

MINNESOTA GEOLOGICAL SURVEY
Harvey Thorleifson, Director



Geologic Mapping Forum 21/22 Abstracts

Edited by: Harvey Thorleifson, Minnesota Geological Survey



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**MINNESOTA
GEOLOGICAL SURVEY**



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INTRODUCTION

The Geologic Mapping Forum in Minneapolis in 2018 and 2019 was attended by ~100 geological map authors, program managers and allied professionals from geological surveys and associated agencies, who met to discuss the status and future of geological mapping in the USA.

Due to the coronavirus pandemic, the 2020 Geologic Mapping Forum planned for April 7th to 9th, 2020, was not held.

It therefore was decided that GMF Online would be held as meetings of about two hours duration on Thursdays at Noon Central, about once per month, from early autumn until spring, in 2020/2021, and again in 2021/2022.

The intended GMF audience is geological map authors and program managers, and the focus again was on geology rather than funding or GIS.

Optional abstracts for the 20-minute invited talks were requested, and are presented here.

John Brock, US Geological Survey

Harvey Thorleifson, Minnesota Geological Survey

OVERCOMING THE CHALLENGES OF GEOLOGIC MAPPING IN URBAN AREAS, WITH EXAMPLES FROM SALT LAKE COUNTY, UTAH

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Surficial and bedrock geologic mapping of mostly urbanized areas requires the use of nontraditional geologic tools to supplement traditional geologic mapping techniques. New geologic mapping of Salt Lake Valley, the Salt Lake City segment of the Wasatch fault zone, and the West Valley fault zone is being supplemented by using historical accounts of geomorphology, geography, and geology. Historical photographs of the city, landscapes, building excavations, neighborhoods, and buildings provide geologic and geomorphic insight to areas now changed by development. In addition to traditional stereographic aerial imagery, early predevelopment stereographic aerial photograph sets are critical for mapping surficial geologic deposits. Consultant geotechnical and surface-fault-rupture investigations provide data on the location and nature of surface faulting, mass movement deposits, and general surficial stratigraphy. Cone penetrometer test (CPT) investigations, geophysical surveys, exploration boreholes, water well data, U.S. Natural Resources Conservation Service (NRCS) soil maps, and other geologic and engineering investigations are useful for determining the composition and stratigraphy of surface and subsurface deposits. Landslides, faults, bedrock, and surficial geologic contacts can be mapped using high-resolution airborne-lidar-derived digital elevation models and topographic contours of the ground surface. Historical topographic maps, early city maps, and early insurance plot maps can be helpful to map surface features like streams or escarpments later removed or modified by development. These tools and methods provide improvements to the spatial accuracy and precision of geologic contacts previously located using traditional methods. Combining these nontraditional mapping resources with traditional ones in a geographic information system provides a powerful platform to conduct geologic mapping in urban areas.

CHARACTERIZING THE BURIED TEAYS RIVER VALLEY IN WEST-CENTRAL OHIO

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The Teays River was the master stream of a drainage network theorized to have covered much of modern-day Ohio and portions of other lower Great Lakes and Appalachian states before the Quaternary Period. The Teays was a mature river with many tributaries and a broad valley that cut through the unglaciated Appalachian Plateau. Pleistocene-aged ice sheets advanced across this watershed multiple times, altering the course of the master stream and burying portions of the Teays River Valley. Within the glacial margin, the Teays River Valley is completely covered and obscured by unconsolidated sediments. The exact path of this valley remains unknown due to a lack of quality subsurface data. Many water wells have been developed into the valley, but few are completed into bedrock aquifers because ample household water supplies are found in Quaternary-aged sand-and-gravel deposits within about 150 feet of the surface. Obtaining new subsurface data for this buried valley allows geologists to create more accurate maps that depict all facets of the surficial and bedrock geology associated with this buried valley.

The Ohio Geological Survey is actively mapping the location, morphology, and stratigraphy of the buried Teays Valley in west-central Ohio. Passive geophysical Horizontal-to-Vertical Spectral Ratio (HVSr) techniques have been used to make relatively rapid and inexpensive calculations of the area's buried bedrock topography. HVSr measurements are calibrated against known bedrock elevations and verified with new drilling. A rotosonic sediment core (Willshire-21) was collected near Willshire, OH in a collaborative project with the Indiana Geological & Water Survey and partial funding through the Great Lakes Geologic Mapping Coalition. This drilling project was completed to verify the accuracy of HVSr bedrock topography modelling and directly observe the stratigraphy of Quaternary-aged sediments that in-filled this valley. The boring was drilled through 329.5 feet of Quaternary-aged unconsolidated sediments and an additional 5.5 feet of Paleozoic bedrock for a total depth of 335 feet. HVSr modelling estimated a bedrock depth of 336 feet, a difference of only 1.67% from the actual bedrock depth.

A description of the Willshire-21 core was completed to separate unconsolidated sediments and consolidated bedrock into eight distinct units (Units A–H). Unit A is a gray silt loam diamicton about 75 feet thick interpreted to be a till from the Wisconsin Glaciation. Unit B is a red silt loam diamicton about 25 feet thick interpreted to be a till from the Illinoian Glaciation. Unit C is a sand-and-gravel glaciofluvial deposit that is about 40 feet thick. Unit D is a uniform dark gray silt loam diamicton that is about 90 feet thick. Unit E is an upwards-fining glaciofluvial and glaciolacustrine sequence that is about 65 feet thick. Unit F is a dark gray silt loam diamicton about 25 feet thick and is the lowermost diamicton in the sedimentary sequence. Unit G is a 10-foot thick glaciofluvial sediment package that directly overlies Ordovician-aged bedrock (Unit H). A downhole gamma log was collected in the field to support noted visual unit breaks and to correlate units to other regional gamma logs collected during Teays Valley drilling projects. Subsamples for each unit were also collected for grain size and pXRF analyses. Results from grain size analysis indicate that the four diamicton units observed in the Willshire-21 core all have silt loam matrices. However, Unit D has greater than 10% more sand on average compared to other analyzed diamicton units. The semiquantitative pXRF analysis was useful in distinguishing all diamicton units from each other. Potassium percentages, titanium-zircon ratios, and silica-calcium ratios were used to distinguish these units. Samples were also collected for XRD and OSL analyses, but the results of these analyses are still pending.

The Willshire-21 core represents a new high-quality data point that affects many of the mapping products previously published by the Ohio Geological Survey in this region. The direct measurement of a specific bedrock elevation acts as a deep calibration point for bedrock topography mapping. The stratigraphy described in the core affects three-dimensional surficial “stack” mapping and interpretations of the Quaternary glacial history in the region. The bedrock samples collected from coring verify the existence of Ordovician-aged limestone at the base of the valley. The bedrock geology mapping in this region is heavily dependent on modelled bedrock topographic surfaces. As these surfaces are updated, the bedrock geology maps will likewise require revision. The Ohio Geological Survey is incorporating this new data into living dataset and database projects that are flexible enough to adapt to newly collected data. As part of our long-term bedrock topography and Quaternary geology mapping plans, the Ohio Geological Survey will continue collecting rotosonic cores in key portions of the buried Teays River Valley.

GEOLOGIC MAPPING FOR THE EARTH MAPPING RESOURCES INITIATIVE IN ARKANSAS

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The Arkansas Geological Survey (AGS), through cooperative programs with the U.S. Geological Survey, has conducted detailed geologic mapping in the Interior Highlands for the last 30 years. In 2000, the focus shifted from Cretaceous areas in southwest Arkansas to the Ozark Plateaus Province in northern Arkansas. Since that time, forty-nine 1:24,000-scale quadrangles have been completed there. The main reason for choosing the Ozark Plateaus was to provide more detailed geologic maps in areas that were previously mapped on a 15-minute base.

In 2019, the AGS began mapping for the Earth Minerals Resources Initiative (EMRI) in the Batesville Manganese District also located in the Ozarks. The mapping area straddles the southern edge of the Salem Plateau and the escarpment of the Springfield Plateau just north of Batesville, Arkansas. It consists of four full quadrangles and portions of five others making an area that is roughly 30 miles long and 15 miles wide.

The goal of this project was to get a better understanding of the Ordovician Cason Formation, a geologic unit that historically produced phosphate and manganese and is now known to be particularly enriched with Rare Earth Elements (REEs). In fact, recent preliminary research by the USGS suggests this phosphate deposit may be one of the largest in the world and could contain some of the highest percentage yields known (Emsbo et al. 2015). Research in by Grosz et al. (1995) indicated that the basal phosphorite in the Cason contained a concentration of REEs approximately four times greater than an average marine phosphorite.

The “key” mapped interval includes an unconformity bound sequence from the Upper Ordovician Fernvale Limestone to the base of the Mississippian Boone Formation. Included in this sequence are the Ordovician Cason Formation along with Silurian Brassfield and St. Clair Limestones. These units consist of thin limestone (locally oolitic) and shale deposited in nearshore-shoal marine environments. Coarse-grained limestone such as that found in the unconformable Fernvale, Brassfield, and St. Clair represent crinoid sand bars. These bars restricted a lagoonal (Cason) environment from the open ocean (Craig, 1984, 1993, and Young et al. 1972).

Current geologic mapping, enhanced with the use of LiDAR, has revealed a more complex geologic history for the area. This updated geologic map depicts more faults and structure than previously portrayed. Because the Cason Formation is such a thin unit, (up to 15 feet thick) it was mapped with the unconformity bound Silurian and Devonian units. Historically, the Cason has been called a shale, however, recent mapping has highlighted the different rock types present in this formation.

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APPLICATIONS OF NEW HIGH-RESOLUTION AIRBORNE RADIOMETRIC DATA IN SOUTH CAROLINA

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From 2019 to 2021, the portion of the U.S. covered by high-resolution airborne radiometric data quadrupled, much through the efforts of the U.S. Geological Survey (USGS) Earth Mapping Resources Initiative (Earth MRI). These data, which represent potassium (K), uranium (U), and thorium (Th) sources within the upper 1 m of the surface through gamma-ray spectrometry, can assist geologic mapping in a variety of geologic environments. Here we present results from a pair of contiguous airborne radiometric and magnetic surveys over the South Carolina Atlantic Coastal Plain.

A primary goal of the surveys is to image shallow titanium-zirconium-rare earth element (Ti-Zr-REE) placer deposits (also referred to as heavy mineral sands) in coastal plain sediments. These deposits often include ilmenite, rutile, zircon, monazite, and other dense minerals. Th-bearing monazite is typically present in varying degrees, and shallow deposits can thus be directly imaged by radiometric data. Such deposits have been mined in the eastern U.S. from the 1800s and continue to be mined today in Georgia and Florida; Ti, Zr, and REEs are each considered “critical” mineral resources.

The 212-km long by 130-km wide airborne survey extends from crystalline rocks of the Piedmont Province to the Atlantic coast, providing a “source to sink” transect for heavy minerals. It includes, from NW to SE: 1) Paleozoic igneous and metamorphic rocks in the Piedmont, including parts of the Carolina Slate Belt (with the Liberty Hill and Winnsboro plutons), the Modoc Zone, and sparse outcrops of the Kiokee Belt; 2) Upper Coastal Plain strata mostly of Cretaceous to Neogene age punctuated by fluvial systems and associated Quaternary sediments; 3) Middle Coastal Plain sediments southeast of the Orangeburg scarp that are mostly siliciclastic Neogene sediments; and 4) Lower Coastal Plain sediments that are mostly Pleistocene and Holocene in age. The Pleistocene sediments rest unconformably upon Neogene and Paleogene strata that is phosphate-rich in numerous places. A detailed study of the Lower Coastal Plain airborne data is provided by Shah et al. (2021).

Over the Piedmont Province, the combined radiometric and magnetic data show direct correspondences with lithology. For example, the Liberty Hill and Winnsboro plutons show high Th, K, and magnetic anomalies within a metavolcanic setting associated with low K, low Th, and linear magnetic anomalies. Other granitic rocks exhibit high K, low Th, and low magnetics, whereas contrasting gabbroic rocks exhibit low K, low Th, and high magnetic values. Sillimanite schist exhibits linear magnetic anomalies with high Th, and low K.

Within the Upper Coastal Plain, comparisons with geologic maps show elevated Th over most Cretaceous strata as well as several younger units. Previous and new mapping efforts have documented concentrations of heavy mineral sands within Cretaceous sediments in some areas, but elsewhere the elevated Th values represent Th-bearing kaolin lenses or rip-up clasts. For the younger strata, elevated Th generally corresponds to heavy mineral sands, but units of interest vary by sub-region. For example, near St Mathews, siliciclastic Eocene sediments of the Orangeburg District beds show high Th, but near Dalzell, the Orangeburg District beds are not present and other siliciclastic Eocene units show low Th; instead fluvial sediments of the Pliocene Duplin Fm. show high Th. In both cases, the elevated Th values appear to represent dense minerals that have been reworked from Cretaceous strata.

Seaward of the Orangeburg scarp, which is the boundary between the Upper and Middle Coastal Plains, Th values show a sharp drop. Within the Middle Coastal Plain, Th values are low except within and alongside the Edisto, Santee-Cooper, and Black River floodplains. These rivers each have headlands in either the Upper Coastal Plain or the Piedmont; elevated Th is attributed to reworking of heavy minerals by fluvial processes, or possibly transport by eolian processes.

The Lower Coastal Plain shows Th variations associated with facies rather than age. Sands show localized, linear Th highs whereas muds show lower, more evenly distributed values. Highest Th values are observed over areas where sediments were likely reworked during multiple episodes or by multiple processes, such as tidal inlets associated with river mouths resulting in more concentrated heavy minerals.

Previous work has shown that radiometric K anomalies in the Atlantic Coastal Plain generally represent immature minerals such as potassium feldspar and mica (biotite and muscovite). Elevated K is observed over river flood plains throughout the Atlantic Coastal Plain, likely representing minerals recently eroded from Piedmont crystalline rock. K is also elevated over sediments younger than about 130 kyr over the width of the survey, including areas more than 100 km from rivers that traverse the Piedmont. These elevated values are attributed to immature sediments delivered by rivers to offshore areas and then reworked onto beaches.

Over most of the Atlantic Coastal Plain, radiometric U and Th are highly correlated, but in certain areas the U/Th ratio is notably high. This occurs in areas where phosphatic Paleogene or Neogene strata are exposed, such as along the edges of incised river valleys and areas mined for industrial minerals. Elevated U is also observed over areas known to contain phosphate mining waste, suggesting possible study areas for considering mineral resources from mining waste.

