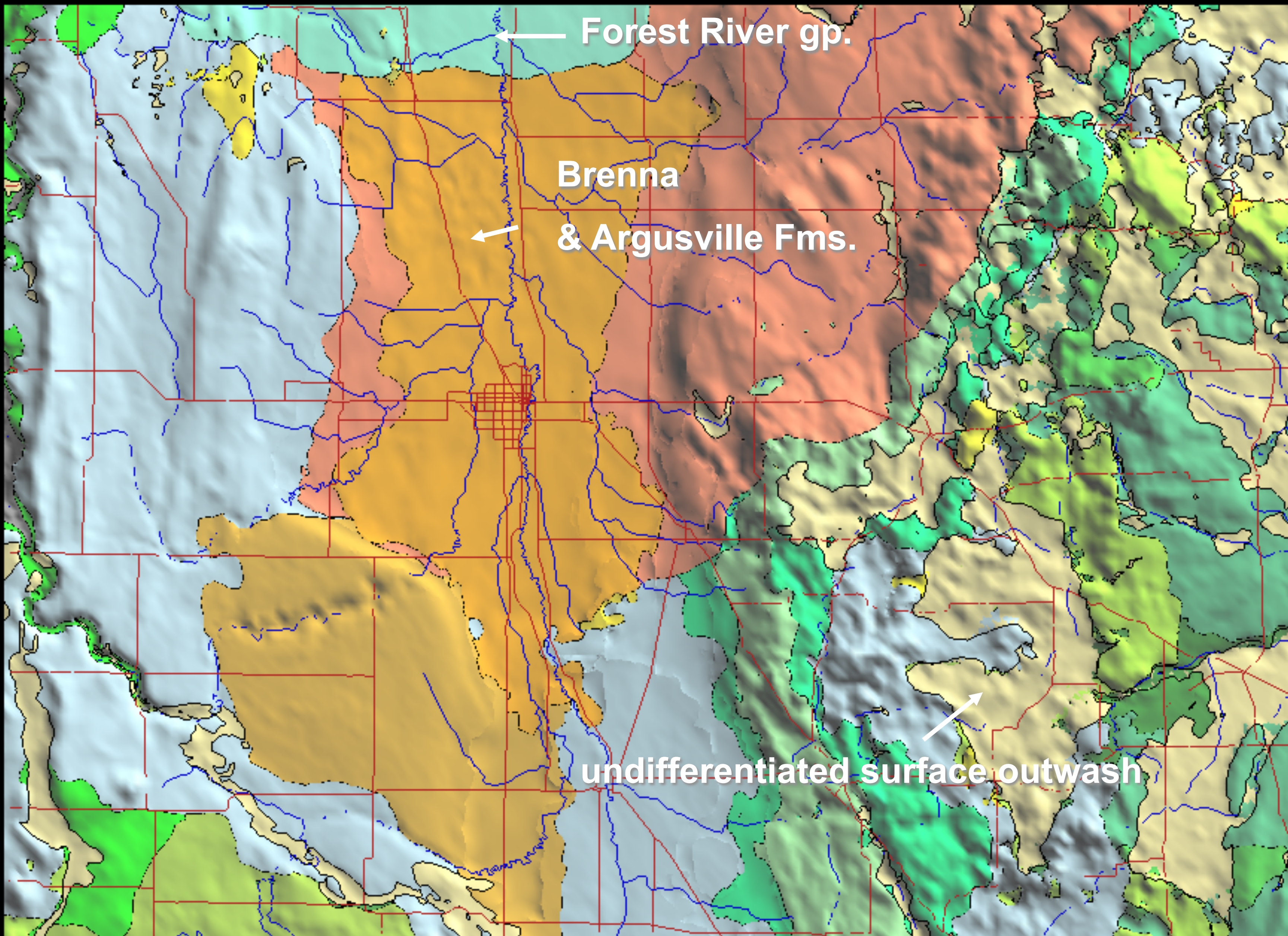
By

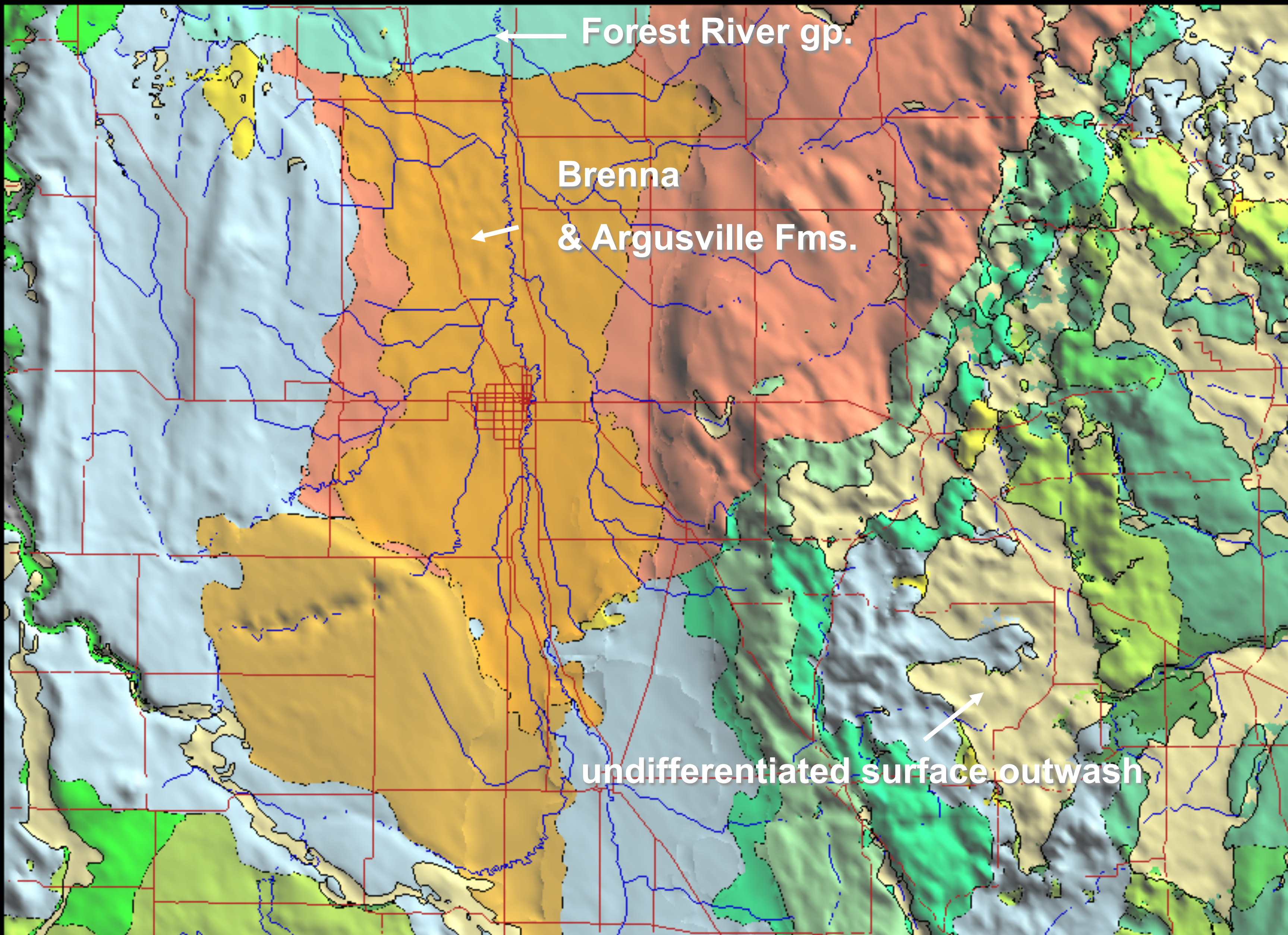




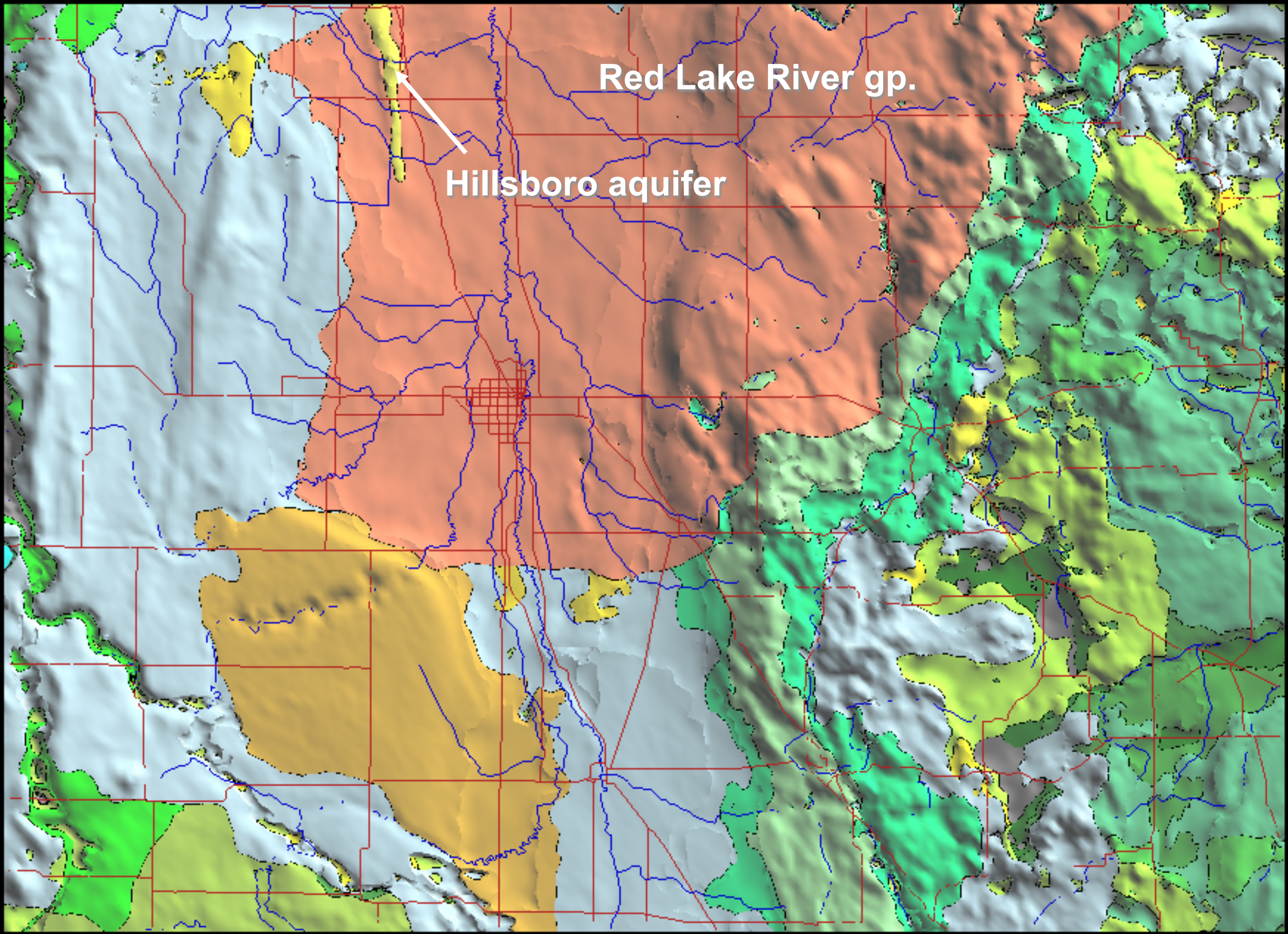
SURFICIAL GEOLOGY OF THE FARGO-MOORHEAD AREA, MINNESOTA AND NORTH DAKOTA

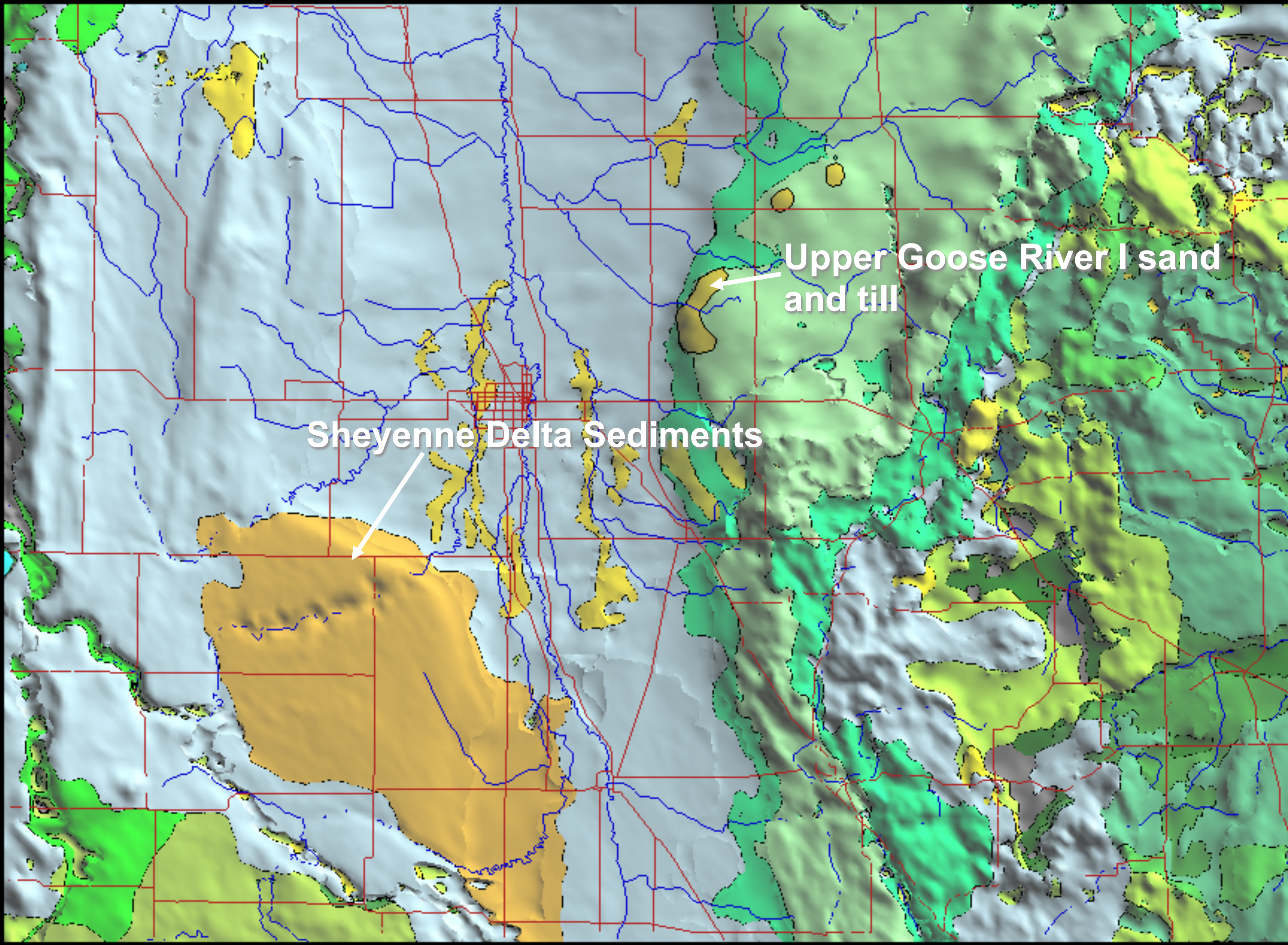

Lake Agassiz beaches
Sherack Fm

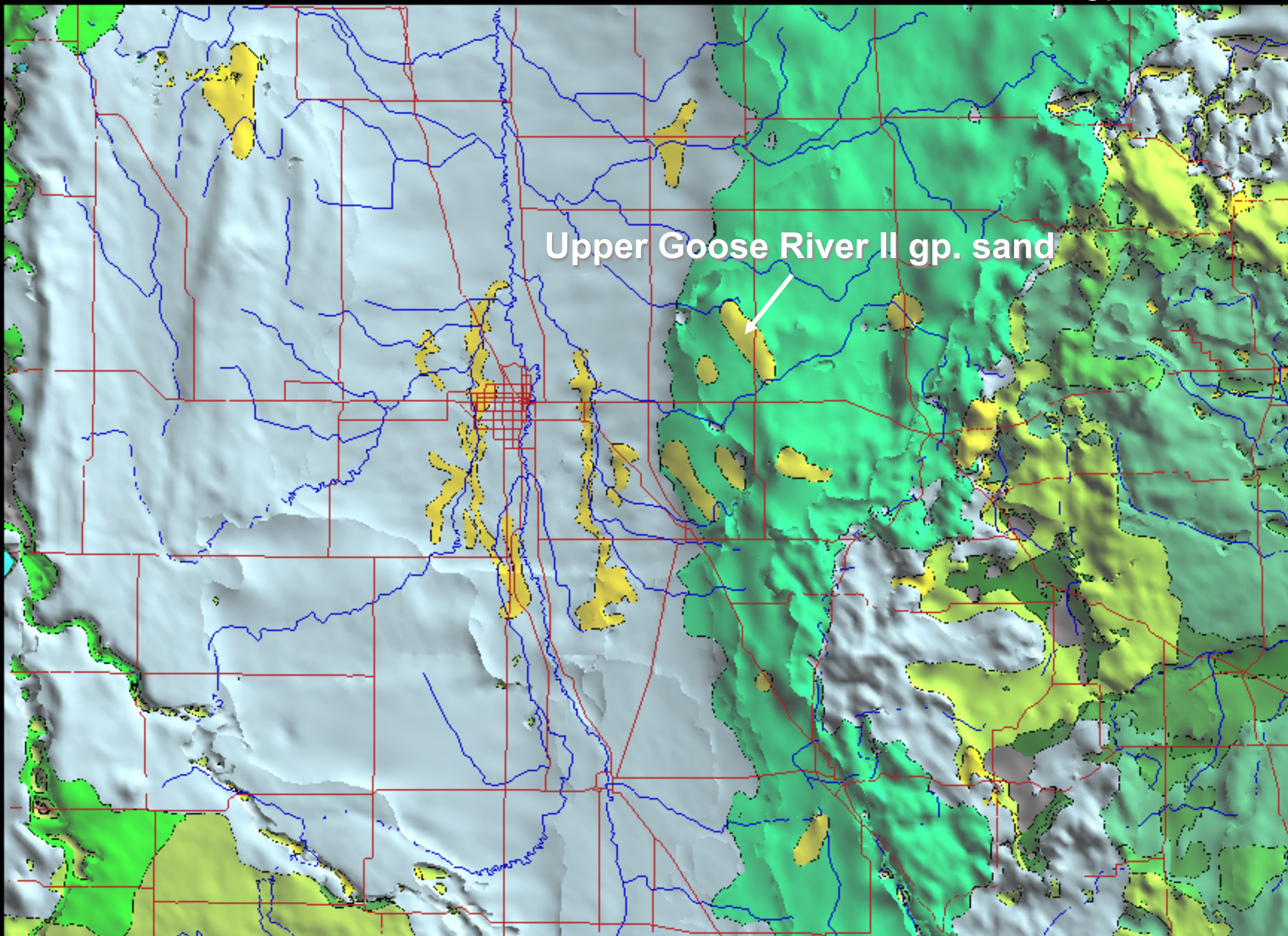

Forest River gp.
Brenna
& Argusville Fms.
undifferentiated surface outwash

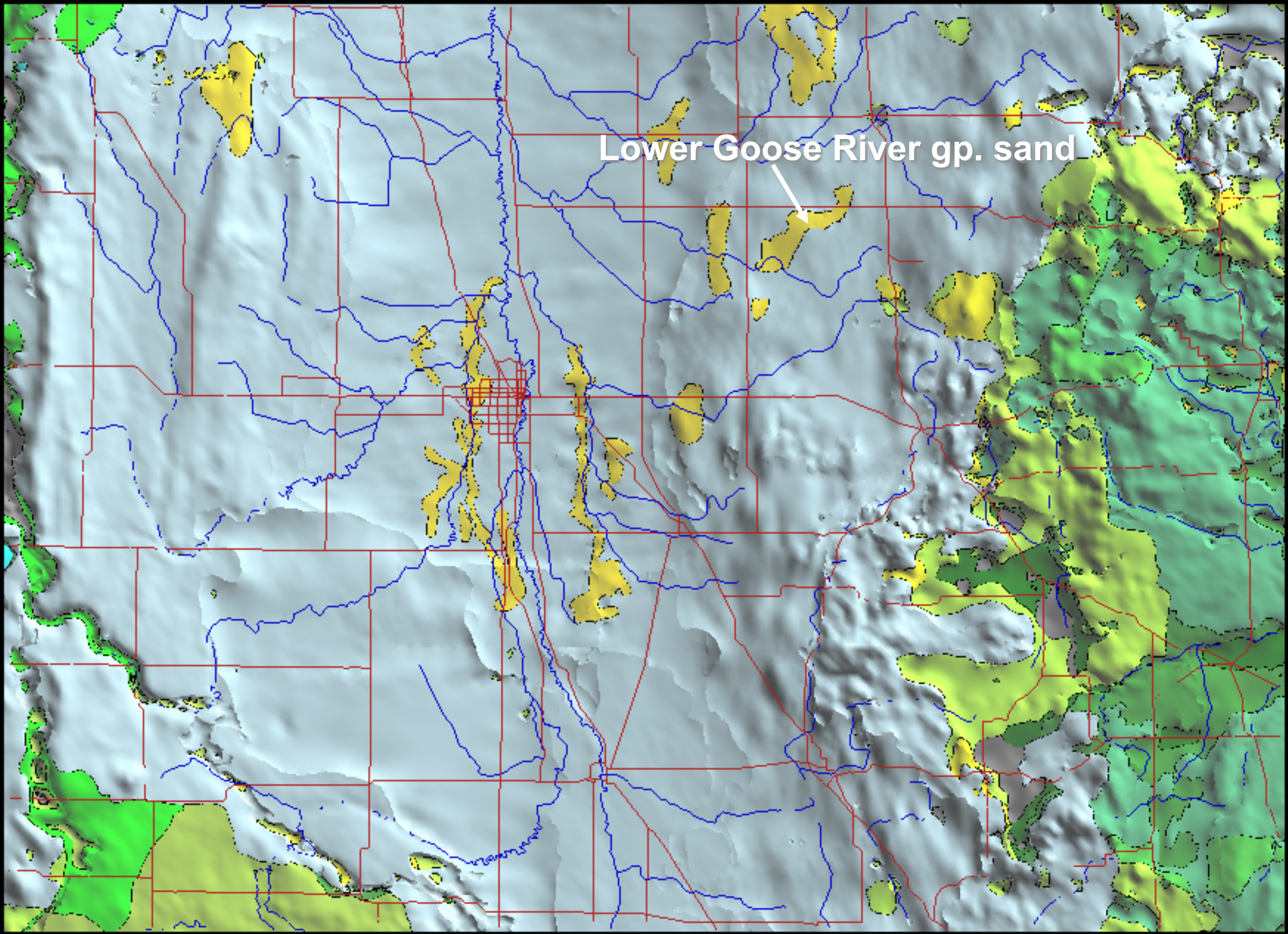


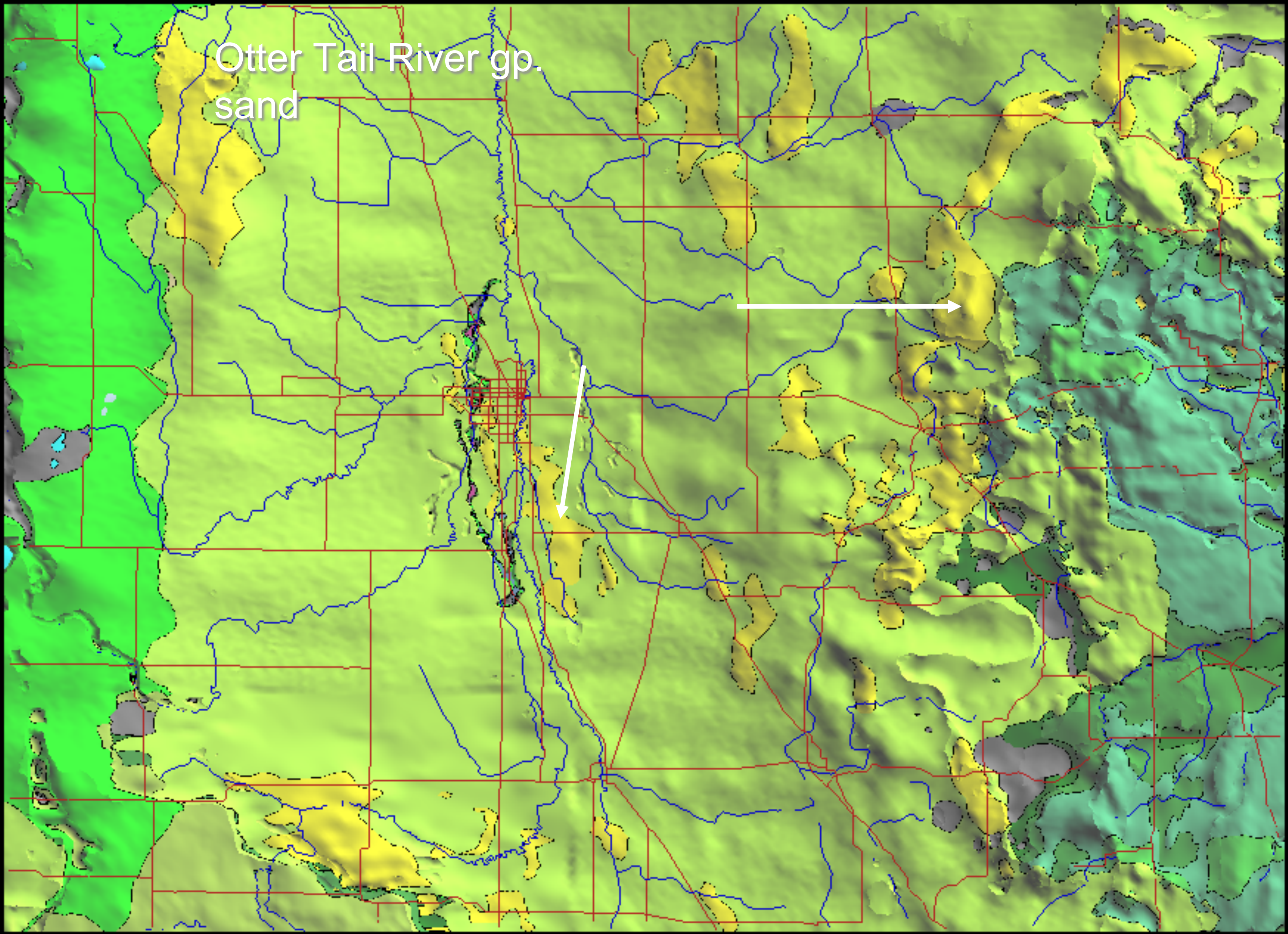
Forest River gp.
Brenna
& Argusville Fms.
undifferentiated surface outwash

