An Open-Source, Data-Driven Interactive Web Framework for 3D Visualization of Geoheritage Sites: A Case Study of the Grand Canyon Arizona, United States

Author: Gul Nawaz [1*]

https://orcid.org/0009-0009-0791-7309[1]
Institute of Geographical Information Systems, National University of Sciences & Technology, Islamabad, Pakistan
Corresponding author email: gnawaz.ms24igis@student.nust.edu.pk

Keywords: Geoheritage, 3D Geovisualization, Open-Source Software, WebGIS, Stratigraphy, Digital Twin, Virtual Field Trips

Manuscript Status & Disclaimer:

This document is a non-peer-reviewed preprint deposited on EarthArXiv. This manuscript has been submitted for peer review to *Geoheritage* (Springer). Subsequent versions may include revisions resulting from the peer-review process.

Abstract

Effective dissemination, public engagement, and educational utilization of prominent geoheritage sites are often hindered by the steep learning curves, high computational requirements, and licensing costs inherent to professional Geographic Information Systems (GIS) and 3D geological modeling software. To bridge this accessibility gap and democratize spatial data, we present a universal, browser-based, open-source 3D visualization framework designed specifically for geoheritage applications. Developed by leveraging modern web technologies (Three.js and Leaflet.js), the framework completely decouples computational rendering logic from hardcoded geological datasets through a centralized, easily modifiable JSON schema (data.json). This novel architecture enables researchers, educators, and park managers to transform structural geological mapping, sequence stratigraphy, and digital elevation models (DEM)without requiring advanced programming knowledgeinto deeply interactive, lightweight web environments. We demonstrate the framework's robustness and scalability by applying it to the iconic stratigraphy and structure of the Grand Canyon (Arizona, USA). The resulting application showcases dynamic 3D SRTM terrain generation, interactive 3D measured stratigraphic boreholes, responsive 2D WebGIS mapping, and analytical figure generation integrated within a unified, client-side dashboard. The proposed framework represents a highly scalable, reproducible, and low-cost approach to virtual geoconservation, digital geotourism, and geoscience education.

1. Introduction

Geological heritage (geoheritage) encompasses significant geological features, landforms, stratigraphy, and structural elements that offer profound societal, educational, cultural, and scientific value (Reynard and Brilha 2018). As digital technologies rapidly evolve, the concept of virtual geotourism and the creation of educational "digital twins" of geoheritage sites have become fundamental methodologies in geoscience outreach and conservation (Cai et al. 2021; Nesbit et al. 2020). These digital representations allow stakeholders to explore fragile or physically inaccessible geological sites, thereby promoting geoconservation through education while minimizing physical degradation (Prosser 2013).

However, the accurate representation of complex 3D geology traditionally relies on proprietary desktop software (e.g., Esri ArcGIS Pro, Schlumberger Petrel, Seequent Leapfrog). These platforms, while powerful, create a significant barrier to entry for the general public, resource-limited academic institutions, and local geopark management entities due to exorbitant licensing fees and the need for specialized training. Furthermore, sharing the output of these proprietary models often requires the end-user to install specialized viewing software, which severely limits public reach.

The rise of WebGL (Web Graphics Library) and WebGIS affords the capacity to deploy sophisticated 3D geological models directly into modern internet browsers, bypassing the need for local installations. Despite this technological leap, existing academic web viewers and virtual field trips often suffer from a critical architectural flaw: they hardcode their spatial and geological data directly into the application's source code. This tightly coupled approach hinders reusability; a web application built to visualize a specific geopark cannot be easily repurposed by another researcher for a different site without fundamentally rewriting the JavaScript logic.

To address these limitations, this paper introduces an entirely data-driven, client-side web framework that facilitates the interactive presentation of *any* geoheritage site. By relying on an extensible JSON (JavaScript Object Notation) data format, the framework separates the rendering engine from the geological data. This paper outlines the architecture of this open-source tool and demonstrates its efficacy through a comprehensive case study of the Grand Canyon, USA, illustrating how raw geospatial data can be transformed into an accessible, interactive digital geoheritage experience.

