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3D modelling of the dolerite dyke network within the Siilinjärvi phosphate deposit

Kauti, Tuomas

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Preface

Dear colleagues,

On behalf of the organizing committee of the Visual3D conference 2019, with the theme "Visualization of 3D/4D models in geosciences, exploration and mining", I would like to present this proceedings document, containing all abstract contributions for which publication permission has been granted by the authors.

EIT Raw Materials is especially acknowledged as the main sponsor of this event through the Visual3D network of infrastructure.

We wish to thank all the contributors who through their efforts made this conference possible, and hope to see you all at a similar event in the near future.

Yours sincerely,

J. Kann

Tobias C. Kampmann, PhD Conference coordinator, Visual3D conference 2019

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Session "Education"

Session chair: Tobias C. Kampmann, Luleå University of Technology, Sweden

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Visualization of 3D/4D models in geosciences, exploration and mining

Dept of Earth Sciences, Uppsala University Uppsala, Sweden 1–2 October 2019

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Keynote: Over 10 years of applying VR to mining education, lessons learnt and where to from here

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The School of Minerals and Energy Resources Engineering (MERE) at the University of New South Wales in Australia has been involved in utilizing virtual reality (VR) in education/research since 2001. Through this period there have been many developments in VR technology, both hardware and software. Over the years, MERE has gained experience with 360° immersive 3D theatres, immersive half-dome projections, mobile VR headsets, high-end VR headsets and various interactive devices. Dr Tibbett is a mining engineer from MERE who used such VR technology to conduct research into rock mechanics using a scientific visualisation in VR of Big Data from a block cave mining system. Since his PhD he has specialised in VR technology, firstly as the VR Development Manager for MERE and then in starting his own VR company (SeePilot) to help other industries access the benefits of immersive learning and build their own experiences. Throughout his time and the experience of MERE there have been many lessons learnt in VR and improvements made to the hardware that is used, the design of the software modules and the forms of interaction within these modules. This presentation steps through the evolution of VR within MERE and focuses on the lessons learnt at each stage. The intent of this presentation is to showcase what can be done in VR/AR when applied to minerals education/research, hoping to inspire others new to the technology by presenting a range of examples. It is also intended to help others learn from the lessons MERE has learnt through applying this technology over the last 18 years to provide a shortcut to success for those looking to follow. Dr Tibbett will then discuss some of the current technologies and modules that MERE and SeePilot are focused on before briefly presenting the possible future of these technologies and where trends may lead.

Visualization of 3D/4D Models in Geosciences, Exploration and Mining, 1–2 October 2019, Uppsala, Sweden

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AusGeol – The Virtual Library of Australia's Geology

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Field work provides essential and formative educational experiences for Earth science students. However, it is not possible to expose undergraduates to a fully comprehensive range of field experiences. Significant field sites are often widely dispersed and may be situated in locations where student visits are difficult or impractical. These logistic issues, together with the need for increased flexible content provision and remote delivery of education programs, mean that resources and strategies to complement, but not replace, conventional field-based teaching programs are now required. The AusGeol Virtual Library of Australia's Geology was created to help address these issues by providing free virtual access to Australia's diverse and iconic geological features.

AusGeol delivers a range of visualisations including: photo-realistic 3D models derived from both terrestrial and UAV photography, full-spherical panoramas and 'deep zoom' imagery. Visualisations of significant localities are integrated to generate virtual tours. All visualisations are accompanied by comprehensive metadata that facilitate display and retrieval of objects that meet specific keyword, stratigraphic or lithological queries. Visualisations are delivered by the AusGeol web portal (www.AusGeol.org) through an interactive map interface (Atlas tab) or by tabular selection and display (Sites tab). Map and GIS data from external web map services can be displayed in the Atlas tab to provide context for the visualisations. 3D models and full spherical panorama data can be visualised within the AusGeol site and all datasets are available for free download and local viewing or incorporation into other applications. AusGeol also provides student activities to accompany the new visualisations. An important outcome of the AusGeol project has been development of new open-access software packages GeoVis3D and GeoVisVR. GeoVis3D allows users to easily measure and analyse virtual outcrops including facilities to measure and plot structural data, to annotate models in 3D, and to measure true-thickness stratigraphic or sedimentological logs. GeoVisVR implements some of the measurement and annotation capabilities of GeoVis3D in an immersive VR environment using HTC Vive headsets.

The AusGeol Library was developed with funding from the Australian Government Office for Learning and Teaching and a consortium of universities and government geoscience agencies. The library now provides free, on-line access to visualisations from over 3,800 sites across the Australian continent. It is the only on-line virtual library that attempts to systematically document the geology of an entire continent. The AusGeol project provides an effective model for collaborative development of virtual geological resource collections and a template for a global visualisation repository. This presentation will showcase the functionality and diversity of the AusGeol library and demonstrate the capability of the free GeoVis3D and GeoVisVR software packages.

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Building digital 3D learning environments to support the teaching in geosciences

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Geological features are three-dimensional. However, by necessity these features are typically displayed on a two-dimensional surface that can result in loss of information or be unintuitive to comprehend. Furthermore, the ever-growing industry demand for 3D modelling and interpretation skills on the field of geosciences emphasizes the need to increase 3D modelling education. Thus, incorporating 3D learning environments, materials and exercises into geological education serves to make learning more effective by allowing the intuitive study of complex, three-dimensional supra- and subsurface structures while simultaneously teaching essential skills required by modern geoscientific industry and academia alike.

In the University of Helsinki, both Bachelor's Programme in Geosciences and Master's Programme in Geology and Geophysics are participants in the "Digiloikka" ("Digital Leap") project that provides resources to study programs to digitalize teaching. Along with other learning materials such as educational videos and ultra-high resolution imagery, the project uses data collected within the project in combination with open geospatial data to produce 1) 3D and virtual reality (VR) learning materials that can intuitively tie together complex structures from photogrammetry-based outcrop models and subsurface structures that have been observed using geophysical methods 2) an application framework and workflow that will allow a single teacher or a researcher to produce 3D model and VR environments from their own imagery, and 3) a physical learning environment that allows the full utilization of 3D materials and VR-environments in different classrooms.

Different 3D and VR models and environments can then be used to augment teaching in a multitude of ways ranging from displaying quaternary phase diagrams to expanding field observations to subsurface structures. Furthermore, working in with 3D models and in VR environments gets students invested in working with 3D software and familiarizes them with the associated workflow. The procedure allows each teacher to create their own learning materials and exercises in 3D and use them in various learning spaces. This will create a foundation that is easy to expand upon and cuts down the resource requirements needed to create and develop further 3D materials.

The outcomes of the project are not aimed only at university students: the material will be made available for a broader audience through the geologia.fi internet portal and can be utilized for marketing geoscience studies for possible applicants. Collaborating with the project, the Helsinki based company Teatime Research Ltd specializes in designing virtual and augmented reality applications and services with plans to advance integrating geoscientific outreach and virtual reality. The project welcomes input and cooperation from everyone interested in developing geological teaching materials and environments and furthering popularization and general knowledge on geosciences.





The SIMS Virtual Mine for education

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Virtual reality (VR) enables a visual experience of invisible or restricted spaces through new technology. If implemented correctly VR can support education as well as student motivation since it allows for learning based on real scenarios and a "learning by doing" approach. Mines are an example of an environment not easy to access for teachers and students, and is therefore a good candidate for building a VR experience. Our idea is to visualize selected parts of a mine in a way that makes the learners believe they are in a mining environment and that they due to the interactive processes involved obtain a better understanding of some of the processes included in mining.

Within the Sustainable Intelligent Mining Systems (SIMS) project, we developed a VR environment consisting of selected parts of a mine. The environment will be used for education in mining and rock engineering. This means that we created a virtual mine in which the learner can walk around experiencing a mine and see on-going activities. The virtual mine is developed to be experienced using a headset together with handheld controllers hence creating a fully immersive first-person experience. The aim of the VR-mine is to give the students an experience of a field visit to a mine.

The virtual mine was developed in Unreal Engine (UE) for Steam VR (HTC Vive) as output. The 3D assets are developed and optimized in Autodesk Maya and then imported to UE. Some vehicles models originates from CAD/Design models and a small number of 3D assets are freeware. The drift system is built in modules and uses parametrized textures (photos and videos have been used for visual reference only). This ensures a pure modular drift underground architecture allowing for easy modification and extension. The VR-environment can be ported and thus be made available for phones, tablets and computers as well.

A fully functional VR environment displaying selected parts and processes of a mine has been developed and tested in several contexts, such as conferences, exhibitions, and schools. It has also been used as a virtual field visit in an introductory course at Luleå University of Technology, thereby serving as a first underground experience for many students. In addition, the VR environment has been tested by miners at the Kristineberg mine. The tests has proven that the VR environment is technically stable in all these situations, and the feedback of the VR experience has unanimously been positive.

The developed VR experience will allow students to see and experience mining situations in an interactive and immersive environment. It also facilitates and makes it possibility to learn from each other's knowledge and experience through the new tools and methods. In addition, the teacher has a new tool to use with the potential to enhance the learning experience as well as the motivation for learning.





MiReBooks – Mixed Reality Handbooks for Mining Education

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The education project MiReBooks, funded by the EIT RawMaterials initiates a series of Virtual & Augmented Reality based (= Mixed Reality, MR) interactive mining handbooks as a new digital standard for higher education across Europe.

MiReBooks is a new digital learning experience. By taking traditional paper based education material and enriching it with virtual and augmented reality based experiences (Mixed Reality), teachers can now convey and students now experience phenomena in the classroom that are usually not easily accessible in the real world. Complex issues of mining are no longer a challenging barrier for learning progress and students complete their studies with a more thorough comprehension of their discipline.

The new method meets the learning habits of present and future generations of students who will enter the job market as digital natives and highly influence the way mining skills are applied.

Project Partner:

Montanuniversität Leoben (Austria, Lead), Epiroc Rock Drills (Sweden), KGHM Cuprum (Poland), LKAB (Sweden), LTU Business (Sweden), Luleå University of Technology (Sweden), RWTH Aachen (Germany), Tallinn University of Technology (Estonia), Technische Universität Graz (Austria), Technische Universität Bergakademie Freiberg (Germany), Technical Research Centre of Finland, Università degli Studi di Trento (taly).

FiReBooks

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This activity has received funding from the European Institute of Innovation and Technology (EIT), a body of the European Union, under the Horizon 2020, the EU Framework Programme for Research and Innovation





Innovative Exploration Drilling and Data Acquisition: Test center and research school

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Innovative Exploration Drilling and Data Acquisition (I-EDDA) was a Network of Infrastructure in the European Institute of Innovation & Technology (EIT) Knowledge and Innovation Community (KIC) "Raw Materials". Its purpose was to unite partners from academia and industry to jointly address challenges that are expected to increase the value of mineral exploration related operations. The development and testing of innovative drilling tools and downhole sensors was a central part of I- EDDA. Based on the cooperation within I-EDDA two larger projects developed, the I-EDDA test center (I-EDDA-TC) upscaling project and the I-EDDA research school (I-EDDA-RS), both started in 2019 and supported by EIT Raw Materials.

