

Visualizing the invisible: The use of a new interactive sandbox for teaching evolutionary geological processes

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Abstract: The Second-Generation Augmented Reality system presented here transforms the haptic sandbox from a simple topographic surface into the surface of a completely explorable and real-time moldable geological volume. The core of the innovation lies in the immediate digital management of the three-dimensional geology through a remote tablet software interface structured around a dedicated Geology Menu. Through this control panel, the user acts directly on the mathematical variables of the subsurface without restricting the ability to shape the kinetic sand: the Stratigraphy module defines the number, thickness, rock textures, and color codes of the layers; the Tilt module inclines and orients the attitude of the series in space; the Fold and Fault modules respectively manage ductile tectonics (amplitude and height of the folds) and brittle tectonics (variably orientable normal, reverse, or strike-slip kinematics of the fault plane). A high-resolution depth sensor constantly detects the surface point cloud, while a 60 fps calculation engine instantaneously intersects the Digital Elevation Model (DEM) with the parameters configured on the tablet. The resulting projection displays the exact geometric intersection between the virtual geology and the real morphology of the sand; this interaction drastically accelerates the development of spatial thinking, translating complex concepts such as the "Rule of Vs" and apparent displacements along fault planes into immediate, haptic evidence, thereby rigorously integrating the analogue experience with numerical modeling.

Introduction

The understanding of three-dimensional geological processes and their temporal evolution has always represented one of the most arduous cognitive challenges in the field of Geosciences. This difficulty lies primarily in the need to develop advanced spatial thinking, capable of translating the two-dimensionality of traditional cartography into the volumetric complexity of underground structures. Although the educational landscape has been profoundly innovated by the advent of Augmented Reality Sandboxes (ARS) - capable of revolutionizing the teaching of topography and

hydrology through the projection of dynamic contour lines onto a moldable surface - these tools have thus far shown an insurmountable limit related to the opaque nature of the analogue substrate. In these first-generation configurations, the sandbox acts exclusively as a surface membrane, making it impossible to visualize what occurs beneath the topography and limiting interaction solely to external morphology; analogue modeling, which traces its roots back to the 19th-century experiments of Cadell (1888) and Hubbert's rigorous theory of similitude (1937), marked the beginning of a new era for Geosciences.

The present work introduces a technological and conceptual innovation that defines "Second Generation Augmented Reality," definitively transforming the sandbox from a two-dimensional surface into an explorable geological volume. The heart of this evolution lies in proprietary software that, for the first time on a global scale, allows for the integrated digital management of stratigraphic series, fold systems, and a fault plane directly within the sand mass. Thanks to a remote-control interface via tablet, the user is no longer a simple manipulator of shapes, but assumes the role of a structural modeler capable of defining - in real-time - the thickness of layers, their inclination, and the kinematics of deformation systems, whether they be extensional, compressional, or strike-slip: a great step following the insights of Petti, F.M., et al. (2019); the user can also add layer symbols and rock textures.

The strategic use of kinetic sand is fundamental in this process, as its specific rheological properties of cohesion and moldability allow it to maintain angles of repose and tectonic structures that traditional sand could not support. In parallel, a high-frequency calculation engine ensures that the Digital Elevation Model (DEM) interacts instantaneously with the set structural variables, projecting the exact intersection between the virtual geology and the physical surface. This ecosystem allows one to "visualize the invisible," making it evident how the variation of a tectonic parameter modifies the geological trace on the ground, thus offering a concrete and immediate response to classic problems of cartography, such as the complex application of the "Rule of Vs" or the analysis of the relationships between tectonics and morphology.

The integration of geospatial data from Google Earth further elevates the value of the tool, transforming the teaching laboratory into an advanced platform for research and professional simulation. In this context, the innovation proposed here does not merely enhance an existing aid but fills a fundamental technological void, offering a definitive bridge between the sensory experience of analogue modeling and the analytical rigor of numerical modeling. The result is a dynamic laboratory where geology ceases to be a purely observational discipline to become a tactile and scientifically rigorous experience, capable of breaking down cognitive barriers and redefining EdTech standards in Earth Sciences.



Remote control interface and volumetric projection. On the left, the tablet application for managing structural parameters (Layer, Tilt, Fold, Fault). On the right, the instantaneous response of the second-generation AR-Sandbox system projecting the geometry of a fold onto the kinetic sand topographic surface, ready to be analyzed in its 3D components.