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NEW HIGH-RESOLUTION AIRBORNE GEOPHYSICS IN SOUTHEASTERN VIRGINIA AND NORTHEASTERN NORTH CAROLINA: BREAKING FRESH GROUND ALONG THE FALL ZONE

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The Fall Zone in southeastern Virginia (VA) and northeastern North Carolina (NC) is where the Atlantic Coastal Plain (ACP) Province meets the Piedmont Province and is a site of known critical mineral deposits. The region has a tectonic history that includes multiple Appalachian orogenic events in the crystalline eastern Piedmont and rift- to drift-related processes that construct the ACP. We present initial results from an airborne magnetic and radiometric survey combined with ground-truth geologic mapping that aim to: (1) better evaluate Ti-Zr-REE placer deposits in the ACP, (2) identify additional possible mineral resources in the eastern Piedmont, and (3) develop a tectonic framework model to better understand these mineral systems.

The airborne geophysical survey was flown in 2021 as part of the Earth Mapping Resources Initiative (Earth MRI) and covers a 234 by 70 km area from Richmond, VA, to Rocky Mount, NC, over the Fall Zone. The 250-m spacing between E-W oriented flight lines represents a 3-to 10-fold improvement in resolution over previous aeromagnetic survey data and a 15-to 35-fold improvement over previous aeroradiometric data.

Comparisons between the new airborne data, existing geologic maps, and recent field observations illustrate direct correspondences between these new geophysical data and regional geologic features. In the Atlantic Coastal Plain, radiometric data show that elevated Th and K characterize river floodplains, which is attributed to erosion and subsequent fluvial transport and deposition of Th-bearing monazite and K-rich feldspar, muscovite, and biotite grains (immature minerals) from the Piedmont. These data also show abandoned river channels that highlight stream capture and rearrangement of ACP drainages. Fall Zone terrace deposits that have elevated Th and lower K correspond to known heavy mineral placer deposits and prospects, including Old Hickory in VA, which was developed for Ti and Zr. The correlation is attributed to low but detectable levels of monazite within the heavy mineral assemblage combined with minimal levels of K-bearing immature minerals.

Radiometric and magnetic data over the Piedmont generally show direct relations to both lithology and structure. For example, gneiss and schist in the Goochland and Raleigh terranes typically show higher Th but typically lower magnetic anomalies. Metavolcanic and/or sheeted metaplutonic rocks in the Roanoke Rapids and Chopawamsic terranes are associated with linear magnetic anomalies that likely represent layered units of mafic, felsic, and metasedimentary rocks. Th and K are low, and the bounding faults of these terranes are well-defined. Late Paleozoic granitic intrusions show elevated K, Th, and magnetic anomalies, but a few show only elevated K. Jurassic diabase dikes are present throughout the area and correspond to narrow (300-600 m wide) linear magnetic anomalies that extend for tens of km. In the Goochland terrane, domes cored by Mesoproterozoic State Farm Gneiss show ovoid ring-shaped magnetic anomalies and high and/or low K and Th values corresponding to the carapace of heterogeneous mafic-, granitic-, and pelitic-composition rocks within the Sabot Amphibolite and Maidens Gneiss. Using these criteria, the new data reveal an unmapped dome in the southern part of the terrane near Fieldstown, VA. This area encompasses granitoid gneiss from the Morefield Mine, which from previous work showed a U-Pb zircon age of ca. 1035 Ma but had been mapped as part of the Paleozoic Maidens Gneiss. Placement of this sample location within a newly recognized dome with a Mesoproterozoic State Farm Gneiss core resolves this apparent conflict regarding published ages.

Throughout the survey area, aeromagnetic data show numerous lineaments that trend NNW to NNE, oblique to the NE trend of the central Piedmont Province. Field measurements demonstrate that the magnetic lineaments are well-aligned with structural trends, many along major bounding shear zones of the eastern Piedmont fault system. These data will allow for detailed structural analysis of the fault zones to determine interconnections and junctions in relation to the dextral transpressive kinematic history of the eastern Piedmont during the late Paleozoic Alleghanian orogeny.

THE 9 AUGUST 2020 MW 5.1 EARTHQUAKE NEAR SPARTA, NORTH CAROLINA: EVIDENCE FROM GEOLOGIC MAPPING THAT CONNECTS SURFACE RUPTURE AND POSSIBLE PALEOSEISMICITY IN THE BLUE RIDGE, NC–VA

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The U.S. Geological Survey (USGS) National Cooperative Geologic Mapping Program (NCGMP) Piedmont and Blue Ridge Project and partners are studying the first documented co-seismic surface rupture in the eastern U.S. associated with the 9 August 2020 Mw 5.1 earthquake near Sparta, North Carolina (e.g., Figueredo et al., 2022). The earthquake epicenter was in polydeformed crystalline rocks of the Cambrian to Neoproterozoic Ashe and Alligator Back metamorphic suites in the eastern Blue Ridge. Our research involves detailed geologic mapping and surficial studies in the Sparta East and West 7.5-minute quadrangles (North Carolina and Virginia) and parts of the Whitehead and Glade Valley 7.5-minute quadrangles (North Carolina). This new mapping is facilitated by new post-earthquake QLO lidar coverage. Geologic mapping and lidar analysis document a co-seismic surface rupture, named the Little River fault, that is traced for approximately 4 kilometers (km). We have classified the fault according to mapped surface expression, characteristics in lidar, and accuracy of location and identification. Individual fault strands occur in an *en echelon* pattern within a 12 meter (m)-wide zone. The fault scarp is marked by a 5–50-centimeter (cm) high ridge with consistent southwest-side up and reverse (thrust) kinematics. Detailed bedrock geologic mapping identified the regional Paleozoic structure (mean foliation $063^{\circ}/52^{\circ}$), the dominant joint pattern (330° – 340° /to 150° – 160°), and several strands of brittle faults oriented similar to the co-seismic rupture and fault (110° – $120^{\circ}/45$ – 70°). The brittle faults are characterized by deformation zones 1 to 25 cm wide, often with several brittle faults localized within several meters in outcrops (<5 m). The Paleozoic foliation is fractured and rotated into the fault, and microbreccia and manganese (Mn)-coated slickenside clay seams occur along some fault fractures. Rotation of the Paleozoic foliation and other strain markers, and oblique slickensides on the fault surface document transpressional kinematics on several faults, but slip estimates are difficult to determine. The brittle faults are mapped for an additional length of 3 km to the northwest of the Little River fault along Bledsoe Creek valley. Numerous other Mn-coated slickensides on faults with variable orientations (most strike 40° – 120°) are mapped in saprolitic bedrock exposures adjacent to the Little River fault, and in the bottom of a major topographic lineament. Surficial mapping, carried out as traverses along rivers and larger streams both in kayak and on foot, documented soft-sediment deformation in alluvium at seven locations, which occur along sections of other NW-trending lineaments. In addition to the first co-seismic rupture in the eastern U.S., these results collectively highlight the reactivation of an older brittle fault and possible paleoseismicity in the Blue Ridge. Further, the combined length of the Little River fault, including its unruptured older segments, increase the total length of rupture and unruptured fault to ~7 km and suggest that a much larger earthquake could be possible on this structure.

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COMPILATION OF A NATIONAL WATER-WELL DATABASE FOR THE UNITED STATES

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The U.S. Geological Survey (USGS), as part of the National Hydrologic Geospatial Fabric (NHGF) project, is compiling a National Water-Well Database (NWWDB) from water-well records contributed by partnering agencies and academic institutions throughout the United States. The disparate water-well data are harmonized to a USGS implementation of the Open Geospatial Consortium (OGC) GroundWaterML2 (GWML2) standard to facilitate modeling and mapping of aquifer systems across administrative boundaries. The harmonized water-well data are to be published in the public domain and served on the USGS ScienceBase data hosting platform for broad use by researchers and water resource professionals. Additionally, a web-mapping interface is under development that will provide users the ability to download subsets of water-well records based on a custom area-of-interest. In an earlier study by Bayless, Arihood et al. (2017), methods were developed to (1) transform free-text descriptions of lithology, commonly noted by licensed drillers during water-well construction, into a constrained set of lithologic codes that are native to the USGS National Water Information System (NWIS), and (2) compute estimates of transmissivity from the results of single-well aquifer tests observed during well completion. The NWWDB will be populated with standardized lithologic logs and values of transmissivity derived using those same computational methods, which for the purpose of reproducibility and open science, will also be published in a Python-based software library consisting of a series of reusable functions. Applications of the NWWDB are envisioned to be wide-ranging and may include mapping of the depth to bedrock, potentiometric surface contouring, identification of vulnerable aquifer formations, inferences on the hydraulic properties of geologic units, estimates of groundwater storage, or other forms of analysis relating to the management of groundwater resources.

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CGMW AND THE WORLD 5M: GEOLOGICAL MAP OF THE WORLD AT SCALE 1:5M

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The development of modern means of communication across the globe has made the Earth smaller, and the need of global views and global maps has become important for public authorities as well as to economists, academia and civil society. The Commission for the Geological Map of the World (CGMW) was created for that in the early 20th century in an attempt to bring scientists together to be responsible for promoting and coordinating the preparation and publication of solid Earth Sciences maps of continents, oceans, major regions of the planet. As a truly international and scientific organization, geologists of all nations participate, under the guidance of the CGMW Bureau, in projects that encompass the many facets of Earth Science. The Bureau is composed of Vice-presidents of each of the 9 continental Sub-commissions (Europe, South America, North & Central America, Africa, Middle East, South and East Asia, Northern Eurasia, Australia-Oceania and Antarctica) and presidents of each of the Thematic Subcommissions (Tectonics, Geophysics, Metallogeny, Hydrogeology, Magmatism & Metamorphism, Hazards, Ocean floor).

As the volume of mapping syntheses increases in order to comply with the amount of more specialized and detailed information, digital databases are nowadays always associated to printed maps.

The necessity and urgency for the global community in Earth Sciences to have a digital geological map of world is considerable since it does not exist at a convenient working scale. The World 5M project aims at establishing a correlation of the world continental geological maps and oceanic structural maps, all digital. It is jointly supported by the CGMW, IUGS Big Science Program DDE and Chinese Academy of Geological Sciences (CAGS). The project involves the construction of a uniform and seamless digital geological map of the world at a scale 1:5M and its complete database (Figure 1), which might be used as a portal or an entry point to access other geological data of the Deep-time Digital Earth (DDE) initiative.

The World 5M integrates 8 continental geological maps and 4 oceanic structural maps at a scale 1:5M which have been produced under supervision of the Commission for the Geological Map of the World (CGMW) over the past 20 years. The main steps include to establish a new standardized legend and adequate metadata for the database, correlate, harmonize stratigraphic cuts and edit map boundaries (Figure 1). Within a 2 year-project framework, high resolution datasets (stratigraphy, structures, earthquakes...) have been harmonized and 3 continents (Europe, Asia and Africa) are now fully seamless.

In the context of this correlation, the CGMW Seafloor commission took the opportunity to upgrade the current digitization of oceanic plate boundaries. In spite of being one of the Earth's major tectonic features, the geometry of mid-ocean ridges at high resolution (~10 km), its segmentation by non-transform offsets vs transform faults, is not yet available on global scale. Existing plate boundary compilations are provided at coarser resolutions (e.g., Bird, 2003), usually suitable only for plate-scale studies. With the increasing extent of high-resolution bathymetry data publicly accessible in addition to a growing body of literature, it is now possible to map in detail the geometry of divergent plate boundaries, and their segmentation, along a significant proportion of the mid-ocean ridge system. While <20% of the seafloor has been mapped with multibeam shipboard systems, the ridge axis is relatively well-surveyed owing to research focused on ridge processes during the last few decades.

Through the World 5M project of the DDE Geological Mapping group, supervised by CGMW and CAGS, we publish the first World Seafloor Map at scale 1:5M. In this map, where we report up-to-date datasets of oceanic features, we have compiled a detailed cartography of the mid ocean ridge geometries, including individual ridge segments, globally. We also performed the digitization of all fracture zones that localize strike-slip deformation along well-defined transform plate boundaries linking ridge segments that are laterally offset. In this new digital dataset, we have also identified several segments that are not offset by transform faults, and which define zones of diffuse deformation accommodated through heterogeneous and complex transfer zones with no localized deformation. Our high-resolution map reveals the variability in the nature and distribution of both ridge segmentation and types of ridge offsets, and their possible dependence on spreading rate. This mid-ocean ridge system digitization is based on of the compiled shipboard bathymetry GMRT v3.9 (Ryan et al., 2009), available through www.gmrt.org and existing published literature. The map also includes other available datasets, such as seafloor magnetic anomalies, age of the oceanic crust, hydrothermal vents, IODP drill sites, sediment thickness, hot spots and large igneous provinces. The World Seafloor Map is built in a GIS environment, and all features are associated with specific metadata (attributes). All the digital data and associated data sources will be made available upon validation and verification to encourage contributions to improve, update, and correct the existing datasets.

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Ryan, W. B. F., et al. 2009. Global Multi-Resolution Topography synthesis, *Geochem. Geophys. Geosyst.*, 10, Q03014, doi:10.1029/2008GC002332.