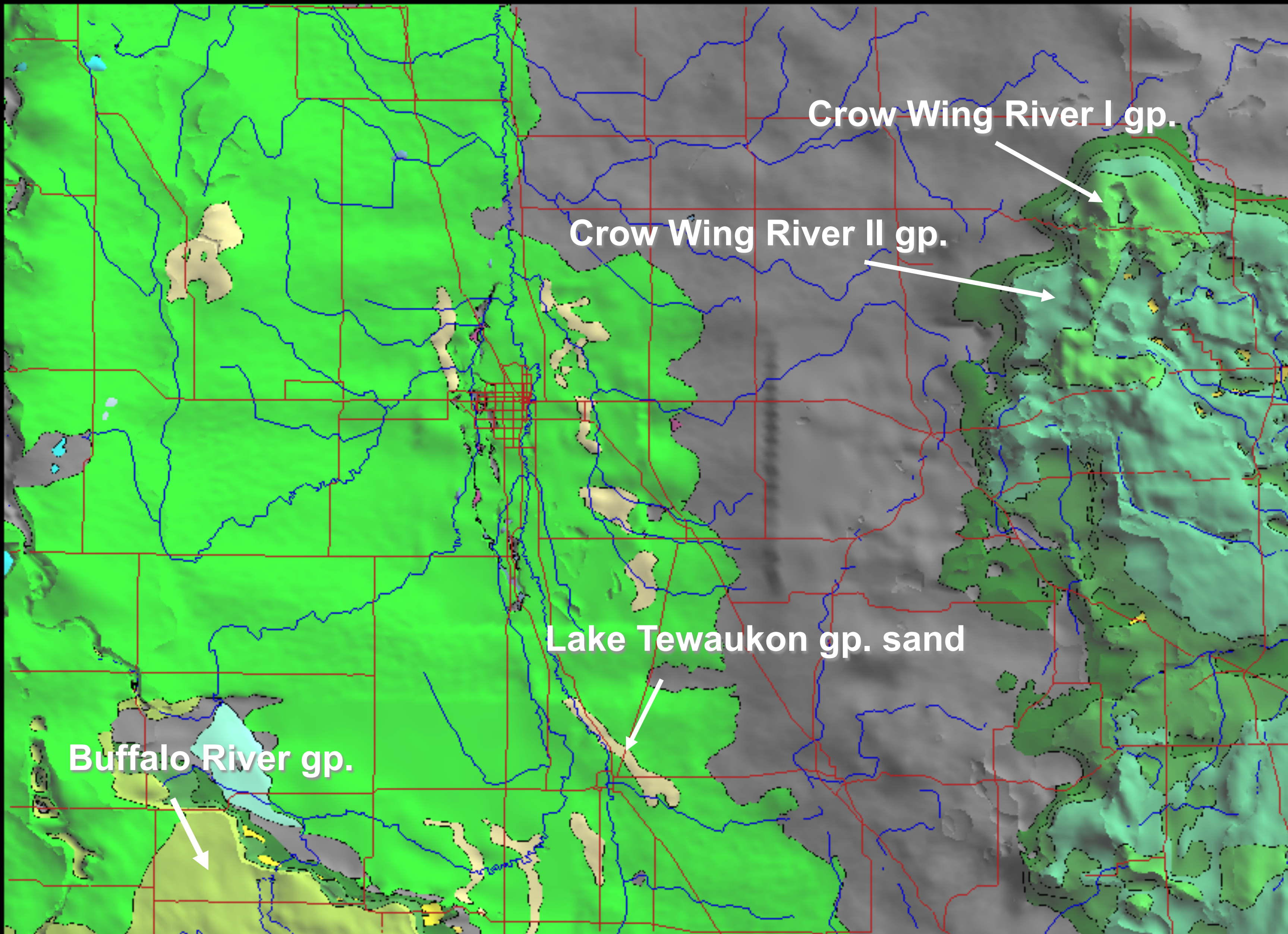

Red Lake River gp.
Hillsboro aquifer

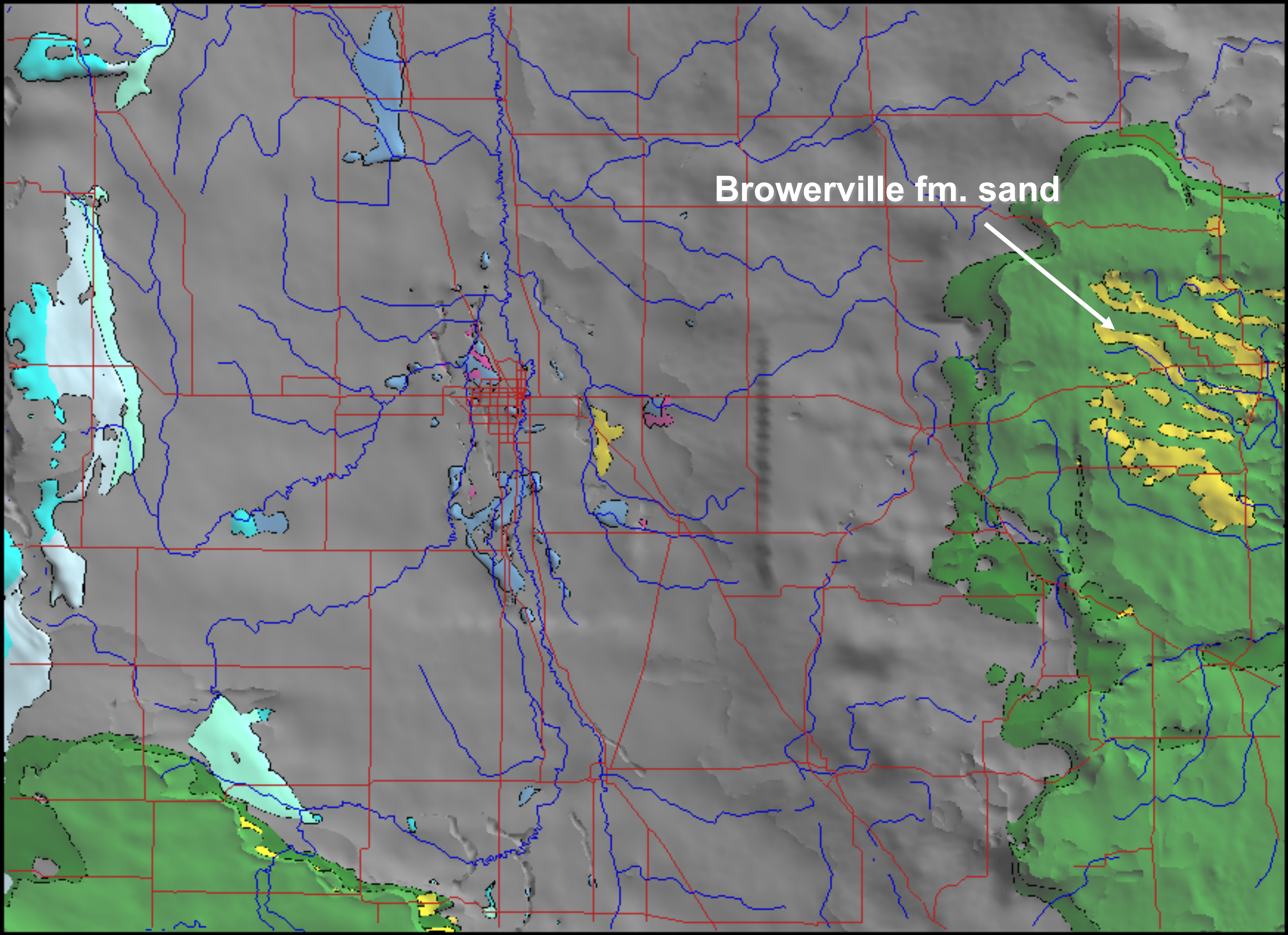

Upper Goose River I sand and till
Sheyenne Delta Sediments

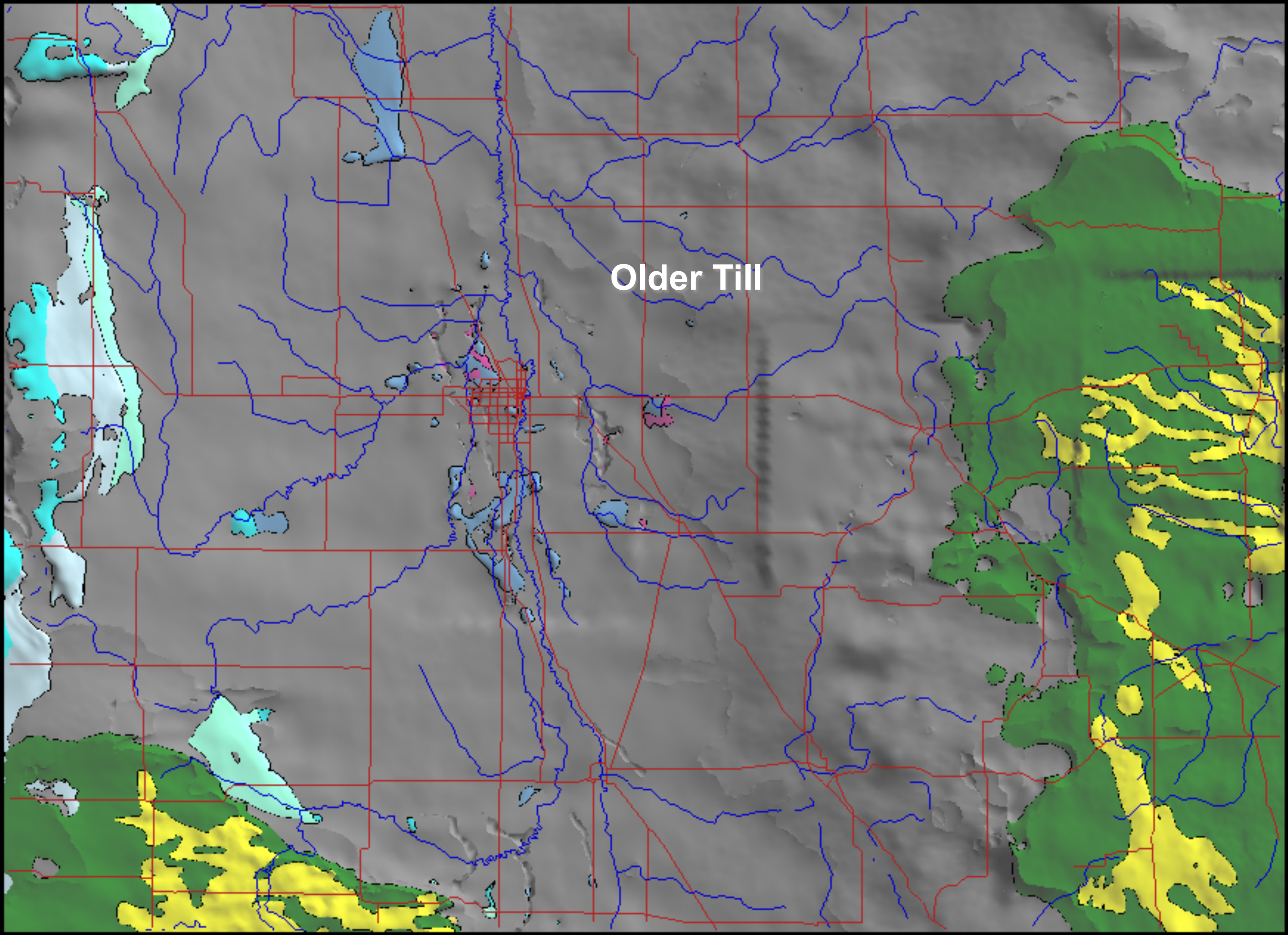

Upper Goose River II gp. sand

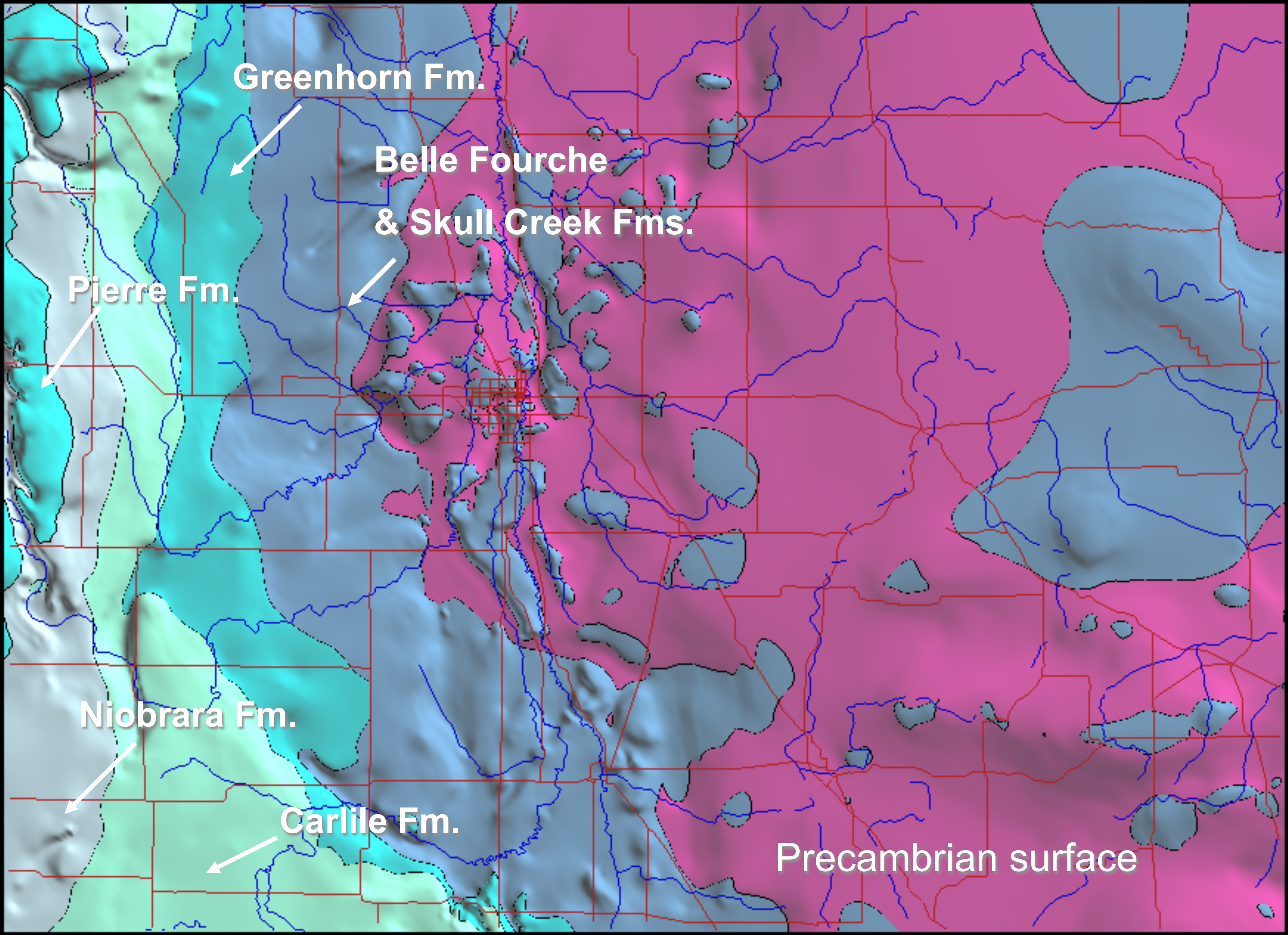

Lower Goose River gp. sand


Otter Tail River gp.
sand

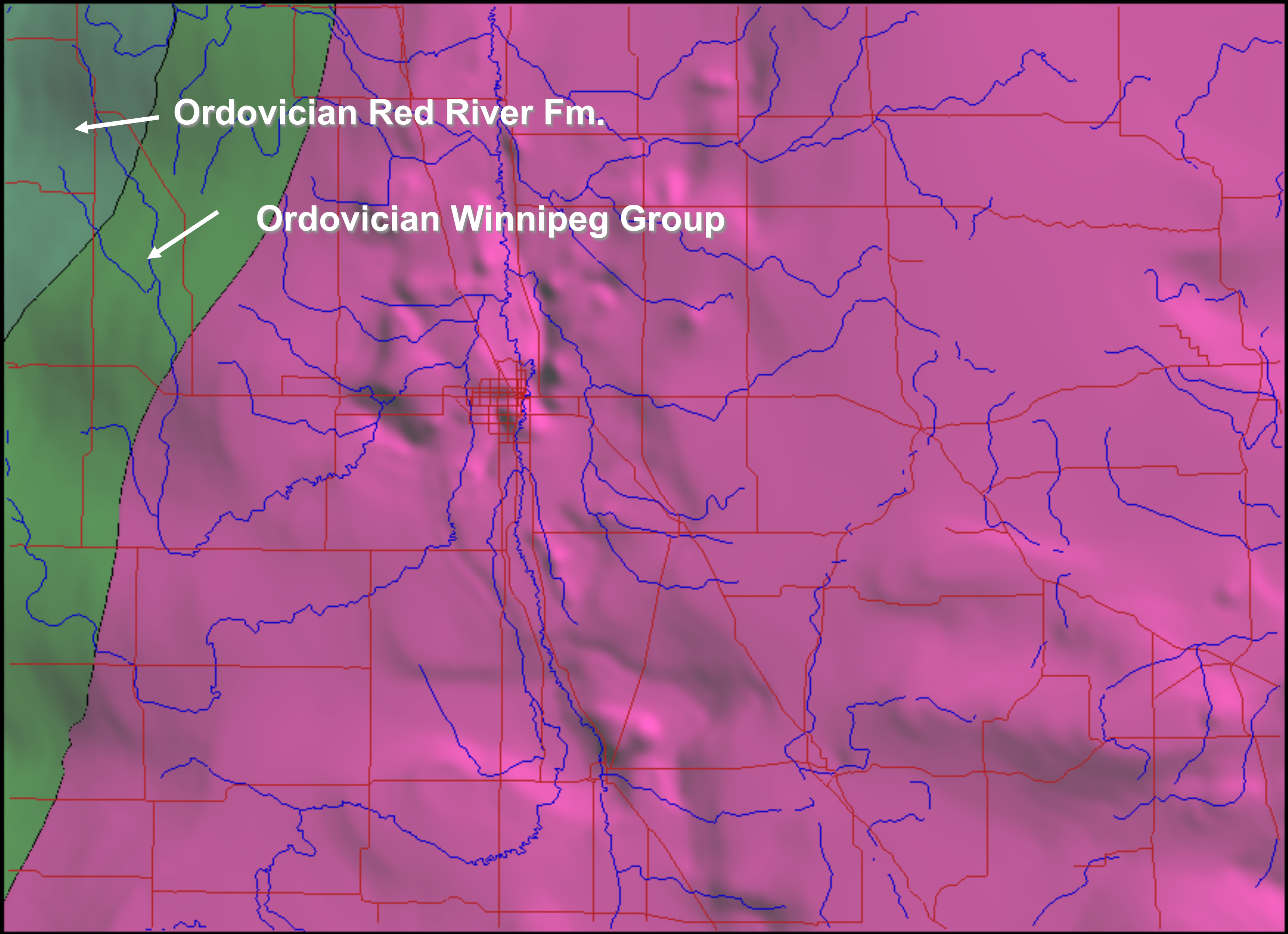

Crow Wing River I gp.
Crow Wing River II gp.
Lake Tewaukon gp. sand
Buffalo River gp.


Browerville fm. sand


Older Till



Bedrock Geologic Map

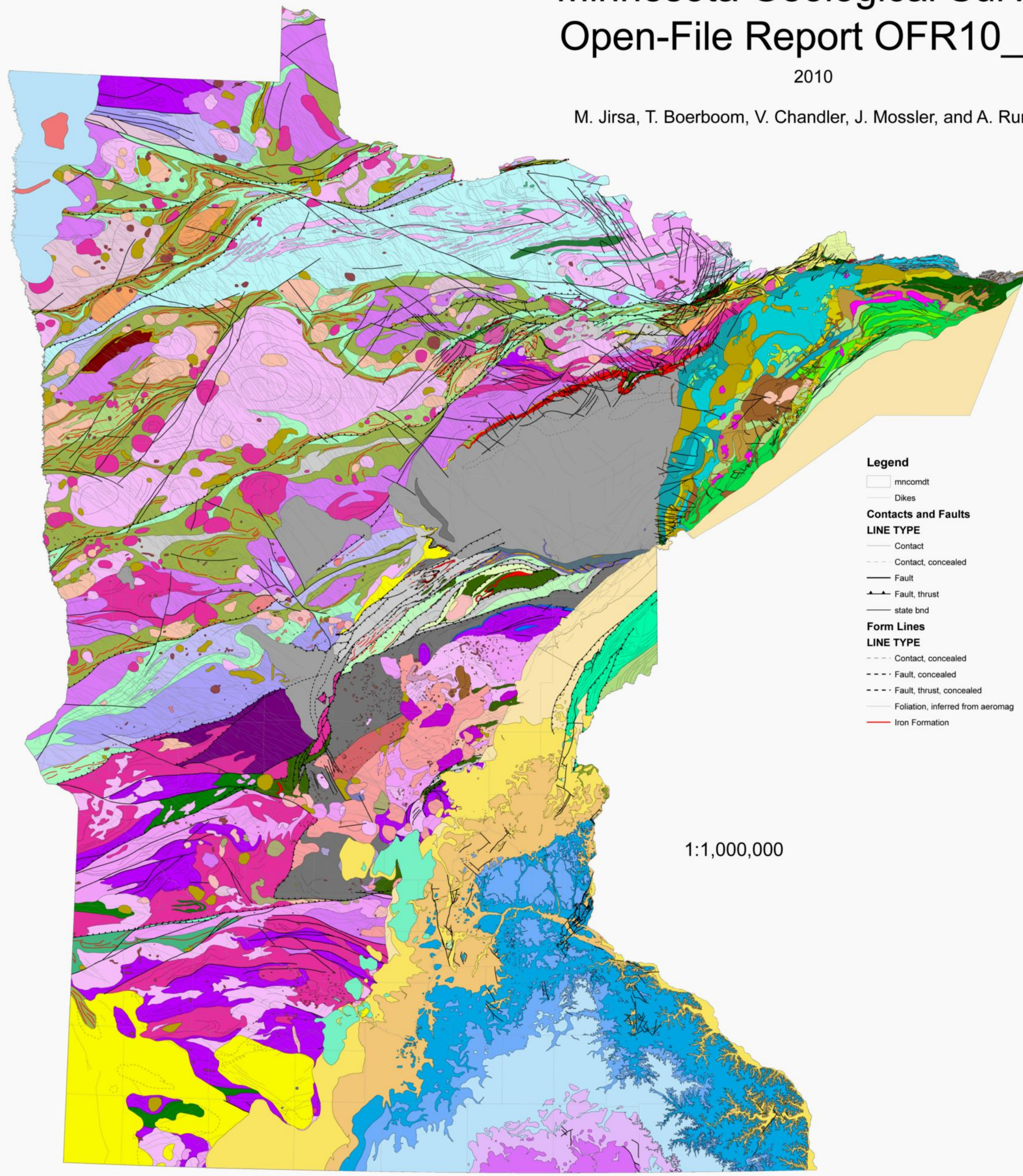

Ordovician Red River Fm.
Ordovician Winnipeg Group

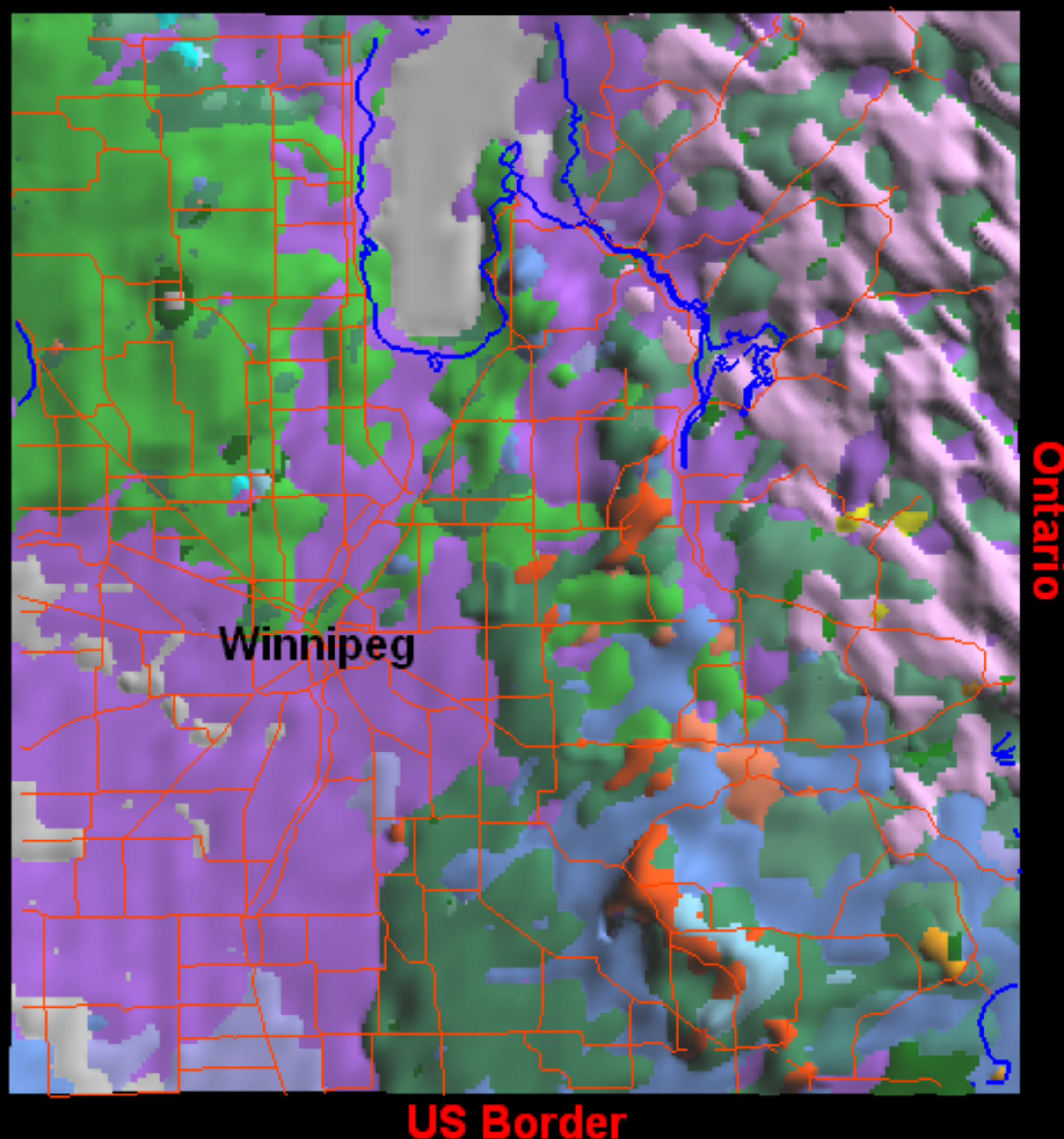
Preliminary Bedrock Geologic Map of Minnesota

Minnesota Geological Survey
Open-File Report OFR10_02

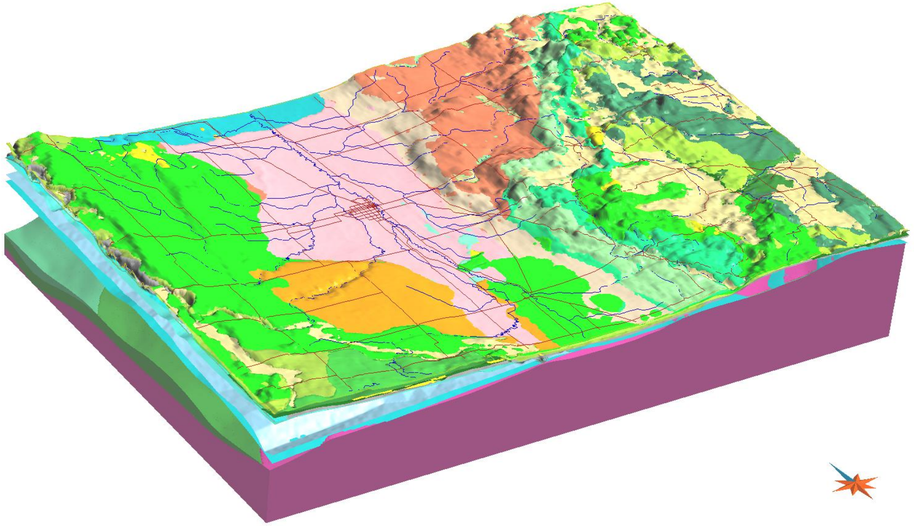
2010

M. Jirsa, T. Boerboom, V. Chandler, J. Mossler, and A. Runkel




Winnipeg
Ontario
US Border

Outline



- Rationale
- Background
- Data compilation
- Data acquisition
- Model construction
- Geostatistics
- Heterogeneity, properties, & uncertainty
- Examples
- Strategies

Rationale

Why do I need to do this?