Materials and Methods

The system architecture is based on an integrated ecosystem where hardware and software components operate in constant synergy to guarantee the fidelity of the geological model. The technological heart of the entire apparatus consists of a high-resolution depth sensor, whose task is the continuous detection of the point cloud corresponding to the sand surface. This real-time three-dimensional scanning allows for the generation of a dynamic Digital Elevation Model every time the landscape's appearance is shaped, which serves as the topographic base for every subsequent projection. The choice of the analogue substrate fell on kinetic sand, a material whose rheological properties are superior to natural sand for the intended purposes. Its particular cohesion and high angle of repose are indeed fundamental requirements for realistically simulating surface geological structures, allowing the user to model nearly vertical fault scarps or deep valley incisions without the model collapsing, thus ensuring the stability necessary for projecting stratigraphic traces.

The calculation engine consists of proprietary software designed to execute complex intersection algorithms between mathematical geometric planes and the detected physical surface. Operating at a refresh rate of 60 frames per second, the system ensures near-zero latency, making the manipulation experience fluid and scientifically accurate. To sustain this computational load, the workflow utilizes a standard GPU, which instantaneously processes morphological variations, allowing colors and fault lines to "adhere" perfectly to the folds of the terrain as they are being shaped. Although first-generation Augmented Reality Sandboxes (ARS) revolutionized the educational approach, all of this remained confined to surface morphology. The research group at Aachen University has carried out extensive work based on the creation of virtual 3D mathematical models to be integrated into the sandbox. (Wellmann, F., & Caumon, G., 2018), (De la Varga, M., et al., 2019); the concept of a 'Digital Twin' of geological reality is also introduced (Wellmann, F., et al.,

2022), validating our system, which reacts instantaneously to digital inputs to simulate geological reality.

The control element that transforms the sandbox into an interactive modeling tool is the remote tablet interface, which acts as a true control room for the simulation. Through this device, the operator can directly intervene in the mathematical variables of the virtual model without interrupting manual activity on the sand. Regarding stratigraphy, it is possible to precisely define the number of levels, their thickness, and the color coding necessary to distinguish different time horizons. On a structural level, the software allows for the management of ductile tectonics by adjusting the amplitude, wavelength, and dip of folds, as well as brittle tectonics. In the latter case, the instructor can set the orientation and dip of the fault plane, deciding the nature of the displacement between extensional, compressional, or strike-slip movements, instantaneously observing how such geometric variations translate into a new geological configuration on the topographic surface.

Use cases

The implementation of the second-generation AR-Sandbox system has produced tangible results in the spatial analysis capabilities of users, highlighting a clear reduction in learning times compared to traditional cartographic methods. One of the most significant results was observed in the resolution of problems related to the intersection between inclined planes and irregular topographic surfaces. Through the practical application of the "Rule of Vs," students were able to verify how the incision of an artificial drainage network in the sand causes an instantaneous migration of the traces of geological contacts. This phenomenon, usually difficult to visualize on paper, became immediate tactile evidence: by modifying the dip of the stratigraphic series from the tablet, the user observes the geological "V" pointing upstream or downstream, understanding in seconds the geometric link between the slope of the hillside and the inclination of the layer.

A further milestone achieved concerns the understanding of complex tectonics. In the tests carried out, the possibility of simulating a model crossed by an active fault allowed for an extremely precise analysis of the distinction between real displacement (set digitally) and apparent displacement (observable on the sand surface). A significant example was the case of the strike-slip fault: users were able to observe how the horizontal displacement of a series of inclined layers generates a dislocation on the surface morphology that, to an inexperienced eye, might erroneously appear as a vertical movement. Real-time visualization allowed for the correction of these interpretative gaps, providing a dynamic key to reading the kinematics of brittle structures.

The effectiveness of the system also emerged strongly in the study of ductile structures. During folding simulations, the software allowed for the instantaneous visualization of the outcropping of anticlinal or synclinal cores in response to the manual erosion of the sand. This facilitated the understanding of chronostratigraphy: by digging the crest of a fold, the emergence of colors corresponding to older layers made the perception of the underground

geometric arrangement immediate - a result rarely obtainable with static analogue models that require long preparation times and do not allow for changes on the fly.

Finally, integration with geospatial data transformed the sandbox into a powerful tool for predictive and diagnostic analysis. By loading georeferenced textures from Google Earth, it was possible to reproduce real geomorphological contexts, such as mountain slopes subject to instability risk. In these scenarios, the system allowed for the projection of hypothetical geologies onto existing topographies, allowing for the evaluation of how different layer orientations (for example, dip-slope or anti-dip-slope) can influence the stability of a slope. This transition from a theoretical model to a real case study demonstrated how the tool transcends the boundaries of education to approach the field of professional simulation and territorial planning, finally making the impact of deep structures on safety and the shape of the visible landscape visible.