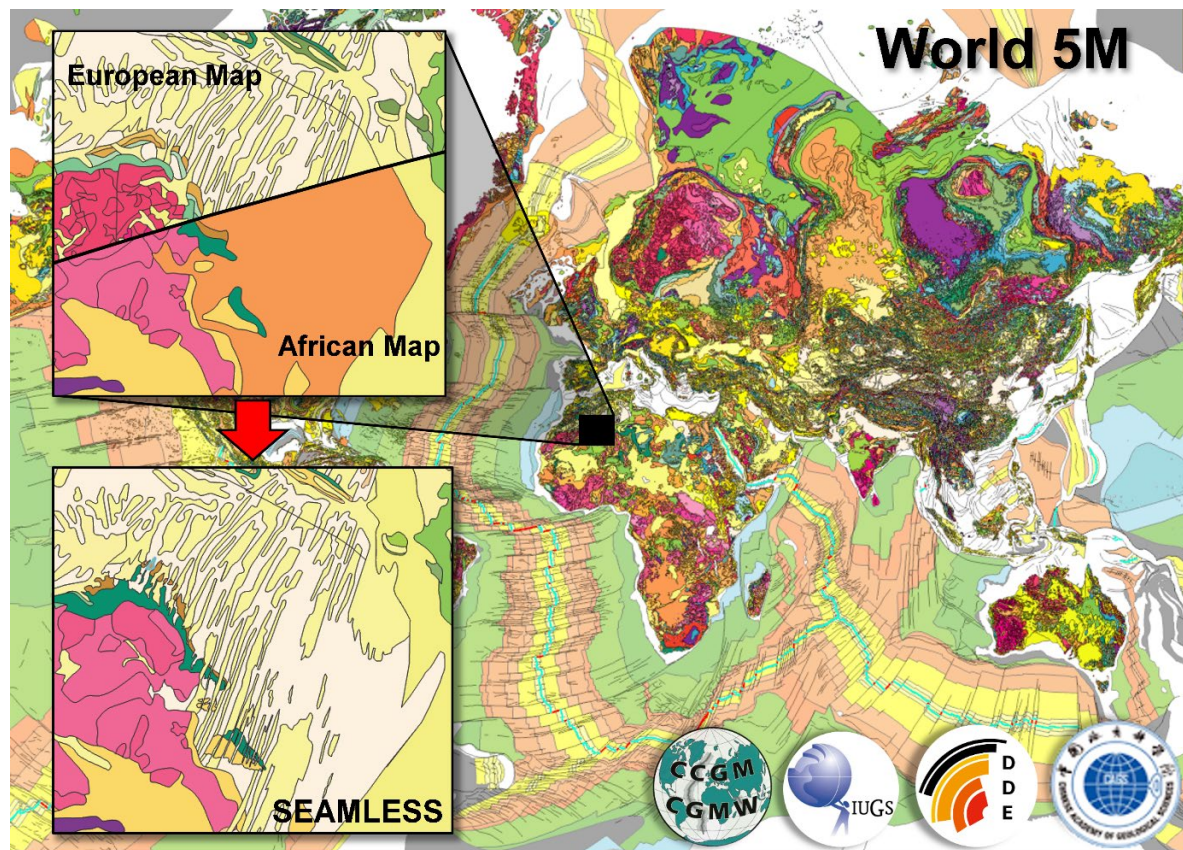


Figure 1: insight on the World 5M project with an example of map boundary harmonization

ON DEMAND, CUSTOM, TOPOGRAPHIC MAPS WITH TOPOBUILDER

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The U.S. Geological Survey's National Geospatial Program has released the topoBuilder application, which enables users to create topographic maps on demand using the best available National Map data. In topoBuilder, users can generate topographic maps, called OnDemand Topo, centered anywhere in the United States or Territories, with customized contour smoothing, and export formats GeoTIFF or GeospatialPDF. Maps are made at 1:24,000-scale for the conterminous United States and Hawaii, 1:20,000-scale for U.S. territories, and 1:25,000 for Alaska. Future releases are planned for additional customizations such as user-selected layers, user-added content, GIS data exports, and other map scales. TopoBuilder, its capabilities, and OnDemand Topo maps will be demonstrated.

CONNECTING THE DOTS: 3D REGIONAL AQUIFER MAPPING WITH AIRBORNE GEOPHYSICS IN THE MISSISSIPPI ALLUVIAL PLAIN

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The Mississippi Alluvial Plain hosts one of the most prolific shallow aquifer systems in the United States but is experiencing chronic groundwater decline. The Reelfoot rift and New Madrid seismic zone underlie the region and represent an important and poorly understood seismic hazard. Despite its societal and economic importance, the shallow subsurface architecture has not been mapped with the spatial resolution needed for effective management. Here, we present airborne electromagnetic, magnetic, and radiometric observations, measured over nearly 80,000 flight-line-kilometers, which collectively provide a system-scale snapshot of the entire region. We develop detailed maps of aquifer connectivity and shallow geologic structure, infer relationships between structure and groundwater age, and identify previously unseen paleochannels and shallow fault structures. This dataset demonstrates how regional-scale airborne geophysics can close a scale gap in Earth observation by providing observational data at suitable scales and resolutions to improve our understanding of subsurface structures.

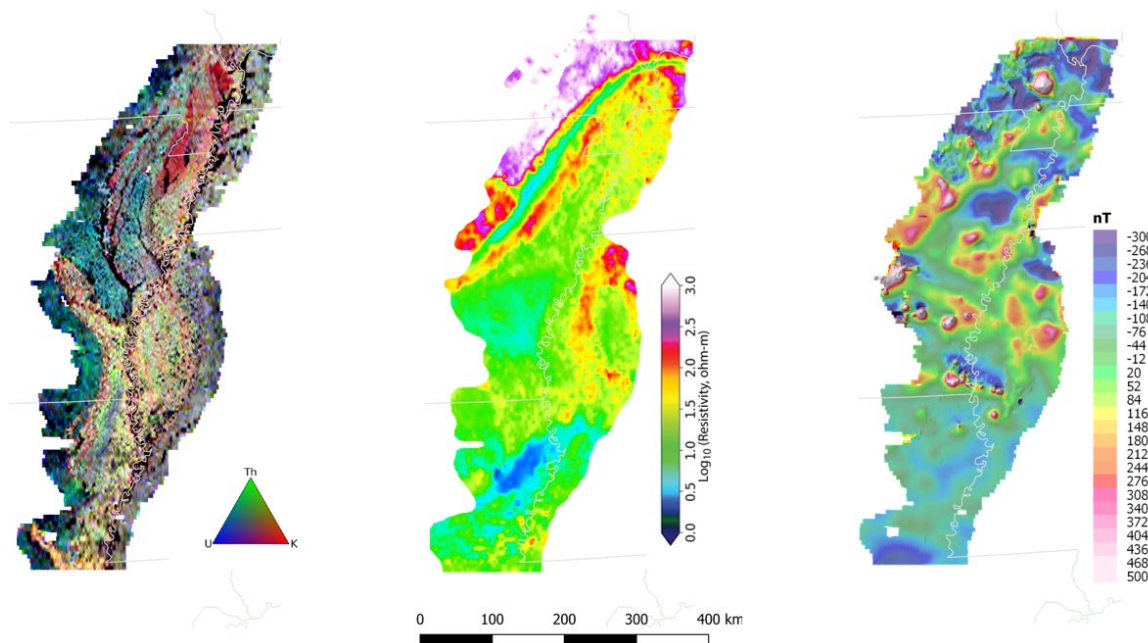


Figure 2. Radiometric ternary diagram, resistivity depth slice at 80 m belowground, and residual magnetic intensity compiled from over 43,000 flight-line-kilometers of airborne geophysical data acquired over the lower Mississippi River Valley covering an area of more than 140,000 square kilometers. These system-scale airborne geophysical data demonstrate capability for mapping geologic and hydrologic properties from the near-surface to depth that support diverse scientific and societal applications .

NEOGENE TECTONO-MAGMATIC FRAGMENTATION AND MIDDLE PLEISTOCENE GLACIOFLUVIAL INTEGRATION AND INCISION OF CENTRAL ROCKY MOUNTAIN FLUVIAL SYSTEMS, WESTERN NORTH AMERICA, U.S.A.

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The physiography of the central Rocky Mountains region is marked by high-elevation plateaus >2300 m asl, mountain summits >3200 m asl, active faults, and regionally-correlative Neogene-Pleistocene erosional and depositional surfaces. The highest elevation region found in Colorado forms a generally concentric headwaters for the Rio Grande, Arkansas, Platte, and Colorado Rivers, which flow through a diverse range of tectonic environments, primarily transtensional in the current framework (i.e., counter-clockwise Basin and Range rotation and east-west extension interacting with northwest-trending, right-lateral and northeast-trending, left-lateral shear zones forming a rhombohedral transtensional shear zone network. This further induced regional crustal thinning and/or created conduits for magma intrusion and associated volcanism). The overall physiography and range summit-valley floor topographic and geomorphic relationships of uplifted terrain can be generated by Neogene transtensional tectonism for the intermountain western, conterminous US at rates of 0.1-0.3 mm/yr, which is in accord with geologic, geodetic, seismologic, paleoseismologic, and geophysical studies. Miocene to early Pleistocene tectonics created broad, high-elevation ranges and abrupt linear valleys, and benches across the region, at elevations generally between 2,200-4,300 meters/7,200-14,000 ft asl, while disconnecting and/or rerouting watersheds and creating closed alluvial/fluvial systems.

For geologic mapping and stratigraphic purposes, we have further identified a regional unconformity between generally finer-grained, oxidized, basin fill and/or local alluvial/fluvial deposits and overlying, coarse boulder-cobble gravel deposits that, based on complex geomorphic relationships, have been interpreted to be any age from Oligocene to Pleistocene. In many areas Lava Creek B ash (~630 ka) from Yellowstone is captured below the unconformity in the underlying finer-grained basin sediments, yielding a maximum age for the unconformity (e.g., Upper Arkansas Valley, San Luis Valley, Wet Mountain Valley, Great Divide Basin). The red oxidized staining of the deposits underlying the unconformity are also suggestive of lateritic pedogenesis, indicative of semi-arid to arid early Pleistocene climatic settings. Boulder deposits above this unconformity are primarily limited to high elevations >2,200 meters asl, mountain-range perimeters and once-depositional, abandoned interfluves, and depositional plains grading to parks, passes, and glaciofluvial surfaces within ranges. The distribution and elevation of these high-level gravels suggests they can be produced by connectivity of broad icefields and permanent snowfields developed prior to major topographic development by fluvial and glacial erosion and stream capture. As subsequent glacial-interglacial epochs occurred, surface area for snow accumulation and development of these icefields was eroded, ever minimizing the icefield lateral breadth and watershed connectivity, and channeling ice and water into fluves and deep, glacial valleys. This induced abandonment of broad depositional surfaces and development of interfluves, parks, and passes, now abundant in the region. In many cases, well constrained late Pleistocene glacial-glaciofluvial erosion rates and geomorphic models can be extrapolated over multiple glacial epochs to produce much of the present landscape in <500 ky. With simplistic structural and geomorphic modeling, we tentatively associate this major unconformity with marine oxygen isotopes MIS 12-11, ~478-374 ka, the strongest excursion signal in the record and inferred largest and longest glacial-interglacial in Mio-Pleistocene time, and a recently recognized analog for the Last Glacial Maximum to present glacial-interglacial cycle and maximum global warming for the Pleistocene

For chronologic constraints on the sediments underlying and overlying the unconformity, we have coupled ¹⁰Be/²⁶Al cosmogenic burial isochron dating techniques with tephrochronology and cosmogenic surface exposure, U-series, and optically-stimulated luminescence dating techniques. At the headwaters of the Arkansas River, ¹⁰Be/²⁶Al cosmogenic burial ages on fine-grained, pre-unconformity sediments coupled with the presence of the Lava Creek B ash indicate local sedimentation and questionable/absence of glacial activity between ~2 Ma-630 ka, with major incision and deposition of glacial and glaciofluvial deposits occurring <630 ka. On the South Platte River system, the previously-thought Oligocene to Miocene Central City Gravel, has limiting burial isochron ages of ~1.5 Ma, and <400 ka incision of Clear Creek across North and South Table Mountains, and integration with the South Platte River. Adjacent Front Range piedmont-Great Plains studies support a <400 ka abandonment of upper surfaces and entrenchment of fluvial networks. Combining our new data with studies along the Rio Grande and Colorado River, we demonstrate coeval capture, incision, and establishment of present fluvial systems in response to middle Pleistocene glacial intensification.

USGS MINE WASTE RESEARCH

Darcy McPhee, Program Manager, Earth Mapping Resources Initiative (Earth MRI), Mineral Resources Program, U.S. Geological Survey, dmcphee@usgs.gov

The USGS Mineral Resources Program is leading the effort to develop a unified plan for mine waste research within the USGS, focused on understanding the potential for extraction of critical minerals from mine waste as well as the environmental impacts related to mineral extraction from mine waste and its remediation. As modern society utilizes increasingly sophisticated technologies, the need for reliable supplies of critical minerals has greatly expanded. In times of vulnerable supply chains, domestic mine waste is a potential source of some critical minerals for which the Nation is currently reliant on foreign suppliers. The USGS endeavors to provide the science needed to understand the potential for extracting mineral resources from mine waste while also improving efficiencies, reducing waste, mitigating the impacts of mining on communities and the environment, and helping to offset the costs of reclamation.

Significant knowledge gaps occur in understanding the locations, compositions, and volumes of mine waste. In order to address these gaps, USGS will lead efforts to develop a national mine inventory that encompasses data and information derived from the U.S. Mineral Deposit Database (USMIN) as well as state and federal mine databases. Additionally, USGS will continue and strengthen efforts to map and characterize mine waste sites in key mineral systems thought to contain appreciable amounts of critical minerals in cooperation with states. Interpretations of these data will contribute to improved descriptive models of mine waste in areas of specific critical mineral deposit types, more refined estimates of the volume and concentration of target minerals in mine waste at local and regional scales, geo-environmental models useful for evaluating the environmental impacts of mineral extraction, and models that will inform economic feasibility. Ultimately, this work will lead to more robust assessments of critical minerals in mine waste and, potentially, reprocessing of mine waste for critical mineral extraction by the private sector. These data, models, and interpretations will also provide the foundations for developing tools to support reclamation and land-use management decision-making regarding critical mineral recovery from mine wastes and their reclamation.

Dave Soller

No abstract

Dave Soller

No abstract

MACROSTRAT: EXTENDING A PLATFORM FOR GEOLOGICAL DATA EXPLORATION, INTEGRATION, AND ANALYSIS

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Macrostrat is a platform for deep-time crustal research that integrates stratigraphic columns and geologic maps into a digital description of the rock record in spatial and temporal context. Macrostrat indexes 1,534 regional stratigraphic columns in its core dataset, and thousands more in “projects” geared towards different use. It also compiles 300+ geologic maps at multiple scales into a seamless product. The database and supporting software power models of continental evolution and provide location-based geological information through multiple user-facing portals (e.g., <https://macrostrat.org>, the Rockd app, and StraboSpot). We are working to extend the Macrostrat platform with new methods to engage with geologic maps and columns, add other proxy datasets alongside our core data holdings, and build new multi-user systems to extend and enhance the underlying stratigraphic and map datasets going forward. This effort constitutes a “version 2” of the Macrostrat platform with an emphasis on scalability and collaboration.

Visualization and engagement: The Macrostrat lab has recently focused on novel visualization methods towards building engaging platforms for interacting with geologic maps and stratigraphic columns. These include efforts towards rendering geologic maps atop 3D terrain and a new systems for digitally representing stratigraphic columns. All of these tools are built with open-source techniques and designed for reusability in other projects.

Alongside maintaining its own libraries, Macrostrat contributes to open-source software managed by other organizations. By partnering with other companies and geoscience organizations, we hope to build a shared set of tools that can enhance the expression of geological data in many settings.

Incorporating proxy data: Aligning Macrostrat’s stratigraphic archives with proxy datasets (e.g., geochronology, fossil occurrences, and stable-isotope geochemistry) is important to answering key science questions. The Macrostrat lab has taken a community-driven approach to developing data integrations with the holders of proxy data: we are a partner in PaleobioDB and a leader of the EarthCube Geochronology Sparrow effort, which empower domain researchers to manage, harmonize, and share digital research data. These efforts will allow the crustal framework maintained by Macrostrat to be compared with focused rock-record data to illuminate inconsistencies and enhance integrated models.

