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BOOK OF ABSTRACTS

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GNSS Reflectometry for detecting glacier lake drainage – an alpine study case

Matthias Aichinger-Rosenberger*, Annelies Voordendag, Andreas Wieser, Benedikt Soja

Institute of Geodesy and Photogrammetry, ETH Zurich, Switzerland,
annelies.voordendag@geod.baug.ethz.ch

Key words: *GNSS reflectrometry, glacier lake monitoring, TLS*

A glacier-dammed lake formed near the tongue of Gornergletscher during several of the past years. Implications of this lake and its discharge on glaciological aspects have been studied extensively in the past, see e.g., Riesen (2011). However, the subglacial drainage of this lake within a few hours poses a risk of flooding for the nearby municipality of Zermatt (Valais, Switzerland). Timely detection of rapid water level changes in the lake is essential for risk mitigation. Since the drainage of the lake can occur virtually at any time, the lake needs to be monitored using a quasi-continuously operating system which detects the drainage reliably and with a latency of no more than 1-2 hours for timely warning and actions.

Within a pilot study, we are currently exploring the use of GNSS Reflectometry (GNSS-R) for this purpose. GNSS-R is already proven for monitoring surface changes at daily resolution (Larson et al., 2013). Its application within a warning system in the aforementioned context requires processing data at hourly or higher resolutions. Furthermore, the conditions at the alpine measurement site are challenging in terms of topography, weather conditions, and surface changes irrelevant for the intended warning. Although some first studies for real-time applications exist (Purnell et al., 2024), the time resolution and local conditions remain major challenges for this approach.

In this contribution, we present the experiments and first results obtained within the pilot study, which is a collaboration between ETH Zurich and the local municipality. It serves three main goals: (1) to demonstrate the feasibility of GNSS-R for detecting short-term lake level variations; (2) to conceptualize a GNSS-R-based monitoring and early warning system tailored to glacier lake hazards; and (3) to assess the maturity of available GNSS-R hardware and software and outline the necessary development efforts for operational implementation.

A mobile GNSS-R station, based on low-cost GNSS equipment (specialized antenna, receiver, power supply, and data logger) is deployed and operates autonomously for an extended period (several days to weeks without interruption). High-resolution terrestrial laser scanning (TLS) is conducted several times during the monitoring period and serves (i) to generate a detailed digital terrain model (DTM), supporting data interpretation and validation, as well as (ii) locate changes in the environment. Hourly ground-based images provided by the local municipality assist in cross-checking inferred water level changes.

We post-process the GNSS-R data using open-source tools (Larson, 2024) to extract water-level time series and detect anomalies indicative of subglacial water movement. We assess these results by comparing them to those obtained from TLS data and photographic evidence as well as to the requirements for a real-time warning system. The study contributes to providing an easily deployable, mechanically robust, real-time system for detection and early warning of subglacial lake drainage events, thus potentially improving hazard mitigation in glacierized catchments increasingly affected by climate-driven meltwater dynamics.

References

Larson, K. M. (2024). Gnssrefl: an open source software package in python for GNSS interferometric reflectometry applications. GPS Solutions, 28(4).

Larson, K. M., Ray, R. D., Nievinski, F. G., and Freymueller, J. T. (2013). The accidental tide gauge: A GPS reflection case study from Kachemak Bay, Alaska. IEEE Geoscience and Remote Sensing Letters, 10(5):1200–1204.

Purnell, D., Gomez, N., Minarik, W., and Langston, G. (2024). Real-time water levels using GNSS-IR: A potential tool for flood monitoring. Geophysical Research Letters, 51(5).

Riesen, Patrick (2011). Variations of the surface ice motion of Gornergletscher during drainages of the ice-dammed lake Gornersee. PhD thesis.

Invited Keynote:

Decoding Landscapes in Motion: From Topographic Time Series to Surface Processes

Katharina Anders[1]*

[1] *Remote Sensing Applications, TUM School of Engineering and Design, Technical University of Munich (TUM), Germany, k.anders@tum.de*

Key words: *Change detection, topographic monitoring, geomorphic processes*

The increasing availability and resolution of topographic data acquired at high temporal frequency has fundamentally transformed how we observe and understand surface dynamics. This capability, often referred to as 4D Earth observation (3D + time), enables detailed spatiotemporal analyses of geomorphic processes across a range of environments. From rockfalls and slope instabilities to riverbank erosion, soil redistribution, and coastal change, these approaches offer new opportunities for process-based insight into landscape evolution. They also allow us to detect and quantify in what way changes may be influenced by anthropogenic activities and climate variability, particularly in sensitive or rapidly changing settings.

This keynote explores how 4D topographic data, captured, for example, through near-continuous laser scanning or time-lapse photogrammetry, can be used to enhance our understanding of surface process characteristics, rates, and ultimately drivers. Recent research highlights the enormous potential in developing analysis frameworks that integrate time series information to derive meaningful, interpretable, and robust indicators of geomorphic activity. This requires not only methodological innovation, but also a consideration of scale, uncertainty, and the nature of geomorphic processes as captured across varying scene conditions and observation intervals.

The talk will focus on methodological advances that enable automated and objective extraction of information from dense 4D datasets. It will discuss how time-aware approaches fundamentally differ from traditional change detection, and how they can support both scientific interpretation and practical applications in risk assessment, environmental management, and climate impact analysis.

The insights presented draw on collaborative research notably within the *Charact4D, Extract4D*, and *AI4ENV* projects, together with partners from Heidelberg University, TU Delft, TU Dresden, and University of Rennes. These joint efforts span diverse applications in coastal, river, agricultural, and high-mountain environments. The case studies highlight the value of advanced observation strategies in capturing the complex spatiotemporal signatures of landscape change. Through them, we explore how the integration of 4D monitoring, multi-modal data sources, and advanced analysis algorithms can help bridge the gap between observation and understanding.

Ultimately, this talk advocates for process-oriented analysis of multi-source 4D topographic observation in geosciences for investigating the mechanisms driving landscape dynamics. By embedding time into spatial analysis, we can better understand how Earth surface systems evolve and how they may respond to ongoing environmental change.

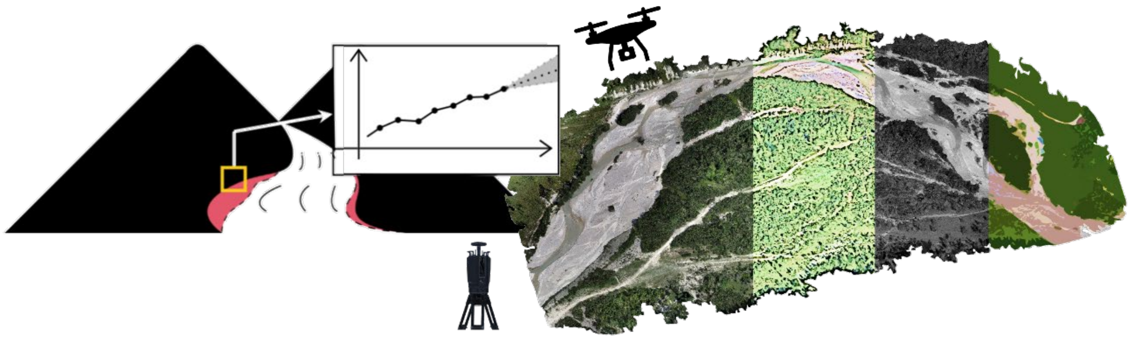

Figure 1: Decoding landscapes in motion through multimodal 4D Earth observation using topographic time series. Figure by M. Letard and K. Anders.

Digital outcrop models in Canton Vaud: Improvement of our subsurface knowledge and valorisation and preservation of our geological heritage

Loïc Bazalgette[1], Pierrick Altwegg[1], David Giorgis[1], Mohamed Laribi[1, 3] and Robin Marchand[2]

[1] *Division GEODES, Direction Générale de l'Environnement, Av. de Valmont 30b – 1014 Lausanne, Switzerland*

[2] *Naturéum, Muséum cantonal des sciences naturelles, Bâtiment Anthropole - Université de Lausanne, 1015 Lausanne, Switzerland*
[3] *GEOREVO Ingénieurs, Av. Haldimand 63, 1400 Yverdon-les-Bains, Switzerland*

Key words: *drone photogrammetry, geotopes, geological heritage, underground resources, valorisation, geological data, outcrops.*

Key missions of the Geology Section of Canton Vaud's Directorate of Environment (DGE) aim at improving our knowledge about the underground and its resources, and at valorising and preserving its rich geological heritage. To support these missions, digital outcrop datasets were acquired around Sainte-Croix (Jura Mountains). Drone-based photogrammetry was used to provide high-quality data in a fast and cost-efficient way. This paper presents two datasets acquired in (1) a historic mining area close to Baulmes and (2) an active quarry close to the "Col des Etroits".

The site of "Mines de Baulmes" is part of the "Inventaire Cantonal des Géotopes" register, which lists protected sites of geological interest. It shows a spectacular cliff face revealing the steep southeastern flank of the "Aiguilles de Baulmes" anticline. Lower-Malm marly limestones (i.e., couches d'Effingen) exposed there form a pluri-decametre scale flexure, locally overturned to the Southeast. Abandoned mining galleries spanning over more than 17 km are present throughout the site, with entrances clearly visible on the outcrop.

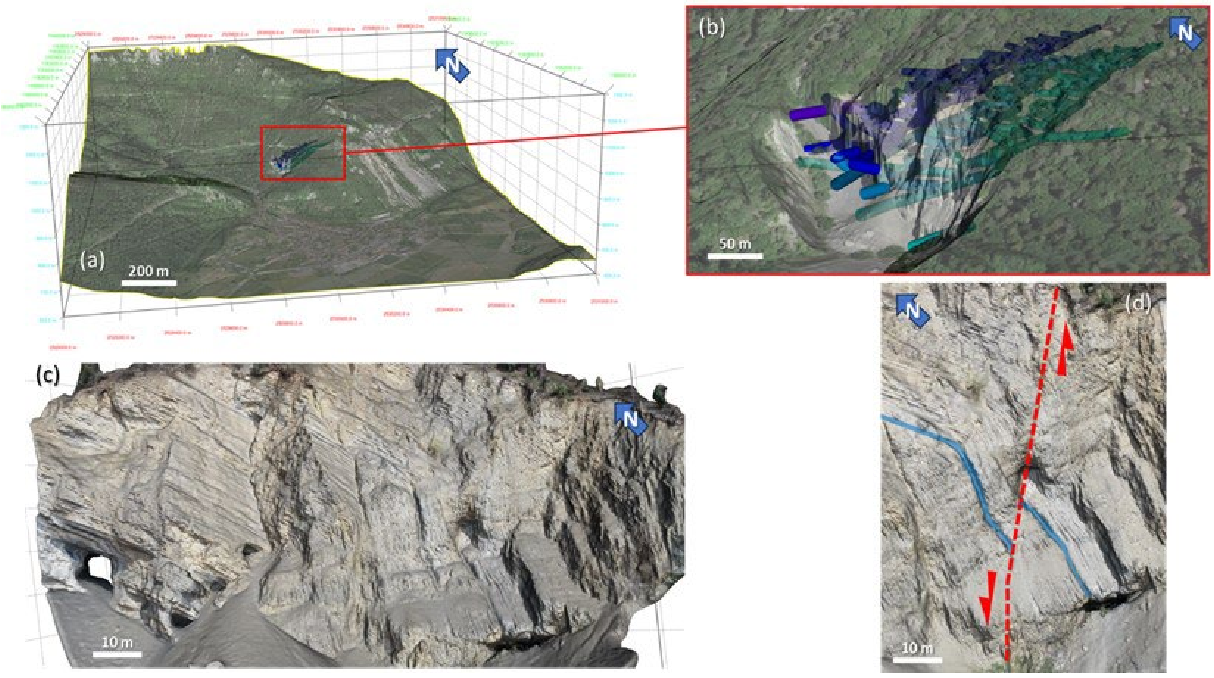

Figure 1: (a) General and (b) zoomed-in views of the "Mines de Baulmes" model. Blue patterns in transparency represent the abandoned mining galleries. (c) Overview of the outcrop model where several gallery entrances are visible. (d) detail view highlighting a steep fault in the Southeastern sector of the outcrop.

A comprehensive model (Figure 1) including the 50 cm-resolution regional LIDAR DEM, the detailed photogrammetry dataset of the outcrop, and a model of the mining galleries (digitized from Dériaz et al.,

2007) is under construction. Regarding the Canton's missions, such a model has multiple interests, including among others:

Public access to geological data: Possibility to make detailed observations across an unstable, dangerous cliff face,

Preservation of the Canton's historic mining heritage via 3D reconstitution of the abandoned mining pattern of dangerous access.

The quarry of Les Etroits offers outstanding exposures of a complex WNW-ESE fault zone. A high-resolution photogrammetry dataset was acquired there, primarily to facilitate detailed structural observations over the fault zone. It provides an excellent analogue to subsurface faults targeted by ongoing regional exploration projects for geothermal energy. Observations target the main slipping zone geometry, the presence of multiple segments and fault rocks, and the existence of a complex fractured damage zone with evidence of karstification (Figure 2). Due to the ongoing quarrying activities, the quality and accessibility of the outcrop evolve quickly. Acquiring high-quality 3D datasets can therefore provide an efficient way to preserve outcrops that could otherwise be irreversibly compromised.

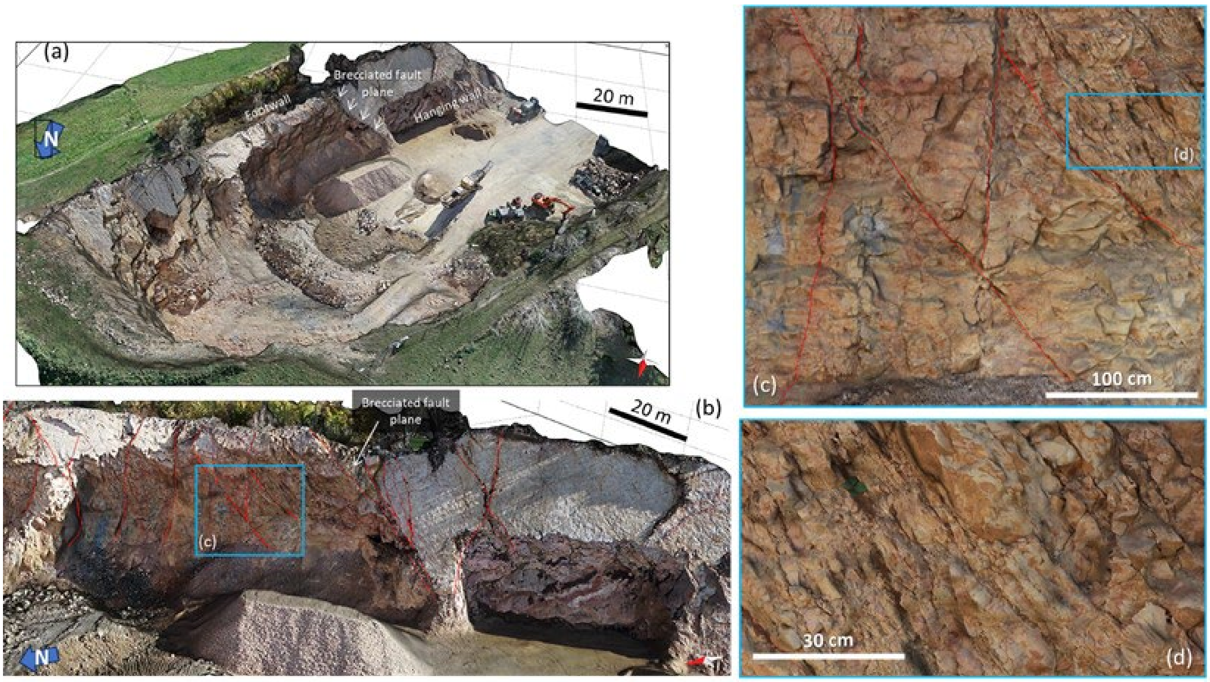

Figure 2: (a) General view of the 3D model of the "Carrière des Etroits". (b) Semi-interpreted view over the main WNW fault and its fractured damage zone. (c) detail view of minor fault planes showing kart evidence. (d) Detailed view of the intensely fractured zone located to the south of sector (c).

In addition to the above, it may be underlined that digital outcrops can be useful for the Canton for the valorisation of geotopes which accessibility is dangerous or to document outcrops that are only temporarily accessible during major infrastructure works.

Acknowledgements:

We are grateful to Mr Christophe Graff (JPF Gravières SA) for granting safe access to the quarry in "les Etroits" and for allowing us to acquire the 3D drone photogrammetry dataset.

Reference:

Deriaz P., Bourret F., Jeannin P.-Y., Lalou J.-C.,Lambelet J., Pauli C., Spring D. & Thévoz P.-Y., 2007. Inventaire spéléologique de la Suisse. Tome V: Nord vaudois. Commission de Spéléologie de l'ASSN, La Chaux-de-Fonds, 132-133.

PZero: An Extensible Open-Source Platform for Intuitive 3D Geological Modelling

Andrea Bistacchi[1*], Waqas Hussain[2], Riccardo Monti[2]

[1] Dipartimento di Scienze dell'Ambiente e della Terra, Università degli Studi di Milano Bicocca, andrea.bistacchi@unimib.it

Key words: *3D geomodelling, Python, open source*

Between December 2019 and January 2020, we began to feel that commercial software had become a limiting factor in extending 3D geomodelling to non-standard applications—particularly those where geological and structural field data play a central role. Although commercial applications are undoubtedly powerful, they are generally highly specialized for specific industrial domains (e.g., hydrocarbon reservoir modelling) and their licensing costs can be prohibitive for small-scale or proof-of-concept projects.

On the other hand, the past decade has seen the development of several open source geomodelling libraries aimed at exploring innovative interpolation algorithms (e.g., De La Varga *et al.* 2019; Grose *et al.* 2021a). However, technical barriers and the absence of a Graphical User Interface (GUI) often hinder their usability, making them almost inaccessible to many field geologists who do not have a sufficient coding background, and sometimes impractical for integration into routine workflows.

Then came the COVID-19 pandemic. During the lockdown months, Andrea Bistacchi initiated the development of PZero, laying the foundations for a project that has grown steadily over the past five years.

PZero (https://github.com/gecos-lab/PZero) is a user-friendly system developed in Python for ease of coding, leveraging the VTK library to ensure high-performance visualization and data processing. Its intuitive multi-window Graphical User Interface (GUI), implemented in Qt (PySide6) for seamless cross-platform deployment, supports the management of all standard components in a geological modelling workflow—including boundary and implicit representations of geological and fluid contacts or volumes, digital elevation models (DEMs) and digital outcrop models (DOMs) including dense point clouds, 2D/3D seismics, remote-sensing imagery, wells, and borehole logs.

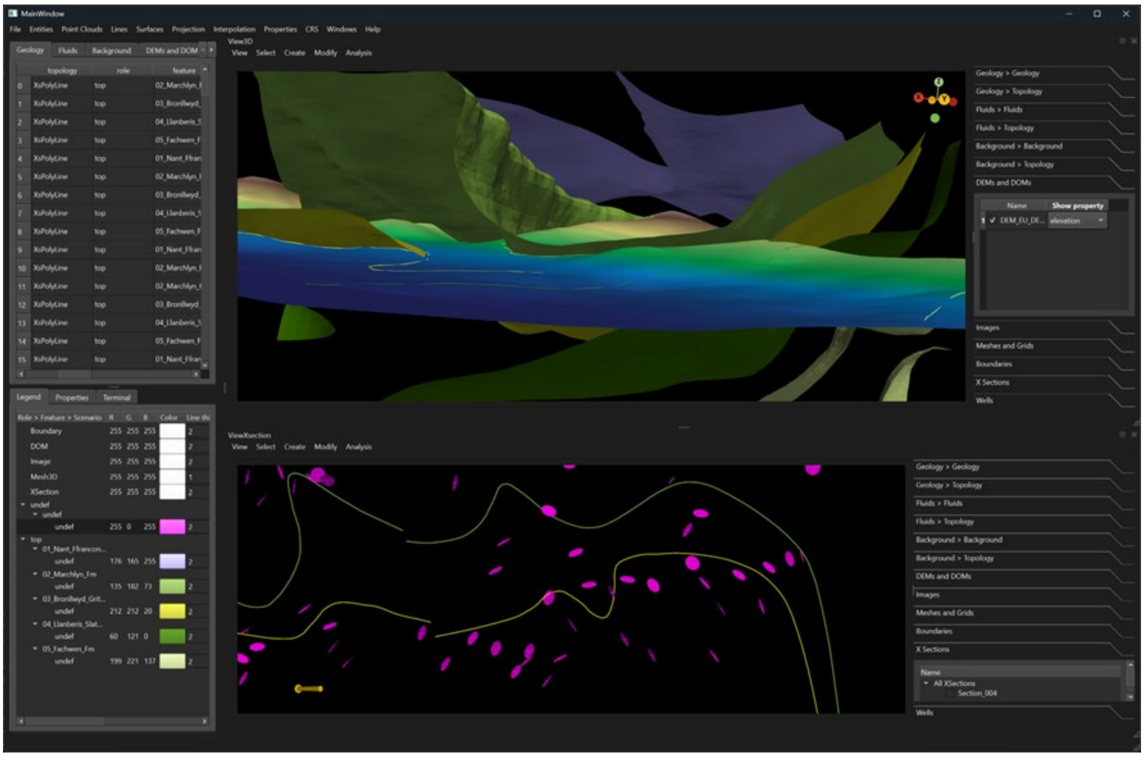

Figure 1: The PZero graphical User Interface.

To support the transition to 3D modelling for a broad audience of geologists, PZero provides integrated tools for standard 2D cross-sections and maps, orientation analysis (e.g., stereoplots), statistics and general-purpose plotting. A central feature of PZero is its geological legend system, designed to be both intuitive for field geologists and natively compatible with implicit modelling algorithms (Monti *et al.* 2025). Importantly, the legend system also transparently incorporates semantic uncertainty in terms of alternative geological scenarios.

Standard explicit interpolation methods, such as Delaunay triangulation, are natively supported by the VTK library. Implicit interpolation methods are integrated via the Loop3D library (Grose et al., 2021a), enabling advanced and efficient modelling workflows, and, at the time of writing, a dedicated GUI is under development to support the modelling of fault and fold "structural frames", as detailed by Grose *et al.* (2017, 2021b). 2D/3D seismics datasets are imported from SEGY files, and we are developing ML- and AI-based automated horizon tracking tools aimed at streamlining seismic interpretation (Hussain *et al.* 2025). Integration with the MeshIt finite-element meshing library (Cacace and Blöcher 2015) is currently in progress thanks to a collaboration with the developer.

Finally, because VTK entities can be seamlessly exposed as NumPy arrays, PZero is easily extensible through simple Python code—requiring no in-depth understanding of its internal architecture. Thus, we actively encourage contributions from geologists and geo-mathematicians who wish to extend PZero for specific geological workflows or harness it as a prototyping environment for developing and testing innovative modeling approaches.

Acknowledgements: We gratefully acknowledge the Geosciences IR PNRR project for funding, and the invaluable contribution of the open-source libraries we are (shamelessly) using: VTK, Qt/PySide6, Pandas, PyVista, NumPy, Matplotlib, LoopStructural, mplstereonet, MeshIt, Shapely, GeoPandas, segyio, Rasterio, Xarray, laspy, ezdxf.

References

Cacace, M. and Blöcher, G. 2015. MeshIt—a software for three dimensional volumetric meshing of complex faulted reservoirs. *Environmental Earth Sciences*, **74**, 5191–5209, https://doi.org/10.1007/s12665-015-4537-x.

De La Varga, M., Schaaf, A. and Wellmann, F. 2019. GemPy 1.0: open-source stochastic geological modeling and inversion. *Geoscientific Model Development*, **12**, 1–32, https://doi.org/10.5194/gmd-12-1-2019.

Grose, L., Laurent, G., Aillères, L., Armit, R., Jessell, M. and Caumon, G. 2017. Structural data constraints for implicit modeling of folds. *Journal of Structural Geology*, **104**, 80–92, https://doi.org/10.1016/j.jsg.2017.09.013.

Grose, L., Ailleres, L., Laurent, G. and Jessell, M. 2021a. LoopStructural 1.0: time-aware geological modelling. *Geoscientific Model Development*, **14**, 3915–3937, https://doi.org/10.5194/gmd-14-3915-2021.

Grose, L., Ailleres, L., Laurent, G., Caumon, G., Jessell, M. and Armit, R. 2021b. Modelling of faults in LoopStructural 1.0. *Geoscientific Model Development*, **14**, 6197–6213, https://doi.org/10.5194/gmd-14-6197-2021.

Hussain, W., Bistacchi, A., Benedetti, G. and Monti, R. 2025. AI-Driven PZero Modeling: Enhanced Seismic Data Loading, Grid Section Management, and Automated Interpretation with Sobel, A* Pathfinding, and SAM2. *In*: EGU General Assembly 2025, https://doi.org/10.5194/egusphere-egu25-16273.

Monti, R., Bistacchi, A., Hussain, W., Herwegh, M. and Musso Piantelli, F. 2025. Building a geological legend for 3D geomodelling in metamorphic belts. *In*: EGU General Assembly 2025, https://doi.org/10.5194/egusphere-egu25-16567.

Thermochronology-Driven Model Selection: A Probabilistic Approach to Reducing Geological Uncertainty

Sofia Brisson[1*], Florian Wellmann[1] , Christoph von Hagke[2]
*[1] Computational Geoscience, Geothermal and Reservoir Geophysics, RWTH Aachen University, Germany, *sofia.brisson@unil.ch*
[2] Department of Environment and Biodiversity, Paris Lodron Salzburg University, Austria

Key words: *3D modeling, uncertainty, Eastern Alps, thermochronology*

Uncertainties in geometry and kinematics are seldom incorporated into geological models. This can pose a problem particularly in areas of poor outcrop conditions, where models are built mostly based on subsurface data. Considering uncertainties is of special importance when building thermokinematic models, and often solutions are non-unique: more than one model geometry can reproduce the same thermochronological signal. Traditional thermokinematic studies often consider only a handful of model geometries and deformation sequences, and competing tectonic hypotheses are thus not tested. In turn, this can lead to inaccurate interpretations about reigning deep-seated processes.

In this work, we develop a routine to evaluate the potential of thermochronological data as a tool for model selection. Starting from two competing 3-D kinematic model hypotheses, key modeling parameters are varied stochastically to generate thousands of model possibilities for each hypothesis. For each set of model realizations, the maximum likelihood estimate (MLE) is calculated based on the fit of each individual model run to the available thermochronological record. Comparing these likelihoods using Bayes factors allows for a probabilistic evaluation of which model hypothesis is more strongly supported by the data.

We apply this approach to two case studies: the Subalpine Molasse and the Eastern Alps' TRANSALP section. In both regions, we test two contrasting kinematic model hypotheses. For the TRANSALP section, results yield strong evidence against the model involving subduction polarity reversal, suggesting that an alternative geometry better explains the observed deep exhumation in the Tauern Window.

Immersive Visualization of the Seafloor for Marine Infrastructure Using Extended Reality in Offshore Wind Projects

Monica A Buitrago-Barrera 1,2*, Alejandro Rodriguez1, Amadeu Deu1, Josep A. Gili 2

1 Geociencias y Exploraciones Marítimas, monica.buitrago@gemigeo.com

[2] Universitat Politècnica de Catalunya, UPC, Barcelona (Spain)

Key words: *Extended Reality (XR), Offshore Wind Infrastructure, Immersive Visualization, Seafloor Data, Virtual Reality, Ground Model*

Immersive data visualization and interaction through technologies such as Virtual Reality (VR) and Mixed Reality (MR), integrated within the broader framework of Extended Reality (XR), are gaining increasing relevance across diverse industries. These technologies are being applied in the visualization, simulation, and personnel training across different sectors ranging from the automotive industry, medicine, and geomatics, as well as in applications within the oil and gas industry and geosciences sectors. These tools enable the representation of physical environments and allow for the incorporation of logical simulation models and advanced 3D visualization techniques, thereby facilitating decision-making and project optimization.

As the global demand for renewable energy intensifies in response to climate change, Offshore Wind Farms (OWF) are attracting growing attention as a compelling and practical alternative (Dimitriou et al., 2025). However, the complexity and multidimensional nature of subsea data presents significant challenges for effective interpretation, communication, and application within multidisciplinary contexts (Bernstetter et al., 2025). This study explores the use of Extended Reality as an innovative methodology for immersive visualization of seafloor data in marine engineering. In addition, XR-based approaches can potentially enhance spatial awareness and cognitive engagement, especially when dealing with geospatial, underground, and/or subaquatic datasets.

This research aims at enhancing the interactive and collaborative visualization of geospatial information relevant to the planning, designing, and monitoring of marine infrastructure projects. This involves the integration of bathymetric, geological, environmental, geotechnical, geophysical, and engineering data, such as submarine cable routing or turbine anchoring, into an immersive 3D ground model environment. The expected outcome is a system that enables users to interact with spatial elements, query data, perform measurements, and ultimately support better-informed design decisions. Furthermore, the goal is to facilitate the understanding, dissemination, and communication of offshore projects among diverse stakeholders and end-users.

Future work includes the development of subsea data visualization and analysis to promote interdisciplinary collaboration and stakeholder engagement. By investigating how immersive technologies can support the planning and communication of offshore wind infrastructure, this research seeks to contribute to technological innovation and the participatory processes, essential for a sustainable energy transition.

References

BERNSTETTER, A., KWASNITSCHKA, T., KARSTENS, J., SCHLÜTER, M., & PETERS, I. (2025). Virtual fieldwork in immersive environments using game engines. *Computers & Geosciences*, *196*, 105855. https://doi.org/10.1016/j.cageo.2025.105855

DIMITRIOU, I. C., SARMAS, E., TRACHANAS, G. P., MARINAKIS, V., & DOUKAS, H. (2025). Multi-Criteria GIS-based offshore wind farm site selection: Case study in Greece. *Renewable and Sustainable Energy Reviews*, *207*, 114962. https://doi.org/10.1016/j.rser.2024.114962

Digital Outcrop Models for Structural Analysis of Fracture Networks: Case Studies from the Swiss Jura and Alps

Jefter N. M. Caldeira[1*], Ana P. B. Tanaka[2], Anindita Samsu[1], Philippe Renard[2]
[1] *Deformation and Tectonics Group, Institute of Earth Sciences, University of Lausanne, Switzerland – jefter.caldeira@unil.ch*
[2] *Centre for Hydrogeology and Geothermics, University of Neuchâtel, Neuchâtel, Switzerland*

Key words: *Fracture Networks, Terrestrial LiDAR, UAV Photogrammetry, Jura, Alps*

Digital Outcrop Models (DOMs) derived from close-range remote sensing technologies are increasingly being used in structural geology to characterize fracture networks in 3D. We present two case studies from the Swiss Jura and Helvetic Alps to evaluate how different DOM acquisition methods perform and exemplify how they are fit for purpose, to support structural analysis.

In the Jura Mountains, a terrestrial LiDAR survey was conducted along subvertical cliffs of the Creux-du-Van (CV) for multi-scale fracture characterization in multilayered Upper Malm carbonates, an outcrop analogue for fractured Upper Malm limestone reservoirs targeted for geothermal exploration beneath the Molasse Basin. In the Helvetic Alps, a UAV-based photogrammetric model originally acquired in 2019 above the Tsanfleuron glacier (TS) was the basis for fracture characterization, using a graph-based approach to analyse the impact of the fracture networks on the preferential fluid flow pathways over the Cretaceous limestone pavement that was exposed due to glacial retreat.

Both datasets were processed into georeferenced 3D point clouds with comparable spatial resolutions: ~110 points/m² (equivalent to ~9.5 cm/pixel) for the CV LiDAR dataset and ~100 points/m² (10 cm/pixel) for the TS UAV photogrammetry. The structures in both datasets were traced manually. At CV, 696 fractures, 73 bedding planes, and 5 internal stratigraphic surfaces were interpreted on the DOM. In addition to the orientation, fractures were classified by relative vertical persistence, and their orientation, length, and spacing were measured. At TS, 2,915 fracture segments were mapped in 2D and correlated with 48 3D measurements extracted from the point cloud. These were cross-validated with field-based structural data to assess the consistency of fracture orientations and kinematic patterns across scales.

In both case studies, DOMs enabled the remote and coherent mapping of structures in areas otherwise inaccessible due to outcrop geometry or terrain conditions, such as vertical cliffs and glaciated pavements. At CV, the LiDAR-based DOM was essential in bridging the scale gap between regional mapping and outcrop-scale observations by capturing 3D fracture properties from decimeter to hectometer scale. It allowed the identification of hierarchical fault systems and fracture typologies and revealed distinct fracture length populations associated with variable vertical persistence across mechanically contrasting limestone-marl units. At TS, the UAV-derived DOM expanded structural data coverage by facilitating 2D mapping across a broad horizontal surface, which was validated with 3D measurements and field observations. The integration of DOM and field data allowed for robust characterization of dip, length, and fracture set distribution. The comparison highlights how DOM acquisition and interpretation must be tailored to geological context, exposure type, outcrop geometry, and analytical goals. Whereas the CV DOM supports fracture stratigraphy and vertical connectivity analysis, the TS DOM is more suited for evaluating lateral connectivity and fluid pathways in karstified pavements.

Improving Digital Image Correlation (DIC) for Uniaxial Compression Tests on Cylindrical Samples

Antonin Chalé[1] ,Fengchang Bu[1],Michel Jaboyedoff[1] and Marc-Henri Derron[1]

[1]Institute of Earth Sciences, University of Lausanne, Lausanne, Switzerland (antonin.chale@unil.ch)

Keywords: Digital Image Correlation, uniaxial compression, cylindrical samples, image preprocessing, strain measurement

Digital Image Correlation (DIC) has become increasingly common in the field of geomechanics for measuring surface displacements during mechanical testing. This optical method enables the determination of full-field displacement and strain with high reliability. In many geomechanical applications especially where the use of traditional strain gauges is not feasible. DIC offers a low-cost and effective alternative for deformation monitoring.

Despite its advantages, DIC has intrinsic limitations that arise from the quality and sampling frequency of the image acquisition system. Additionally, image distortion caused by camera lenses can introduce measurement errors. A major limitation of conventional DIC becomes apparent when applied to cylindrical samples. In such cases, the method fails to account for perspective effects inherent in 2D imaging, leading to significant inaccuracies. This issue is particularly problematic in the evaluation of transverse deformations and, consequently, the Poisson's ratio.

To address these limitations, we have developed a novel preprocessing method to rectify images before DIC analysis. The proposed workflow includes several key steps: image denoising, camera calibration, lens distortion correction (figure1), and unwrapping of the cylindrical surface using a custom Python script(figure 2). This process effectively flattens the cylindrical sample, making it suitable for accurate 2D DIC analysis. The final displacement measurements are obtained using the NCORR DIC software (J.Blaber 2015).

To evaluate the effectiveness of our preprocessing method, we compared DIC results against a 3D-DIC (Solva 2018) system using physical sensors. Preliminary results indicate significant improvements in displacement measurements, particularly on the lateral surfaces of the cylindrical sample. This enhancement also leads to more accurate determination of the Poisson's ratio. Future work will focus on refining the unwrapping algorithm and improving pixel-level interpolation to further enhance measurement accuracy.

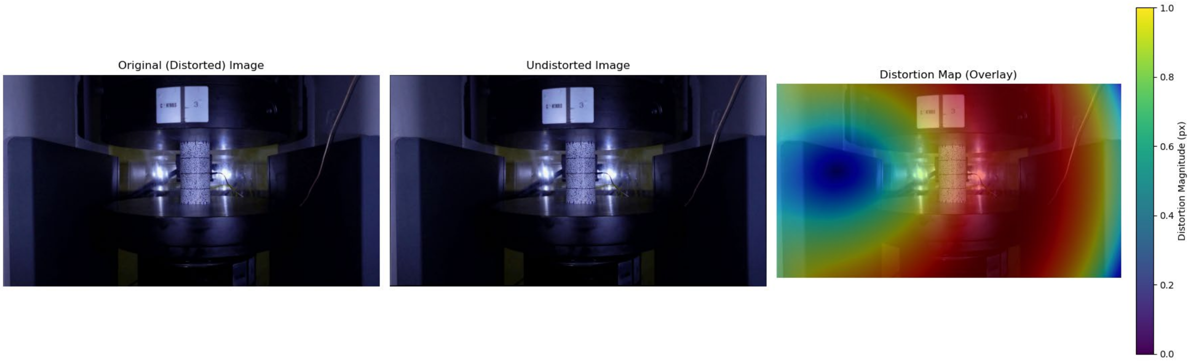

Figure 3 lens distortion rectification on the les the original images in the center the undistorted image on the right the distortion map.

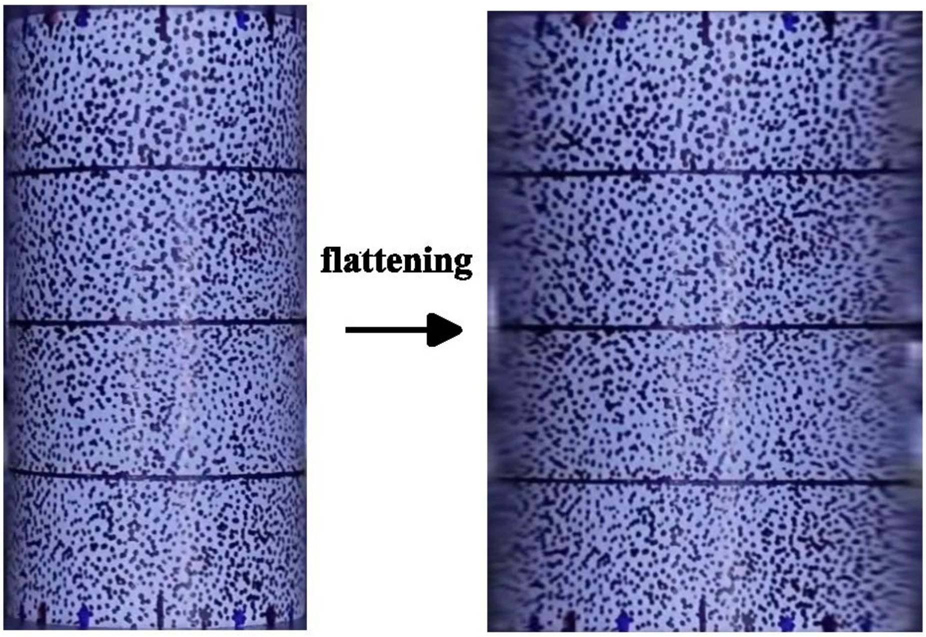

Figure 4 Flattening procedure applied to cylindrical samples

Reference :

J Blaber, B. A. (2015). Ncorr: Open-Source 2D Digital Image Correlation Matlab Software. Experimental Mechanics.

Solav, Dana & Moerman, Kevin & Jaeger, Aaron & Genovese, Katia & Herr, Hugh. (2018). MultiDIC: an Open-Source Toolbox for Multi-View 3D Digital Image Correlation. 10.31224/osf.io/fv47e.

Multi-Platform LiDAR Integration for Post-Earthquake Visualization Analysis: A Case Study at Changchun Shrine, Taroko National Park, Hualien, Taiwan

Chen Rou-Fei [1*], Chang Kuo-Jen [2], Chen Tsung-Ting [1], Li Yuan-Chi [1], Chang Chia-Shin [3], Chi Chien-Yu [3], Derron Marc-Henri [4]

[1] *Institute of Mineral Resources Engineering, National Taipei University of technology, Taipei, Taiwan*

[2] *Department of Civil Engineering, National Taipei University of technology, Taipei, Taiwan*

[3] *Department of Geotechnical Engineering, CECI Engineering Consultants, Inc, Taipei, Taiwan*

[4] *Risk Group, University of Lausanne, Lausanne, Switzerland*

Contact: roufei@mail.ntut.edu.tw

Keywords: *UAV-LiDAR, Ground LiDAR, SLAM, post-earthquake analysis, 3D visualization*

Taroko National Park, renowned for its deeply incised V-shaped gorges carved into massive marble outcrops, presents an exceptional case study in mountain geomorphology and engineering geology. The Changchun Shrine is perched on a steep, vegetation-clad slope punctuated by cascading waterfalls. On April 3, 2024, a moment magnitude (Mw) 7.2 earthquake induced widespread slope failures, rockfall events, and subsurface fracturing throughout the park. The Changchun Shrine Trail—with its average slope gradient exceeding 60°, exposed bedrock benches, and remnant talus accumulations—suffered severe escarpment collapse and progressive undercutting, prompting the Ministry of the Interior to initiate an eight-year reconstruction and resilience program in 2025. This program emphasizes structural stabilization, hydrological control, and long-term geohazard mitigation (Ministry of the Interior, 2025).