2. Geological Context of the Case Study: The Grand Canyon

To rigorously test and validate the framework, the Grand Canyon in Arizona, USA, was selected as the primary case study. Recognized globally as a premier geoheritage site and a UNESCO World Heritage site, the Grand Canyon provides an unparalleled natural laboratory for testing 3D geological visualization due to its immense scale and excellent exposure.

The canyon exposes a nearly continuous, two-billion-year window into Earth's geological history. The stratigraphy is broadly categorized into three main sets of rocks:

1. **Early Proterozoic Crystalline Basement:** The Vishnu Basement Rocks, comprising heavily deformed schists and gneisses intruded by granites, forming the steep Inner Gorge.
2. **Late Proterozoic Grand Canyon Supergroup:** A thick sequence of tilted sedimentary strata preserved in isolated fault block remnants.
3. **Paleozoic Strata:** The iconic, horizontally bedded sedimentary sequences dominating the canyon's upper walls, ranging from the Cambrian Tonto Group up to the Permian Kaibab Limestone, which forms the canyon rim (Beus and Morales 2003).

Visualizing this region requires a framework capable of handling extreme topographic relief, complex structural lineaments (faults), and highly detailed vertical stratigraphic sequences. Therefore, it serves as the ultimate stress test for the proposed web architecture.

3. Methodology and System Architecture

The application is architecturally designed as a fully decoupled Single Page Application (SPA). This design philosophy emphasizes high performance, minimal server-side processing, low hosting overhead (static delivery), and universal applicability across desktop and mobile platforms.

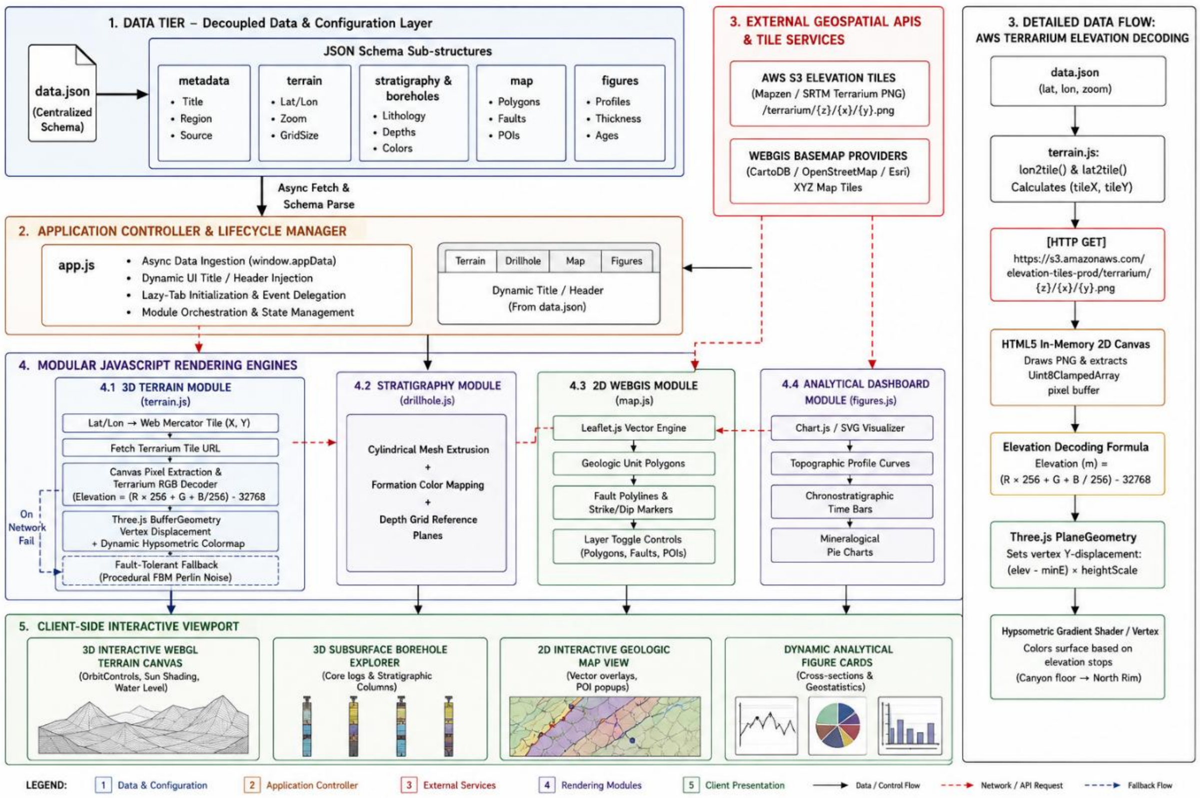

Figure 1. Schematic overview of the framework's architecture, demonstrating the separation of the data.json schema from the JavaScript rendering modules, and the flow of external APIs such as AWS Terrarium for elevation data.

