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Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

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Interactive web mapping tools and custom subsurface cross-sections for interdisciplinary geologic investigation

Tessica Anne Gardner Oldemeyer, Glenn Paul Russell *

Idaho National Laboratory, Idaho National Laboratory, 1955 N Fremont Ave, Idaho Falls, ID, 83415, United States

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ABSTRACT

Using Python-based geospatial analytics, open-source web mapping technologies, geophysical data models, and subsurface stratigraphy models from the Regional Geology Geologic Framework Model database assembled by Los Alamos National Laboratory, we developed a suite of web-based geologic investigation tools to identify and understand subsurface structures and geophysical properties concerning salt and shale formations within the contiguous United States. Coupled with a web map interface, these tools allow for the interactive visualization of various geologic data and demonstrate the ability to quickly generate custom subsurface cross-sections, borehole charts, and diagrams for azimuthal orientation data. These capabilities were developed for stakeholder and researcher use to facilitate informed decision making for spent nuclear waste disposition. However, these capabilities provide a flexible model for a variety of subsurface investigation needs, and we have demonstrated this flexibility by adapting these tools to meet visualization needs for various subsurface models within a web-based platform.

1. Introduction

Disposition of nuclear waste is a large and complicated goal. Subsurface siting for potential underground repositories is complex and relies on extensive geological assessments and an understanding of subsurface structure (e.g., lithologic, mineralogic, and hydrologic properties of potential host rock and the properties of the stratigraphic sequence that lies above and below the host rock) for site suitability analyses. These analyses (e.g., as conducted within the U.S. Department of Energy [DOE] Office of Nuclear Energy [NE] Spent Fuel and Waste Disposition [SFWD] program) require convenient data access and visualization of diverse geologic and geophysical data for informed decision making. Web-based map applications can be excellent tools for providing accessibility and visualization of various geologic datasets through convenient access from a web browser, interactive visualization, and ease of use. However, spatial relationships among subsurface data (e.g., geologic framework models and complementary geophysical data) may still be difficult to visualize within traditional two-dimensional web mapping interfaces. Within a web map application, adding the ability to quickly visualize multidimensional spatial relationships among these subsurface and geophysical data would provide added assessment value to researchers and stakeholders. Integrated, interactive custom cross-sectional profiling tools and custom charts can provide the expanded visualization capability needed to understand this subsurface structure.

Cross-sectional profiles are important tools for understanding subsurface structure. In the geosciences, it is useful to provide two-dimensional diagrams of the subsurface to allow for vertical interpretation of data-poor subsurface environments in relation to surface topography (Sousa et al., 2020; Yuksel et al., 2020). Geologic cross-sections are two-dimensional graphical representations of subsurface geologic structure along a horizontal or vertical profile line. Vertical profiles are represented in borehole charts, which are considered informative figures of the subsurface used by geoscientists and often used for diagrams of real-world well logs. Cross-sections and borehole diagrams are both widely used visualization tools within the geosciences. To construct these subsurface diagrams, researchers often rely on orientation measurements of strata gathered at the surface, which are derived from vertical electrical sounding, seismic refraction, or drilling methods. These diagrams are traditionally hand-drawn by domain experts for specific areas of interest, which is a lengthy and time-consuming process. Providing web-based tools, such as custom subsurface, geologic cross-sections and borehole charts, would allow researchers convenient visibility into subsurface structure. Additionally,

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* Corresponding author.
E-mail address: glenn.russell@inl.gov (G.P. Russell).

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incorporating multidimensional charts of subsurface structure and supplementary geophysical data would provide researchers and stakeholders a valuable visualization tool for multi-parameter, spatial evaluation of data of interest. With the ongoing evolution of web map application technology and spatial data visualization tools, the integration of a robust, georeferenced geologic framework model within a web-based map application provides for a unique opportunity to generate custom geologic cross-sections using framework model data. Besides applications for spent nuclear fuel waste disposition, these web-based tools for custom subsurface cross-sections could augment a variety of subsurface research, including petroleum research, rare-earth materials, aquifer management, carbon sequestration, and geothermal research.

Upon a survey of existing software packages and tools for providing researchers and stakeholders with these types of subsurface visualization capabilities, we found several desktop-based software solutions, including rule-based modeling options (e.g., Sousa et al., 2020), and several desktop-based geologic visualization software packages, including options like Petrosys, Petrel, RockWorks, Seequent's Leapfrog, Dynamic Graphics' Earth Vision, NeuraSection, and Strater to name a few (e.g., Turner et al., 2021). However, many of these desktop software options require tedious workflows to produce a single cross-section diagram. Additionally, several desktop-based geospatial software packages (e.g., ArcGIS, QGIS) provide options for building these subsurface cross-section visualizations (e.g., Turner et al., 2021). It is worth noting that some of these desktop-based options may require significant borehole and other data inputs for subsurface profile generation (e.g., Albion QGIS plugin). Other options, more suitable for the needs of this work, include generating stack profiles and fence diagrams in Esri geospatial software, 3D modeling techniques (e.g., Carrell 2014), or by applying a variety of approaches within custom script tools within ArcGIS workflows (e.g., Williams, 2021). However, many multi-purpose geospatial desktop-based options (e.g., Esri's Stack Profile tool) require spatially continuous data of congruent spatial extent, where our framework models and supporting datasets were often spatially discontinuous (i.e., spatially discrete) with varying spatial extents. Given the heterogeneity and discontinuity presented by geologic formations, these types of spatially continuous data requirements presented numerous data preprocessing challenges including data size, effective handling of null values, and effective preservation of data values unique to a distance along a profile line.

While desktop-based options provided insight for data exploration and analysis, providing such tools from a web-based platform for convenient accessibility and interoperability, was a primary focus of this work. Web-based options, such as Yuksel et al. (2020) and Hunter et al. (2016), provided options for flexible visualization tools for easy user access. Yuksel et al. (2020) demonstrates the incorporation of seismic resistivity and drilling data into rule-based, fuzzy-logic generation of 2D geotechnical cross-section models. Hunter et al. (2016) provided a web-based solution to visualize 3D subsurface models using Cesium software. Giuliani et al. (2016) explored 3D subsurface data visualization in a Web Graphics Library (WebGL) browser-based plugin. Although these solutions provided helpful insight into web-based subsurface data visualization, we hoped to provide subsurface visualization options to SFWD researchers and stakeholders within a web map-based interface where users could quickly explore data models for custom, user-defined areas of interest within the contiguous United States. Additionally, we hoped to find a solution, which would allow for the use of native spatial resolutions of spatially discontinuous, discrete raster data, to avoid extensive data preprocessing and unnecessary data footprint expansion.