In this context, our study integrates three complementary remote-sensing modalities—Unmanned Aerial Vehicle Light Detection and Ranging (UAV-LiDAR), Terrestrial (Ground-based) LiDAR, and Simultaneous Localization and Mapping (SLAM)—to deliver a multi-scale, three-dimensional characterization of post-seismic terrain dynamics. UAV-LiDAR surveys enable the rapid acquisition of high-density point clouds for generating digital elevation models (DEMs) that capture large-scale morphological features, lineament networks, and potential failure planes on inaccessible slopes (Neuvition, 2023; Huang, 2024). Ground-based LiDAR furnishes ultra-high-resolution scans, enabling detailed mapping of joint sets, fracture apertures, and surface roughness within the Changchun Shrine tunnel and adjacent cut slopes. SLAM algorithms facilitate precise localization and real-time point cloud registration in GPS-denied environments—such as heavily forested ravines and subterranean passages—thereby overcoming occlusion and positional drift.

By integrating UAV-LiDAR, Ground LiDAR, and SLAM into a unified 3D visualization, we mapped ephemeral gullies, head-scarp propagation, and shallow landslide scars above the Changchun Shrine parking lot. A high-resolution SLAM scan of the tunnel revealed multiple discontinuity sets, quantifying their orientation, spacing, and persistence to characterize potential weakness planes. This multi-scale modeling framework enables the volumetric quantification of unstable rock masses, kinematic failure analysis, and the development of spatially explicit early-warning systems. Interactive 3D tools support scenario-based risk assessments, optimized emergency response, and prioritized mitigation. Beyond aiding Taroko National Park's post-quake reconstruction, these methods provide a scalable approach for hazard mapping and resilient infrastructure design in seismically active, high-relief terrains.

References

HUANG, Z.M., 2024. Emerging remote sensing technologies in geotechnical applications. Geotechnical Engineering, 181: 1-15.

MINISTRY OF THE INTERIOR, 2025. Taroko National Park 0403 earthquake anniversary reconstruction plan. National Park Service Report, 45 p.

NEUVITION, 2023. Applications of LiDAR in disaster management and response. Technical Report, 28 p.

TAROKO NATIONAL PARK ADMINISTRATION, 2025. Post-earthquake reconstruction assessment of geological hazards in Taroko National Park. Management Report TR-2025-03, 67 p.

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Geohazard Assessment of Railway Slopes Triggered by the 2024 Hualien Earthquake: Integrating UAV-LiDAR and InSAR Technologies

Chen Tsung-Ting [1*], Chen Rou-Fei [1], Li Kwei-Shr [1], Chang Kuo-Jen [2], Au Suet-Yee [1], Yin Han-Hsuan [3], Chang Chia-Shin [4], Chi Chien-Yu [4]

[1] *Institute of Mineral Resources Engineering, National Taipei University of technology, Taipei, Taiwan*

[2] *Department of Civil Engineering, National Taipei University of technology, Taipei, Taiwan*

[3] *Department of Geoinformatics, CECI Engineering Consultants, Taipei, Taiwan*

[4] *Department of Geotechnical Engineering, CECI Engineering Consultants, Inc, Taipei, Taiwan*

Contact: fggd0721@gmail.com

Keywords: *UAV LiDAR, InSAR Surface deformation, Geohazard Assessment, Railway Infrastructure Risk*

On April 3, 2024, a magnitude 7.2 earthquake struck the Hualien region in eastern Taiwan, triggering widespread slope-related geohazards. The region's complex topography, characterized by significant elevation differences and highly metamorphosed rock formations with well-developed unloading joints, heightened its vulnerability to slope failures during the seismic event. The study focuses on the 36 to 58 km section of Taiwan Railway's North-Link Line, which suffered severe damage due to landslides and rockfalls from adjacent slopes, disrupting railway infrastructure.

This study integrates pre-earthquake ALOS-2 and coseismic Sentinel-1 InSAR data to evaluate changes in slope activity and associated hazards. Additionally, airborne LiDAR data from 2015 and 2022 (pre-event) and high-resolution UAV-based LiDAR data from April 30, 2024 (post-event) were utilized to construct a 5-cm resolution Digital Elevation Model (DEM) for engineering-scale analysis. These datasets enabled precise estimation of landslide volumes, detailed interpretation of slope morphology, and identification of high-risk zones. By combining surface deformation data with high-resolution topographic features, the study assessed slope hazard potential, traced rockfall propagation, and estimated rockfall energy, providing essential references for post-earthquake railway rehabilitation and hazard mitigation planning.

The coseismic analysis employed Sentinel-1 InSAR data acquired between March 28 and April 8, 2024, alongside pre-earthquake ALOS-2 data from 2015 to 2022, to calculate surface deformation within slope units. Slope activity was categorized into four levels—high, moderate-high, moderate, and low—based on deformation magnitude and spatial extent. A comparison of pre-seismic and coseismic data revealed a significant increase in slopes with moderate-high to high activity levels (Fig. 1). Field observations and photographs further validated the InSAR-derived deformation data , highlighting landslides, debris accumulation, rockfalls, and railway infrastructure damage caused by the earthquake.

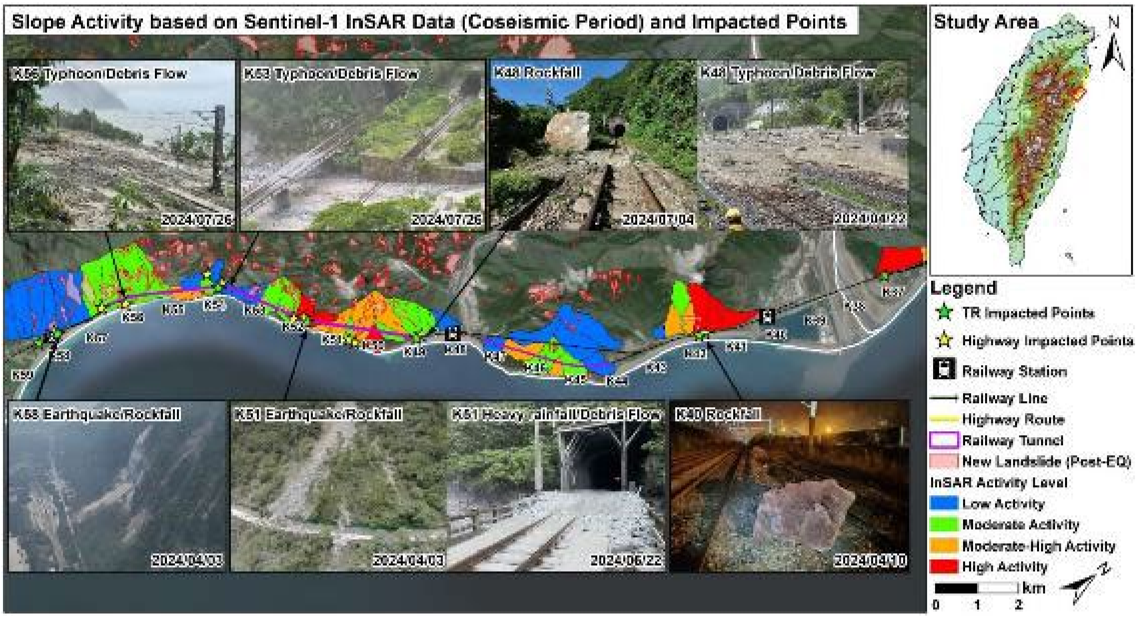

Figure 1: Sentinel-1 InSAR analysis of slope activity along the North-Link Line railway, showing failures triggered by the 2024 Hualien earthquake. Field photographs validate the InSAR data, highlighting landslides, debris accumulation, and railway infrastructure damage.

High-resolution UAV-LiDAR imagery played a crucial role in rapidly capturing post-earthquake conditions, providing detailed information on rockfall size, locations, trajectories, and deposition patterns (Fig. 2). These datasets revealed substantial volumes of unstable material on upper slopes, posing significant threats to roads and railway segments below. By integrating UAV-LiDAR data with interpreted geological structures, the study effectively identified high-risk collapse zones and reconstructed rockfall movements based on field-observed impact evidence. This precise information supports immediate slope management and geohazard mitigation strategies while offering vital input for medium- to long-term railway planning, thereby enhancing infrastructure resilience and safety.

Additionally, the study incorporated InSAR deformation monitoring to conduct an in-depth analysis of slope activity. InSAR technology provided precise surface deformation data, which, when combined with high-resolution topographic features derived from UAV-LiDAR, enabled the identification of high-risk collapse zones and reconstruction of rockfall trajectories. The integration of these two advanced technologies not only facilitated accurate post-disaster assessments but also established a robust foundation for engineering construction and long-term planning, significantly improving the safety and resilience of critical infrastructure.

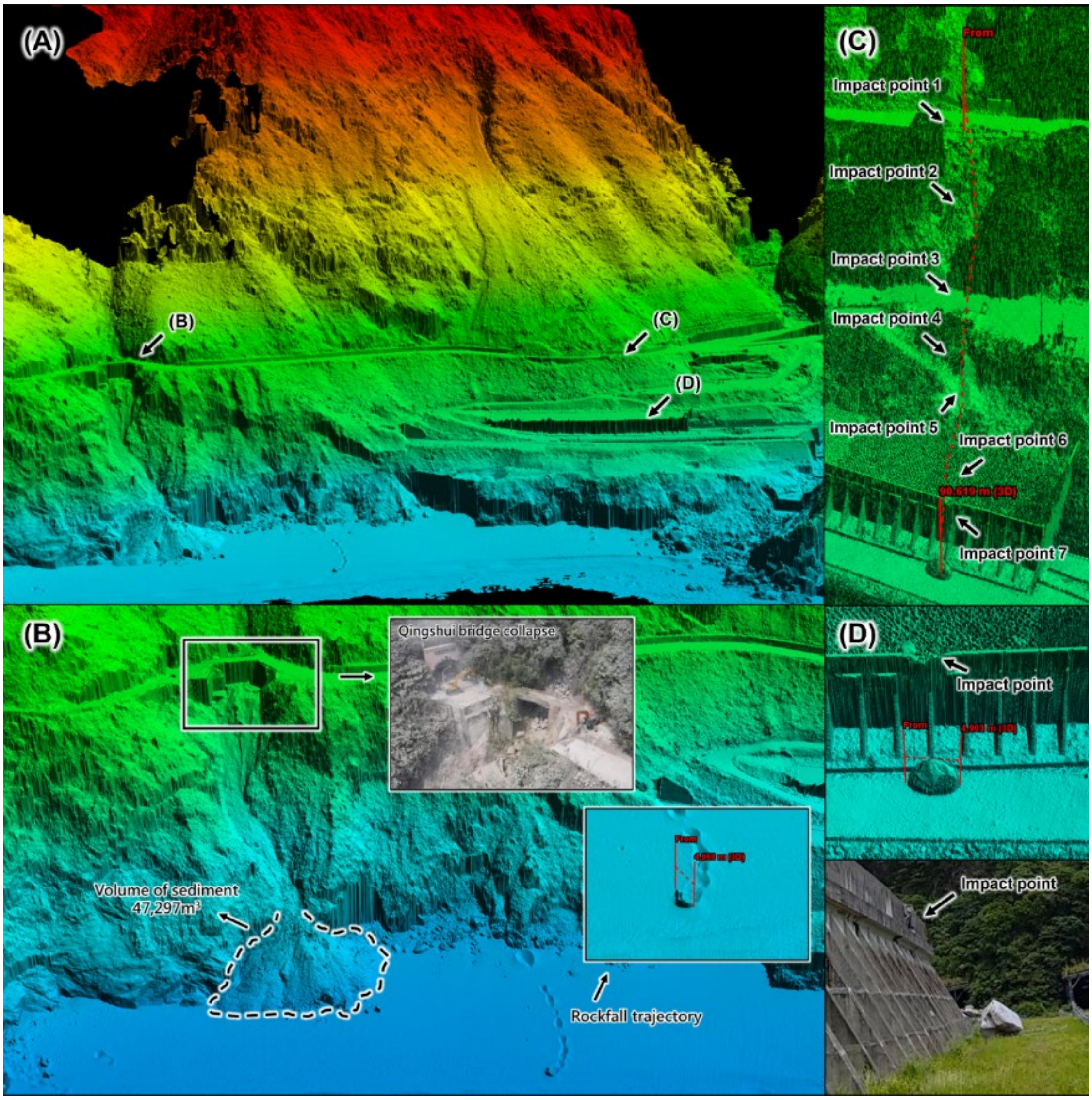

Figure 2. High-resolution UAV-LiDAR analysis of the K51 slope failure area along Taiwan Railway's North-Link Line. (A) 5-cm resolution DEM showing post-failure terrain variation and erosional gully structure; (B) Collapse zone of Qingshui Bridge with debris deposition and an estimated sediment volume of 47,297 m³; (C) Rockfall trajectories and damage to railway infrastructure; (D) Impact evidence on railway structures from UAV-LiDAR models and field-verified photographs.

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Virtual Geological Field Trips: Preparing students for fieldwork in South Africa

Charl D. Cilliers 1*, Henok G. Solomon1, Jan M. van Bever Donker 1

[1] *Department of Earth Sciences, Faculty of Natural Sciences, University of the Western Cape, Private Bag X17, Bellville 7535, South Africa, 2475326@myuwc.ac.za*

Key words: *DJI drone, LiDAR, Pano2VR, geoheritage, geo-education*

South Africa's rich geological diversity includes numerous sites of exceptional scenic, geohistorical, educational, and economic significance. Notable examples include the Vredefort Dome—the oldest meteorite impact structure on Earth and a World Heritage Site (UNESCO, 2005); greenstones and stromatolites of the ancient Barberton Mountains (also a World Heritage Site); turbidity sequences of the potentially fossil fuel-rich Ecca Formation in the Laingsburg and Tanqua Karoo areas; spectacularly deformed sediments of the Cape Fold Belt; and intrusive granites at the "Sea Point Contact", famously visited by Charles Darwin in 1836 (Bailie *et al.*, 2018). These geoheritage sites preserve invaluable records of Earth's geological history, the evolution of life, and the formation of mineral deposits. As such, institutions such as the Geological Society of South Africa (GSSA) have sought to document key outcrops to promote geological understanding among both geoscientists and the public (GSSA, 2025a, b).

Driven by this objective, we have developed a new series of virtual field trips (VFTs), focusing on accessible Cape Granite Suite (Figure 1), Cape Supergroup, and Karoo Supergroup outcrops. Our primary aims were to create geoheritage- and geotourism-focused VFTs for the GSSA, and to produce comprehensive geo-education-focused VFTs to support undergraduate students in preparing for field excursions.

Historically, the production of VFTs has been technologically complex and cost-prohibitive, particularly in terms of equipment and software. To address these challenges, we have developed a simplified workflow using a DJI Mavic 3 Pro Cine drone; an Apple iPhone 15 Pro Max equipped with a LiDAR scanner and a YesIDo lapel microphone; the software Pano2VR; and the web-based version of Google Earth. This approach enables the creation of interactive VFTs—without the need for cumbersome equipment in the field—featuring high-resolution, geo-located 360-degree images enhanced with links to Sketchfab-hosted LiDAR scans, field and hand specimen photographs, thin-section imagery, relevant scientific publications, and explanatory videos.

Previous work has demonstrated that exposure to VFTs significantly enhances students' understanding of key geological concepts (Van Bever Donker *et al.*, 2023, 2024). In 2025, we expanded our testing database through trials involving over 300 students at first- and fourth-year levels. First-year Earth Sciences students at the University of the Western Cape completed a formative, non-graded test at the end of the first semester to assess baseline knowledge of sedimentary, structural, and igneous geology. They then were exposed to the VFTs and immediately repeated the test. Fourth-year students, by contrast, received lectures covering the same topics prior to the initial test, followed by VFT exposure and a repeat of the same assessment.

By restructuring our method of assessing test results, we have clearly demonstrated the educational value of VFTs. Statistically significant learning gains were observed, with the degree of improvement correlated to students' prior geological education (i.e. greater gains in fourth-year students than in first-year students).

We will showcase these new VFTs at VGC 2025 and welcome feedback—particularly regarding our methods, fields of application, and geo-educational approach.

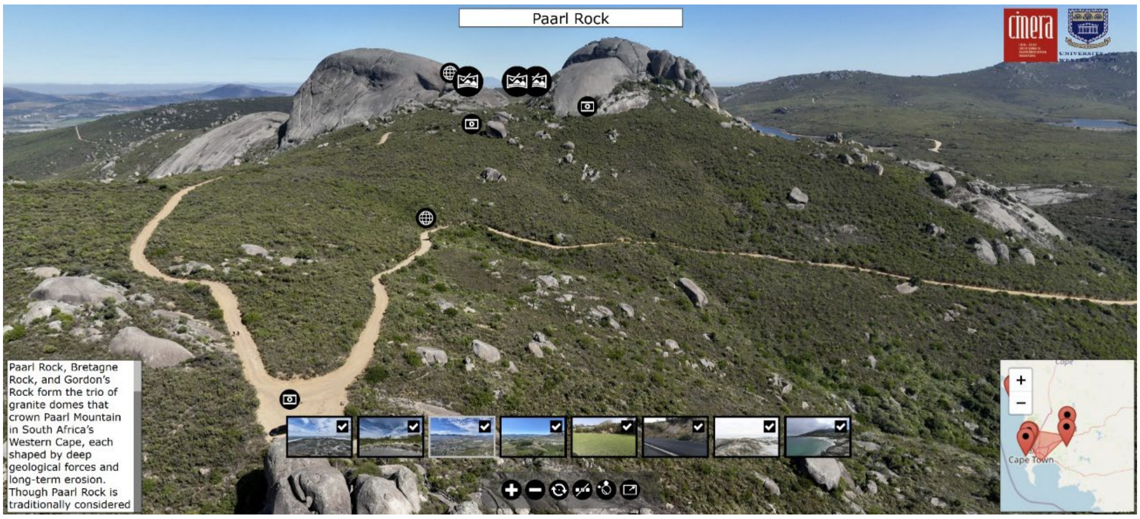

Figure 1: Pano2VR screenshot of a VFT node at Paarl Rock, one of the largest exposed granite domes in the world.

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References

BAILIE, R.H., MHLANGA, M., & REINHARDT, J., 2024. The Sea Point contact, Cape Town, South Africa: a geological site made famous by Charles Darwin's visit. *Geological Society, London Special Publication*, 543: 409-420. https://doi.org/10.1144/SP543-2022-237.

GEOLOGICAL SOCIETY OF SOUTH AFRICA, 2025a. Geoscience and Society Division. Geological Society of South Africa. Available at: https://www.gssa.org.za/?page_id=6289 [Accessed 3 June 2025].

GEOLOGICAL SOCIETY OF SOUTH AFRICA, 2025b. Geodyssey. Geological Society of South Africa Western Cape Branch. Available at: https://www.gssawc.org.za/geodyssey [Accessed 3 June 2025].

UNESCO, 2005. Vredefort Dome. UNESCO World Heritage Centre. Available at: https://whc.unesco.org/en/list/1162 [Accessed 3 June 2025].

VAN BEVER DONKER, J., MAART, R., MARSHAL, D., MAYEKISO, L., HUBER, M., SOLOMON, H. & MGABISA, N., 2023. The effectiveness of Virtual Reality Field Trips (VFTs) in Field Geology education. *Proceedings of the Virtual Geoscience Conference 2023*. Available at: https://tud.qucosa.de/api/qucosa%3A87480/attachment/ATT-0/ [Accessed 3 June 2025].

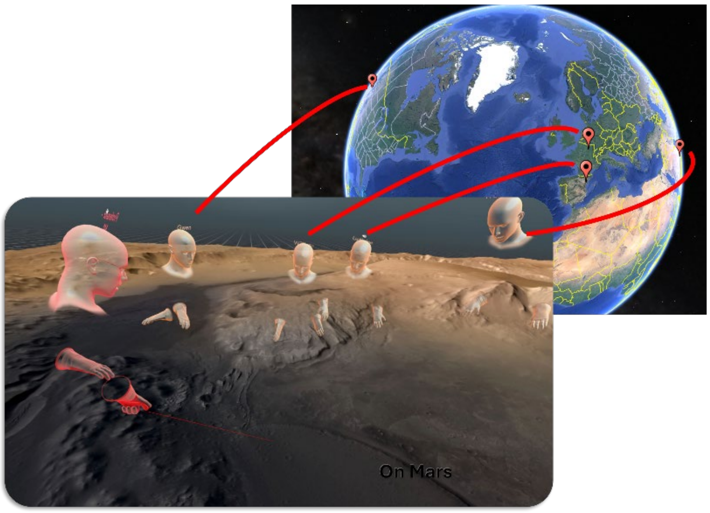
VAN BEVER DONKER, J., MARSHAL, D., MAART, R., MAYEKISO, L., SOLOMON, H., HUBER, M., & MGABISA, N., 2024. Can Virtual Field Trips be used to prepare students for real fieldwork? *EGU General Assembly 2024*. Available at: https://doi.org/10.5194/egusphere-egu24-18133 [Accessed 3 June 2025].

VRExplorer : The immersive collaborative tool to teach geology

Civet F.1*, Richard P.2, Clarke L.1, Vandergucht D.1, Costard K.1, Clochez C.1
[1] *VR2Planets, 42 rue la Tour d'Auvergne, 44200, Nantes, France, fcivet@vr2planets.com*
[2] *PRgeology, 24 Domaine des dryades, 5370 Sarzeau. rpascal64@icloud.com*

Key words: *Virtual reality, 3D, photogrammetry, satellite images, DTM, orthoimages, point clouds,immersion, collaboration, cloud-based platform, education, virtual field trips*

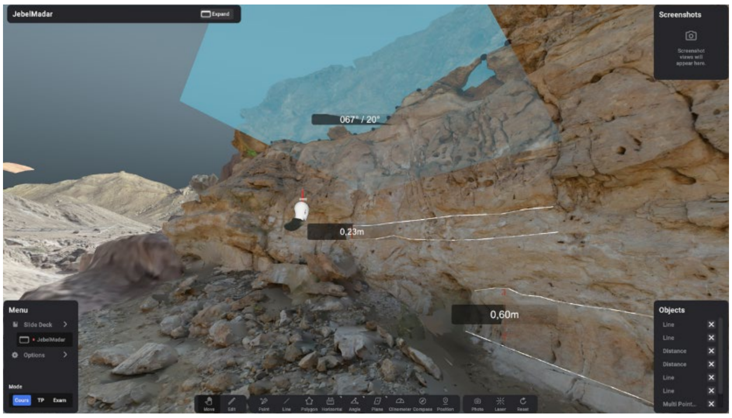
Massive 3D geospatial datasets—photogrammetric meshes, point clouds, digital terrain models, and raster images—have become central to planetary and terrestrial geosciences. Yet visualizing, storing, and sharing these datasets remains a major technical bottleneck. Files are too large for local storage, graphics hardware is quickly overwhelmed, and collaborative exploration across multiple users is virtually impossible. Conventional 2D software cannot convey the full topographic complexity, and many VR solutions rely on aggressive down-sampling, which inevitably compromises resolution and scientific accuracy. These limitations slow down both research and education, leaving students and scientists frustrated with partial, disconnected experiences.

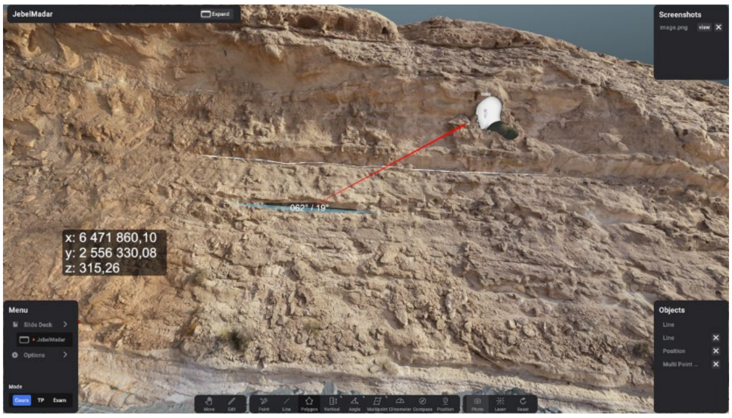


VRExplorer transforms this landscape. Developed by VR2Planets, it is an immersive, cloud-based platform purpose-built to remove all these barriers. Users can upload standard geoscience formats (DTM/DEM, orthoimages, 3D meshes, point clouds), and the platform automatically processes, tiles, and integrates them into interactive virtual scenes—while preserving full resolution and georeferencing. This eliminates the need for local high-end hardware or manual data preprocessing and allows seamless scaling from small study areas to planetary-size terrains.

Inside the virtual environment, multiple users appear as avatars, navigate terrains, and communicate in real time. VRExplorer integrates a comprehensive toolbox for analysis and collaboration: precise measurements of distances, angles, dips, and strikes; drawing of polylines, polygons, and planes; laser pointing; screenshots; and the ability to call a teacher or collaborator directly. All interactions are georeferenced, automatically stored on the cloud, and exportable to GIS software, enabling further scientific analysis or archival.

VRExplorer also redefines virtual pedagogy. Educators can create interactive sessions enriched with text, images, quizzes, and guided exercises, transforming massive geospatial datasets into immersive learning experiences. Students gain hands-on exposure to terrains that would otherwise be inaccessible, improving comprehension, spatial reasoning, and memory retention. Initial classroom deployments demonstrate strong engagement and learning outcomes ([1], [2], [3], [4], [5], [6]), while laboratory evaluations confirm enhanced measurement accuracy and collaborative decision-making ([7], [8]).





Beyond education, VRExplorer empowers researchers to work with **previously unmanageable datasets**. Its georeferenced, multi-user environment supports collaborative field campaigns, virtual conferences, and team-based exploration of planetary terrains in ways that were previously impossible. Open catalogues of 3D objects, satellite imagery, and user datasets can be combined to create shared, reproducible workflows that accelerate both discovery and training.

By combining cloud-based massive data management, immersive 3D visualization, real-time collaboration, and integrated pedagogy, VRExplorer is not just a software—it is a **complete virtual geoscience ecosystem**. It addresses critical challenges in dataset handling, scientific analysis, and education, while providing a platform for innovation in both research and teaching.

VRExplorer demonstrates that immersive technology is not a gimmick, but a strategic enabler for the future of geosciences. It provides the tools to explore, measure, and learn from planetary terrains at full scale, collaboratively and in high resolution, setting a new standard for virtual fieldwork and geoscience pedagogy worldwide.

Acknowledgements: This work is the sum of nearly 15 years of VR2Planets. It has been supported for 4 years by AMU/CEREGE within the framework of VIRTUAFIELD project.

References

[1] F. Civet, F. Marchis, R. Lambert, et A. Graykowski, « VRExplorer an Immersive and Collaborative Tool to Multiply Field Trip Experiences », in *AGU Fall Meeting Abstracts*, in AGU Fall Meeting Abstracts, vol. 2024. déc. 2024, p. IN11C-2139.

[2] F. Civet, L. Clarke, D. Vandergucht, G. Bertrand, K. Costard, et C. Clochez, « VRExplorer an immersive and collaborative tool to multiply field trip experiences », in *European Planetary Science Congress*, sept. 2024, p. EPSC2024-1265. doi: 10.5194/epsc2024-1265.

[3] S. Carpy *et al.*, « GeoPlaNet project: a transnational collaboration for planetarygeosciences », in *European Planetary Science Congress*, sept. 2024, p. EPSC2024-1325. doi: 10.5194/epsc2024-1325.

[4] R. Lambert, F. Marchis, A. Graykowski, et F. Civet, « VRExplorer: A Flexible Virtual Reality Software Designed for Planetary Geophysics Education », in *AGU Fall Meeting Abstracts*, in AGU Fall Meeting Abstracts, vol. 2023. déc. 2023, p. ED34A-1.

[5] S. Viseur *et al.*, « Learning geology using VR: student feedbacks on the VirtuaField applications », in *EGU General Assembly Conference Abstracts*, in EGU General Assembly Conference Abstracts. mai 2020, p. 13208. doi: 10.5194/egusphere-egu2020-13208.

[6] S. Le Mouélic *et al.*, « Using virtual reality to investigate geological outcrops on planetary surfaces », in *EGU General Assembly Conference Abstracts*, in EGU General Assembly Conference Abstracts. avr. 2018, p. 13366.

[7] A. Triantafyllou *et al.*, « 3-D digital outcrop model for analysis of brittle deformation and lithological mapping (Lorette cave, Belgium) », *J. Struct. Geol.*, vol. 120, p. 55-66, mars 2019, doi: 10.1016/j.jsg.2019.01.001.

[8] M. Jaud, L. Geoffroy, F. Chauvet, E. Durand, et F. Civet, « Potential of a virtual reality environment based on very-high-resolution satellite imagery for structural geology measurements of lava flows », *J. Struct. Geol.*, vol. 158, p. 104569, mai 2022, doi: 10.1016/j.jsg.2022.104569.

High-resolution drone-borne photogrammetry and synthetic numerical temperature and stress simulation to resolve cooling induced fracturing in the Lesutoskraal impact melt dike of the Vredefort Impact Structure (South Africa)

Martin D. Clark1*

[1*] *MAGIC Lab, Department of Geology, University of the Free State, South Africa. clarkmd@ufs.ac.za*

Key words: *thermal modelling, MAVIC 2 Pro, sub-millimetre resolution, digital preservation.*

Drone-borne photogrammetry is globally applied, as a fundamental geospatial approach to constraining 3-dimensional geometries of solid scenes and objects. Here, photogrammetric modelling using a DJI MAVIC 2 Pro enabled a fracture distribution in a continuous outcrop of the Lesutoskraal impact melt dike of the Vredefort Impact Structure in South Africa. Unique to this outcrop is that it is the only known location on Earth where the primary geometry of fractures within an impact melt dike can be studied in cross-section at a deep crustal level, free from post-impact deformation, erosion, or burial. Using 202 drone-collected photos at 1.5m altitude, Agisoft Metashape was used to generate an orthophoto[1](Fig. 1), DEM[2], and 3D model[3] were generated at 0.612mm/pix[1], and 0.492 mm/pix[2,3], respectively.

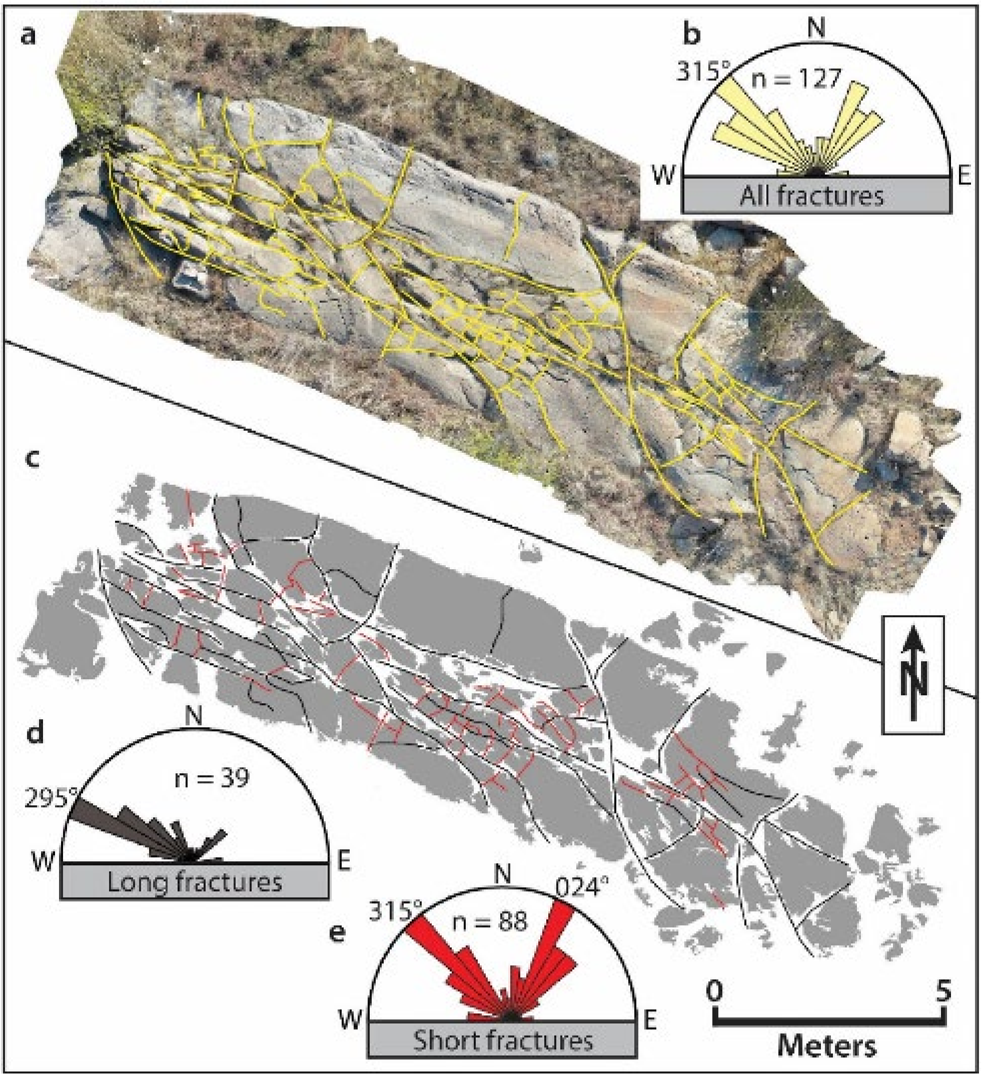


Figure 5: Fracture traces extracted from (a) the 0.612mm/pix drone-generate orthophoto and (c) classified image product (CLARK et al., 2025). Half-plot rose diagrams (b), (d), and (e), displaying orientation of all fracture traces (a: yellow lines), > 1 m fractures (c: black lines) and ≤ 1 m fractures (c: red lines), respectively. Full resolution orthophoto available at: https://figshare.com/s/6365bc5c337810b9cf0d.

Fracture orientations and distributions extracted from the outcrop were compared to a synthetic numerical temperature and stress simulation of impact melt cooling from 1200°C and 1800°C with similar geometric conditions (Fig. 2). Fracturing that concentrates in the centre of the impact melt is shown to be generated through tensional stress during cooling, supporting a cooling-induced fracture mechanism to enable multiphase impact-melt emplacement, as well as the central-emplacement of later melt phases. Additionally, tensional stress relating to cooling are shown to reach up to -75 MPa, sufficient to overcome lithostatic stresses at a mid-to-upper crustal depth, temporally constrained to 150 days, when impact melt temperatures were predominantly above its solidus.

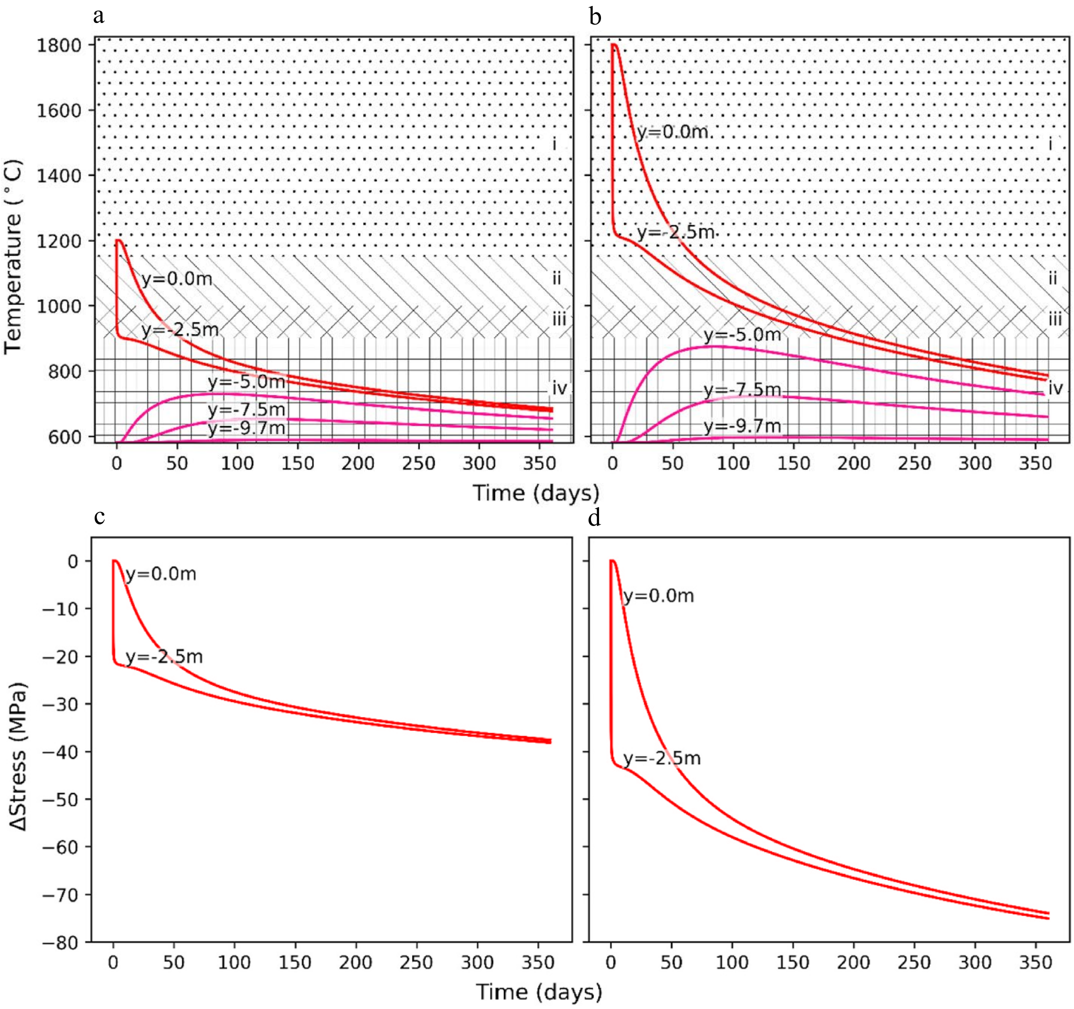


Figure 6: Cooling paths (a-b) and thermal stresses (c-d) for the synthetic numerical temperature and stress simulation. a and c represent impact melt at a starting temperature of 1200°C and 1800°C, respectively. y = labels denote distance from the middle of a 5m thick dike geometry.

Through the combination sub-millimetre drone-based photogrammetric modelling, image processing, and numerical modelling, is sufficient evidentiary data generated. Rare processes like gravity driven dike emplacement of superheated impact melt, demand comprehensive argumentation using limited data. High-resolution field data collection through drone-borne photogrammetry promoted argumentation, digital dissemination, and preservation.

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References

CLARK, M.D., KOVALEVA, E., HUBER, M.S., RIEKERT, S., FOURIE, F.D., 2025. Cooling induced fracturing in impact melt dikes derived from drone photogrammetry and Python simulation: Example from the Lesutoskraal Granophyre Dike in South Africa. *Journal of Structural Geology*, 197, 105428.

GNSS Reflectometry for detecting glacier lake drainage – an alpine study case

Matthias Aichinger-Rosenberger*, Annelies Voordendag, Andreas Wieser, Benedikt Soja

Institute of Geodesy and Photogrammetry, ETH Zurich, Switzerland,
annelies.voordendag@geod.baug.ethz.ch

Key words: *GNSS reflectrometry, glacier lake monitoring, TLS*

A glacier-dammed lake formed near the tongue of Gornergletscher during several of the past years. Implications of this lake and its discharge on glaciological aspects have been studied extensively in the past, see e.g., Riesen (2011). However, the subglacial drainage of this lake within a few hours poses a risk of flooding for the nearby municipality of Zermatt (Valais, Switzerland). Timely detection of rapid water level changes in the lake is essential for risk mitigation. Since the drainage of the lake can occur virtually at any time, the lake needs to be monitored using a quasi-continuously operating system which detects the drainage reliably and with a latency of no more than 1-2 hours for timely warning and actions.