Role of geological mapping
Current societal needs
How surveys need to respond

Geological mapping

- **Geological mapping is a mature field**
- **Analyses show large positive economic returns**
- **National, multi-resolution, updated 2D mapping is needed**
- **2D maps commonly are accompanied by a cross section**
- **A 3D map can be a sufficient number of cross sections**
- **All principles that apply to plan view apply to section view**
- **3D mapping thus an extension of 2D mapping**
- ***So, if you are wondering about how to make a 3D map, start by thinking about how you make 2D maps***

Societal needs

- groundwater capacity & vulnerability
- anticipation of ground conditions in engineering
- assessment of sedimentary basins re energy, minerals, & waste injections

Needed response

- Jurisdiction-wide, multi-resolution, continuous lateral tracing of the extent, thickness, and properties of lithologic units, to support inference of a 3D matrix of properties such as hydraulic conductivity

- Survey work is evolving to 3D due to data, technology, intensified land use, and escalating societal expectations

Background

What do I need to understand?

Applications

Stratigraphy

3D mapping

Complex geology

Information

Applications

- Qualitative groundwater modeling
- Aquifer sensitivity
- Wellhead protection
- Hydrogeological conceptual modeling
- Hydrogeological property attribution
- Groundwater modeling
- Engineering
- Sedimentary basin assessments

Stratigraphy

- Facies & basin analysis guides all work
- Inferred lithology is needed as a basis for property attribution
- Users need continuous tracing of the extent, thickness, and properties of lithologic units
- Combined allostratigraphic and lithostratigraphic approaches may apply
- Naming should be orderly & parsimonious
- Need to extend our work to hydrostratigraphy

3D mapping

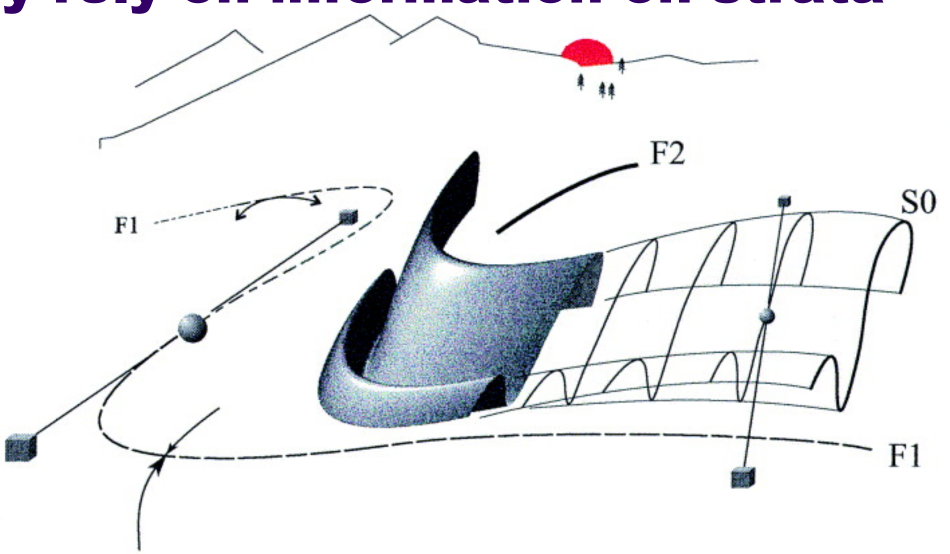
- Structure symbols, x-sections, structure contours, isopachs, stack-units
- Mathers and Zalasiewicz (1985) - regularly spaced, orthogonal cross-sections
- 3D GIS - Vinken, 1988; Turner, 1989; Raper, 1989; Vinken, 1992
- Bonham-Carter (1994) – 2D GIS systems differs from 3D; 3D has x, y, and multiple z values, unlike plan view 2D, or perspective 2.5D methods based on a single z per site
- Houlding (1994) – comprehensive conceptual structure for 3D GIS
- Soller, Price, Berg, & Kempton (1998) worked out a method for regional 3D geological mapping based on geological maps, stratigraphic control points, and large public drillhole databases
- Hydrocarbon industry – e.g. Zakrevsky (2011)
- Applied hydrogeology – e.g. Kresic and Mikszewski (2012)
- 3D workshops since 2001 – Berg, Thorleifson, Russell

Complex geology

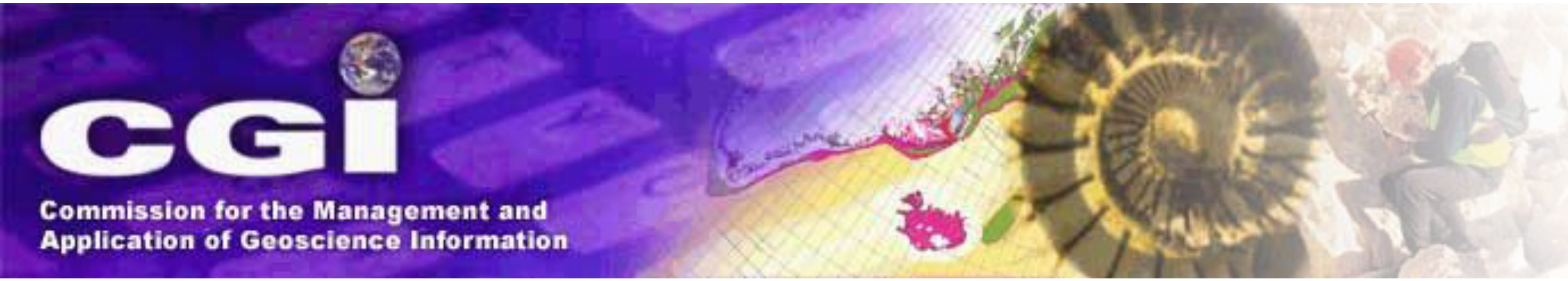
- Regional 3D mapping applies to sediments and sedimentary rocks no more deformed than subsidence and normal faulting

- Complexly deformed strata, as well as igneous and metamorphic rocks, can not readily be mapped on a regional 3D basis

- Nevertheless, many pressing societal issues related to water, engineering, and energy rely on information on strata readily mappable in 3D



Information



Data compilation

What do I need to compile?