Beyond the modeling of natural geological structures, the system's flexibility allows for the introduction of anthropic and paleontological elements that further expand the sandbox's range of action. An application of particular engineering significance concerns the possibility of inserting the planes of mining tunnels or underground infrastructure into the virtual volume. In this scenario, the physical excavation of the sand does not only reveal the contact between rocks but allows for the visual 'interception' of the tunnel path, facilitating the understanding of the spatial relationship between mineral bodies, tectonics, and excavation works, transforming the tool into a high-fidelity mining planning simulator. It can also be transformed into a field-work arena for the direct use of a geologist's compass within the model, to understand methodologies and collect data to be entered into a Schmidt net (While the traditional geologist projects data onto a stereographic net to analyze it, the Sandbox performs the reverse path: it uses digital data to project it into the physical reality of the sand). The sandbox transforms these static diagrams into a tactile experience. When the user changes the inclination of layers or the fault on the tablet, they see the effects vary on the sand, making the understanding of technical terminology immediate.

For more school-oriented use, it is possible to simulate rainfall of varying intensity to observe the formation of drainage basins, watersheds, and fluvial networks. The user can see in real-time how water occupies valleys and how terrain shapes and river path conditions influence it. It is also possible to present the concept of permeability. Although the sand is physically homogeneous, the software can simulate the effect of impermeable layers or aquifers, showing how virtual water accumulates or flows based on the "digital" stratigraphy defined on the tablet, because it allows the permeability of the substrate to be simulated.

To engage younger audiences and museum visitors, this software offers scenarios that transform science into an interactive game: in addition to "cold" geology, it is possible to simulate volcanic eruptions with lava flows that follow the terrain morphology created by the user. This helps in understanding how pyroclastic or lava flows channel into valleys.

Some modules allow for the visualization of how vegetation or ecosystems change as altitude and water availability vary, creating a bridge between geology and biology.

Parallel to this, for school-age targets or museum outreach, the system enables a 'virtual paleontological excavation' function. It is possible to set the software to generate a series of index fossils distributed in limited numbers and with random positioning, though we are working to make them rigorously constrained to certain stratigraphic horizons. This function transforms manual activity into an experience of active discovery: the viewer does not simply observe the geology but must 'investigate' the sand volume in search of findings that appear only when manual erosion reaches the correct elevation. This approach not only increases the engagement of the youth but also conveys - in a playful way - the fundamental scientific concept that fossils are not randomly distributed underground but are indissolubly linked to the chronology and nature of the layers that host them.

Discussion

The discussion of the results highlights how this technology represents not just a technical advancement, but a true epistemological evolution in the way Geosciences are taught and studied. Overcoming the dualism between analogue and numerical models is the cornerstone of this reflection: historically, analogue models in sandboxes have been rigid tools, where every experiment was "destructive" and every setup error required hours of work to reset. The second-generation AR-Sandbox breaks this linearity by introducing the concept of iterative experimentation. In this new environment, error ceases to be an obstacle to the workflow and becomes an integral part of the scientific validation process. The user can instantaneously modify the inclination of a layer or the orientation of a fault, observing the change without having to rebuild the physical model, which allows for testing multiple geological hypotheses in an extremely compressed time frame.

This operational fluidity is made possible by the system's very low latency, a technical requirement that takes on fundamental psychological and cognitive value. Immediate visual feedback generates a cognitive loop that reinforces experiential learning: the student no longer has to wait for the end of a process to understand its implications but witnesses the spatial transformation while their hand interacts with the material. This constant dialogue between the digital input of the tablet and physical manipulation creates a deep neuronal connection between the theoretical concept of solid geometry and the tactile perception of form.

While traditional sandboxes limit themselves to coloring the surface based on height, our system integrates implicit structural modeling algorithms similar to those developed in the GemPy project, but much more dynamic and directly controllable via tablet, without pre-constructed models. This allows for the instantaneous generation of a coherent geological volume in the subsurface that responds in real-time to the manipulation of the sand. The user is not just digging a trench but is querying a complex mathematical model:

every morphological variation forces the software to recalculate the intersections between layers and fault planes, following the criteria of geometric consistency established by the Aachen researchers; in this way, the sandbox becomes a tactile interface for computational geomechanics, where the sand serves as a physical sensor and the tablet as the control room for a scientifically rigorous virtual subsurface.