3.1 The Decoupled Data Schema (data.json)

The core innovation of this framework lies in the strict separation of concerns between the JavaScript rendering modules and the geological dataset. All site-specific parameters are encapsulated within a centralized, human-readable data.json file.

The schema is structured to accept:

- **Bounding Coordinates:** Latitude and longitude extents for dynamically streaming terrain.
- **Stratigraphic Definitions:** Arrays defining formations, their absolute ages, lithological descriptions, standard RGB/HEX color codes, and typical thicknesses.
- **Vector Geometries:** GeoJSON-compatible arrays for geologic map polygons, fault polylines, and point markers (e.g., fossil localities, sample loci).
- **Analytical Metadata:** Arrays formatted to populate profile-view analytical charts.

Consequently, researchers can repurpose the entire interactive application for a new geoheritage site (e.g., the Jurassic Coast in the UK, or the Dolomites in Italy) simply by editing the JSON dictionary, requiring zero modifications to the underlying index.html or main JavaScript files.

3.2 Framework Rendering Modules

The architecture leverages a suite of modular scripts, each responsible for a distinctive visualization domain, coordinated by a central application state manager.

3.2.1 3D Terrain Module (terrain.js)

This module utilizes Three.js (a lightweight cross-browser JavaScript library for WebGL) to construct the primary 3D environment. Rather than forcing users to pre-process and upload heavy DEM files, the framework fetches real-time Shuttle Radar Topography Mission (SRTM) elevation tiles via the AWS Terrarium API based on the bounds defined in data.json.

These tiles are mathematically transformed into custom BufferGeometry. The terrain is dynamically styled using a custom shader material that applies hypsometric tinting or drapes satellite imagery, adapting seamlessly to the user-defined geographic boundaries.

3.2.2 Stratigraphic Borehole Module (drillhole.js)

To represent 1D geological data in 3D space, this module dynamically generates cylindrical geometries. These represent physical drill cores or surface measured sections. The module reads depth intervals and lithological IDs from the JSON file, extruding 3D cylinders at specific XYZ coordinates on the terrain. It binds standard geological coloring and allows users to click specific strata within the 3D model to trigger pop-up informational modals containing detailed petrographic or paleontological data.

3.2.3 Geological Map Module (map.js)

For traditional 2D spatial analysis, the framework integrates Leaflet.js. This module parses the spatial arrays from the JSON schema to render vector polygons (formations) and polylines (structural faults). It features interactive CircleMarkers for points of interest, layered over interchangeable basemaps (e.g., OpenStreetMap, Esri Satellite). The 2D map view is linked to the 3D view; selecting a feature on the 2D map updates the informational UI across the entire application.

3.2.4 Presentation and Analytics Module (figures.js)

To provide quantitative context, the presentation module orchestrates Chart.js to render dynamic, interactive graphs. Based on the data schema, it generates statistically derived formation distribution tables, age-correlation log graphs, and idealized geomorphological cross-sections, turning raw data into publication-ready visual analytics.