Topography

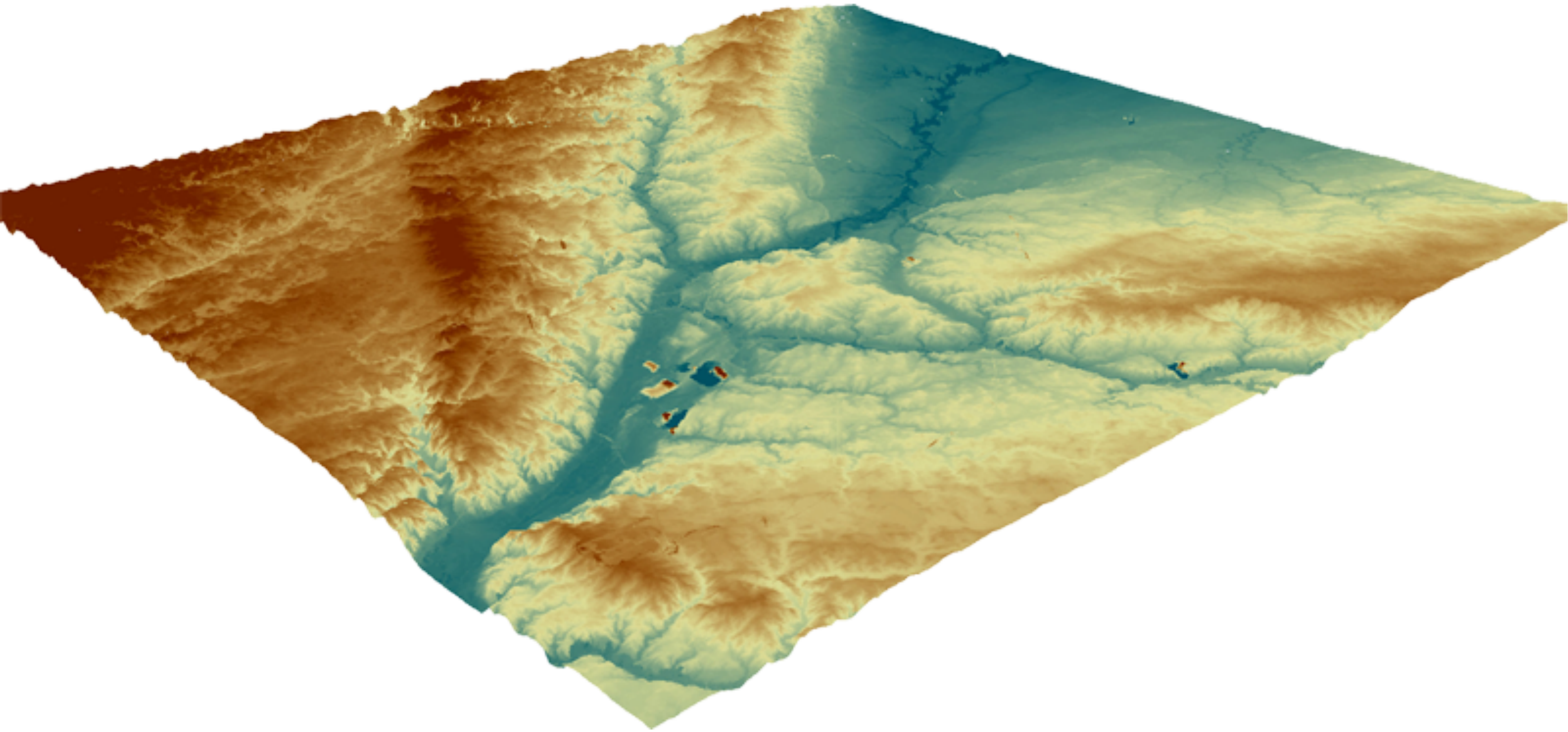
Bathymetry

Soil mapping

2D geological mapping

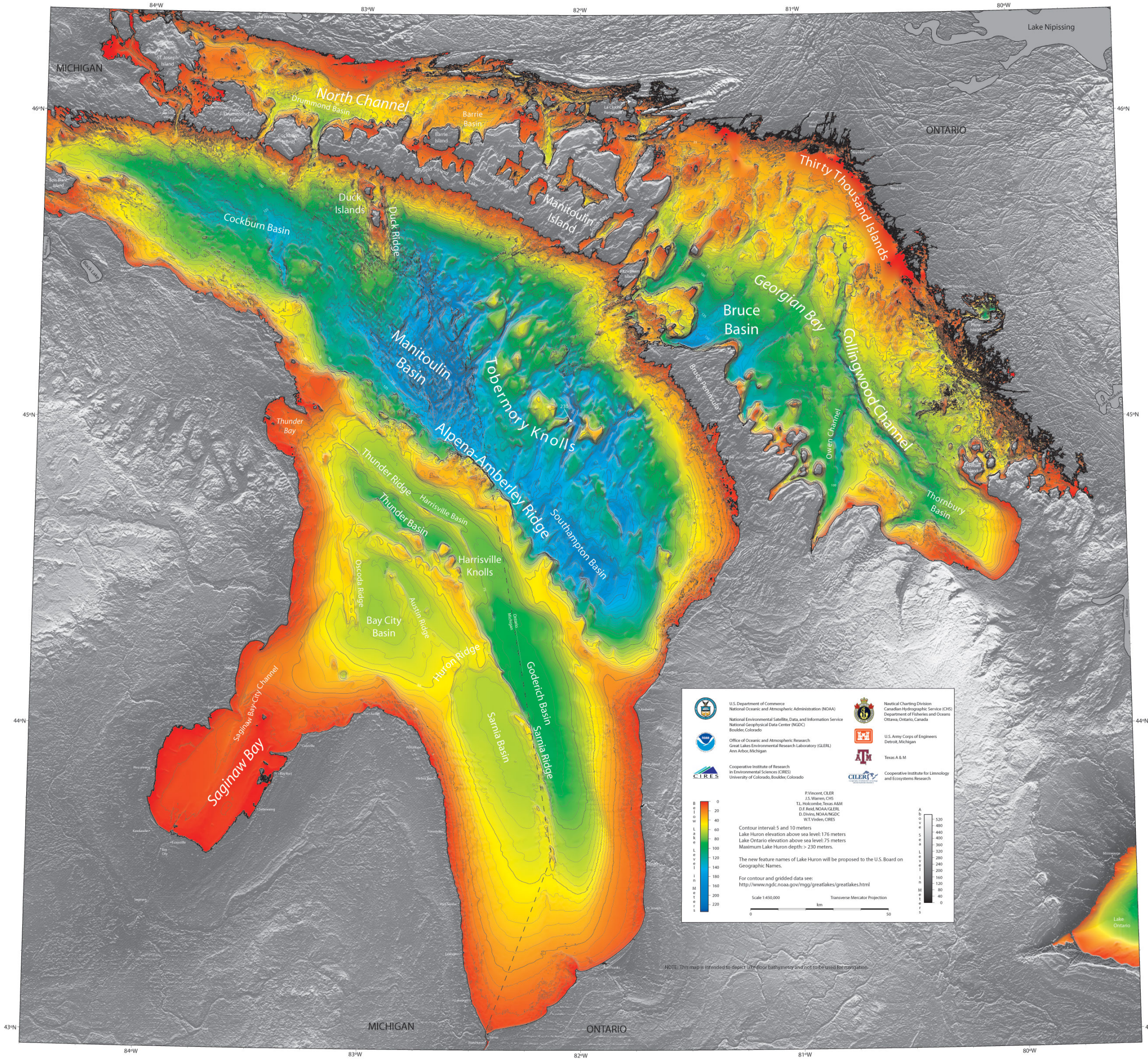
Drillhole data

Topography

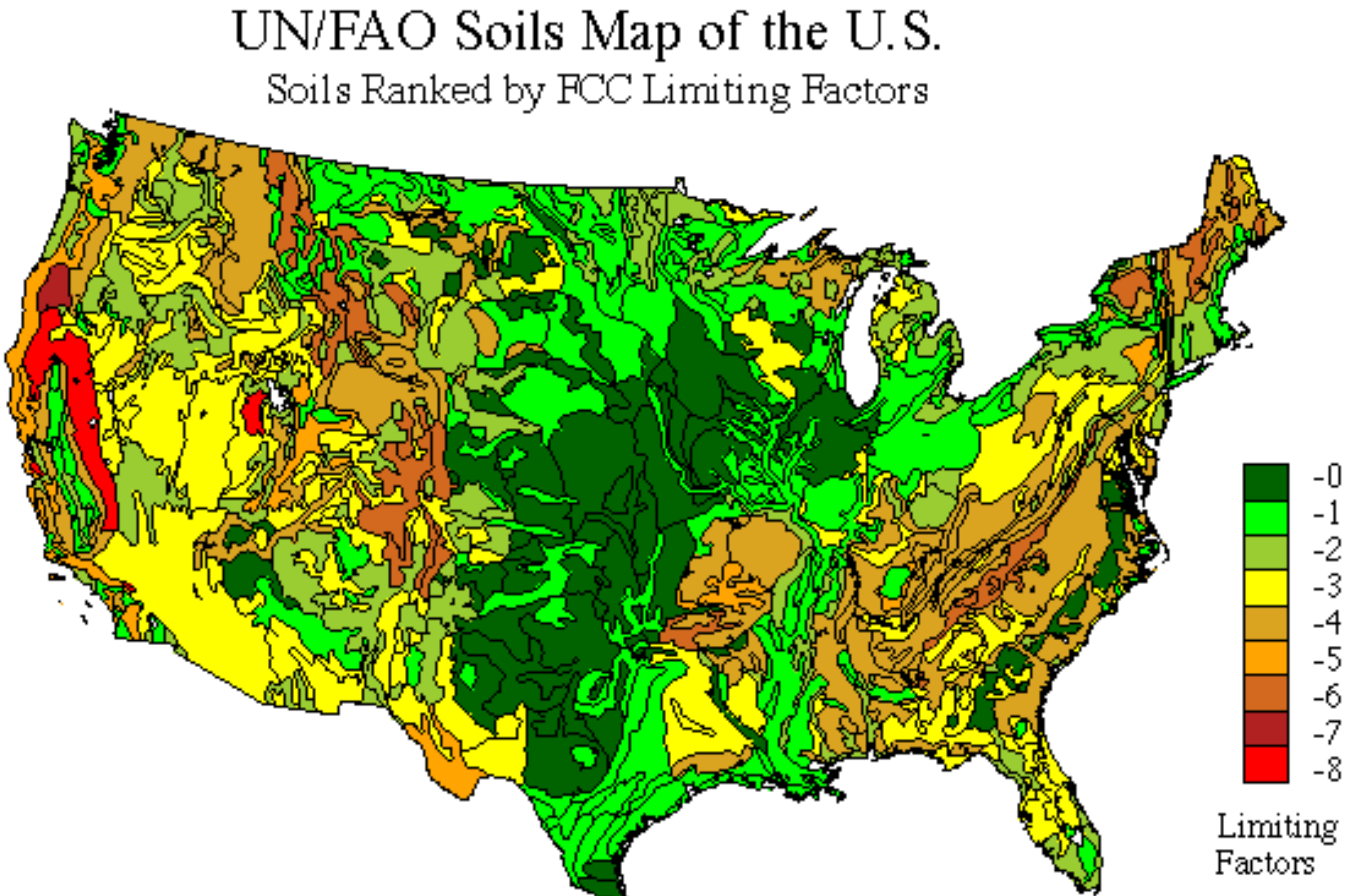


Bathymetry

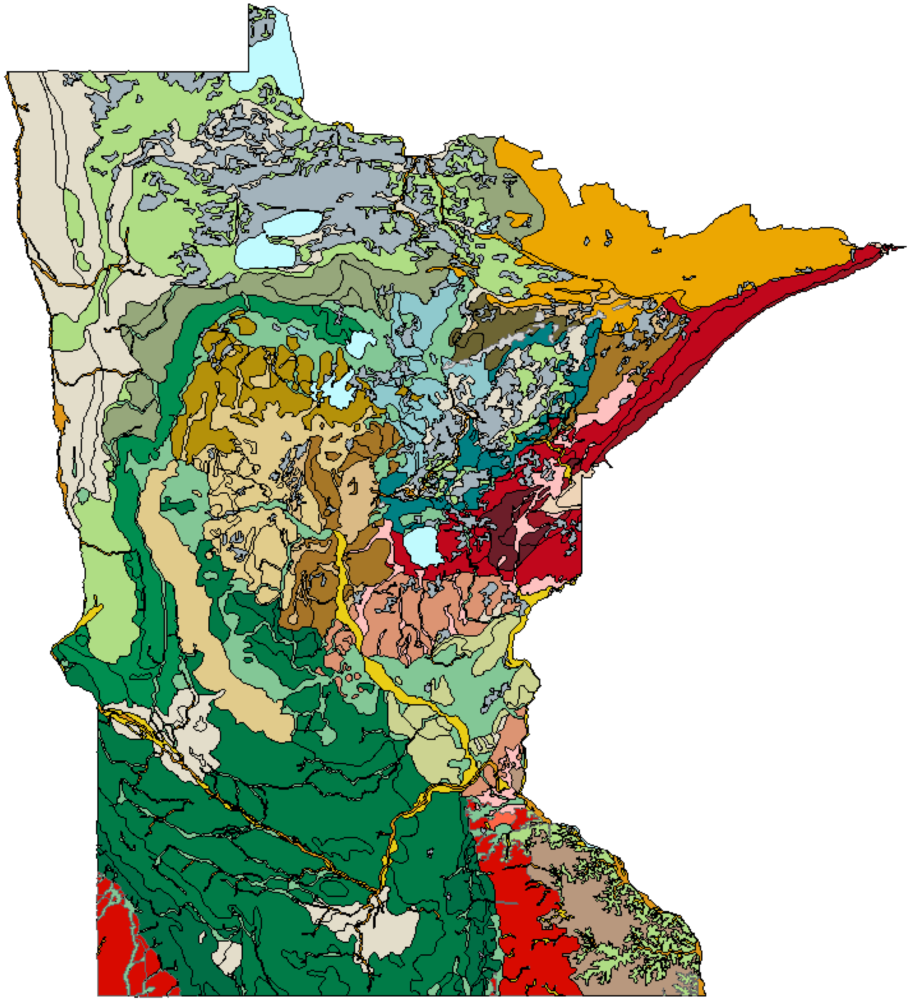
Bathymetry of Lake Huron with Topography

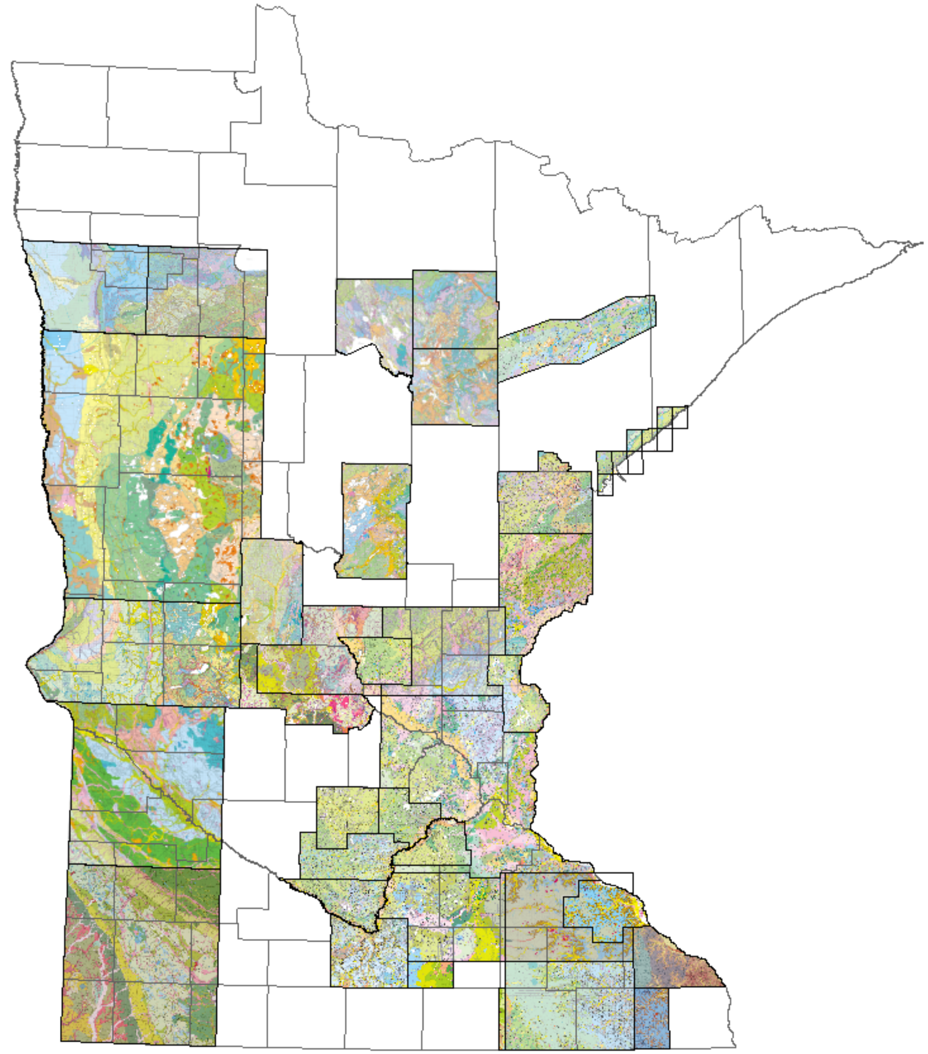


Soil mapping



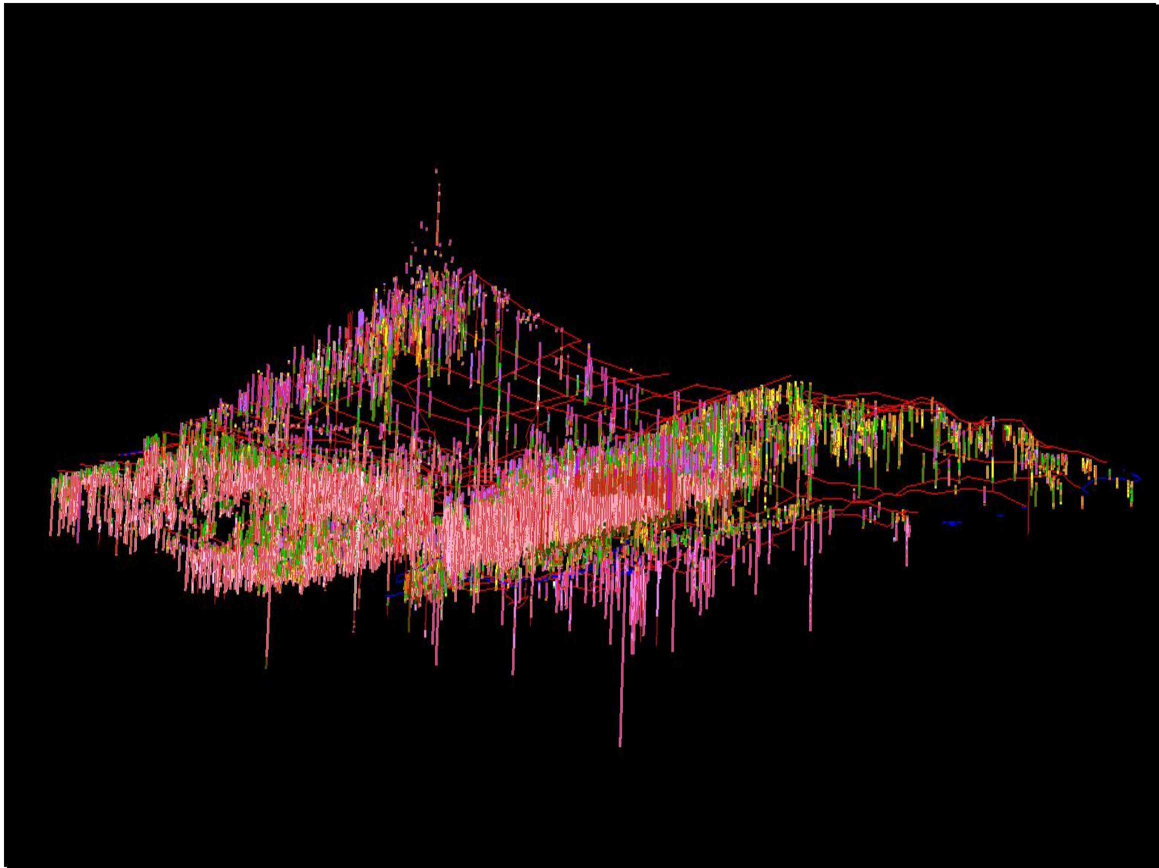
Plan view geological mapping





Drillhole data

- acquire
- digitize
- georeference
- categorize



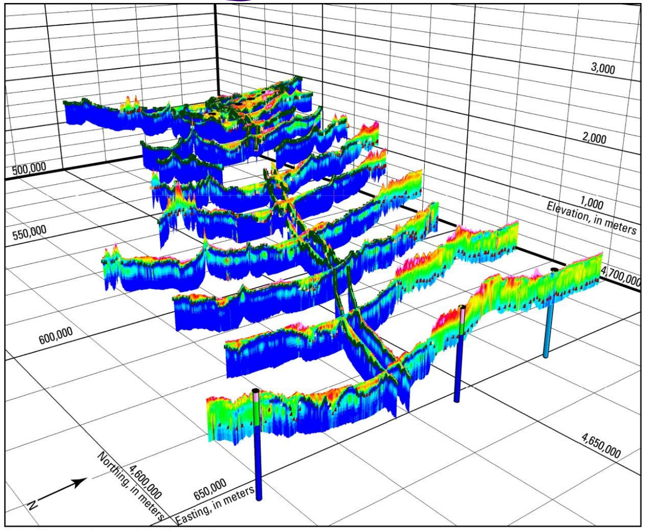
Data acquisition