With our work discussed in this paper, we built a web-based map application designed for versatile accessibility and exploration of geologic framework data while also providing users with the ability to quickly create custom cross-section and borehole profiles to visualize geologic and geophysical data models with interactive charting capabilities. Providing these data in a web-based mapping interface allows for users to conveniently explore various spatial relationships among geologic framework data and supplementary geophysical spatial datasets. This web-based interface enables access to a unified application as a comprehensive foundation to support informed decision making for geologic characterization within underground repository siting analyses.

2. Data and methods

2.1. Data

2.1.1. Regional Geology Geologic Framework Model database

The primary objective of this development was to achieve useful navigation and visualization of the robust Regional Geology Geologic Framework Model (GFM) database via a web map application. This database was developed by Los Alamos National Laboratory to contain data on the distribution of geologic host media for waste disposition within a geologic repository (Perry et al., 2014). Spatial information in this database includes surface models for the distribution of crystalline rock (including basement depth) and over 40 distinct salt and shale formations within the subsurface of the contiguous U.S. assembled from data composed by a variety of agencies over two decades. These data were constructed using terrane maps of crystalline basement rocks, an inventory of U.S. salt and shale formations, rock properties, and in-situ conditions for shale estimated from sonic velocity measurements (Perry and Kelley, 2017). This work focuses on the rasterized depth models for subsurface salt deposits, shale formations, and crystalline basement structures. These models were developed primarily from drilling data and the interpretation of geologic relationships within sedimentary basins, regions apt to preserve thick and laterally continuous occurrences of salt and shale at depths potentially suitable for hosting a geologic repository (Perry et al., 2014). These GFM products provide documentation of representative geologic structures and hydrologic characteristics for site evaluation and decision support (Sevougian et al., 2019, Stein et al., 2009).

2.1.2. Geophysical models and supplementary geologic data

As geophysical data such as aeromagnetic anomaly, gravity anomaly, and heat flow can provide additional insight into subsurface geological characteristics and structure, spatial comparison of these metrics with the Regional Geology GFM was key to SFWD researchers. Given this, nationwide data models for these metrics were integrated into the application's development. Aeromagnetic anomaly data (Bankey et al., 2002) are included to depict variations of intensity in Earth's main magnetic field. As various surface and subsurface features can affect these data, these data can allow for researchers to characterize subsurface structure and features. Similarly, we include gravity anomaly data (Phillips et al., 1993) to provide researchers with additional data with which to understand and characterize subsurface structure. We incorporated heat flow data (Blackwell et al., 2011), as heat flow values can have implications for subsurface structure and SFWD objectives. Stress field, faulting, and seismic hazard data were also compiled from the USGS and included within the web mapping application.

2.2. Methods

2.2.1. Data preparation for client

To prepare GFM data, geophysical data, and other supporting map layers for use within the web mapping application, we leveraged Esri ArcGIS products (Environmental Systems Research Institute, 2019). Subsurface stratigraphy GFM models, geophysical data models, and administrative data of interest were prepared for web map visualization within Esri Desktop software (v. 10.8.1) and published as representational state transfer (REST) map services for ArcGIS Server (v. 10.8.1) to be ingested within the web map. Spatial data to be used in interactive subsurface and charting tools were formatted as Esri file geodatabase raster (GDBR) datasets in a folder structure prepared for relative file access for processing on the hosting server. To allow for vertical profiling along the cross-section transects, geologic formation depth data were converted to elevation values respective to mean sea level (MSL) by subtracting GFM depth values from a smoothed surface digital elevation model. All geospatial data layers used in the application were projected to World Geodetic System (WGS) 1984 Web Mercator Auxiliary Sphere (European Petroleum Survey Group [EPSG]:3857).

To prepare GFM and other geophysical data for use within custom, interactive charts, we built custom Python-based RESTful geoprocessing services hosted via ArcGIS Server. Custom Python geoprocessing services were prepared and optimized to generate interactive profile graph components from user input within the web map interface. To produce custom subsurface profiles based on user-defined, custom profile lines, Python scripts were designed to take user-defined input polyline geometry from the web map and generate a table of data values for subsurface models intersecting the polyline geometry. These scripts effectively take user-defined input polyline geometry, add sample nodes along the line at a predefined interval, record elevation values for all intersecting raster layers at these nodes, and then produce an output table along with the descriptive attribute information (i.e., feature name) required to plot the elevation values within a chart in the web application. For cross-section profiles within the contiguous U.S., the predefined sample node interval along user-defined profile lines was set to 3000 m. This spatial resolution is specified within the geoprocessing script and can be adapted as needed to account for profile lines over smaller spatial extents, for site-specific applications, or complex terrain. This sampling resolution effectively standardizes the plotted resolution of these spatial layers within the interactive chart and enables fluid mouse indicator interaction. As this process standardizes the chart's data resolution, this approach allows for the raster layers to be sampled from native resolution, avoiding the introduction of excess error to these data through resampling techniques. The Python scripts used within these subsurface profile data processing scripts leverage Esri's ArcPy library (version 2.7.18), Esri's Spatial Analyst extension, and standard Python modules. These scripts were adapted to include various geophysical datasets (i.e., heat flow, gravity anomaly, and aeromagnetic anomaly) to meet various SFWD subsurface visualization needs. These Python scripts were then used within ArcGIS script tools (ArcGIS Desktop, version 10.8.1) and published as ArcGIS Server (version 10.8.1) RESTful geoprocessing services for web application use.

To prepare data for a borehole chart, we used a similar method as the subsurface profiling tools. However, the input geometry was designed to be a point location. From this user-defined input point, all intersecting raster elevation values and their attribute information are sampled and prepared as a tabular output to be used for the borehole chart. The Python scripts used for the borehole profile data processing scripts leverage Esri's ArcPy library, Esri's Spatial Analyst extension, and standard Python modules. The Python script for this functionality was also utilized within ArcMap as a script tool and published as an ArcGIS Server geoprocessing service for use by the web map application.