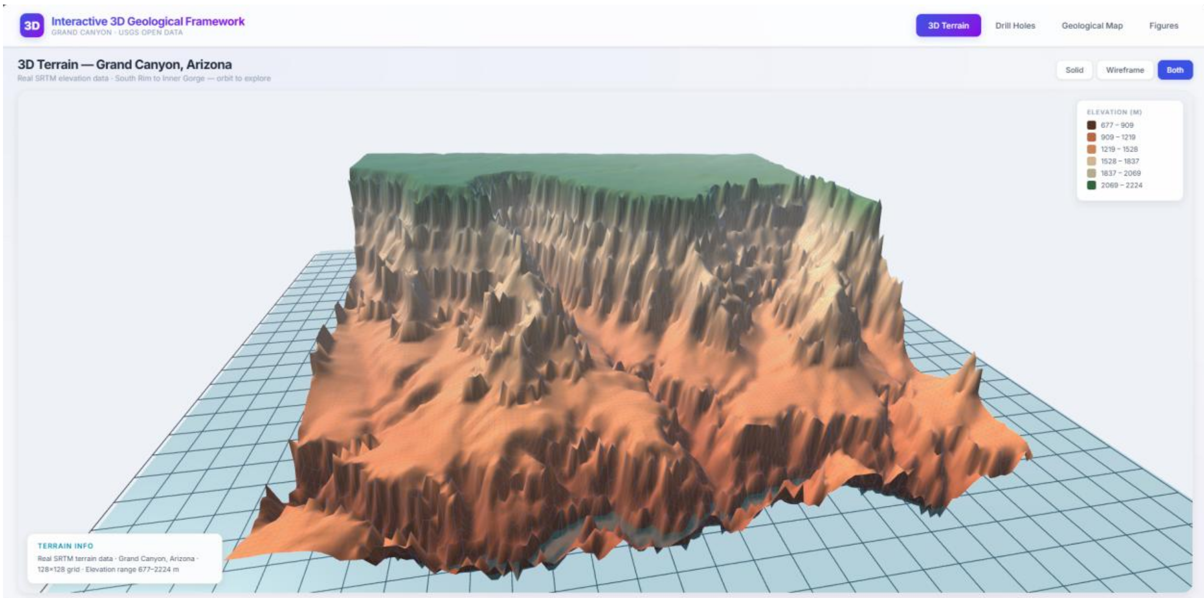

Figure 2. Screenshot of the user interface, highlighting the integration of the 3D viewer

4. Results: Application to the Grand Canyon

To validate the framework, geological and geospatial data from the Grand Canyon was formatted into the data.json schema. The dataset was aggregated and digitized from foundational geological surveys, specifically Billingsley (2000) (USGS Map I-2688) and Beus & Morales (2003).

4.1 3D Topographic and Structural Rendering

The framework effectively processed the bounding box for the Grand Canyon, automatically generating the 3D terrain mesh. The viewer accurately renders the sweeping topographic plunge from the Kaibab Limestone plateau (elevations >2000m) down to the Vishnu Basement Rocks of the Inner Gorge. Performance remained stable at 60 frames per second (FPS) on standard desktop hardware, demonstrating the efficiency of the BufferGeometry implementation.

4.2 Interactive Stratigraphic Analysis

Six specific measured stratigraphic sections from various points along the canyon were visualized interactively as 3D drill logs protruding from the digital terrain. Users can navigate the 3D space, zoom into a specific section (e.g., the Bright Angel Trail sequence), and click on individual layers. This interaction immediately populates the UI with the layer's name (e.g., Redwall Limestone), age (Mississippian), and dominant lithology.

Figure 3. Close-up view of the 3D stratigraphic borehole module in action

4.3 Unified Spatial Context

The application allows users to fluidly switch between the immersive 3D topographic view and the traditional 2D interactive structural field map. This dual-view capability provides an unprecedented, unified spatial context that is highly beneficial for undergraduate educational workflows, bridging the cognitive gap between flat geologic maps and real-world 3D topography.