Multiscale stratigraphy: Macrostrat supports multiple working scales of mapping and stratigraphy, from continent-level summaries to single quadrangles and measured sections. Currently, Macrostrat’s core datasets are regional chronostratigraphic summaries, and its spatial footprint is biased heavily to North America. While this data is of sufficient scale and resolution to generate insights about the continents’ evolution through Earth history, increasing resolution and spatial coverage will support regionally-targeted scientific inquiries. This especially requires a new focus on lithostratigraphic datasets that are not initially calibrated to an age model.

Collaborative data curation: The current Macrostrat team is small and saturated with tasks. This presents a major barrier to substantially extending the system with new data. This is particularly true as work extends to high- resolution records that require substantial local expertise to compile and evaluate. New collaborative approaches to building the data archive will be required to drive the continued enhancement and spatial expansion of Macrostrat’s core data holdings. Macrostrat’s “project” infrastructure, which allows new datasets to be developed separately from the canonical dataset, forms the core of a new user-facing data curation software pipeline. This will incorporate new web-accessible tools to assemble and visualize regional stratigraphic datasets, an authentication and versioning framework for column datasets, systems to evaluate and refine multiple working age models, and tools to allow capture of the full-resolution measured sections that underly stratigraphic compilations. Ultimately, we hope to build a software system that incorporates processes for submission, review, coordination, and assimilation of community- contributed datasets of a variety of types and scales, in a framework that allows the original source to be tracked for all parts of the archive.

We are making progress towards these objectives on multiple fronts. We are building visualization software atop the Mapbox and Cesium commercial platforms and in open-source collaboration with NASA and NSF-funded researchers. Efforts are underway to compile column datasets focused on New Zealand, Russia, South America, and the deep sea. The eODP project, targeted at incorporating comprehensive IODP, DSDP, and ODP drill-core records has been particularly effective over 2021, and has pushed Macrostrat to evolve towards a more sophisticated system for high-resolution stratigraphic data. We have begun planning for deeper integrations with other projects such as the Paleobiology Database and the Sedimentary Geochemistry Project. We hope to continue this work while broadening and deepening collaborations going forward.

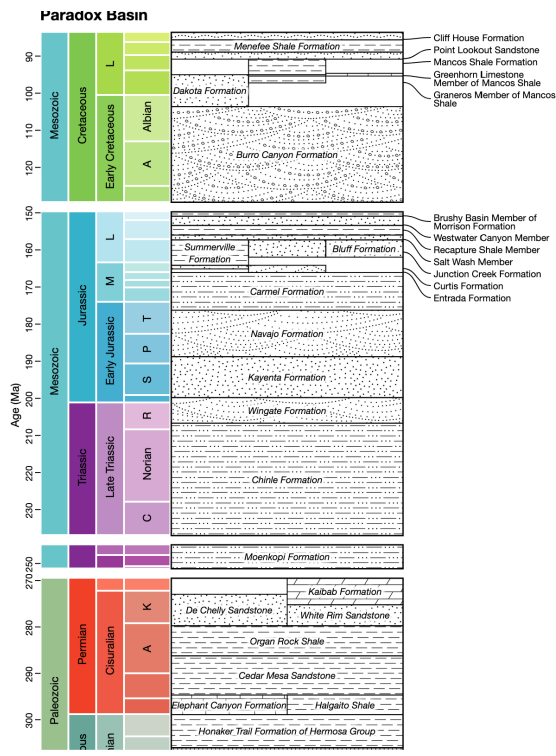


Figure 1. Rich web-based renderers for stratigraphic columns using Macrostrat-developed software libraries. (left) regional-scale chronostratigraphy of the Paradox Basin (below, left) Drill core record from ODP measured in the depth domain. (Below, right) Lithostratigraphic log with an associated stable-isotope record.

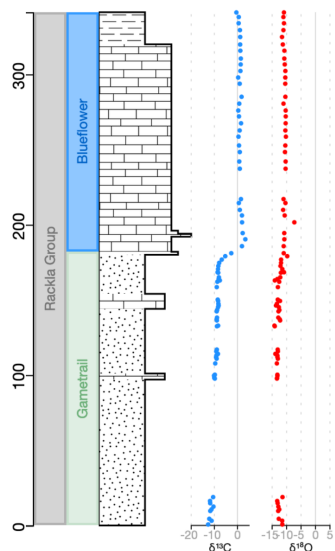
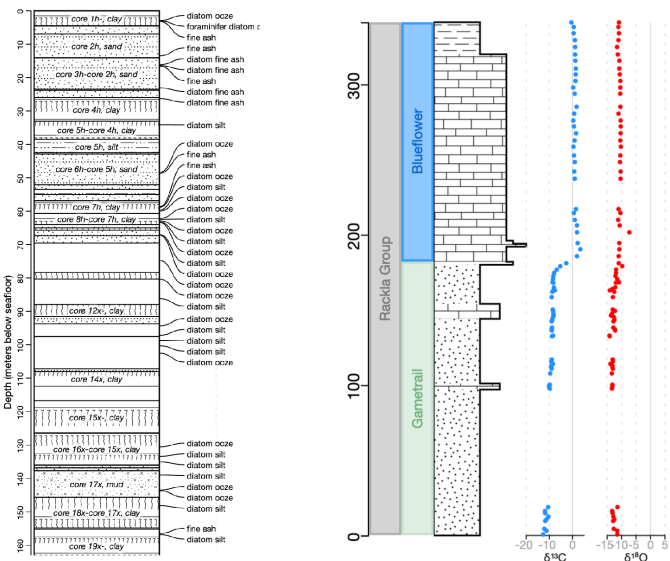


Figure 2. (left) A web-based paleogeographic reconstruction to the Visean period (346-330 Ma) showing Macrostrat columns (blue polygons), Macrostrat measurements (blue circles), Sedimentary Geochemistry Project measurements (red circles) and PaleobioDB fossil collections (grey circles). This hybrid view emphasizes the interoperability of digital datasets from multiple sources.

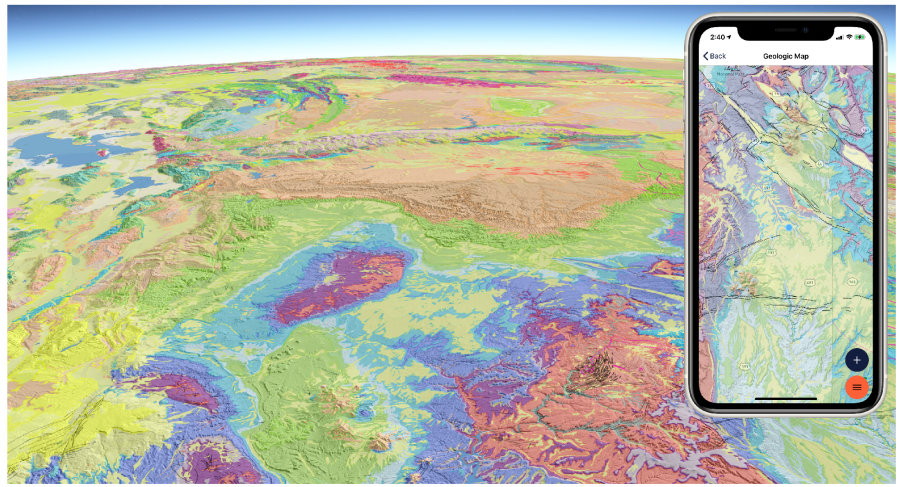


Figure 3. (left) Two different environments to view the Macrostrat geologic map compilation: a 3D digital globe using the CesiumJS platform, and the Rockd mobile application. Standardized web services allow the same underlying mapping data to be used for multiple public-facing purposes.

David Dockery

No abstract

Dean Peterson

No abstract

BIG DATA METHODS IN WATER MANAGEMENT

Debra Perrone, Assistant Professor, Environmental Studies Program, University of California, Santa Barbara

Water overuse is a complex problem that raises fundamental questions about management. Data themselves are not the solution, but they help us understand processes – human behaviors that influence demand or physical processes that inform supply – and can provide insights in how to best manage our groundwater and surface water resources. This talk focuses on the results of a five-year endeavor to collect construction details of millions of groundwater wells. The research highlights the tremendous amount of data available from agencies across the world and the value of stitching this data together to provide a local understanding of groundwater and the impacts of depletion at continental scales.

Doug Kreiner

No abstract

Drew Andrews et al.

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HIGH-PRECISION AEROMAGNETIC UAS SURVEYS

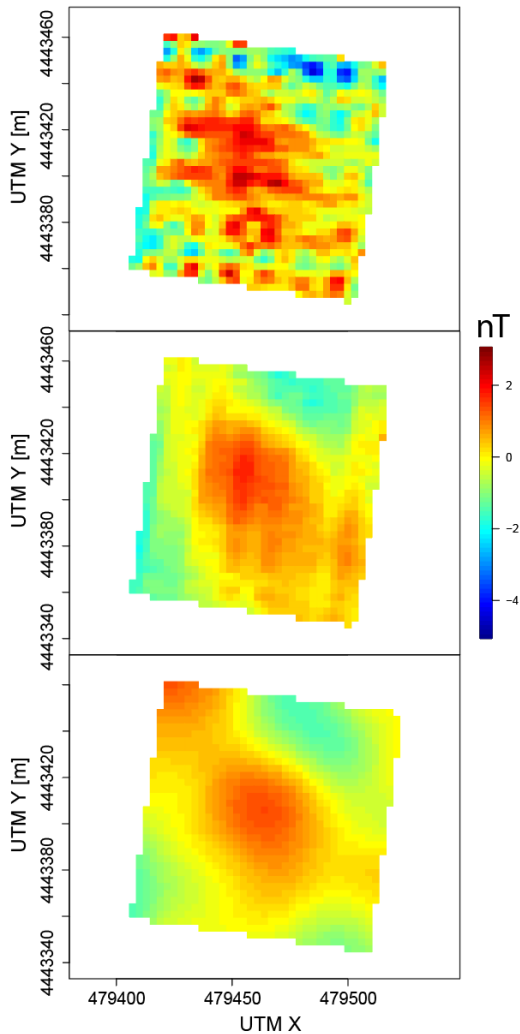
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Multirotor unpiloted aerial systems (UAS) that include a sling-load total field magnetometer sensor are a new method of collecting local(km²), detailed aeromagnetic data. Aeromagnetic UAS surveys typically fill the resolution gap between piloted aeromagnetic and ground magnetic surveys. The resolution of the collected data is typically better than most piloted aeromagnetic surveys, but not as precise as ground magnetic surveys, due to both the higher noise level introduced by the UAS and its greater height above ground.



In this talk we describe a modified sling-load aeromagnetic UAS that approaches the precision of ground magnetic surveys, while maintaining the advantages of rapid, spatially dense sampling across a much broader area than is generally achievable with ground surveys. By increasing the length of the sling to remove the sensor package from the magnetic noise produced by the aerial vehicle, and by applying a custom data processing algorithm that models the magnetic noise of the sensor package itself, we have been able to improve survey precision by about an order of magnitude relative to most commercial aeromagnetic UAS, from ~5 nT to ~0.5 nT. This increased precision permits the detection of geologic sources that produce low-amplitude magnetic anomalies a few meters across, such as diffuse mineral deposits, that were previously undetectable. This new UAS is capable of bridging the data resolution gap between ground level and piloted aeromagnetic surveys, largely obviating the need for ground magnetic surveys.

To characterize precision and repeatability of the aeromagnetic UAS, we surveyed a test site 100 m X 100 m for which we collected ground magnetic data. We flew four UAS surveys over the site, two at 25 m height above ground, and two at 40 m, with otherwise identical flight specifications. We used the 40 m flights to build two separate models of sensor package noise and applied both models to each 25 m flight, for a total of four aeromagnetic datasets (two models each, two 25 m flights). We completed a quantitative comparison of these four datasets to one another, and to the ground magnetic data, to evaluate the precision and repeatability of this aeromagnetic UAS. While most commercial aeromagnetic UAS have a precision of approximately 5 nT, we found that surveys flown with this system and data processing procedure are repeatable to within < 0.5 nT and match the ground-based aeromagnetic survey to within 0.5 nT. Frequency analysis of the data indicate that the magnetic noise caused by the sensor package is significantly reduced when the custom data processing algorithm is used.

Figure 3. Unprocessed (top) and processed (middle) aeromagnetic data for the test site, compared with the ground magnetic data (bottom).

Geoff Zeiss

No abstract

SEAMLESS 3D GEOLOGICAL MAPPING OF THE USA

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Introduction: Geological mapping is of escalating importance. People strive for safety, health, wealth, and respect for our human and natural heritage. Geological knowledge is needed by society to fulfil all of these aspirations. Geologists provide this knowledge as research, mapping, monitoring, modeling, and management. Our efforts help clarify energy, minerals, water, hazards, infrastructure, and research. There is an urgent need for us to better enable management of these topics. Examples of applications that require complete, consistent, queryable, and model-ready geology include sedimentary basin analyses, mineral resource assessments, inclusion of groundwater in regional and national water resource management, hazards modeling such as for earthquake propagation and magnetic storm vulnerability, infrastructure design, and all research on our planet and its life. The US Congress therefore has directed us and funded us to build the multi-resolution, queryable 2D and 3D geological mapping that is required by the people of this Nation.

Mapping: Geological mapping is an activity that is familiar to us all, and we all know what a geologic map is. All mapping is guided by a specification, and assessment of progress toward goals. We map the atmosphere, land surface, water depth, and subsurface/subbottom. The latter includes soil mapping, underground structures, and geology. Geology is an asset in our national geospatial knowledge infrastructure.

Soil mapping: Soil mapping and geologic mapping are the same thing. Soil mappers think in cm, whereas geologic mappers think in m and km. Soil mapping has advanced to a dynamic, seamless database. Soil mapping is the best reference for geologic properties for the 1st m on land.

Underground structures: There is a need for coordination between geology and mapping of underground structures such as pipes, wires, and tunnels.

Geology: Due to the sparsity of data and the need for interpretation, our maps are authored by researchers who can visualize the geology. Our research informs our mapping, and our mapping informs our research. Academics balance research, teaching, and service, whereas survey geologists balance research, mapping, and service.

Data: Observations enable our inferences that are meant to support applications. Our mapping serves as a window on the data. Our data need to be findable, accessible, interoperable, and reusable (FAIR). Each database of observations, collections, or measurements requires ongoing assessment, under data stewardship programs.