I-EDDA-TC will allow real-world test drilling that is ultimately required to verify improved and new technologies and provide critical feedback to the engineers. Similar is the situation for downhole sensors. Improved or newly developed technology needs to be tested under real-world conditions and in an operational setting. However, a dedicated and well-characterised test site for diamond core- drilling from the surface and with realistic conditions is still missing. I-EDDA-TC is being developed together with the industry partner Epiroc and will include excellent access to infrastructure, workshop facilities and proximity to expertise in that field. The planned test site location in Örebro (south-central Sweden) is easily accessible and is situated in Paleoproterozoic bedrock (gneisses and metasediments) similar to the bedrock of many mining districts that are located in crystalline rock. The test site is planned to cover an area of approximately 4000 m². Superb characterisation of the physical and chemical parameters in the subsurface performed within I-EDDA-TC will allow for an integrated interpretation of technical and geoscientific test results. Geophysical investigations will be combined with a suite of fully-cored exploration boreholes of varying depth (some down to at least 1 km), as well as downhole and laboratory investigations. A long-term utilization of the test facility will be the ultimate goal, including an invitation to the research community and to companies to partake.

I-EDDA-RS has the aim to convey advanced and novel methods with high potential for improved deep mineral exploration from academia and academia-industry partnerships to the general exploration sector. The target audience is PhD students, but the courses are open to experienced professionals for lifelong learning and MSc level students. I-EDDA-RS education is grouped into three major themes that on their own and in combination have the potential to fundamentally advance future mineral exploration; (1) "Scientific methods applied to deep mineral exploration", (2) "Exploration engineering" and (3) "The life cycle of exploration data". The above themes will be complemented by the topic "Entrepreneurship", which will provide the tools that are necessary to become an entrepreneurial scientist who will work with novel methods in a future-oriented exploration market.

Both these projects will help form the basis for generating the data necessary to fully exploit the potential of 3D visualization of exploration data.





'VirtualMine as a modeling tool for Wider Society Learning' project as an example of VR application in youth education and its potential for further use

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The use of VR visualization technology has developed significantly in recent years and its application is observed in increasing number of industrial branches. Virtual Reality is also being implemented in the mining industry, as is evidenced by the VirtualMine project. The main goal of the project was to increase the awareness among local community about the importance of raw materials and its use for the development of the EU. Moreover, its aim was to popularize mining among the general public, especially children and students who start to develop their path career, as well as to show the importance of the minerals in the modern world. The didactic character of the project assumed the creation of an interactive museum exhibition, which allowed to present basic issues related to the exploitation of raw materials deposits, focusing mostly on copper deposits. One of the resulting elements was a virtual walk within the underground mine during which the user could perform a number of activities related to the basic mining activity. The virtual tour is didactic in nature and its main aim is to attract younger audiences to the subject of mining. During the virtual walk, in order to get used to the VR operation, the user undergoes a short training on its operation by completing simple tasks in a form of finding and collecting lost tools or manual extracting of the output using an air hammer. When the user becomes more familiar with VR operation, one is given the task of carrying out the blasting process in the excavation. The task is to prepare explosive charges and, in the final stage, to detonate them. However, the potential of using such solutions is much wider. If properly developed, virtual reality and its variations, can also allow for training of new employees, cyclical trainings related to work safety, commercial trainings and others. The results of the project are exhibited in Legnica Copper Museum and are going to be developed in the future. The VirtualMine project was coordinated by KGHM Cuprum and funded by EIT RawMaterials.





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VR learning environments for rock engineering and mining education

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Virtual reality (VR) can be used to enhance teaching in engineering education as it enables designing interactive and immersive exercises integrated with digitized learning spaces, which can increase the active time spent on learning activities, and reduce the teaching expenses. Two VR learning systems related to rock engineering and mining education have been developed at Aalto University, Finland. The first system is the Virtual Underground Training Environment (VUTE) developed for the training of fracture mapping and rock mass characterization as part of Mining Education and Virtual Underground Rock Laboratory (MIEDU) research project. VUTE consist of a photorealistic 3d digital twin of the Aalto Research Tunnel that was digitized using Structure from Motion (SfM) photogrammetry and virtual tools designed for practicing rock wall fracture mapping. The VR system enables remote visual inspection of the rock surface and virtual measurements of the orientation spacing, and roughness of discontinuities (an example vide of the VUTE system can be viewed here https://youtu.be/8Zxtotw_vyg). The system was tested on a group of 20 students, and the measurements performed in VR were compared against real-life mapping performed by students in the tunnel. The results demonstrated that students could identify the same three major joint sets with analogous orientations in both VR and tunnel mapping. The measurements made in the VR system were more systematic, and exercise completion time was reduced by 50% compared to manual compass measurements performed in the tunnel. The second VR learning system for teaching students how to identify rocks and minerals is currently being developed in the Educational Virtual Rock Collection (EDUROCK) research project. A collection of more than 100 rock and mineral specimens was digitized using photogrammetry and turned into a digital online learning asset. The virtual collection will be accessible on a desktop via an online model repository Sketchfab for self-study by students; it will be also implemented into an interactive learning platform developed in Unity game engine for HTC Vive VR headsets. The obtained output of the project will be used during the execution of the "Geology and geomechanics" course at Aalto University.

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Session "Applications and case studies"

Session chairs: Pietari Skyttä, University of Turku, Finland Jana Rechner, DMT GmbH & Co. KG, Germany

Substitution chair on-site: Tobias Ladinig, Montanuniversität Leoben, Austria

Visual3D conference 2019

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Keynote: Digging deeper – visualisation and analysis of postglacial faults through remote sensing and field-based methods

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Cratonic intraplate areas pose a challenge to seismic hazard assessment due to their low deformation rates and lack of large magnitude earthquakes, which makes the prediction of the long-term seismicity of such areas difficult. This is especially a concern for the seismic hazard assessment of high-level nuclear waste repositories located in intraplate settings, such as in Finland. Large intraplate earthquakes do, however, occur, as shown for example by the prominent postglacial surface ruptures located in Finland, Sweden and Norway and which are often referred to as postglacial faults. Postglacial faults are the result of sudden release of excess horizontal stresses accumulated during glacial period, triggered by the deglaciation phase.

In order to shed light on the nature of the postglacial faults and the long-term seismicity of Finland, Geological Survey of Finland and Posiva Oy, the nuclear waste company in Finland, established a project to investigate the postglacial faults through the use of airborne, high-resolution LiDAR-DEM, geophysics, paleoseismological trenching and field mapping. Using the high-resolution LiDAR-DEM, which currently has a coverage of ca. 95% in Finland, the project screened an area of 318 000 km², covering most of southern and central Finland and extensive areas close to the known postglacial faults in Finnish Lapland. The project employed both 2D- and 3D-softwares in the screening and resulted in the identification of 143 surface ruptures covering a total length of 223 km. Approximately 50 to 60 km of the mapped surface ruptures were previously unknown, showing the power of the high-resolution LiDAR-DEM in the mapping of the postglacial faults.

Seismic hazard assessment requires information on the moment magnitudes of past earthquakes and the high-resolution LiDAR-DEM were further used for the extraction of continuous offset profiles from the surface ruptures and in the analysis of the potential moment magnitudes of the earthquakes the postglacial faults may have hosted. This was accomplished by digitising polylines both to the upthrown and downthrown sides of the scarps and dividing the polyline either in the upthrown or downthrown side into set of points with specified distances. For each of the points, the closest point to the remaining polyline is then searched and the offset distance between the point pairs computed. For this task we employed Rhinoceros 3D-software and its graphical scripting plugin Grasshopper, which allowed direct interaction with the 3D-models of the digitised polylines. With the methodology, we were able to derive continuous offset profiles from all of 143 surface ruptures and derived detailed statistics of the offset values, instead of having isolated offset measurements along the surface ruptures. The derived data was then used in the assessment of earthquake moment magnitudes by using scaling laws linking fault offset values to earthquake magnitudes.

The offset magnitudes and characteristics of the postglacial faults were further confirmed by the use of paleoseismological trenching at selected locations and by documenting the trenches with photogrammetric 3D models. The use of observations from the trenches and later analysis of the 3D models showed that the cumulative offset values derived from the LiDAR-DEM were of similar magnitude with the true offsets observed in the bedrock, giving confidence to the LiDAR-based methodology and the workflows applied within the project.





Everyday application of 3D geotechnical modelling in infrastructure planning – 3 examples

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Driven by the BIM concept and the ongoing digitization in infrastructure planning (i.e. railways, roads, bridges) 3D geotechnical models have become almost one of the standard deliverables, and if not a key tool for the design team all through the design process. One of the key issues is to define what models are needed in each project. Some models could be seen as standard models, for example the top of the bedrock or the bottom of a peat layer. Other models could be more project specific, such as the rock cover along a railway tunnel or a contamination plume. In each project the required models should be defined at an early stage, not at least since it has an impact on the field investigation program. What models do the designers need? What models do the structural engineers want? What models does the contractor need?

The type of model also has an impact on the use of the model – design, visualization, machine control? It could be the same model but may require delivery in different data formats etc depending on the purpose of the use of the model. The use of the model must also be accompanied by specifications on QA and uncertainties, and also if there is a need for classifications (CoClass or other) of all the objects, which is a must to fulfil BIM maturity level 3.

This paper/presentation will exemplify and discuss the abovementioned with three infrastructure projects in Sweden in which 3D geotechnical modelling has been an important tool for the design process.

The Candy factory, Gävle – a contaminated site being remediated. In a complete digital chain from sampling to models for machine control, the geoenvironmental models were downloaded to each individual excavator for precise handling of the soil depending of the level of contamination.

New Road 27, Backaryd – in an area with very tough terrain to investigate (boulders, steep slopes, swamps, dense forest) the available data was from many different methods, sometimes unconventional, and both the density and the quality of the data was not always the best. Although an acceptable geotechnical model was produced.

Example site 3 – **The Södertörn Crosslink Project** – parts of this new highway link SW of Stockholm consists of rock tunnels. The soil around the Glömsta tunnel is mainly clay and both during the construction and in the permanent phase lowering of the groundwater is necessary, resulting in settlements and general environmental impact. In order to predict the settlements a detailed model of the thickness variation and the geometry of the clay layer is crucial, and hence requires careful modelleing.





UK Geo-energy observatories: developing a visualisation for site appraisal, investigation, and communication

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Here, GeoVisionary is used to visualise and interpret data above and below ground in a digital twin replicating everything that exists in the real world in a virtual reality environment. This approach is being taken at three sites as part of the UK GeoEnergy Observatories project https://www.ukgeos.ac.uk/): the Cheshire Energy Research Field Site (Thornton, Cheshire, England), the Glasgow Geothermal Energy Research Field Site (Scotland), and Cardiff Urban Geo Observatory (Wales). The Glasgow site will study geothermal energy from flooded mineworkings. The Cheshire site will study the geology around Ince Marshes for energy science research. The Cardiff site will improve our understanding of the way groundwater moves in a complex geological environment with an emphasis on shallow geothermal heat recovery and storage. All the field sites will have a network of deep and shallow boreholes containing state-ofthe-art telemetric monitoring devices. These will act like stethoscopes to precisely measure the state of the underground environmental baseline and changes that may occur. GeoVisionary can visualise the live data from the monitoring along with maps and 3D models, highlighting changes in the subsurface that occur naturally but also from the experiments that are planned. Contextualising the data in 3D using GeoVisionary will help various groups to understand the data and possible explanations behind changes that may occur.