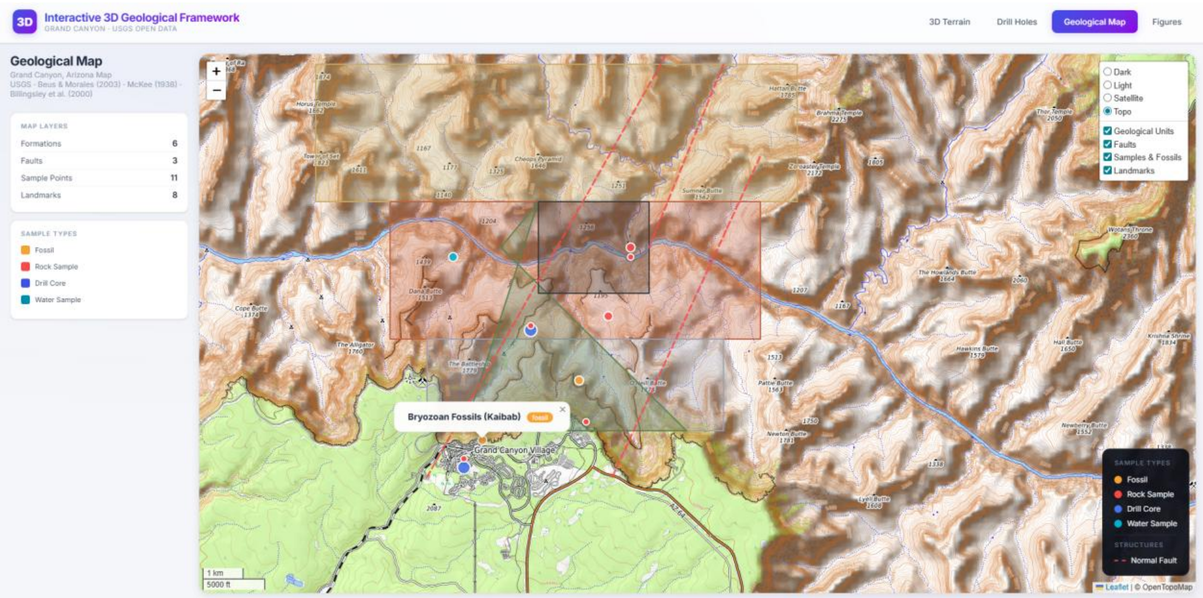

Figure 4. Close-up view of the Geological map

4.4 Integrated Data Analytics and Presentation Dashboard

A dedicated "Figures" tab within the application framework successfully synthesizes published quantitative data into an interactive dashboard, demonstrating the tool's capacity for deep-dive geological analysis. As derived from the JSON schema, the module renders four distinct analytical charts:

1. **Topographic Profiling:** A line chart plotting the elevation profile of the Bright Angel Trail from the canyon rim down to the Colorado River (725m ASL). This provides users with a quantified 2D cross-sectional perspective of the terrain they navigate in the 3D viewer.
2. **Mineralogical Composition:** A donut chart dynamically illustrating the detailed petrographic breakdown of specific formations, such as the Kaibab Limestone (adapted from McKee, 1938), highlighting the relative percentages of Calcite, Dolomite, Chert, Quartz sand, and fossil fragments.
3. **Stratigraphic Thicknesses:** A horizontal bar chart detailing the average measured thicknesses of formations across the Paleozoic sequence, allowing for immediate visual comparison of depositional volumes (e.g., the massive Redwall Limestone versus the thinner Temple Butte Formation).
4. **Geochronology Timeline:** A vertical bar chart displaying the absolute ages of the formations (in millions of years, Ma). The framework effectively utilizes a logarithmic scale on the Y-axis to accommodate the massive "deep time" unconformity between the Paleozoic sedimentary sequence and the 1.75 billion-year-old Vishnu Basement rocks.

