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Application of GemPy to Improve Students' Implicit Creation of Complex Geological Models

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Abstract

Understanding subsurface geological structures is a persistent pedagogical challenge in earth science and resource-economics education, owing to the inherent difficulty of visualizing three-dimensional spatial relationships from two-dimensional maps, cross-sections, and borehole logs. This paper examines the application of GemPy, an open-source Python library for implicit three-dimensional structural geological modelling, as a tool for improving students' capacity to construct and interpret complex geological models. GemPy uses an implicit modelling approach, interpolating geological surfaces directly from spatially referenced input data such as orientations and interface points, thereby allowing users to generate, and interactively update, three-dimensional representations of stratigraphic layers, faults, and folds without manual digitization of each geological boundary. Drawing on constructivist and technology-enhanced learning theory, and a qualitative synthesis of geoscience education literature and documented classroom applications of open-source modelling software, this paper argues that GemPy's interactive, code-driven, and probabilistically extensible framework offers particular pedagogical value: it allows students to iteratively test structural hypotheses, visualize the consequences of changing input parameters in real time, and engage directly with the mathematical logic underlying implicit interpolation, rather than treating geological modelling software as an opaque black box. The paper further considers GemPy's relevance to economics and resource-management curricula, where geological structural understanding underpins mineral and hydrocarbon resource valuation. It concludes that structured integration of GemPy into relevant coursework, supported by adequate technical scaffolding, can meaningfully improve students' spatial reasoning and conceptual grasp of subsurface structural complexity, while noting that the tool's Python-based interface presents an initial learning-curve barrier that instructors must actively manage.

Keywords: GemPy, implicit geological modelling, geoscience education, structural geology, resource economics

1. Introduction

The teaching of structural geology, and by extension the resource-economics disciplines that depend on it, has long grappled with the challenge of helping students develop robust three-dimensional spatial reasoning from inherently limited two-dimensional data sources such as geological maps, cross-sections, and borehole records. Traditional pedagogical tools, including physical models, hand-drawn cross-sections, and static computer-aided design outputs, provide useful but comparatively rigid representations that do not readily accommodate iterative hypothesis testing or the incorporation of uncertainty.

GemPy, an open-source Python library developed for implicit three-dimensional structural geological modelling, offers an alternative pedagogical pathway. Rather than requiring the manual digitization of every geological surface, GemPy interpolates continuous three-dimensional surfaces directly from sparse input data, specifically the spatial coordinates and orientations of geological interfaces, using a co-kriging based implicit interpolation algorithm. This approach allows users, including students with limited prior programming or geological modelling experience, to construct, visualize, and modify complex stratigraphic and structural scenarios with a comparatively small set of input parameters.

This paper examines the application of GemPy as an instructional tool, asking: in what ways, and to what extent, does GemPy's implicit modelling approach improve students' capacity to construct and reason about complex geological models, and what pedagogical and technical conditions are necessary to realize this benefit? The paper is organized as follows: section two reviews relevant literature on geoscience education technology and implicit geological modelling; section three presents the theoretical framework; section four outlines the methodology; section five discusses findings across curriculum integration, spatial reasoning development, and technical barriers; and section six concludes with recommendations.

2. Literature Review

2.1 Implicit Geological Modelling

Implicit geological modelling techniques construct three-dimensional geological surfaces by mathematically interpolating a scalar potential field from spatially distributed data points, rather than requiring the explicit manual construction of each surface, as is typical in traditional explicit modelling workflows. This approach, formalized in geoscience software including GemPy, SKUA-GOCAD, and Leapfrog Geo, allows for more rapid model construction, straightforward incorporation of structural uncertainty, and efficient updating of models as new data become available. GemPy distinguishes itself within this landscape by being fully open-source, Python-native, and designed for integration with probabilistic and machine-learning workflows, making it particularly suited to educational and research contexts where cost, transparency, and extensibility are valued.

2.2 Technology in Geoscience Education

A substantial body of geoscience education literature documents the benefits of interactive, visualization-based tools for improving student comprehension of three-dimensional spatial relationships, a competency widely recognized as one of the more cognitively demanding aspects of structural geology instruction. Studies examining virtual outcrop models, augmented reality sandboxes, and interactive block-diagram software report improvements in students' spatial reasoning and their ability to translate two-dimensional data into coherent three-dimensional mental models. Comparatively fewer studies have examined the specific pedagogical role of open-source, code-based implicit modelling tools such as GemPy, representing a gap this paper seeks to address.

2.3 Geology and Resource Economics Curricula

Within resource-economics and mineral-economics curricula, structural geological understanding underpins core competencies such as reserve estimation, resource valuation, and extraction feasibility analysis. Literature on interdisciplinary curricula in mineral and energy economics has noted persistent gaps between students' economic-analytical training and their grounding in the geological fundamentals that determine resource availability and extraction risk, suggesting a rationale for the deliberate integration of accessible geological modelling tools such as GemPy into economics-adjacent coursework.