As a supplementary tool to the subsurface profiling capabilities and to further meet SFWD objectives, stress field data were prepared for rose diagram visualization, showing the azimuthal orientation of selected stress field information. To prepare stress field orientation data for this type of interactive visualization, custom Python geoprocessing scripts were used to generate a histogram of azimuth data for selected stress fields from a user-defined selection polygon. Histogram bins were set at 5° intervals. The Python scripts used for the rose diagram data processing leverage Esri's ArcPy library (version 2.7.18), the Pandas Python data analysis library, the NumPy scientific computing Python library, and standard Python modules. As with the subsurface profiling Python scripts, these scripts were used within ArcMap script tools and published as ArcGIS Server geoprocessing services.

Several steps were taken to optimize the performance of the geoprocessing services used to provide interactive charting interfaces within the SFWD web map application. These included the use of ArcGIS ArcMap layers rather than paths to datasets on disk, writing intermediate data to memory, and using data local to ArcGIS Server. Additionally, ensuring sufficient server processing and memory resources allowed for minimal geoprocessing time requirements. Ultimately, this application is running on a Windows (2016) server with 50 gigabyte (GB) random access memory (RAM) and 8 virtual processors. This server machine is running ArcGIS Server 10.8.1 and hosts many other applications. Hardware components may be scaled as needed to meet performance demands or to accommodate geoprocessing of expanded datasets.

2.2.2. *Front-end development and data handling*

To develop a web map application interface, Esri's ArcGIS API for JavaScript (version 3.38) was used within the Configurable Map Viewer (CMV) framework, an open-source JavaScript (JS) web map application framework built with the ArcGIS API for JavaScript and the Dojo Toolkit (Configurable Map Viewer, 2020). The Dojo Charting library and Plotly were utilized within the framework for interactive charting capabilities. Subsurface profile charting capabilities were built using the open-source Dojo Charting library, a JavaScript development toolkit (JS Foundation, 2005), and aimed to expand the elevation profile widget within the CMV framework (Configurable Map Viewer, 2020) to also include discontinuous, subsurface layers.

Upon a geoprocessing request from the client (i.e., upon completion of a profile line drawn on the web map using a subsurface profile widget), the user drawn input geometry (i.e., a profile line) is submitted to the associated geoprocessing service and tabular elevation and attribute values that are necessary to plot the data within the interactive charting interface are returned to the client. The returned elevation values for the surface topography, subsurface formations (i.e., shale formations and salt deposits), and crystalline basement rock are then plotted in a Dojo chart within the web map application. Fig. 1 shows an overview of the client and server-side processing steps to provide custom, user-defined subsurface cross-sectional profile charts.

Surface and crystalline basement series are added as area plots and symbolized to show the distinction among surface elevation values and the sediment thickness overlying the crystalline basement layer. Salt deposits and shale formation series are added to line plots and colored based on formation type. To provide a sense of connectivity with the charting interface and the corresponding profile line on the map, a feature present within Esri's elevation profile widget, a mouse indicator was added to the charting interface that corresponds to the position along the profile line in the web map (i.e., denoted by an 'X' symbol along the profile line in the map interface). To include geophysical data (e.g., magnetic anomaly) for direct comparison with surface and subsurface features, an additional y-axis was added to the Dojo chart. Geophysical data returns are added to a line plot using this second y-axis.

In a similar method as the subsurface profile charts, the borehole chart capability uses the Dojo Charting library to plot elevation values for subsurface data, which intersects the user-defined input geometry. When a user places a point location on the map using the borehole profile widget, the input point geometry is submitted to the borehole profile geoprocessing service, and tabular elevation and attribute information from the intersecting elevation raster data are returned to the client. These data are then plotted as separate series for each elevation surface within a Dojo chart. To emulate the look and feel of a borehole diagram, point location y-values were cloned, and $x + 1$ was added to x-value of the duplicate data to give the data plots a width characteristic for easier visualization. Surface and crystalline basement data series are added as area plots and symbolized to provide intuitive points of reference for the user. Salt deposits and shale formation series are added as line plots and colored based on formation type. Tooltips (popups) were added to each data series in the chart to enable a user to mouseover