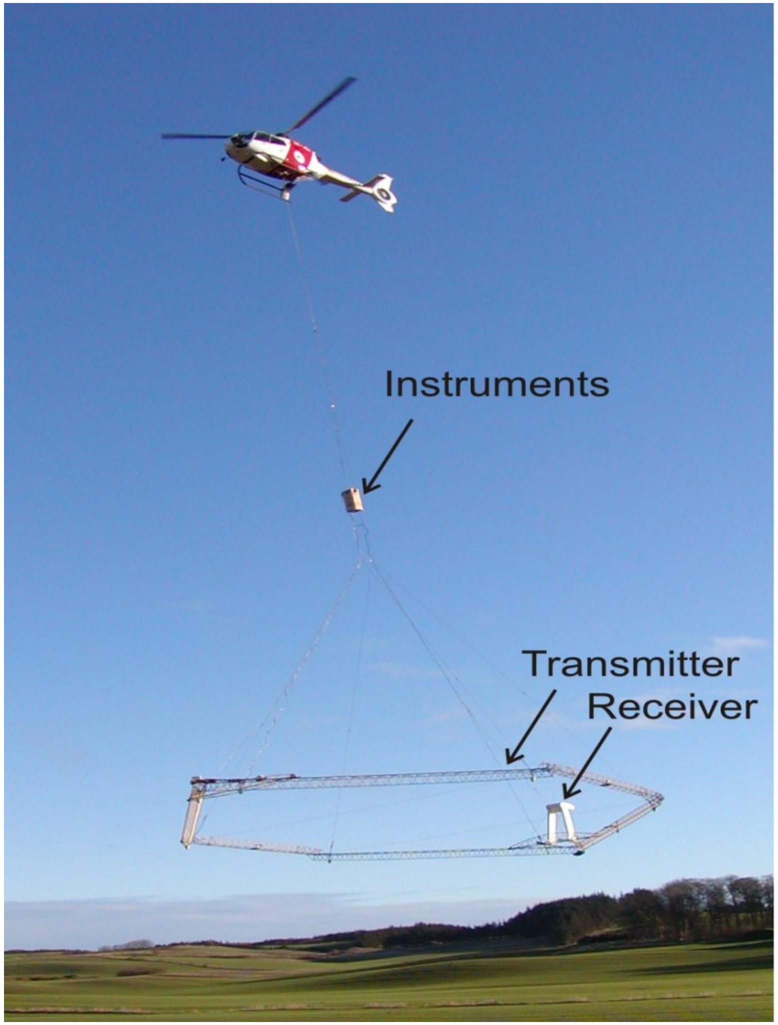
What field work is needed?

Geophysics

Drilling

Geophysics





- EM
- Seismic
- Radar
- Borehole geophysical surveys
- Marine geophysics

Drilling

- Stratigraphic benchmarks

Model Construction

How do I draw layers?

Resolution

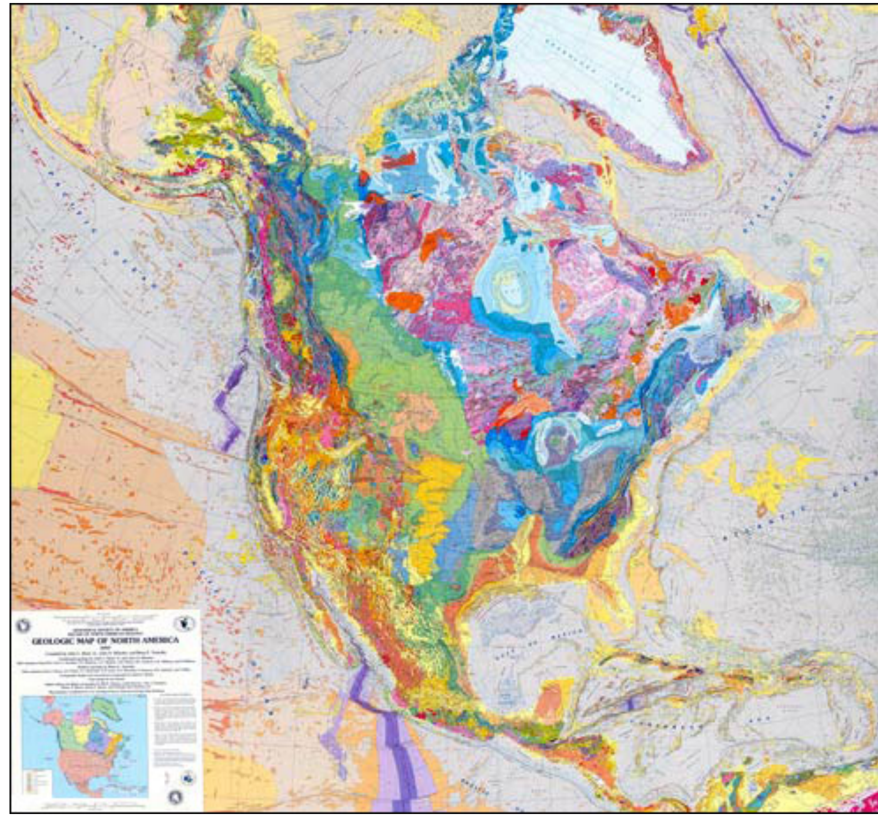
Data adequacy

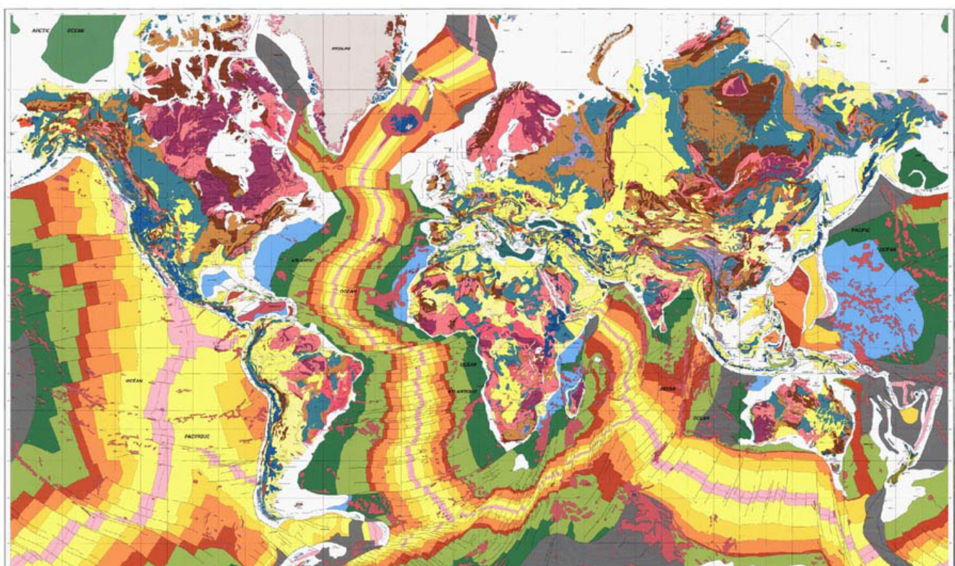
Lithological data

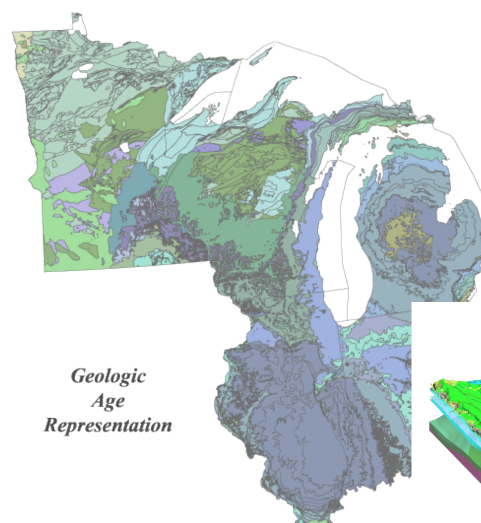
Stratigraphic data

Resolution

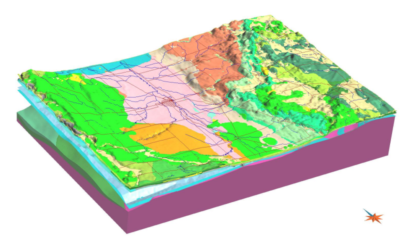
- Global
- Continental
- Regional
- Local