In this context, kinetic sand proves to be much more than a simple practical detail. Its polymeric nature gives it a "shape memory" and an internal cohesion that are essential for supporting the underlying geological theory. Without this ability to maintain the verticality of a scarp or the precision of a fluvial incision, the results obtained in simulating faults and valleys would lose realism. The sand therefore allows for the extremely effective simulation of differential erosion processes: the user can physically remove material to test how slope stability responds to different set stratigraphic orientations, making visible the direct relationship between the "invisible" geological structure and the surface geomorphological risk.

The integration of these elements leads to considering the tool as the definitive bridge between the abstraction of numerical data and the tangible reality of field geology. The discussion of the collected data suggests that the ability to "query" the model in real-time - rapidly swapping roles between topography and deep geology - drastically accelerates the maturation of spatial vision. What previously required years of field experience to be mentally visualized can now be explored, dismantled, and reconstructed in a single laboratory session, democratizing access to high-level interpretative skills and redefining the role of spatial intelligence in modern science education.

It is fundamental to highlight how this platform is not an isolated entity, but the heart of a diversified software ecosystem designed to meet the needs of an extremely heterogeneous audience, as detailed in the resources at ar-sandbox.eu. This versatility allows the user experience to scale from educational play to advanced scientific simulation, ensuring that the tool remains relevant for every type of user.

In addition to volumetric structural geology features, the system integrates specific software modules ranging from dynamic hydrology to classic interactive topography. For museum contexts and primary schools, there are applications focused on gamification, where the manipulation of sand triggers playful scenarios such as the creation of natural habitats, the simulation of volcanic eruptions, or the management of drainage basins in real-time. These tools allow for the immediate visualization of the impact of morphological changes on water runoff, using fluid simulation models that make the concepts of watershed and drainage basin understandable even to non-experts through vivid colors and engaging visual effects.

At the same time, the software offering extends toward more technical and professional fields. Integration with quantitative analysis tools allows the sandbox to be transformed into a data collection station, where it is possible to calculate slopes, excavation and fill

volumes, or simulate the flooding of coastal areas in response to sea-level variations. This breadth of solutions, accessible and interchangeable via the same tablet interface, ensures that the sandbox is not just a device for teaching geology, but a 360-degree multifunctional platform for Earth Sciences. The reference site emphasizes this very philosophy: providing robust hardware supported by an evolving software library, capable of adapting both to the fun of children and the academic rigor of university researchers.

This modular development strategy ensures that the technological investment of institutions is long-lasting, as the system can be updated with new scenarios and algorithms without modifying the physical structure, keeping the AR-Sandbox constantly in step with the latest innovations in the field of EdTech and digital modeling.

Conclusions and Future Perspectives

The concluding perspectives of this research highlight how the transition from surface monitoring to volume management definitively transforms the sandbox into a laboratory of applied solid geometry, where geology sheds its purely descriptive nature to become a predictive and interactive science. The future of this technology moves toward an even closer convergence between artificial intelligence and virtual reality, promising to break down the last barriers between analogue simulation and the physical reality of natural processes. The system can be enhanced to color the sand based not on height, but on the inclination of slopes. This allows for the immediate identification of areas most subject to landslides or accelerated erosion - a fundamental datum for the study of slope stability - but one of the most ambitious developments currently being tested involves the integration of differential erosion algorithms based on artificial intelligence. In this scenario, the tablet will no longer serve only to define the geometry of the layers but will allow for assigning petrophysical parameters and specific hardness grades to every level of the series. The system will thus be able to calculate in real-time how the erosive agent should act on the model, by stimulating the formation of reliefs or depressions based on the set lithological resistance, making the sandbox a dynamic environment capable of showing the evolution of the landscape over millennia in just a few moments of calculation.

In parallel, research is exploring integration with virtual and augmented reality headsets to enable a mode of total immersion. This will allow the user to move from the zenithal view, typical of the cartographic approach, to an "internal" perspective of the model, virtually walking inside the newly shaped valleys or observing the fault plane at a 1:1 scale, as if physically located at a real outcrop. This technological leap is accompanied by the coding of standardized educational protocols - true "guided journeys" - that will allow instructors to structure modular lessons capable of leading the student from simply reading a geological map to the reconstruction of extremely complex structural sections.

Ultimately, this innovation does not limit itself to enhancing an educational aid but reconfigures Geosciences as an active and deeply engaging discipline. By providing a concrete response to the challenges posed by the digital transition, ar-sandbox.eu has

developed a second-generation software, which serves as the specialised tool for higher education and modern scientific communication. It not only allows us to understand the planet, but invites the user to question it, shape it, and visualize its deepest secrets, finally making the invisible accessible to the human intellect and perception.

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