Within a pilot study, we are currently exploring the use of GNSS Reflectometry (GNSS-R) for this purpose. GNSS-R is already proven for monitoring surface changes at daily resolution (Larson et al., 2013). Its application within a warning system in the aforementioned context requires processing data at hourly or higher resolutions. Furthermore, the conditions at the alpine measurement site are challenging in terms of topography, weather conditions, and surface changes irrelevant for the intended warning. Although some first studies for real-time applications exist (Purnell et al., 2024), the time resolution and local conditions remain major challenges for this approach.

In this contribution, we present the experiments and first results obtained within the pilot study, which is a collaboration between ETH Zurich and the local municipality. It serves three main goals: (1) to demonstrate the feasibility of GNSS-R for detecting short-term lake level variations; (2) to conceptualize a GNSS-R-based monitoring and early warning system tailored to glacier lake hazards; and (3) to assess the maturity of available GNSS-R hardware and software and outline the necessary development efforts for operational implementation.

A mobile GNSS-R station, based on low-cost GNSS equipment (specialized antenna, receiver, power supply, and data logger) is deployed and operates autonomously for an extended period (several days to weeks without interruption). High-resolution terrestrial laser scanning (TLS) is conducted several times during the monitoring period and serves (i) to generate a detailed digital terrain model (DTM), supporting data interpretation and validation, as well as (ii) locate changes in the environment. Hourly ground-based images provided by the local municipality assist in cross-checking inferred water level changes.

We post-process the GNSS-R data using open-source tools (Larson, 2024) to extract water-level time series and detect anomalies indicative of subglacial water movement. We assess these results by comparing them to those obtained from TLS data and photographic evidence as well as to the requirements for a real-time warning system. The study contributes to providing an easily deployable, mechanically robust, real-time system for detection and early warning of subglacial lake drainage events, thus potentially improving hazard mitigation in glacierized catchments increasingly affected by climate-driven meltwater dynamics.

References

Larson, K. M. (2024). Gnssrefl: an open source software package in python for GNSS interferometric reflectometry applications. GPS Solutions, 28(4).

Larson, K. M., Ray, R. D., Nievinski, F. G., and Freymueller, J. T. (2013). The accidental tide gauge: A GPS reflection case study from Kachemak Bay, Alaska. IEEE Geoscience and Remote Sensing Letters, 10(5):1200–1204.

Purnell, D., Gomez, N., Minarik, W., and Langston, G. (2024). Real-time water levels using GNSS-IR: A potential tool for flood monitoring. Geophysical Research Letters, 51(5).

Riesen, Patrick (2011). Variations of the surface ice motion of Gornergletscher during drainages of the ice-dammed lake Gornersee. PhD thesis.

Static Continuous Laser Scanning of Trees and Dunes with the Livox AVIA

Thomas de Jong1*, Daan Hulskemper1, Roderik Lindenbergh1, Sierd de Vries2 & Steven van der Linden1

[1] *Dept. of Geoscience and Remote sensing, Delft University of Technology, Stevinweg 1, 2628 CN Delft, The Netherlands, t.m.s.dejong@student.tudelft.nl*

[2] *Dept. of Hydraulic Engineering, Delft University of Technology, Stevinweg 1, 2628 CN Delft, The Netherlands*

Key words: *LiDAR, Low-cost, Dynamic Processes, Sensor validation, Autonomous Monitoring*

Introduction

Remote sensing of dynamic natural environments has traditionally relied on bulky and expensive LiDAR systems. New sensors like the Livox AVIA (LIVOX, 2025) enable more compact and cost-effective monitoring of various time-varying geomorphological phenomena at relatively high spatial and temporal resolution.

When operating the AVIA as a static scanner in dynamic natural environments, the setup benefits from its small size, affordability, ease of use, and portability. To evaluate its potential and limitations relative to more expensive systems, this research tests its characteristics and applications in a stationary setup. The goals are to optimize the setup and system settings for different measurement scenarios, and to assess the AVIA's performance in generating sequential 3D point cloud videos of dynamic processes. To achieve this, first some key manufacturer specifications will be validated.

Two case studies are planned to explore the applicability and setup specifics for the generation and evaluation of the sequential point clouds. The first examines the way different tree parts move under wind loading; the second will investigate the morphological evolution of manmade dune blowouts during storms. These examples will demonstrate how effectively and accurately a stationary AVIA scanner can produce uninterrupted 3D reconstructions of evolving scenes. Ultimately this approach aims to provide an autonomous monitoring solution that remains easy to use for single-instance measurements.

Methodology

A custom setup integrates the AVIA with a Raspberry Pi, battery power, and auxiliary environmental sensors like an anemometer which logs the windspeed and can be used to automatically trigger a scan. Controlled testing validates key factory specifications like range, depth accuracy, FOV coverage time and tests the sensors resilience against vibrations. While autonomously operating, the AVIA captures sequential scans at pre-determined intervals (e.g., every 15 minutes), producing a time-series of point clouds. For the tree movement study, the AVIA scans several trees subject to different wind speeds, correlating LiDAR-measured displacement with anemometer data. For the monitoring of dune notches, repetitive scans during windy conditions document erosion and deposition patterns. Python, CloudCompare and PlantMove (WANG *et al*., 2022) are used to transform file formats, filter data, estimate movement and animate the 3D frames to visualize dynamic changes.

Initial and Expected Results

The point cloud videos reveal clear patterns of tree movement and movement amplitudes. Evaluating scans of blowouts during storm events offers an opportunity to, in real time, observe and quantify morphological changes. A comparative analysis with different or higher-end systems (e.g., Leica P40) will contextualize the AVIA's performance, highlighting trade-offs between cost, portability, and precision. Findings will be compared with other AVIA-based studies (RUTTNER-JANSEN et al., 2024; CZERWONKA-SCHRÖDER et al., 2025).

Initial tests show that after 1000ms of scan time, 92% of the FOV is covered, which gives first a first indication of the temporal resolution temporal resolution that can be achieved by the AVIA. Results for FOV coverage and tree movement estimation are shown in Fig. 1 and 2. Limitations may occur during adverse weather conditions (e.g., fog or heavy rain) and due to battery life. Overall, this study aims to highlight the Livox AVIA's potential for generating 3D "videos" of dynamic natural processes and to support broader adoption of compact LiDAR stations in environmental monitoring.

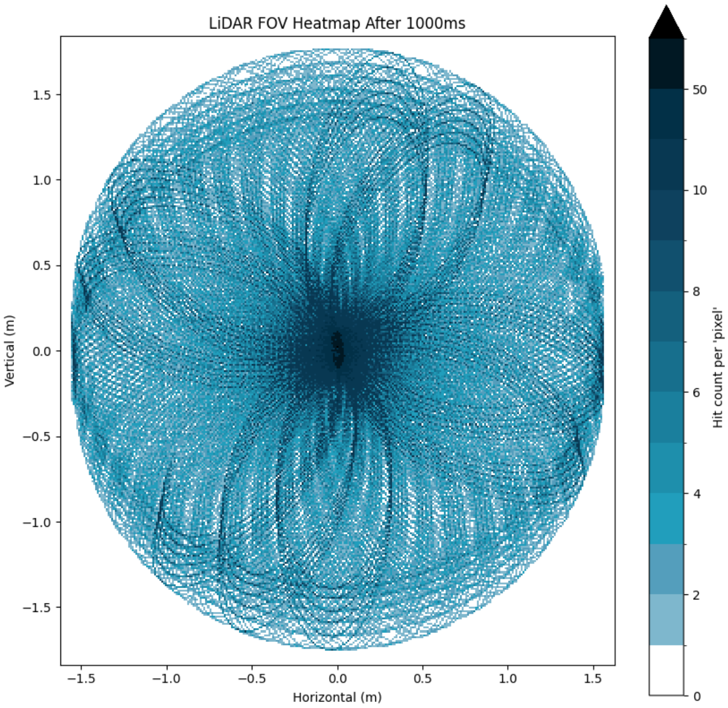

Figure 1: Livox AVIA FOV coverage heatmap. Approximately 92% of the FOV is covered after 1000ms

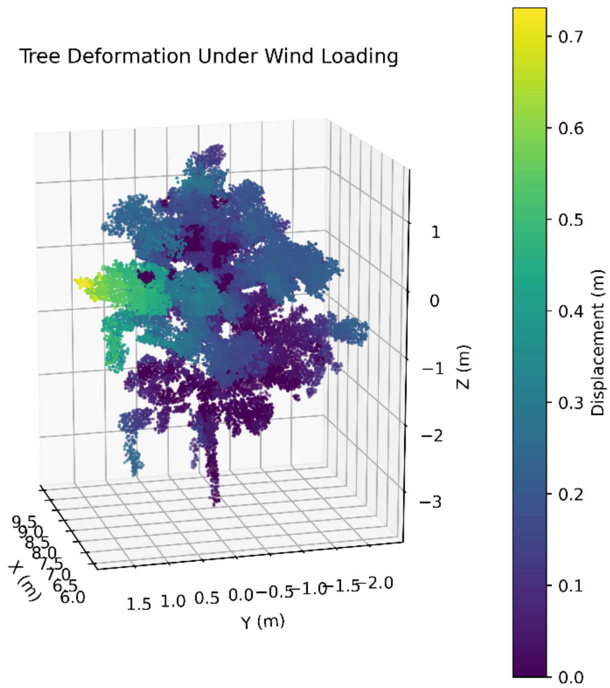

Figure 2. Tree deformation estimation of up to 70cm between 2 consecutive 1000ms scans using PlantMove

References

Czerwonka-Schröder, D. ; Schulte, F. ; Albert, W. ; Hosseini, K. ; Tabernig, R. ; Yang, Y. ; Höfle, B.; Holst, C. ; Zimmermann, K., 2025. AImon5.0: Echtzeitüberwachung gravitativer Massenbewegungen – Eine Fallstudie am Trierer Augenscheiner. In: Weinold, Thomas (Hrsg.): 23. Internationale Geodätische Woche Obergurgl 2025. Berlin, Wichmann Verlag 2025, pp. 240-251 .

LIVOX, 2025. Avia LiDAR sensor – Livox. Available at: https://www.livoxtech.com/avia

Ruttner-Jansen, P., Voordendag, A., Hartmann, T., Glaus, J., Wieser, A., & Bühler, Y. (2024). Monitoring snow depth variations in an avalanche release area using low cost lidar and optical sensors. EGUsphere, 2024, 1-20.

Wang, D., Puttonen, E., & Casella, E. (2022). PlantMove: A tool for quantifying motion fields of plant movements from point cloud time series. International Journal of Applied Earth Observation and Geoinformation, 110, 102781.

Thermal imaging for geothermal exploration (Dajia River, Taiwan)

Derron Marc-Henri1*, Chen Rou-Fei2, Li Yuan-Chi2, Lin Chih Chiao3, Kao Yu Hui3
[1] *University of Lausanne, Switzerland, marc-henri.derron@unil.ch*
[2] *Institute of Mineral Resource Engineering, National Taipei University of Technology, Taipei, Taiwan*
[3] *Chung Hsing Surveying Co, Taichung, Taiwan*

Key words: *thermal imaging, infrared, lidar, geothermal, fractures*

Since 2023, the Guguan geothermal research project in Taichung City has been initiated to align with Taiwan's renewable energy goals and net-zero carbon emissions strategy (GSMMA 2023). Guguan is located within the geologic region of the Hsuehshan Range with lithologies primarily composed of metamorphic sandstone and slate. The area is characterized by the development of northeast-southwest trending fault and fold systems, with an uplift rate of approximately 1 cm per year (Chen 1977).

This study aims to evaluate the effectiveness of thermal imaging technologies—ranging from satellite-based sensors to unmanned aerial vehicles (UAVs)—in detecting geothermal groundwater discharge zones within mountainous terrains. A key objective is to investigate the influence of flight altitude on the apparent surface temperatures recorded in thermal imagery and to compare these observations with in situ ground temperature measurements for validation. Additionally, the study seeks to map the spatial distribution of thermal anomalies associated with geothermal activity and to analyze their correlation with local tectonic structures, as identified through field surveys and high-resolution digital elevation models.

Thermal imagery utilized in this study includes Landsat 8 and Landsat 9 and UAV acquisitions with Workswell Pro camera and DJI Mavic 3T. To support structural analysis, a regional airborne LiDAR dataset with a spatial resolution of 1 meter, as well as UAV-based LiDAR datasets with a resolution of 5 centimeters, are available. All UAV thermal surveys were conducted at around 5am to minimize solar heating effects. Complementary field campaigns were carried out to collect structural measurements and to record water temperatures along the Dajia River using contact thermometers, synchronized with UAV flight times.

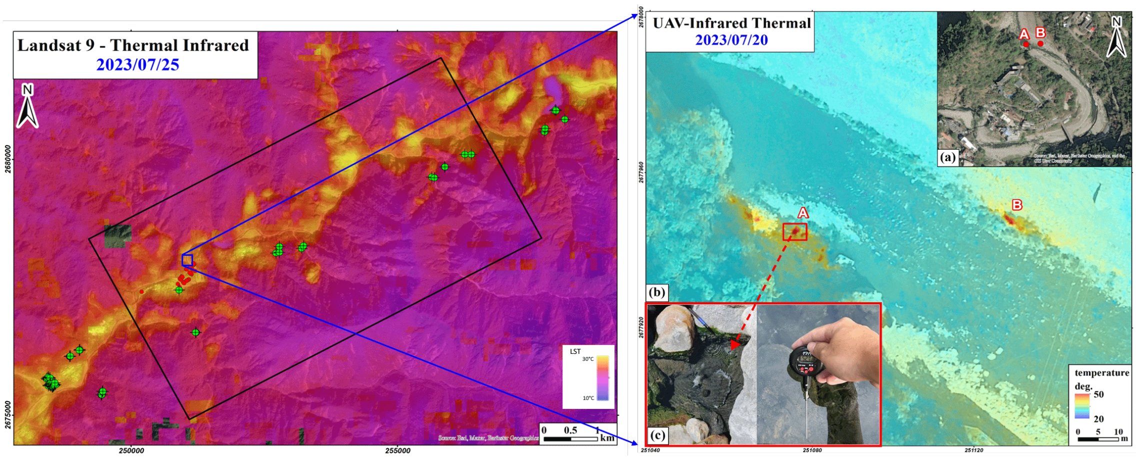

Figure 1: Left: Landsat 9 – band 10 thermal image along the Dajia river. Right: a) locations of two hot springs (A and B) at Guguan locality; b) thermal UAV orthophoto (temperature in °C); c) sampling point at spring A (52°C).

The results indicate that some geothermal features can be discerned in Landsat thermal imagery. However, numerous other thermal anomalies an their coarse resolution makes them inoperant for detecting small thermal features. In contrast, thermal orthoimages acquired by UAVs prior to sunrise and with a spatial resolution of 25 cm, demonstrate superior capability in identifying fine-scale thermal patterns. Both known hot springs and newly identified geothermal inflows along the Dajia River were successfully detected and subsequently validated through ground-based verification. The spatial distribution of thermal discharge points clearly indicates that geothermal groundwater emerges along brittle, vertically oriented NE–SW structural features.

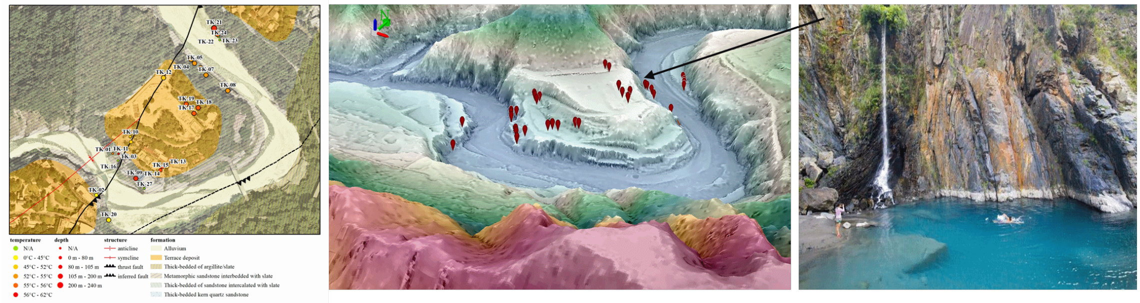

Figure 2: Left: geological map of Guguan area with locations of springs and boreholes. Middle: 3D view of ALS data. Right: natural hot spring along a vertical fault.

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Chen, C.H., 1977. Some stratigraphic problems of the Hsuehshan Range of Taiwan: Proc. Geol. Soc. China, no.20, p.61-70.

Geological Survey and Mining Management Agency (GSMMA) of the Ministry of Economic Affairs, 2023. Integrations of geothermal exploration techniques in the Guguan hot spring Area, Taiwan.

Landslide Susceptibility Mapping and Assessment in the Kurdistan Mountains, Northern Iraq

Jamal Doski[1*]
[1] *Technical College of Engineering, Duhok Polytechnic University, Duhok, Kurdistan, Iraq*
(jamal.ali@dpu.edu.krd)

Key words: *Landslide Mapping, Hazard Assessment, Zagros Mountains, Frequency ratio (FR), Analytical hierarchy process (AHP*

Landslides are major geological hazards in mountainous regions, driven by both natural processes and human activities. They pose significant environmental challenges, causing extensive damage to infrastructure, property, and landscapes, often resulting in casualties. This study focuses on evaluating and mapping landslide susceptibility in the Zagros Mountains of Kurdistan, northern Iraq, using GIS-based techniques. A comprehensive landslide inventory map was developed through detailed field investigations, remote sensing data analysis, and Google Earth imagery interpretation. Ten key influencing factors—elevation, rainfall, lithology, slope, curvature, aspect, land use/land cover (LULC), NDVI, and proximity to roads and rivers—were analyzed using a combined frequency ratio (FR) and analytical hierarchy process (AHP) approach to assess their relationship with landslide occurrence. The results reveal that landslide susceptibility in the Kurdistan Mountains is predominantly influenced by tectonic structures, landscape characteristics, and environmental conditions, particularly rock lithology (competency), slope gradient, rainfall intensity, and human activities. The resulting susceptibility maps provide critical insights for regional planners, policymakers, and infrastructure developers, offering a foundation for effective landslide mitigation strategies and the protection of lives and property in the region.

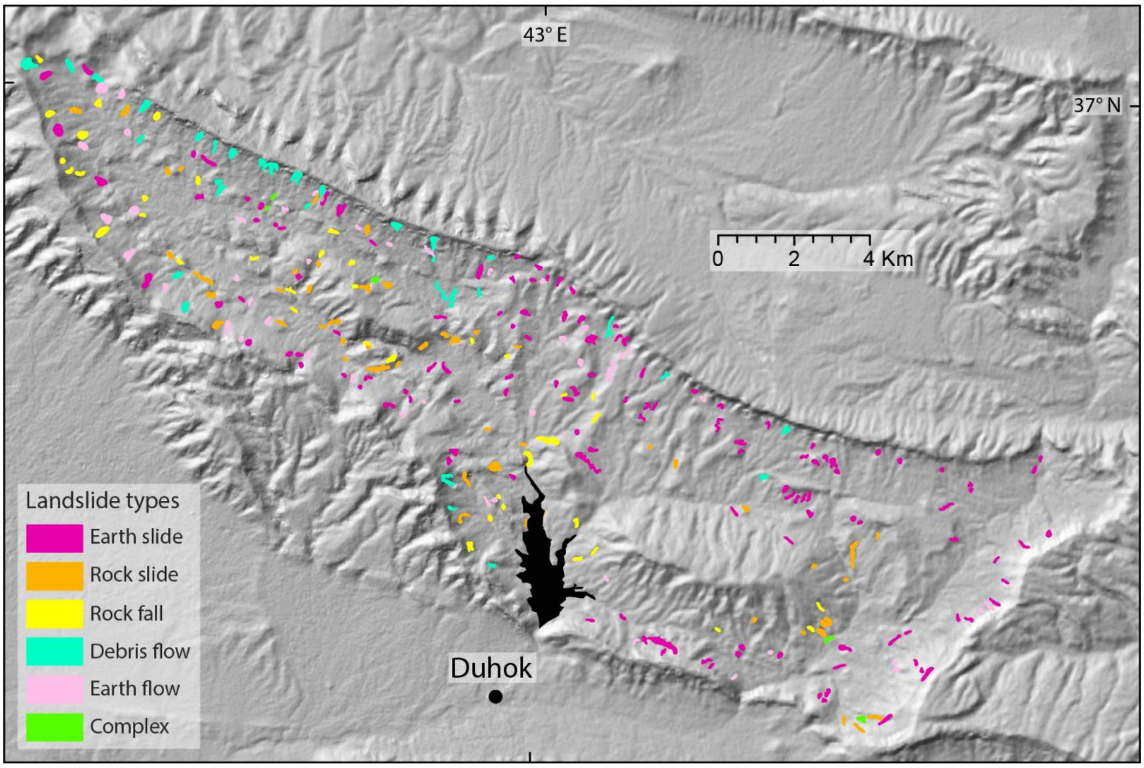

Figure 1: Inventory map showing the landslides distribution in the Bekhair anticline's core, , Kurdistan Mountains.

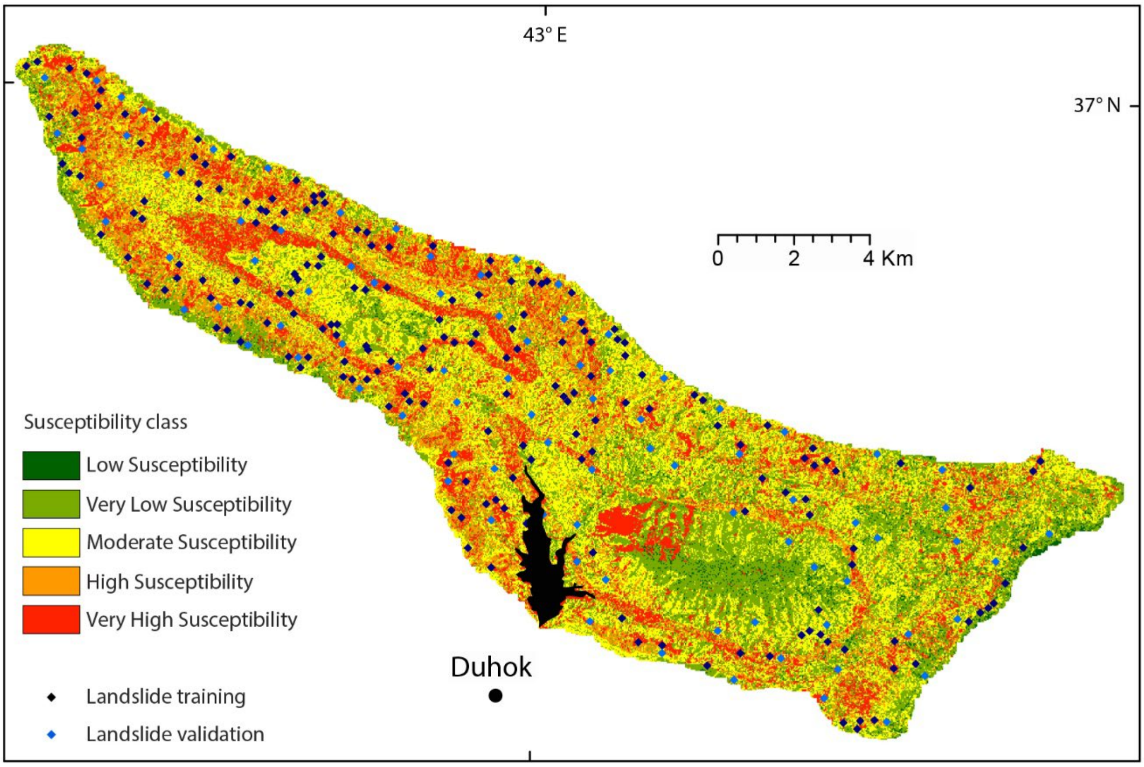

Figure 2: Landslide susceptibility map for the Bekhair anticline's core, Kurdistan Mountains

Towards 4D Monitoring of Glacier Calving: A Multi-Sensor Photogrammetric System and Data Processing Strategy

Laura Camila Duran Vergara[1*], Xabier Blanch[2], Anette Eltner[1]
[1] TUD Dresden University of Technology, Junior Professorship in Geosensor Systems
Address: Helmholtzstraße 10, 01069 Dresden, Germany
Email: laura_camila.duran_vergara@tu-dresden.de
[2] Universitat Politècnica de Catalunya, Department of Civil and Environmental Engineering.
Address: Av. Dr. Marañón, 44-50, 08028 Barcelona, Spain

Key words: *Glacier Calving, Multi-Sensor Photogrammetry, MEMI, Image Quality Degradation*

Glaciers are fundamental components of the Earth's climate system and serve as vital indicators of climate change (IPCC, 2022). They store around 70% of global freshwater (BAMBER, et al., 2018) and their accelerated mass loss, attributed to anthropogenic warming, poses increasing risks for ecosystems and water resource security (FOX-KEMPER, et al., 2021). In this context, frontal ablation, and especially glacier calving, represents a major component of mass loss, yet remains challenging to monitor and predict (BENN & ÅSTRÕM, 2018). To address the need for high-resolution, continuous monitoring of calving dynamics, we are installing a novel multi-sensor photogrammetric system at the Perito Moreno Glacier as part of the project AI4Glaciers (AI-Enabled Prediction of Glacial Calving based on 4D Real-Time Multi-Sensor Monitoring). The system includes a Multi-View Stereo (MVS) setup composed of RGB cameras and thermal infrared (TIR) cameras, as well as a seismograph.

The MVS-RGB system comprises eight high-resolution DSLR cameras (600×400 pixels) (Fig. 1, top), synchronized with second-level precision, capturing stereo image pairs every 30 minutes during daylight. Moreover, as proof of concept, three TIR cameras were installed for some days to evaluate the possibility of calving monitoring also at night. Data is transmitted twice daily via 4G for near real-time data analysis. Our setup allows the construction of 3D models using Structure-from-Motion MVS (SfM-MVS) techniques from approximately 10,000 images collected monthly. The resulting 3D models of change will support long-term (multi-seasonal) monitoring and enable time-series analysis of calving events and pre-failure deformations (Fig. 1, bottom).

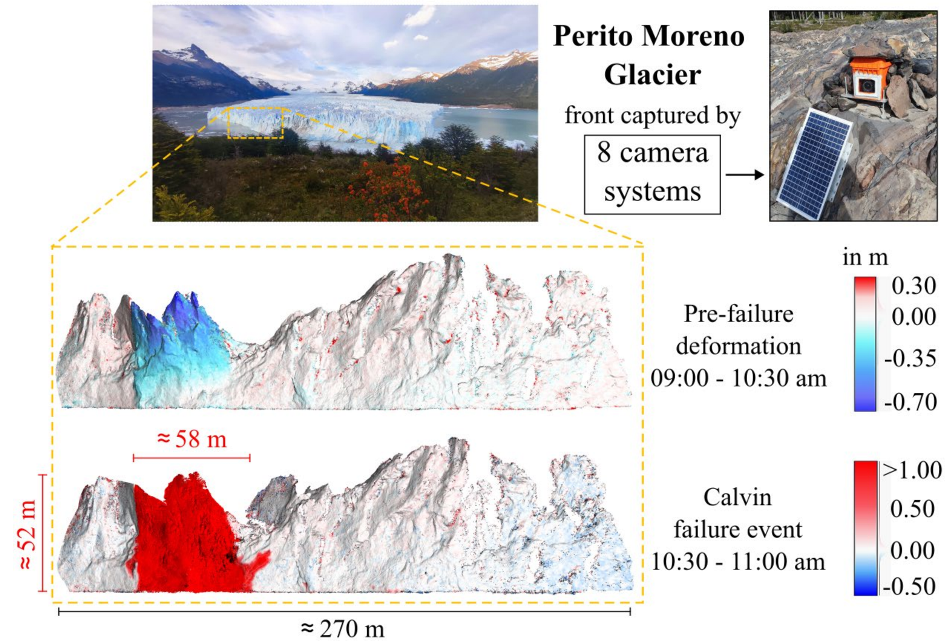

Figure 7: Top: Location of the observed Perito Moreno Glacier front, monitored by eight autonomously powered and remotely operated RGB camera systems. Bottom: 3D pre-failure deformation leading up to the calving event on 21 December 2024 (adapted from (BLANCH, et al., 2025)).

To process the collected data, currently exceeding 4000 epochs (as assessed from the system activity over time in Fig. 2, top), a robust pipeline for 3D reconstruction of the glacial front is being implemented, including the integration of change detection techniques such as the Multiscale Model to Model Cloud Comparison (M3C2) (LAGUE, et al., 2013). For 3D reconstruction, a Multi-Epoch, Multi-Image strategy (MEMI) is employed to improve model alignment by increasing redundancy, as it incorporates not only images from a single multi-view stereo acquisition but also from two successive temporal epochs. This redundancy enhances the quality and accuracy of change detection results, aiming for centimeter-level precision (BLANCH, et al., 2021).

However, environmental conditions pose challenges for image quality evaluation, particularly due to moisture, water droplets (Fig. 2, bottom) and fog, as well as blurriness. These issues are difficult to differentiate using classical filters, given the homogeneous visual structure of the glacier's surroundings, such as lake water, sky, and snow-covered background mountains. Moreover, the inherent movement of the glacier, contrasted with the fixed position of the surrounding mountains and waterline, may affect image alignment accuracy. AI-based techniques for image quality assessment and glacier segmentation are currently being explored as potential solutions to improve processing reliability and alignment precision.

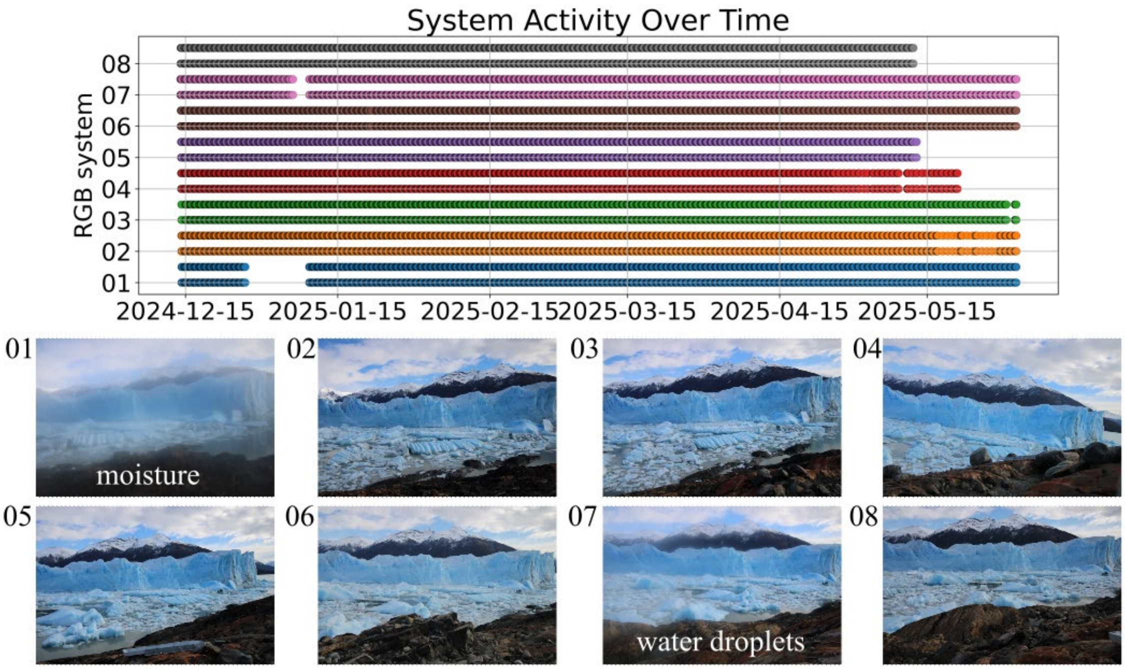

Figure 8: Top: Temporal activity and system failures of the MVS-RGB system, based on data from 4,050 point clouds as of 03 June 2025. Bottom: Fields of view of the eight cameras showing cases of image quality degradation on 6 May 2025 at 15:30.

Acknowledgements: We sincerely thank Steffen Welsch for his valuable support during the installation of the monitoring systems and for logistical assistance in the field.

References

BAMBER, J. L., WESTAWAY, R. M., MARZEION, B. & WOUTERS, B., 2018. The land ice contribution to sea level during the satellite era. *Environmental Research Letters*, 06, 13(6).

BENN, D. I. & ÅSTRÕM, J. A., 2018. Calving glaciers and ice shelves. *Advances in Physics: X,* 3(1).

BLANCH, X., DURAN VERGARA, L. C. & ELTNER, A., 2025. *AI4Glaciers: Introducing a multi-sensor system for calving monitoring at the Perito Moreno glacier.* Vienna, Austria: EGU25.

BLANCH, X., ELTNER, A., GUINAU, M. & ABELLAN, A., 2021. Multi-Epoch and Multi-Imagery (MEMI) Photogrammetric Workflow for Enhanced Change Detection Using Time-Lapse Cameras. *Remote Sensing,* 13(8).

FOX-KEMPER, B., HEWITT, H. & XIAO, C., 2021. *Chapter 9: Ocean, Cryosphere and Sea Level Change.* Cambridge: Cambridge University Press.

IPCC, 2022. *The Ocean and Cryosphere in a Changing Climate. In The Ocean and Cryosphere in a Changing Climate.,* Cambridge, United Kingdom: Cambridge University Press..

LAGUE, D., BRODU, N. & LEROUX, J., 2013. Accurate 3D comparison of complex topography with terrestrial laser scanner: Application to the Rangitikei canyon (N-Z). *ISPRS Journal of Photogrammetry and Remote Sensing,* Band 82.

Leveraging Drone Technology to Enhance Geoscience Education in Ghana

Elikplim Abla Dzikunoo [1, 2]
[1] *Department of Earth Science, University of Ghana* [2] *Department of Geology, University of Johannesburg*

Key words: *traditional geoscience, drone mapping, 3D modelling, 3D interactive map*

Traditional geoscience training in Ghana, is often hampered by limited fieldwork and field laboratory exercises that do not fully immerse the student in the practical nature of geosciences. With increasing student numbers, often exceeding 100, combined with the large student to lecturer ratio and limited field/exposure time, detailed knowledge transfer on the field becomes challenging. However, drone mapping which is emerging as a transformative tool to enhance geoscience education and learning in Ghana can be used to provide students with the practical experiences they lack.

The combined technologies of drone mapping and 3D modeling present the opportunity to create virtual interactive laboratories. These tools can offer immersive learning experiences for students in the Department of Earth Science – University of Ghana, and other such institutions, allowing them to engage with significant local geological features that are also gradually being lost. This was tested at an abandoned quarry site in Accra – Ghana, where students applied the technologies to develop a 3D interactive map. Preliminary development saw the production of an interactive 3D model that allows for zooming and rotation, the next step is to incorporate clickable geological annotations.

Another significant feature to this study is the incorporation of data analytics, web development as well as remote sensing and Geographic Information Systems (GIS) techniques into the workflow to enhance the output models. The opportunity to apply such a multidisciplinary approach broadens the students' technical skill set and fosters critical thinking, problem-solving and innovation. Such an approach paves the way for collaborative initiatives in other areas such as geoheritage preservation among others.

Acknowledgements: I would like to acknowledge the contributions of Prof. Sandow Mark Yidana, Dr. Yvonne Sena Akosua Loh, Mr. John Kudadjie, Mr. Isaac Antwi, Mr. Kenneth Ansah and Miss Angelica Annan of the Department of Earth Science, University of Ghana.

Immersive Visualizations for Marine Geohazards: Virtual environment of Santorini for Science and Stakeholder Engagement.

Jan Oliver Eisermann1,2*, Felix Gross1,2, Josephin Wolf2, Heidrun Kopp3, Klaus Reicherter4, Sebastian Krastel1, Christian Hübscher5, Christian Wagner-Ahlfs2, Steffen Kutterolf3, Tom Kwasnitschka3

[1]*Institute of Geosciences, Marine Geophysics and Hydroacoustics, Kiel University, Kiel, Germany oliver.eisermann@ifg.uni-kiel.de,* [2]*Center for Ocean and Society (CeOS), Kiel University, Kiel, Germany,* [3]*GEOMAR Helmholtz Centre for Ocean Research Kiel, Kiel, Germany,* [4]*Institute of Neotectonics and Natural Hazards, RWTH Aachen University, Aachen, Germany,* [5]*Institute of Geophysics, University of Hamburg, Hamburg, Germany*

Key words: *geohazards, terrestrial, marine, digital twin, virtual environment*

The MULTI-MAREX research mission, initiated by the German Marine Research Alliance (DAM), is establishing a living lab in Santorini, Greece. The aim is to study extreme marine geological events and associated hazards, and to build knowledge that will help to better manage geohazards at different scales. However, communicating the results and risk assessments of the research mission to stakeholders can be challenging, and traditional media may not be sufficient to convey the full range of processes involved. Additionally, news images of devastating events, such as tsunamis and volcanic eruptions, can evoke prejudice and fear, hindering the efforts for fact-based awareness-raising. Virtual representations of different local scenarios provide an opportunity to engage in discussion with experts, policymakers and the general public, overcoming abstraction and prejudice, and transforming scenarios into realistic, spatial experiences. Digital reconstruction of real physical study sites enhances situational awareness, resulting in a personalised, in-depth understanding of local scenarios. Recent advances in computer graphics and virtual reality headset hardware make immersive visualisation methods more accessible to a wider scientific community.

Our aim is to create a scalable solution for highly immersive experiences, ranging from head-mounted displays to dome theatres. These diverse platforms ensure that immersive visualisations can be adapted to the needs of different users.

Using popular game engines such as Epic Unreal 5 and Unity as real-time 3D rendering platforms enables us to integrate real-world spatial data. This creates a 3D representation of the area based on real world data, as well as a dynamic, interactive environment in which users can explore different geohazard scenarios in real time. The results of numerical simulations are used to accurately visualize the effects of tsunamis and volcanic eruptions. Our main work focuses on developing workflows for geoscientists, enabling semi-automated, asset-enhanced, immersive visualisation inside such game engines. The virtual environments synthesise collected remote sensing data, including terrestrial and marine digital outcrop models from drone and submersible imagery and hydroacoustic bathymetry. Digitally placed assets such as high-resolution synthetic textures, vegetation and buildings enhance the visual appearance and help to bridge the gap between different scales. We present our latest work on developing the virtual environment of the Columbo-Santorini-Christiana volcanic field. This is a 3000 km² terrestrial and marine landscape, represented at the decameter to centimetre scale. The example in Figure 1 shows step by step the pathway from real data to 3D construction and finally implementation into an immersive visual model showing an inaccessible outcrop of volcanic deposits of the volcanic island Santorini that can be now virtually be visited.

Virtual environments are a great tool to enhance scientific analysis and stakeholder engagement, bridging the gap between complex geohazard science and effective stakeholder understanding. This enables informed decision-making and risk management.