As part this work, Virtalis and BGS are developing a cloud-based version of GeoVisionary as another channel to effectively communicate the science behind these borehole networks and the data that will be captured. The cloud version will have a specially designed Graphical User Interface (GUI) that will allow users of this system to easily zoom to bookmarked locations. Follow 'fly-throughs, alter the state of view by turning-off and on pre-loaded data, incorporate contextual data such as reports, presentations and videos, while also enabling the user to have the full raft of tools to fly freely around the surface and subsurface and interrogate the data.



Figure 1. GeoVisionary enhanced GUI for site investigation and communication.

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Towards 3D/4D visualization for geothermal site characterization

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3D visualization has become commonplace in reservoir engineering (e.g. Ebigbo et al., 2016; Hobé et al., 2018). Experiences gained in reservoir engineering prompted this study into using 3D and 4D visualization for geothermal site characterization. We mainly visualize Local Earthquake Tomography (LET) with some results from Magnetotellurics (MT). Both methods are sensitive to variations of physical properties that arise from e.g. hydrothermal processes. Although 3D visualization of seismic tomography is not new, most recent papers only include horizontal and vertical 2D slices, while earthquakes are often plotted in 3D. Many LET investigations are conducted solely in 2D. There are certainly benefits to plotting slices in 2D and most seasoned researchers are used to making interpretations in 2D. Nevertheless, there are major benefits to visualizing LET results in 3D. With the use of visualization softwares like, e.g. Vislt or Paraview, it is possible to effortlessly compare different fields of results. Figure 1 shows isosurfaces of both the Vp and Vs fields. The ellipsoidal Vp anomaly between 5 and 8 kms depth is almost entirely contained within the larger Vs anomaly. Transparancy of the fields allows us to show the location of the earthquakes as well. These fields can be constrainted further by other fields. As examples, one can 1) remove areas with low tomographic resolution, or low ray-coverage, 2) show the Vp-field contained within a Vp/Vs-anomaly, 3) plot only those rays that sample a chosen anomaly, and 4) use isosurfaces of LET to look at results from MT and viceversa. We aim to develop a workflow using 4D visualization to aid robust appraisal of subsurface changes with time. Without this appraisal, one cannot differentiate between "true" changes and artifacts due to, e.g. differences in source and ray-path geometry. All of these benefits of 3D and 4D visualization greatly aid geothermal prospecting and reservoir monitoring. These benefits should also transfer to virtual reality, where additional benefits are sure to be obtained.

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Analysis of data from Unmanned Aerial Systems (UAS) in a Virtual Reality environment

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The use of Unmanned Aerial Systems (UAS) is getting increasingly popular for many different types of applications. The field of geology is slowly catching up resulting in new and innovative UAS solutions for various kinds of airborne measurement techniques. These techniques comprise a wide range of geophysical and remote sensing methods used to investigate the sub-surface. At Luleå University of Technology two different types of UAS are used in combination with a Virtual Reality environment in order to analyze geological structures and related ore deposits and mineralizations. The two UAS comprise a) a custom made quadrocopter (HUGIN) with a pay load of approx. 3.5 kg and an operational time of 5 times (batteries) maximum 35 minutes depending on payload, ambient temperatures and wind speed; and b) a foldable DJI Mavic Pro with an operational time of 3 times 30 minutes. The HUGIN system can be operated with a high-resolution optical camera for photogrammetry surveys and a 3-axial fluxgate magnetometer for measuring magnetic anomalies within bedrock and ultimately delineating geological structures. The system is highly flexible and a thermal camera is currently added to the system in order detect water fluxes in relation to geological structures or exothermal mineral processes. The DJI system is equipped with an optical camera for photogrammetric surveying and is a highly valuable tool in remote areas due to its lightweight and compact construction.

Data acquired from both UAS is subsequently analysed in a Virtual Reality lab utilizing a 6m wide screen with active stereo functions. Photogrammetry data is first processed using the Aigsoft software package following a Structure for Motion (SfM) workflow where dense point cloud models and subsequently meshed and textured 3D surface models are produced. These models are then converted and transferred to the GeoVisionary software package that allows visualization of models in stereo 3D view. This allows digitizing geological structures such as foliation, fractures, and faults among others in an immersive 3D environment and provides an efficient tool complimentary to traditional field mapping. In particular, this makes it possible to capture and analyse data from hardly accessible and dangerous areas such as rock faces in open pits. Another complimentary method of data analysis comprises SCAT analysis of the meshed surfaces using the MOVE software package.

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Virtual field reconnaissance for mapping and exploration (Chile)

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Fieldwork is expensive and geology is a three-dimensional and often complex science therefore any tool which enables a greater understanding of the geology prior to and during fieldwork and hence saves time in the field is welcome.

GeoVisionary enables the geologist to compile all the existing data for a field area into a threedimensional environment and virtually visit that area before going into the field. This workflow has been termed Virtual Field Reconnaissance (VFR).

The 'geologists toolkit' within GeoVisionary allows the geologist to record their interpretations as spatially referenced and attributed lines, points and polygons, which are then easily transferable to digital field systems. Tools such as the '3-point plane', 'orientated dip surfaces' and 'profile generation tool' allow the geologist to understand the three-dimensional structure of an area and form ideas for the underlying 3D geological model of an area to be mapped.

The BGS VFR workflow was recently used in cooperation between the BGS and Chilean Geological Survey (SERNAGEOMIN) and the Chilean National Mining Company (ENAMI) for geological mapping in a complex area of Andean Geology. Pre-fieldwork, geologists used GeoVisionary with high resolution satellite imagery, terrain models and geological information to digitise geological features, re-interpret existing maps and identify & prioritise targets for field investigation. This interpretation was taken to the field locations to be verified and augmented by geologists using the BGS digital data capture system (BGS SIGMA), leading to a final geological interpretation and creation of a geological map. Using GeoVisionary and the BGS VFR workflow means that geologists go into the field with a good understanding of the terrain which they are interpreting. Pre-field interpretation and target prioritisation focus the field effort and increase efficiency: valuable field time is not wasted in areas, which could be interpreted with VFR. The result is an improved geological map in less time.



Figure 1. BGS VFR workflow collaboration between BGS, the Chilean Geological Survey (SERNAGEOMIN) and Chilean National Mining Company (ENAMI)

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3D-photogrammetry in the Arctic

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Since the 1960's the Geological Survey of Denmark and Greenland (GEUS) have used photogrammetry to produce geological maps in Greenland employing both aerial and oblique imagery. Over the last ten years, modern digital mapping tools developed at the GEUS Photogrammetry Laboratory have supported field-based geological mapping in Greenland. These include a digital photogrammetric workstation setup with modern 3D-monitors and a specialized software solution that enables high-resolution, 3D-visualization of outcrops in their geographic coordinate system. The tool allows the user to interpret and map geological features from oblique/aerial photos collected from helicopter/boat/aircraft and georeferenced with global navigation satellite systems (GNSS). The GEUS workflow also enables the extraction of structural data as well as instant generation of geologic cross-sections. Furthermore, the identified geological features in 3D and associated databases are exported in standard GIS format for geological map compilation and 3D-modelling.

During the last years, GEUS studies and geological mapping campaigns (in collaboration with the Ministry of Mineral Resources of Greenland-MMR) have focused on the West Greenland Archean and Paleoproterozoic complexes and on the East Greenland basins. Current projects are based on a combination of traditional fieldwork, supplemented with the acquisition of oblique photos from a helicopter along the steep cliffs exposing continuous outcrops. In addition to the geological maps at 1:100 000 scale in Greenland, the projects aim to generate detailed structural maps; analogue studies for petroleum exploration in East Greenland; integration of 3D-photogeology and aeromagnetic data in exploration for strata-bound copper; correlation of geology and results of 3D inversion of MT-data for Ni-Cu targeting.

Geological mapping in the Arctic can benefit greatly through support from 3D-Photogrammetry due to the remoteness of the region, inaccessible terrain and scale of the exposures. The photogrammetry workflow developed at GEUS allows for geological mapping and observation of structures at detailed outcrop scale while allowing for swift changes in observation point and map scale. The method thus provides the geologist with an extremely powerful tool in the interpretation of geology at both local and district scale.







3D investigation of authigenic calcite in lignite by means of Xray microtomography

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Microtomography, together with 3D image analysis, is becoming more and more widely recognized in geological sciences as a powerful tool for the spatial characterization of wide range of different minerals. The main goal of the presented study was to identify different types of authigenic calcite, which often occur in lignite layer of Velenje Basin, Slovenia and analyse their 3D distribution. The latter is important for understanding geomechanical and other characteristics of mineralised lignite as well as for mineralisation genesis.

The calcite in Velenje Basin occurs in two main lithotypes of lignite: xylite and gehlite, which have different amount of xylite component. Based on macroscopic observations six different structural types of mineralisation occur: (1) laminae and thin beds; (2) small lenses and lenticular bodies; (3) dispersed mineral matter in organic detritus; (4) calcite-substituted xylite (organic) fragments; (5) encrusted xylithic fragments; and (6) calcite-coated and calcite-filled pores. Spatial microscopy of different types of samples was carried out with the microXCT400 microtomograph (XRADIA). For 3D image analyses we used AVIZO FIRE (FEI). The final resolution achieved on samples of 3cm in diameter was 31.6 μ m. With 3D image analysis the orientation of lamines, size and distribution of individual spatial elements were determined. After 3D analyses the files were exported to SKUA-GOCAD, where microtomographic data can be integrated in geological modelling and used for models' interpretation.



Figure 1. Calcitic structures in lignite imaged by means of X-ray microtomograph and analysed with AVIZO Fire.





3D visualisation of structural, geochemical, textural and density data of drill cores from X-Ray scanning – New tool for understanding mineralisations

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A scanning technique is presented where a combination of X-ray tomography, X-ray fluorescence and automatic weight measurement is used to scan and analyse drill cores – giving access to high resolution 3D visual information about mineral structures, elemental distribution, textures and density.

Getting digitised data representing the core, and being able to select and annotate planar and linear features in the 3-D volume, is a significant leap forward, together with the ability to export all or selections of the data into geology modelling, and other software.

The technique has been further refined through deployment at two European mine sites – with field tests, use and follow on feedback from geologists – within the European X-Mine project. As part of the project a work flow is also being developed from drilling, scanning, analysing, annotating and 3D deposit modelling, subsequently used for mining.

Extracting this type of data has traditionally been done in several separate steps - many of them also destructive, and requiring long sequences of sample preparation, or being very labour intense. For instance, traces of structures being interpreted by looking at their 2D projection at the drill core surface. The presented technique is producing actionable results within hours, with an aim of keeping up with the speed of core drilling.

Making optimal use of the geological data is key to efficient, sustainable and economically viable exploration and mining, and helps further our understanding of the mineral resources.