Geologic
Age
Representation



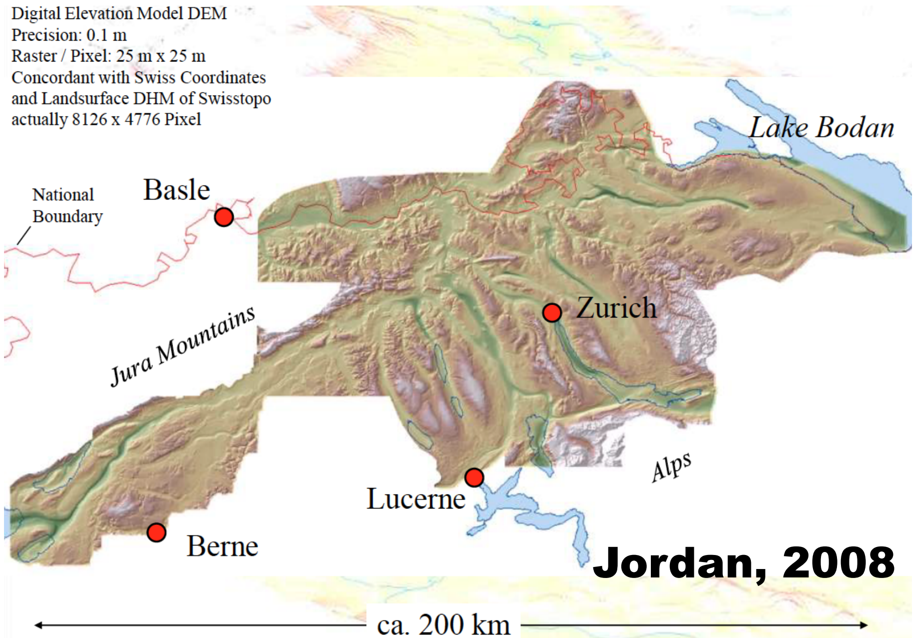
Lithological data

- the model is anchored at stratigraphic benchmarks
- strata are drawn by a geologist through lithological data
- a facies model guides interpolation
- strata are drawn to the extent supported by data

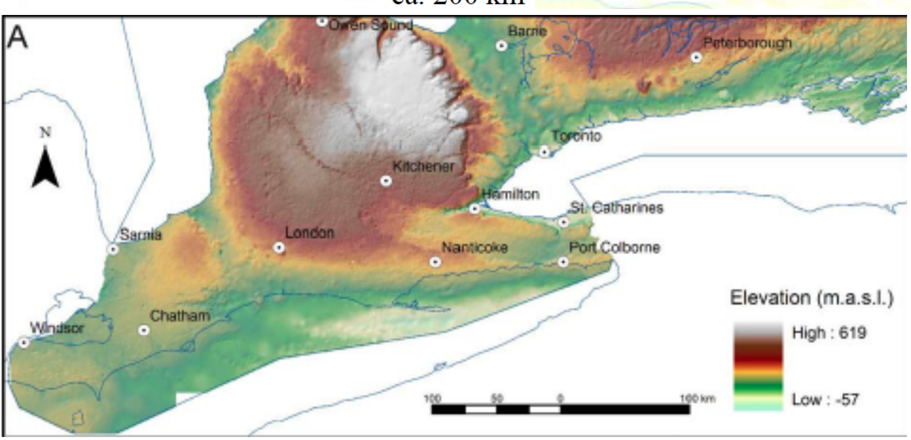
Stratigraphic data

- modeling may proceed directly from regularly spaced, correlated data

Two-layer model



Jordan, 2008



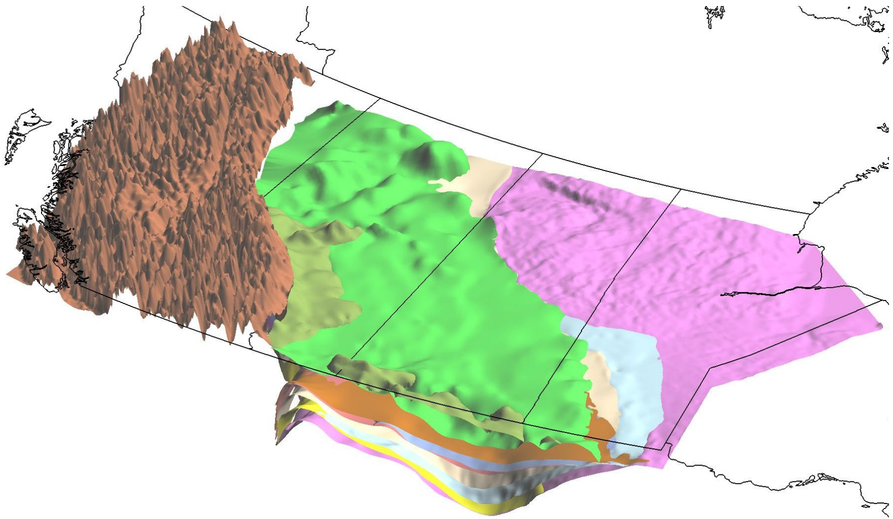
Gao et al., 2006

- depth to bedrock or depth to basement can motivate data compilation and clarify data collection priorities

- bedrock or basement elevations may be machine or hand modelled

- *everyone can do 3D*

Legacy stratigraphic models

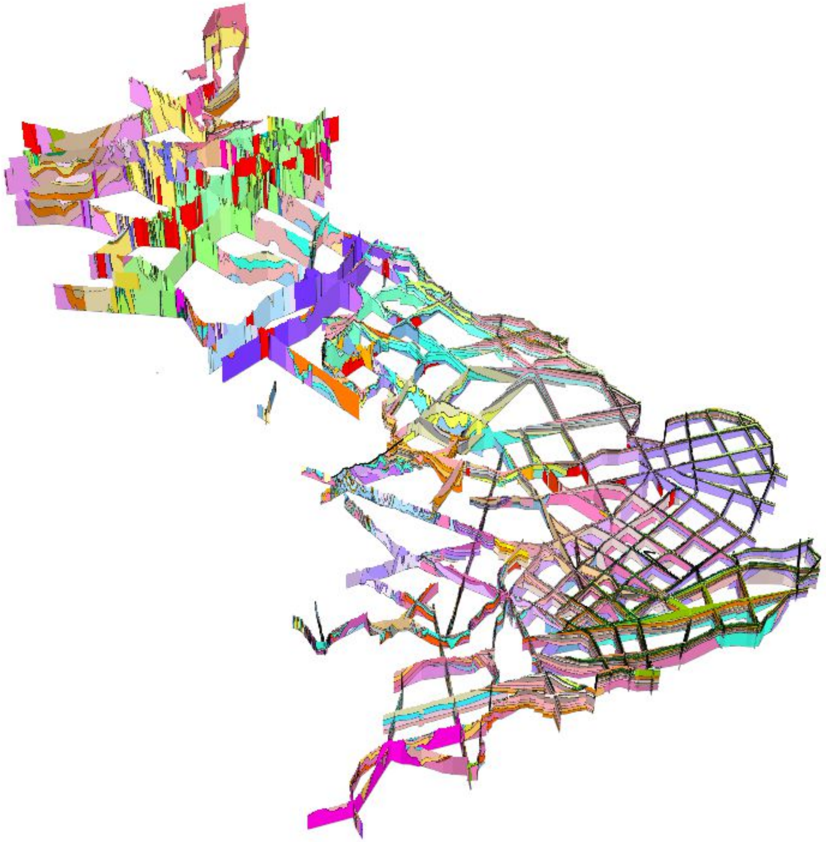


- oil and gas-producing regions commonly have stratigraphic atlases in need of digitizing

- modeling likely guided by stratigraphic markers, seismic surveys, and lithologic trends identified in borehole geophysics and other means

Keller et al. (2009)

Legacy stratigraphic models

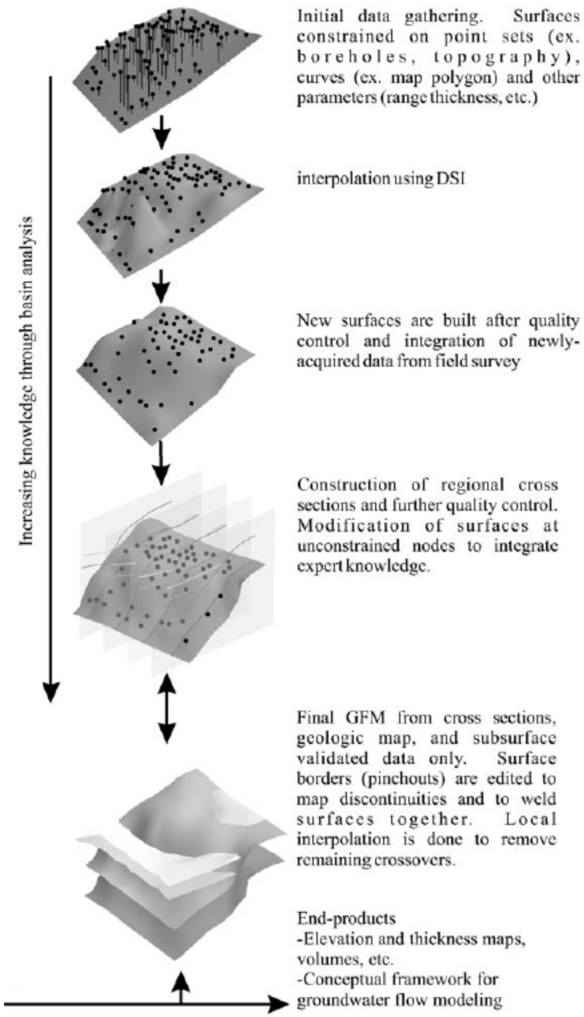


Mathers, 2011

- intersecting surfaces and gaps commonly are present in structure contours, and may require reconciliation of in data-poor areas

- such models provide immediate value as a basis for planning, data collection, and higher resolution modeling

Cross-sections drawn through lithologic data

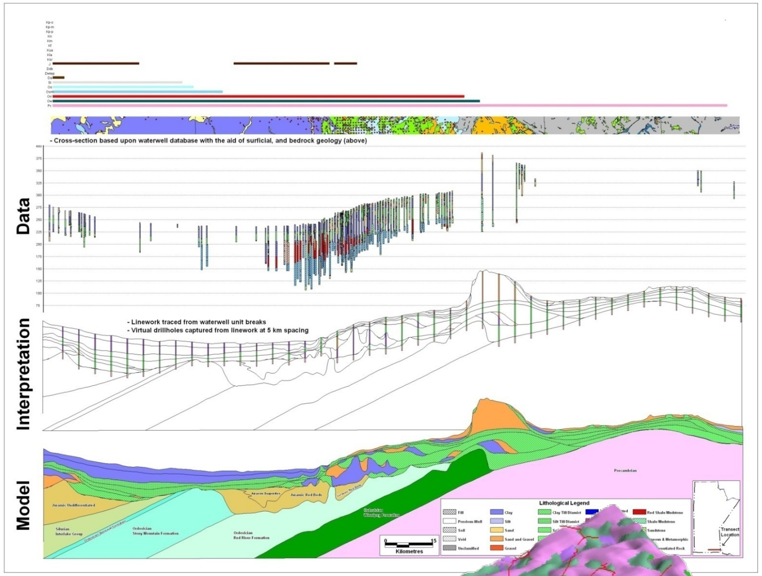


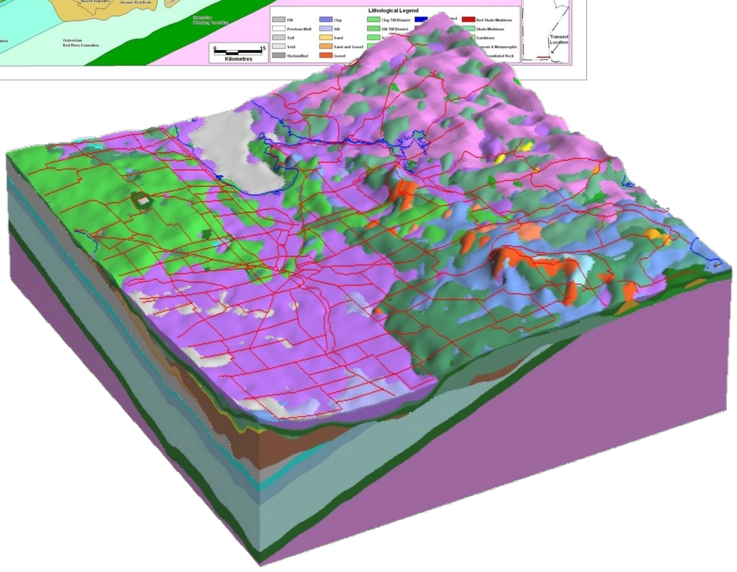
Modified from Ross et al., 2005

- a common scenario is a region in which regional 3D mapping is needed to support groundwater management, and the available basis for modeling is scattered cores and geophysical surveys, along with an abundance of water well data

- an approach in this case is data compilation, acquisition of stratigraphic control sites using coring and geophysics, and construction of cross-sections

Cross-sections drawn through lithologic data

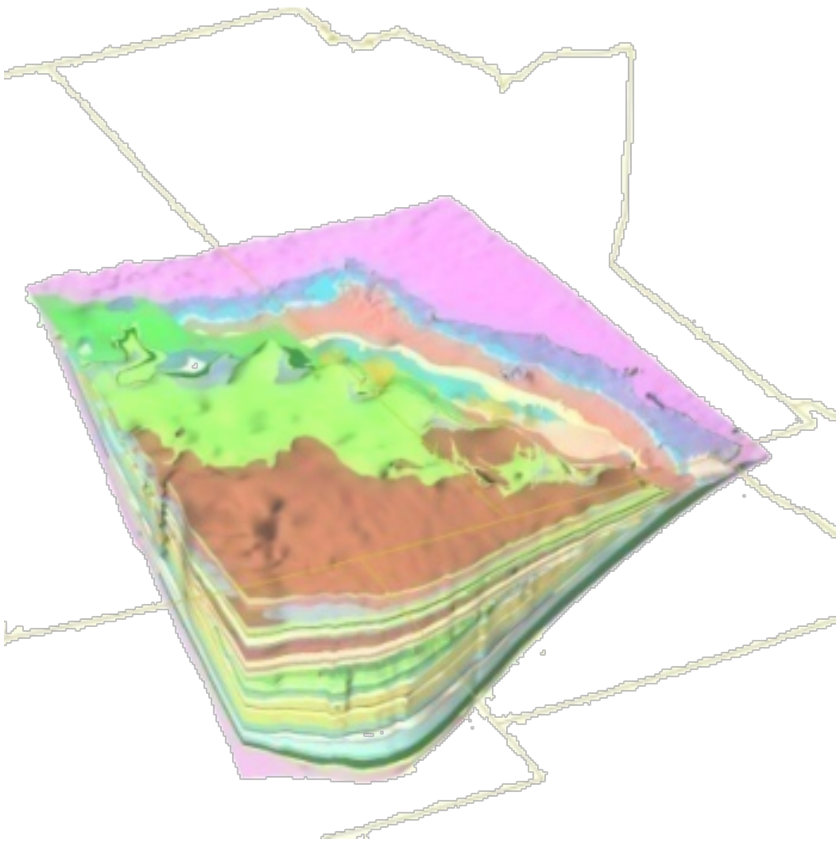




- this results in depiction of a fully plausible geology that conforms to the geological conceptual model, and from which data issues have been filtered by the geologist

- incorporation of new data is challenging

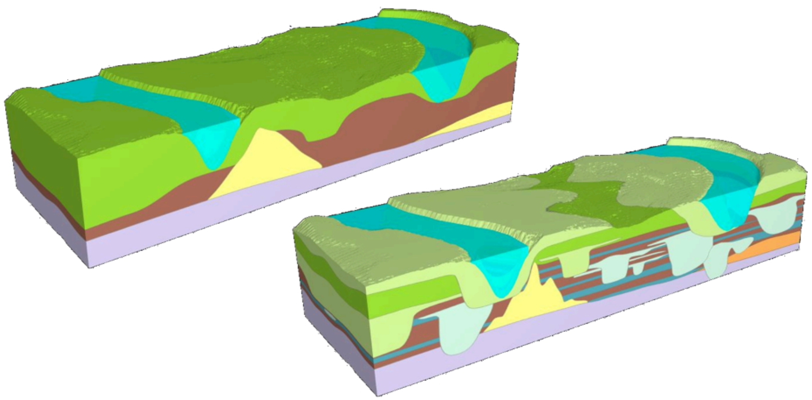
Interpolated stratigraphic data

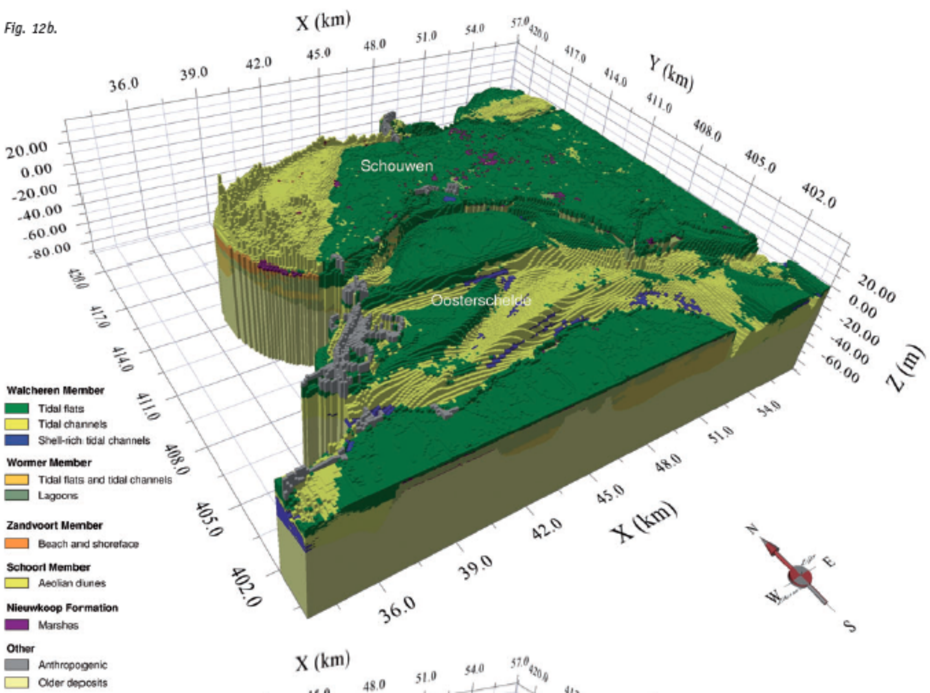


• well-distributed drillholes correlated by means such as micropaleontology or lithological trends may be ready for machine modelling, although expert-generated synthetic profiles may be required in data-poor areas for an acceptable result to be obtained

• new data are more readily incorporated into iterations

Solid Models





- **Progression from surfaces to fully attributed volumes will ultimately be essential for applications**

- **This may require data collection or transfer to another software platform, depending on nature of the discretization and attribution**

- **Solid models may also be constructed from geophysical data**

Geostatistics

Can I use geostatistical methods to infer solids?