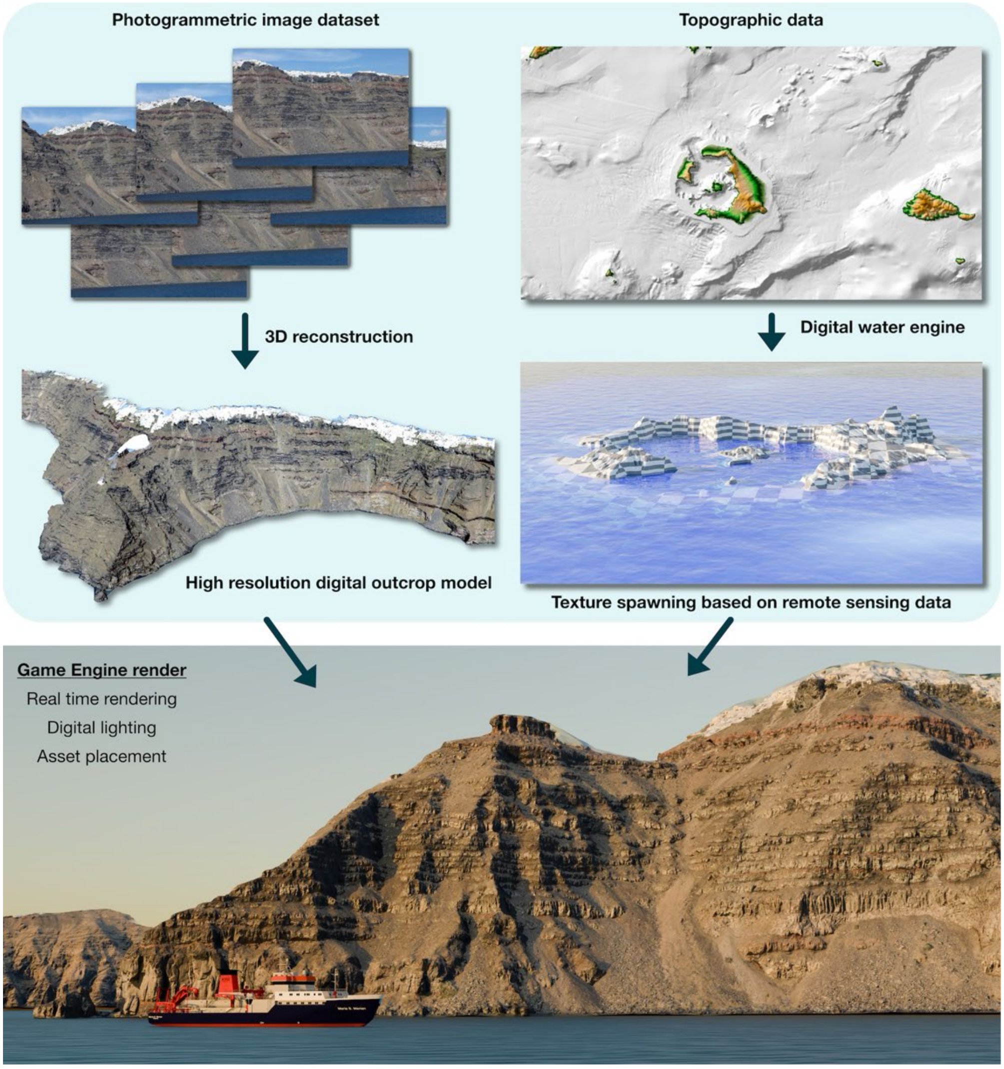

Figure 1: Sketch illustrating the data components of a virtual environment that leads to the final real-time render in the game engine.

Integrated Seismo-Optical Stereo Monitoring for Robust and Low-Cost Flash Flood Observation in Arid Regions

Anette Eltner[1*], Robert Krüger[1], Noreen Rabenau[1], Michael Dietze[2], Jens Grundmann[3], Ghazi Al-Rawas[4], Xabier Blanch[5], Pedro Zamboni[1]

[1] Institute of Photogrammetry and Remote Sensing, Dresden University of Technology, Germany (anette.eltner@tu-dresden)

[2] Institute of Geosciences and Geography, Georg-August University Göttingen, Germany

[3] Chair of Hydrology, Dresden University of Technology, Germany

[4] Department of Civil and Architectural Engineering, Sultan Qaboos University, Oman

[5]Department of Civil and Environmental Engineering, Universitat Politècnica de Catalunya, Spain

Keywords: *stereo-photogrammetry, multi-sensor integration, AI-based image matching, camera gauge, seismic gauge*

In recent years, Oman has faced increasing challenges with flash floods due to the accelerating water cycle from climate change and ongoing urban expansion into natural floodplains. This trend significantly heightens flood risk, particularly in ephemeral river systems known as wadis. However, Oman's flood preparedness remains limited by a lack of dense, reliable monitoring networks and early warning systems. Traditional water level sensors face considerable challenges: pressure gauges are prone to destruction during high-magnitude flash flood events, while radar gauges can be rendered ineffective due to shifting wadi channels caused by erosion and sediment deposition.

In response, this study presents a robust and low-cost seismo-optical monitoring system that combines stereo camera gauges with seismic sensors to overcome the limitations of current techniques. Stereo photogrammetry, using a two-camera setup, enables the generation of 3D river reach models and hence a frequent update of the river cross-section (Fig. 1a). Recent developments in deep learning-based feature matching have improved the robustness of stereo reconstruction under challenging conditions such as low lighting or low-texture surfaces, enhancing the applicability of this method.

Video footage from the same setup allows for near-continuous monitoring of water levels by extracting the water surface via AI-based segmentation and intersecting the resulting polygon border with the 3D model of the river reach (BLANCH *et al.*, 2025, Fig. 1b). In addition, the video is used to estimate the river surface velocities via particle tracking velocimetry (ELTNER *et al.*, 2020). Eventually, water level, cross-section and velocities enable the wadi flow discharge estimation.

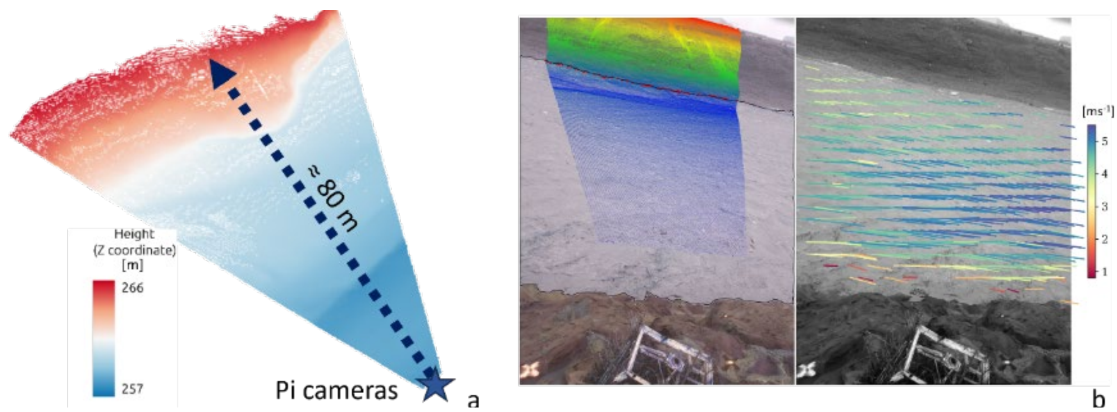

Figure 1: a) 3D reconstruction of the river cross-section using AI-based image processing applied to the stereo-camera setup. b) Water level and flow velocity measurement using a single camera (KRÜGER et al., 2024).

Nevertheless, optical techniques are limited at night or in poor visibility conditions (e.g., during heavy rainfall), however times when many flash flood events occur. To address this, we integrate low-cost seismic sensors that capture ground vibrations generated by turbulent flow and bedload transport (Fig. 2). By applying physically-based models to seismic spectra, river levels can be inferred (DIETZE *et al.*, 2019).

Crucially, the optical measurements serve to constrain model parameters, improving the reliability of seismic estimations during periods when visual data is unavailable.

We implemented this integrated monitoring system through the research project *SR/DVC/CESR/22/01* at two sites (Lehbab and Guzayeen) along Wadi Al-Hawasinah in Oman and evaluated its performance during diverse wadi flow conditions. The results demonstrate the feasibility and effectiveness of this hybrid approach, offering a resilient, scalable, and cost-efficient tool for hydrological monitoring in complex and data-scarce environments.

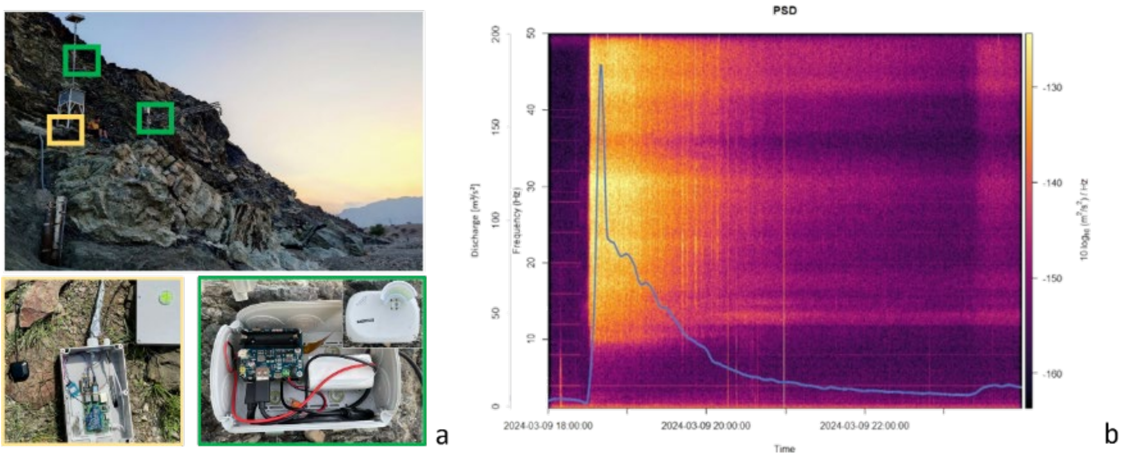

Figure 2. a) System setup: green box shows location and parts of the camera system and yellow box indicates location and content of the seismological system. b) Blue line shows measured discharge with radar gauge and power spectral density (PSD) diagram reveals seismic flood signature as broadband 10–50 Hz power transient (Krüger et al., 2024).

References

Blanch, X., Grundmann, J., Hedel, R., and Eltner, A., 2025. AI Image-based method for a robust automatic real-time water level monitoring: A long-term application case. *EGUsphere* [preprint], 10.5194/egusphere-2025-724.

Dietze, M., Lagarde, S., Halfi, E., Laronne, J. B., & Turowski, J. M., 2019. Joint sensing of bedload flux and water depth by seismic data inversion. Water Resources Research, 55: 9892–9904. 1029/2019WR026072.

Eltner, A., Sardemann, H., Grundmann, J., 2020. Technical Note: Flow velocity and discharge measurement in rivers using terrestrial and UAV imagery. *Hydrology and Earth System Sciences*, 24: 1429-1445.

Krüger, R., Blanch, X., Grundmann, J., Al-Rawas, G., Eltner, A., 2024. Low-Cost sensors for measuring wadi discharge - a Raspberry Pi based seismometer and time-lapse camera setup. ISPRS Archives, XLVIII-2/W8-2024: 243–250, 10.5194/isprs-archives-XLVIII-2-W8-2024-243-2024.

Invited Keynote:
How Different Are Our Fracture Models? Examining User-Generated Uncertainty in Fracture Mapping

Leila Evans[1*], Zoe Shipton[1], Clare Bond[2], Jen Roberts[1] & Namgwon Kim[1]
[1] *University of Strathclyde, Glasgow, Scotland, *leila.evans@strath.ac.uk*
[2] *University of Aberdeen, Aberdeen, Scotland*

Key words: *uncertainty, fractures, observations, subjectivity*

Applied geoscience relies on robust structural models that are appropriately scaled and detailed to address a specific challenge. However, the process of developing these models is influenced by human biases, shaped by personal and professional experiences, area of expertise, values, cognitive abilities and styles. This diversity of approaches to geoscience observation and interpretation impacts every stage of the process when taking geological observations through to usable, geoscientific knowledge. In the context of fracture characterisation, this variability affects the reliability of structural models, which are critical for geoenergy, resource and infrastructure applications. Ensuring robust interpretations is vital for improving safety, enhancing decision-making, and securing project success.

Previous studies on 3D seismic data have shown that geoscientists' experience and approach significantly impact structural models. Our research systematically assesses similar variability in observations using outcrop data. Given the prevalence of remotely sensed, or proxy data in geosciences (drone or satellite imagery, geophysical data, well logs etc.) we have investigated the individual variability in fracture observations made on a drone image of a fractured outcrop. Eighty-four participants from 5 cohorts, which included university geoscience students and staff, professional geoscientists and geological engineers, have been asked to make observations of fractures on the same image. We compare outputs such as fracture frequency, orientation & density, and network topology across participants to assess the variability in their observations and the uncertainty that this may generate.

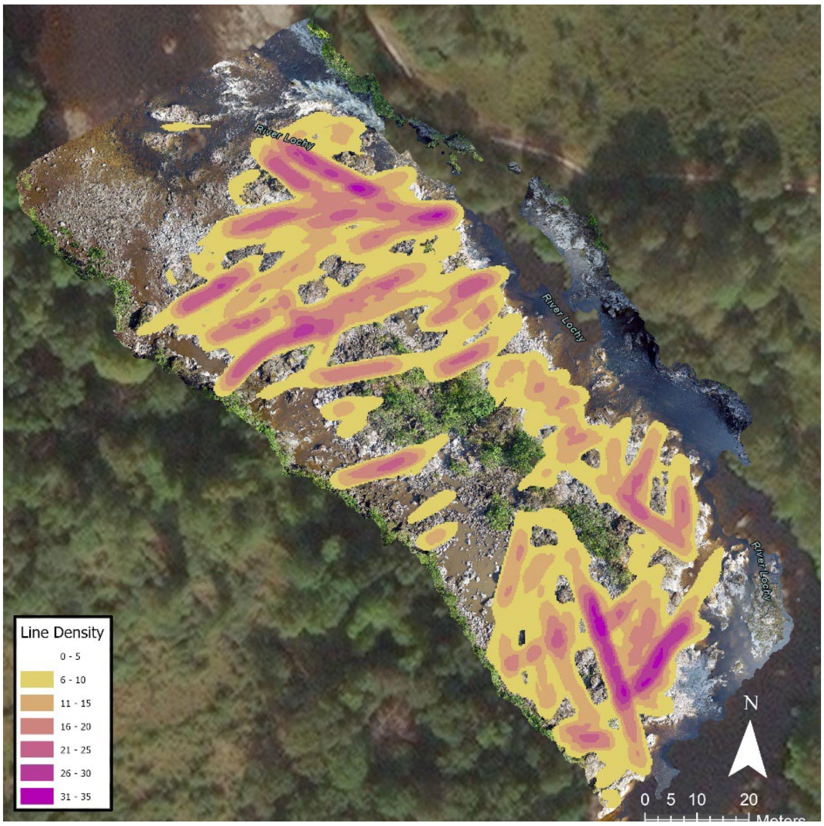

Figure 9 Line density map from aggregation of all participants' fractures, showing areas of "agreement" in pink.

Our results show that while our participants agree on the "big stuff" (Figure 9), there is much less consensus when we examine the detail. The properties of the derived fracture networks do not depend in a simple way on participant age, experience, education level etc. As an example of how this variability could pull-through into project outcomes, the orientation distribution derived from the interpreted fracture networks varies widely: from closely clustered around one orientation, conjugate sets or widely scattered (Figure 10). Each of these orientation distributions would produce a very different estimate of bulk permeability or rock mass strength.

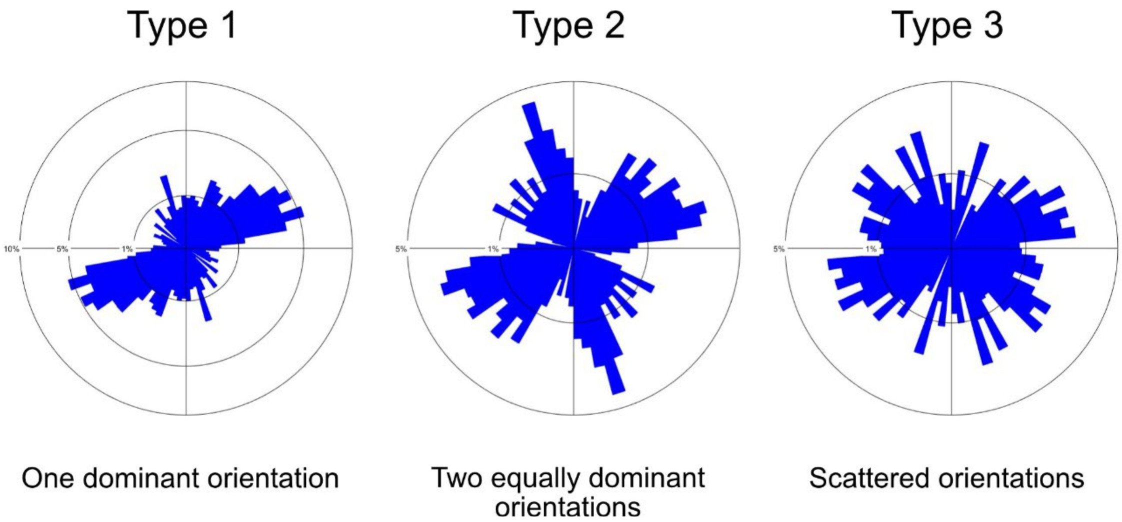

Figure 10 Example rose diagrams for each of the three orientation pattern types identified in participants' individual fracture network outputs.

By illustrating these uncertainties, we can begin to inform improved interpretation workflows, team arrangements, assurance processes, and geoscience education and communication. Understanding biases in fracture observation is a critical step towards enhancing interpretational accuracy. Coupled with a clear idea of how "good" the structural model needs to be for the problem being solved and appropriate mitigation measures, (if necessary) this ensures better project outcomes and supports the development of reliable geoscience outputs across applications.

Acknowledgements: This work is part of my PhD which is sponsored by University of Strathclyde as part of their match-funding for the Centre for Doctoral Training (CDT) in Geoscience and the Low Carbon Energy Transition. Their support is gratefully acknowledged.

The scientific colour map "buda" (Crameri, 2018) is used in Figure 9 to prevent visual distortion of the data and exclusion of readers with colour-vision deficiencies (Crameri et al, 2020).

References

CRAMERI, F., 2018. Scientific colour maps. Zenodo. http://doi.org/10.5281/zenodo.1243862

CRAMERI, F., SHEPHARD, G. E., AND HERON, P. J., 2020. The misuse of colour in science communication, *Nature Communications,* **11**, 5444. https://doi.org/10.1038/s41467-020-19160-7

Petrophysical Rock Typing Using Machine Learning to Identify Carbonates in an Early Miocene Fluvial System: A Case Study from the PA Field, Central Sumatra Basin

Muhammad Fachreza, ST[1*], Dr. Dwiharso Nugroho, ST., MT[2],
Alfend Rudyawan, ST., MSc., MT., PhD[3]

[1] *Pertamina, Bandung Institute of Technology, muhammad.fachreza@pertamina.com*
[2,3] *Bandung Institute of Technology, Indonesia*

Key words: *Carbonates, Machine-learning, Petrophysical rock-typing*

The PA Field, discovered in 1971 in the Rokan Block, Indonesia, lies approximately 95 km northwest of Duri and spans 16.5 km². It remains an active oil field under primary recovery, with 69 wells drilled as of March 2025. Reservoir production is sourced from the Bekasap, Bangko, and Menggala Formations. The Menggala Formation is generally interpreted as a post-extensional, fluvial-dominated system with blocky sands and favorable reservoir quality.

Recent core observations revealed an unexpected carbonate presence in the upper section of the Menggala Formation (Upper Menggala), historically overlooked and misinterpreted as tight sandstone due to cementation. These carbonates exhibit distinct log signatures—elevated bulk density (RHOB), low neutron porosity (NPHI), and high resistivity—marking a clear deviation from typical clastic responses.

To characterize this thin, seismically unresolved carbonate layer, a quantitative analysis integrating core and log data was conducted. Petrophysical Rock Typing (PRT) was applied and validated using both conventional core and side-wall core (SWC) data. Four carbonate rock types were identified: *Foraminiferal Packstone* (FP), *Coral Rudstone* (CS), *Foraminiferal Grainstone* (FG), and *Crystalline Boundstone* (CB).

The PRT model was developed using the Multi-Resolution Graph-Based Clustering (MRGC) method—an unsupervised machine learning technique within the Facimage module. MRGC clusters well log data into electrofacies based on petrophysical similarities. Proper log selection is critical, as it directly affects propagation accuracy. This approach offers a robust framework for capturing reservoir heterogeneity and provides new insight into the mixed carbonate–clastic setting of the Upper Menggala.

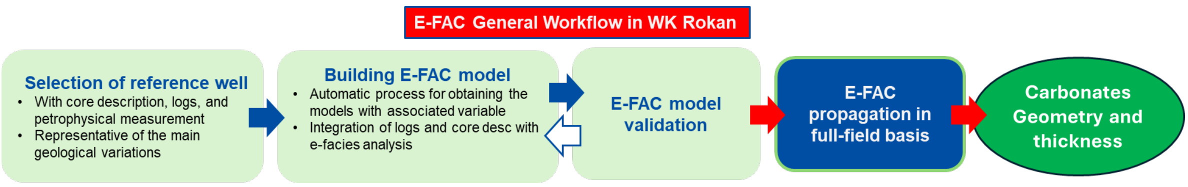

Figure 1. Tailored Petrophysical rock-typing (PRT) workflow deployed in PA Field using MRGC to generate E-FAC.

A preliminary Petrophysical Rock Typing (PRT) model—referred to as the CNC model (Carbonates–Non-Carbonates)—was developed to distinguish carbonate from sandstone intervals in the Menggala Formation, PA Field. This unsupervised model employed Multi-Resolution Graph-Based Clustering (MRGC), using only two wireline logs—normalized gamma ray and bulk density—due to limited availability of other key logs such as NPHI, DT, and PEF. These will be integrated in future advanced MRGC models. The current approach ensures clustering is driven purely by spatial log behavior, independent of core-defined rock types, improving model objectivity and eliminating the need for blind testing.

The CNC model was applied to 39 wells across the field, where 10 wells contained core data. The model achieved a 100% match with carbonate intervals identified in the conventional core and approximately 80% consistency with SWC descriptions, validating its reliability for wider field-scale application.

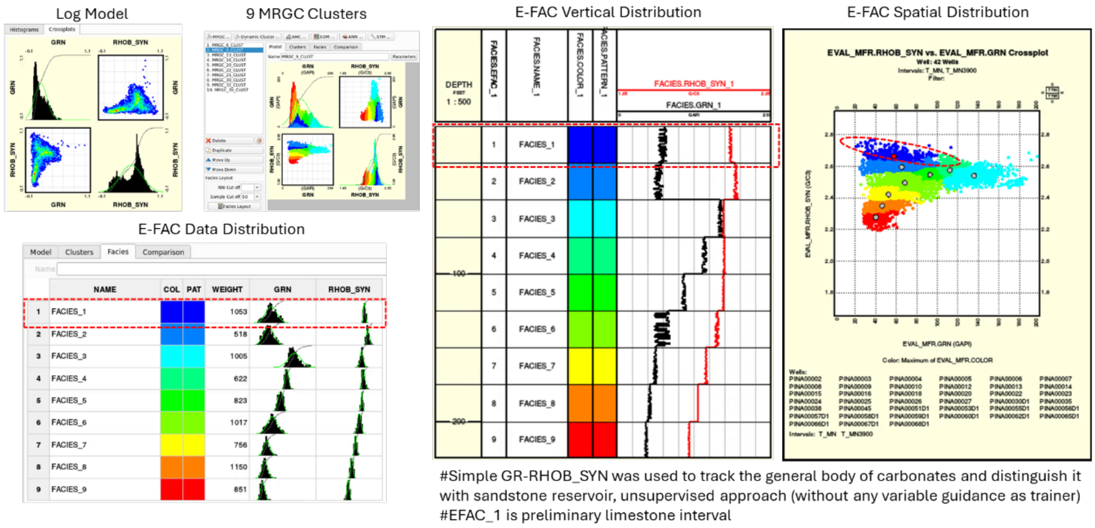

Figure 2. Preliminary CNC (Carbonates non-carbonates) MRGC-driven Model for PRT in MN Formation, PA Field.

The spatial observation revealed that the Upper Menggala carbonates are laterally discontinuous, forming isolated bodies with varying thickness. These bodies are oriented perpendicular to the regional paleocurrent direction. Stratigraphically, they overlie and pinch into fluvial sandstones. The geometry indicates this was deposited as isolated patch-reef during the transgressive system then mostly reworked during the high-stand phase, causing mixed carbonate-clastic environment. This finding challenges the traditional interpretation of the Menggala Formation as a purely fluvial post-extensional deposit of the Early Miocene. The full study presents an advanced PRT model incorporating four lithofacies types derived from core data, offering deeper insight into reservoir heterogeneity and depositional complexity of this overlooked carbonate system.

Acknowledgements: The authors would like to express their gratitude to **PT Pertamina Hulu Rokan** for providing the datasets and technical reports that supported this study. Appreciation is also extended to the **Geological Engineering Department, Institut Teknologi Bandung**, for granting study permission and offering valuable technical guidance.

References

CUI, YUNJIANG. SHI, XINLE., 2018. Accurate Permeability Estimation in a Heteregeneous Middle East Carbonate Field through Facies Classification and Core-Log Integration. *Offshore Technology Conference.* Houston, Texas, 30th April-3rd May.

EBANKS W J.,1987. Flow Unit Concept-Integrated Approach to Reservoir Description for Engineering Projects. *AAPG Bulletin.* 71(5):551-552.

SHI, XINLEI. CHEN, HONGBING. LI, RUIJUAN. YANG, XIAOYAN. LIU, HUAN., 2019. Improving Permeability and Productivity Estimation with Electrofacies Classification and Core Data Collected in Multiple Oilfields. *Offshore Technology Conference.* Houston, Texas, 6-9th May.

SHI, XINLEI. CUI, YUNJIANG. GUO, XUYANG. YANG, HONGWEI. CHEN, RONGTAO. LING, TI. LI, RUIJUAN. WANG, RUIHONG. WANG, JIAN. MENG, LI., 2017. Logging Facies Classification and Permeability Evaluation: Multi-Resolution Graph Based Clustering. *Society of Petroleum Engineers*. San Antonio, Texas, USA, 9-11th Oct.

Automated monitoring of individual armour units in coastal breakwaters from 3D point cloud time series using template registration and digital footprints

Laurent Froideval[1*], Ayoub Yamoul[1], Xavier Pellerin Le Bas[2], Christophe Conessa[1], Laurent Benoit[1], Dominique Mouazé[1]
[1] *Normandie Univ, UNICAEN, UNIROUEN, CNRS, M2C, 14000 Caen, France,*
laurent.froideval@unicaen.fr
[2]*Scienteama, 4 av. de Cambridge 14200 Hérouville-St-Clair, France*

Keywords: *photogrammetry, 3D point cloud processing, registration, machine learning, coastal infrastructure monitoring*

3D point clouds time series are now routinely acquired for monitoring applications using widely adopted techniques such as photogrammetry and LiDAR. Yet, the lack of robust and automated processing workflows remains a major limitation. This gap becomes particularly critical in the context of coastal infrastructure, where new dike designs, composed of individually placed concrete blocks, are increasingly implemented in response to climate change. Continuous monitoring of these protective infrastructures is crucial to detect displacement or damage to individual blocks, thereby maintaining structural integrity and safety (FROIDEVAL ET AL., 2022). However, conventional monitoring methods often struggle to precisely identify and track changes at the scale of individual blocks, especially when using photogrammetric point clouds, which inherently present shadow artifacts and incomplete surfaces.

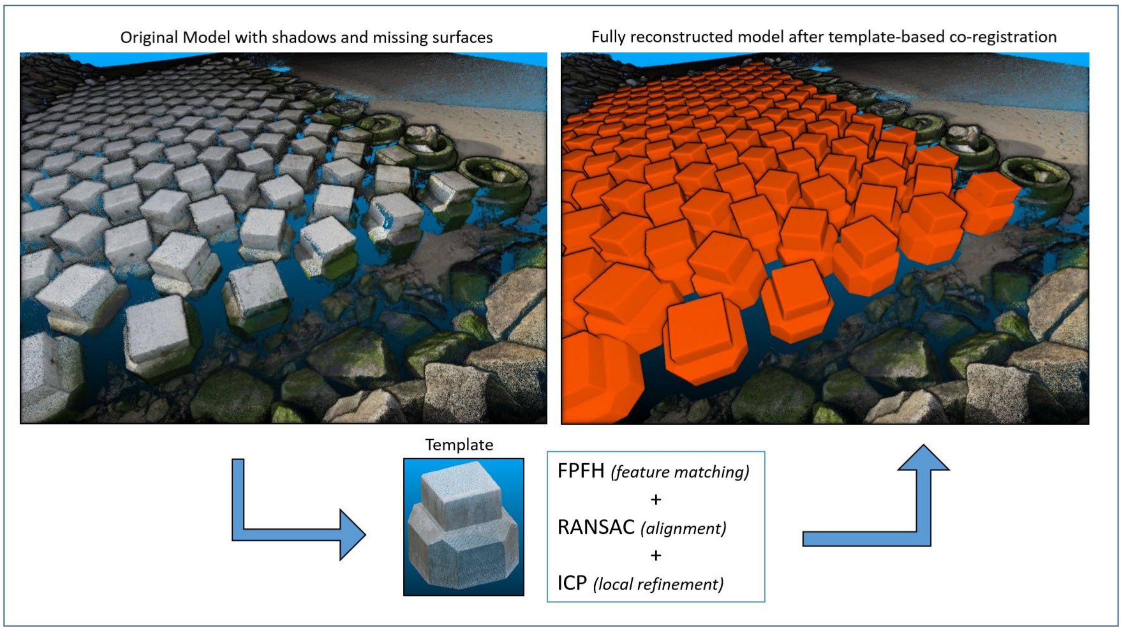

Figure 1: registration pipeline for photogrammetric point cloud reconstruction

This work introduces an efficient and precise workflow tailored specifically to the monitoring of individual concrete blocks within coastal defense structures. The workflow begins by preprocessing photogrammetric point cloud data using cLASpy_T, an open-source software based on machine learning algorithms (PELLERIN LE BAS ET AL., 2024), which accurately isolates points belonging exclusively to concrete blocks from surrounding structures and terrain. Subsequently, each extracted block point cloud undergoes a reconstruction process leveraging a robust co-registration pipeline, which combines Fast Point Feature Histograms (FPFH) for initial feature-based matching, Random Sample Consensus (RANSAC) for robust global alignment, and Iterative Closest Point (ICP) for precise local refinement. This pipeline significantly reduces shadowing effects and incomplete surface issues as seen on Figure 1, generating geometrically accurate, fully reconstructed each of the 147 individual block models with a mean RMSE of 6 mm. These reconstructed block models then serve as precise templates enabling the extraction of corresponding point clouds. In addition, the corresponding images used during the photogrammetric process are first identified for each point cloud, and then analyzed using the Scale-Invariant Feature Transform (SIFT) algorithm. This allows the definition of a unique visual footprint for each individual block, ensuring accurate and repeatable matching over time. This step ensures robust temporal consistency, essential for reliable monitoring over multiple observation campaigns. This approach enables precise, repeatable tracking of individual block displacements over time.

References

FROIDEVAL, L., CONESSA, C., PELLERIN LE BAS, X., BENOIT, L., & MOUAZE, D., 2022. Efficient dike monitoring using terrestrial SFM photogrammetry. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. 52, p. 359-366.

PELLERIN LE BAS, X., FROIDEVAL, L., MOUKO A., CONESSA, C., BENOIT, L., & PEREZ, L., 2024. A New Open-Source Software to Help Design Models for Automatic 3D Point Cloud Classification in Coastal Studies. *Remote Sens.,* 16, 2891. https://doi.org/10.3390/rs16162891

Integrating Virtual Reality into a Structural Geology Curriculum

Cael Gallagher, Christoph Schrank, Selen Türkay
Queensland University of Technology, Australia - cael.gallagher@qut.edu.au

Key words: *Virtual Reality, Blended-Learning, Geovisualisation, Structural Geology, Pedagogy*

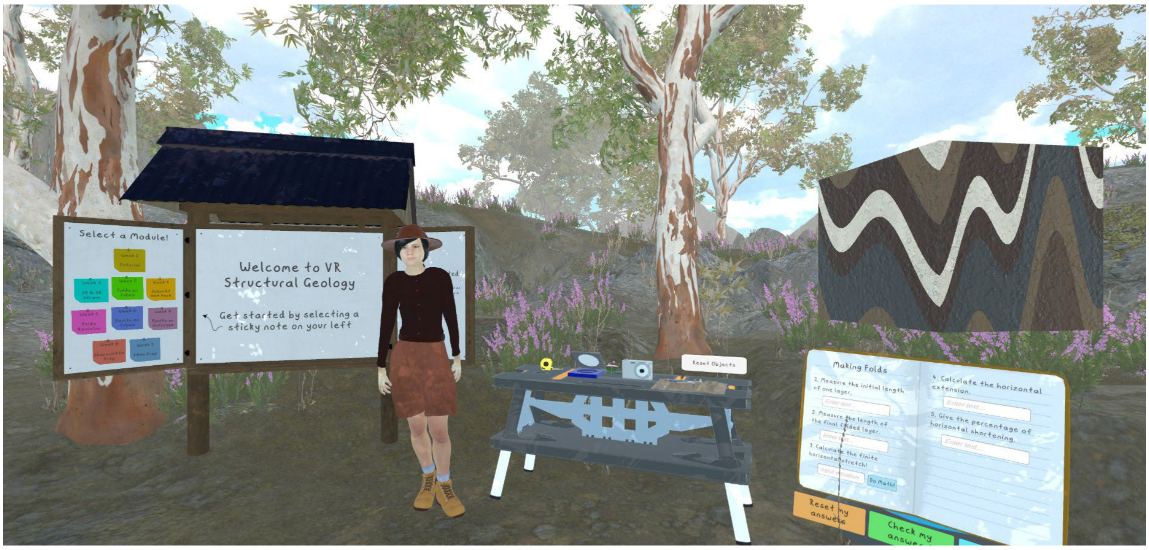

Figure 11 - Welcome to VR Structural Geology: A view of the collection of the tools created for the VR curriculum described herein.

Structural geology is known to challenge undergraduate students' spatial skills where it is imperative to make sense of maps, spatial diagrams (e.g., stereonets), and deformation structures at various scales. Here we consider a blended-learning approach to an undergraduate structural geology unit using virtual reality (VR) to teach these 3-D concepts. We evaluated the benefits and limitations of this approach over two consecutive years by studying the experiences of instructors and two student cohorts at an Australian university. We created a VR curriculum which could embed our students in a combination of real-world and imaginary scenarios. The VR content was designed to complement traditional structural geology teaching by 1) developing students' spatial abilities (as they are used to understand deformation structures); 2) offering practice opportunities for field-based skills (e.g., taking measurements); and 3) creating assessment material for spatial tasks to measure academic performance.

Each week, students were led in a two-hour VR workshop through demonstrations and student-directed activities. In the demonstrations, one instructor wore the VR headset and walked through the activity, while a second instructor commented on observations and directed questions to the students. Afterward, students individually applied what they learned using their own VR headsets on a separate set of activities. The structure of the curriculum followed traditional scaffolding but primarily focused on the most common families of deformation structures: folds & faults. A custom geovisualisation tool was created to represent these on simple 3-D objects (e.g., cubes), complex 3-D objects (e.g., mesoscopic scale models), and terrain (e.g., macroscopic elevation models; see Fig. 2). This tool allowed us to show students what deformation structures look like in the field on incompletely exposed outcrops. To develop students' spatial skills, some activities involved squishing (deforming), rotating, slicing open, and animating cubes. Some activities required a measurement tape, geological compass, camera, and field book (see Fig. 1). Overall, these workshops helped students to: 1) find and measure features of interest they overlooked or misinterpreted; 2) learn how to make predictions about macro-scale geometries based on mesoscopic observations; and 3) understand how they should interpret their results.

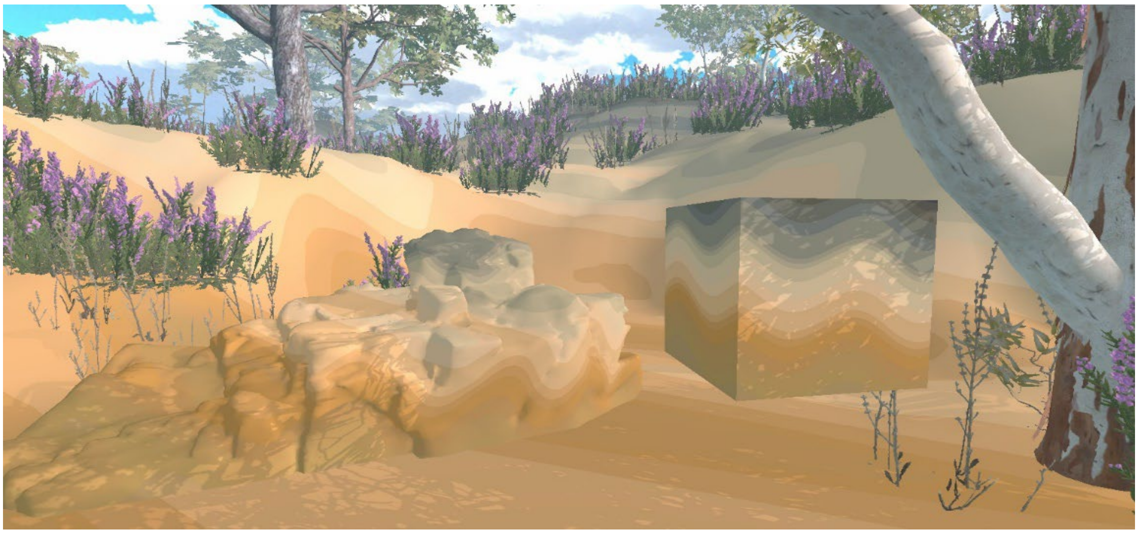

Figure 12 – Our custom geovisualisation tool representing folded layers on a cube, outcrop, and surrounding terrain.

Students indicated overall that they preferred the instructor-led demonstrations over their self-directed activities due to the engaged discussions that were supported by dynamic visualisations. This has promising implications for using VR as a tool for re-creating field-style teaching in classrooms. Students also described some deterrents for long-term engagement in a VR curriculum, including challenges with using VR that required continuous on-boarding, and scheduling issues that made it difficult to attend an additional voluntary VR workshop. Regardless of these challenges, we found that students 1) were interested in learning through VR, 2) enjoyed their experiences, 3) improved their sense of competence over time, and 4) recognised that VR helped them apply their knowledge in the field. We aim to include a multi-user approach in future studies, where instructors and students can be co-located in a VR environment, and can choose to join these sessions remotely from home.

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Enhancing Paleoearthquake Detection with Hyperspectral Imaging: Case Studies from Southeastern and Eastern Spain

John Gallego-Montoya1*, Maria Ortuño1, Moritz Kirsch2, Sam Thiele2, Eduardo García-Meléndez3, Marc Ollé-López1, David Garcia-Sellés1 & Eulàlia Masana1

[1] *RISKNAT Research Group, GEOMODELS Research Institute, Universitat de Barcelona, 08028 Barcelona, Spain. jj.gallego.montoya@ub.edu*
[2] *Helmholtz-Zentrum Dresden-Rossendorf, Helmholtz Institute Freiberg for Resource Technology, 09599 Freiberg, Germany.*
[3] *Research Group Environmental Geology, Quaternary and Geodiversity (QGEO), Universidad de León, León 24007, Spain.*

Key words: *Hyperspectral Data; Paleoearthquake; Advances in Paleoseismology; Eastern Betics Cordillera; Catalan Coastal Ranges.*

Paleoseismology investigates ancient earthquakes, providing valuable data to expand historical and instrumental seismic catalogs, improve seismic source characterization, and advance the understanding of fault behavior and interactions, ultimately refining seismic hazard assessments. Traditionally, paleoseismological studies involve excavating trenches across faults to identify and characterize stratigraphic and structural evidence of deformation associated with paleoearthquakes events. However, tectonic complexity combined with erosion, weathering, and other exogenic processes frequently obscures these features, hindering the precise identification of paleoearthquake evidence. Ground-based hyperspectral imaging has been successfully applied in paleoseismology, offering non-invasive data acquisition and improved structural characterization of trench exposures (RAGONA et al., 2006; KIRSCH et al., 2019).

This study adapts existing workflows by integrating hyperspectral data with millimeter-resolution 3D digital outcrop models of paleoseismic trenches to achieve two key objectives: (1) enhance paleoseismic stratigraphic characterization, (2) resolve previously undetected subtle deformation structures to improve the accuracy of paleoearthquake horizon identification in active fault systems. We used SPECIM hyperspectral cameras (FX10: 400-900 nm; FX17: 900-1700 nm; AISA Fenix 1K: 400-2500 nm) to scan trenches excavated in unconsolidated alluvial sediments at two tectonically complex areas of southeastern and eastern Spain: (1) the Alhama de Murcia Fault Zone, a strike-slip fault within the Eastern Betics Shear Zone, and (2) the Sant Rafel Fault, a normal fault within the Baix Ebre mountain front in the Catalan Coastal Ranges. We generated 3D point cloud models of the trenches using photogrammetry (Fig. 1A) and LiDAR, then fused these with hyperspectral data through the Python package *hylite* (THIELE et al., 2021). We applied spectral dimensionality reduction (Fig. 1B), classification, and ratio-based indices (Fig. 1C) to produce a range of false color images with enhanced lithological contrast. Spectral signatures from sediment trench samples were measured using a FieldSpec 4 spectroradiometer (SPR) to validate the hyperspectral data obtained with the cameras. The processed data facilitated high-resolution digital 3D trench interpretation and comparison with 2D field logging.