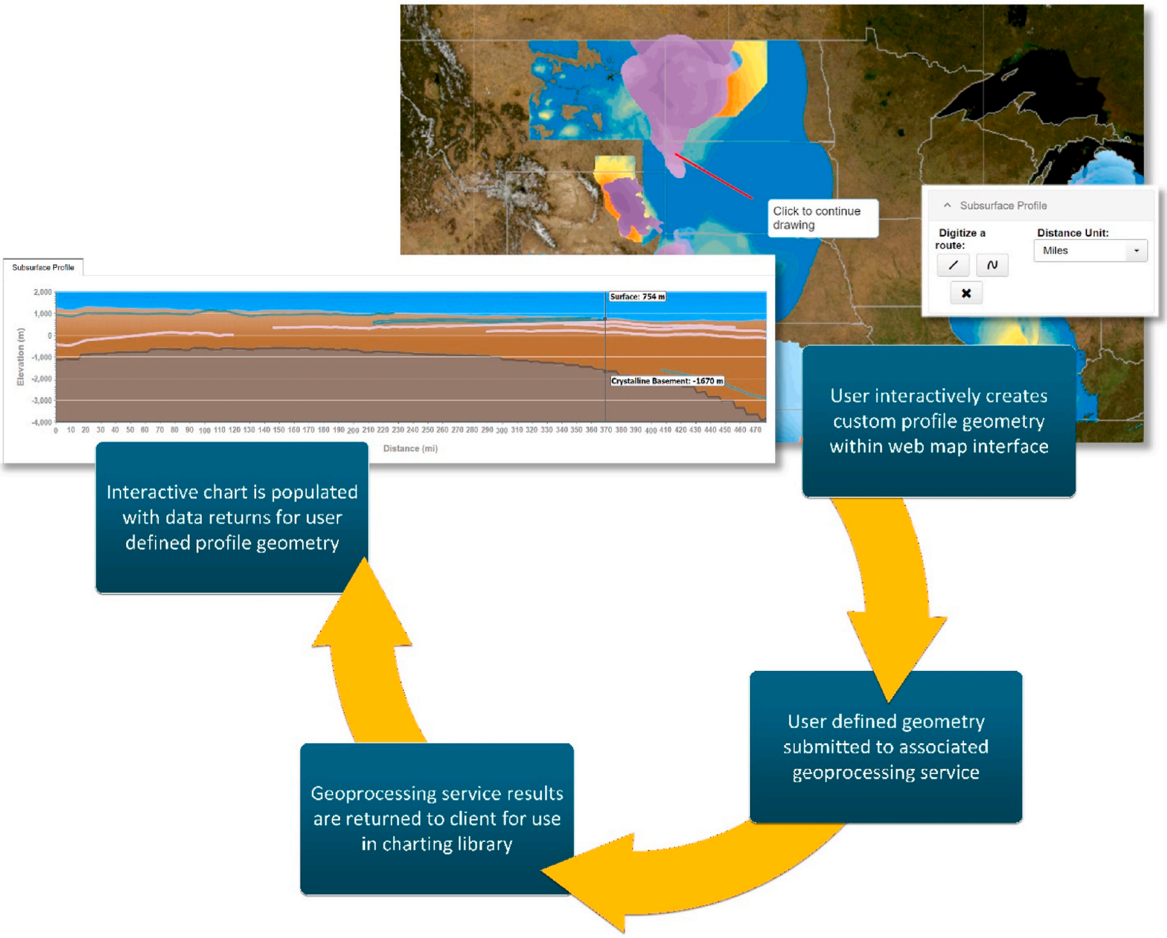


Fig. 1. A general workflow overview for generating custom, user-defined cross-sectional profiles and interactive charts.

a data series to reveal the series' name.

To generate rose diagrams of orientation values for selected stress field data, Plotly's polar charts graphic library was used within the CMV framework. Upon the completion of a user drawn polygon in the web map (using the Stress Fields Rose Diagram widget), the custom polygon geometry is used in a geoprocessing request to the rose diagram geoprocessing service to return the intersecting stress field azimuth feature data to plot the orientation data in a rose diagram displayed within the web map application. A user can then interact with the rose diagram to view a count of data points within each 5° orientation bin.

3. Results and discussion

3.1. Interactive web map application for subsurface, geophysical investigation

The resulting web map application (Fig. 2) provides an easy and convenient resource for SFWD researchers and stakeholders to compare and navigate a variety of spatial datasets compiled into a single web mapping interface. The CMV framework and the ArcGIS API for JavaScript provide an intuitive user interface where a user can adjust layer transparency, easily navigate the layer list, and turn layers on or off as needed. This provides users with the powerful option of being able to spatially compare GFM data along with geophysical and administrative layers critical to understanding subsurface structure as it pertains to SFWD project needs. In addition, we have provided a suite of interactive charting capabilities, which provide additional insight into subsurface structure and geophysical attributes.

3.2. Interactive subsurface profile and charting capabilities

The web-based subsurface profiling tools we built provide users with the capability to quickly (within seconds) generate a cross-sectional profile of subsurface models for any given user-defined profile line drawn within the web mapping interface (Fig. 3). This allows for a user to visualize subsurface GFM structure in any area of interest. Coupling a map-view perspective with an interactive subsurface cross-sectional chart gives researchers and stakeholders a geographically intuitive, multidimensional understanding of the underlying geologic structure. Our custom data processing scripts allow for the use of discrete, discontinuous raster data of variable spatial extents, allowing for flexibility of use with heterogeneous, spatially discrete subsurface raster data to visualize geologic formations. This enables processes to accept spatially variable subsurface raster data of any spatial extent with minimal data preprocessing requirements and a minimized data footprint. In addition, the use of gridded raster data to calculate subsurface cross-section diagrams enables lightweight data storage and access.

The borehole profile tool (Fig. 4) provides similar functionality as the subsurface profile tool; though, as opposed to a line transect, this tool provides a drilldown perspective of subsurface features, much like that of borehole well logs. This tool provides a user with the functionality of viewing GFM features at a point location within a vertical, interactive chart integrated into the web map application.

These data processing and visualization techniques allow for easy adaptation to include various types of geophysical data. We have demonstrated this by adapting these tools to incorporate aeromagnetic anomaly, heat flow, and gravity anomaly data along with surface topography and subsurface structures. To achieve this, we integrated