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The 3D room at SGU – a new way to visualize the geology of Sweden

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At the Geological Survey of Sweden (SGU), we have recently updated our 3D room/lab. The main purpose of this room is to visualize 3D geological models at both regional and local scales in an integrated manner. Two of SGUs key tasks is to fulfil society's need for geological information and to bring geology and geological knowledge to the fore in social debate and education. Visualizing Sweden's geology in 3D is one way to achieve these goals.

The room is equipped with a 180 inch screen, a DLP laser phosphor projector (with rear projection and a short throw lens) and two Virtual Reality (VR) headsets (HTC-Vive and Oculus Rift). With the visualization software GeoVisionary (Virtalis) and shutter glasses, we can show geological models together with high-resolution elevation data and orthophotos in 3D.

We also made a geologically inspired interactive VR world where visitors can walk around in a room and interact with rocks, geological maps, reports, posters and bedrock models. They can take the elevator up to the roof and look out over different views of Uppsala, Stockholm and Mount Kebnekaise. They can switch the surface between orthophoto, topographic map and geological maps. If they stand at a certain place they are able too change the water level below them. They may also take on the jetpack and fly out over the world below.

On our website, you find all our 3D geological models at: <u>https://apps.sgu.se/sgu3d</u>. This page is made with the 3D Visualization software OpenCities Planner (Bentley) and works well on any platform. Unlike Google Earth, the user is able to look and go below the ground. In the 3D room, one can enter this page in VR.

We invite all conference attendees to come and visit the 3D room at SGU during the conference!



Figure 1. The virtual geology room at SGU

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One Model - Geoscience integration and communication through 3D modelling

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Drilling of electromagnetic plates, geophysical red bumps and geochemical anomalies, often with limited geoscientific thinking behind, is commonly seen in exploration. Reasons for this originate in the fact that historically available tools and working methods often were split into geoscience disciplinary silos, which are still present in many of the exploration projects today.

Today's geoscientists have access to good tools to communicate their thinking through 3D models. Every discipline can provide their input towards building a common geological model that explains the physical and chemical responses observed. Only when the observed responses cannot be satisfyingly represented by modelling of geological units, should we consider that we have something anomalous in the volume of interest.

To facilitate the change from anomaly testing to generating geoscientifically valid targets, focus should be directed to building the best possible models and hypotheses from available data. This is most efficiently done in the 3D environment by including all the data and continuously validating interpretations in one common model.

Exploration projects benefit greatly when they are conducted with a sound understanding of the limitations of the geological, geochemical and geophysical characteristics of the project volume of interest. Working through an iterative integration process, in which the geological model is built using constraints from the geophysical and geochemical responses, involves several different geoscience disciplines and leads to better communication and understanding. Practise of working with common models in a 3D environment also allow us to think thoroughly the model through at a very early stage. This makes it possible to tailor geochemical sampling programs and geophysical surveys to suite the geological environment and to answer specific questions. Adaptive designs assure that the data we collect can be used to test our geological hypotheses or most efficiently direct detect economic mineralisation.

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Improving communication of 3d geological models by integrating borehole and seismic data in a web viewer

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To allow a broader community to engage with geomodels and geodata in 3d space, readily accessible means of communication are needed. Due to recent developments, more and more involved 3d content can be displayed in ordinary web browsers, which allows for a sophisticated visualization of complex 3d geomodels as well. Yet the sole display of modelled surfaces in 3d space is not enough for a thoughtful communication of underlying concepts and rationale. Additional data, especially if it is related to the modelling process, should be presented in such a viewer simultaneously.

For several years GiGa infosystems has been developing GST Web as a platform to display 3d geological models in a modern web browser. Whilst working with several customers, the amount of data to be displayed as well as the data variety kept growing. In general, the raw data used for the creation of such models is requested within the viewing context more and more frequently.

Together with multiple partners, two major raw data types have been prioritized, boreholes and seismics, and a strategy for their visualization has been developed.

The visualization of boreholes allows the end user to get an impression of the overall quality of the model by assessing the number of incorporated boreholes in a certain area and, moreover, the quality of the used boreholes itself for the creation of such sophisticated 3d models.

By adding the possibility to display gridded data, GST Web is now also able to display e.g. seismics together with the model directly in the web browser. Thus expert users can step into the discussion and verify the quality of the model without the need of any sophisticated software package. Tools for visually examining and also querying the data at particular spatial locations provide the necessary tools to asses properties of the model and raw data.



Figure 2. A 3d seismic volume alongside the resulting model allows to communicate the model and its quality easily. After application of a slicing tool it can be seen easily that the horizons follow the seismic clearly.





3D visualisation for resources and reserves evaluation – a case study

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Resources and reserves evaluation are crucial stages at the beginning of each mining project. The evaluation process usually starts with the generation of a 3D geological (resource) model based on exploration data obtained from various sources, e.g. geological mapping, drilling, geophysical surveys, which is then used to design the mine layout allowing the estimation of ore reserves. These are highly complex tasks, which require the application of suitable modelling and design methods and tools to handle and visualise different sources of mining and geological data. In contrast to time and resource intensive traditional methods, modern approaches include the application of advanced 3D software packages allowing fast data processing and analysis of spatial relations as well as evaluation and simulation of different mine layout alternatives and strategies. 3D modelling applications therefore have constantly been gaining significance in exploration and mining, particularly with regards to an increasingly digital environment, the challenging and demanding nature of future mining projects, and the emerging trend of mine site automation. With this case study of an open pit project, DMT aims to demonstrate the importance of 3D visualisation techniques and tools for resources and reserves evaluation.

Applying GEOVIA Surpac and MineSight (Hexagon Mining), 3D geological modelling and mine planning was conducted based on geological and geotechnical data obtained during several exploration campaigns. Starting with the 3D visualisation of the data available, a simplified lithological wireframe model of the deposit was generated. Based on this geological model, a complex 3D resource model (block model) of the orebody was created containing all relevant parameters, such as grade, density, and resource classification.

For reserves evaluation, a geotechnical stability analysis was conducted combining the geological model with geotechnical information obtained from drill core. Based on these results and additional information on processing, mining, infrastructure, and environment, the open pit mine was planned and visualised in 3D. This was completed by a long-term production schedule allowing a financial analysis of the project, and determination of the economically mineable part of the deposit. The resulting 3D Run-Of-Mine (ROM) model simulates the sequence in which the ore will be extracted from the deposit.

The application of specialised 3D software packages for this resource and reserve evaluation exercise significantly reduced time and resource requirements, particularly with regards to complex procedures like geological modelling and geotechnical analysis as well as mine drafting and modelling, and scheduling. They are powerful and inevitable tools for exploration and mining providing a thorough understanding of interrelationships between the spatial data from various sources.





3D geomodeling of the Alces Lake rare earth element project (Saskatchewan, Canada): New insights to targeting mineralization

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3D/4D geological modeling allows us to better understand and interpret a given prospective mineralized area for new targets and to develop effective geo-metallurgical delineation plans for future mining operations.

In this research study, a 3D geological-geophysical model of the Alces Lake property (SK, Canada) was constructed. Alces Lake is a high-grade rare earth element ("REE")-Th-U deposit of critical REEs, located within the Beaverlodge Domain. Seven high-grade zones, plus additional REE showings and prospects, have been discovered to date; in particular Dylan, which consists of up to 31.8 wt% Total Rare Earth Oxides (TREO). The REE mineralized system is hosted by Proterozoic late-orogenic to metasomatic massive braided biotite schist, quartzofeldspathic pegmatite augen, and monazite accumulations that fully host all the REEs. These metamorphic rocks underlying the Alces Lake property have been subjected to upper amphibolite to granulite facies metamorphism and four major phases of folding and deformation. Alces Lake monazites yielded a crystallization age of 1927.1 +/- 1.2 Ma, which places mineralization within the Taltson-Thelon Orogeny.

During this geomodeling exercise, three-dimensional structures, surfaces, and mineralization objects were built based on geological maps, cross-sections, airborne and ground geophysics, whole-rock geochemistry, metal assays, and drill hole data. The model was constructed using the Oasis Montaj and SKUA-GOCAD software packages. Based upon the gravity and magnetic worm data, fault surfaces and major domain boundaries were built. The current 3D model, supported by geostatistical analysis of the given geochemical and metal assay data, shows the distribution of REEs within the property. Although having some limitations due to the lack of deep drill-holes, such a 3D model can provide an excellent base for future exploration, mine planning, and pre-mining activities.



Figure 1. Location and regional geology (left); screen capture of 3D Geosoft model (right).

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Three-dimensional geological mapping and modelling at the Geological Survey of Sweden

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Until a few years ago, the 3D-modelling activities at SGU were limited to the interpretation of different geophysical models, both from airborne and ground surveys. Nowadays, 3D-modelling of geology, including layering, implicit as well as explicit, is undergoing a rapid development at SGU. We expect that in the near future, modelling will be incorporated into our routine activities, such as 3D modelling of aquifers, ore deposits, local and semi-regional subsurface geology and layered geological formations in general. This includes integrated interpretations of the existing surface geological observations, borehole data and geophysical models.

Some of SGU's ongoing work that include 3D-modelling aspects are listed below.

- Aquifer identification and modelling: SGU is commissioned by the government to identify and map aquifers that are important for the water supply in areas frequently subjected to water shortage during drought. Resistivity-models from both airborne and ground TEMmeasurements (Transient Electromagnetic Measurements) are used as input data in the modelling process. The geological features modelled are eskers, glacial deposits, as well as areas with sedimentary bedrock (Öland and Gotland). The work includes both geological layer sequences and voxel modelling.
- Mineral resources are modelled in 3D using geophysical potential field data, petrophysics, geological observations and measurements. Ongoing investigations in the Bergslagen mining district as well as in mining districts in Greece, Bulgaria and Cyprus (X-mine and Smart Exploration projects, Horizon 2020) have resulted in 3D multi-parameter geomodels on a district- to deposit scale highlighting structural features, alterations and mineralizations.
- Soil-depth/rockhead modelling (implicit modelling): the national soil depth model, one of SGU's most requested products, is re-constructed /updated at least once a year, by including new information from boreholes, geophysical measurements and surface mapping.
- Fault modelling in urban areas: engineering geological information from existing tunnel systems is combined with the data from other sources to produce a 3D-model of the fault network in the Stockholm region. The faults are characterized and combined with soil depth, rock and soil type profiles in a 3D presentation on our website. The aim is to provide a basis for the initial planning stages of future infrastructure projects.
- Development of a 3D-room, virtual reality (VR), visualization on the web and 3D-printing of models.





Visualizing complex Quaternary stratigraphy and weathered/fractured bedrock zone with Leapfrog Geo in Sakatti area, northern Finland

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Leapfrog Geo (Seequent Limited) was used to construct a 3D model of surficial sediments and upper fractured and weathered zones of bedrock in the valley of the River Kitinen area covering the Sakatti mining project (Brownscombe et al. 2015) area. In this study, we tried to find an optimized way to visualise the geology of the area with Leapfrog. We also tested importing of the complex 3D model to a graphical user interface for further groundwater flow modelling.

The stratigraphy of the area is complex due to several stadial/interstadial cycles that have deposited interlayered glacial and fluvial deposits. In addition, weak glacial erosion has in many places preserved thick remnants of the Neogene weathering crust (Hall et al. 2015) below the sediments. There is a large Viiankiaapa mire on top of the sediments as well as the River Kitinen flowing through the study site.