Geologic maps: In geological mapping, we have focused on 2D maps that are not necessarily positioned vertically, nor fully categorized, although each is seamless and includes some 3D. Paper-format 2D geological maps have distinct advantages, and in the future will be more important than ever. In resource, hazard, and engineering applications, geological maps commonly need to be translated and augmented as derived maps. Geological mapping returns a very positive cost/benefit. All mapping has resolution levels, each with appropriate generalization. Resolution levels for geology are here described as urban (<24K), detailed (24/250K), national (500K/2M), continental (5M), and global (~30M). Detailed geological maps are based on fieldwork, analyses, topography, and geophysics, or on assembly of new and compiled data for covered geology. For the US, a simple definition of detailed mapping is any new map more detailed than the current state geologic map. Our mapping is guided by an evolving stratigraphic model. Coordination with neighbors is an essential activity that leads to consistency needed by users. Compilations are based on assembly and reconciliation of multiple published maps. For generalized compilations, such as a state geologic map, gaps are infilled at consistent resolution as required. That, I think, was a summary of geologic mapping as we have known it.

Seamless 3D: However, new and unfamiliar forms of geological mapping have emerged, and we still lack consensus on our direction. Change is being driven by the realization that research, mapping, and monitoring are essential for the quantitative modeling and management that are needed to respond to societal expectations. In the digital era, compilations no longer have to be generalized to fit on a sheet of paper. Seamless, queryable, updatable databases therefore have emerged in all mapping fields. It seems likely that paper-format geologic maps will mainly be used as PDFs by eye, while GIS users will prefer seamless. It might not be possible, nor even desirable, to save the GIS files for every paper map, forever. Seamless is a standardized compilation, without generalization, and with ongoing harmonization and facilitation of query. Seamless shows gaps, to ensure consistent resolution, to show where mapping is needed, and to attract funding. Lower resolution mapping can be used to infill gaps to make a best-available map for some users. The purpose of seamless is queryability. Interoperability is not enough. Ongoing maintenance of seamless requires standards to support interoperability, ongoing assessment of progress, synthesis in part to test harmonization, and iteration to incorporate ongoing updates. In the past, 3D was done as sedimentary basin atlases. In 3D, vertical position and properties of surfaces, strata, and structures are specified as allowed by data. In 3D, a layer is a seamless 2D map polygon whose thickness can be mapped. To be queryable, seamless 3D has to be built from a mature 2D map. For layers, we map extent, vertical position, thickness, properties, heterogeneity, and uncertainty. Dominant lithology allows inference of properties such as hydraulic conductivity. To support a 3D program, jurisdiction- wide, onshore/offshore, and cross-border cross-sections are needed at

the outset. This will help resolve stratigraphic issues, and clarify surfaces to be mapped. 3D also requires long-term effort on data and geophysical surveys, especially drillhole data. 3D mapping can be expressed as a grid of synthetic drill holes. Below the layers is basement. In layers, we map strata, and in basement, we map structures, then discretized properties.

Modeling: These new forms of mapping are a transition from conceptual models to the mesh paradigm. Our work in research, which is conceptual, mapping, which is spatial, monitoring, which is temporal, modeling, which assembles research, mapping, and monitoring, and management, which is enabled by modeling, is required, especially in fields such as groundwater. We thus can foresee that a future role for geological mapping will be to support nested dynamic models. Model-ready, machine-readable geology is best done primarily by geologists, with appropriate roles for modelers or machines methods. Modeling may be done on a one-time project basis, or as an indefinitely maintained digital twin. The 1st and most important step in modeling is the conceptual model, a qualitative depiction that guides subsequent quantification. Geological maps are conceptual models meant to primarily be used by eye, that are not necessarily positioned vertically, and that often are not fully categorized. The 2nd step in modeling is mesh, for all space of interest, varying in resolution if necessary, with uncertainty specified. Seamless and 3D function in the mesh paradigm – quantifiable, complete for all horizontal and vertical space in the area of interest, structured resolution, with uncertainty indicated. In seamless, legends are parsed to facilitate query, and in 3D, everything is vertically georeferenced.

Roles: All information is most usable if standardized, and users demand standardization. Geological mapping therefore now involves: 1) maps, 2) standards, and 3) seamless and 3D. This three-fold approach was recognized two decades ago in the design of the National Geologic Map Database (Soller and Berg, 2000; 2001). Geologic maps presented as research publications and conceptual models are NGMDB Phase One – the catalog. Protocols needed to make our geologic maps usable and interoperable are NGMDB Phase Two – the standards. Seamless and 3D are NGMDB Phase Three – the framework database. Paper maps are static, authored publications that undergo one-time peer-review. Standards are developed through consensus with guidance from standards organizations. Seamless undergoes recurring audits, and is updated indefinitely as versioned databases. International agencies are considering alignment with these three functions. Multinational geological maps are published by the Commission for the Geological Map of the World (CGMW). CGMW is focusing on a continental-resolution bedrock for the global Deep- Time Digital Earth (DDE) project. Development of international geologic map standards is led by the Commission for the Management and Application of Geoscience Information (CGI). Seamless 3D is a good task for OneGeology.

Evolution: We are evolving. From the 1980s to the 2020s, soil mapping has evolved from photomechanical, to digital, to web accessible, to seamless, to gridded, to raster, to dynamic. Geological mapping is entering the seamless phase. Geological mapping as we know it began with the 1815 William Smith geology of England and Wales. Our 1st century involved national surveys and hand-colored wall maps. Our 2nd century involved the printing press. It can be foreseen that our 3rd century will focus on enabling model-ready national 3D geology to support digital twins.

NCGMP: We all will play a role in building the geological mapping that the people of this Nation require. Congress has directed us, and funded us, to build detailed, national, and continental-resolution seamless 2D and 3D. The National Cooperative Geologic Mapping Program (NCGMP) is facilitating critical functions: program office, conference support, coordination, geospatial reporting, stratigraphic naming, NGMDB Catalog, NGMDB Standards, NGMDB Phase Three, international coordination, and cross-border harmonization. There are crucial federal roles: detailed mapping, including cross-border, federal priorities, and mapping needed to optimize synthesis; stratigraphic, paleontological, structural, geochronological, and other research, especially as needed to support synthesis; and arrangements for national synthesis products, with arrangements for indefinite updating. Federal databases can largely be built from iterated State contributions: mapping, derivatives, catalog, training, digitizing and conversion, regional mapping, seamless, surfaces, correlation, strata, and geochronology. At detailed, national, and continental resolution, as allowed by data, we require seamless for all pieces of the puzzle: bedrock geology, bedrock elevation, surficial geology, basement geology, basement elevation, 3D rock strata, 3D sediment strata, and 3D basement structures. We need to learn from synthesis work by USGS Energy, Hazards, Minerals, and Water. We need a great acceleration in data compilation and geophysical surveys. We need to focus on an orderly progression of tasks. As in all mapping, completeness is first achieved at low resolution. We have a mature continental-resolution bedrock, so we are ready to begin seamless 3D by assigning thickness and properties to these layers. We need a 2D, than 3D seamless continental resolution surficial map, and a basement map after we decide what will be layers. An urgent priority is a seamless national resolution bedrock. We could be ready to start seamless 3D at this resolution in as little as a half decade. Our focus for detail will be on reconciling annually updated statewide seamless. Seamless 3D detailed mapping is likely to consist of local stratigraphic models, and geostatistical lithology based on drillhole databases audited by geologists and supplemented with new drilling and geophysical surveys such as airborne EM. Urban applications largely will be based on data.

Status: We need consensus on what we will do, and measures of our progress. Status mapping is required, to develop consensus on goals, to monitor and manage our progress, to identify priorities, to stimulate funding, and to cause us all to strive. A status map differs from a publication index, which indicates the spatial footprint of published maps, including obsolete, superseded maps. Status mapping requires local knowledge, judgement about needs, a composite index, and thus an indication of progress toward evolving goals. This nationally standardized, annually updated status procedure, implemented in stages, will require consideration of 2D mapping, depth to bedrock and basement or equivalent, subsurface data and mapping of sediment and rock layers, and basement mapping.

Hazen Russell

No abstract

ISOTOPE MAPPING AND CONSTRAINING THE GROWTH AND MODIFICATION OF NORTH AMERICA'S PRECAMBRIAN BASEMENT

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Nearly all of North America is underlain by Precambrian crust. This ancient foundation influences all younger geologic and tectonic processes including seismicity, igneous and metamorphic events, sedimentary basin development, and mineralization. Further, these rocks span essentially the entire preserved rock record and have the potential to provide important insights into the processes that form, modify, and stabilize continental crust. The paucity of diagnostic fossils commonly used for constraining rocks of younger time periods and the fact that distinctive textural or tectono-stratigraphic features in Precambrian rocks may have been altered or even erased by metamorphism pose challenges to constraining the boundaries, age, and provenance of North America's basement.

Isotope geochemistry has been used over the last five decades as a critical tool to fingerprint tectonic and crustal blocks, map their spatial extents, and to characterize their histories. However, a comprehensive understanding of the North American basement provinces has been limited due to scatter of isotopic data across various sources and the lack of consistent data analysis. To rectify this, we are compiling a new geospatial isotope database. To date >36,000 published isotopic analyses have been digitized and georeferenced. This dataset is sourced from peer-reviewed literature and geological survey reports and includes radiogenic (Sm-Nd, Lu-Hf, Sm-Nd, Rb-Sr, Re-Os) and stable (O) isotopic systems. We will present preliminary results of internally consistent, quantitative analyses of this dataset using both geologic- and geochemical-informed parameters. These datasets reveal peaks in the timing of crustal growth and modification and demarcate major crustal boundaries. Additionally, this comprehensive compilation reveals gaps in the extent of current datasets. To rectify this, we have collected new samples from critical bedrock exposures and drill cores for modern in-situ analysis. Geochronologic, geochemical, and isotopic analysis of phases such as zircon, feldspar, monazite, and xenotime yield micron-scale data that have map- and continental-scale implications. Taken together, this dataset has direct implications for constraining the first order lithospheric structure of North America, for understanding the multi-phase tectonic evolution of North America from the Archean to present, and for detrital mineral and provenance studies related to mineralization and archeology.

MAPPING MAJOR TERRANE BOUNDARIES IN EAST-CENTRAL ALASKA

James V. Jones III, USGS Alaska Science Center

The boundary between the allochthonous Yukon-Tanana terrane (YTT) and parautochthonous North America (PNA) in eastern Alaska marks the inboard limit of accreted terranes in the northwestern Cordillera. The YTT-PNA boundary represents the culmination of a long-lived and complex series of tectonic events along and outboard of the North American plate margin. The terrane boundary presently comprises a series of low-angle penetrative structures that formed and/or were reactivated during multiple episodes of regional Permian to middle Cretaceous tectonism, and it is difficult to identify because 1) rocks on either side have similar compositions and early Paleozoic histories, 2) kinematic indicators are complicated by polyphase metamorphic and deformation events, 3) the geophysical character of YTT and PNA assemblages is generally similar, 4) older contractional structures were overprinted or reactivated by middle Cretaceous extensional structures, and 5) extensive Cretaceous and younger plutons cross-cut and obscure key relationships. Targeted geologic mapping and geochronology focused along the international border in eastern Alaska provides key constraints for delineating the terrane boundary and interpreting its kinematic evolution and tectonic history. A suite of new zircon U-Pb ages of meta-igneous rocks do not provide unique constraints because ca. 366 to 355 Ma deformed granitoids (i.e., orthogneiss) are present in both the YTT and PNA assemblages. Detrital zircon age characteristics of YTT and PNA strata are also similar because they have common Neoproterozoic to Paleozoic origins. Allochthonous YTT rocks yield Jurassic and older hornblende, muscovite, and biotite $^{40}\text{Ar}/^{39}\text{Ar}$ ages, whereas PNA assemblages consistently produce Cretaceous cooling ages. Our integrated data and observations suggest that, in eastern Alaska, the boundary between the YTT and PNA is a zone of low-angle, ductile to brittle-ductile deformation that separates allochthonous YTT lithotectonic assemblages that are structurally higher from more deeply exhumed Late Devonian PNA assemblages that are structurally lower. Collectively, the YTT domains are lithologically heterogeneous and structurally complex, and they contain a mix of Late Devonian to Permian rocks that were thrust onto PNA and then exhumed along middle to Late Cretaceous low-angle detachment faults. Our findings provide new constraints on the timing and processes involved in formation, evolution, collision, and unroofing of a major accreted pericratonic terrane along the Mesozoic North American continental margin and bear on the geologic evolution of the northwestern Cordillera and other accretionary orogens worldwide. Furthermore, they provide a robust bedrock geologic framework that provides new and important insights into the formation and distribution of mineral resources in the region.

PRODUCING SUBSURFACE GEOLOGIC MAPS THROUGH BOREHOLE INVESTIGATION IN DAY COUNTY, SOUTH DAKOTA

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Subsurface investigation efforts are continually being conducted within the South Dakota Geological Survey through drilling test holes and installing observation wells with our in-house drilling rigs. High-quality lithologic and geophysical logs preferably spaced upon a 3-mile by 3-mile grid, are utilized to produce county-based 1:100,000 scale maps including: subsurface cross-sections, bedrock geologic maps, bedrock contour maps, aquifer maps, and aquifer materials maps. County-wide studies are conducted by geologists to produce the suite of maps listed above, as well as surface geologic maps. Day County resides in northeastern South Dakota, almost completely upon the Coteau des Prairies, which is a flat-iron shaped highland that has been extensively glaciated during the Quaternary period. Due to the immense deposits of glacial sediment residing over Cretaceous-aged bedrock, high quality lithologic and geophysical logs are paramount in developing subsurface geologic maps.