The hyperspectral data enhanced the interpretation of paleoseismic logs in both study areas, resolving key uncertainties regarding the presence or absence of coseismic fractures, faults, and surface ruptures and improving the characterization of paleoearthquake events. Paleoseismic interpretations revealed previously unrecognized surface rupture evidence along the northern strand of the Alhama de Murcia Fault. We identified and confirmed secondary fault structures in trenches along the Sant Rafel Fault and characterized mineralogical variability across the fault damage zones. Additionally, spectral band ratios enabled the identification of sedimentary facies, paleosols, and erosional contacts, as well as a more precise delineation of alluvial channels in the trenches. The comparison of different hyperspectral cameras enables the detection of their limitations and applications in paleoseismology, highlighting their specific potential to enhance observational methods in earthquake geology.

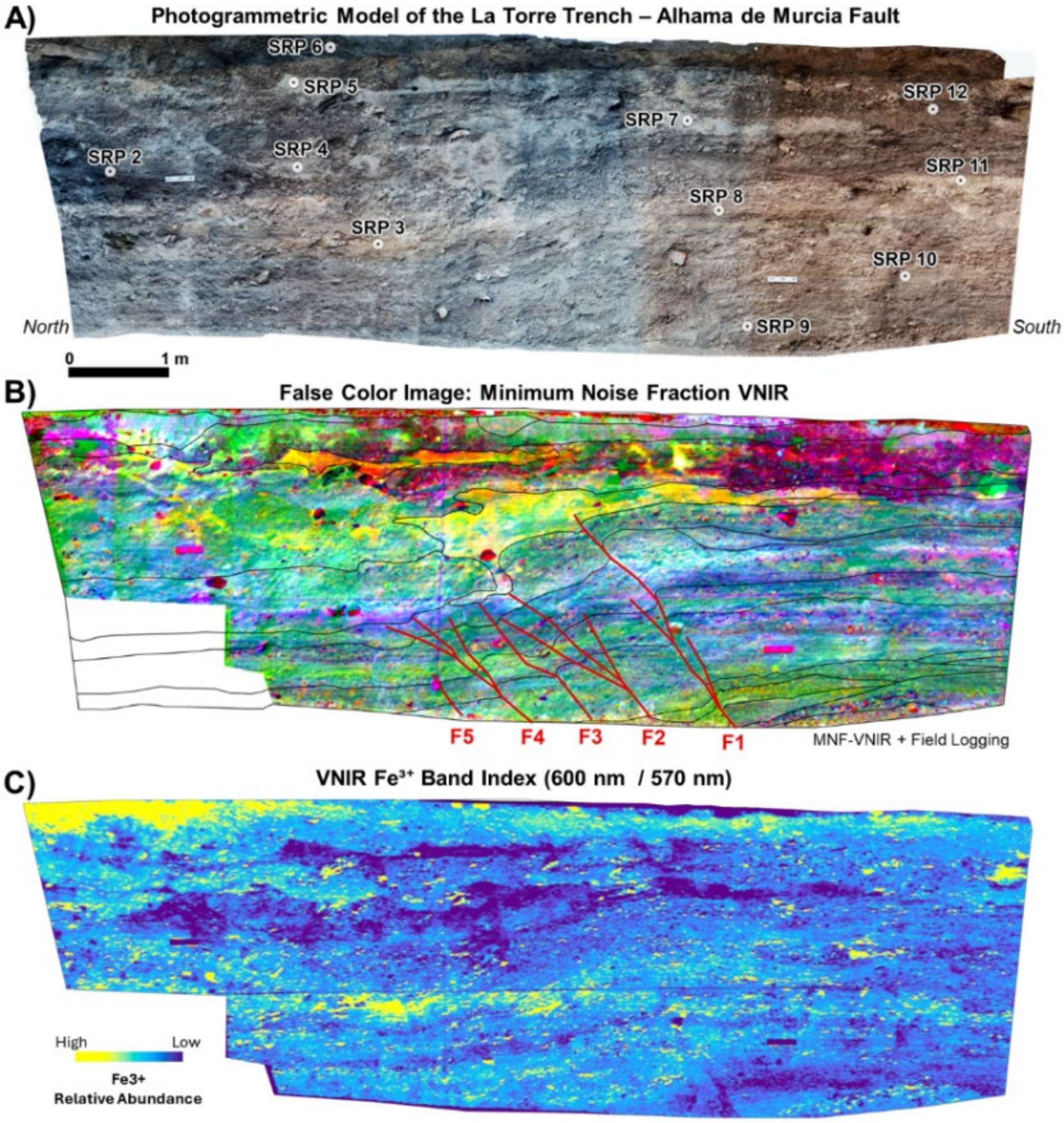

Figure 1 (A) Photogrammetric model of the La Torre A trench (Northern strand, Alhama de Murcia Fault) displaying locations of spectral radiometer (SPR) validation samples. (B) False-color composite using Minimum Noise Fraction transformation of VNIR data overlain with field-mapped stratigraphic unit boundaries and identified fault traces (F1-F5). (C) VNIR Fe^{3+} band ratio index (600/570 nm) highlighting iron oxide/hydroxide mineralogical distribution

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References

KIRSCH, M.; LORENZ, S.; ZIMMERMANN, R.; ANDREANI, L.; TUSA, L.; POSPIECH, S.; JACKISCH, R.; KHODADADZADEH, M.; GHAMISI, P.; UNGER, G.; ET AL., 2019. Hyperspectral Outcrop Models for Palaeoseismic Studies. *Photogramm. Rec.* 34, 385–407.

RAGONA, D.; MINSTER, B.; ROCKWELL, T.; JUSSILA, J., 2006. Field Imaging Spectroscopy: A New Methodology to Assist the Description, Interpretation, and Archiving of Paleoseismological Information from Faulted Exposures. *J. Geophys. Res. Solid Earth* 111, 2006JB004267.

THIELE, S.T.; LORENZ, S.; KIRSCH, M.; CONTRERAS ACOSTA, C.I.; TUSA, L.; HERRMANN, E.; MÖCKEL, R.; GLOAGUEN, R., 2021. Multi-Scale, Multi-Sensor Data Integration for Automated 3-D Geological Mapping. *Ore Geol. Rev.* 136, 104252.

Immersive and Interactive 360° Image-Based Tours of for Educational and knowledge transfer Applications

Felix Gross1,2, Jan Oliver Eisermann1,2*, Josephin Wolf2, Jannes Vollert2, Sebastian Krastel1

[1]*Institute of Geosciences, Marine Geophysics and Hydroacoustics, Kiel University, Kiel, Germany oliver.eisermann@ifg.uni-kiel.de,* [2]*Center for Ocean and Society (CeOS), Kiel University, Kiel, Germany*

Key words: *360° Image, marine, digital twin, virtual tour*

While modern 3D computer graphics have significantly advanced, creating fully photorealistic representations of complex environments remains a technical and resource-intensive challenge. Immersive 360° imagery offers a practical and visually accurate alternative by capturing real-world settings. However, traditional 360° images and videos are often constrained to rather static scenarios, limiting user interaction and spatial understanding. To address this, we present a method for constructing interactive virtual tours by capturing a network of 360° images and linking them to form a semi-free, navigable environment.

Our approach enables the development of interactive 360° image tours that simulate a "Google Street View"-like experience, allowing users to explore spaces with a high degree of freedom. These tours are further enhanced through the integration of contextual multimedia elements, including audio, embedded videos, graphical overlays, and descriptive text. This transforms static imagery into an engaging, layered learning experience.

We have applied this methodology across multiple knowledge transfer and educational use cases: virtual research vessel tours to explain shipboard scientific operations, interactive profiles of local fisheries and marine resource users, guided virtual field trips for remote teaching, step-by-step walkthroughs of land-to-sea mapping workflows, and interactive introductions to scientific institutions and laboratories. Each tour is designed for a diverse user groups in mind, ranging from students and educators to policymakers and the general public.

To maximize accessibility and impact, our virtual tours are compatible with a wide range of hardware platforms. These include smartphones and tablets for mobile learning, desktop browsers for classroom use, head-mounted displays (VR) for immersive experiences, and large-scale video walls for use in museum and exhibition settings. This cross-platform adaptability ensures the tours can meet diverse accessibility needs while enhancing user engagement through immersive visualization.

The development process relies on a streamlined workflow involving 360° image capture, spatial planning, and authoring.

Interactive 360° image tours represent a powerful, scalable, and accessible tool for science communication, education, and knowledge transfer. By combining the visual realism of photography with the flexibility of interactive navigation and multimedia content, they foster a intuitive and engaging environment.

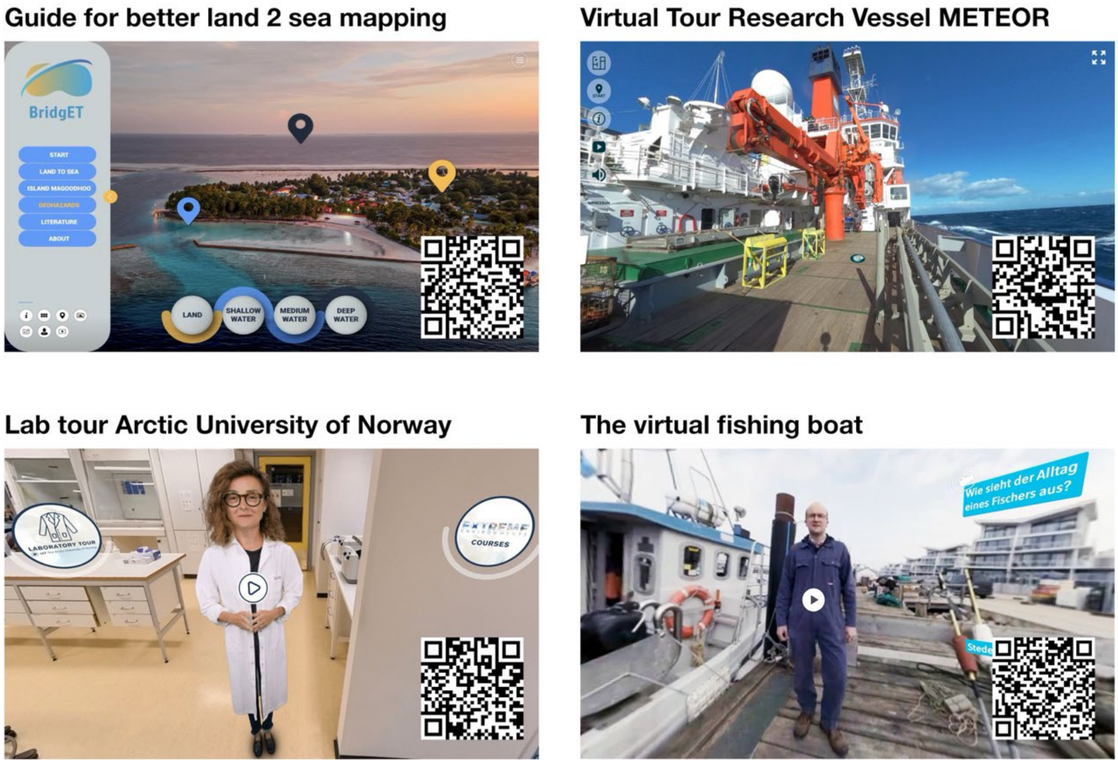

Figure 1: This synopsis delineates a selection of the completed virtual experiences.

Invited Keynote:
Digital Outcrop Modelling for All: A Beginner's Guide

Dr. David Hodgetts
VRGeoscience Limited. UK. david@vrgeoscience.com

Key words: Digital Outcrop Models, Virtual Outcrops, Photogrammetry, Fieldwork

Digital outcrop modelling is a vital tool for geoscientists, enabling high-resolution, spatially accurate, 3D representations of geological exposures. Recent advances in mobile technology and photogrammetric software means that digital outcrop modelling is more accessible than ever and is not just in the domain of well-funded research projects and industrial surveys. This talk offers a practical introduction to digital outcrop modelling for field geologists, students, and educators demonstrating how accurate and georeferenced models can be generated with minimal equipment and limited technical background.

A standard smartphone camera can be used to collect images suitable for photogrammetric processing. Optimal image acquisition strategies in the field will be discussed, including lighting conditions, camera overlap, and coverage techniques. Smartphone camera quality has improved over the years making them the most accessible solution for image collection. The limitations to using smartphone cameras will be presented and it will be demonstrated that modest drone platforms such as the DJI Mini 4 Pro can expand coverage, particularly in inaccessible or vertical outcrop settings.

Ensuring spatial consistency and interpretability is critical, especially when working with minimal equipment. The talk will demonstrate how to introduce scale into models using simple field items (e.g., a ruler), and how to achieve geospatial referencing using a single GPS point and geological orientation data. With the increased availability of high-quality regional elevation model data (for example the Ordinance Surveys 1.0 metre DEM of England and Wales), these too can be used to georeference photogrammetric models through matching topographic features, and/or using iterative closest point alignment techniques. These accessible approaches allow users to align models to real-world coordinates without requiring RTK GPS or total stations.

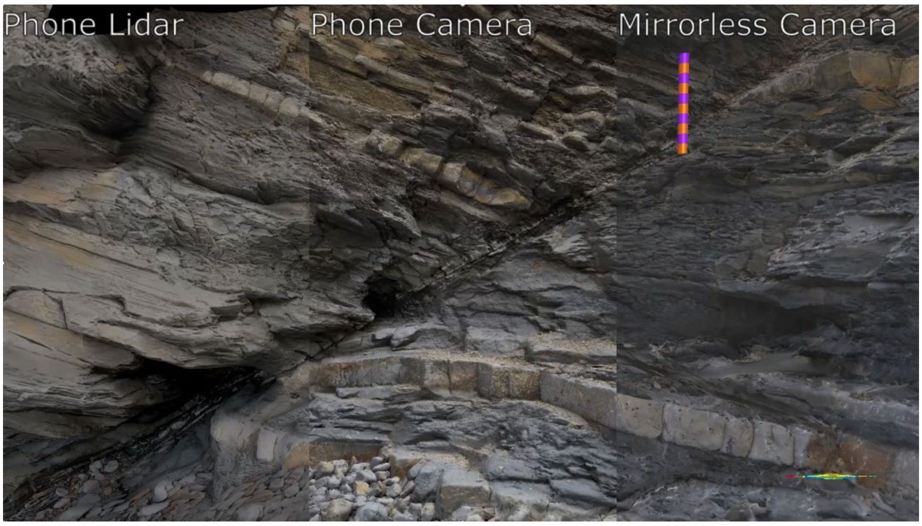

Figure 13: A comparison of 3 models of the same exposure using iPhone lidar, iPhone camera and a Nikon Z7 mirrorless camera. Scale bar is 1.0m.

Lidar-equipped smartphones offer offer a promising level of ease of use for indoor or small-scale outcrop settings. An evaluation will be made of whether their resolution, range, and registration quality justify the added cost particularly since, when properly executed, high-quality photogrammetry is often found to match or out-perform them in outdoor settings.

By focusing on practical, field-based methods and a minimal-tech philosophy, this presentation aims to empower geoscientists to begin generating their own outcrop models immediately. Through real-world examples, it will be shown that digital outcrop modelling is not reserved for experts, but is an accessible, scalable, and powerful tool for all geoscientists.

A Graph Representation for Change Detection in Dutch Coastal Topography using Multi-Annual Aerial LiDAR

Daan Hulskemper[1*], Thomas Dewez[2], José A. Á. Antolínez[3] & Roderik Lindenbergh[1]

[1] *Dept. of Geoscience and Remote Sensing, Delft University of Technology, Delft, The Netherlands, d.c.hulskemper@tudelft.nl*

[2] *BRGM: French geological survey, Orléans, France*

[3] *Dept. of Hydraulic Engineering, Delft University of Technology, Stevinweg 1, 2628 CN Delft, The Netherlands*

Key words: *LiDAR, Change Detection, Coastal Monitoring, Graphs, Medial Axis Transform*

Aerial LiDAR measurements of the Dutch coastal system have been acquired annually for over a decade, resulting in a large and dense dataset of topographic point clouds. This growing dataset holds extensive and detailed information on morphological change of the backshore and foreshore. For example, the temporal variability of dunes, berms, shoals, and sandbars can be assessed, allowing derivation of sediment budgets and transport connectivity along and across the beach and its features. Under changing climate and anthropogenic interventions, change in the interplay between beach feedback processes at several spatiotemporal scales might cause long-term changes in beach and dune morphology (Moore et al., 2025). Thorough study of the time series dataset can improve our understanding and management of these changing processes.

The size of the dataset, however, makes analysis of spatiotemporal variability and connectivity impractical using established methods. Consequently, current analysis is based on cross-sectional profiles sampled at 250–500 m longshore intervals (van IJzendoorn, 2021). Information on the interaction of detailed and local 3D processes is thus lost. To, alternatively, allow for *scale-aware* analysis, the LiDAR datasets should be reduced to a dataset of morphological objects of different scales. By comparing these representations, one can then assess the year-to-year changes.

In this work we investigate how a graph representation of the point clouds can be used to achieve a large-scale analysis of morphological change that incorporates small-scale variations. Our graph representation is based on the Medial Axis transform (MAT, Peters & Ledoux, 2016). The MAT represents an internal surface of the topography from which the geometric attributes describe the shape of the morphological objects they constrain. (Lindenbergh et al., 2025). Ridge points of morphological objects like dunes can be derived through intersection of the MAT surface with the topographic surface. Morphological objects of different spatial scales, e.g. small juvenile dunes vs. large mature dune structures can be assessed through filtering on MAT radii.

It takes three steps to go from the MAT ridge points to a connected graph representation of morphological objects like dunes and bars. First, the ridge points are spatially clustered using DBSCAN, forming groups representing individual morphological features. Second, each cluster is triangulated using Delaunay Triangulation. Third, a minimum spanning tree is computed from the triangulation to build a connected graph linking ridge points within objects.

The graph representation of point clouds of 2017 and 2024 at Hargen in The Netherlands, is visualized in Figure 1. In 2017, the ridges of a single dune (blue) were connected, but by 2024 the bottom ridge of the main dune had grown taller and separated from the others. Meanwhile, an embryonic dune field with several connected ridges developed to the left.

In future work, we will tune and validate this method on a single epoch, and derive descriptive parameters of the graphs, to be compared between years. For example, graph connectivity could reveal the degree to which foredunes or embryonic dunes merge to the main dune. Once useful parameters have been identified, the approach will be applied on the full temporal dataset.

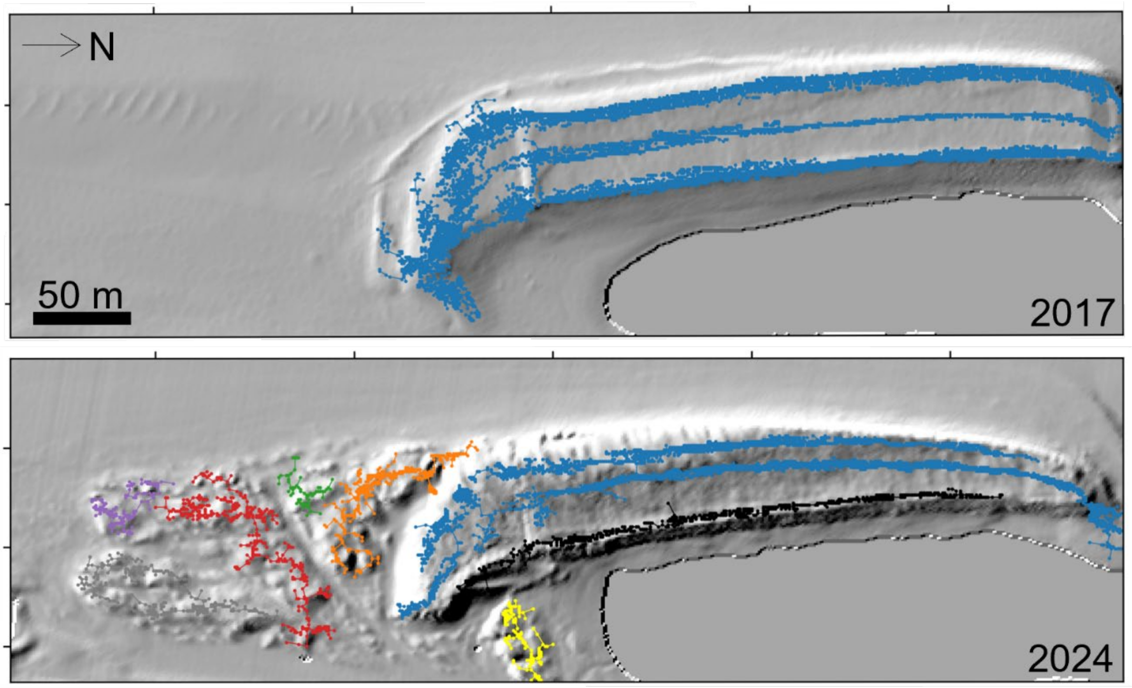

Figure 1: Graph representations of a coastal area in The Netherlands on top of a hillshade (2017, top; and 2024, bottom). Each colour represents a single connected ridge line. Data obtained by Rijkswaterstaat, accessed through GeoTiles (Geotiles, n.d.).

Acknowledgements:

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References

GeoTiles. (n.d.). *GeoTiles – Rijkswaterstaat*. Delft University of Technology. Retrieved May 27, 2025, from https://geotiles.citg.tudelft.nl/

van IJzendoorn, Christa. '*Jarkus Analysis Toolbox: parameter extraction from coastal profiles* (Version 1)', 2021, In: 4TU.ResearchData. https://doi.org/10.4121/C.5335433.V1

Lindenbergh, Roderik, Thomas Dewez, and Daan Hulskemper. 'Assessing 3D Morphological Dune Changes Using Medial Axes', 2025. In: Proc., 6th Joint International Symposium on Deformation Monitoring (JISDM) 7.-9. April 2025, Karlsruhe, Germany pp. 1-8. https://doi.org/10.5445/IR/1000179777

Moore, Laura J, Sally D Hacker, Josh Breithaupt, Sierd de Vries, Thomas Miller, Peter Ruggiero, and Julie C Zinnert. "Ecomorphodynamics of Coastal Foredune Evolution." Nature Reviews Earth & Environment, 2025, 1–16. https://doi.org/10.1038/s43017-025-00672-z

Peters, Ravi, and Hugo Ledoux. 'Robust Approximation of the Medial Axis Transform of LiDAR Point Clouds as a Tool for Visualisation'. *Computers & Geosciences* 90 (May 2016): 123–33. https://doi.org/10.1016/j.cageo.2016.02.019.

Digital Mapping and Virtual Visualization of Klang Cave, Krabi: Integrating Laser Scanning, Smartphone LiDAR, and UAV for Geoscientific Research and Education

Sukonmeth Jitmahantakul[1*], Wonlop Panityayon[2], Pannita Limakara[3], Sakonvan Chawchai[2], Raphael Bissen[4]

[1] *Applied Mineral and Petrology Special Task Force for Activating Research (AMP STAR), Department of Geology, Faculty of Science, Chulalongkorn University, Bangkok, 10330, Thailand, sukonmeth.j@chula.ac.th*
[2] *Department of Geology, Faculty of Science, Chulalongkorn University, Bangkok, 10330, Thailand*
[3] *PTT Exploration and Production, Enco Building A, 555 Vibhavadi Rangist Road, Chatuchak, Bangkok, 10900, Thailand*
[4] *Department of Mining and Petroleum Engineering, Chulalongkorn University, Bangkok, 10330, Thailand.*

Key words: *Terrestrial Laser Scanning (TLS), Cave Mapping, Digital Twin, Karst Geomorphology, Virtual Geotourism, Fracture Analysis*

Klang Cave, located in Krabi Province, southern Thailand, is one of Asia's most visually spectacular karst systems, developed within Permian limestone of the Ratburi Group. The cave extends approximately 370 meters through a network of chambers and passages, accessible via a through-trip from the tourist entrance to the lake-side monastery exit. Given its geological significance and public appeal, this study aimed to develop a high-resolution digital map and immersive virtual representation of Klang Cave to support geoscientific research, geoconservation, and education.

We employed an integrated approach combining terrestrial laser scanning (TLS) using a Leica BLK360, smartphone-based LiDAR, and UAV photogrammetry to overcome the limitations of conventional survey methods in visually and structurally complex cave environments. A total of 148 TLS scans were acquired for the cave interior, complemented by mobile LiDAR in areas with low cave ceilings and UAV imagery for the surrounding karst landscape (Fig. 1). This multimodal dataset enabled the creation of a detailed 3D model and morphometric products, including slope maps, elevation profiles, and cross-sectional analyses of both the cave floor and ceiling.

A key result was the fracture analysis conducted using the 3D ceiling model, supported by field observations at 13 locations (Fig. 2). Two dominant fracture sets trending NE–SW and NW–SE were identified, closely matching the zigzag geometry of the main passage. These orientations are likely influenced by regional tectonics associated with the active Khlong Marui Fault zone. The spatial alignment of stalactites along these fractures suggests structural control on speleothem development and highlights potential rockfall hazards, particularly under seismic activity. These findings underscore the value of 3D mapping not only for structural interpretation but also for hazard assessment and cave conservation planning.

The digital dataset was further utilized to develop a publicly accessible, bilingual virtual cave tour featuring 360° panoramic imagery, embedded narration in Thai and English, and interactive quizzes, available at www.geo.sc.chula.ac.th/klangcave. This platform enhances educational outreach and provides access for users unable to physically explore the site. In addition, local guides can use the detailed cave maps and the online platform as tools to better communicate geological knowledge and safety information to tourists, enriching the geotourism experience through science-based storytelling.

Compared to traditional hand-drawn maps, the digital outputs offer significantly improved spatial accuracy and detail. The workflow developed in this study presents a practical framework for cave documentation and demonstrates how the integration of advanced and accessible technologies can support research, education, and sustainable geotourism through digital twin solutions.

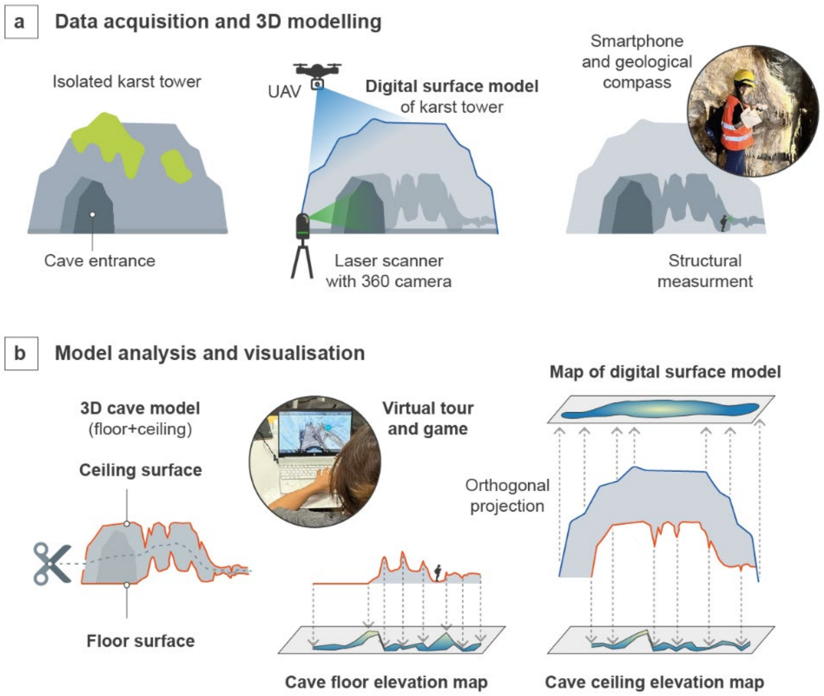

Figure 1: Methodological workflow for digital mapping and analysis of Klang Cave, Krabi. (a) Data acquisition and 3D modelling. (b) Model analysis and visualization.

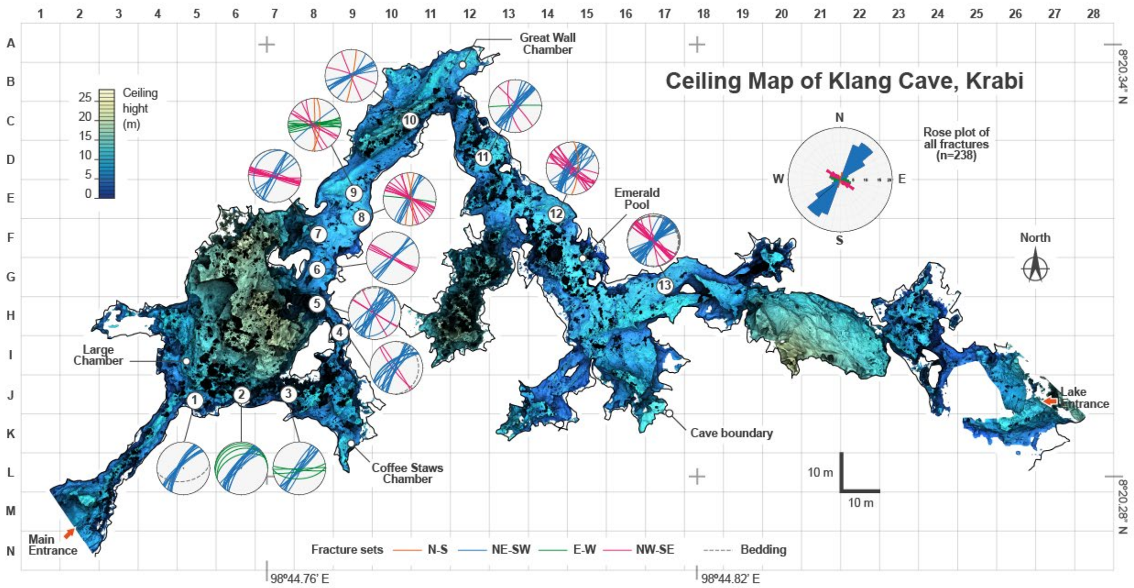

Figure 2: Ceiling map of Klang Cave, Krabi, derived from high-resolution 3D point cloud data. Overlaid rose diagrams show fracture orientations measured at 13 locations throughout the cave, highlighting dominant NE–SW and NW–SE trends.

Acknowledgements: The project was generously supported by the Faculty of Science, Chulalongkorn University (Sci-Super VIII_65_006).

Curlew: Turning outcrops into geological models

Akshay Kamath[1*], Sam Thiele[1], & Richard Gloaguen[1]
[1]*Helmholtz-Zentrum Dresden-Rossendorf, Helmholtz Institute Freiberg, 09599 Freiberg, Germany.*
a.kamath@hzdr.de

Key words: *3D geological modelling, neural fields, data fusion*

Digital outcrop methods have revolutionized geological fieldwork, making detailed spatial information about geological outcrops readily accessible. However, the integration of detailed outcrop models with subsurface datasets, such as borehole logs, geochemical analyses, and geophysical surveys, into cohesive 3D geological models remains a significant challenge. To address this we introduce Curlew, a novel Python-based geological modelling tool that leverages the flexibility and computational efficiency of spatial neural networks to combine diverse datasets into detailed geological models.

In this contribution we present a workflow in which geological horizons delineated from 3D point cloud data using open-source software (CloudCompare) are directly integrated into the geological modelling workflow. Neural fields and Random Fourier Features (as implemented in Curlew) are used to accurately reconstruct geological interfaces and continuous property distributions across the model domain, using only the constraint that the interpolated implicit field should have isosurfaces following the digitised contact traces, and have a gradient direction matching bedding orientation measurements. The loss function optimised by our neural network also allows the addition of physics-based constraints, encouraging conformable and constant-thickness stratigraphy and penalising physically impossible topologies (e.g., “bubbles”) that often result using different interpolation approaches. Finally, we explore several multi-data fusion approaches that could directly access outcrop information (e.g., colour or hyperspectral response) to further adapt the modelled geometry and reduce interpretation bias.

We demonstrate these various features, and the potential use of Curlew geological models for kinematic reconstruction of structurally complex outcrops, using open-source digital outcrop data from Newcastle, Australia (available on AusGeol.org). The resulting model captures several common geological structures, including stratigraphy, a normal fault and a crosscutting dyke. Displacements induced by the fault (Fig. 1) and the dyke are then removed, to reconstruct a pre-deformation digital outcrop model containing only the undeformed stratigraphic units (Fig. 2). To conclude, we suggest that the flexibility afforded by neural field based geological models provides an exciting new approach to geological modelling, and hope that Curlew provides a foundation on which detailed, integrated and time-aware digital outcrop analyses can be conducted.

Figure 1: The original Newcastle point cloud (left, AusGeol.org) and the corresponding un-deformed version of the point cloud (right) with the fault offset removed.

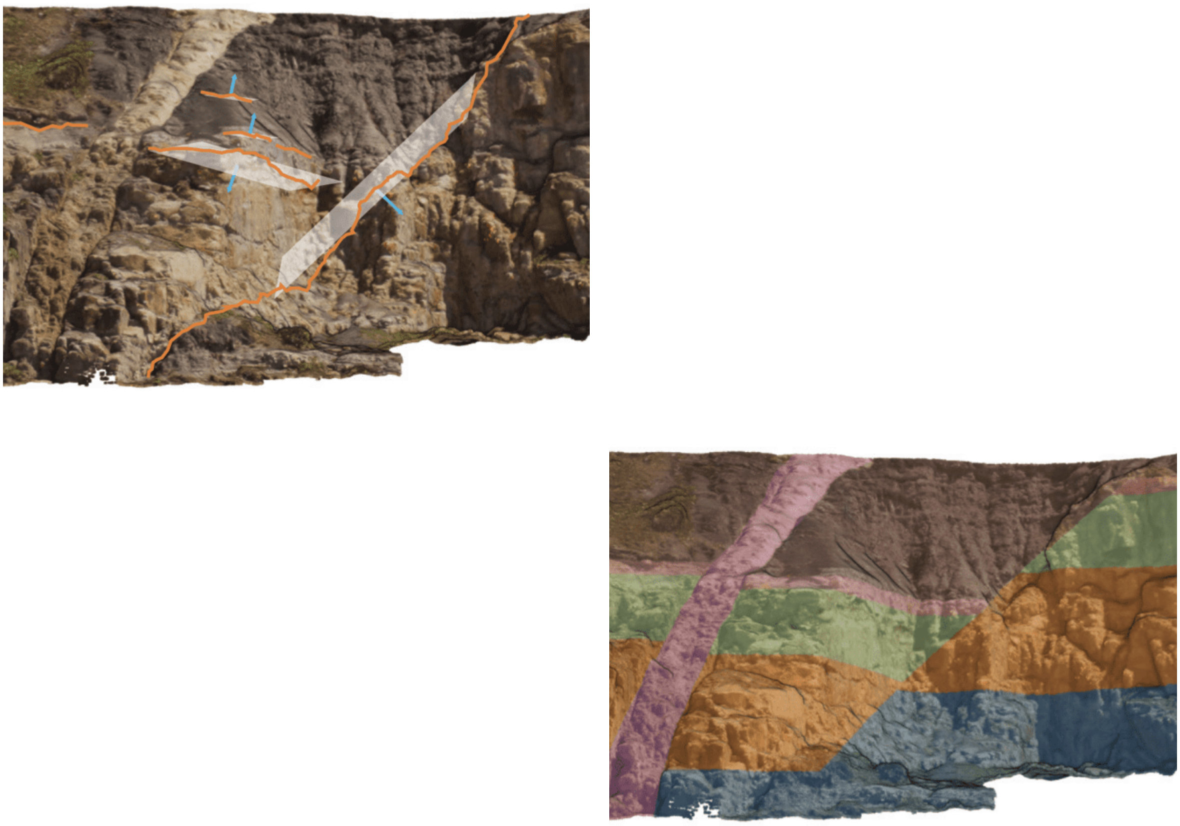

Figure 2: A point cloud of an outcrop from Newcastle, with horizons marked in CloudCompare (left), and the corresponding geological model generated in Curlew (right), superimposed on top of the outcrop.

Hypercloud-enhanced virtual field trips for Geopark outreach

Moritz Kirsch[1*], Sam Thiele[1], Yuleika Madriz[1], Filipa Simões[1], René Booysen[1], Philipp Baumgart[2] & Richard Gloaguen[1]

[1] *Helmholtz-Zentrum Dresden-Rossendorf, Helmholtz Institute Freiberg for Resource Technology, Freiberg, Germany, m.kirsch@hzdr.de*

[2] *GEOPARK Sachsens Mitte e.V., Dorfhain, Germany*

Key words: *virtual field trip, web visualisation, point clouds, hyperspectral, multimedia, geotourism*

Virtual field trips (VFTs) are increasingly used in geoscience education and public engagement to provide immersive access to geologically significant sites. In this contribution, we present a prototype VFT developed with the open-source RockHopper platform (see accompanying abstract by Thiele et al.), demonstrating how digital outcrop models and multimedia content can be integrated to support the outreach goals of geoparks.

Geoparks, whether nationally certified or recognised as UNESCO Global Geoparks, link geodiversity with education, cultural heritage, and sustainable development. In Germany, geoparks such as *Sachsens Mitte* (Central Saxony) offer a wide range of educational formats, including exhibitions, thematic trails, interpretive signage and brochures. Building on this strong foundation, digital tools offer new opportunities to extend engagement through interactive experiences that complement on-site visits and reach broader audiences, including those with limited mobility or geographic access.

At the core of the presented prototype VFT is a “hypercloud”, a photogrammetrically derived 3D model enriched with hyperspectral data attributes, serving as the centerpiece of an immersive virtual exploration of a key geological site. Captured at an outcrop in the Tharandter Forest in Saxony, the model reveals the contact between metamorphic basement schist and rhyolitic volcanic rocks, interpreted as part of the marginal fault zone of the Carboniferous Tharandt Caldera. The spectral and spatial detail of the hypercloud enhances the contrast between visually similar units and offers a scalable view of the outcrop, allowing users to recognise the complex contact relationships that are not easily discernible during direct field observation. The hypercloud is embedded in a 3D-enabled, browser-based environment that also integrates supporting geodata such as geological maps, digital elevation models, photographs and annotated sketches, along with multimedia explanations to guide interpretation and learning.

This example illustrates how RockHopper can be used to develop and deploy multimedia-rich VFTs that support inclusive geoscientific education, broaden public understanding of Earth processes, and strengthen connections between people and their local geological heritage. Designed for scalability and reuse, this approach provides a practical blueprint for geoparks aiming to expand their digital outreach and embrace innovative geo-communication tools.

Immersive Approaches in Geoscience Education: Exploring XR Applications and Student Perspectives

Ryan Kromer1[1*], Suzanne Bickerdike[2], Johanna Fenton[2], Elanor Dufton[2]
[1]School of Earth and Environment,[1, 2]University of Leeds, [*]r.a.kromer@leeds.ac.uk

Key words: *Extended Reality (XR), Virtual Reality (VR), Mixed Reality (MR), virtual outcrop models, immersive learning, virtual field trips, geospatial visualization*

The integration of immersive technologies into geoscience education offers new opportunities to enhance student engagement, geospatial visualization and understanding (JANERAS *et al.,* 2022) and accessibility to diverse geological environments (PUGSLEY *et al.,* 2022). This study presents the development and implementation of a suite of extended reality (XR) learning resources designed for undergraduate geoscience and MSc engineering geology students along with best practices and lessons learned from their application. Modelled sites include geohazards along the Jurassic Coast and geological field areas in the South Pennines, UK. A mixed-methods evaluation of student feedback collected over the past three academic years is also presented.

The XR resources were designed to not only simulate field-based learning experiences, but also to enable experiential exploration of complex 3D geological environments. Teaching formats included small-group collaborative mixed reality (MR) lessons using 3D models constructed from lidar and photogrammetry, and independent, self-paced virtual reality (VR) and web-based VR resources built from 360° imagery, contextual teaching videos, and drone footage.