GIS-based data from drill holes, sediment samples, ground penetrating radar surveys and sediment sections were used as the input for the 3D model. The major factors that define the geological structure within the study area are interlayered glacial and fluvial deposits, thick weathering zone and fractured upper zone of bedrock. The modelling method was a combination of implicit and explicit modelling. The bedrock surface was modelled with a combination of both. The weathered and fractured zone were represented as offsets surfaces from the bedrock surface and drill hole data. Glacial and fluvial deposit layers were modelled manually with Leapfrog's polyline editing tools since most of them were sediment samples of random depth without a full profile.

In the end, input data determine how to use Leapfrog tools in modelling. GPR data showed very detailed structures whereas soil samples only gave information about sediment type. Due to the variable nature of the input data, explicit modelling was detected to be more useful in constructing the sediment layers. However, since Leapfrog relies on layered structures, modelling scattered unconsolidated sediments, such as river deposits, require a lot of polyline editing. By relying on only implicit modelling with our complex dataset with infrequent complete layers structure/stratigraphy, Leapfrog generates unrealistic models. Thus, the understanding of possible connections and knowledge of sediment deposition is needed to develop the model further. The 3D model was simple to convert as MODFLOW groundwater flow model and it was easily edited with ModelMuse graphical user interface.

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Implicit modelling techniques applied to vein deposits and lithologies with 3D modelling software

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Modelling deposit domains and lithological surfaces is an important task for resource estimation. This domain envelope limits the volume of resources that can be estimated. The orebody or domain has a substantial impact on the economical assessment of a mineral deposit. Over the last years, efficient methods for implicit modelling of deposits have been available for resource estimation. These methods allow an efficient interpretation of a drillhole database, while allowing standardization of the geological modelling process. This translates into large time savings in the geological modelling tasks. This presentation outlines the implementation of the tangent surfaces method for modelling vein deposits and the implementation of radial basis functions for modelling lithologies. Case studies highlight the advantages of these methods. The methods are implemented within the suite of Promine software, a geology and mining software integrated to AutoCAD.

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Geologic 3D model within Alaliesi seismic profile in Sodankylä, northern Finland

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Experiment of Sodankylä Deep Exploration (XSODEX) project acquired data in a collaboration between Geological Survey of Finland (GTK), University of Oulu (UO) and TU Bergakademie Freiberg (TUBAF) in 2017-2018. Deep structures of the earth were investigated with reflection seismic survey and audiomagnetotelluric (AMT) measurements to the depths exceeding 3 km. In addition, gravity and petrophysical data was collected along the seismic profiles. These data sets were utilized in constructing a regional scale geological 3D model of the Sodankylä area in Central Lapland Greenstone belt (CLGB). The data, modelling methods and the 3D geological model are presented in here from Alaliesi sub-area.

A geologic 3D model is representation of bedrock map in 3 dimensions. A model needs always to be in most parts well correlated with the input data (geophysical surveys) and it needs to have a connection to the geological history of the area expressed as a geologic map at the surface. The use of 3D modeling techniques forces a modeler to consider scenarios that need to be realistic. Thus a 3D modeling exercise eventually can raise new questions in addition to the new insights to the geology of the study area.

The Alaliesi area consists of a section of the stratigraphically lowermost units of the 2.45-2.0 Ga Central Lapland Greenbelt, located in the proximity of 2.45 Ga Koitelainen layered intrusion. Based on current geological maps Archaean basement rocks are explosed in the central part of the intrusion. This feature has been interpreted to be due to a basement dome at the footwall of the sheet-like intrusion. In contrast to this large scale lateral geological feature, the supracrustal rocks appear to be more tightly folded and N-S and NE-SW trending. Thus, the area provides structurally very interesting modeling target.

Prior to geological modelling unconstrained 3D inversions done for potential field data for understanding the orientation and depth extent of the lithologies. Reflection seismic data, 3D inversions and AMT data were used in conjunction with bedrock observations and drill core data in generating the geological 3D model. The modeled geological features consist of the most critical parameters defining the mineral systems for orogenic gold and magmatic Ni-Cu deposits, i.e. the main structures and main intrusions and other geologic formations. The 3D modeling can be considered always to be iterative. The initial geological model is used in generating geological y constrained 3D inversions of the potential field data and subsequently modified back into a final geological 3D model. Mineral prospectivity models for orogenic gold and magmatic Ni-Cu deposits will be generated based on the modeling results for the study area.

This work was done within European Regional Development Fund "Exploration Lapland 3D – XL3D" – project EURA2014 code A73339.







3D modelling of the dolerite dyke network within the Siilinjärvi phosphate deposit

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This work aims at providing geologically constrained 3D dyke network models allowing the estimation of the volume of waste rock (dolerite) dykes transecting the Archaean Siilinjärvi phosphate deposit in Eastern Finland. The deposit is cut by several populations of dykes, of which the sub-vertically oriented ones are well-constrained, but the continuation of sub-horizontal ones is poorly known. This work integrates dense production drilling data (Fig. 1), exploration drillholes, photogrammetric 3D models and GigaPan images, open pit mapping and Ground Penetrating Radar (GPR) data to generate detail-scale models from the southern part of the deposit. Subsequently, the detail-scale models are extrapolated to cover the whole deposit, and correlated with reflection seismic data and in-depth drillhole data.

The work at the detail-scale has shown that i) field geological constraints, such as systematic offsets of dykes along minor reverse faults and the topological relationships of the dykes of different generations, are required to distinguish variably oriented dykes from production drilling data from the already excavated parts of the mine, and ii) GPR may be used to recognize important structural features, in the present case providing dip constraints for features recognized in the open pit walls. At the larger modelling scales, the kinematic framework including the pre-dyke structural framework and the shear evolution of the major sub-vertical shear zones transecting the deposit play a major role in defining the present-day geometry and extent of the deposit.

The work is conducted under the Smart Exploration project. Smart Exploration has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No.775971. The GigaPan images and photogrammetric 3D models have been produced by the Digital Leap Project of the University of Helsinki, Finland.



Figure 1. A and B: Production drilling based contacts of the dolerite dykes. A = unclassified, B = grouped into orientation sets. C and D: Examples of sub-horizontal dykes modelled based on the production drilling data.





3D integrated geophysical modelling of the Kautokeino greenstone belt in Finnmark in northern Norway

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The Palaeoproterozoic Kautokeino Greenstone Belt (KKGB) in Northern Norway has been analysed by integrating all available geological and petrophysical data in combination with 3D density and magnetic modelling into a crustal-scale 3D structural model. The new high-resolution geophysical data and surface observation have made it possible not only to identify several new structures but also have shown that the existing geological maps must be corrected. The study area was expanded to include northern part of Finland and Sweden to have a better control on the regional setting of the KKGB and to reduce the border edge effect around the key area. Even though the northern part of KKGB is covered by metasedimentary rocks of Caledonian nappes, gravity and magnetic integration enabled us to trace KKGB northwards and link it with the other exposed parts in the tectonic windows in the northern part of the belt. Based on the new 3D model, Kautokeino Greenstone Belt is interpreted to be longer and broader than it had been proposed before. The 3D model suggests that the belt reaches depths of approximately 5-6 km (7-8 km locally) which is located as a varying dipping structure between the Jergul Gneiss Complex (JGC) in the east and Cierte greenstones in the west. The Raiseatnu Complex (RGC) along the western margin of the KKGB is characterised by magnetic anomalies trending NNW-SSE parallel to the main KKGB. In addition, there are some circular anomalies which have not been mapped geologically. In the new 3D model, the greenstone belt is assumed to include the RGC complex as a migmatized portion of KKGB . The Kautokeino Greenstone Belt is highlighted by a sequence of high and low gravity anomalies where most of the negative gravity anomalies are assumed to be caused either by the Masi quartzite or granitic bodies or a combination of both. An elongated gravity low in the central, northern part of the KKGB coincides with the Čáravárri Formation, representing the youngest sandstone unit within the KKGB. The highmagnitude positive gravity anomalies are due to dense rocks of amphibolite-facies volcanosedimentary rocks. The depth extension of some of these structures, for example the Adjit granite, reaches 7-8 km. This shows at a large scale a similarity of this Proterozoic greenstone belts to their older Archean counterparts where most of the deformation is most likely caused by gravitational tectonics. This study shows that careful integration of geological and geophysical data can vastly improve the 3D understanding of complex, poorly exposed terranes of the northern Fennoscandian Shield.





Error analysis of clastic dyke dip measurements using digital outcrop data: An example from the Dosados Canyon, Panoche Hills, California

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The focus of this study is to address the challenges associated with measuring the geometry of irregular bodies, in this case sandstone intrusions. Uncertainties and errors are common in physical measurements, and it is important for such errors to be estimated in order to validate our results and develop better interpretation techniques. Inaccuracies in measurements, due to nature of the exposure, limit the accuracy and precision of our results. These inaccuracies give rise to reduction in the confidence level of our resulting statistical dataset of body size and orientation. In this study, a virtual outcrop of the Dosados Canyon, produced from terrestrial lidar, was utilized to acquire dip measurements of discordant sandstone intrusions in order to quantify the geometry and topology. Because sandstone intrusions alter the structure of hydrocarbon reservoirs, promoting migration and discharge of reservoir fluids, as well as increased connectivity, it is highly essential to develop a representative model of their geometrical characteristics.

The conducted analysis involved taking 50 repeated dip measurements of 20 sandstone dykes and evaluating the distribution of the measurements statistically in order to extract an estimate of the present errors. Using a normal distribution, it was determined that 68% of measurements lie within 1 standard deviation of the mean, while 95% lie within 2 standard deviation of the mean. The margin of error was considerable when interpreted points were close to collinear. This shows that there is a need to improve current interpretation techniques for geometrical characterization of complex irregular bodies in field areas of low topographic complexity. Future works will focus on addressing these challenges.

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The Water Story - Obtaining a social licence for groundwater abstraction at Kurikka aquifer, Finland through the use of a community accessible hydrogeological data and software platform

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The Water Story -rollup is a story of cutting-edge science, technology and democracy: how geologists, IT specialists, municipality officials and water companies have worked together to win public support for extracting water from the Kurikka aquifer.

Groundwater has a strategic importance in Finland, especially in western coastal areas that lack large groundwater bodies. The city of Vaasa is the capital of the Ostrobothnia and has always been struggling with sufficient access to clean drinking water, which is largely sourced from the surface water. After the discovery in 2010 of large buried valley aquifer system in the Kurikka region the water supply company of Vaasa became interested in the resource as a much more sustainable alternative. The region of Kurikka has been developed into an agricultural centre in the Finland due to a presence of clean and sustainable groundwater resource. The local community have a strong connection to their natural environment and concerned about the environment. Water is important for everybody and geologists here are trying to convince people that extracting groundwater is safe and sustainable.

A massive geological surveys in the region proves hydrogeological units interlink between bedrock faults, fractures and other structures, the topography of the bedrock surface and glacial deposits above. Buried valley aquifers are connected to high standing areas covered by sands and gravels formed under the shoreline processes. The 50 - 100 m deep bedrock palaeovalleys are filled by multiple thick sand and gravel beds (aquifers) with till (aquitards) between them, and a marine clay/silt deposit forms an impermeable cap for the aquifer system.