VOLCANO-TECTONIC HISTORY OF THE HOOD RIVER GRABEN: A LATE PLIOCENE-HOLOCENE INTRA-ARC GRABEN AT THE CREST OF THE NORTHERN OREGON CASCADE RANGE, USA

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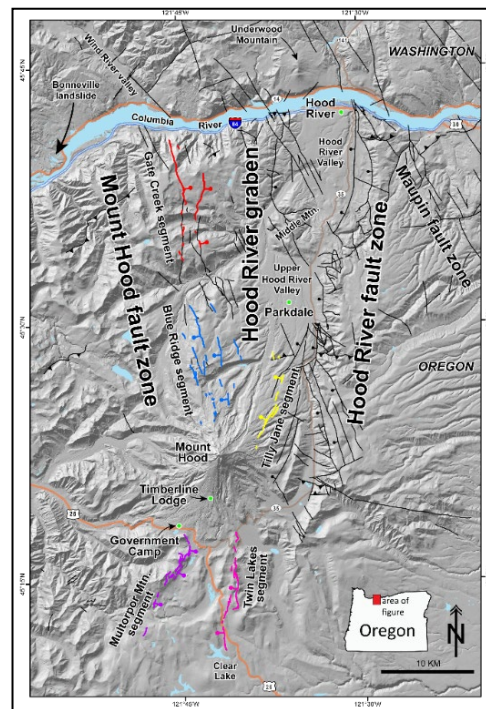
The High Cascades intra-arc graben is a segmented and structurally discontinuous, ~20-to 30-km-wide, arc-parallel graben system running for ~150 km along the crest of the Oregon Cascade Range, from the Three Sisters of central Oregon north across the Columbia River and into southern Washington. This graben system is segmented into three northward younging parts by NNW-striking faults: a southern segment between the Three Sisters and Mount Jefferson; a central segment between Mount Jefferson and Mount Hood; and a northern segment between Mount Hood and Mount Adams known as the Hood River graben (McClaughry et al., 2012, 2020; Conrey et al., 2019). All segments of the High Cascades graben are defined by significant offset along eastern boundary normal faults and asymmetric uplift of the western graben margin. Paleo-drainages west of the graben are elevated 600 to 800 m above modern base levels, suggesting broad uplift of the Western Cascades concurrent with rifting (Conrey et al., 2019). Tilted fault blocks invariably dip eastward off the structural high. The High Cascades intra-arc graben records a regional northward younging pattern for both the eruption of low-K tholeiitic basalt (LKT) and the related onset of extensional faulting, from 8 to 5 Ma at the latitude of the Three Sisters, 6 to 4 Ma near Mount Jefferson, 4 to 2 Ma in the Hood River graben, and ca. 1 Ma and younger in the Indian Heaven volcanic field in southern Washington (Conrey et al., 2004). Geothermal drill-core data suggest a total subsidence of 3 km in the southern segment and 1 km in the central segment; geologic mapping and cross sections indicate subsidence of <1.2 km in the Hood River graben (McClaughry et al., 2020). Subsidence developed along each graben segment as volcanism declined, typically after ~2 m.y. of elevated eruption rates. Volcanism immediately preceding graben formation is notable for the association of LKT basalt, Fe-rich andesite, and rhyolite lava flows, and rhyolitic ash-flow tuffs (Conrey et al., 2019; McClaughry et al., 2020).

The Hood River graben is a late Pliocene to Holocene structural depression superimposed across ENE- trending folds and thrust faults that deform the lower to middle Miocene Columbia River Basalt Group and the upper Miocene to lower Pliocene Dalles Formation in this part of the Yakima Fold Belt. Situated between the NNW-striking Mount Hood fault zone (MHFZ) on the west and the NNW-striking Maupin fault zone (MFZ) on the east, the graben is defined by a 20- to 25-km-wide complex network of distributed north-striking normal faults and NNW-striking right-lateral normal oblique faults (Fig. 1; McClaughry et al., 2012; 2020). Middle Mountain, a structural block of the Columbia River Basalt Group bounded by NNW-striking oblique-slip(?) faults, divides the graben into two rhombohedral-shaped segments, known as the Hood River and Upper Hood River Valleys (Fig. 1; McClaughry et al., 2012). The eastern structural margin of the graben is the prominent west-facing escarpment of the Hood River fault zone (HRFZ), mapped for ~50 km along the eastern flank of Mount Hood to the Columbia River (McClaughry et al., 2012, 2020). The HRFZ is a 1- to 3-km-wide zone of generally N-striking and W-dipping normal faults that are segmented by and are possibly linked to the NNW-striking right-lateral normal-oblique slip faults. Near the Columbia River, the northern end of the HRFZ appears to merge with MFZ, while near Mount Hood, the southern end of the HRFZ may merge with the MHFZ (Fig. 1). The HRFZ has accommodated hundreds of meters of vertical offset along the eastern graben margin after 3.7 Ma, with cumulative displacement >1,220 m on the south at Mount Hood decreasing northward to ~130 m at the Columbia River (McClaughry et al., 2012, 2020). The western structural boundary of the graben is more diffuse and less topographically obvious than the eastern boundary. It is defined by the NNW-striking MHFZ, a fault system consisting of multiple segments, including the Multitorpor Mountain, Blue Ridge, and Gate Creek faults (Fig. 1; Madin et al., 2021). Many of these fault segments are demonstrably pure dip-slip, but a few NNW-striking faults record subtle evidence for a minor right-lateral component (Bennett et al., 2019; Madin et al., 2021). Post-Miocene east-side-down vertical fault offset at the northern end of the MHFZ may exceed 200 m in the Columbia River Basalt Group exposed in the Oregon cliffs of the Columbia River Gorge with similar offsets observed in overlying late Pliocene LKT basalt cropping out at the top of these cliffs (Bennett et al., 2019; Madin et al., 2021). Holocene activity has been documented in recent paleoseismic trench excavations on several of these faults, including the west-dipping Blue Ridge fault (Madin et al., 2017), the east-dipping Gate Creek fault (Bennett et al., 2021), and the west-dipping Twin Lakes fault (A. Streig, Portland State University, oral communication, 2020), where they offset late Pleistocene glacial till or post-glacial Holocene deposits (Fig. 1).

Development of the Hood River graben is related to a long history of regional clockwise tectonic rotation and NW translation of crustal blocks along NNW-striking fault systems in the upper plate of the Cascadia subduction zone. NNW-striking dextral-oblique fault systems appear to be kinematically linked with N-striking normal faults to collectively accommodate right-lateral shear and east-west extension across the axis of the High Cascades volcanic arc to form the Hood River graben as a transtensional pull-apart basin (Fig. 1; Bennett et al., 2019; McClaughry et al., 2020). The south-to-north time-transgressive pattern observed along the High Cascades intra-arc graben is also observed at the scale of the Hood River graben. Normal faulting along the HRFZ at Mount Hood is chiefly post-3.7 Ma; normal faulting along the HRFZ is

chiefly post–3.05 Ma at the Columbia River (McClaghry et al., 2020). The stress fields, in the form of regional clockwise tectonic rotation, do not appear to have changed over the past ~16 m.y. across the northern Oregon Cascade Range. Changes in the dominant style of deformation from Yakima-style folding to NW-trending transtension at ca. 4 to 3 Ma, thus may be related to the arrival of a major pulse of LKT volcanism as the High Cascades rift propagated northward to the latitude of the Columbia River. Intra-arc rifting in the Hood River graben may have been enhanced where NW-striking right-lateral structures pass through the arc.

Figure 1. Tectonic and physiographic map of the Hood River graben and surrounding areas. Fault strands with evidence for late Quaternary activity within the graben are colored by their fault segment: Gate Creek (red), Blue Ridge (blue), Tilly Jane (yellow), Twin Lakes (magenta), and Multoppor Mountain (purple). Faults that lack evidence for late Quaternary activity (black) compiled from Washington Department of Natural Resources and Oregon Department of Geology and Mineral Industries. Tick and ball symbol on downthrown side of normal faults. Teeth on upthrown side of thrust faults. Modified from Madin et al. (2021). The basemap is a U.S. Geological Survey 10-m DEM.



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CONNECTIVITY ACROSS OPEN SPACE AS A POTENTIAL DRIVER FOR BREAKTHROUGH SCIENCE

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Geologic mapping occurs at a variety of scales, from outcrop to continental scales. State and federal agencies in the U.S. map at a variety of scales, generally ranging from 1:24,000 to 1:1,000,000. In most cases, when developing these maps, there isn't enough time or funding to collect all the data that one would wish.

In contrast, mining and exploration companies typically produce larger scale maps that show a smaller area with a greater amount of detail. These maps include face maps in underground mines, bench maps in open pit mines, and prospect-scale maps at exploration properties. In many cases, these maps are informed by rich data sets that include geological, geochemical, and geophysical data from drill core and surface work, and it's becoming common for companies to use these available data to build three-dimensional geological models.

There is a great deal of open space in both the scales of work and the data richness between government and industry geologists. In many cases, there is a lack of collaboration between industry and researchers, so integration across this open space is rarely achieved.

This talk will present case histories from the Midcontinent Rift of North America, the Coeur d'Alene mining district of Idaho, and from the Hauraki Goldfield of New Zealand that demonstrate how researchers collaborated with industry to produce science that integrated across open space to generate fundamental new insights. In all three cases, these insights could not have been achieved without the support of industry. These examples are intended to remind us of the benefits that can be achieved through diverse partners collaborating across a range of scales.

Jenna Shelton

No abstract

GEOLOGIC MAPPING PROGRESS ALONG THE SAN ANDREAS FAULT, SOUTHERN CALIFORNIA

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The California Geological Survey began geologic mapping within the Lancaster 30' X 60' quadrangle in 2006 utilizing the USGS's STATEMAP program and state matching funds. This quadrangle is comprised of the San Gabriel Mountains in the south, the Mojave Desert in central region and a portion of the Tehachapi Mountains in the north. The terrain is both geologically and topographically complex, crossing three geomorphic provinces, a plate boundary, and three major faults, including the San Andreas, San Gabriel and Garlock. These faults and susceptible landforms pose seismic risk to communities and infrastructure within Los Angeles, Ventura, and Kern counties. The map area has several urban centers and a mixture of public and private land. There is also economically important infrastructure, including U.S. Interstate 5 and the State Water Project's California Aqueduct. CGS has completed 15, 7.5-minute quadrangles, with an additional two in-progress, and plans to compile the detailed 7.5-minute data into a published 30'X60' quadrangle and pamphlet by 2025. As part of the STATEMAP deliverables and support for partners that manage risks to the state's infrastructure, geologic mapping coupled with geochronologic dating within the Lancaster quadrangle helped to identify Late Pleistocene activity on the San Gabriel Fault, suggesting the fault is active by definition of the California Department of Water Resource's Division of Safety of Dams (35,000 ybp). This advancement in the map area indicates the seismic source models in the region have been underrepresenting the hazard, especially with respect to the seismic safety of the Pyramid and Castaic reservoirs. In addition to the seismic source improvements, numerous landslides have been mapped around both reservoirs that could, during an earthquake, be reactivated causing a tsunami and possible overtopping or failure of the dam structure. Landslide mapping along highway corridors also serve as a basic hazard identification dataset for highway managers. Improvements to geologic mapping along the San Andreas fault has also rectified long standing inconsistencies with the interpretation of geologic units displaced along the fault, but has also unveiled new questions about the geologic evolution of Neogene and Quaternary landscapes in the region.

John Brock

No abstract

John Yellich

No abstract

ANNUAL MONITORING OF LANDSLIDES IN VERMONT USING DRONE AND GEOLOGIC SURVEYS

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Landslides are a risk to human health and safety and property assets. Since 2019, geologists from the Vermont Geological Survey, Norwich University, and the University of Vermont have collaborated with the VTrans Unoccupied Aerial Service (U.A.S) Team on the annual monitoring of active landslide sites in north-central Vermont.

Intensive field surveys are necessary to understand the underlying geologic framework for a landslide and drone surveys give a critical aerial perspective. Game cameras can be used to view parts of a landslide area on an hourly basis. Each of these field methods is completed annually. All data sets are integrated using photogrammetry software to produce 3-D geologic maps and animations.

Our multi-disciplinary surveys have detected significant differences over a year at the Cotton Brook landslide and delta and also at the Smugglers Notch rockfalls and debris flows. Our landslide team plans to apply this methodology to other active landside sites of interest to VTrans, including Westmore (Lake Willoughby) and Buels Gore.

Keith Turner

No abstract

Kelsey MacCormack

No abstract

USGS GEOCHRON: A NEW DATABASE OF GEOCHRONOLOGICAL DATA

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Amy Gilmer, Geosciences and Environmental Change Science Center, U.S. Geological Survey, Denver, CO

Geochronological data provide essential information necessary to address fundamental Earth science questions. Understanding the timing of geologic processes and events as well as quantifying rates and timescales is key to geologic mapping, mineral and energy resource assessments, and natural hazard assessments.

The existing USGS National Geochronology Database was last updated in the early 1990s. We have used this as a starting point to develop, populate, and update a new centralized database: USGS GEOCHRON. This new database has been expanded to include all types of geochronological data generated by USGS analytical labs, covering analytical techniques from optically stimulated luminescence (OSL) and cosmogenic nuclide dating to U-Th-Pb, Sm-Nd, and $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology. We will serve the data using a map-based web interface, providing advanced search functionality accessible via the interface and API.

The geochronology and geochemistry working group of the Geologic Framework of the Intermountain West project has developed a modern database structure for capturing and serving geochronology data. Our initial focus has been on USGS-collected data, but we are now expanding our focus to include published data collected by state geological surveys and other stakeholders.

Our workflow involves four ongoing parallel efforts to populate the new NGDB:

1. Data from the existing NGDB is being migrated to the new database.
2. Published literature data will be input into the new database by project staff, including NAGT interns.
3. Recent and future data can be extracted from ScienceBase tables using automated scripts to migrate the data into the new database. These scripts are in development by colleagues at geochron.org/University of Kansas.
4. Published data will be input into templates by state surveys and other stakeholders.

As part of the National Cooperative Geologic Mapping Program's Intermountain West Geologic Framework project, we have initially focused on capturing geochronology data that falls within the mapping footprint of that project. Staff on that project are locating the relevant data through literature searches and archived lab data. This will allow the geochronology data to be integrated with geologic map and subsurface data.

Lindsay Powers

No abstract

BEST PRACTICES AND RESOLUTION-BASED STANDARDS FOR GEOLOGIC MAPS: IMPORTANT STEPS IN THE DEVELOPMENT OF A RELIABLE NATIONAL GEOLOGIC MAP

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The stated vision of the National Geologic Mapping Program is to create an integrated, three-dimensional, digital geologic map of the United States and its territories to address the changing needs of the Nation by the year 2030. We have taken important steps to make this map more reliable for end users by 1) establishing standards for geologic map symbols, geologic database formats, and nomenclature, 2) providing funding opportunities for stratigraphic correlation and collaborative interstate mapping projects, and 3) encouraging the development of national databases for ancillary geologic information.

It is also important to develop best practices for new geologic data collection and digital compilation. Variable methods for data collection and compilation, examples of which will be provided in this presentation, result in map products with different levels of accuracy, precision, and quality. These variations can be problematic for users of 2D maps and will become more significant as we develop high resolution 3D models in the future. Standards are needed for the types and dimensions of geologic features to be included on different resolution maps. The inconsistent portrayal of geology is problematic for regional compilations and will take considerable effort to resolve at the national level if we are to meet our goal of an integrated national map. This effort can be reduced if standards are established sooner rather than later.

Some best practices and standards can be enacted nationally and others will be appropriate for a particular geologic province. Consistency within each geologic province is most important to provide dependable information to end users. For new mapping, best practices can establish the minimum density of observations needed to make maps at different resolutions, the minimum types of data that should be collected at observation points, the appropriate methodology for drawing geologic contacts remotely using LIDAR imagery, and the process for adequately field checking remotely drawn contacts. For geologic compilation, best practices can establish the appropriate scales at which to digitize existing contacts from paper maps, the best way to migrate digital line work into map products at different scales, and consistent approaches for documenting and resolving map boundary issues. Resolution-based standards can include the minimum dimensions of mappable geologic units and structures, the manner in which thin units or dikes are portrayed, the range of contact types that are used, the types of point data that are appropriate to include, and whether geologic lines such as fold axes are shown.