Students consistently highlighted the value of immersive learning in building confidence, promoting experiential and self-directed learning, and increasing accessibility—particularly when used alongside traditional field experiences. Survey data showed comparable learning outcomes to traditional fieldwork in most categories, though some skills and experiences could not be digitally replicated. While the intention was not to replace fieldwork, immersive tools were found to add value when used in conjunction with them. One student noted: *"Being able to virtually revisit the site allowed me to reconsider some initial assessments that I had made."*

In line with JANERAS *et al.* (2022), quantitative student survey data showed that MR helped students better visualise outcrops and comprehend geological geometry compared to traditional resources such as maps, stereonets, and photographs (see Fig. 1). MR also enabled the integration of multiple data sources (*e.g.,* photos, videos, maps, charts, 3D models), which aided understanding. As one student commented: *"It's a lot easier to organise multiple data sources together for a smoother experience."*

Independent VR resources particularly benefited learners who preferred to work at their own pace, required greater flexibility, and appreciated the ability to revisit areas to reinforce their understanding. In contrast, small-group MR teaching supported students who valued face-to-face interaction with instructors and peers. While VR created from 3D imagery was perceived as more realistic and immersive than 3D-model-based MR, a slight preference for MR was observed, with some students finding it more comfortable. Overall, both approaches can be effectively used to support the diverse needs and learning preferences of students.

Although XR headsets were found to enhance visualisation and immersion, some students experienced discomfort. To address this, web-based VR versions were provided as an accessible alternative allowing students to review resources in their own time. MR sessions were also supported by screen projection and the option to join via non-headset device using a digital avatar.

This work offers practical insights for educators seeking to integrate XR into geoscience curricula, underscoring its potential to provide inclusive, flexible, and engaging learning experiences that enhance both learning outcomes and student experience.

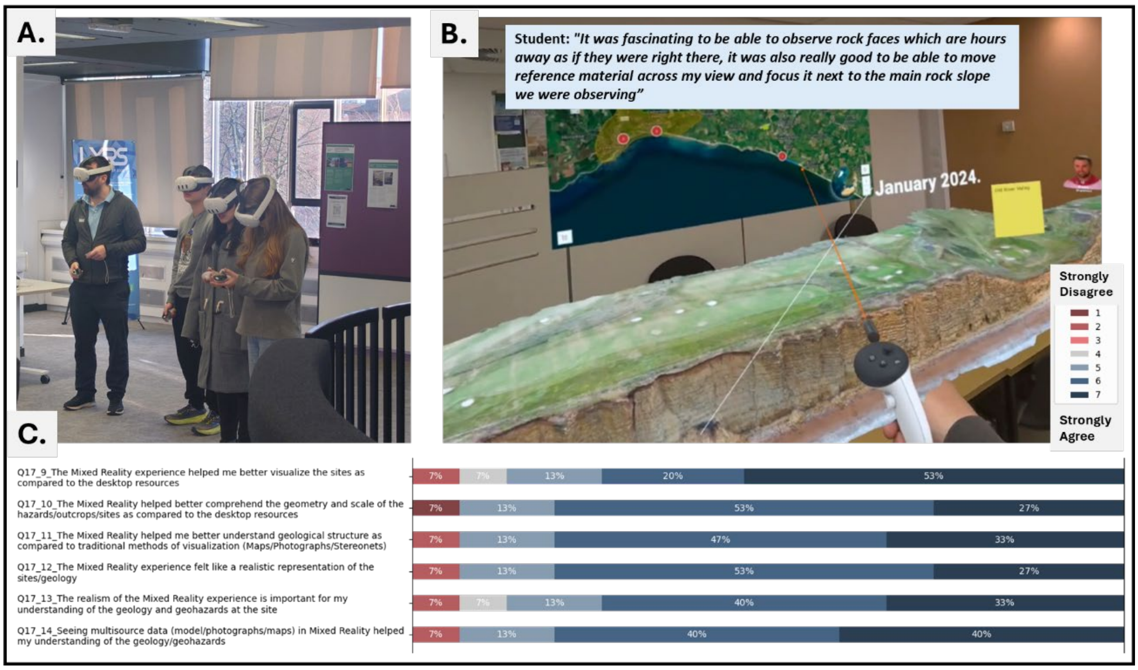

Figure 1: Student engagement with XR in geoscience education. A. Small group MR teaching session. B. Visualising 3D geological outcrop and integrated data in MR. C. Survey responses (n = 15) indicating strong agreement that MR enhanced visualization, comprehension of geological geometry, and understanding of geohazards through realistic and multisource representations.

Acknowledgements: This research was funded by the Leeds Institute of Teaching Excellence (LITE) and received ethical approval by the Faculty Research Ethics Committee for Business, Environment, and Social Sciences at the University of Leeds. Learning resources were created with the help of Jason Williams, Buena Galleposa, Matthew Wilson, Ben Pierce. Classroom XR teaching was supported by Ed Wilson Stevens and Liv Huett.

References

Janeras, M., Roca, J., Gili, J.A., Pedraza, O., Magnusson, G., Núñez-Andrés, M.A. & Franklin, K., 2022. Using mixed reality for the visualization and dissemination of complex 3D models. geosciences—application to the Montserrat massif (Spain). *Geosciences*, 12(10): 370.

Pugsley, J. H., Howell, J. A., Hartley, A., Buckley, S. J., Brackenridge, R., Schofield, N., Maxwell, G., Chmielewska, M., Ringdal, K., Naumann, N., & Vanbiervliet, J., 2022. Virtual field trips utilizing virtual outcrop: construction, delivery and implications for the future. *Geoscience Communication,* 5(3): 227–249.

Towards a coherent 3D geological model of the Swiss Jura: methods, challenges and future perspectives

Eva Kurmann [1], Salomè Signer [1], Anina Ursprung [1]
[1] *Swiss Geological Survey, Seftigenstrasse 264, CH-3084 Wabern (eva.kurmann@swisstopo.ch)*

Key words: *3D geological modelling, fold-and-thrust belt, potential for implicit modelling*

The Swiss Geological Survey is developing a coherent 3D geological model for the Swiss part of the Jura (Internal and External Folded Jura) northwest of the Swiss Molasse basin to the national borders with France and Germany. The objective is to produce a 3D geological model that aligns with the geological maps at the surface and provides a consistent interpretation of the subsurface geology. To achieve this, Jura3D comprises of three key components (see figure below): a network of geological profiles (fence diagram, 1-2 km spacing), modelled fault surfaces (fault model) and a fully modelled reference horizon surface (horizon model 'Top Dogger').

At surface, the main input data for Jura3D comes from the geometrically harmonised vector data of the Geological Atlas of Switzerland (1:25,000 scale). In contrast, subsurface data remain heterogeneous due to a lack of comprehensive harmonisation efforts in the past. This includes geological profiles, well data, and geophysical surveys, which require careful integration—particularly in relation to the tectonic evolution of the fold-and-thrust belt.

A coherent tectonic interpretation and a consistent kinematic framework are essential for building a reliable geological 3D model of the Jura. Therefore, an overall tectonic concept was developed and is continuously refined as well as adapted to detailed mapping at the surface. This conceptual refinement goes hand in hand with the step-by-step densification of the geological fence diagram, which provides the foundation for the detailed modelling of the fault surfaces and the modelled 'Top Dogger' horizon surface.

With the completion of the first model area, a harmonised and structured dataset is now available for further development. Currently, the model comprises three explicitly constructed components: a fence diagram, fault surfaces, and a reference horizon. Apart from the reference horizon, continuous modelling of remaining stratigraphic horizons between the cross-section of the fence diagram is still missing.

The existing model components are geometrically consistent and conceptually aligned, providing a solid foundation for developing implicit modelling workflows. When combined with geological contacts from surface maps and dip measurements, the available dataset can be used to construct continuous 3D geological horizons.

This opens the door for testing implicit modelling techniques in a structurally complex setting. Is the dataset too complex or extensive for these methods? Or might its level of consistency and structure currently be favourable for generating continuous 3D surfaces or volumes? We are keen to examine the potential of implicit workflows and to assess whether they could enhance or optimise existing modelling strategies.

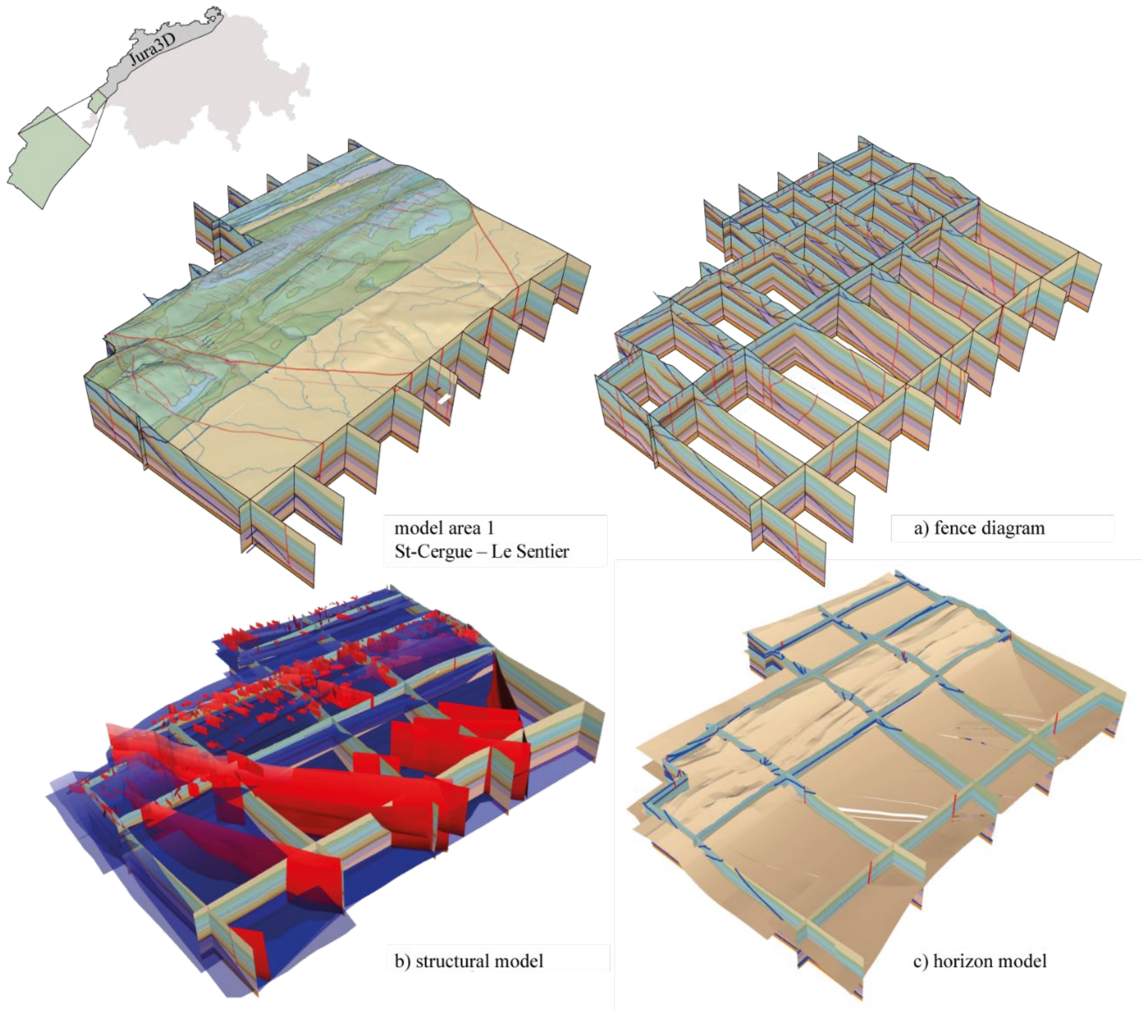

Figure 1: The 3D geological model Jura3D consists of a fence diagram (a); for reasons of visibility, only 13 of the 40 sections of the model are shown here, accompanied by the fault model (b) and the modelled surface of the Top Dogger horizon (c).

34-Yrs of Satellite-based Monitoring of a Slow-moving Retrogressive Landslide in Central Nepal.

Léo Letellier1*, Simon Daout1, Jérôme Lavé1 & Nicolas d'Oreye de Lantremange2
[1] Univ. of Lorraine, CNRS, CRPG, F-54000, Nancy, France, leo.letellier@univ-lorraine.fr
[2] European Center for Geodynamics and Seismology, L-7256, Walferdange, Luxembourg, Luxembourg

Key words: *Pixel Tracking, Slow Moving Retrogressive Landslide, Central Nepal*

Himalayan mountain ranges are affected by numerous small to medium-sized landslides, and erosion products are dominated by material issued from unweathered bedrock (MORIN ET AL., 2018). A specific type of landslide affects old destabilized hillslopes over hundreds of meters. The material of these panels is intensely fractured and has lost its cohesion. Several of these slopes moves at rates of several tens of mm/year, with some accelerating during or just after an earthquake or during the monsoon periods. Disentangling the spatio-temporal complexity of the activity of those slow (<m/yr) regressive landslides requires to investigate their evolution in the past. In addition, such landslides have been rarely considered in mountain range erosion contribution, to the contrary to rapid landslides.

In this study, we use satellite-based methods, that include Digital Surface Models (DSMs) generations and pixel-tracking on optical and radar archives to document over 34 years the 3D displacements and erosion contribution of the Bolde landslide in central Nepal.

The data set comprises high-resolution (0.7m) Pleiades optical images (acquired in 2016, 2019, 2021 and 2025), Sentinel-2 medium resolution (10m) optical data, and radar images from ERS, Envisat, and Sentinel-1 (pluri-metric resolution in range and decametric in azimuth) missions. High resolution imagery (Pleiades) is acquired on request only, thus only a small amount of archive is available. To the contrary, Sentinel 1 and 2 medium resolution images are freely available with systematic acquisitions since 2014 with a return time of about 6 days. Processing methods leverage on the Ames Stereo Pipeline (ASP) software (ALEXANDROV ET AL., 2024), which provides various algorithms and disparity resolution of about 1/10th of a pixel. Radar images are coregistrated using AMSTer software.

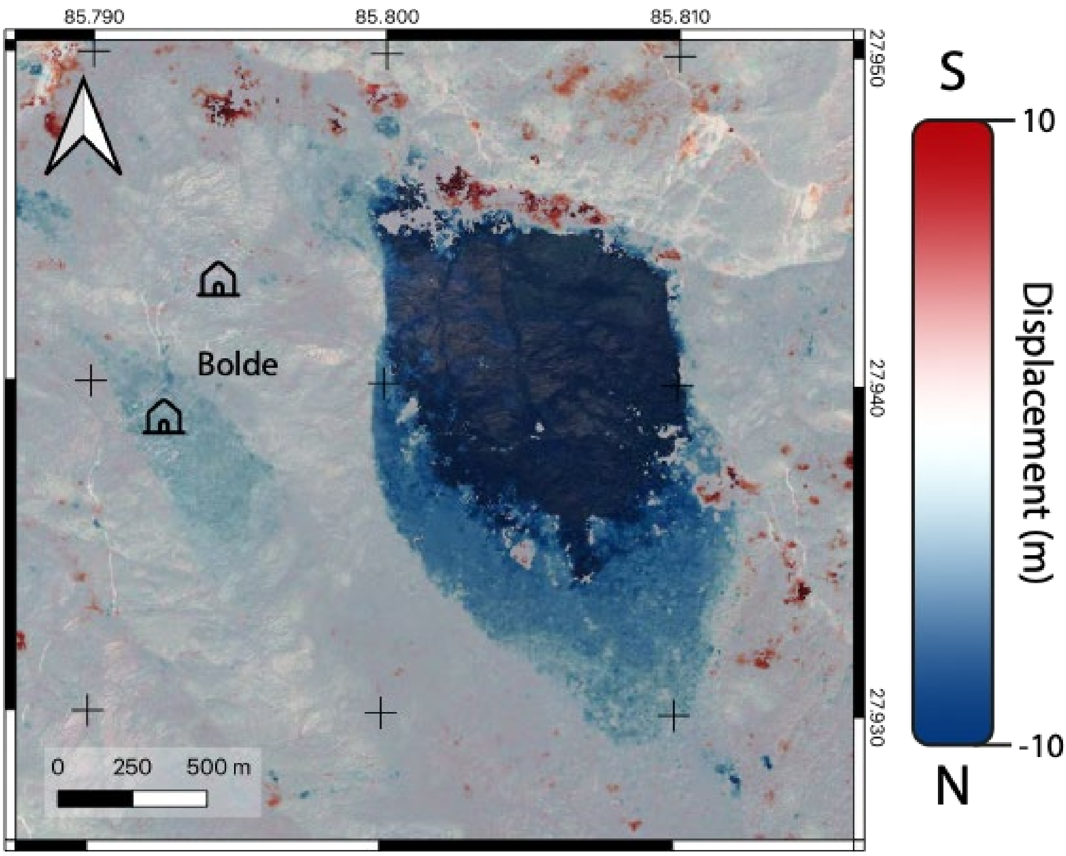

Figure 1: North to South Pleiades displacement over the Bolde village between 2016 and 2025

Pleiades' disparities show large displacement over the Bolde village and neighbouring farming fields, with displacement ranging from 0.27 m/y to 1.11 m/y to the North and divided into separate blocks (Fig 1). In addition, sharp gradients of displacement correspond to cumulative scarps that can be observed in the field and on satellite images. By integrating the displacement at the river interface, a flux of 1.99e5m^3/y of material is estimated, equivalent to a drainage basin of 70km^2 by considering a mean erosive rate of 3mm/y. Sentinel 1 and 2 images allow identification of this landslide for multi-year baselines but without morphological details, enabling large-scale periodic monitoring. This permits to monitor monsoon and earthquake induced accelerations, including during the 2015 Gorkha Mw7 earthquake. Historical movement activities since 1992 are retrieved using ERS and ENVISAT images. The anisotropy of the pixel of full resolution radar images hinders the proper functioning of pixel tracking algorithms and mitigation possibilities are being investigated.

Acknowledgements: The Pleiades images were provided by the Incitation à l'utilisation scientifique des images Spot (ISIS) program from Centre national d'études spatiales (CNES) (https://dinamis.teledetection.fr). The authors thanks ESA for providing open-source access to the Sentinel missions archives. This study was founded by the ANR SLIDE.

References

ALEXANDROV OLEG, MCMICHAEL SCOTT, BROXTON MICHAEL, LUNDY MIKE, BEYER ROSS, HUSMANN KYLE, EDWARDS LARRY, … & LAURA JAY. (2024). NeoGeographyToolkit/StereoPipeline: ASP 3.4.0 (3.4.0). Zenodo. https://doi.org/10.5281/zenodo.12176190

MORIN, G.P., LAVÉ, J., FRANCE-LANORD, C., RIGAUDIER, T., GAJUREL, A.P. & SINHA, R., 2018. Annual Sediment Transport Dynamics in the Narayani Basin, Central Nepal: Assessing the Impacts of Erosion Processes in the Annual Sediment Budget. JGR Earth Surface 123, 2341–2376. https://doi.org/10.1029/2017JF004460

Fault reactivation during the 2024 Southwest Rift Zone eruption using photogrammetry survey

Stefano Mannini1*, Joël Ruch 2, Marc Henri Derron1, Nicolas Oestreicher 3, Ryan Perroy4

[1] ISTE – Institute of Earth Sciences, University of Lausanne, Geopolis 3793, 1015, Lausanne, Switzerland, stefano.mannini@unil.ch
[2] Department of Earth Sciences, University of Geneva, Geneva, Switzerland, joel.ruch@unige.ch
[3] WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland, Nicolas.oestreicher@slf.ch
[4] Department of Geography and Environmental Science, University of Hawai'i at Hilo, Hilo, HI 96720, USA, rperroy@hawaii.edu

Key words: *photogrammetry, GPS, imagery correlation, dike*

On June 3, 2024, a fissure eruption occurred on the south-western flank of the Kīlauea volcano caldera on Big Island, Hawaii. The eruption is the first to occur in the area in 50 years, following the 1971 and 1974 eruptions. The 2024 event was preceded by multiple dike intrusions in November 2023 and February 2024, which did not reach the surface. However, the repeated intrusions have reactivated numerous fractures, affecting an area approximately 12 km by 2 km. These surface fractures are linked to magma propagation originating from the caldera and extending down-rift, and are part of a large flank instability of the Kīlauea volcano.

In September 2024, we conducted a photogrammetric survey of the newly fractured area. We used a photogrammetry platform fixed beneath an aircraft with two high-resolution cameras (Fig. 1) connected to an on-board Global Navigation Satellite System (GNSS).

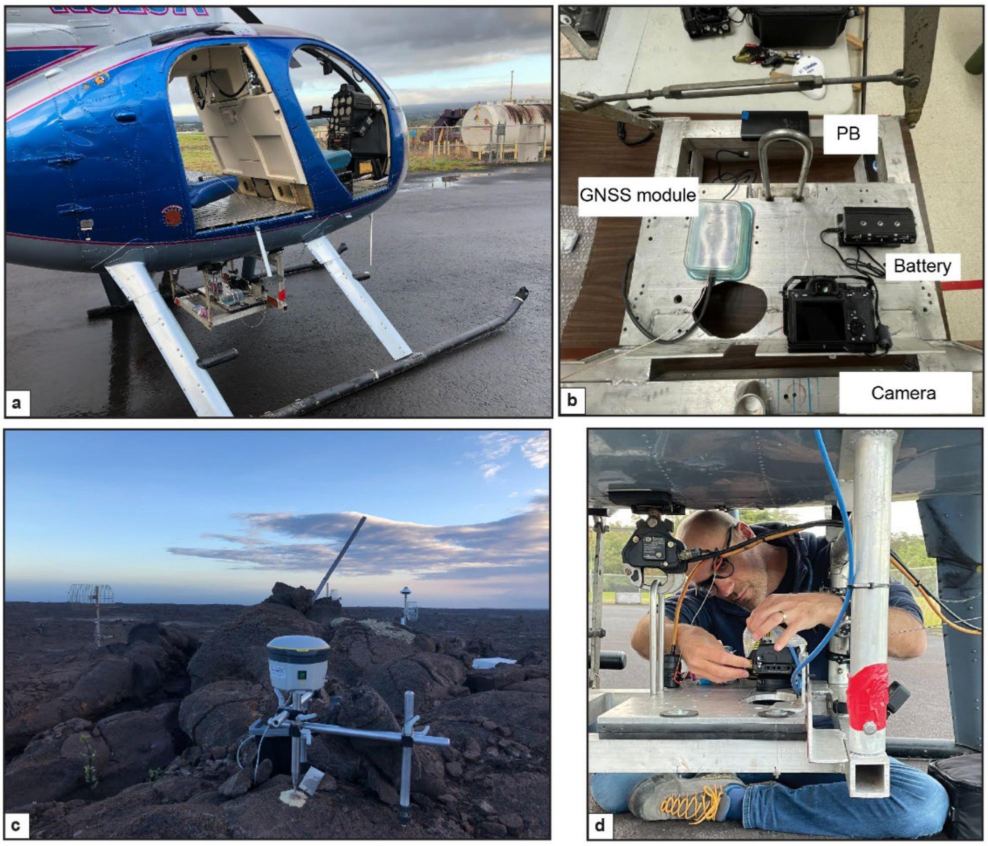

Figure 1: Photogrammetry platform showing the instruments located below the helicopter and the GPS used for the post-processing correction

Approximately 2300 images were acquired, covering an area of ~20 km^2. Multiple continuously operating GPS base stations managed by the USGS, which collect data at 1 Hz, were used to correct the GPS information acquired on board the helicopter. Additionally, several markers were strategically positioned within the flight polygon and measured with the Emlid kGPS high precision (Fig. 2). We used two Emlid modules, one configured as a base and the other as a rover (Fig. 2). This setup allowed us to obtain real-time GPS measurements, which were subsequently corrected to improve positional accuracy. Base station precise point positioning (PPP) is based on collecting 8 hours of raw data, processed by the Natural Resources of Canada Spatial Reference System service. Surveys consist of occupation by rover kGPS units for 30 seconds and corrected using the static base station position to correct for errors of position. Their coordinates were corrected using the same continuously operating GPS base stations. This integration of accurately positioned control points significantly enhanced the overall precision of the model.

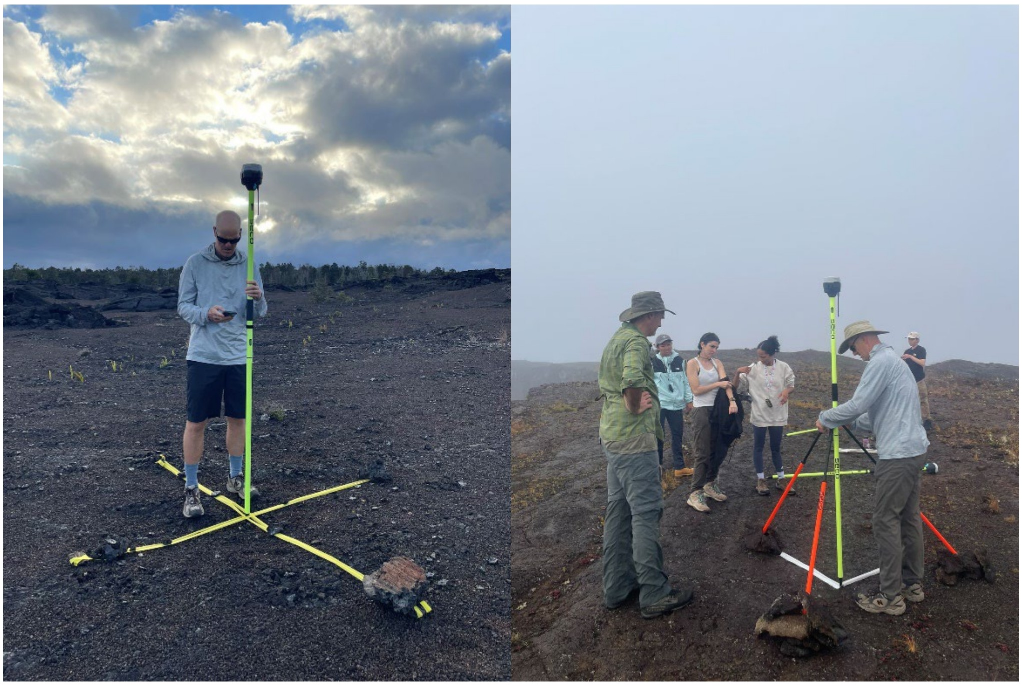

Figure 2: Example of marker measured in the field using the module Emlid. Rover on the left and base on the right.

Using this imagery, we generated high resolution orthomosaics and DEMs (~4-10 cm GSD). We combined this new dataset with a previous survey we conducted in the same area in February 2022 using the same setup. By correlating both orthophotos and DEMs, we quantified the vertical and horizontal displacements using different software tools such as COSI-Corr and MicMac. Results show the formation of new structures as well as the reactivation of pre-existing fractures providing new insights into near-field deformation and faulting processes during a rifting event.

Acknowledgements: we would like to thank the USGS, University of Hilo and our pilot David Okita for supporting us during our missions.

Optimising Facies Interpretation Using Neural Networks on Images and Photogrammetric Data: A Case Study from Salta (Argentina)

J. Marchini[1*], E. Roemers-Oliveira[1,3], S. Viseur[1], I. Gomes-Goncalves[2], F. Guadagnin[2], A. C. Freccia[2], G. Rangel[2], G. Pederneiras Raja Gabaglia[3], F. Fournier[1]

[1] *Aix-Marseille University, CNRS, IRD, Collège de France, INRAE, CEREGE, UMR7330, Avenue Louis Philibert, 13545, Aix-en-Provence, France, viseur@cerege.fr*

[2] *Universidade Federal do PAMPA, Caçapava do Sul, Brazil*

[3] *Petrobras – Petróleo Brasileiro S.A, Rio de Janeiro, Brazil*

Key words: *CNN, Photogrammetry, Labelling, optimisation, time-efficiency, evaluation*

The interpretation of sedimentary facies in outcrop analogues provides valuable insights for characterising subsurface reservoirs, particularly when integrated with high-resolution imaging and deep learning methods. This study aims to evaluate the application of Convolutional Neural Networks (CNNs), specifically a U-Net architecture, for pixel-wise lithofacies classification from photogrammetric images of two well-exposed outcrops, Assado and Vapumas, located in the Salta Basin (Argentina). This work relies on a workflow whose effectiveness has already been demonstrated in (Guadagnin et al., 2025; Roemers-Oliveira et al., under review) and which combines acquisition of images, manual interpretation, CNN-based automatic labelling, and 3D lithofacies point cloud generation.

A series of tests were conducted to evaluate the performance of this CNN-based workflow while trying to reduce the most time-consuming steps and minimise the reliance on expert manual labelling. The testing strategies included modifications to input image resolution, number of epochs, expansion of the training dataset, changes in the geological interpretation, and data augmentation. The limited reproducibility of the CNN algorithm was mitigated by fixing the seeds of the random number generators, enabling comparative analysis of performance metrics across the same set of training images under multiple test configurations.

To apply the CNN algorithm, photo labelling was required. A small subset of the total image dataset (~500 per outcrop) was manually interpreted by generating one image mask per facies within each photo (Fig. 1). The labelled dataset comprises 49 images for Assado and 31 for Vapumas, with lithofacies classes defined based on *prior* sedimentological and stratigraphic studies.

Good results were achieved, with 83% overall accuracy for Assado using a training set comprising 10% of the full image dataset, and 84% for Vapumas using just 7% of the total dataset.

As a result, optimal resolution and number of epochs versus running time have been determined in this work. Moreover, it was first demonstrated that a CNN model using a dataset with raw images combined with brightness, contrast, and colour equalised across the entire training dataset enhances results without requiring new labelling. This highlights the importance of the developed approaches, as manual interpretation is the most time-consuming expert task associated with the workflow presented in this study. Secondly, the facies classification may also have an impact on results. Facies can vary gradually, and it is not always easy to group hybrid facies into coherent sets. In this work, several facies association groupings were tested to determine which produced the most effective results, while being consistent with the reservoir application of this study.

Finally, point clouds coloured by predicted lithofacies enabled the visualisation and parametrisation of geological bodies in 3D Digital Outcrop Models (DOMs), confirming the consistency of spatial patterns with known stratigraphy (Fig. 2). Figure 2 shows the first 3D facies mapping of the Vapumas outcrop.

Despite positive results, challenges remain, including sensitivity to class imbalance. Future works includes cross-outcrop model transfer, i.e., applying a CNN trained on one outcrop to another with similar facies.

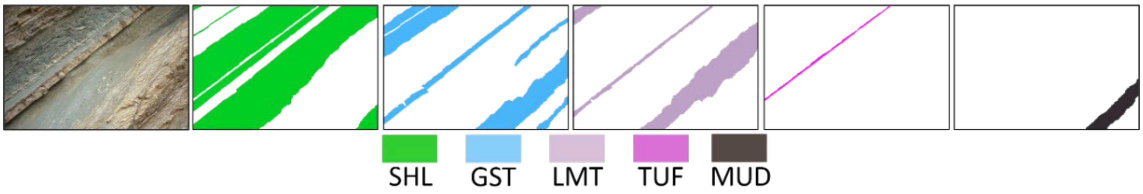

Fig. 1. Example of mask export for CNN training. Each lithofacies present in the outcrop image is exported as a separate binary mask, corresponding to a specific label class used in the supervised learning workflow.

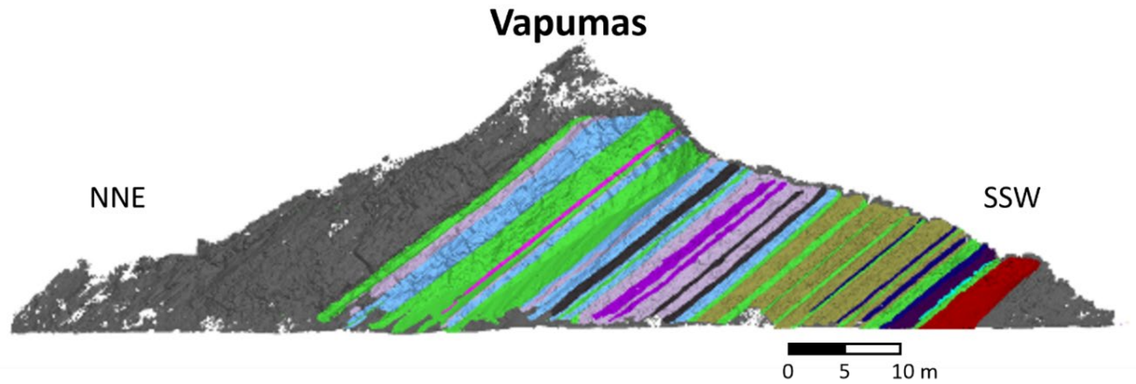

Fig. 2. 3D point cloud generated for the Vapumas outcrop. Lithofacies were grouped and coloured in CloudCompare, using the same colour code applied in the CNN. The point cloud was also manually edited.

References

Guadagnin, F., Gonçalves, I.G., Roemers-Oliveira, E., Guedes, P.L., Souza, E.G., Silveira, M.M.L., Raja Gabaglia, G.R., Gonçalves, L.A., Oliveira, L.F.R., Selk, R., 2025. Building of classified 3D point clouds of outcrop with automatically segmented images. Geodata and AI.

Roemers-Oliveira, E., Viseur, S., Fournier, F., Gonçalves, I.G., Guadagnin, F., Raja Gabaglia, G.R., Bento Freire, E., Fragoso, D.G.C., Freccia. A. C., Rangel. G. G., n.d. Advanced digital techniques applied to outcrop models: Integrating LBP and CNN to support stratigraphic and sedimentological interpretation of reservoir analogs in the Salta Basin, Argentina. Mar Pet Geol.

Lightweight Machine Learning Models for Automatic Water Detection in 3D Airborne LiDAR Point Clouds

Enzo Marrec[1*], Xavier Pellerin Le Bas[2], Laurent Froideval[1], Christophe Conessa[1]
[1] Normandie Univ, UNICAEN, UNIROUEN, CNRS, M2C, France : enzo.marrec.auditeur@lecnam.net
[2] Scienteama, 4 av. de Cambridge 14200 Hérouville-St-Clair, France
24 Rue des Tilleuls, 14000 Caen

Key words: *3D, Point Cloud, Machine Learning, Airborne LiDAR, Coastal monitoring.*

The classification of LiDAR point clouds remains a time-consuming task, particularly in large-scale geospatial projects. This study presents the development of lightweight machine learning (ML) models for the automatic identification of water bodies in 3D airborne LiDAR datasets in coastal environments. Implemented using CloudCompare and cLASpy_T, our approach avoids the computational overhead of deep learning, making it accessible for use and understanding on standard desktop environments without high-end GPU requirements.

cLASpy_T is an open-source software designed for supervised classification tasks along with CloudCompare processing. It enables users to train, validate, and apply classification models on point clouds using well-established algorithms such as Random Forest, Gradient Boosting and light Neural Network (Multi-Layer Perceptron), with a simple interface. Its compatibility with multiple input formats and flexibility in feature selection made it a key tool in this study (PELLERIN LE BAS *et al., 2024*).

The decision to not use deep learning was motivated by practical considerations: standard ML models require less data for training, less computational power, are faster to train, and offer more transparent decision-making processes. This makes them particularly suitable for integration into lightweight workflows, without sacrificing classification quality.

Initially trained on airborne LiDAR data provided by the M2C laboratory, the models are meant to be broadly applicable, distinguishing between water and non-water zones with high accuracy. This method significantly reduces manual classification time, offering a scalable solution for both research and industrial applications. This work demonstrates the potential for efficient, user-friendly machine learning tools to accelerate geospatial analysis and support wider adoption of automated classification workflows in the geoscience community. The first results lead to 95% precision and 86% recall on water field. Manual corrections and validations are still required; indeed, the goal of these models is to reduce the time dedicated to manual classification not to be an autonomous process.

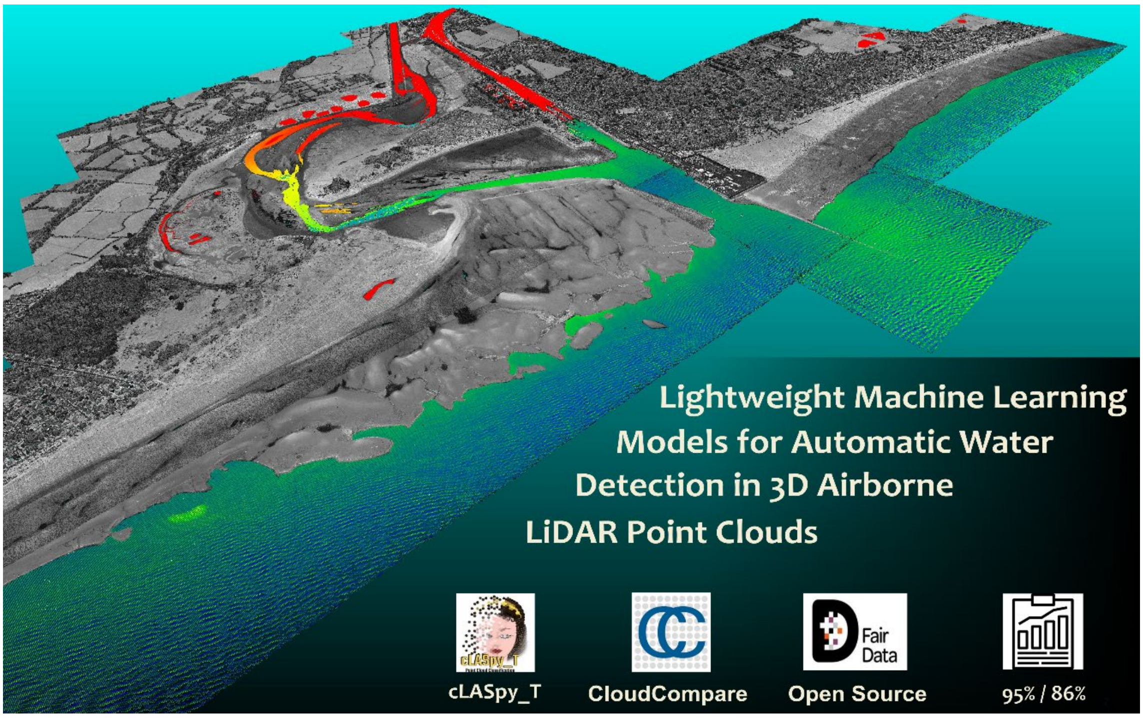

Figure 1: Water detection on the Orne's estuary LiDAR point cloud

Beyond its initial application, the model is now being adapted for use with LiDAR HD (IGN), a more general and increasingly common LiDAR data. This step ensures the classifier's usability across a wider range of environments and acquisition platforms. A critical advantage of the model lies in its reliable detection of non-water classes, not just water bodies. This reinforces its value in broader classification tasks where accurate exclusion of water features is equally important.

References

P. Bretel, O. Monfort, L. Froideval, S. Vallée, L. Benoit 2024. Mesure topographique par LiDAR aéroporté et Modèle Numérique Terrain de l'estuaire de l'Orne du 18/10/2013. *SNO DYNALIT*. https://doi.org/10.12770/f801d0b6-1170-45e7-be6a-15389a9d60a0

L. Froideval, O. Monfort, L. Benoit, Y. Bonte 2015. Mesure topographique par LiDAR aéroporté et Modèle Numérique Terrain de l'estuaire de l'Orne du 03/06/2015. *SNO DYNALIT*. https://doi.org/10.12770/93c7ba76-9a65-4144-8802-acb86343cc47

L. Froideval, C. Conessa, O. Monfort, L. Benoit 2022. Mesure topographique par LiDAR aéroporté et Modèle Numérique Terrain de l'estuaire de l'Orne du 11/08/2022. *SNO DYNALIT*. https://doi.org/10.12770/7b323484-c578-4cf6-b89c-dfc1e08c6d6b

X. Pellerin Le Bas, L. Froideval, A. Mouko, C. Conessa, L. Benoit, L. Perez 2024. A New Open-Source Software to Help Design Models for Automatic 3D Point Cloud Classification in Coastal Studies *Remote Sensing* 16, no. 16: 2891. https://doi.org/10.3390/rs16162891

Low-angle normal fault systems: insights from the digitalized fossil distal Adriatic margin in SE Switzerland

Leïla Morzelle[1], Peter Betlem[2], Geoffroy Mohn[1] & Julie Tugend[1].

[1]CY Cergy Paris Université, Sorbonne Université, CNRS-INSU, Institut des Sciences de la Terre de Paris, ISTeP, F-95000 Cergy, leila.morzelle@cyu.fr; [2]NGI, Norwegian Geotechnical Institute, Oslo, Norway

Key words*: Digital Outcrop Models (DOM), Low-angle normal fault (LANF), Alps.*

Low-angle normal faults (LANFs), characterized by dips of less than 30°, are frequently observed in rifted margins. Despite extensive research, their mechanical behavior (initiation angle, evolution, three-dimensional geometry, and deformation in the hanging-wall and footwall) remains poorly constrained. Addressing these issues is essential for appraising resource potential in sedimentary basins and understanding extensional processes, including continental crust thinning and mantle exhumation in rifted margins.