Due to the hydrogeological setting and the long route from the recharge area to the valley bottom the clean groundwater circulation and storage is enough big for Kurikka and Vaasa cities. The local community is very proud of their clean natural environment where their organic and wide variety of agricultural products come from. The future challenge for the water companies therefore is not the water treatment, but to demonstrate to the local communities and landowners that the large water use and drawdown of groundwater will not adversely affect the local environment.

To achieve this the Geological Survey of Finland and Brittish Geological Survey are now working together to develop a free and open web system, which will be able to display live and historic groundwater level monitoring data in boreholes, cross-sections and maps, putting the data in context with real world geological features. The project is as much a geological or technological challenge as a social experiment to see if better visualisation of complex scientific data will give the water companies the much needed social license to secure Vaasa's and Kurikka's future demand for water.





Use of complex 3D hydrostratigraphy in groundwater flow modelling to estimate groundwater recharge/discharge patterns in mining development site

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An evaluation of the water balance is a crucial part of the environmental assessment of mining projects, and it can be studied and visualized with 3D flow modelling using a graphical user interface. The use of 3D hydrostratigraphical modelling is often beneficial (Artimo 2004, Barthel & Banzhaf 2016, etc.) especially when there is a large variation of hydraulic conductivity and complex lithostratigraphical package of sediments affecting groundwater flow patterns and groundwater discharge. In sensitive natural environments, this can be an important environmental factor.

The Sakatti exploration project in northern Finland (Browncombe *et al.* 2015) is located in an area of complex hydrostratigraphy that consist of unweathered/competent or weathered/fractured bedrock units and variating till and sorted sediment units (Åberg *et al.* 2017). Understanding of the surficial Quaternary aquifer-aquitard system and its possible connection to the fractured/weathered bedrock aquifer is needed especially in order to evaluate groundwater dependency of the ecosystems in Viiankiaapa mire that occupies the terrain above the Sakatti ore deposit.

MODFLOW has been commonly used for conditions that are applicable to Darcy's law. However, it can be used in bedrock as well if the fractured zone can be assumed to behave like porous media. In northern Finland, it is common that Quaternary unconsolidated sediments can locally cover weathered/fractured bedrock, which can in some locations be highly conductive and behave as an aquifer. The variation of sorted glaciofluvial sediments and glacial tills creates a complex aquifer-aquitard system depending on variations of hydraulic properties within the units. While the variation and the extension of the confining and the conducting units can be poorly known, the 3D flow modelling with the graphical user interface like open source ModelMuse (USGS) can be used as a tool for estimating the reliability of the expected hydrostratigraphy by studying the groundwater discharge-recharge patterns. Simplification of the stratigraphy is needed, and it can be compensated with variating hydraulic conductivities with interpolation within the layers. In bedrock, it would be important to understand and define the variation of hydraulic conductivity within discrete fractures and chemically differently weathered unit.

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Volcanic Igneous Plumbing Systems (VIPS): A multi-scale Analysis in 3D

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Field observations of volcanic and igneous plumbing systems (VIPS) date back to more than a thousand years, e.g. the 79 AD eruption of Mt. Vesuvius destroying the city of Pompeii. Traditionally these observations were initiated to describe the hazardous nature of volcanic events. However, the wide range of scales of field observations and the traditionally outcrop-dependent geoscientific approach can make their understanding difficult. Today's technological advances for outcrop data acquisition, e.g. user-friendly Unmanned Aerial Vehicles (UAVs; "drones"), photogrammetry and structural measurements with mobile devices help to significantly speed-up and improve the data coverage in the field.

In the VIPS research group, we use different tools and software packages, e.g. *CloudCompare*, *MicMac*, *Lime*, *Agisoft Metashape*, *Move*[™]/*Fieldmove Clino* (Midland Valley), to analyse extended field data sets. These tools allow us to: (1) constrain 3D geometries, volumes, and fracture networks of igneous bodies at various scales, (2) reconstruct (volcano-)stratigraphic units and their deformation history using kinematic models, and (3) develop detailed maps using 2D orthophotos, digital elevation models (DEMs) and 3D outcrop models. Moreover, the combination of traditional field descriptions, photogrammetry, and quantitative structural measurements with a high spatial precision allows for a more comprehensive, time-effective and reproduceable analysis of our field data even at distance from the actual field area. This remote accessibility and the comprehensive datasets can significantly improve hazard-analysis and support both scientific impact and societal outreach.

We will present examples of studies that apply the above-mentioned techniques and that range in scale from hand specimens (cm) to plutons (km; Fig. 1).



Figure 1. 3D visualizations of photogrammetry data. (a) Point cloud showing small scale features: microcracks (blue) and planes of crystal alignment (yellow). (b) 3D model of a mafic dyke displaying meso-scale features: fracture networks (green) and intrusion morphology. (c) Textured digital elevation model with large-scale interpretations of fault systems and intrusion geometry (red).





3D-Photogrammetry in the Arctic – Interactive presentation

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Photogrammetry is a classical remote sensing technique that enables the user to extract three dimensional outcrop data from stereo images. It has historically been a key tool within the topographic and geological mapping society. Nowadays, digital photogrammetry has become a prime supplier of three dimensional input data for digital outcrop models that can be visualized in virtual reality environments. In this interactive presentation we explore how classical stereo imaging techniques using just raw stereo images and human stereo vision is still an important component in the visualization of three dimensional data as well as in the geological workflow implemented at the Geological Survey of Denmark and Greenland (GEUS). Central to the presentation is the digital photogrammetric workstation, which is essentially a photogrammetric software running on a computer that is connected with a stereo-display system for visualization of the geological outcrop data. Using examples from GEUS mapping programs in the arctic we aim to stereoscopically demonstrate the potential of classical photogrammetry.

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Session "Outreach and communication"

Session chair: Tobias E. Bauer, Luleå University of Technology, Sweden

Visual3D conference 2019

Visualization of 3D/4D models in geosciences, exploration and mining

Dept of Earth Sciences, Uppsala University Uppsala, Sweden 1–2 October 2019

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Keynote: Making geoscience accessible to all through digital technologies

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There is currently and explosion in the use 3D data, and particularly VR and AR, for teaching, outreach and communication across many disciplines (medicine, geosciences, engineering among others). Though 3D visualisation approaches and systems have been around for some time now, the technology has only recently become suitable for mainstream use. The current VR systems are easy to use, take up minimal space and are available at reasonable costs, making them feasible for use in teaching and communication at a variety of levels. In addition to the hardware, the costs and expertise required for building photorealistic 3D models has reduced greatly, and the wealth of available elevation data and satellite images makes the building of virtual field trips for a whole variety of purposes readily achievable.

In the geosciences we deal with having to understand geological features at a variety of scales from microscopic and smaller through to global, this is taught in traditional lecture and practical classes. To assist with this understanding, we also take students into the field to experience the scale of outcrop geology first hand in the real world. This problem-based constructivist approach requires students to synthesise information and to make interpretations of complex 3D and 4D spatial and temporal relationships. These fieldtrips are crucial to the understanding of geoscience but are expensive both financially and logistically and often inaccessible to students with disabilities. As these trips are both essential to learning geoscience, and are a requirement for accreditation of geological programmes, ensuring we get most out of the learning experience is essential.

In addition to the education side 3D visualisation can be used to enhance public understanding of what the geosciences are, and why we are important. Geoconservation is another area where digital datasets are finding more use. We can now capture a geological site before it is lost, overgrown on degraded by weathering, and then provide that data to a wide audience, ensuring the continuation of our geological heritage for year to come.

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Adding the third dimension to historical maps of mining districts: A novel interactive augmented reality setup

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An experiment conducted by the authors demonstrates how the visualization of historical maps of mining districts from the collection of the TU Bergakademie Freiberg can be enriched through a novel interactive spatial augmented reality setup. Printed or hand-drawn two-dimensional depictions containing topographical information are amended with projected lighting and shading so that an illusion of observing a three-dimensional surface is created. The virtual depth clues on the paper surface are rendered in real time while a user interacts with the system via smartphone, increasing visual realism and improving spatial perception.



Figure 1. Two-dimensional historical maps (left figure) are augmented with lighting and shading rendered from digital elevation models (middle figure). Right figure: a projector (not seen in the picture) overlays the paper depictions with new depth clues. The tracked pose of a smartphone defines the position and orientation of the virtual spotlight source, producing the illusion that the smartphone is lighting a three-dimensional surface.

Lighting and shading augmentations are generated from data of a 25 m resolution digital elevation model (DEM). It is important to notice that very old maps are not as precise as modern DEMs, so distortions must be taken into consideration when projecting over the real map. The elevation data is cropped to fit the map area and used to generate a three-dimensional elevation grid with 1000x1000 vertices. This elevation grid – colored with a white material without texture or specular reflections – is illuminated by a virtual spotlight source, creating a rendered pattern of lighting and shading that is then projected over the real printed map. The virtual spotlight is rotated and translated according to the tracked movements of a smartphone held by the user. Tracking is implemented by standard state-of-the-art augmented-reality APIs available for Android, and tests were made with a Samsung Galaxy S9. Turning on the light-flash of the smartphone is not necessary for the setup to work, but doing so increases the realism of the experience.

The proposed setup is relatively affordable (when compared to alternatives like head mounted displays or CAVEs) since it is composed of only one smartphone, one PC and one projector. Preliminary tests reveal that interaction is very intuitive, and that depth information is perceived not only by the user that directly interacts with the system but by all passive observers, resulting in a valuable tool for group visualizations.





The benefits of organized networking and matchmaking for the development of 3D/4D geomodel visualization

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While huge territory of the EU shows a very high exploration potential and many EU countries remain attractive to investors (e.g. Fraser Institute, 2015), a mere 4% of global exploration expenditure is currently invested within European countries. One tool to trigger a higher degree of investment in exploration and to secure the domestic supply of both main commodities and critical raw materials (CRM) is to enhance our three-dimensional geometric understanding of the Earth's crust.

For these reasons, EIT Raw Materials decided to fund the Visual3D network of infrastructure (NoI) for three years (2017–2019). Visual3D involves to-date 14 partner organisations from nine EU countries. The NoI aims to integrate expertise within exploration and 3D modelling from industry, academia and research institutes, with the ambition to increase the understanding of geological bodies in 3D and 4D through improved visualisation techniques. The network believes firmly that the integration of novel visualization technologies (e.g. virtual and augmented reality) into workflows of exploration, mining and geoscientific research will bring a much-needed innovation boost to the European raw materials sector and increase its competitiveness.

During its first year, Visual3D has compiled the network expertise and infrastructure regarding visualization tools available at the partner facilities. An overview of this infrastructure, as well as projects conducted by network partners is available on the Visual3D homepage (www.visual3d.info). The network also managed to identify common issues in the field of geomodelling, the solutions to which may be facilitated by a pan-European network approach, such as data compatibility, communication of geomodels, as well as complexity and variety of software. Subsequent years have been dedicated to the conceptualization of possible projects in order to solve the issues name above, as well as matchmaking to find expert consortia for these projects.