The Geologic Mapping Forum and Digital Mapping Techniques Workshop are ideal platforms to achieve consensus on best practices and standards. The ideas developed at these meetings can build on existing best practices and be published as a companion document to the FGDC Digital Cartographic Standard for Geologic Map Symbols and the GeMS format for digital geologic maps.

UPDATE OF GEOLOGIC MAPPING IN COLORADO AND THE GEMS PROCESS

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The Colorado Geological Survey (CGS) has been mapping 7.5-minute geologic quadrangles since 1993 under the USGS STATEMAP component of the National Cooperative Geologic Mapping Program (NCGMP). Funding is provided by the USGS and is matched by the CGS using funds from severance taxes paid on the production of natural gas, oil, coal, and mining. As of 2022, we have mapped 132 quadrangles in 31 Colorado counties since the program began. The purpose of the mapping is to provide geologic information that could be used for mineral and groundwater resource assessments, geologic hazards identification, and land-use planning.

Our mapping season typically runs from July through November. Field personnel collect their geologic information (points and lines) using Ipads equipped Avenza Maps, StraboSpot and FieldMove Clino, and also keep records in field notebooks. Compilation of the geologic map begins in December-January when the data is downloaded into ArcGIS and combined with lidar, imagery and other datasets. Map plate elements include an extended description of map units, correlation of map units, text describing the mineral and water resources, geologic hazards, and geologic history of the mapped area, at least one cross section and a 3-D oblique rendering of the map. The data is made available on the CGS bookstore for free download (Coloradogeologicalsurvey.org).

Thus far, CGS has achieved GeMS compliance by relying on our GIS contractor; geologists digitize their maps via their preferred method before the contractor converts them into the GeMS format. Though this process has been highly successful in producing GeMS-compliant maps, it has inherent issues. As CGS consistently moves towards higher-quality standards and integrated 3-D geologic mapping, the need for institutional understanding of GeMS has increased. For the 2022-2023 mapping season, we will begin a more intensive GeMS training program for our mappers. This program includes creating standard mapping templates for ArcMap and ArcGIS Pro, step-by-step guides, and group training focused on incorporating GeMS earlier in our map production process. Progress and feedback from this year will mold the following year's training. The overarching goal is to increase publication efficiency, enhance data quality, and better utilize the benefits of the standardization of map data.

SCALABLE IMPLICIT GEOLOGICAL MODELLING METHOD USING A DEEP LEARNING APPROACH TO SUPPORT NATIONAL SCALE MODELLING INITIATIVES

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There is a growing demand to build larger and more complex three-dimensional geological models for a multitude of geoscientific and societal purposes. At Geological Survey Organizations (GSOs), it is becoming more common to support national scale three-dimensional modelling initiatives (Berg et al. 2019) and highlights the limitations of current methodologies for building such geo-models. Currently, the most widely used modelling methods are based on the implicit approach. However, these methods can have challenges in producing geologically plausible models in structurally complex settings. Also, they often do not scale well as the number of point constraints or size of volumetric grids increases. Under these circumstances, existing implicit-based workflows can be very time consuming, an aspect that can severely restrict the construction of massive scale three-dimensional geological models.

To address these challenges, we develop an implicit geological modelling method using a deep learning approach that establishes a new frontier for geo-modelling. These approaches have unique advantages over classical approaches, namely their flexibility with incorporating different types of data and information as well as with how well they scale as the number of constraints increases. These advantages provide potential for the integration of a wide range of relevant geological data and knowledge, thereby opening up new opportunities for building better representations of the subsurface at massive scale. In addition, the parallelization capabilities of deep learning approaches and the seemingly endless supply of computational resources available in cloud computing platforms provides the means to support such intensive modelling objectives. While it is unrealistic to expect a completely new methodology to support all the advanced features of existing methodologies (e.g., complex fault architectures, kinematic restoration, water-tight meshes) that were developed and refined over the course of the last three decades, the work presented here lays the foundation for future work.

We base our technical developments on our previous work using graph neural networks (GNN) (Hillier et al. 2021) and extend the concept with a new deep learning neural network architecture using multilayered perceptrons. Comparatively, our latest methodology: (1) includes improved loss functions for contact and intraformational point constraints that lead to more accurate and geologically representative modelled horizons, (2) enables the inclusion of unconformities in the geological model, and (3) offers an efficient and scalable method to support provincial and national scale geo-modelling. These advances and capabilities support the aforementioned initiatives at Geological Survey Organizations (GSO). The new method is used to model the Western Canadian Sedimentary Basin (WCSB) in Saskatchewan, Canada from well data consisting of over 500, 000 top markers and intraformational picks of 49 geological formations. In addition, the modelling performance for representing unconformities within the lower Paleozoic portion of model is highlighted (Fig. 1). Modelling results demonstrate that the implicit deep learning method can be used efficiently to produce massive scale geo-models.

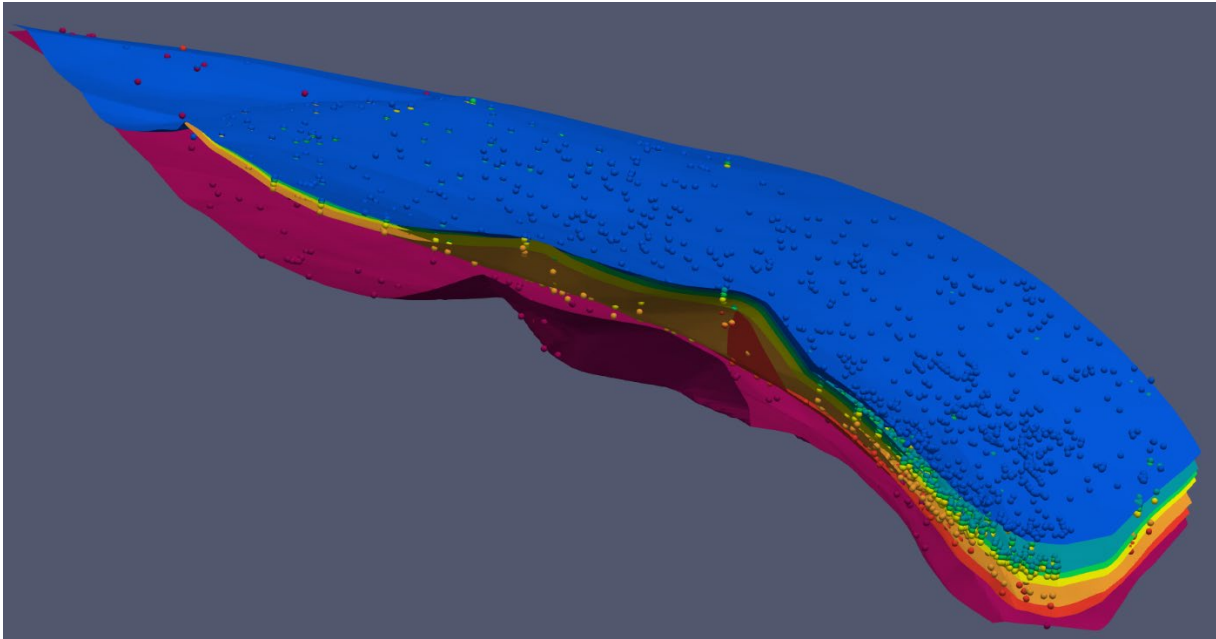


Figure 1: Three-dimensional geological model of the lower Paleozoic portion of the Western Canadian Sedimentary Basin in Saskatchewan, Canada obtained from the developed implicit deep learning method.

Future work in using neural network methodologies for three-dimensional geological modeling includes the application of the method to build larger models (e.g., the entire WCSB), and the incorporation of geological maps into the modelling step. In addition, future methodological enhancements address the ability to model more complex structures by neural network architectural improvements, new loss functions, and data augmentation techniques.

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DETAILED GEOLOGICAL MAPPING IN NORTHERN OHIO

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The production of geologic maps has changed in the past two decades with use of modern tools, aerial images, LiDAR, and GIS software becoming standard practice. The mass production of geologic maps at regional scales and in limited timeframes is made possible with these innovations. Simply relying on older geologic map data during modern regional mapping, with limited time for field verifying the critical points, restricts precision and reliability of the maps for resource estimation and planning for civil projects. It is possible and common in GIS-based regional mapping that the outlying data points are considered inaccurate measurements and normalized to match to the regional geology.

One example of this potential issue with GIS-based regional geologic maps is the bedrock geology maps near Chappel Creek and Old Woman Creek in Erie County, Ohio. Here, GIS-based regional geologic maps were prepared using old geologic map data with limited or no field verification. The resulting regional geologic maps display horizontal geologic formations with some Quaternary till cover, whereas detailed geologic maps of the area display evidence of folded geologic units as anticlines and synclines. During this study, stratigraphic and structural geometric field data were collected and used in the mapping process in ArcMap and Adobe Illustrator. The region is mainly covered by glacial till, and the bedrock units are partially exposed only in the valley walls and creek bed. The exposed formations in the study region are the Devonian Chagrin and Cleveland Members of the Ohio Shale, the Bedford Shale, and the Berea Sandstone. Sixteen anticlines with wavelengths around 200 m and amplitudes up to 50 m are exposed in the study area. The flanks of the folds dip up to 40 degrees and at one location the fold flank is overturned. The geometry of the folded Ohio Shale is different than the geometry of the Berea Sandstone, and the Bedford Shale between these units acted as a décollement zone.

The discovery of the Chappel Creek and Old Woman Creek anticlines, along with the presence of similar structures in Rattlesnake Creek east of Norwalk, and banks of Vermillion River indicates that more anticlines might exist under till-covered and uneroded areas. These underground structures with potential for oil and gas exploration could be easily missed in normalized GIS-based regional geological mapping. Detailed, field-verified geologic mapping needs to be considered along with GIS-based regional maps for major civil planning and investment projects.

UPDATES TO AND APPLICATIONS OF THE USGS NATIONAL CRUSTAL MODEL FOR SEISMIC HAZARD STUDIES

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Abstract

The U.S. Geological Survey (USGS) National Crustal Model (NCM) is being developed to assist in the modeling of seismic hazards across the conterminous United States. The NCM is composed of a grid of geophysical profiles, extending from the Earth's surface into the upper mantle. It is constructed from a three-dimensional (3D) geologic framework and geophysical rules defined by (1) a petrologic and mineral physics database; (2) a 3D temperature model; and (3) a calibrated rock type- and age-dependent porosity model. Parameters needed to estimate site response for existing ground motion models (GMMs), including the time-averaged velocity in the upper 30 meters (V_{S30}) and the depths to 1.0 and 2.5 km/s shear-wave velocity ($Z_{1.0}$ and $Z_{2.5}$), can be extracted from the NCM. As GMMs develop, other metrics could also be extracted or derived from the NCM such as sediment thickness and travel times, fundamental frequency, a fully frequency-dependent site response function, or 3D geophysical volumes for wavefield simulations. Application of the NCM may also benefit other aspects of seismic hazard analysis including better accounting for path-dependent attenuation and geometric spreading, more accurate estimation of earthquake source properties such as hypocentral location and stress drop, and calculation of crustal strength profiles that inform estimates of the base of seismicity.

Introduction

Seismic hazards and associated risks are present in many regions across the United States. The USGS is tasked with producing the National Seismic Hazard Model (NSHM), which includes maps of ground shaking that are exceeded with specified levels of probability based on earthquake source models and GMMs. The NSHM has been used to inform public policy, building codes, and emergency response protocols since the 1970s.

GMMs within the current NSHM incorporate one or more model parameters that account for site response— V_{S30} , $Z_{1.0}$, and $Z_{2.5}$. For building codes and consistency with previous practice, the original version of the 2014 NSHM applied a uniform V_{S30} of 760 m/s to the entire United States, with default V_{S30} -based values of $Z_{1.0}$ and $Z_{2.5}$ in the western United States where these parameters are applied, leaving refinement for specific site conditions to end users such as engineers. Due to spatial variability in subsurface physical properties and the application of relatively simple site response functions, the implementation of a V_{S30} map with default values of $Z_{1.0}$ and $Z_{2.5}$ and National Earthquake Hazards Reduction Program (NEHRP) site amplification factors can lead to substantial differences between predicted and observed ground motions. To reduce these differences, the USGS is moving towards (1) implementing different values of V_{S30} directly in the GMMs, rather than using NEHRP amplification factors; (2) accounting for spatially variable $Z_{1.0}$ and $Z_{2.5}$ as can be obtained from local seismic velocity models and as was implemented in the 2018 NSHM for select areas; and (3) including knowledge about ground motions gained from urban hazard modeling efforts.

A USGS NCM (<https://doi.org/10.5066/P9T96Q67>—published for the western United States) supports these efforts and can help to standardize site response prediction on a national scale by providing site response parameters for current and future GMMs. Development of an NCM can also improve the consistency between models used to develop GMMs and those used to predict a hazard. It could also improve other elements of seismic hazard analysis, for example those related to earthquake source properties.

Elements of the NCM

Geologic Framework

The depth to strong impedance contrasts such as bedrock and basement is one of the most critical parameters for estimating earthquake ground motions. In the NCM, numeric grids containing estimates of the depth to bedrock (equivalent to the thickness of unconsolidated sediments and originally assumed to be the base of Miocene deposits) and depth to pre-Cenozoic and pre-Phanerozoic basement are combined and integrated from previous studies or derived directly from gravity analyses. Once estimates of the depth to bedrock and basement are obtained, estimates of the material properties on either side of the contact are needed to better model how the seismic waves will propagate. A 3D geologic framework is developed based on a 1:250,000 to 1:1,000,000 USGS State Geologic Map Compilation, the Geologic Map of North America, maps of basement geology, and the depths to multiple subsurface geologic contacts including the base of Miocene, Cenozoic, Phanerozoic, and the Moho.

Petrologic and Mineral Physics database

A petrologic and mineral physics database was compiled to help convert geology to geophysical parameters. Presently, 132 distinct rock types are part of the geologic framework within the NCM, each of which is assigned a mineralogical composition according to generalized classifications and updated where more information is available for specific geologic formations. The mineral physics database builds off previous work by adding to the database the physical constants of 13 minerals common to continental rock types.

Temperature Model

The NCM thermal model is used to estimate the α - β quartz phase transition in the mid crust and the change in seismic velocities and amplitudes at greater temperatures where melt may be present and seismic attenuation can be high. Like the α - β phase transition, relatively high temperatures typically occur in the mid to lower crust but can occur near the surface in areas of high heat flow, such as where recent volcanism occurs. The thermal model can also inform strength profiles within the crust and can be used to develop maps of the depth extent of seismicity.