Principles

Methods

Principles

- Geostatistical methods infer or characterize solids based on 3D data

- Introduction: McKillup and Dyar (2010)

- Overview: Houlding (1994) and Kresic and Mikszewski (2012)

- Guides: Isaaks and Srivastava (1989), Goovaerts (1997), Olea (1999; 2009), Chiles and Delfiner (1999), Deutsch (2000), Davis (2002), Coburn et al. (2006)

Methods

- simple kriging; ordinary kriging; universal kriging; block kriging, training image-based multiple-point geostatistics, support vector machines

- cellular partitions, tessellations, discrete smooth interpolation, differential geometry, piecewise linear triangulated surfaces, curvilinear triangulated surfaces, stochastic modeling, discrete smooth partitions

Role of geostatistics; e.g.

- **inference of solids directly from lithological data, at least a 1st draft**

- **property attribution following definition of hollow strata – *deterministic layers, stochastic infill***

Heterogeneity, properties, & uncertainty

How do I specify the characteristics of layers?

Heterogeneity

Property attribution

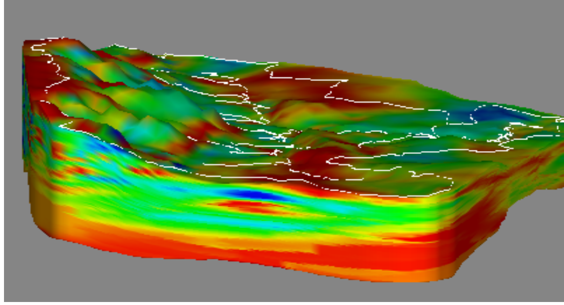
Uncertainty

- **3D mapping seeks relatively homogeneous strata**

- **We then revisit strata, to better recognize heterogeneity**

- **With heterogeneity adequately considered, property attribution proceeds, with uncertainty indicated**

Heterogeneity



- <u>structure-imitating approaches</u> that rely on correlated random fields, probabilistic rules, and/or deterministic constraints developed from facies relations, including spatial statistical algorithms and geologically based sedimentation pattern-matching approaches

- <u>process-imitating models</u> that include aquifer model calibration methods that relate hydraulic properties to heads and solute information through history and steady state data matching, and geologic process models that combine fundamental laws with sediment transport equations to simulate spatial patterns in grain size distributions, as well as basin subsidence models

- <u>descriptive methods</u> that couple geologic observations with facies relations to divide an aquifer into zones of characteristic hydraulic properties (Koltermann and Gorelick (1996)

- Anderson (1997) concluded that most porous media are heterogeneous, that simulation of facies patterns using depositional models is appealing but difficult, and that <u>indicator geostatistics with conditional stochastic simulations</u> are a promising approach to quantifying connectivity, thereby inferring preferential flow paths

Property attribution

- inferring properties from lithology
- use measurements to guide inference from lithology
- interpolation and extrapolation from measurements such as hydraulic conductivity values, while respecting the geological model to the appropriate degree

Uncertainty

- uncertainty in 3D varies inversely with data density, while data requirements vary with geological complexity

- uncertainty thus relates to data, complexity, and interpretation

- stochastic techniques may be used to compute the probability for each grid cell to belong to a specific lithostratigraphic unit and lithofacies

Examples

What have other people done?

Australia & New Zealand

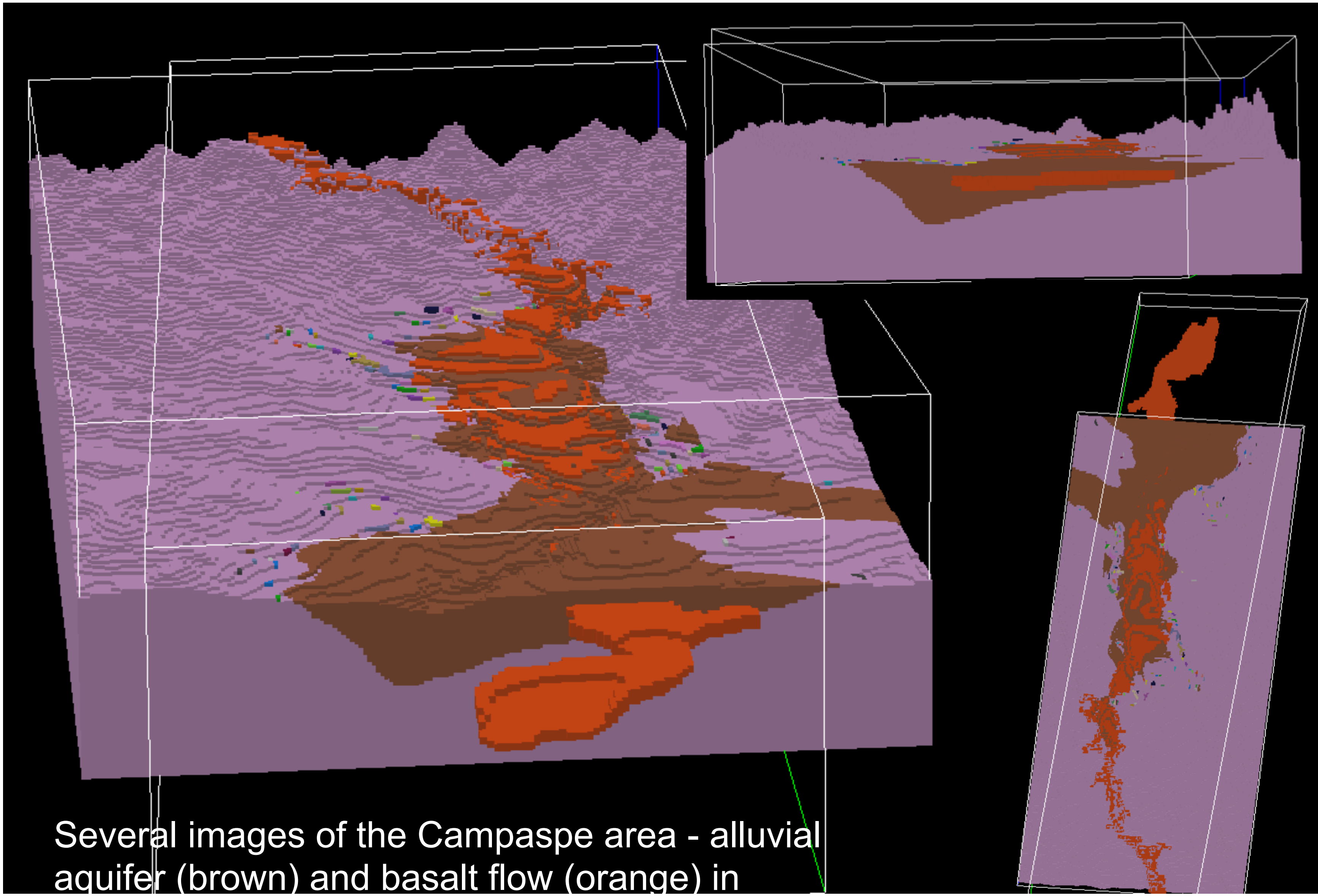
Continental Europe

UK

Canada

USA

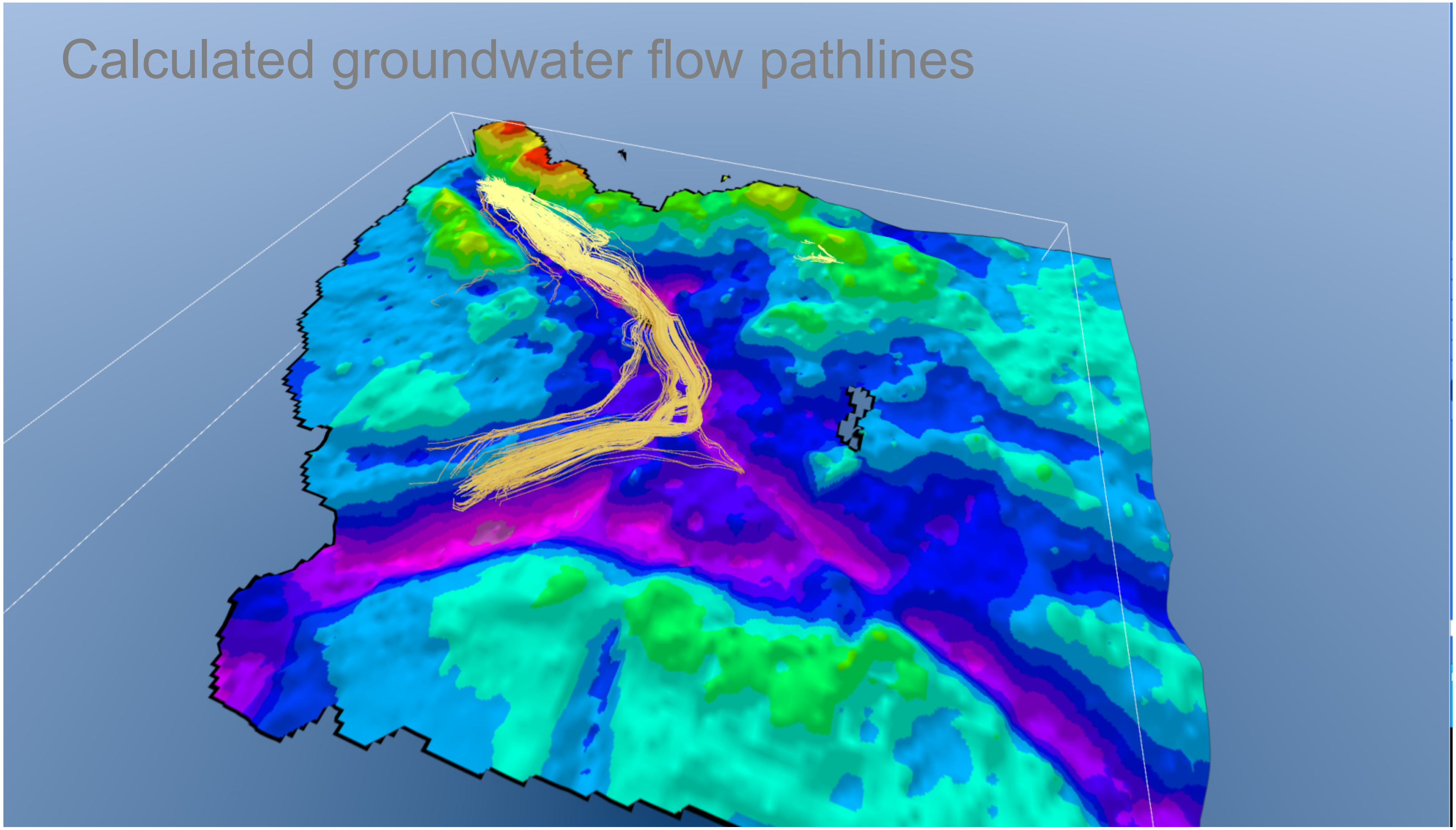
Australia & NZ



Several images of the Campaspe area - alluvial aquifer (brown) and basalt flow (orange) in