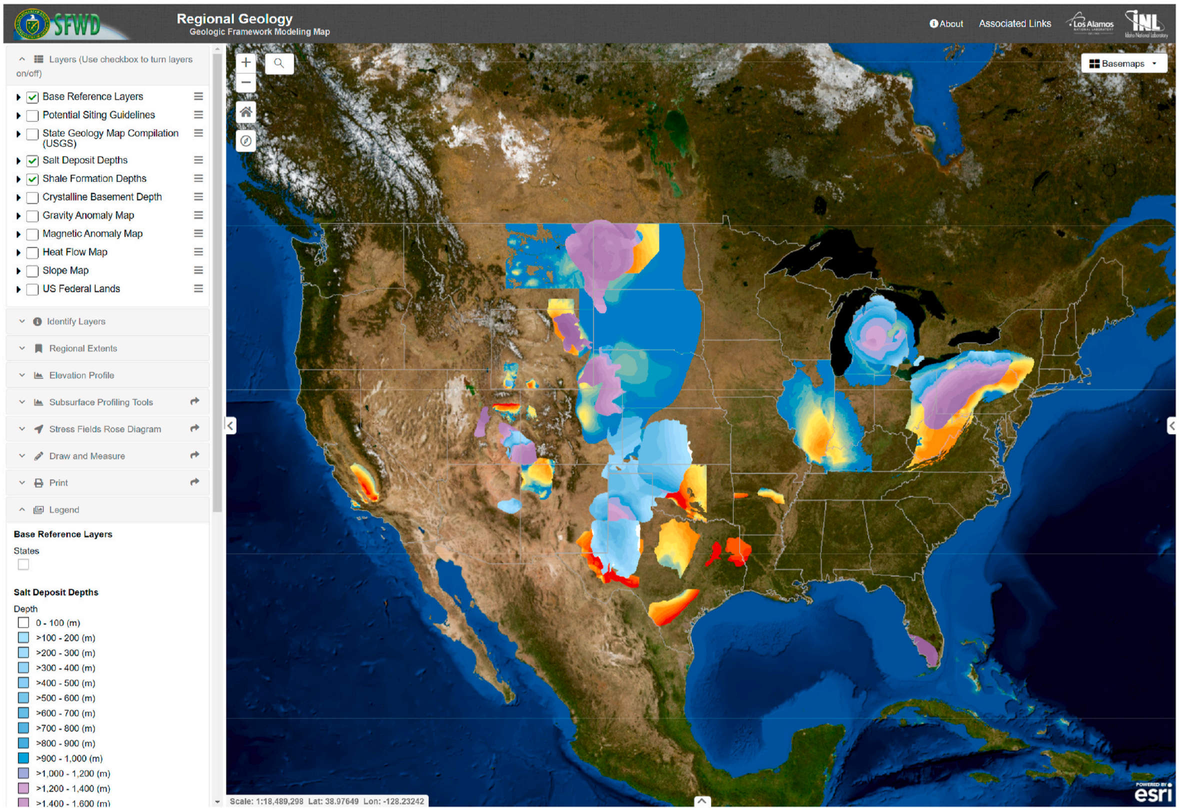


Fig. 2. The launch page of the SFWD Regional Geology web mapping application. Note that Regional Geology GFM data for salt deposits, shale formations, and crystalline basement, as well as several complimentary geophysical data layers are available to navigate within the layer list. Additionally, several interactive widgets (including subsurface profiling tools) are available for users to explore the data within the web map interface.

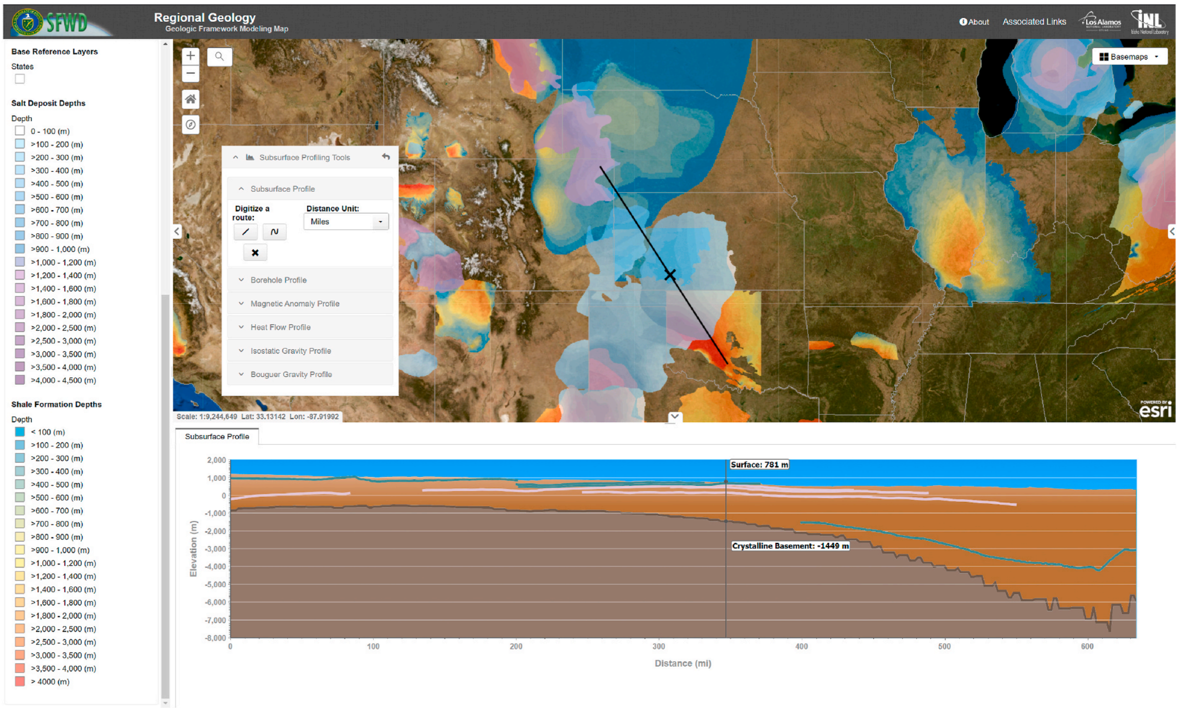


Fig. 3. An example cross-section (bottom panel) produced within the midwestern U.S. using the Subsurface Profile tool within the SFWD Regional Geology web mapping application. This cross-section shows salt (pink) and shale (blue) GFM elevations along with crystalline basement (dark brown) and surface elevation (light brown). Note the ‘X’ on the profile line within the map interface that corresponds to the current mouse indicator position within the Subsurface Profile chart.