Regarding construction, the thermal model assumes steady state conduction with heat production for the continent and cooling of a half space in the oceans. It is constrained by (1) surface temperature from the Moderate Resolution Imaging Spectroradiometer; (2) near-surface temperature gradients, conductivity, and heat production using multiple databases; and (3) estimates of Moho temperature based on the velocity of P-waves that travel along the base of the crust.

Porosity Model and Calibration

Calibration of the porosity model makes use of Biot-Gassmann theory and over 2000 compressional- and /or shear-wave velocity profiles (<10 km deep) from across the conterminous United States and southwest Canada. The calibration relies on the fact that rock porosities have a significant effect on seismic velocities and ground motion amplitudes. As is observed for in situ rock specimens, porosity is assumed to be dependent on rock type and to decrease exponentially with depth.

Geologic Framework Updates

Western United States

Miocene and younger volcanic deposits were not properly considered in the initial geologic framework model, which assumed that the base of Miocene coincided with the top of bedrock. The geologic framework model is updated to include estimates of the thickness of Miocene and younger volcanic deposits, which are added to what was called the depth to bedrock map to produce a better estimate of the base of Miocene deposits.

Another update that is detailed in this presentation includes a revised gravity analysis for the thickness of unconsolidated sediments in the Basin and Range. The published version was implemented to resolve a 50-meter limit on the input base map of sediment thickness, but this analysis produced a new floor around 600 meters and heavily smoothed the maps, placing thick sediments in locations where none was expected. The revised analysis is more consistent with a steady decrease (increase) in sediment porosity (density) with depth, honors the base map's estimates at locations with thin or no sediment, and is constrained by estimates of the depth to base of Miocene along the Wasatch and elsewhere in the Basin and Range.

Central and Eastern United States

Surficial geologic maps in the central and eastern United States are made more seamless by resolving geologic discontinuities across state borders, which is needed to properly assign rock types and ages in the subsurface. Regionally, available state datasets for the base of Miocene are supplemented with a new background model that is more consistent with the state datasets than the global background model used in the western United States. Furthermore, depths to the base of Miocene, Cenozoic, and Phanerozoic deposits from hydrogeologic models and other datasets along the Atlantic and Gulf Coastal Plains are implemented.

Applications

Base of Seismicity

Earthquake ground motions at a site depend not only on an earthquake's latitude and longitude but also on its depth. In previous versions of the NSHM, crustal background earthquake sources, not including those on or within subducting slabs, are placed at a specified depth, generally independent of latitude and longitude. However, we know that the base of seismicity varies across the United States and is correlated with crustal temperature. We therefore develop a model of the depth to the base of seismicity by calculating crustal strength profiles using the NCM thermal model as well as maps of stress regime and strain rate, which could be used in future versions of the NSHM.

Z_{1.0} and Z_{2.5}

Updates to the NSHM may include implementation of Z_{1.0} and Z_{2.5} estimates in the Great Valley of California. Because the Valley's southern extent is not included in the Bay Area Seismic Velocity Model and regional tomographic models are inconsistent with the Bay Area model where there is overlap, hazard estimates using tomographic models are expected to be problematic. Therefore, estimates of Z_{1.0} and Z_{2.5} extracted from the NCM, which are more consistent with the Bay Area model, are being considered for use in the Great Valley.

Sediment Travel Time

In addition to potentially accounting for the thick sediments in the Great Valley of California, the NSHM project is also evaluating the impact of the thick sediments beneath the Atlantic and Gulf Coastal Plains. While site amplification models have recently been developed for the Coastal Plains, ground motion analysis has revealed that effects similar to those occurring in the Coastal Plains may be occurring in the continental interior where generally older rocks are present. I show that the use of sediment travel times in both regions can be used to explain some of the variance in earthquake ground motions relative to ground motion models for hard rock.

DIFFERENTIATING THE MISSISSIPPIAN GREENBRIER GROUP IN WEST VIRGINIA, IMPLICATIONS FOR KARST POTENTIAL

Philip Dinterman, West Virginia Geological & Economic Survey (WVGES)

West Virginia Geological & Economic Survey (WVGES) has been conducting 1:24,000-scale bedrock geologic mapping in the southeastern portion of the state over the past several years. One of the main objectives of this field mapping has been to differentiate the units of the Mississippian-age Greenbrier Group. Previously this unit had been mapped only at group level. The focus on the Greenbrier is due to the common occurrence of karst in these units. WVGES has focused on mapping areas of karst potential as the number one mapping priority for several reasons. These include, but are not limited to, impacts on groundwater, geological hazards, potential impacts from oil & gas drilling, and announced pipeline development in the region. Much of the current mapping area is in a rural part of the state and many people rely on water wells and/or springs for sources of fresh water. Additionally, this area is a popular tourist and caving destination.

Several years ago, WVGES was approached by the West Virginia Department of Environmental Protection (WVDEP, and which regulates oil & gas well permitting in West Virginia) to define areas of potential karst in West Virginia for purposes of identifying both surface and subsurface areas that may require further oversight for oil & gas well permitting. If a well was determined to be in an area identified karst area, legislative rules indicated that additional safeguards may be put in place to ensure that any drinking water zones would be unaffected by drilling activities. At the time of that request, WVGES supplied WVDEP with a map defining the carbonate outcrops in West Virginia and identifying areas by tax districts that would fall under the karst legislative language. This map was created using a state geologic map at 1:125,000 scale, available 1:24,000 scale mapping, locations of publicly known caverns, and consultation with the West Virginia caving community. Since that time, WVGES has been conducting mapping in some of the most prominent karst areas and has been working to further differentiate geologic units where karst is more common within the Mississippian Greenbrier Group.

Currently, WVGES separates the Greenbrier Group into the following units, in ascending order, Hillsdale Limestone, Denmar Formation (includes the Sinks Grove and Patton limestones), Taggard Formation, Pickaway Limestone, Union Limestone, Greenville Shale, and Alderson Limestone. Overall, the Greenbrier thickens from approximately 500 feet in Pocahontas County, ~800 feet in Greenbrier County, to approximately 1,100 feet in Monroe County. Overall, the Greenbrier represents two shallowing upward cycles. The first cycle represents a rise in sea level from the underlying unconformable contact with the Mccrady Formation and up to the Taggard Formation. The Pickaway Limestone unconformably overlies the Taggard Formation and represents the beginning of the second cycle which continues through the Alderson Limestone at the top of the Greenbrier.

Lidar reveals karst features at the surface, however, these features are not always indicative of a particular unit of the Greenbrier. Lidar is useful for some unit delineation, but examination of the units in the field is necessary for bedrock mapping. Caverns are more prone to be present in certain units or certain intervals, most commonly the Hillsdale and Union limestones. Within the Union, water sinks at or near the contact and relatively enhanced solubility causes many of the passages forming at the top of the Union to be vertical in nature. In some of these areas, the passages can either cut through the entire thickness of the Union in one pitch or, due to the presence of small beds of less permeable limestone, follow a stair-step approach to the base. Upon reaching the base (or near the base) and near the contact with the Pickaway, downward development either stops or becomes far more gradual. The Hillsdale Limestone, while being one of the most cavernous in the state, forms caves under quite different conditions when compared to the Union. Most of the caves formed in the Hillsdale are actually formed at the contact between the Hillsdale and the Maccrady; hence the term "Contact Cave." WVGES is continuing to map at 1:24,000 scale and is working towards completing the areas of karst in Greenbrier County. This mapping will connect with a FEDMAP project that is ongoing in Monroe County and connect with previous mapping of what is now the New River Gorge National Park. This effort will further refine maps for oil & gas permitting, as well as, provide data, maps, and information for users interested in karst potential in West Virginia.

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No abstract

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No abstract

MAPPING THE UNDERGROUND TO SAVE LIVES

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Based on more than three years of discussions between the Minnesota underground utilities sector and GIS community, in August 2020, Minnesota established an Underground Utility Mapping Project Team (UUMPT) to tackle the issue of poor quality utility maps and the negative impact it has on underground utility damages. The MN UUMPT is developing guidelines and capabilities for 1.) facility operators to create and maintain accurate maps of their utilities, and 2.) utility operators to allow design engineers, locators, and excavators to view the utility map(s) when needed to perform their work. This presentation will provide an overview of the substantial issues facing the UUMPT and where the effort is currently headed.

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Tim Connors

No abstract

THREE-DIMENSIONAL GEOLOGIC MAPPING OF PRECAMBRIAN ROCKS IN MINNESOTA: THE CREATION OF REMOVEABLE GEOLOGIC LAYERS USING GRAVITY AND MAGNETIC DATA INTERPRETATION

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As part of the National Geological and Geophysical Data Preservation Program (NGGDP) of the U. S. Geological Survey, the Minnesota Geological Survey (MGS) compiled geophysical models from past and on-going investigations to create three-dimensional representations of several Proterozoic basins, consisting of elevation contours and inferred bedrock geology of the underlying basement surfaces. Thus defined, the Proterozoic basins are represented as removeable, three-dimensional layers in the Precambrian bedrock map of the state. The NGGDP-MGS work focused on several basins including those associated with the Sioux Quartzite, the Animikie Group, the sedimentary rocks of the Midcontinent rift system, and the somewhat more complicated basin enclosing the North Shore Volcanic Group and the Duluth Complex (NSVG-DC). In this presentation we will focus on the results from the main bowl of the Animikie basin and the adjoining NSVG-DC basin. Figure 1 presents the elevations estimated for the basement of these two basins.

The basement elevations estimated for the main bowl of the Animikie basin are primarily based on Euler analysis, a semi-automated depth interpretation scheme, in which a non-magnetic basin sequence is assumed to overlie an assortment of anomaly sources that suitably approximates a basin floor. Correspondingly much of the Animikie sequence consists of non-magnetic slates and grauwackes, with anomaly sources restricted to iron-formation near the base of the sequence, or to sources within the underlying Archean basement. The Euler results were cross-checked in a few areas by conventional, two-dimensional modeling, and the geology of the inferred basin floor is based on extrapolating the bedrock geology of adjacent areas, as guided by gravity and magnetic anomaly signatures. The results (Figure 1) indicate that northern and western margins of the Animikie basin are rimmed by a shallow (0-1.5 km elevation) shelf. The northern part of the shelf has been previously inferred from earlier investigations, but the western shelf is somewhat novel, and it appears to be significantly controlled by NW-striking structures. Several prominent sources underlying the Animikie sequence are interpreted to be strongly magnetic, consistent with iron-formation-bearing horizons, and the steep northward dips interpreted for some of these sources are most consistent with Archean rocks in the region. The deeper parts of the basin are locally below -4 km elevation, including the area along the basal contact of the NSVG-DC basin. This ~5 km.-thick Animikie sequence could presumably continue to the east in some fashion beneath the NSVG-DC sequence. Such a scenario has implications for the metallogenesis and upper crustal geology of the region.

Euler analysis cannot resolve the base of a magnetic sequence so the base of the NSVG-DC basin is estimated along twenty two-dimensional gravity and magnetic models that transect the complex in strategic areas. Of these, ten models have been recovered and revised from earlier investigations and ten models have been created specifically for this study. Wherever possible, modeling has been constrained by geology mapped at the bedrock surface (Jirsa et al. 2012) and by rock-property data (Chandler and Lively, 2011). The modeling results were used to compile basement elevation contours beneath the land surface, and these contours were smoothed and merged with elevation contours beneath Lake Superior, which were compiled from 3-d gravity modeling and seismic reflection interpretations (Allen et al. 1997). The two lowest parts of the NSVG-DC sequence are interpreted lie ~15 km. below MSL, and are plausible candidates for major feeder zones. A prominent basement high separates these two lows, and it appears to ultimately connect with major basement ridges beneath Lake Superior, including Walter White ridge to the south, and with the Grand Marais ridge to the east. Estimated dips along the base of the NSVG-DC basin generally range from 25 to 60 degrees, with the steepest dips inferred along the northern and western basal contacts. A shelf-like structure inferred beneath the northwestern margin of the NSVG-DC basin lies roughly along-strike with the shelf inferred beneath the northern margin of the Animikie basin.

The interpretations presented here represent our current "best guess" of subsurface structure, based on available data, and many improvements should be possible in the future. As such, the interpretations presented here should serve as a helpful starting point for future three-dimension investigations, including the gravity, magnetic, and electromagnetic studies that has been recently initiated by the U. S. Geological Survey in the region.

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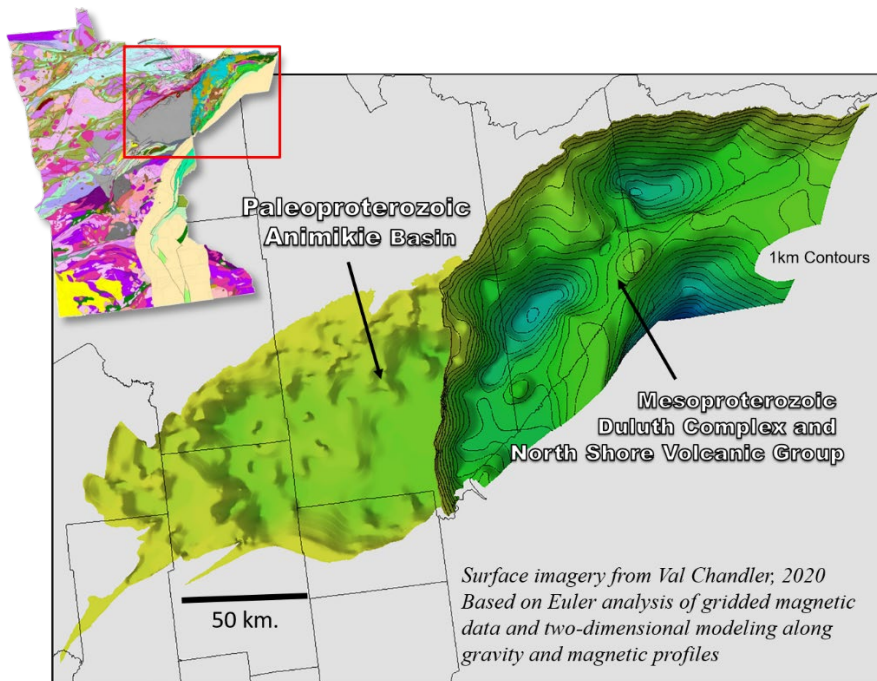


Figure 1. Estimated elevation of the basement surface below the main bowl of Animikie basin and the combined igneous sequence of the North Shore volcanic Group and the Duluth Complex. Elevations are relative to mean sea level, and range from 0 to 2,000 m. (yellow), -2,000 to -5,000 m. (light green), -5,000 to -15,000 m. (green), and <-15,000 m. (blue). Elevations beneath the North Shore Volcanic Group- Duluth Complex basin are highlighted with 1000 m. contours.

Vicki Lukas

No abstract

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No abstract