3. Theoretical Framework

This paper adopts constructivist learning theory, associated with Jean Piaget and later elaborated by Seymour Papert's constructionist extension, which holds that learners build understanding most effectively through active construction of knowledge artifacts rather than passive reception of information. Papert's constructionism, in particular, emphasizes the pedagogical value of learners building tangible or computational models as a means of externalizing and refining their own mental models. GemPy's workflow, in which students actively input geological observations and observe the resulting three-dimensional structural consequences, aligns closely with this framework, positioning the software not merely as a visualization aid but as a constructive learning environment.

This is complemented by technology-enhanced learning (TEL) theory, which examines how digital tools mediate and potentially amplify learning outcomes when appropriately scaffolded within curriculum design. TEL scholarship emphasizes that the pedagogical benefit of a given technology is contingent not on the tool itself but on the quality of its instructional integration, a consideration directly relevant to evaluating GemPy's classroom application.

4. Methodology

This paper employs a qualitative, exploratory research design based on a desk review of geoscience education literature, technical documentation and published case studies of GemPy and comparable implicit modelling software, and documented instructional practices in structural geology and resource-economics curricula. Thematic analysis is applied to identify recurring patterns across three dimensions: curriculum integration strategies, evidence of spatial reasoning improvement, and technical barriers to adoption. This approach is appropriate given the comparatively recent emergence of GemPy as an educational tool and the corresponding scarcity of large-scale quantitative classroom trials specific to its use.

5. Findings and Discussion

5.1 Curriculum Integration

The reviewed evidence suggests that GemPy is most effectively integrated into curricula as a structured laboratory or project-based component within existing structural geology, geological engineering, or resource-economics modules, rather than as a standalone course. Instructional designs that pair guided input datasets, such as simplified stratigraphic sequences with known outcomes, with progressively open-ended modelling tasks appear to support students in building both technical competence with the Python-based interface and conceptual understanding of implicit interpolation principles.

5.2 Spatial Reasoning Development

Consistent with the broader geoscience education literature on interactive three-dimensional visualization tools, the evidence suggests that GemPy's capacity to generate immediate, manipulable three-dimensional output from student-supplied input data supports the iterative refinement of spatial mental models. Because students can adjust orientation and interface data and observe the resulting structural changes in real time, the tool appears well suited to helping students develop an intuitive grasp of how localized geological observations propagate into broader three-dimensional structural interpretations, a competency that is comparatively difficult to develop through static cross-sections alone.

5.3 Technical Barriers

A significant constraint identified in the literature concerns GemPy's Python-native interface, which presumes a baseline familiarity with Python programming and scientific computing libraries that many geoscience and, particularly, economics students may not possess at the outset. This technical barrier is consistent with broader findings in technology-enhanced learning scholarship indicating that the pedagogical benefits of code-based tools are contingent on adequate instructional scaffolding, such as pre-built starter notebooks, guided tutorials, and instructor-mediated debugging support, to prevent the technical overhead of the tool itself from displacing engagement with the underlying geological concepts.

5.4 Relevance to Resource Economics Curricula

For students in economics and resource-management tracks specifically, the findings suggest that GemPy offers a valuable bridge between geological structural understanding and the economic analysis of resource extraction feasibility, reserve estimation, and risk assessment. By enabling students without extensive geological training to construct and interrogate simplified structural models relevant to a given resource scenario, the tool has the potential to strengthen the geological literacy that underpins sound economic decision-making in mineral and energy resource contexts, provided that the technical barriers identified above are adequately addressed through curriculum design.

6. Conclusion and Recommendations

This paper has examined the application of GemPy, an open-source implicit geological modelling library, as a tool for improving students' capacity to construct and reason about complex three-dimensional geological models. The evidence reviewed indicates that GemPy's implicit, interactive, and code-driven modelling approach aligns well with constructivist learning principles, offering students the opportunity to actively build and iteratively refine structural models rather than passively consuming static representations. At the same time, the tool's Python-based interface presents a technical learning-curve barrier that must be actively managed through instructional scaffolding.

The paper recommends: first, structured integration of GemPy into structural geology and resource-economics curricula as a laboratory or project-based component, supported by guided starter materials; second, deliberate scaffolding of the Python and scientific-computing prerequisites required for effective use, particularly for students, such as those in economics programmes, without a strong prior programming background; third, the design of progressively open-ended modelling tasks that move students from guided exercises toward independent structural interpretation; and fourth, further empirical classroom research, including pre- and post-intervention assessment of students' spatial reasoning and structural interpretation competencies, to more rigorously quantify GemPy's pedagogical impact.

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