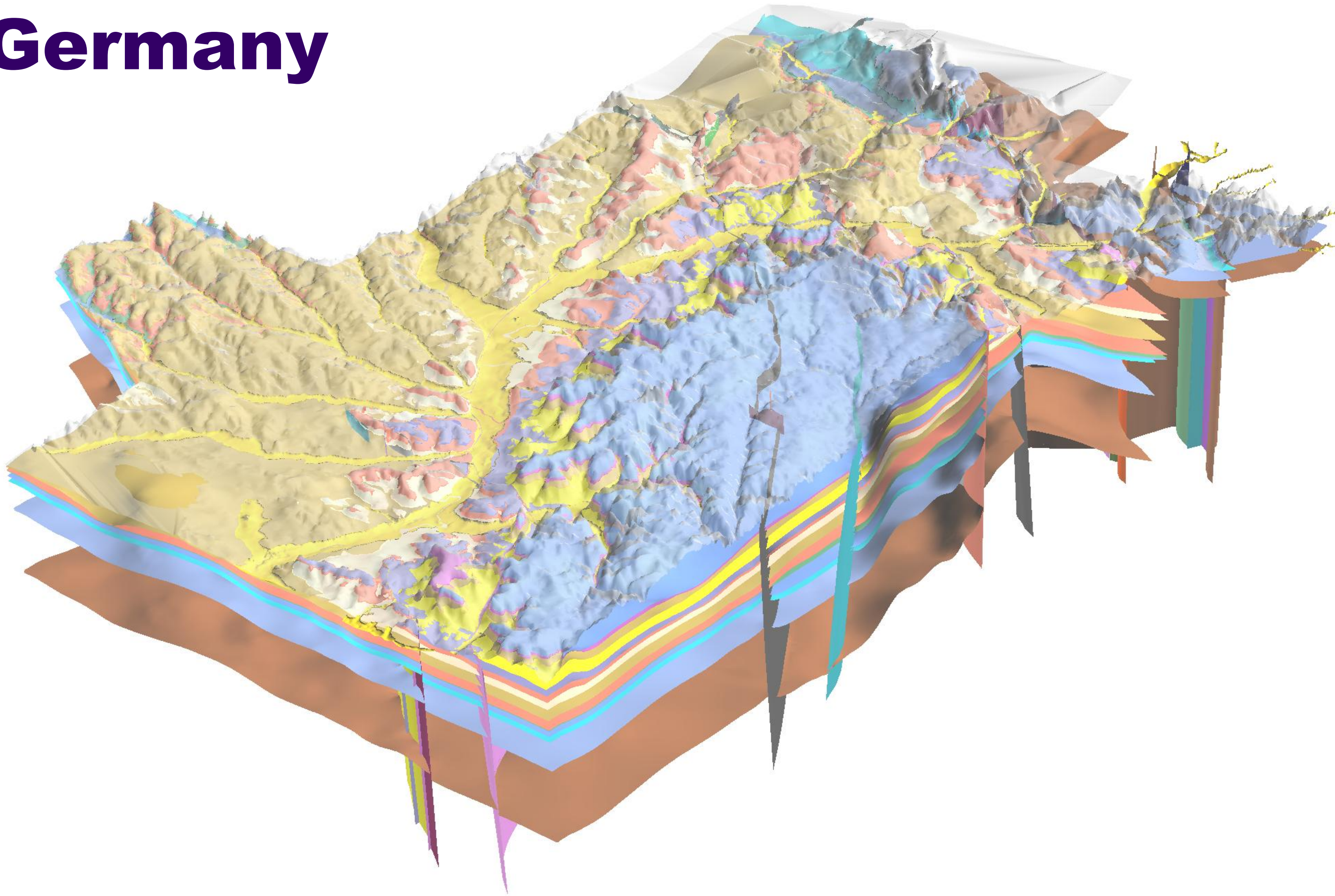
Continental Europe

- **Denmark**



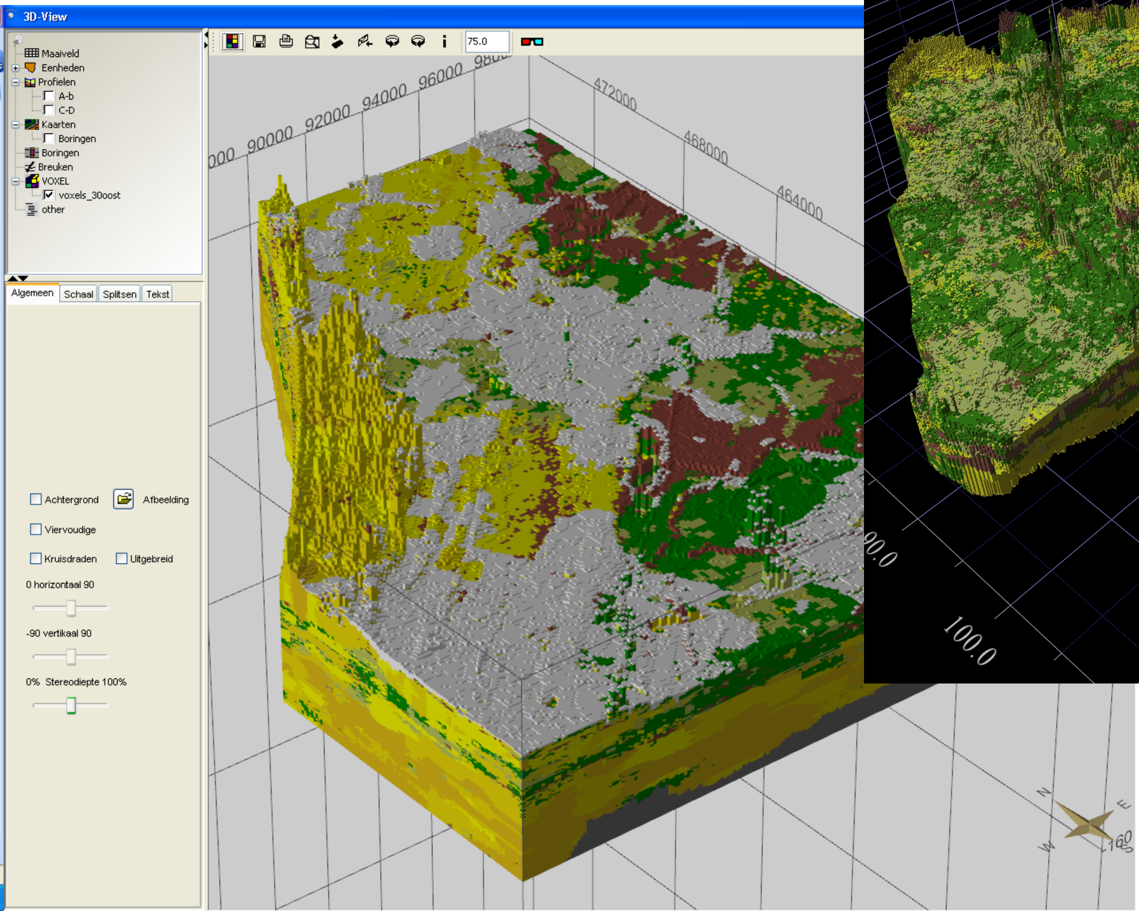
Continental Europe

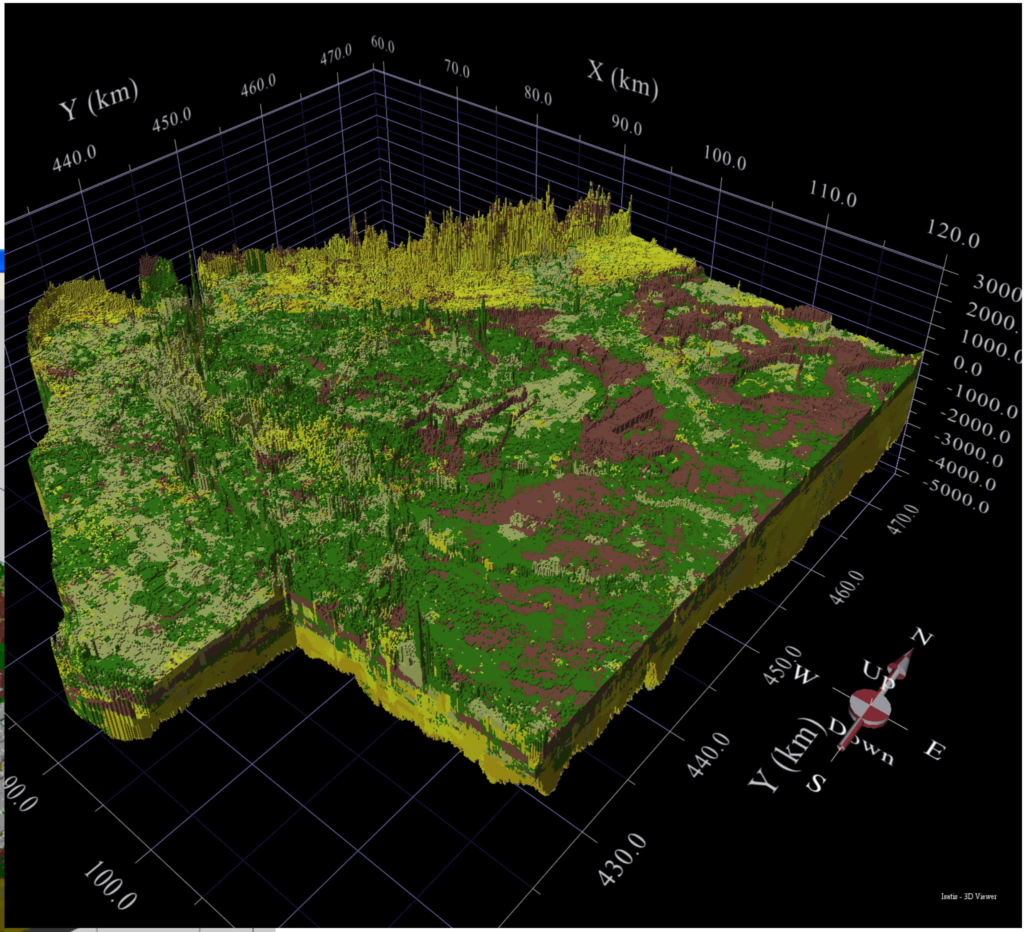
- Germany



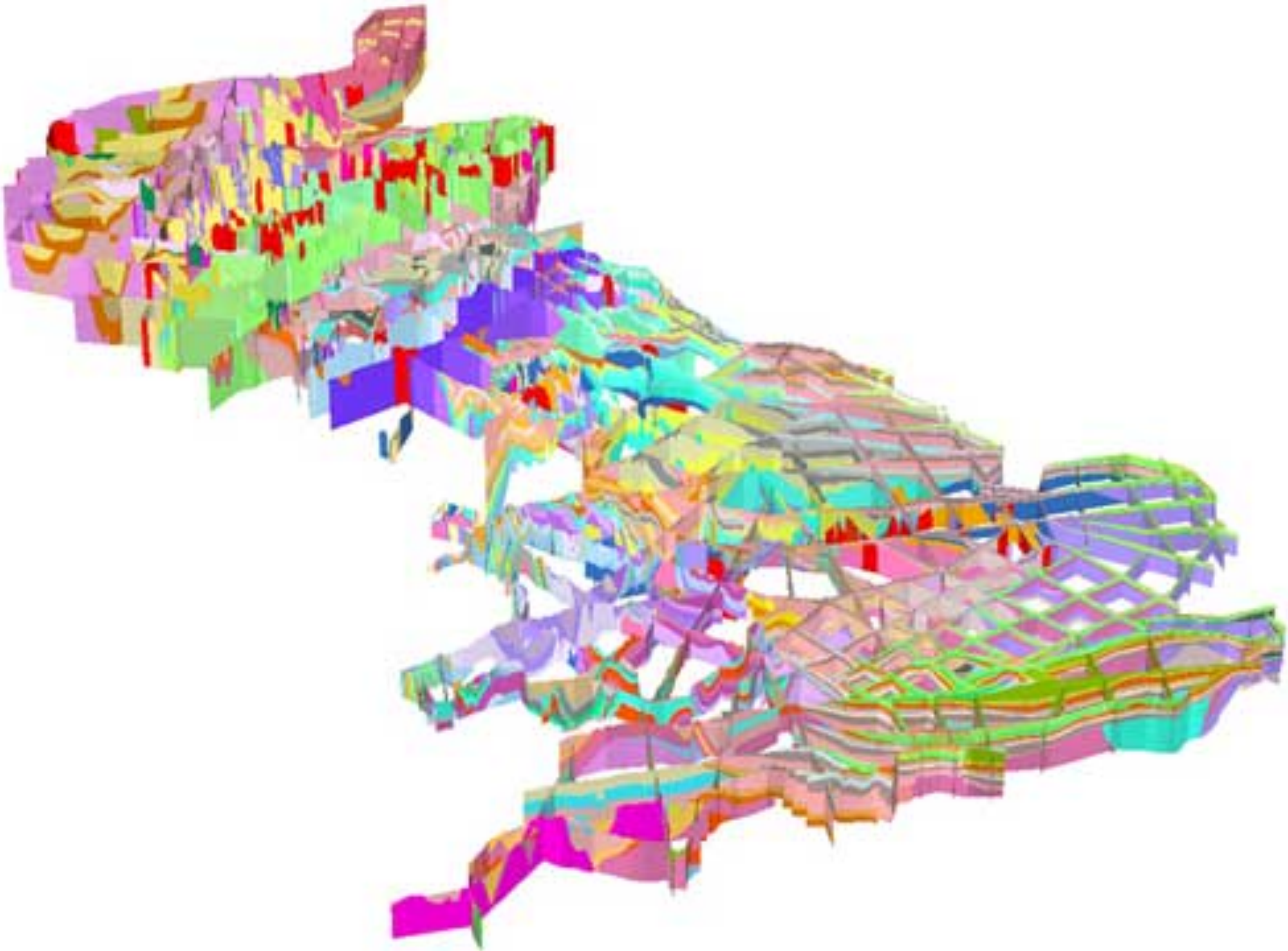
Continental Europe

- **Netherlands**

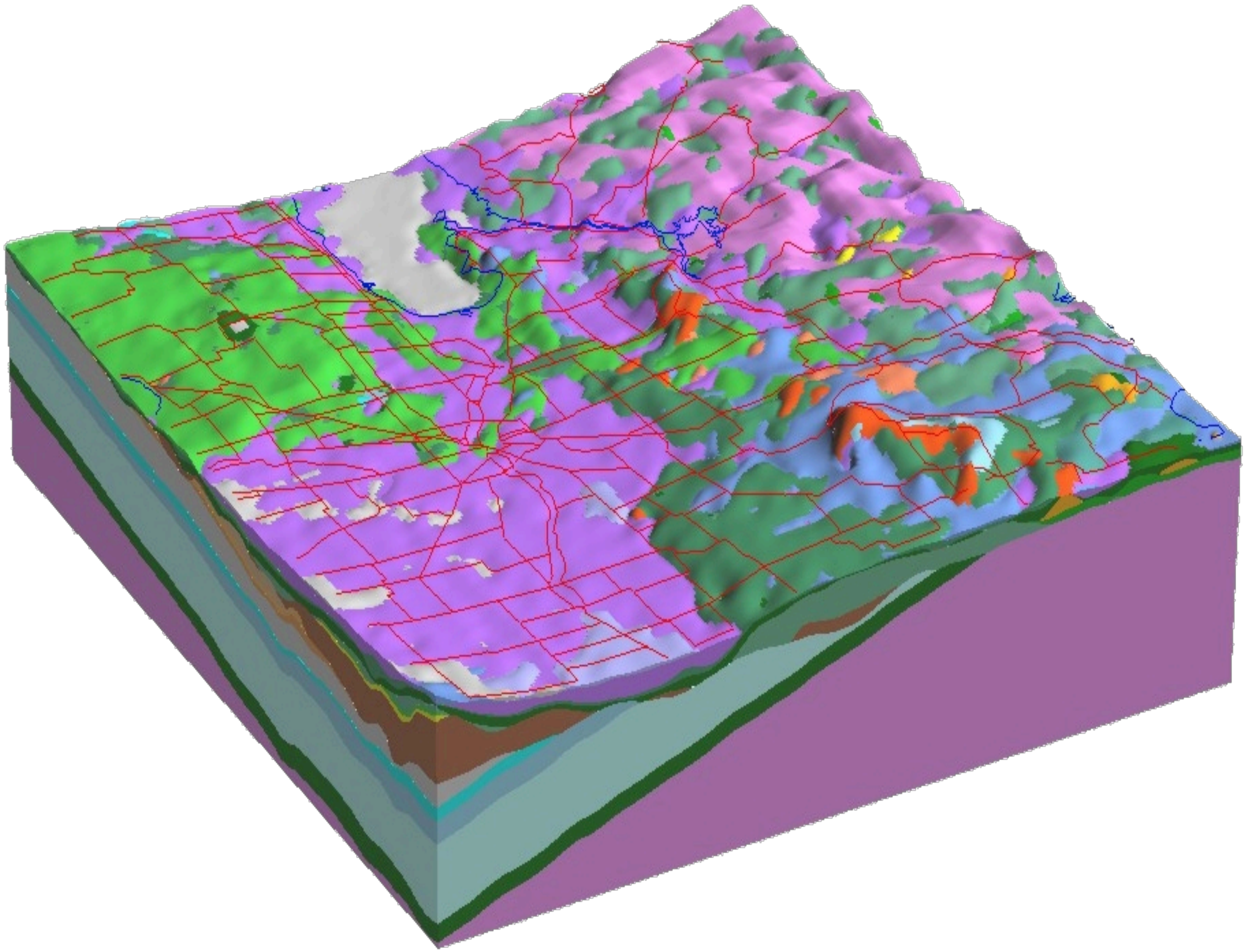




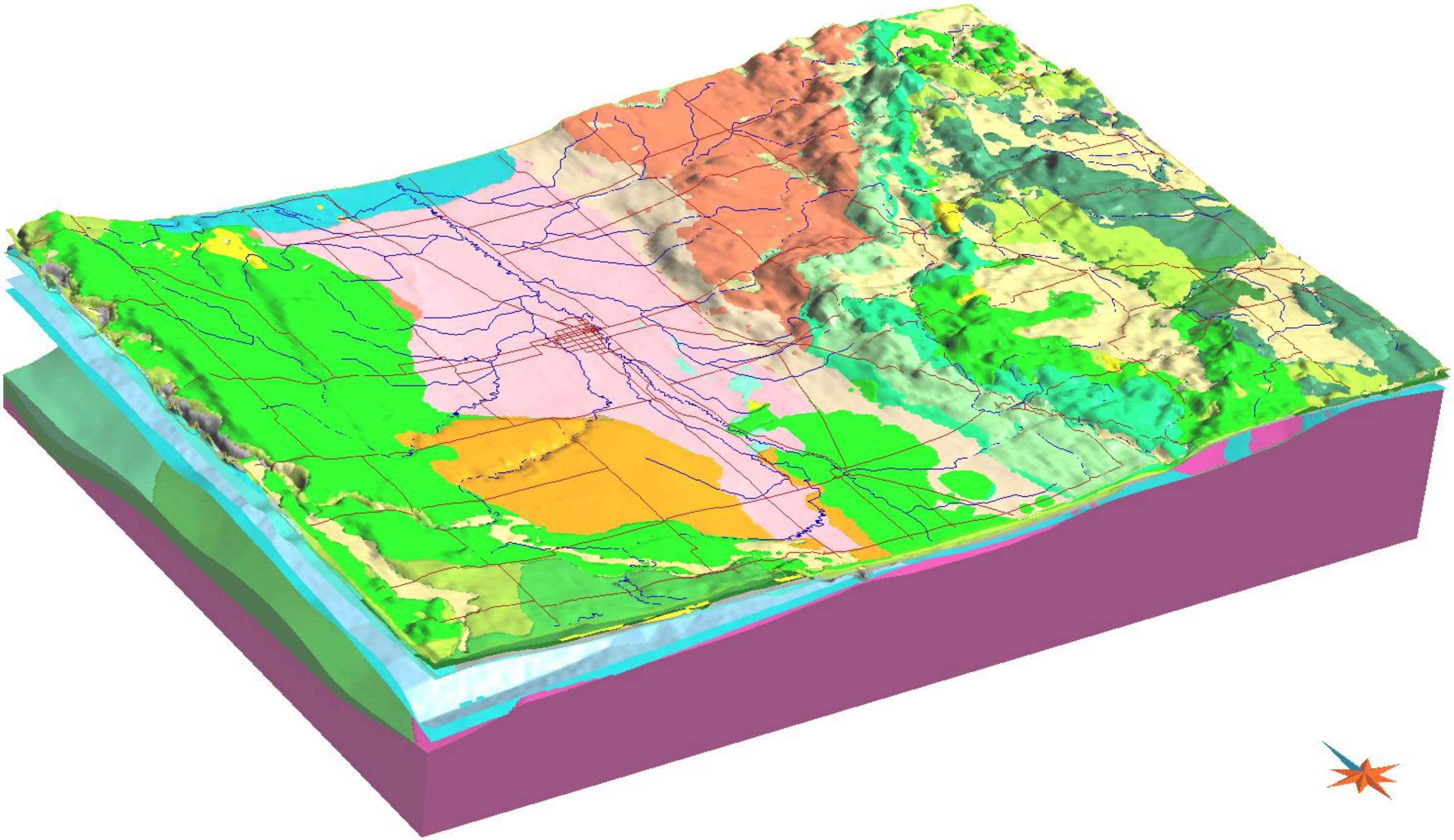
UK



Canada



USA



Strategies

What should I do next?

Focus on societal needs
Assess status of data county-by-county
Raise expectations
Long term planning
Institutional databases
Reconcile strat – statewide x-sections
Harmonize 2D mapping
Geophysics & drilling
Choose an appropriate approach
Make a plan; build support

Rationale and Methods for Regional 3D Geological Mapping – *summary of topics*

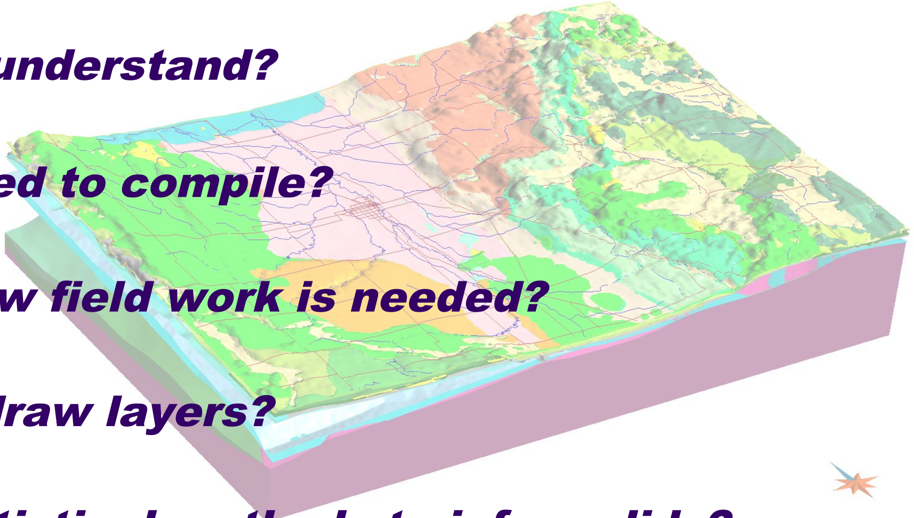
Rationale - ***Why do I need to do this?***

Background - ***What do I need to understand?***

Data compilation - ***What do I need to compile?***

Data acquisition - ***How much new field work is needed?***

Model construction - ***How do I draw layers?***



Geostatistics - ***Can I use geostatistical methods to infer solids?***

Heterogeneity, properties, & uncertainty - ***How do I specify the characteristics of layers?***

Examples - ***What have other people done?***

Strategies - ***What should I do next?***

Rationale and Methods for Regional 3D Geological Mapping

Harvey Thorleifson, Minnesota Geological Survey