The Err and Bernina extensional detachment systems, preserved within the lower Austroalpine nappes of the Central Alps, offer a rare natural laboratory to study LANFs. Formed during the Jurassic rifting in the distal Adriatic rifted margin of the Alpine Tethys, these LANFs are exceptionally well-preserved despite the subsequent deformations from the Alpine Orogeny (MOHN *et al,* 2012 ; EPIN & MANTSCHAL, 2018). Modern digital technologies offer significant potential to preserve these seismic-scale outcrops digitally (BURNHAM et al, 2024) and integrate them with seismic data across present-day system, opening new perspectives and insights into the evolutionary mechanisms of LANFs, an approach that remains largely underexplored yet is highly valuable to resource exploration.

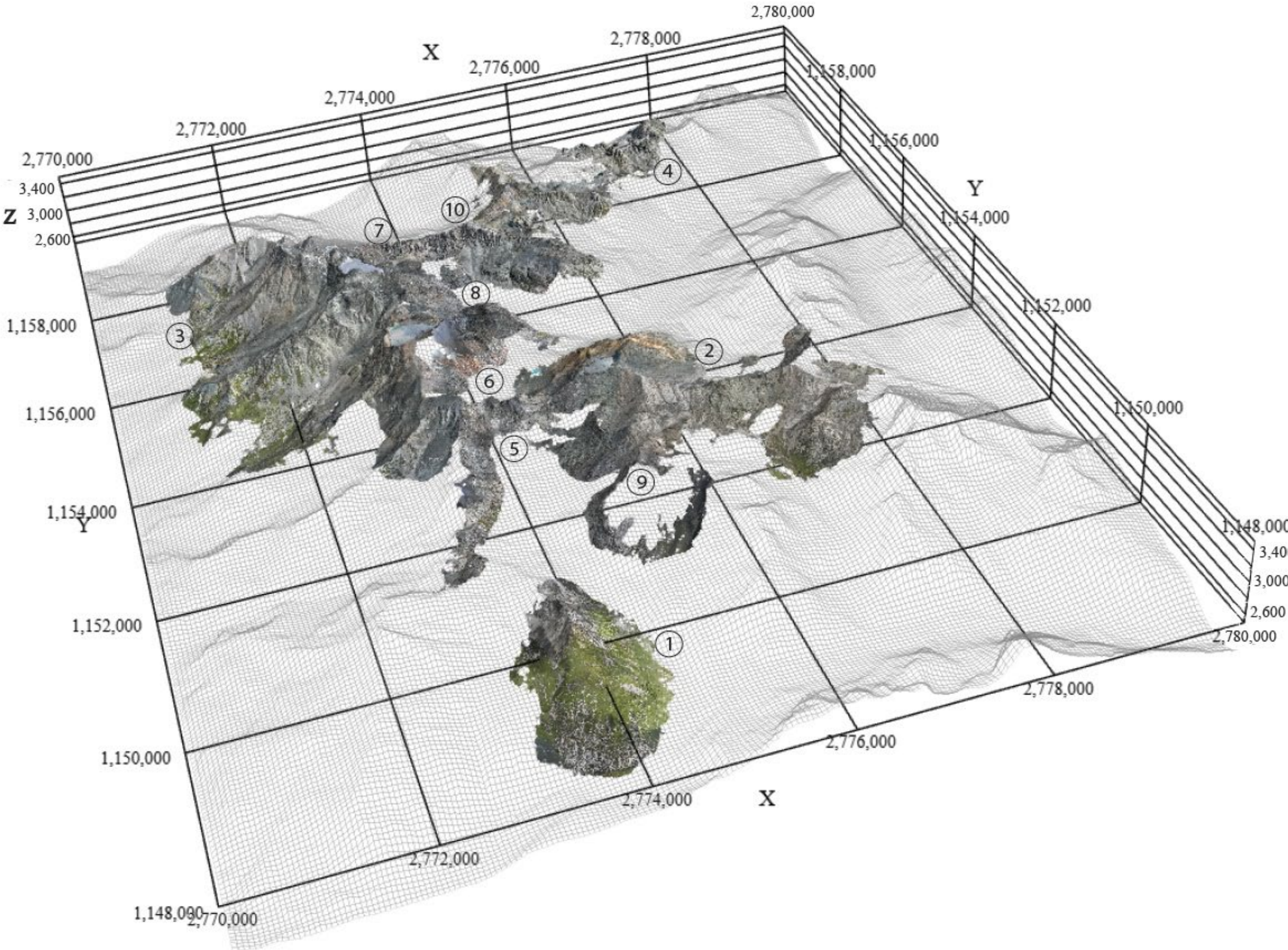

Figure 1: Spatial extent and visualisation of the digital outcrop models of the Err nappe. Numbers refer to the different models, including the Laviner and Jenatsch model (10) detailed in Fig. 2.

This study presents results from extensive field campaigns (2022 to 2024), during which high-resolution data were collected over a ~100 km² area (Fig. 1) using Unmanned Aerial Vehicle (UAV) surveys supplemented by field mapping (BETLEM et al, 2023). Rigorous quality control and processing (Fig. 2) ensured the generation of 3D high-resolution Digital Outcrop Models (DOMs) of the Err and Bernina extensional detachment systems. We implemented differential positioning and SwissTopo terrain data to obtain absolute spatial errors in line with available DEM data. The DOMs allow us to resolve centimetre to decimetre-scale details and facilitate mapping of the spatial evolution of LANFs as well as the tectono-sedimentary architecture of the overlying extensional allochthonous blocks. Detailed interpretations reveal their internal structure, including lithological changes, and the extent of fracture, fault networks, and deformation patterns at various scales. Not least, the large extent covered by the DOMs allows us to characterize the sedimentary basins formed during the Jurassic extension and integrate observations at a scale not previously possible, shedding light on their development and spatial relationships with the detachment systems. Finally, this work forms an important contribution to the development of 4D evolutionary models of LANFs that are key to explain deformation structures and important for subsurface resource exploration, including mineral deposits, hydrogen, geothermal energy, and subsurface storage.

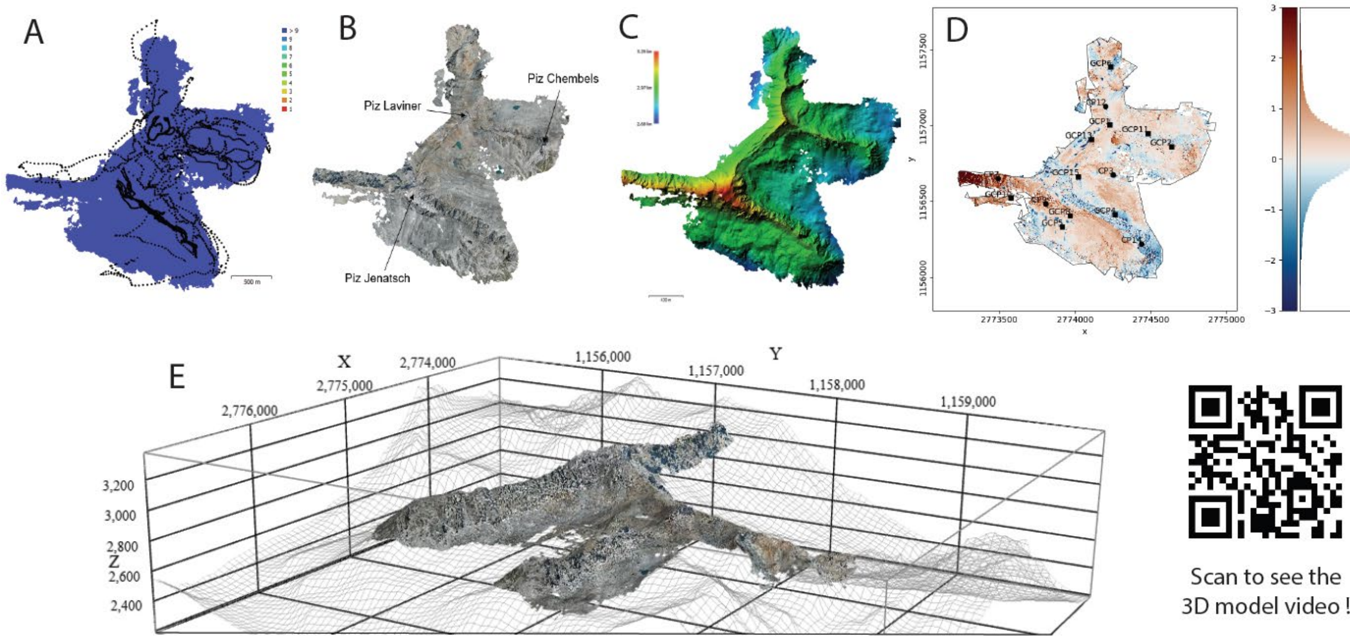

Figure 2: The Laviner and Jenatsch model (10). A. Camera location and image overlap. B Orthomosaic. C. Digital Elevation Model (DEM). D. DEM comparison map based on the reference SwissALTI3D DEM, with control points, and the histogram of deviation distribution. E. Digital Outcrop Model (DOM).

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References

BETLEM, P., MOHN, G., TUGEND, J., & MANATSCHAL, G., 2023. High-resolution digital outcrop models of fossil-rifted margins: 3D imaging of extensional detachment systems. *First Break*, Volume 41, Issue 5, p. 31 – 40.

BURNHAM, B. S., BOND, C. E., FLAIG, P. P., VAN DER KOLK, D. A., & HODGETTS, D., 2022. “Outcrop Conservation: Promoting Accessibility, Inclusivity, and Reproducibility through Digital Preservation.” *The Sedimentary Record* 20 (1): 5–14.

EPIN, M.-E., & MANATSCHAL, G.,2018. Three-dimensional architecture, structural evolution, and role of inheritance controlling detachment faulting at a hyperextended distal margin: The example of the Err detachment system (SE Switzerland). *Tectonics*, 37, 4494–4514.

MOHN, G., MANATSCHAL, G., BELTRANDO, M., MASINI, E., & KUSZNIR, N., 2012. Necking of continental crust in magmapoor rifted margins: Evidence from the fossil Alpine Tethys margins. *Tectonics*, 31, TC1012.

Building a large-scale model of the Central European Alps: challenges and opportunities

Ferdinando Musso Piantelli[1*], Eva Kurmann[1], Philip Wehrens[1], Pauline Baland[1], & Herwig Müller[1]

[1] *Federal Office of Topography swisstopo, Swiss Geological Survey, Seftigenstrasse 264, 3084 Bern, Switzerland*
ferdinando.mussopiantelli@swisstopo.ch

Key words: *Alpine regions, Large-scale 3D geological modelling*

The Swiss Geological Survey (SGS) is the competence centre for the subsurface and georesources of the Swiss Confederation. Between 2024 and 2030, the SGS is leading the Swiss Alps 3D (SA3D) project, which consists of eight modelling and research projects involving several universities. The aim is to develop a consistent, large-scale underground 3D geological model of the main contacts and structures of the Swiss Alps. This model will serve as a regional framework for future higher resolution 3D models, enabling a wide range of applications in infrastructure planning, groundwater studies, natural hazard assessment, education and research.

The purpose of this contribution is to present and discuss the challenges that must be confronted, as well as the opportunities that such a large-scale modelling project can offer.

The two main challenges of 3D modelling in Alpine regions are the lack of subsurface data (e.g., seismic and borehole data) and the complexity of the geological systems to be modelled. These challenges also limit the modelling techniques (implicit vs explicit) that can be employed to construct such large-scale models. Furthermore, the aim of building the SA3D model through eight independent projects requires significant coordination and collaboration between modelling teams to ensure that the model is technically and conceptually consistent.

On the other hand, modelling 3D network of structures and lithostratigraphic contacts of mountain ranges provides valuable insights into the still largely unexplored subsurface of these regions. This opens many doors to many opportunities. Indeed, the characterization of large-scale 3D fault patterns is relevant for understanding at the regional scale the effects of tectonic preconditioning on the distribution of natural hazards and meteoric water penetration and upflow in orogens. This has important implications for example in the establishment of underground policies and regulations, in regional-scale hazards mitigation, for the exploitation of thermal anomalies in orogenic geothermal systems, as well as for the evaluation of the influence of meteoric water on the seismicity of regional faults. Furthermore, the development of a large-scale, consistent model, built by eight research projects, will promote the establishment of a collaborative scientific community in the field of Alpine geology and 3D geological modelling.

Towards an Automated Change Detection Workflow for Rockfall Monitoring with PyRockDiff

Oriol Pedraza[1*], Xabier Blanch[2], Antonio Abellán & Marc Janeras[1]
[1]*Institut Cartogràfic i Geològic de Catalunya (ICGC), Parc de Montjuïc, 08038 Barcelona, Spain,*
**oriol.pedraza@icgc.cat*
[2] *Department of Civil and Environmental Engineering, Universitat Politècnica de Catalunya (UPC), Marañón 44-50, 08028 Barcelona, Spain*

Key words: *Rockfall monitoring, change detection, multitemporal point cloud.*

Quantitative hazard analysis of rockfalls is a fundamental tool for sustainable risk management, particularly in areas where a balance must be struck between the preservation of natural heritage and public safety. This is especially relevant in locations such as the Montserrat Massif and the Castellfollit de la Roca cliff (Spain), where the Cartographic and Geological Institute of Catalonia (ICGC) is currently conducting monitoring activities using remote sensing techniques and a geotechnical instrumentation network, as part of rockfall risk mitigation projects.

After more than 15 years of LiDAR monitoring across 10 stations, with 120 scans and over 1,000 detected rockfall events, it has been possible to establish a magnitude–frequency (M-F) relationship at each site. This relationship correlates the magnitude of potential rockfall events with their probability or temporal frequency of occurrence, based on historical activity (JANERAS *et al.*, 2023). The resulting dataset has been processed by the RISKNAT research group at the University of Barcelona (UB), on behalf of the ICGC, using a methodology and criteria developed through several doctoral theses (ABELLÁN, 2009; ROYÁN, 2015; BLANCH, 2022).

With the aim of incorporating new monitoring sites and generating new activity inventories in different geological contexts—obtaining the new M-F scenarios—it was deemed necessary to enhance the change detection workflow for identifying rockfall events (ABELLÁN *et al.*, 2011; PEDRAZA *et al.*, 2022), to streamline processes and reduce time requirements. These improvements have been developed within the framework of a GitHub project named *PyRockDiff*, building upon the recent advances proposed in BLANCH *et al.*(2022).

This project presents a Python-based pipeline designed to automate the comparison of two 3D point clouds—specifically of rock surfaces—by combining functions from CloudCompare and the Open3D library (ZHOU et al., 2018). The workflow begins with essential preprocessing steps, including data cleaning and vegetation removal, to prepare the datasets for analysis. It then applies algorithms for fast global registration and Iterative Closest Point (ICP) alignment, enabling accurate change detection between epochs.

The software detects surface changes using the M3C2 algorithm, isolates spatial clusters through the DBSCAN algorithm, and calculates the volumes of detected changes using alpha-shape triangulation. At this stage, manual validation of the identified clusters is still required to confirm whether they correspond to actual rockfall events. This validation process is supported by high-resolution panoramic images (Gigapixel) captured with a Gigapan system during each scan (Fig. 1).

For the next stages of developement, it is expected to incorporate additional functionalities, such as artificial intelligence for vegetation filtering and erroneous cluster detection (BLANCH *et al.*, 2020), as well as the integration of tools developed in the *py4Dgeo* project.

Initial results demonstrate that the tool is capable of efficiently processing large datasets and it's a good starting point for geologists specialising in geomatics. Furthermore, it supports flexible integration with existing workflows for rockfall identification. The use of open-source libraries and software enables improvement and promotes collaborative development. Achieving this level of automation enables professionals to offload repetitive manual tasks and focus their expertise on those that still require human judgement—particularly final validation—thus paving the way for broader and more systematic monitoring strategies.

Acknowledgements: We acknowledge the RISKNAT research group at the University of Barcelona and the doctoral researchers for laying the groundwork that currently enables automated rockfall detection.

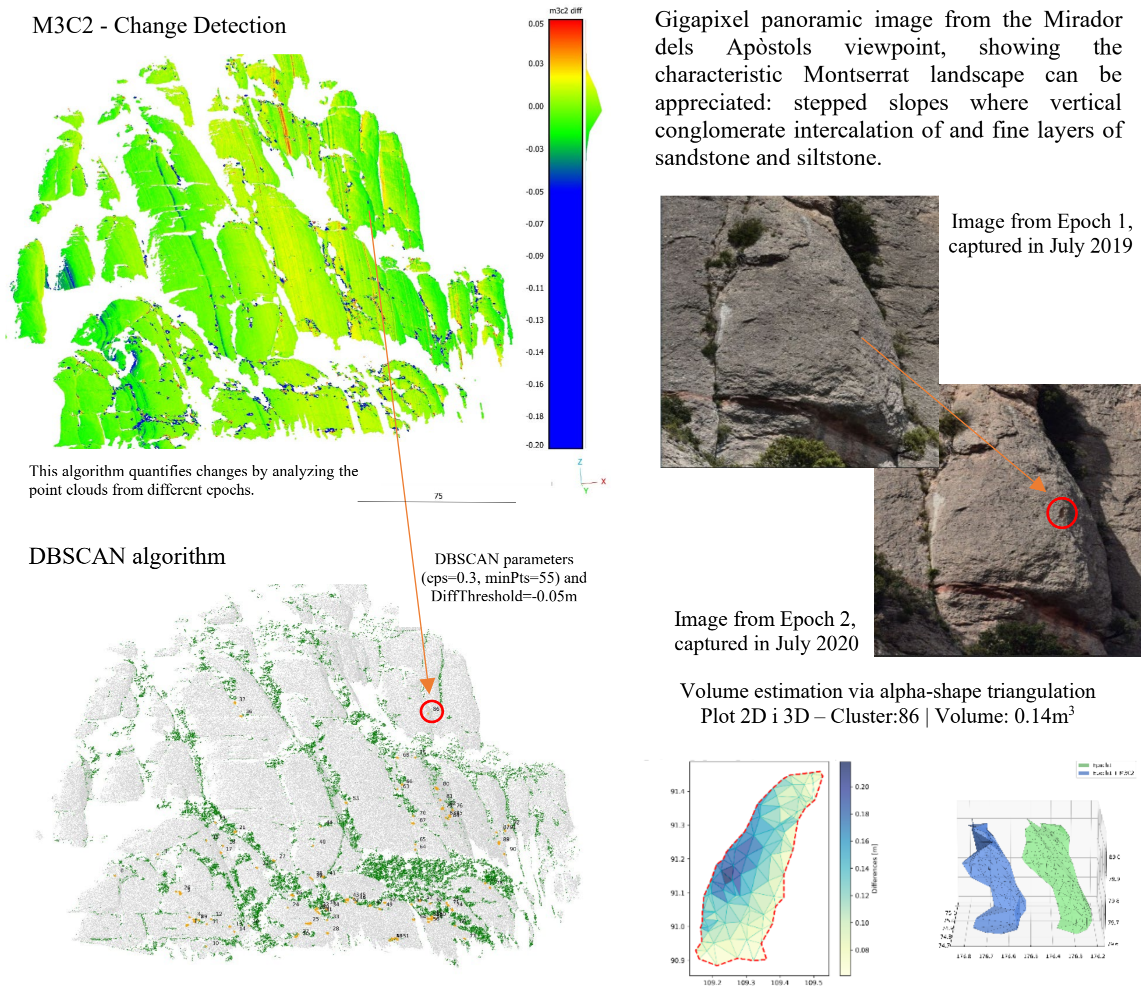

Figure 1: This is an example of the change detection workflow for rockfall monitoring using PyRockDiff.

References

ABELLÁN, A. 2009. Improvements in our understanding of rockfall phenomenon by Terrestrial Laser Scanning - Emphasis on change detection and its application to spatial prediction. PhD Thesis, Vilaplana (Adv.) Universitat de Barcelona

ABELLÁN, A.; VILAPLANA, J.M.; CALVET, J.; GARCÍA-SELLÉS, D.; ASENSIO, E. 2011. Rockfall monitoring by Terrestrial Laser Scanning—Case study of the basaltic rock face at Castellfollit de la Roca (Catalonia, Spain). *Nat. Hazards Earth Syst.* Sci. 11, 829–841.

BLANCH, X. 2022. Developing Advanced Photogrammetric Methods for Automated Rockfall Monitoring. PhD Thesis, Guinau & Abellán (Adv.) Universitat de Barcelona

BLANCH, X.; ABELLAN, A.; GUINAU, M. 2020. Point cloud stacking: A workflow to enhance 3D monitoring capabilities using time-lapse cameras. *Remote Sensing*. 12, 1240.

JANERAS, M., LANTADA, N., NÚÑEZ-ANDRÉS, M. A., HANTZ, D., PEDRAZA, O., CORNEJO, R., GUINAU, M., GARCÍA-SELLÉS, D., BLANCO, L., GILI, J. A., PALAU, J. 2023. Rockfall Magnitude-Frequency Relationship Based on Multi-Source Data from Monitoring and Inventory. *Remote Sensing*, 15(8), 1981.

PEDRAZA, O., ARONÉS, Á. P., PUIG, C., JANERAS, M., GILI, J. A. 2022. Rockfall monitoring: comparing several strategies for surveying detached blocks and their volume, from TLS point clouds and GigaPan pictures. *5th Joint International Symposium on Deformation Monitoring (JISDM)*, Valencia.

PYROCKDIFF: https://github.com/xabierblanch/PyRockDiff.git

PY4DGEO: https://github.com/3dgeo-heidelberg/py4dgeo

ROYÁN, MJ. 2015. Rockfall characterization and prediction by means of Terrestrial LiDAR. PhD Thesis, Vilaplana (Adv.) Universitat de Barcelona.

ZHOU, Q.-Y., PARK, J., & KOLTUN, V. 2018. OPEN3D: A Modern Library for 3D Data Processing. *arXiv preprint* arXiv:1801.09847

Using mobile LiDAR and 2D shape analysis to capture the geometric diversity of karst conduits

Tanguy Racine1*, Celia Trunz1, Julien Straubhaar1, Philippe Renard1

[1] *Centre for Hydrogeology and Geothermics, University of Neuchâtel, Switzerland, tanguy.racine@unine.ch*

Key words: *LiDAR, geomorphology, cave mapping*

In karst landscapes, the formation of voids through the dissolution of limestone occurs across many spatial scales. Over time, speleogenetic processes lead to the formation and reorganisation of networks of conduits and focus the majority of water flow and modulate the dynamics of solute and particle transport. Empirical physical flow and transport laws require an estimate of geometric parameters such as a scaled ratio of conduit section area and perimeter i.e. the hydraulic diameter and the average size of obstacles to flow i.e. the roughness. The first can be computed from the topometric data of traditional cave surveys, while the second is usually sampled from a range of plausible values. One fundamental challenge in modelling flow in karst is the representation of the complex three-dimensional geometry of conduits. There are two key requirements to address this challenge: 1) a robust method for generalising the complex 3D surface of a karst conduit to a hydraulically equivalent 1D conduit 2) reality-based probability density functions for the various geometric descriptors that may be ascribed to model conduit elements in network flow simulations.

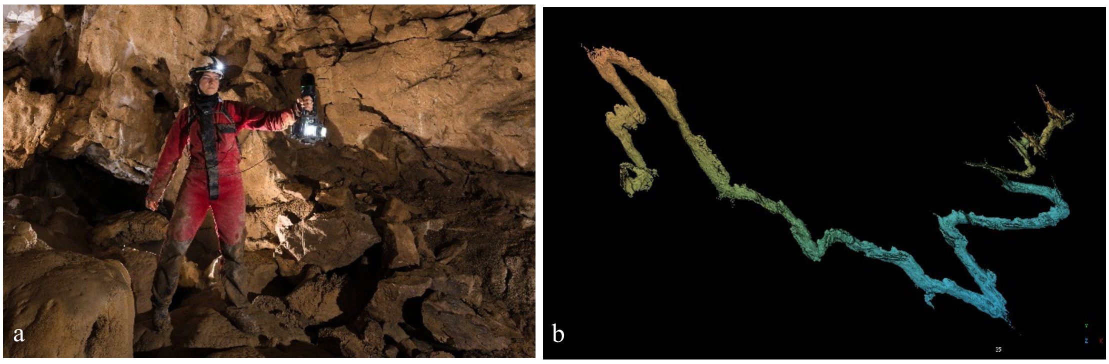

Figure 1: a) Mobile laser scanning of cave conduits using the Leica BLK2GO device (Tanguy Racine) b) Point cloud of a typical tortuous cave passage geometry (Lauiloch, Switzerland)

We acquired first the detailed geometry of a series of real karst conduits located in Switzerland, France and Slovenia, using mobile LiDAR scanning technique. We selected a subset of hydrologically active cave passages from various karst massifs and put together a KarstConduitCatalogue (Racine et al., 2025), available at: https://doi.org/10.60544/sbjr-z851. To describe these cave passages in a systematic geometric fashion we computed first a triangulated mesh and second a centreline i.e., an approximation of the curve skeleton of the 3D surface. We then calculated a series of intersections between planes perpendicular to the centreline and the mesh surface and performed a detailed shape characterisation of each resulting polyline using known 2D morphology. We present the first order statistics on the distributions of 2D shape descriptors for over 5 km of cave centreline. We also treat the descriptor values along the centreline coordinate as 1D signals and compile correlation length and variogram ranges for the descriptors, which we contrast with existing compilations of cave geometric data. We finally investigate to correlations between the various profile shape indicators through Principal Component Analysis.

Acknowledgements: We are thankful for the critical help of many local speleologists for their contribution in collecting the data in the various caves. We also acknowledge funding by the European Union (ERC, KARST, 101071836).

References

Racine, T., Trunz, C., Straubhaar, J., Jaillet, S., and Renard, P. (2025). KarstConduitCatalogue: a dataset of LiDAR derived point clouds for the analysis of karstic conduit geometry and morphology. *Earth System Science Data Discussions*, 2025:1–28.

Spatial Gaussian Mixture Model for Geological Predictive Mapping

Herbert Rakotonirina [1*], Théophile Lohier [1], Julien Baptiste[1], Hélène Tissoux [1]
[1] *BRGM French Geological Survey, 3 Av Claude Guillemin, Orléans, h.rakotonirina@brgm.fr*

Keywords: *Predictive Mapping, Machine Learning, Gaussian Mixture Model, Unsupervised Learning*

Predictive mapping is a cornerstone task in geoscience, aiming to identify the spatial distribution of geological features or resources based on indirect or partial observations. It plays a critical role in exploration, environmental assessment, and risk management. Traditionally, supervised machine learning methods have shown promise in this domain, but their performance strongly depends on the availability of labeled training data, a significant limitation in geoscientific contexts where ground truth is sparse or expensive to obtain.

To address this, unsupervised learning approaches such as Gaussian Mixture Models (GMMs) offer a compelling alternative by discovering hidden structures in the data without the need for labeled samples. GMMs model the data as a mixture of Gaussian components, each representing a latent cluster with its own mean and variance. However, standard GMMs only consider the attribute space and ignore spatial relationships, which are crucial in geological systems that often exhibit strong spatial coherence

In this study, we propose a novel spatial extension to GMMs that enhances predictive mapping by incorporating spatial context. Our method adjusts the posterior probabilities of a classical GMM by averaging them over a sliding window across the spatial domain, thereby integrating local neighborhood information while preserving the probabilistic nature of the model. We evaluate the approach on synthetic datasets characterized by clear spatial patterns. Comparative results against classical GMM, classical Kmeans and two state-of-the-art spatial GMM variants (ZHAO *et al*., 2016; ZHOU *et al.,* 2020) demonstrate the superior ability of our method to produce geologically plausible and spatially consistent predictions.

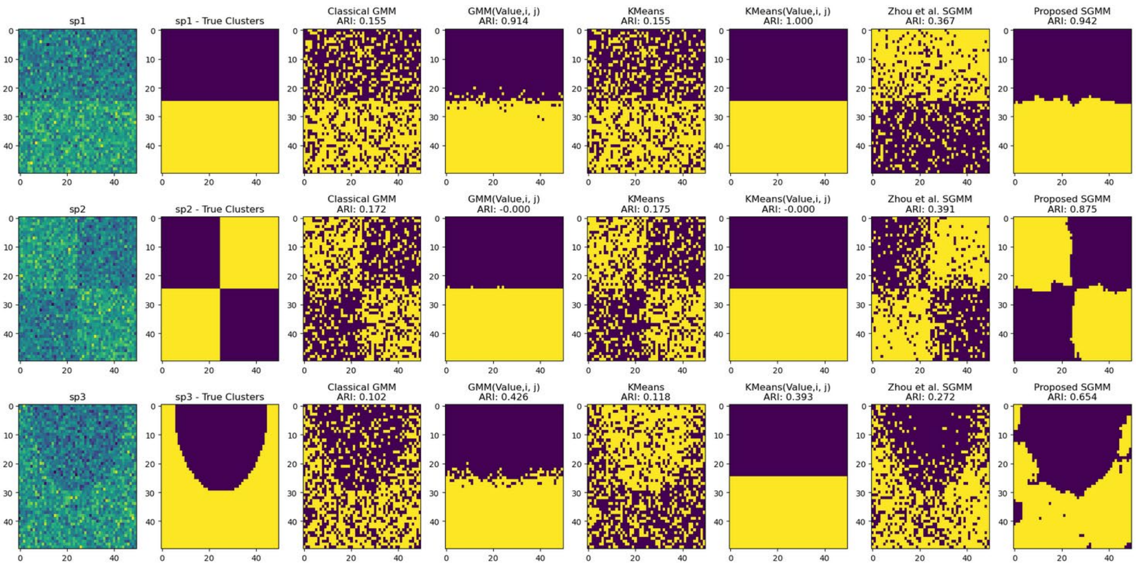

Figure 1: Clustering results on three synthetic spatial datasets (sp1, sp2, sp3). Each row shows the input data, ground-truth clusters, and results from six methods: classical GMM, GMM on (value, i, j), KMeans on values, KMeans on (value, i, j), Zhou et al.'s spatial GMM, and the proposed spatial GMM. Adjusted Rand Index (ARI) scores indicate clustering accuracy. The proposed method better preserves spatial structure and achieves higher ARI scores overall.

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References

B. Zhao, Y. Zhong, A. Ma and L. Zhang, "A Spatial Gaussian Mixture Model for Optical Remote Sensing Image Clustering," in IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, vol. 9, no. 12, pp. 5748-5759, Dec. 2016, doi: 10.1109/JSTARS.2016.2546918

Zhou, S., Bondell, H., Tordesillas, A., Rubinstein, B. I. P., & Bailey, J. (2020). EARLY IDENTIFICATION OF AN IMPENDING ROCKSLIDE LOCATION VIA A SPATIALLY-AIDED GAUSSIAN MIXTURE MODEL. The Annals of Applied Statistics, 14(2), 977–992. https://www.jstor.org/stable/27119672

Low-cost survey techniques applied to an archaeological site in southern Madagascar

Guido Schreurs*1 & Marc-Henri Derron2
[1] *Institute of Geological Sciences, University of Bern, Switzerland, schreurs@geo.unibe.ch*
[2] *Risk Analysis Group, Institute of Earth Sciences, University of Lausanne, Switzerland, Marc-Henri.Derron@unil.ch*

Key words: UAV, Photogrammetry, DEM, Madagascar, cultural heritage

Since 2021 Malagasy and Swiss researchers investigate the archaeological site of Teniky in southern Madagascar. The isolated site is situated within the Isalo National Park and can only be accessed on foot, requiring an 8-hour trek across rugged, mountaneous terrane transected by steep gorges. All equipment and food is carried to the site on foot. The archaeological structures at Teniky are about 1000 years old and include man-made terraces and rock-cut architecture, such as niches and chambers, carved into the vertical cliffs of a natural cirque formed by fluvial erosion (SCHREURS ET AL., 2024).

In 2024 we used low-cost survey techniques to enhance documentation of the archaeological site. We used a DJI Mavic 3T drone to map and visualize the terrain, in particular the man-made terraces, and both an iPad and an iPhone to document the rock-cut architecture in 3D. In the absence of any existing infrastructure at Teniky, we used three portable and foldable Goal Zero Nomad 50-Watt solar panels in combination with a Goal Zero Sherpa 100AC power station for charging our technical equipment. Each 50-Watt solar panel weighs 3.1 kg. The three solar panels can be chained to 150 Watt. During our four-week stay at the site, the weather conditions were nearly always dry and sunny, allowing us to regularly (re-)charge the drone batteries (six in total), as well as the iPad, iPhone and other equipment, such as a satellite phone.

Using the drone survey at Teniky, an orthophoto mosaic and a DEM were produced using SfM photogrammetry software Metashape. About 7000 images from an altitude of 50m above ground level were collected. The DEM has a 5 cm pixel resolution, whereas the orthophotos have a 2.5 cm pixel resolution. As there is little vegetation within the natural cirque, the orthophotos and the DEM allowed us to clearly distinguish and map the man-made terraces (Fig. 1). With the aim of optimizing visualization of both geomorphological features and archaeological remains, an original shading procedure was applied, combining various techniques (multidirectional hillshading, skyview factor and slope shading).

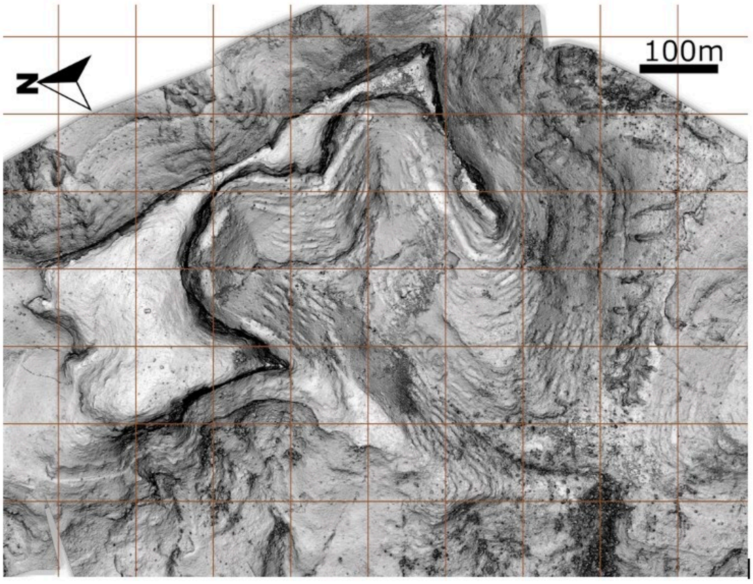

Figure 1: Digital elevation model of the natural cirque at Teniky showing man-made terraces

We used the Polycam application on iPad and iPhone to document the 3D geometry of rock-cut architecture at Teniky. Polycam is a versatile, intuitive and simple-to-use 3D scanning application that produces high-quality 3D models using LIDAR and photogrammetry. A prerequisite is that iPads and iPhone of the newer generations are used. Examples of 3D images produced at the site of Teniky are shown below (Fig. 2, with link).

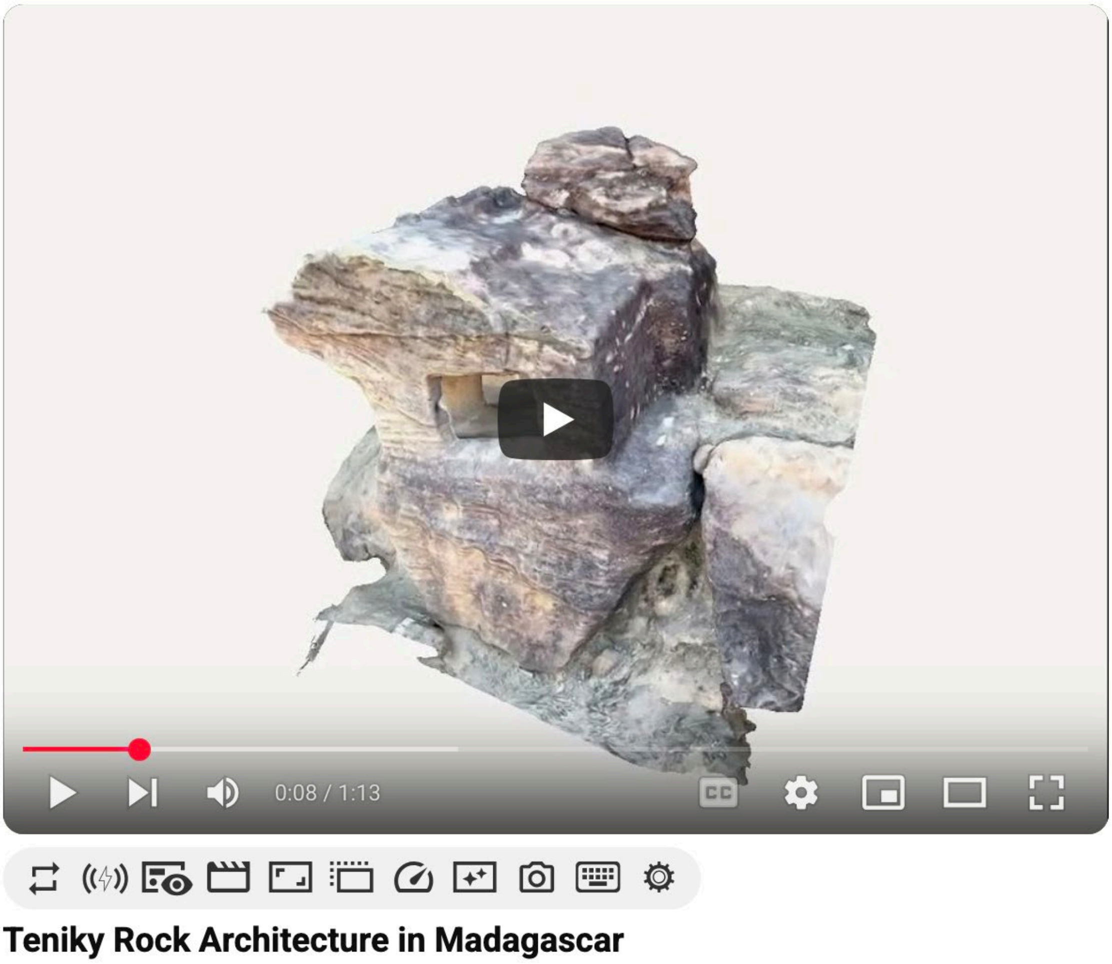

Figure 2. 3D visualisation of rock-cut architecture at Teniky - https://theconversation.com/madagascars-mysterious-teniky-rock-architecture-study-suggests-a-link-to-ancient-persia-240725 or https://www.youtube.com/watch?v=IqHHLzKz3vs

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References

Schreurs, G., Allegro, T., Rouvinez, M., Radimilahy, C., Raharinoro, J., Sabe, N.F., Rakotoarisoa, J.-A., Rakotomavo, L., Rakotondrazafy, N.A., Randrianarivelo, N., Szidat, S. 2024. Teniky: Enigmatic architecture at an archaeological site in southern Madagascar. *Azania: Archaeological Research in Africa,* DOI: 10.1080/0067270X.2024.2380619

LiquidEarth: Enabling Collaborative, Unified Workflows for 3D Geodata and Rapid Geological Modeling

Fabian A. Stamm*[1], Dr. Simon Virgo[1] & Miguel de la Varga[1]
[1] Terranigma Solutions GmbH, Laurentiusstr. 59, 52072, Aachen, Germany,
fabian@terranigma-solutions.com

Key words: *3D visualization, remote collaboration, geological modeling, VR & AR, digital twin*

Despite major technological advances in cloud computing, remote connectivity, and modern 3D visualization methods, many geoscientific workflows remain under-digitized, fragmented, and are often limited to 2D or make ineffective use of 3D. Gaps persist between field data acquisition and office-based data processing and modeling, between distributed teams and siloed experts, as well as between diverse data types, formats, and software tools. These inefficiencies result in delays from data collection to actionable insight, hinder collaboration, and lead to underutilization of data and models. As a result, significant potential remains untapped in how complex 3D subsurface information could be interpreted, shared, and understood.

We present LiquidEarth, a cloud-based platform that leverages recent advancements in computational and visualization technologies to unify 3D geodata workflows and enable geoscientists to work digitally and collaboratively across platforms and locations. The platform provides an intuitive and interactive 3D environment for the visualization, interpretation, modeling, and communication of geological data.