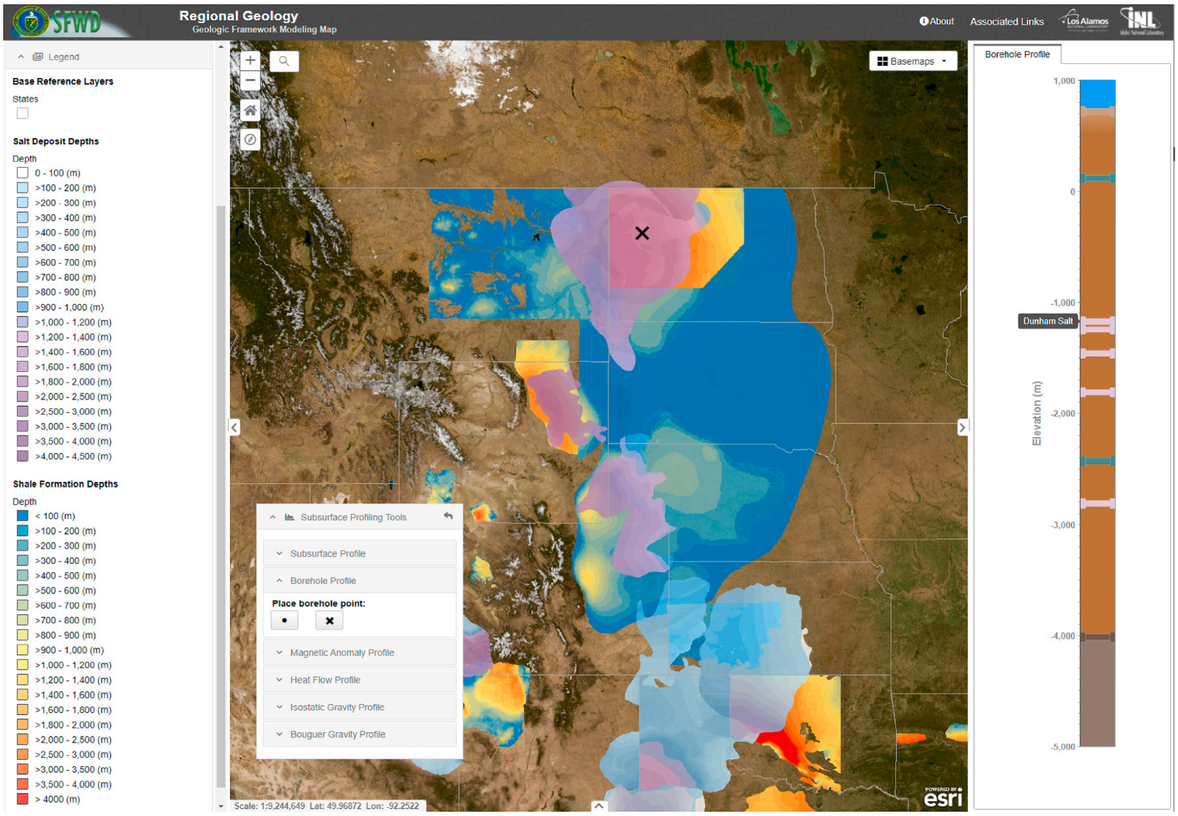


Fig. 4. An example borehole profile chart (right side panel) created with the Borehole Profile tool within a sedimentary basin in the midwestern U.S. This cross-section shows salt (pink) and shale (blue) GFM elevations along with crystalline basement (dark brown) and surface elevation (light brown). Note the popup within the borehole chart specifying the subsurface feature name (i.e., Dunham Salt, for this example) when a user hovers over the data series in the chart. Also, note the 'X' mark on the map interface denoting the location of the borehole profile data.

dual y-axes within the subsurface profile charts to display various supporting geophysical data. This resulted in the convenient ability for a user to generate custom cross-section profiles of aeromagnetic anomaly (Fig. 5-a.), heat flow (Fig. 5-b.), and gravity anomaly (Fig. 5-c and 5-d.) data models along with subsurface and surface elevation models. This enables users to quickly assess how a geophysical parameter (e.g., heat flow, aeromagnetic anomaly, or gravity anomaly) varies spatially with surface and subsurface features.

As an additional, complementary tool for geologic data visualization within this web mapping application, the rose diagram tool allows for users to quickly visualize stress field orientations from selected stress field features (Fig. 6). This tool is highly adaptable to accept any type of azimuthal orientation data, such as paleomagnetic anomaly, contact boundary orientations, and other structural properties, where understanding the distribution of orientation values may be useful. The ability to quickly visualize this information provides researchers and stakeholders greater insight into regional structural characteristics of interest as they navigate the framework model data within the application.

These web-based visualization tools provide several advantages to our project's researchers and stakeholders. These include the absence of software installation or licensing requirements and the absence of platform restrictions and update requirements. All processing and visualization steps are executed either client-side or on a server, requiring no user programming. Additionally, the results and outputs of these visualization tools can be easily reproduced and shared without data dependencies (Hosseini et al., 2018).

3.3. *Versatile applications for geologic, subsurface data visualizations*

These subsurface data visualization tools are highly adaptable to meet various visualization needs and to accommodate a variety of subsurface geospatial data, regardless of region or scale. We have demonstrated the adaptability of these subsurface profiling tools by using these tools within a site-specific application using data from the Black Hills Shale GFM (Fig. 7) (Sevougian et al., 2019). To expand the value of these subsurface profiling capabilities within the SFWD project, we are currently integrating alluvium models and groundwater data within these subsurface profiling tools using the workflow described in this paper. These data will provide additional insight into subsurface characterization, but this is a small sample of the types of geologic data that could be included in these subsurface visualizations. We plan to expand the charting capabilities provided by these toolsets, both with an expansion of the included subsurface data and the visualization techniques.

While the depth models used in this study provide information on formation boundaries, further detail could be captured within these subsurface profiling capabilities with supporting raster data of increased vertical resolution (i.e., additional raster data at specific depths or values). This could be helpful for creating more robust cross-sectional profiles for complex subsurface structure (e.g., for visualizing regional anisotropy, complex terrains, or geophysical inversion data). To capture such complexity, the horizontal sample interval designated within the geoprocessing scripts (as described in section 2.1.1) may need to be adjusted accordingly. Furthermore, if converted to raster format, any vector data (i.e. points, lines, or polygons) could be included within cross-sectional profiles with this methodology. This could be beneficial for capturing additional geologic information such as fault planes, surface measurements of strike and dip, and paleomagnetic samples.

