EXPLORATION OF PLANETARY SUBSURFACES USING 3D GEOLOGIC MODELING.

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Introduction: Planetary exploration began with Earth-based observations and evolved through orbital remote sensing to in-situ investigations. In the last two decades, the subsurface of Solar System bodies has become a major frontier for the search for life and resources. As exploration increasingly extends beneath planetary surfaces, we must reconstruct three-dimensional subsurface architectures from available observations. The challenge lies in building reasonable models from heterogeneous, sparse, and often irregularly distributed data.

Geologic modeling focuses on developing representations of subsurface conditions under limited observational constraints, particularly when sampling is insufficient or unevenly distributed to resolve all uncertainties. The objective of geologic modeling is to predict geological characteristics at any location within a three-dimensional space, starting from observations and progressing toward geometric representations and uncertainty evaluation. This three-dimensional perspective enables new analyses, such as the representation of complex structures, volume estimation of rock bodies, or the use of models as inputs for further investigations. Over the last two decades, several modeling approaches, algorithms, and software environments have been proposed, developed, and widely applied on Earth for environmental and resource-related studies [e.g. 1–7].

A geological model generally serves one or more purposes, and its level of complexity depends on the specific objectives of the study. Interest in and application of geologic modeling to planetary exploration began in the last decade, with studies focusing on lunar regolith [8], Comet 67P [9], and programmatic and conceptual aspects of planetary exploration [10]. This work aims to explore and test current geologic modeling techniques across a diverse set of environments relevant to planetary science.

Source of Information: Building a geological model requires the synthesis of geometric data and conceptual geological knowledge [3, 4]. Geometric data inputs include the geometry of geological interfaces and point-wise orientation measurements obtained from surface or subsurface observations, when available. Subsurface data may derive from direct observations, such as drilling cores, or indirect investigations, including geophysical inversions, petrophysical models, or combinations thereof.

Because hard data are often sparse, geological models rely heavily on formalized geological knowledge, such as the chronostratigraphic order of units and the rules defining depositional, erosional, and truncational relationships between geological units. For this reason, geologic mapping is a foundational prerequisite for building a geologic model. It serves as the primary source of spatial and qualitative data required to define the geometry, distribution, and relationships of subsurface rock units. This is true for geologic modeling in general, but it is particularly critical in planetary exploration, where geologic interpretation derived from remote sensing data is often the only information available for model construction.

Experiments and Applications: I designed a set of experiments to explore two planetary science applications of three-dimensional geologic modeling using the GemPy modeling environment [6].

Figure 1 shows a three-dimensional model developed from a subset of the geologic map of Tempe Terra [11], where the primary model input consists of interpretative knowledge encoded in the geologic map. The contacts between geologic units are interpolated and propagated through the entire volume of the model, providing a full volumetric description of the model below the topographic surface.

Figure 2 presents a geologic model of Barringer Crater (also known as Meteor Crater) in Arizona, USA, developed from subsurface data extracted from lithostratigraphic analyses of drilling data [12, 13]. The model numerically defines the modeled quantity (in this case, the geologic unit) at each point in three-dimensional space, enabling the extraction of cross-sections along arbitrary directions. From these cross-sections, it is possible to study variations in the geometry of the contact between the Permo-Triassic bedrock and the material ejected and emplaced by the impact process that formed the crater (Figure 2, bottom).

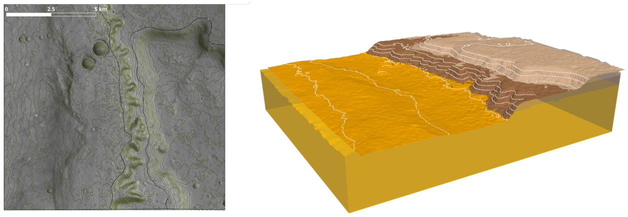

Figure 1: Geologic mapping information (left, from [11]) transformed into a three-dimensional geologic model (right). Thickness of the model is 400 meters.

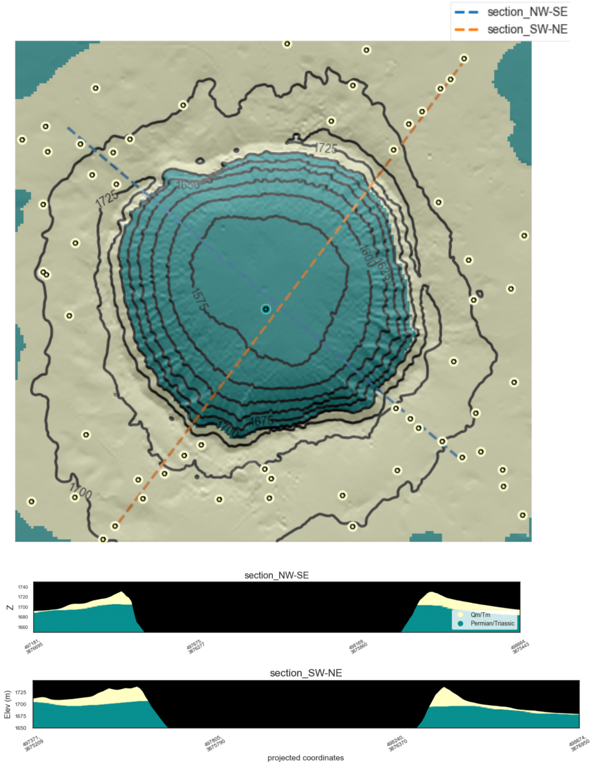

Figure 2: A geologic model of the 1.2 km-wide Barringer Crater in Arizona, USA, developed from the interpretation of exploration drilling data [13]. Blue-green unit is the Permian and Triassic bedrock, while pale yellow unit correspond to material ejected and emplaced by the impact process. The upper panel shows the geologic model in map view; dots indicate the locations of exploration wells used to build the model, and dashed lines mark the traces of the NW–SE and SW–NE geologic cross-sections reported below the map.

Conclusions and Next Steps: Three-dimensional geologic modeling techniques have expanded significantly over the last two decades, and active research continues in this field. This work explores the application of geologic modeling environments to two planetary science case studies, constructing models from solely geologic interpretations derived from remote sensing data (the geologic map of Tempe Terra) and from actual sparse subsurface data (the Barringer Crater in Arizona).

Three-dimensional geologic models have the potential to impact both fundamental scientific investigations of the subsurface—such as the search for life on Mars—and applied research areas, including in-situ resource utilization (ISRU). However, reasonable results strongly depend on interpretative and often arbitrary decisions made according to the modeling objectives, underscoring the need for a clear and transparent narrative describing the modeling process. Because these models are algorithm-based and frequently rely on interpretative inputs, it is essential to avoid "black box" solutions. Free and open-source software environments, such as GemPy and other platforms [5, 7], allow the development of fully traceable and reproducible workflows, facilitating continuous refinement and improvement of both models and techniques, prioritizing interoperability of methods and data formats over the exclusivity of specific solutions. The models presented here will be further developed through the testing of alternative configurations, multiple spatial scales, and different modeling environments, in close discussion with colleagues and modeling developers.

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