So far, four workshops including project partners and invited external stakeholders have been held. Networking and matchmaking during these workshops has resulted in successful project proposals in the EIT RawMaterials KAVA calls for educational (MireBooks), as well as upscaling projects (FARMIN). Both these projects are presented at the Visual3D conference 2019. Further project ideas have been discussed within Visual3D and will be developed further.

The benefits of organized networking in novel research and developments fields, such as visualization of 3D/4D models for exploration and geosciences, has become apparent during the lifetime of the Visual3D network. The network partners would encourage pan-European funding institutions such as EIT RawMaterials to provide continuous funding to similar networking initiatives, especially in highly innovative and novel research fields. Well-organized communication between different stakeholders is the basis of technological innovation and has the potential to give the European raw materials sector the leading edge in this highly competitive global market.





Virtual minerals industry education

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The mining and mineral processing industries are significant employers and major contributors to Australia's economy. However, few people in the Australian community have ever visited a mine or have a clear appreciation of the integrated nature of modern mining or mineral processing activities. Logistical and occupational health and safety considerations make site visits very difficult, even within tertiary education programs, and so alternative digital approaches are required to educate the entire community about the mining process. The challenge for educators is to capture and present the diversity of minerals operations using media that can provide immersive, explorative and non-linear experiences for a range of potential participants, including primary and secondary students, tertiary students, industry professionals and the general public.

The University of Tasmania and University of South Australia are producing a range of 'virtual' products that incorporate full-spherical panoramas, 360 degree and conventional video, photo-realistic 3D models derived from terrestrial and UAV photogrammetry, and deep zoom gigapixel images. These digital resources are weaved into educational narratives that explore topics from the fundamentals of geology to specific skills used in the mining and mineral processing industries. The most appropriate medium for delivery of virtual content depends critically on the target audience. We integrate immersive visualisations into game-like challenges for primary and lower secondary aged students, produce interactive virtual tours for upper secondary and tertiary students as well as industry professionals, and augmented reality experiences for all sectors. The scope of the educational material ranges from introductory field activities and applications that showcase significant geological sites, to complex tours that document the entire minerals process from greenfields exploration through to secondary metallurgical processing.

This project is supported by the Australasian Institute of Mining and Metallurgy Future Professionals Program, and has logistical and in-kind support from a number of Australian mining and mineral processing companies. The project outputs will be made freely available for interactive use and download and we will systematically evaluate the educational efficacy of these tools. The first public release is scheduled for the end of 2019. This presentation will showcase the diversity of virtual educational and outreach resources that we have generated and describe our plans for expansion and enhancement of this initiative.

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A mobile app to visualize 3D geological structures in a collaborative augmented reality environment

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Fully understanding a complex, three dimensional geological structure has always been a challenging endeavor and is largely connected to the geological experience a curious observer has built up over the years. While we are leaving two dimensional geological maps behind with great strides, the inspection of 3D scenes in specialized programs can be a tricky process, even without taking into consideration that not everyone has access to expensive expert software. To gain a basic spatial and structural understanding, a user usually has to move the camera around the model on their own or be presented with an animation. A still image of a three dimensional scene will not suffice by itself.

And while solutions are in place to allow more and more people to visualize and manipulate three dimensional geological models, e.g. via ordinary web browsers, new technologies such as virtual and augmented reality (VR and AR) present new opportunities for improving access to, and understanding of these models. Although VR has left its novelty status behind in the last years and certainly arrived in the mainstream, it remains somewhat inaccessible due to involved technical requirements, the need to isolate oneself from the environment, or just sheer upfront cost. AR on the other hand has a lower barrier to entry by being supported on more and more common handheld devices such as tablets and smartphones and is thus readily available to a large portion of people that can quickly give it a try.

To explore the potential of AR more deeply, a prototype iOS app has been implemented which allows users to access a number of geological models, place and manipulate them in augmented reality and even share their session with others. When a session is shared, all users taking part are able to visualize the same scene at the same location in augmented reality. Everyone is then able to interact with and manipulate the scene, which in turn is seamlessly communicated with all other connected clients. This makes it effortless for all participants to explore the model at their own pace or to point out special features to others. Furthermore, all sessions are accessible from a website which allows for both the manipulation of scenes and the guiding of groups through a model.

Technologies used include ARKit and ARCore for augmented reality as well as Firebase to enable collaboration. The geological models are currently still stored on device, but it is planned to provide them from a central source, in this case GST Storage, to reduce effort of model preparation and conversion. GST would be able to seamlessly provide models for the app right after their creation, independently from the modeling workflow that has been used. It would also provide additional functionality such as the dynamic creation of virtual boreholes or intersections, enriching the user experience significantly. Even without a more sophisticated backend, features implemented on device such as an exploded view or animations hold potential to improve the usability.

A very rudimentary prototype for Android exists as well and could be brought up to par to reach even more people. In addition, refining this approach for mixed reality devices such as Microsoft's HoloLens remains an exciting opportunity for the future.





Urban geological models on the web

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The models show key parts of the revised 'construction geological map' concept.

 Fracture/weakness zones: generally brittle deformation zones with poorer rock quality and often higher permeability. Where information has been available from tunnels etc., sections of these zones have been locally visualized and identified as 'high confidence' (relative) in the menu tree. Clicking on such a zone brings up a selection of available information. Adjusting the transparency in the tools menu allows you to see the 3D extension of the zones beneath the ground surface.

At the surface, assumed lateral extension of these zones are visualized with 'middle' confidence (blue) and other zones, based largely on topographic lineaments (linear depressions), are visualized with 'low confidence' in green.

- 2. In Stockholm the regional folding pattern in the bedrock has been visualized. In Gothenburg the bedrock conditions have allowed a simplified bedrock model to be visualized covering the municipality.
- 3. Soil, soil depth and bedrock profile: clicking on a position activates links to SGU's databases and provides a visualization of the soil and rock types as well as the overall soil depth at that point.
- 4. Both the Stockholm and Gothenburg models are supported by written reports that summarize the local geological conditions and the geological evolution.

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Session "Software and implementation"

Session chairs: Miguel de la Varga, RWTH Aachen University, Germany Simon Virgo, RWTH Aachen University, Germany

Visual3D conference 2019

Visualization of 3D/4D models in geosciences, exploration and mining

Dept of Earth Sciences, Uppsala University Uppsala, Sweden 1–2 October 2019

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Parametric surface-based geological representation: Application in virtual and augmented reality

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Virtual Reality techniques are nowadays increasingly used for the visualization of geological models. In geological interpretation, the immersive and stereoscopic rendering in virtual reality can help engineers to gain better insights. However, most of these models are static and lack the possibility of manual modification. Here we present examples of parametric surface representations as a possibility to bring interactivity to geological modelling.

Common representations of 3D models in virtual and augmented reality are 2D surfaces of 3D solid objects. In computer graphics, implicit and parametric representation are two major approaches for surface representation. In the parametric surface representation, instead of dealing with 3D problems on the surface, we are dealing with 2D problems in the parameter domain with some control points. Manipulating these control points makes it easy and intuitive to modify geological models in VR.

We showed two different examples of parametric surface approaches; NURBS and Subdivision Surfaces. NURBS (Non-Uniform Rational B-splines) is a popular and common standard for CAD (Computer-Aided Design). These surfaces are based on NURBS curves and a set of weighted control points. Subdivision Surfaces defines smooth surfaces after a series of refinement and are a popular tool in animation, computer games and entertainment industry. In this technique, each of the regions, based on its complexity can have an individual number of control points which help engineers to have finer details and better control in the complex regions of the surface.

In recent years, some groups have explored the possibility of using NURBS to model some geological structures and reservoirs. However, based on many computer graphics references, one of the main drawbacks of this method is that adding new control points to an existing surface may be difficult. Also, many NURBS patches are needed for modelling complex geometries. Geometrical constraints of these surfaces patches complicate the surface representation. By using subdivision surfaces instead of NURBS, adding control points and also modelling and controlling complex geometries will be easier.

In this interactive demonstration, we compare NURBS and subdivision surfaces as two promising techniques for parametric surface-based representation of geological models in VR and AR.

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Session "Research and development"

Session chairs: Florian Wellmann, RWTH Aachen University, Germany Simon Lopez, The French Geological Survey (BRGM), France

Visual3D conference 2019

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Keynote: Surface analysis and reconstruction from point sets Julie Digne¹

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Surface analysis is often performed on meshes reconstructed from 3D measures. However the acquisition devices seldom output meshes directly, the raw output being in many cases a list of unordered 3D coordinates. In this talk, I explain how valuable information can be estimated directly from this raw output namely a point cloud describing a surface. First I review some methods to improve the surface quality and efficient storage by taking into account the self-similarity of surfaces, then I describe a way to describe local surface variations that permit to modify the local surface dynamics, exaggerating the details by point position modification or even inverting and skewing the details by modifying the normals to the surface. A third part of the talk is dedicated to geometric shapes with both curve and surface parts. This challenging data is common at a LiDAR acquisition scale for example. This type of data can be elegantly handled using machine learning tools and a local probing field descriptor, encoding the deformation of small templates onto the surface. I will show Applications to consolidation and denoising of surface data.

Relevant references:

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Mapped vs. simulated uncertainty: which aspects of geological model uncertainty can be estimated with stochastic simulations?

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In recent years, several methods have been developed to quantify uncertainties in 3-D structural geological models - often based on the analysis of multiple automatically generated model representations. These representations are usually obtained through stochastic simulations, which are based on multiple assumptions and simplifications. The valid question is therefore: are these estimates of uncertainty really meaningful?

We have generally no way to evaluate if we capture the complete uncertainty in a practical context, as we do not know the true complexity of the underlying geological system - in geology, there are many "unknown unknowns". However, we can compare these automatically generated models to sets of models created by different geologists for the same region, if multiple comparable models are available, which is certainly the exception.

One such data set is, fortunately, available from a study of twelve years of a geological mapping and modelling exercise within an area near Alès, France (Courrioux et al., 2015). This study reveals a high variability in the resulting geological models regarding layer interface positions and fault surfaces in 3D space. This raises the question of the source of this variability – is the variation in the resulting models due to measurement errors or are important features missed during the mapping process? In other words, can the epistemic uncertainty observed in the twelve geological models be captured and, ideally, represented as an aleatory uncertainty?

To address this question, we performed geological mapping in the same area with the dedicated aim to obtain measures of uncertainty for each observation, where possible. This information was then fed into a stochastic geological modelling process and the resulting estimated uncertainties were compared to the variability in the manual interpretations. We generally observe a good agreement, although differences remain. We discuss potential sources of these differences, which are potentially related to bias, limited sampling, and the basic fact that geological observations always depend on previous experience and expectations. Still, the results are promising for a wider investigation into the use of stochastic modelling approaches to quantify subsurface uncertainties.

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Field augmented reality for mineral exploration and mining — An upscaling project

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Currently, it is still common practice in the mining industry to display three-dimensional geological, geotechnical and resource data and models as 2D projections on maps, office computers and in written reports. This introduces uncertainties and time inefficiencies regarding data acquisition, interpretation and decision-making. The need in the mining and exploration industry for an improvement of these workflows, as well as for more objective and accurate data, facilitated quality control, as well as more cost-efficient and accurate exploration targeting, has been identified within the VIisual3D network of infrastructure (www.visual3d.info). The FARMIN project aims to develop an augmented reality (AR) solution that visualizes 3D geological data and allows exploration and mining professionals to modify models in the field.