4. Conclusions

To address the need for versatile and accessible subsurface

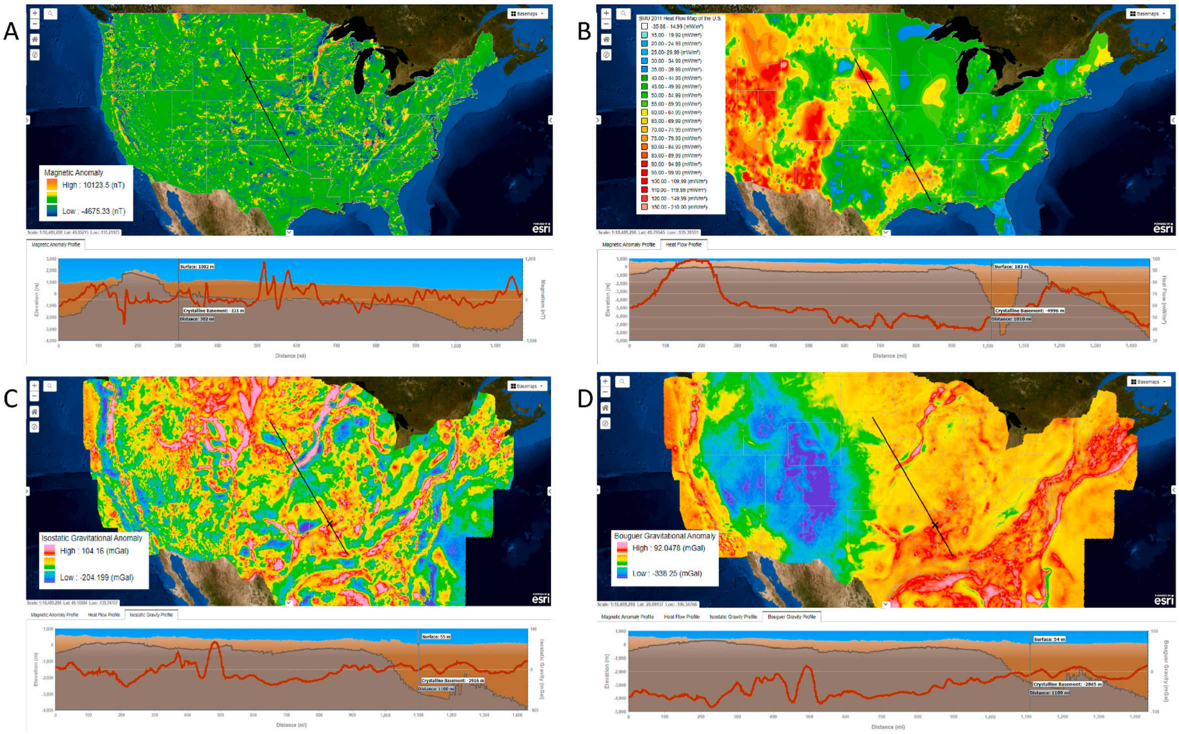


Fig. 5. Examples of cross-sectional profile charts for (a) aeromagnetic anomaly, (b) heat flow, (c) isostatic gravity anomaly, and (d) Bouguer gravity anomaly produced from user-defined profile lines drawn across portions of the midwestern United States within the SFWD Regional Geology web mapping application. Surface elevation (and sediment thickness) is denoted by the light brown data series and the crystalline basement is denoted by the dark brown data series. The red data series represents the respective geophysical data of interest. Note the ‘X’ on the profile lines within the map interface that corresponds to the current mouse indicator position within the respective cross-sectional chart.

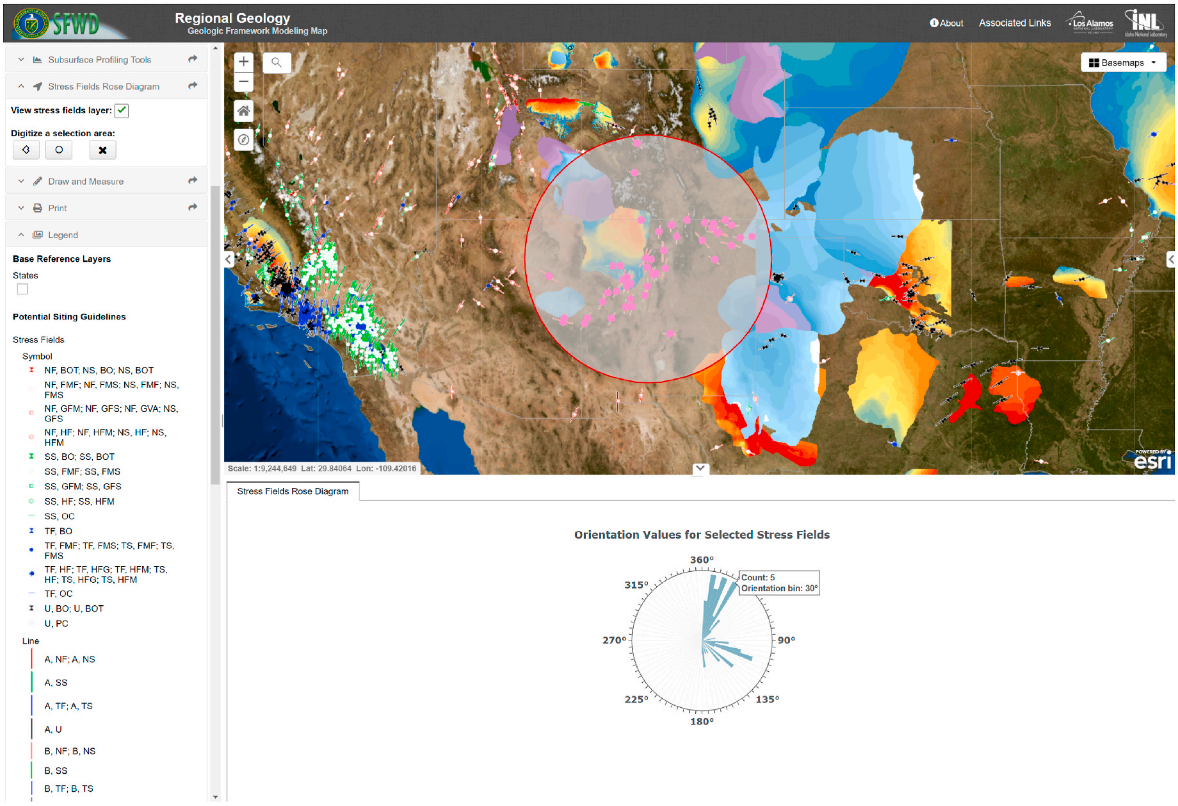
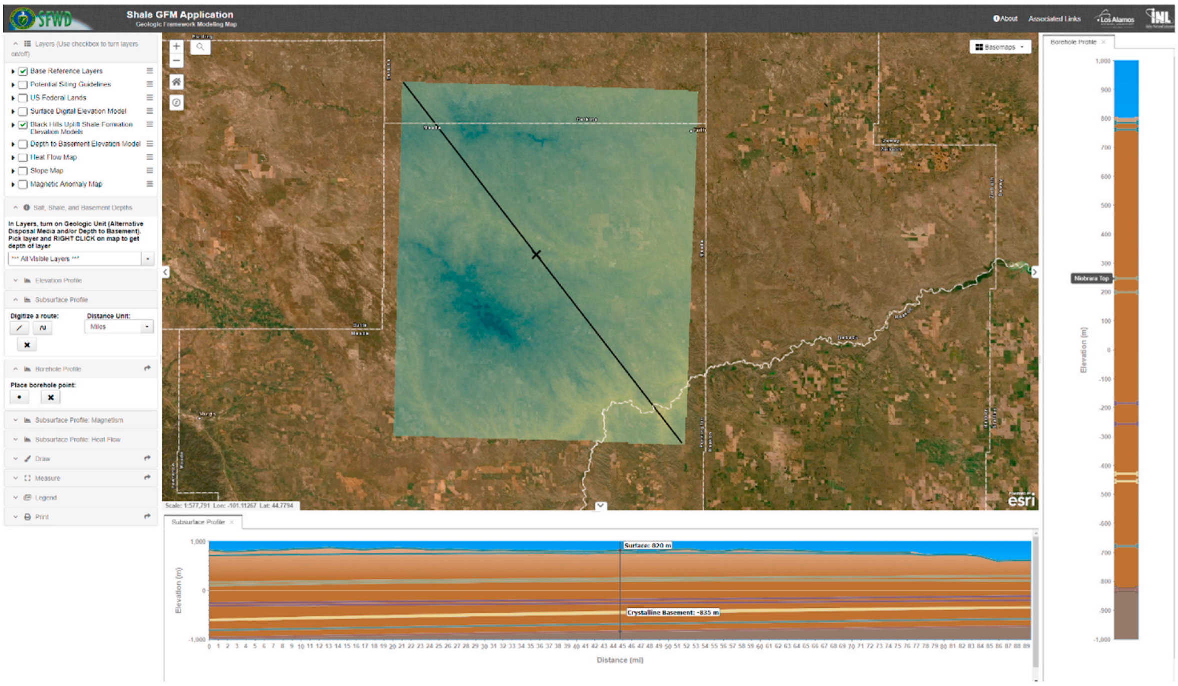