LiquidEarth supports next-generation 3D visualization across desktops, tablets, and immersive XR headsets, enabling “true 3D” interpretation of complex subsurface datasets. It supports a wide variety of data types, including drillholes, geological surfaces, geophysical volumes, and remote sensing data, and unifies them in a single spatial context for integrated visualization and interpretation. Remote teams can collaborate in real time using shared online sessions, annotations, and interpretation tools, replacing static slides and video calls with dynamic, spatially contextualized interaction. These capabilities are further extended by tools dedicated to building presentations, offering a novel approach to interactively communicating complex subsurface projects directly in 3D.

The platform also integrates GemPy, an open-source modeling engine co-developed and maintained by our team in collaboration with the CG3 Institute at RWTH Aachen University. This integration enables rapid geological 3D modeling within LiquidEarth's interactive environments, including XR, supporting intuitive conceptualization of models as well as continuous, data-informed updates to geological interpretations.

Together, these capabilities enable a connected digital workflow in which field data from various sources is immediately integrated, visualized in 3D, and made accessible for collaborative interpretation. Experts can inspect the data remotely, including in real-scale immersive XR, and contribute new insights that directly inform continuously updated geological models.

The result is a persistent, shared digital 3D representation of the subsurface that is continuously accessible and updateable, enabling integrated collaboration and deeper spatial understanding through fully interactive 3D environments.

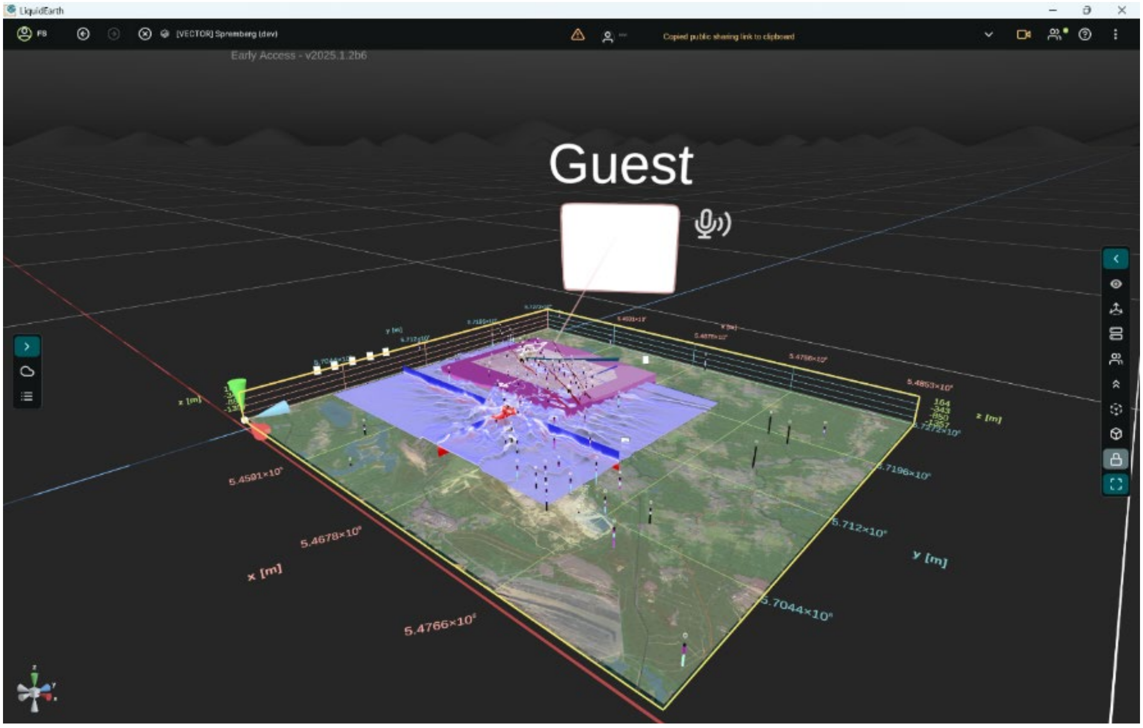

Figure 1: Visualization of multiple exploration datasets in LiquidEarth, including a 3D geological model, boreholes, volumetric data, and satellite imagery. The screenshot also demonstrates the live collaboration feature, with a guest user's avatar, highlight pointer, and microphone icon indicating active voice communication.

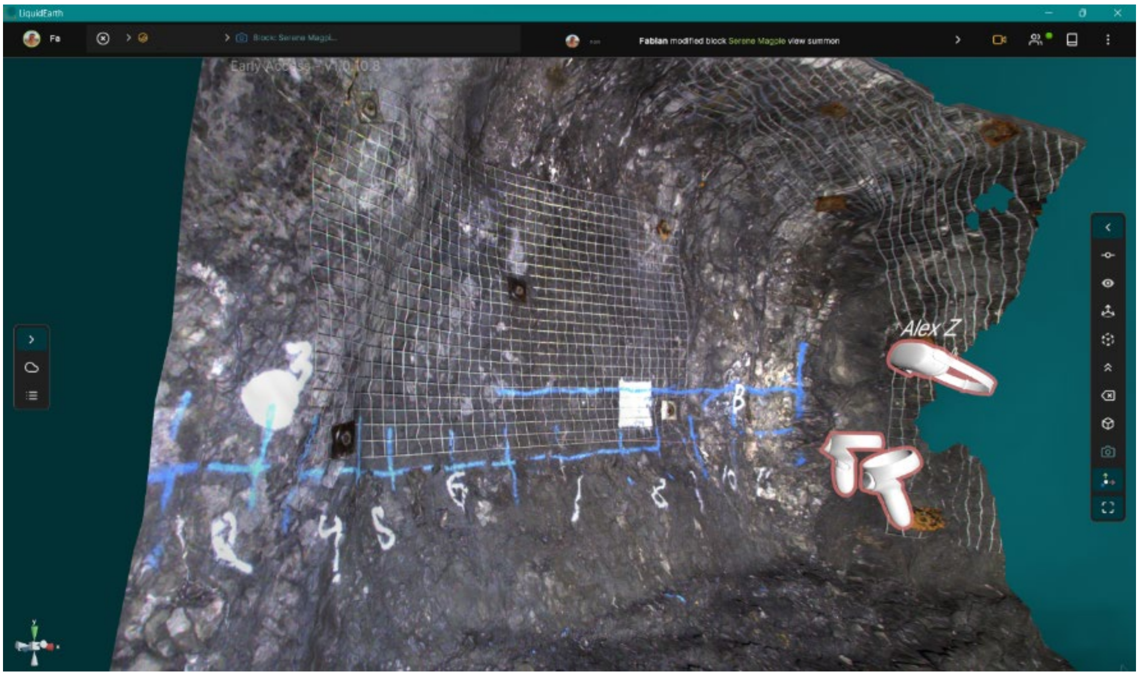

Figure 2: A user represented by an XR headset avatar inspects a 3D scan of a rock face from an underground mine gallery. The scan is visualized at true scale, allowing the user to experience spatial proportions realistically, simulating the sense of being on-site while remaining in the office.

Acknowledgements: Development of LiquidEarth has been supported by the EIT RawMaterials Upscaling project FARMIN, and by the EU Horizon Europe project VECTOR, which has received funding from the European Union's Horizon Europe research and innovation program under grant agreement nº 101058483.

Building Sustainable Alpine Monitoring: Integrating UAVs, Aircraft, and Geoweb for Long-Term Environmental Observation

Joshua Theule[1*], Saskia Gindraux[1]
[1] *Centre de recherche sur l'environnement alpin (CREALP), Rue de l'Industrie 45 CH-1950 Sion, joshua.theule@crealp.vs.ch*

Key words: *Sustainable environmental monitoring, UAV, manned-aircraft, multi-platform remote sensing, geohazard assessment, change detection, alpine monitoring*

Mountain regions worldwide are experiencing unprecedented environmental changes, with accelerating glacier retreat and permafrost degradation, evolving sediment regimes, and increasing geohazard frequency. Traditional monitoring approaches often fail to capture these interconnected processes at the necessary spatial and temporal scales. In addition, the efforts to monitor these regions are often dis-coordinated which makes the hazard management difficult.

Climate change is transforming high mountain environments at unprecedented rates, creating urgent needs for robust, continuous monitoring of glaciers, sediment systems, and evolving hazards. This project establishes a novel operational framework designed to meet these challenges through an integrated monitoring program combining remote sensing technologies with stakeholder-driven data services.

At its core, the initiative has developed a multi-platform observation system specifically designed for alpine conditions. The program's first phase (2022-2024) successfully demonstrated the technical feasibility through intensive monitoring of three key Swiss sites: Mattertal, Aletsch Glacier, and the Zinal region. These geomorphologically active areas serve as critical testbeds for evaluating monitoring technologies while providing immediate value to regional/communal stakeholders. Our approach uniquely combines Beyond Visual Line of Sight (BVLOS) drone operations using the DeltaQuad EVO platform with cost-effective light aircraft surveys, achieving 5-15 cm resolution through Structure-from-Motion photogrammetry with PPK georeferencing (Fig. 1).

The operational realities of high-altitude (3,000-4,000 m ASL) monitoring have driven important innovations. While BVLOS drone operations represent a significant technical achievement - including successful autonomous flights in extreme conditions - administrative complexities and communication challenges (for 120m and higher above ground operations) in busy mountainous terrain have highlighted the complementary value of manned-aircraft. Our custom tilting camera pod system, deployable on multiple light planes, has proven particularly valuable for regional-scale surveys, requiring fewer personnel and no airspace permissions while covering larger areas (multiple catchments, >100km reach) more efficiently.

The project's service-oriented design is manifested in two key outputs: First, a growing multi-temporal geodatabase capturing landscape changes at unprecedented resolution, including detailed documentation of glacier evolution, rock slope destabilization, and sediment transfer processes (Fig. 2). Second, the 3DGeoWeb platform prototype (http://www.3dgeoweb.crealp.ch) provides stakeholders with access to both raw imagery and processed products, serving diverse needs from fundamental research to hazard assessment.

Looking ahead, the program faces both opportunities and challenges in transitioning from demonstration to sustained operation. Key considerations include:

- Optimizing the balance between drone and aircraft deployment based on monitoring objectives and operational constraints
- Developing sustainable funding models to maintain multiple low-cost surveys needed annually for effective detection for sites throughout a region
- Expanding stakeholders' collaboration to ensure the system meets the evolving needs of cantonal authorities, research institutions, and infrastructure operators
- Addressing data governance challenges while maintaining open access principles

Ultimately, this work demonstrates how integrated monitoring systems can bridge the gap between scientific observation and practical decision-making in rapidly changing mountain environments. By combining technological innovation with operational pragmatism and strong stakeholder engagement, the project provides study cases for environmental monitoring applicable to other alpine regions worldwide.

Figure 1: DeltaQuad EVO autonomous VTOL drone (above) and the dual-camera pod attached to a plane (below)

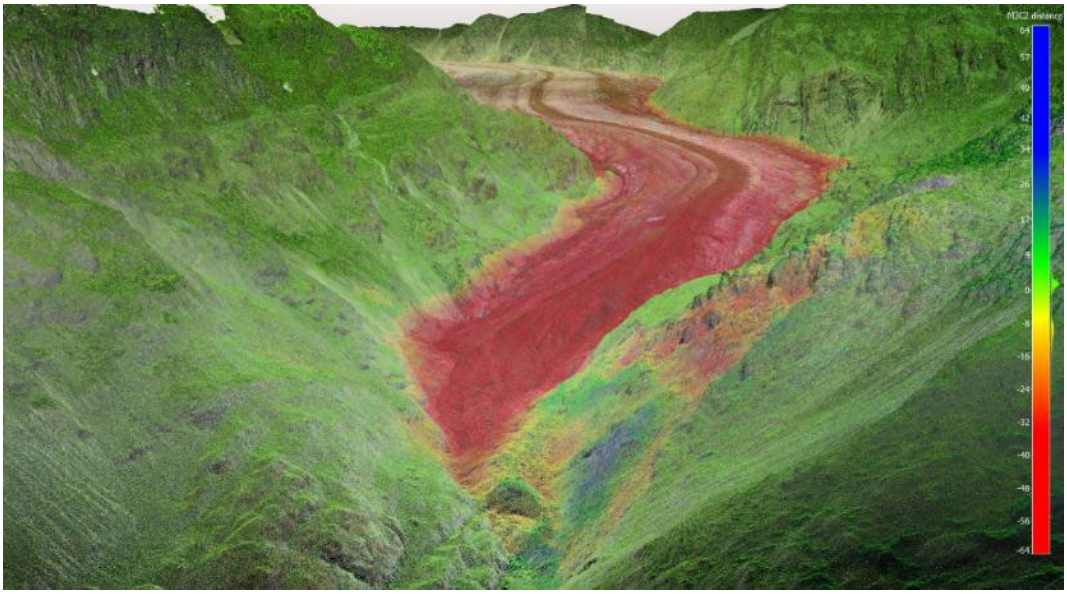

Figure 2. Point cloud difference from photogrammetric light plane surveys (2022-2023) over the Aletsch glacier and the Moosfluh landslide.

Acknowledgements: This project was funded by the FOEN Environmental Technology Promotion and CREALP.

Introducing RockHopper: An open-source toolkit for web-based virtual field trips

Sam Thiele[1*], Akshay Kamath[1], Moritz Kirsch[1] & Richard Gloaguen[1]

[1]*Helmholtz-Zentrum Dresden-Rossendorf, Helmholtz Institute Freiberg for Resource Technology, Freiberg, Germany, s.thiele@hzdr.de*

Key words: *virtual field trip, web visualisation, point clouds, multimedia, geotourism, teaching*

Virtual field trips (VFTs) are becoming an integral part of modern inclusive geoscience education, and have additional potential for geotourism and public engagement. Many VFTs, especially geological ones, involve interactions with digital outcrop models – photorealistic 3D reconstructions of outcrops or landscapes. As digital outcrop data becomes more widely available, important repositories, including eRock, V3Geo, AusGeo, DDE-Outcrop3D, Sketchfab, and PoTree, have emerged. These platforms provide visualisation capabilities and, in some cases, tools to make annotations or notes, but they generally have limited capability to integrate the digital outcrop data and the multimedia content (e.g., photographs, photospheres, videos, explanatory text etc.) needed to build narrative rich VFTs.

In this contribution, we present a new open-source python library and javascript application, RockHopper, designed to help rapidly build and serve multimedia rich VFTs. RockHopper seamlessly integrates photosphere and point-cloud content with formatted text, imagery and videos supplied using markdown files. It is unique in allowing multiple colour or style attributes to be associated with each point cloud. It thus facilitates the visualisation of e.g., false-colour visualisations derived from hyperspectral data, the highlighting of specific structures or lithologies, and multi-temporal point cloud data. RockHopper VFTs are also designed to be developed locally using a simple python toolbox, and then deployed on any static web-server. Platforms like GitHub can then be used to facilitate community development and sharing.

To demonstrate the performance of RockHopper, we developed a VFT for northern La Palma (Canary Islands, Spain) using a range of digital outcrop, photosphere, audio, video and field photography datasets (Fig. 1). This VFT provides a broad overview of La Palma's fascinating geology and volcanic past, before exploring some more technical aspects of the volcanic plumbing system exposed within Caldera Taburiente (https://samthiele.github.io/LaPalmaVFT/#/start). We look forward to welcoming contributions to RockHopper, and hope it will serve as a widely used community-driven platform to build multimedia and virtual field trips with rich narratives.

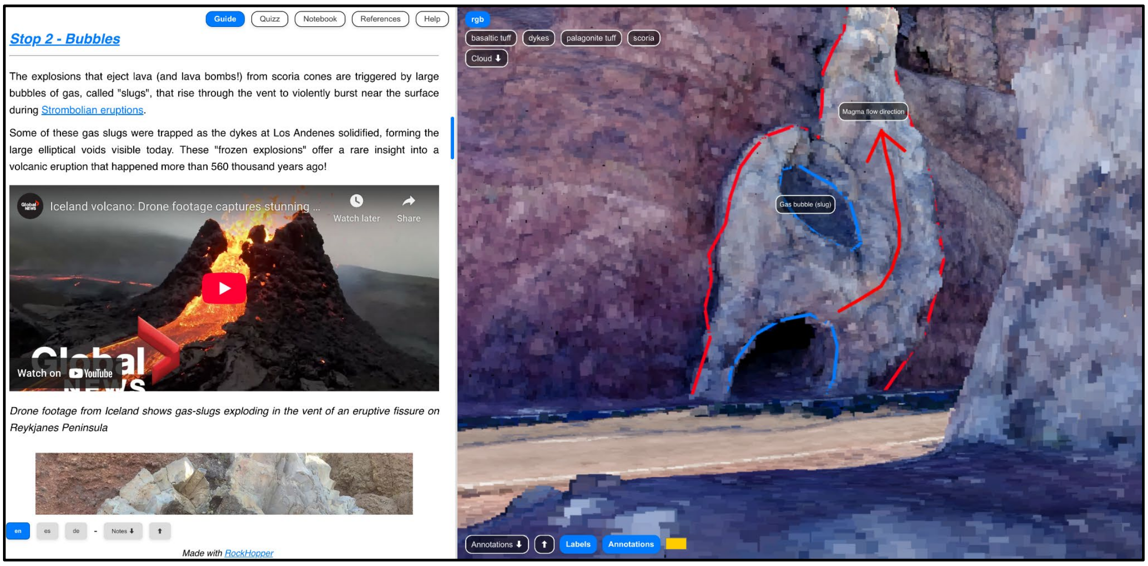

Figure 1: Screenshot of one "stop" in the demonstration VFT developed using RockHopper, showing gas "slugs" frozen in a feeder-dyke exposed near the rim of Caldera Taburiente, La Palma, Spain.

Geomorphology-Aware Deep Models for Terrain Surface Completion

Tianxin Lu1*, Michel Jaboyedoff1, Ruoshen Lin1
[1] *Faculty of Geosciences and Environment, University of Lausanne*

Key words: *Topography, Deep learning, Voids completion, DEM, Generative models*

Digital elevation models (DEMs), which aim to represent bare-earth surfaces, are typically created using sensing techniques such as structure from motion (SfM) and light detection and ranging (LiDAR). However, the raw data often contain non-terrain elements, such as vegetation and man-made structures. Filtering out these non-terrain elements often introduces discontinuities and voids, which can compromise the quality of subsequent geospatial analyses.

To address this challenge, we propose a deep learning–based framework for terrain data completion that incorporates geomorphological constraints to more effectively preserve terrain semantics and structural continuity. Our approach explores generative and non-generative models to capture large-scale terrain formations and fine-grained surface details.

To evaluate the practical relevance of the proposed framework, we present a preliminary evaluation protocol that examines the impact of both traditional interpolation techniques and AI-based approaches on downstream tasks such as hydrological modelling and slope stability analysis.

Overall, the framework demonstrates the potential of deep learning techniques to generate coherent and geomorphologically plausible terrain surfaces, providing a reliable foundation for geospatial applications.

References

Lo, K.S.H. and Peters, J., 2024. Diff-DEM: A Diffusion Probabilistic Approach to Digital Elevation Model Void Filling. *IEEE Geoscience and Remote Sensing Letters*.

Zhao, J., Yuan, Y., Dong, Y., Li, Y., Shao, C. and Yang, H., 2024. Void filling of digital elevation models based on terrain feature-guided diffusion model. *Remote Sensing of Environment*, 315, p.114432.

Panangian, D. and Bittner, K., 2025. Dfilled: Repurposing Edge-Enhancing Diffusion for Guided DSM Void Filling. *arXiv preprint* arXiv:2501.15440.

Do VFTs achieve meaningful learning outcomes?

Jan M. van Bever Donker[1*], Henok G. Solomon[1], Charl D. Cilliers[1]

[1] *Department of Earth Sciences, Faculty of Natural Sciences, University of the Western Cape, Private Bag X17, Bellville, 7535, South Africa, jvanbeverdonker@uwc.ac.za*

Key words: *Geo-education; Virtual Field Trip; Statistics*

While many institutions worldwide have occasionally used Virtual Field Trips (VFTs) to enhance the teaching of geological principles, their role expanded significantly during the global lockdown of public facilities amid the COVID-19 pandemic. During this period, many universities and schools replaced physical field trips with virtual alternatives out of necessity (e.g. Bown *et al.*, 2020), often relying on their collections of photographs to construct VFTs rapidly.

At the University of the Western Cape (UWC), increasing student enrolments—from 12 first-year students in 1980 to 320 in 2025—prompted the development of VFTs from as early as 2017. The initial goal was to better prepare students for in-person field excursions by showing them in advance what to expect and why it matters, thereby reducing reliance on field-based tuition. However, the ongoing rise in transport and accommodation costs, growing class sizes, and increasingly stringent health and safety regulations have brought the prospect of replacing physical field trips with VFTs closer to reality.

This shift raises a key pedagogical question: *Do VFTs achieve meaningful learning outcomes?* To investigate this, we designed a protocol to generate statistically valid data on learning gains. We applied this protocol to both our first year and fourth-year classes in 2025. The methodology involves pre-testing students with questions related to the VFT content to establish baseline knowledge, followed by guided exposure to the VFT, including classroom discussion on the geological features and their development. Afterwards, the students complete a follow-up questionnaire, which includes the original questions alongside inviting feedback on their VFT experience and suggestions for improvement.

Both questionnaires are graded using a grading system that takes the test-retest reliability and internal consistency into account, while a Paired Samples T-test is applied to assess the presence and significance of any learning gains. Earlier studies using smaller sample sizes but with a similar approach conducted by three different postgraduate students showed a measurable improvement in learning outcomes (Van Bever Donker *et al.*, 2023, 2024). At this meeting, we will share results from our much larger 2025 undergraduate cohort.

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We sincerely thank the following contributors to our VFTs, namely: R. H. Bailie, D. Isaacs, R. B. Maart, T. Sathekge (University of the Western Cape), R. T. Tucker (Stellenbosch University), W. L. Taylor (Arizona State University), M. S. Huber (University of KwaZulu-Natal), P. Prins (Prins & Prins Diamonds), G. van Aswegen (Overberg Geoscientists Group), C. R. Penn-Clarke, L. R. Gardner, C. W. Lambert, and J. Rogers (Geological Society of South Africa).

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References

BOWN, P., DOBSON, D., KAMINSKI, D., LIU, E., & MITCHELL, T. 2020. Earth Sciences enters the world of online fieldtrips and virtual reality. *UCL Earth Sciences*. Available at: https://www.ucl.ac.uk/earth-sciences/departmental-newsletters/departmental-newsletter-spring-2020 [Accessed 4 June 2025].

VAN BEVER DONKER, J., MAART, R., MARSHAL, D., MAYEKISO, L., HUBER, M., SOLOMON, H. & MGABISA, N., 2023. The effectiveness of Virtual Reality Field Trips (VFTs) in Field Geology education. *Proceedings of the Virtual Geoscience Conference 2023*. Available at: https://tud.qucosa.de/api/qucosa%3A87480/attachment/ATT-0/ [Accessed 3 June 2025].

VAN BEVER DONKER, J., MARSHAL, D., MAART, R., MAYEKISO, L., SOLOMON, H., HUBER, M., & MGABISA, N., 2024. Can Virtual Field Trips be used to prepare students for real fieldwork? *EGU General Assembly 2024*. Available at: https://doi.org/10.5194/egusphere-egu24-18133 [Accessed 3 June 2025].

Reading Rock Record through Digital Outcrop Models: An Integrative Workflow for Decoding Stratigraphy and Facies in the Salta Basin, Argentina

E. Roemers-Oliveira[1,3], S. Viseur[1*], I. Gomes-Goncalves[2], F. Guadagnin[2], J. Marchini[1], A. C. Freccia[2], G. Rangel[2], G. Pederneiras Raja Gabaglia[3], F. Fournier[1]

[1] *Aix-Marseille University, CNRS, IRD, Collège de France, INRAE, CEREGE, UMR7330, Avenue Louis Philibert, 13545, Aix-en-Provence, France, viseur@cerege.fr*

[2] *Universidade Federal do PAMPA, Caçapava do Sul, Brazil*

[3] *Petrobras – Petróleo Brasileiro S.A, Rio de Janeiro, Brazil*

Key words: *Digital Outcrop Model, Reservoir analogues, Sedimentology, Roughness, texture, Machine Learning*

For several decades, Digital Outcrop Models (DOMs) have facilitated the geological study of outcrops, allowing detailed interpretations of sedimentary or tectonic structures. However, processing all this data still remains tedious despite the implementation of automatic detection techniques, such as recently developed neural networks. Moreover, when using these outcrops as reservoir analogues, the big question is what level of information to include in 3D models, especially since the studied outcrops are carbonate cliffs several kilometres long, for two reasons: i) carbonates are difficult to differentiate from a distance; ii) cliffs involve large amounts of data to process. On the one hand, large-scale analyses miss fine levels of facies that are crucial for flow or dating, and on the other hand, detailed analyses are time-consuming and provide information that is not easily integrated or useful in models. The present work aims to propose a multi-approach workflow to optimise the information extraction from outcrops for reservoir modelling.

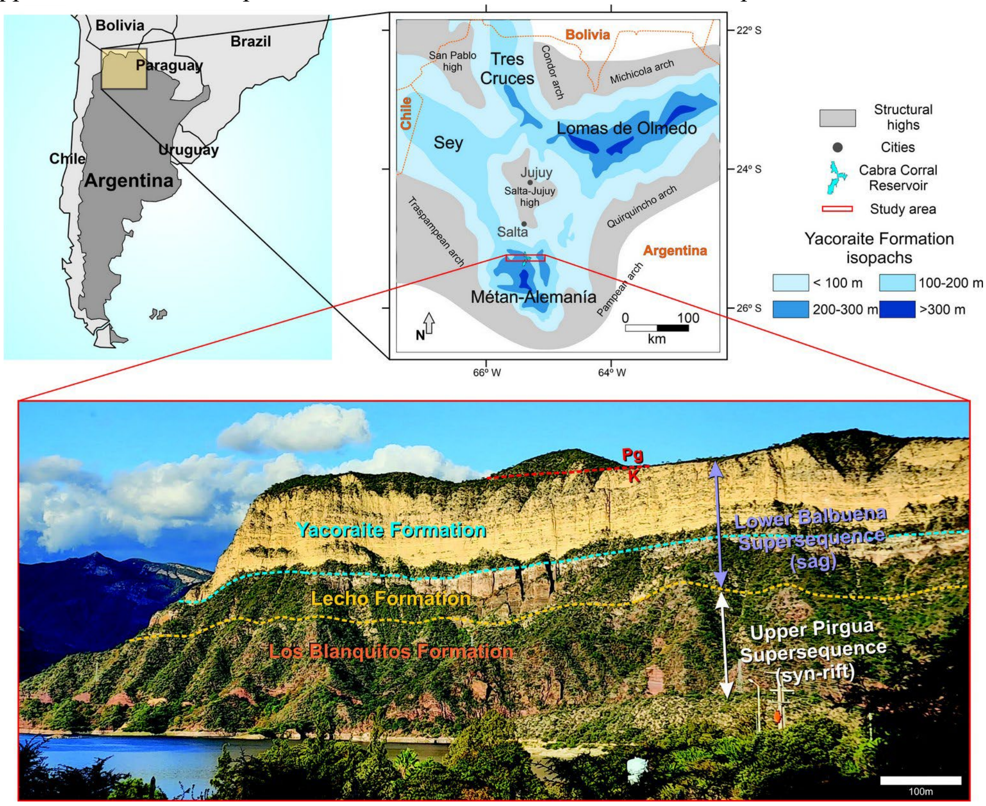

Figure 1: Case study: top) Location map of the Salta Basin and its sub-basins; bottom) photo of an outcrop near the Cabra Corral reservoir with the stratigraphic nomenclature of the units.

The Balbuena III Sequence of the Salta Basin, Argentina, is a well-known basin analogue for Brazilian pre-salt carbonate reservoirs (RAJA GABAGLIA *et al.*, 2011). The lacustrine successions, observable at several outcrops, consist of carbonate, siliciclastic, mixed, and volcanic facies, arranged in stacking patterns that can be correlated over tens of kilometres, and are interpreted to reflect climatically driven base-level changes (Fig. 1). Outcrops are located in the southern part of the Salta Basin, close to the Cabra Corral reservoir. We have developed a multi-approach workflow (Fig. 2) to improve the understanding of depositional environments, facies architecture and cyclic stacking patterns within the Balbuena III Sequence but also to extract quantitative key information for nourishing further 3D surbsurface reservoir models. It combines high-resolution sequence stratigraphy (HRSS), supported by traditional field-based methods, with digital techniques: texture (Local Binary Pattern, LBP) and roughness analyses (VISEUR et al., 2022), and Convolutional Neural Networks (CNNs) applied onto the photogrammetric data.

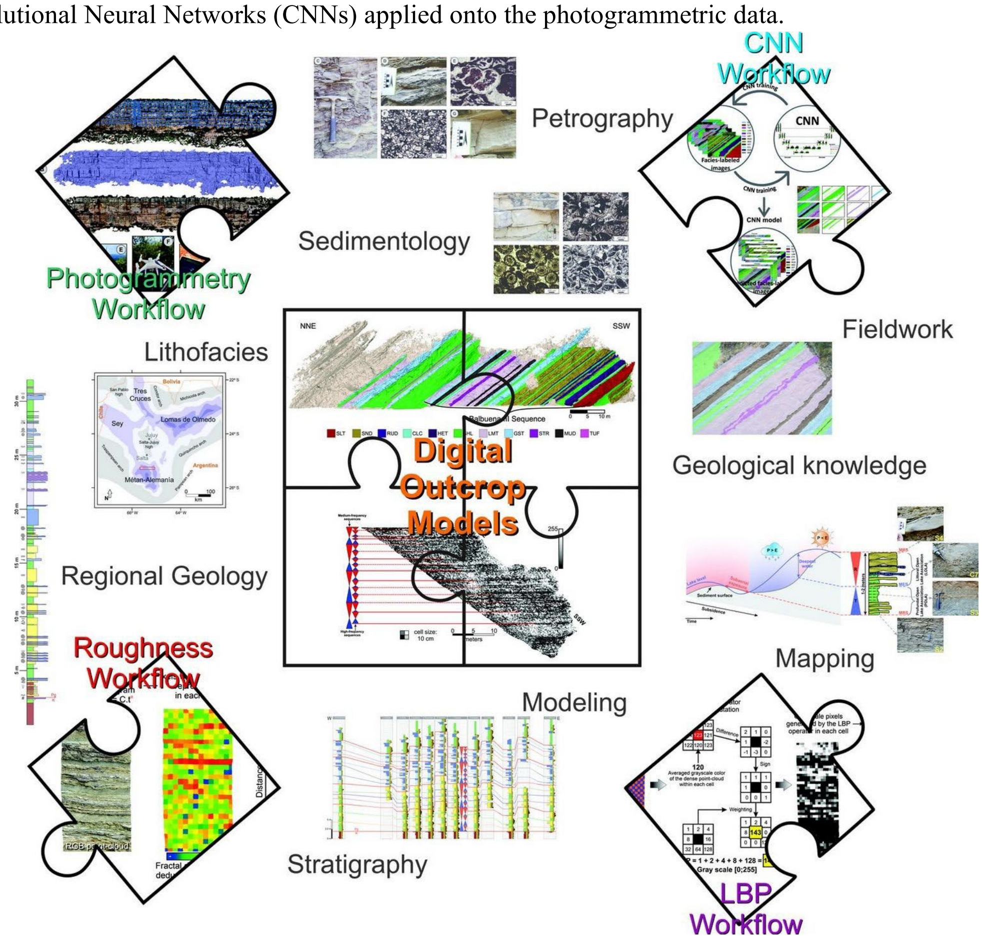

Figure 2. Imbricated and multi-approach workflow for extracting essential information from data.

The LBP and roughness analyses defined proxies for stratigraphic interpretation: LBP seems more efficient in exhibiting high-frequency cycles and roughness analyses in highlighting medium-frequency stratigraphic sequences. A CNN-based segmentation combined with photogrammetric algorithms (GUADAGNIN *et al.*, under review) provided facies maps directly on outcrops, allowing 11 lithofacies to be identified, including carbonate, siliciclastic, mixed, and volcanic facies. The combined numerical approaches allow for a more in-depth analysis by increasing efficiency, and thus capacity to analyse large datasets. Combining these techniques with traditional methods improves the analysis of outcrop analogues and thus contributes to a more adequate geological modelling of oil fields and hydrocarbon recovery.

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References

GUADAGNIN, F., GONÇALVES, I.G., ROEMERS-OLIVEIRA, E., GUEDES, P.L., SOUZA, E.G., SILVEIRA, M.M.L., RAJA GABAGLIA, G.P., GONÇALVES, L.A., OLIVEIRA, L.F.R., SELK, R., UNDER REVIEW. BUILDING OF CLASSIFIED 3D POINT CLOUDS OF OUTCROP WITH AUTOMATICALLY SEGMENTED IMAGES. GEODATA AND AI.

RAJA GABAGLIA, G.P., BENTO FREIRE, E., TERRA, G.J.S., RODRIGUES, E.B., LYKAWKA, R., HERNÁNDEZ, R.M., 2011. Cyclostratigraphy and climatic control on microbiol influenced sedimentation (Balbuena Supersequence, Yacoraite Formation, Paleocene, Salta–Argentina, in: 28th Internatinal Association of Sedimentology Meeting. Zaragosa.

VISEUR, S., LAMARA, T., PAREL, G., BENEDETTI, L., 2022. Automatic tools for quantitative analysis of multi-scale spatial slip variabilities from DEM and DOM, in: 21 Annual Conference of the International Association for Mathematical Geosciences. IAMG

Automated glacier monitoring with long-range TLS and the ice lollipop: a case study at Hintereisferner

Annelies Voordendag1*, Rainer Prinz2
[1] *Institute of Geodesy and Photogrammetry, ETH Zurich, Switzerland,*
annelies.voordendag@geod.baug.ethz.ch
[2] *Department of Atmospheric and Cryospheric Sciences (ACINN), Universität Innsbruck, Austria*

Key words: *terrestrial laser scanning, glacier monitoring, point cloud registration, Hintereisferner, ice lollipop*

High-resolution monitoring of 3D glacier velocities offers critical insights into spatiotemporal ice dynamics and glacier mass balance. At Hintereisferner (Ötztal Alps, Austria), we developed and deployed a customized mass balance stake, referred to as the *ice lollipop*, which is continuously monitored by an automated terrestrial laser scanning (TLS) system (Voordendag et al., 2021, 2023).

This ice lollipop is an ablation stake consisting of a 6-meter aluminum rod topped with a 20 cm diameter polyethylene sphere coated with high-reflective paint, facilitating precise detection in TLS point clouds (Fig. 1). The ice lollipop has been scanned (near-)daily with a Riegl VZ-6000 laser scanner from September 2019 until December 2022. TLS point clouds are first registered to a stable local coordinate system using an automated pipeline implemented in Open3D. Stable reference areas include snow-free rock faces and a mountain hut, selected based on visual stability in long-term webcam imagery.

To track the ice lollipop's position, a 5×5 m bounding box centered on the previously known location is searched in each point cloud. The lollipop sphere appears as a saturated disk-like feature (Ø ~60 cm) due to the blooming effect (Lichti et al., 2005, Fig. 1). We filter out the lower 50% of intensity values and apply a RANSAC-based planar fitting to identify the disk. The disk center is computed as an intensity-weighted average of x-, y-, and z-coordinates of inlier points and this position is assigned as the ice lollipop center.

Simultaneously, the surrounding glacier surface is determined by fitting a RANSAC plane to nearby points after excluding those belonging to the ice lollipop. This enables derivation of local slope, and glacier surface ablation and accumulation.

The combined positional data from the lollipop and surface plane allow us to resolve three-dimensional surface velocities. Preliminary results over three hydrological years indicate horizontal glacier flow of ~10 m a^{-1}, with enhanced surface velocity during melt seasons. The vertical motion exhibits a seasonal pattern, with a downward trend during summer and slight upward emergence in winter (Fig. 2). While only upward movement is theoretically expected in the ablation zone, the observed seasonal pattern deviates from this, and its causes remain uncertain; the underlying reasons are still the subject of ongoing research but might include lateral flow extension.

This approach enables fully automated, high-frequency monitoring of point-scale glacier motion and surface elevation change, bridging geodetic and glaciological mass balance methodologies. Expanding the network of ice lollipops across the glacier holds potential for capturing spatial variability in surface melt and ice flow, ultimately contributing to a more comprehensive understanding of glacier-wide mass balance and ice dynamics.

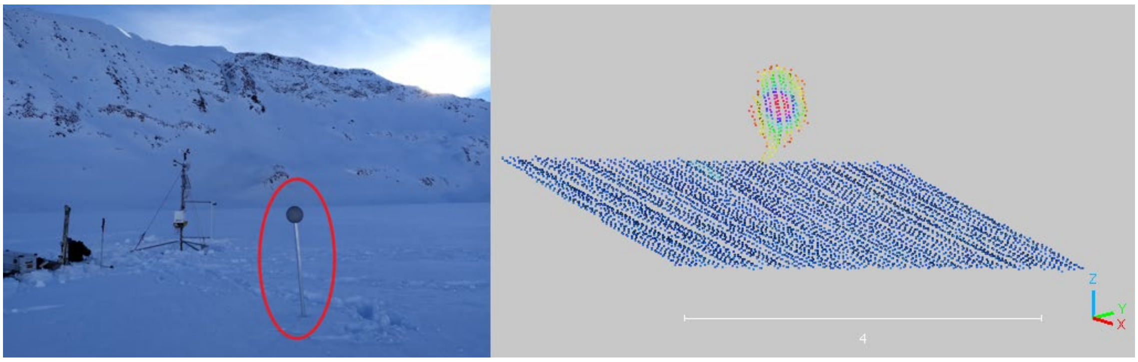

Figure 14: Left: The ice lollipop (red ellipse) on 17 December 2020. Photo by Rainer Prinz. Right: Point cloud of the TLS data from the same date, with colors indicating the intensity of the points.

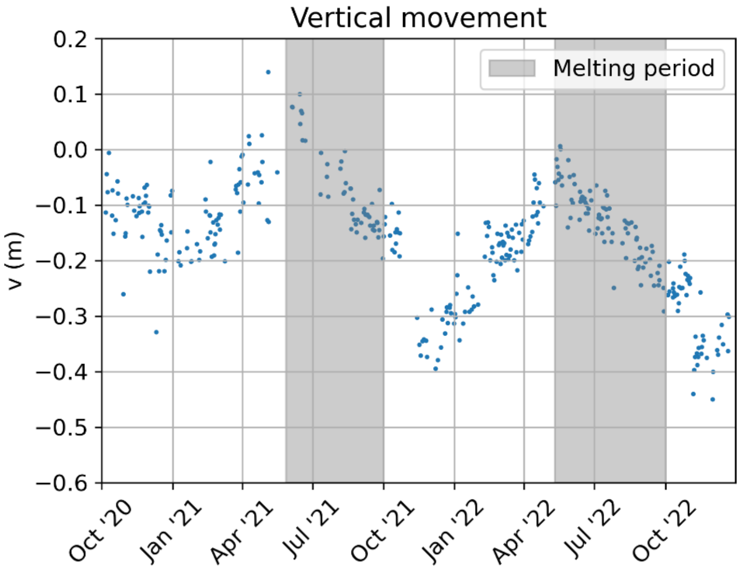

Figure 15:Vertical movement of the ice lollipop sphere over time

References

Lichti, D. D., Gordon, S. J., and Tipdecho, T. (2005). Error models and propagation in directly georeferenced terrestrial laser scanner networks. Journal of Surveying Engineering, 131(4):135–142.

Voordendag, A. B., Goger, B., Klug, C., Prinz, R., Rutzinger, M., and Kaser, G.: Automated and permanent long-range terrestrial laser scanning in a high mountain environment: setup and first results, ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, V-2-2021, 153–160, https://doi.org/10.5194/isprs-annals-v-2-2021-153-2021, 2021.

Voordendag, A., Goger, B., Klug, C., Prinz, R., Rutzinger, M., Sauter, T., and Kaser, G.: Uncertainty assessment of a permanent long-range terrestrial laser scanning system for the quantification of snow dynamics on Hintereisferner (Austria), Frontiers in Earth Science, 11, https://doi.org/10.3389/feart.2023.1085416, 2023.