We aim to close an identified development gap in the visualization of geological data: the link of gathering data in-situ, updating the models and match virtual and real coordinates while exploring in the field or working in a mine site. We will close this gap in this project, by combining developments on highly efficient 3D geomodelling with state-of-the-art augmented reality (AR) hardware and software, as well as expertise in exploration and mining. The resulting solution will be a game changer for how geologists see and collect data and update their models in the field and in the mine.

Augmented reality smartglasses (e.g. Microsoft HoloLens) enable users to interact with highdefinition holograms in the real world. Microsoft Hololens, for example, allows users to view, control and interact with 3D content using their hands and voice. Field-compatible augmented reality solutions, including but not limited to Microsoft HoloLens technology, coupled with interactive IoT (internet of things) networks allow not only for the manipulation of holograms in a mock-up size, but even in real scale and location. Similar technology has been successfully established in other industrial sectors such as for construction and maintenance, resulting in increased efficiency, as well as reduced operating costs and working hours.

The combination of geomodelling and AR technology will be based on GemPy, an open-source library for implicit geological modelling, developed by RWTH Aachen University, and rexOS, an AR-operating system, developed by Robotic Eyes GmbH. The remaining project consortium consists of two European mining and exploration companies (Boliden Mineral, MATSA Mining), as well as a major consulting company for the mining sector (DMT), a business development company (LTU Business) and a university partner with strong expertise in exploration and ore geology research (Luleå University of Technology). The project will kick off in January 2020 and run for three years. Continuous updates on the project progress will be published via the project homepage, as well as social media channels.





3D modelling of bedrock and ore deposits: Insights from XRF-XRT drill core scanning and field surveys in Sweden and Europe

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Modelling the subsurface for mineral resources demands integration between geological, geochemical- and geophysical datasets. As a starting point for modelling, geological information can be extracted from existing maps, depth profiles, field reports and geophysical surveys. However, hard constrains for modelling the third dimension can only be obtained from drilling. As such, data from historical drilling and drill logs are a critical input to mineral resource models. If the drill core is well preserved, additional information can be collected by re-sampling, re-logging and analysis according to modern standards (chemistry, petrophysics, textures etc.). Unfortunately, most types of rock analysis are expensive and time-consuming. Typically, it will take up to 4-6 months before the results are delivered and it is not until then interpretation and modelling can be undertaken.

The X-mine project (EU, Horizon 2020) aims to: 1) Analyse drill cores for its chemical composition, structures/textures and density by fast (hours), non-destructive scanning combining XRF (X-Ray Fluorescence) and XRT (X-Ray Transmission) and 2) Interpret and implement the scanning results into a tree-dimensional workspace allowing fast updates and refinements of the 3D orebody models while drilling. To test the above, 3D near-mine models of four mining sites in Europe have been produced on various scales, which all will be used as frameworks for planned orebody (in-mine) modelling using data derived from combined XRF-XRT scanning. The test sites are: the Assarel porphyry copper deposit in Bulgaria, the Stratoni Pb-Zn-Ag-Au carbonate replacement deposit in northern Greece, the Lovisa stratiform Zn-Pb sulphide deposit and nearby Fe-oxide deposits in Sweden; and the Apliki West copper prospect in Cyprus.

At the current state, the produced near-mine geological- and geophysical models provide a good three-dimensional overview on the shape and spatial distribution of multiple ore bodies and their hosting lithologies as well as their regional-scale structures. A structural control on the Pb-Zn sulphide mineralization in Sweden and Greece is now evident from observations on ore textures and 3D modelling results. To continue modelling, more data on petrophysical properties is needed enabling a better integration between the geological- and geophysical modelling results and to reduce the non-uniqueness of the inversion process of potential field data (gravity, magnetics, conductivity). Subsequently, orebody (in-mine) models will then be produced for each test site building heavily on data derived from XRF-XRT scanning on oriented core drilled for the X-mine project.





Exploration Lapland 3D (XL3D) data mining, data integration and 3D modelling concept

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Vast digital geological and geophysical data sets exist in districts with prolonged history in geological research and exploration history. Exploration and mining industry is using these data sets for locating new mineral deposits. Exploration Lapland 3D (XL3D) project aims to create a scalable data mining, data integration and 3D modelling concept for GTK and private enterprises providing mineral exploration services. This is needed due to large and constantly accumulating exploration data sets. The concept is tested by using it in generating a new geological 3D model Central Lapland area currently under active exploration by a number of companies. The model will provide key geological criteria for magmatic Ni-Cu and orogenic Au mineral systems which in turn will be used in generating new mineral prospectivity maps of the area.

The XL3D uses GTK's geological, geochemical and geophysical data sets of the target area including bedrock observation and drill core data, till geochemistry, aerogeophysical data (magnetic, electromagnetic and radiometric), ground gravity data, petrophysical data, audiomagnetotelluric data and 2D reflection seismic data. The workflow consists of following steps: a) data compilation, b) unconstrained 1-3D geophysical inversions, c) the generation of the initial 3D model, d) an iterative re-modeling phase where the initial geological 3D model is used in generating constrained geophysical inversion models and the geological model is updated for the model to best fit the data e) mineral prospectivity modelling. The main novelty in the concept is the use of Self-Organizing Map (SOM) methodology both in 2D and 3D in data mining and data integration in various steps of the process.

The XL3D data mining, data integration and 3D modelling concept, the 3D models, and the prospectivity maps generated will be made publicly available for the industry, SME's providing services for the industry and scientific community upon the end of the project.

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Mapping procedures and scaling relationships of brittle structures in southern Finland

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Brittle structures of the bedrock play an important role in the suitability of bedrock volumes for different underground applications, let it be conventional underground construction where bedrock stability needs to be assessed or more advanced application, such as construction of deep geological nuclear waste repositories. In the latter case, faults and fractures form the main conduits for e.g. groundwater flow and are the main risk in respect to short- and long-term stability of the rock volume. In all of these underground applications, characterisation and modelling of brittle structures is an important aspect. With the aid of both field-based and desktop-based studies, brittle structures can be mapped to a certain extent but due to time, resource and data constraints, it is typical that some areas, dimensions and scales have to be overlooked during such studies. In terms of the properties of fracture systems in Finland, relatively few studies are available and there is still quite little understanding about the characteristics of fracture networks and on their variation regionally. To address these shortcomings, a research project has been established at the Geological Survey of Finland to study bedrock fracturing patterns in different scales.

Our studies are targeted to areas with exceptionally well-exposed outcrops along the coastline of southern Finland. For these areas, new brittle data is collected at several different scales - regional lineament interpretation on the basis of geophysical and topographic data, fracture trace data based on UAV (Unmanned Aerial Vehicle) photogrammetry and detailed-scale outcrop mapping. To analyse fracture length, intensity and topology we are mostly limited to 2D datasets. For the topographic lineament interpretation, data is interpreted in three different scales. For the UAV photogrammetric fracture trace mapping we use a Phantom 4 Pro drone for taking photographs with flight altitude varying between 2–100 m depending on the purpose and required resolution. A flight altitude of 20 m has proved to be suitable for surveying relatively large areas and for mapping most fractures over 1 m in length. To obtain data from the cm scale fractures, we photographed smaller areas of in size of 5x5 m from a 2–3 m altitude. From the photographs we produce high-resolution orthomosaics and digital elevation models which are used for manual mapping of fracture traces. Unfortunately any current automatic techniques for lineament and fracture identification have not yet provided us with a better solution than manual mapping, but could be an interesting field for future research and development. An automatic technique would remove interpretation variances and the main bottleneck, manual mapping, for acquiring very large datasets.

The starting point of the comparisons between the different scales is the evaluation of the fracture length and intensity distributions and the comparison of the distributions to the known scaling distributions of fracture systems (power law, exponential, gamma and log normal). If the fracture scalability relationships on different scales can be detected, then the fracture lengths and intensities can be predicted between different scales.

Within this project different workflows for collecting and analysing datasets will be tested to define an efficient workflow for data collection and analysis, with the ultimate aim of assessing and mitigating the current uncertainties related to 3D and stochastic modelling of brittle structures.





Multiscale mineral potential studies of Outokumpu ore zone using 3D modelling and high performance computing for forward geophysical modelling

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Handling of increasingly huge and diverse data sets on multiple spatial scales and variable sources are major challenges of 3D mineral potential and mine site evaluation studies. Datasets comprise, for instance, airborne and ground geophysical data, structural field data, geological maps and cross sections, geochemical data, drill hole data and core logs. Since direct geological information is often sparse the subsurface geology has to be inferred through inversion of measured geophysical data. Inversion methods, however, do not produce unique solutions but stochastic and inversion methods require input of geological constraints in order to achieve geologically reliable models.

The Outokumpu ore zone is hosting a number of ore bodies within the Palaeoproterozoic North Karelia Schist Belt. Mining activity started 1913 and several mines have already been closed (e.g. Keretti/Outokumpu and Vuonos) but serve as valuable data sources for ore exploration.

This presentation demonstrates the GECCO workflow for the area containing historical Keretti and Vuonos massive Cu-Zn-Co and disseminated Ni sulphide ore deposits hosted by a distinct lithological assemblage, the Outokumpu assemblage, consisting of peridotite and serpentinite enveloped by Cr-bearing carbonate-quartz rocks. The calculated gravity and magnetic responses were used to validate the alternative geological 3D models based on varying lithological subdivisions associated with different conceptual models. High performance computing using GPU for calculating gravity and magnetic responses in real time. Electromagnetic forward modelling using Julia programming language was applied to trace conductive zones.

The project is funded by the Finnish Academy of Science and led by the Geological Survey of Finland. Collaborating scientists are from Åbo Akademi University, the Geological Survey of Norway, and the University of Western Australia. The workflow has to integrate many steps which have to be tested and evaluated before all threads can be finally brought together. Work is progress; the presentation at this stage aims to give an introduction to the project idea and some first interim results.

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Hyperspectral point clouds for mineral exploration and geological research

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Virtual outcrop models and hyperspectral imaging are powerful geological tools in their own right. In combination, however, these datasets allow the evaluation of material properties in 3D space and thus provice a valuable asset to any modern geological field campaign. With applications ranging from mine face mapping to paleoseismic trenching analysis, we showcase the benefits of integrated infrared hyperspectral and photogrammetric data from vertical outcrops through selected case studies. The presented virtual models are based on Structure-from-Motion point clouds co-registered to hyperspectral imagery, which is geometrically and radiometrically corrected, prepared using established image processing algorithms and machine learning approaches, and validated using analytical sample data. The described workflow is flexible enough to incorporate ground- or drone-based visible to near-infrared (VNIR), short-wave infrared (SWIR) and long-wave infrared (LWIR) hyperspectral data. Hence, hyperspectral point clouds not only provide an intuitive visualisation of the outcrop and a versatile data archive, but also enable a safe, efficient, and unbiased assessment of the mineralogical composition of lithologic units and a semi-automatic delineation of contacts and deformational structures in a 3D virtual environment.

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