Fig. 6. An example of a rose diagram chart produced from the azimuth orientation values of selected stress fields within the SFWD Regional Geology web mapping application. Note the popup for the orientation bin and count of selected features when a user mouses over the rose diagram chart components.



In Layers, turn on Geologic Unit (Alternative Disposal Media and/or Depth to Basement). Pick layer and RIGHT CLICK on map to get depth of layer

Digitize a route:

Distance Unit: Miles

Place borehole point:

Scale: 1:577,791 Lon: -101.11267 Lat: 44.7794

Fig. 7. An example of a subsurface profile and a borehole diagram of the Black Hills Uplift Shale Formation within a site-specific (i.e., Black Hills Shale) version of the SFWD Regional Geology web mapping application. Note that the top (surface) and bottom of each formation model are included within the chart.

visualization of the SFWD Regional Geology GFM, we leverage the CMV framework, the ArcGIS API for JavaScript, the Dojo Toolkit, Plotly, and ArcGIS Enterprise software to build a web-based, interactive map application offering a variety of subsurface, geologic visualization tools including a suite of subsurface profiling tools. These tools allow users to interact with and visualize geologic data models from their web browser, facilitating SFWD stakeholders in making informed decisions. The subsurface profiling capabilities provided by this application allow users to easily produce cross-sections and borehole profiles of salt deposits, shale formations, and crystalline basement depth for custom areas of interest, within seconds. To provide for the spatial comparison of geophysical data with the Regional Geology GFM, we include dual axis charting functionality within subsurface, cross-section profiles to plot heat flow, aeromagnetic anomaly, and gravity anomaly data with surface elevation and crystalline basement depths. Additionally, with the use of Plotly, we provide a rose diagram to display azimuth data for user defined data selections.

The robust lithostratigraphic subsurface raster models from the SFWD Regional Geology GFM provided a unique opportunity to create web-based visualizations of subsurface data with cross-section profiles and borehole diagrams. We recognized the utility and convenience of web-based map applications in enabling the interactive exploration of various geologic data, and we extended those capabilities to include custom tools to visualize subsurface features and geophysical data in an easy to navigate, 2D web interface. The cross-section and borehole profile tools enable SFWD researchers and stakeholders to quickly generate visualizations commonly used by geoscientists, without a reliance on time-consuming, hand-drawn diagrams or specialized desktop-based software. These tools allow for intuitive, versatile, and convenient subsurface geologic data exploration all within a highly navigable, web-based map application. In addition, as we employ techniques that allow for the use of spatially variable, discrete gridded geologic data, the methods used to generate these visualizations allow for these tools to be highly adaptive to various heterogeneous, subsurface geologic data without extensive data preprocessing and unnecessary expansion of data footprints. Furthermore, these techniques enable effective integration of a large volume of GFM data.

Data availability

Data used in the SFWD Regional Geology web map application can be acquired by submitting a request to Los Alamos National Laboratory's Records Management.

Interactive web use of the SFWD Regional Geology web map application is available in the public domain and can be accessed here: https://gis.inl.gov/regionalgeology.

Code availability

Subsets of relevant code used in this study are available for download at https://doi.org/10.5281/zenodo.5784363. Version: 1.0. License type: MIT. This includes test raster data, Python scripts used for geoprocessing services, and JavaScript, CSS, and HTML resources for an overview of widget functionality in the web map application. The Python script resources require ArcGIS Desktop and ArcGIS Server. We used ArcGIS Desktop version 10.8.1 (Python 2.7.18) and ArcGIS Server 10.8.1 for testing and publishing these geoprocessing services. Hardware requirements for ArcGIS Desktop includes a minimum 4 GB RAM (8 GB recommended) and a minimum CPU speed of 2.2 GHz. JavaScript, CSS, and HTML code made available through this resource provide an overview of web application functionality for the subsurface profile, borehole profile, and rose diagram tools within the CMV framework. Development environment dependencies can be found at http://docs.cmv.io/.

Link to the software

https://gis.inl.gov/regionalgeology/.

Authorship statement

Glenn Paul Russell and Tessica Anne Gardner Oldemeyer share equal contributions to this submission. Both senior authors worked together to develop the web-based visualization concepts, implement the web application and specific functionality, and write and edit the content of this manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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