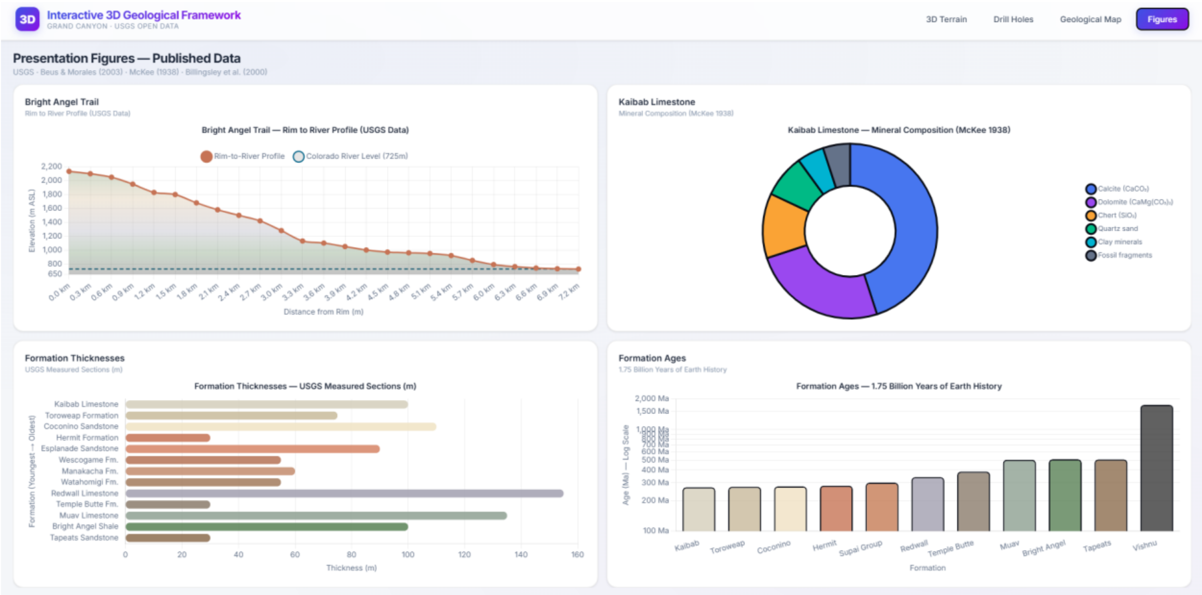

Figure 5. The interactive presentation dashboard generated by the framework.

5. Discussion

The successful deployment of this framework highlights several foundational benefits for the geoheritage, geoconservation, and academic communities.

5.1 Democratization and Accessibility

Because the framework is built purely on HTML5, CSS, and JavaScript, it requires absolutely zero installation on the client side. It runs natively in any modern web browser (Chrome, Firefox, Safari). Furthermore, its static nature means it does not require an expensive backend server or database; it can be hosted for free on platforms like GitHub Pages or standard university web servers. This democratizes the publication of 3D geological data, allowing geoparks with limited funding to offer world-class digital exhibits.

5.2 Reproducibility and Standardization

By enforcing the storage of spatial arrays, stratigraphic attributes, and metadata in a single JSON structure, the framework promotes a machine-readable, interchangeable data standard. Researchers can share their data.json files alongside their publications, ensuring that their 3D models are fully reproducible by peers. This addresses a major criticism of current digital geology, where models are often locked inside proprietary project files (e.g., .mxd or .pet).

5.3 Public Engagement and Geotourism

The aesthetic quality achieved by dynamic 3D lighting, shadowing, and interactive legends enhances the communicative power of raw geological data. For geotourism, this framework can easily be deployed on touch-screen kiosks at visitor centers or accessed via QR codes on trailheads, turning static educational placards into exploratory, user-driven digital exhibits.

5.4 Limitations and Future Work

While highly effective, the current framework faces limitations inherent to browser-based rendering. Extremely high-resolution terrain meshes or datasets with hundreds of thousands of vector polygons may cause memory issues or drop frame rates on lower-end mobile devices. Future iterations of the framework will focus on implementing Level of Detail (LOD) algorithms and 3D Tiles (e.g., CesiumJS integration) to handle massive regional datasets. Additionally, integrating WebXR to allow users to view the geoheritage models in immersive Virtual Reality (VR) directly from the browser represents a primary avenue for future development.

6. Conclusion

The digital conservation and promotion of geoheritage depend heavily on open-access, intuitive dissemination paradigms. The Open-Source Data-Driven Interactive Web Framework presented in this study provides a versatile, lightweight foundation that allows geoscientists, educators, and park managers to securely, rapidly, and compellingly "publish" their local geological mapping and modeling as a unified WebGL environment. By decoupling the complex rendering code from the geological data schema, the tool removes the programming barrier to entry. As demonstrated by the Grand Canyon case study, the framework effectively bridges the gap between complex geological datasets and public accessibility, standing as a vital tool designed to amplify open-science initiatives in global geoheritage.

Declarations

Funding: The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Competing Interests: The authors have no relevant financial or non-financial interests to disclose.

Data and Software Availability:

The source code for the framework, complete with the Grand Canyon sample data.json dataset, is provided under the MIT License.

The code and live demonstration are hosted openly and can be accessed at : https://github.com/Gull01/interactive-3d-geological-framework

Author Contributions:

Conceptualization, methodology, software development, and writing were performed by Gul Nawaz.

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